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Type #: 

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Document: GTRC

Title: WORKSHOP ON "RESEARCH NEEDS IN POWER SYSTEM OPERATIONS AND PLANNING"

PROJECT ADMINISTRATION DATA

A contact: David B. Bridges 894-4820

Sponsor technical contact

WJAN BOSE
202)357-9618
SF
300 G ST.
J 20550

Security class (U,C,S,TS): U

NSF
1800 G ST.
DC 20550

Sponsor issuing office

SHIRLEY WOODS
(202)357-9602

NSF supplemental sheet

NONE PROPOSED

PROJECT INITIATION, FUNDS IAO $26,690, TERMINATES 7/31/90; FOR WORKSHOP THEREFORE FOLLOW GUIDELINES IN NSF F.L. 26
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 03/25/91

Project No. E-21-609

Project Director MELIPOULOS A P

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. ECS-8914842

Contract Entity GTRC

Title WORKSHOP ON "RESEARCH NEEDS IN POWER SYSTEM OPERATIONS AND PLANNING"

Effective Completion Date 910131 (Performance) 910430 (Reports)

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Project Under Main Project No. 

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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 03/25/91

Project No. E-21-609
Project Director MELIPOULOS A P
School/Lab ELEC ENGR

Center No. 10/24-6-R6802-0A0

Sponsor NATL SCIENCE FOUNDATION/GENERAL

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END

* indicates the project is a subproject.
I indicates the project is active and being updated.
A indicates the project is currently active.
T indicates the project has been terminated.
R indicates a terminated project that is being modified.
April 1, 1991

Dr. Kevin A. Clements
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20277-2806

Dear Dr. Clements:

Enclosed please find the completed NSF Form 98A for the "Workshop on Research Needs in Power System Operations and Planning", Award No. 8914842.

Sincerely,

A.P. Sakis Meliopoulos
Professor

APSM/mmc

Enclosure

cc: Ms. Kathy Knighton
NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

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| 4. Institution and Address | Georgia Tech Research Corp  
|                          | Administration Building  
|                          | Atlanta GA 30332 |
| 5. Award Number         | 8914842 |
| 6. Project Title        | Workshop on "Research Needs in Power System Operations and Planning" held in Atlanta, GA - September 5-8, 1989 |

This Packet Contains
NSF Form 98A
And 1 Return Envelope
Grant Conditions (Article 17, GC-1, and Article 9, FDP-II) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days after the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (F Grants Policy Manual Section 677).

Submit, or on a separate page, provide a summary of the completed projects and technical information and attach it to this form. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

A summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence starting the project’s major thesis. The summary should include, if pertinent to the project being described, the following items:

1. Primary objectives and scope of the project
2. Techniques or approaches used only to the degree necessary for comprehension
3. Findings and implications stated as concisely and informatively as possible

The NSF Workshop on Research Needs in Power System Operations and Planning was held on the Georgia Institute of Technology campus on September 5-8, 1989. It was attended by 49 recognized researchers in the field. There were four caucus meetings, four technical presentation sessions, four round table discussion meetings, and a dinner meeting. The technical discussions focused on four specific areas of research: (1) Security Assessment, (2) Power System Economics 2000 and Beyond, (3) Strategic Planning, and (4) Emerging Technologies. The final report is the proceedings of the workshop including an executive summary of the conclusions.

PART III - TECHNICAL INFORMATION (for program management use)

References to publications resulting from this award and briefly describe primary data, samples, physical collections, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community.

The participants contributed 12 technical papers. In addition, the discussions of the workshop have been condensed into an executive summary. The 12 technical papers and the executive summary have been published as "Workshop Proceedings", NSF Workshop on Research Needs in Power System Operations and Planning. The proceedings have been mailed to about 250 recognized experts on the field.

April 1, 1991

Principal Investigator/Project Director Signature Date

IMPORTANT:
MAILING INSTRUCTIONS

Return this entire packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the Attention line on the envelope.

NSF Form 98A (Rev. 5/90)
PART IV — FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL
(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the “Decline to Provide Information” box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant. Do not enter information for individuals working less than 40 hours in any calendar year.

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DISABLED³

Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

This part will be physically separated from the final project report and used as a computer source document. Do not duplicate it on the reverse of any other part of the final report.

³USC 1885C includes, for example, college and precollege teachers, conference and workshop participants.

²Use the category that best describes the ethnic/racial status for all U.S. Citizens and Non-citizens with Permanent Residency. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

³A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. (Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as “Other Non-U.S. Citizens.”)

AN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

IAN: A person having origins in any of the original peoples of East Asia, Southeast Asia and the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

ACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

SPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

IFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific Territories of Guam, American Samoa, or the Northern Marianas; the U.S. Trust Territory of Palau; the islands of Micronesia or Melanesia; or the Philippines.

HITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.
The NSF Workshop on Research Needs in Power System Operations and Planning was held on the Georgia Institute of Technology campus on September 5-8, 1989. It was attended by 50 recognized researchers in the field. There were four caucus meetings, four technical presentation sessions, four round table discussion meetings, and a dinner meeting. The technical discussions focused on four specific areas of research:

1. Security Assessment
2. Power System Economics 2000 and Beyond
3. Strategic Planning
4. Emerging Technologies

The final report is the proceedings of the workshop including an executive summary of the conclusions. The proceedings have been distributed to about 200 individuals/researchers working in the area of power system operation and planning.
NSF WORKSHOP ON

RESEARCH NEEDS IN POWER SYSTEM OPERATIONS AND PLANNING

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332
SEPTEMBER 5-8, 1989

WORKSHOP PROCEEDINGS

NATIONAL SCIENCE FOUNDATION
LARGE SCALE NONLINEAR SYSTEMS PROGRAM
WASHINGTON, DC 20550
NSF WORKSHOP ON

RESEARCH NEEDS IN POWER SYSTEM OPERATIONS AND PLANNING

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332
SEPTEMBER 5-8, 1989

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LARGE SCALE NONLINEAR SYSTEMS PROGRAM
WASHINGTON, DC 20550
## NSF WORKSHOP ON RESEARCH NEEDS IN POWER SYSTEM OPERATIONS AND PLANNING

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ACKNOWLEDGEMENTS

The workshop organizers, Felix Wu, Sarosh Talukdar, Roger Webb, and Sakis Meliopoulos, would like to thank Dr. Anjan Bose for supporting the workshop and his helpful and constructive suggestions. Dr. G. T. Heydt is also acknowledged for his enthusiastic support of the workshop and his contributions to the workshop discussions.
EXECUTIVE SUMMARY

The workshop was held on the Georgia Tech campus. It brought together recognized researchers in Power Systems Operations and Planning and provided a forum for discussions of research needs. A list of attendees is attached. Four specific areas in research needs were addressed. A summary of the conclusions follows:

Security Assessment

The principle objectives of power system operators are to minimize costs while maintaining security at adequate levels, and staying within the bounds prescribed by regulatory policy. Two of the principle challenges in meeting these objectives are:

1. How to characterize and measure security. (Security covers both quality of service and system integrity from the viewpoint of real-time operations. As such, security has fuzzy, qualitative components that are hard to quantify and hard to include in assessment methods.)

2. How to resolve conflicts among the objectives. (The objectives, particularly cost and security, are often in conflict. These conflicts are likely to become more acute in the future. Therefore, it is important to develop and maintain methods for resolving conflicts that will at least keep pace with the growing strengths of the conflicts.)

The "security portion" of the workshop examined these challenges, attempted to identify the key research problems that must be solved, and discussed approaches to these problems.

Power System Economics 2000 and Beyond

(Dedicated to late Professor E. Schweppe)

The electric power industry in the U.S. is undergoing unprecedented transformation. A visionary view of the future was debated and an attempt was made to define research needs within this framework.
The forces behind the changes in electric power systems were examined along three dimensions: (1) organizational, (2) operational, and (3) technological. Impact of these forces on future power systems will be discussed. Innovative research to meet the challenges will be outlined.

1. **Organizational**
   - Industrial/regulatory structures
   - Market and pricing

2. **Operational**
   - New operating philosophy
   - Changing concerns in economics and security

3. **Technological**
   - Computers
   - Communications
   - Control.
Research Needs in Strategic Planning

Electric power supply systems provide about 1/3 of the total U.S. energy, and it is certain that they will play an increasingly critical role in the nation's energy economy. Strategic planning of these systems is pivotal for a strong economy. Traditional strategic planning of electric power systems has been based on selecting the minimum overall cost expansion plan which will be capable of supplying the demand with a historically accepted level of reliability. Presently, Power System planning is undergoing basic changes due to three basic events: (a) the energy dislocations of the 70's, (b) the 1978 PURPA, and (c) deregulation. The changes will be constrained by public policy, technological innovation, environmental concerns and economic forces. It is certain that under the present environment, strategic planning of power systems will be an evolutionary process. Within this process, the following issues will be very important:

1. Transmission Access
2. All Source Bidding
3. Role of Regulation/Deregulation
4. Uncertainty
5. Reliability
6. Environmental Issues
7. Industry Evolutionary Restructuring

The process can be better served, and with beneficial results to the power industry and the national economy in general, if the research community provides proper analytical tools. In this context the following issues have been identified.

Uncertainty has always been present in the planning process. What is changing is the dynamics of the uncertainty caused by rate structures, deregulation, competition, non-utility producers, and development of electrotechnologies. A challenging research need is to provide descriptive models of uncertainty and its dynamics encompassing the changing environment and the interrelationships of the above-mentioned issues.

Demand Side options are becoming an integral part of the planning process. Load Management, Direct load control, and customers with generation are affecting utility operation and economics. Yet, reliable analytical tools to describe the aggregate impact of such issues do not exist.
Transmission Access is an emerging critical issue which impacts system security, reliability, transmission losses and operating economics (optimization). It raises operational, as well as institutional issues. Assuming that institutional issues are resolved, open transmission access will result in increased expenditures to provide the proper infrastructure. The related subject of increased interchanges among utilities place higher emphasis on transfer capability.

Power systems reliability is becoming a challenging issue under the present environment. Five major areas have been identified where challenges need to be met. These are: (a) conceptual problems, (b) modeling issues, (c) optimization, (d) new methodologies, and (e) communications. The conceptual problems are probably the most important. First of all, deterministic approaches, still much in use, are restricted in the quantity and quality of the information they produce and certainly cannot address all present concerns. The probabilistic approach is becoming a viable alternative. The probabilistic approach is based on the use of probabilistic indices. Probabilistic reliability criteria (standards) are established in terms of these indices. Another set of conceptual issues are related to system analysis. These are (a) definition of what constitutes a system failure, (b) definition and prediction of rare events, (c) data requirements to carry out reliability calculations, and (d) verification of methods. Modeling issues still exist because present methods cannot adequately address all the complexities of the problem. Modeling issues relate to (a) unit duty cycles, (b) unplanned outage postponability, (c) system dynamics, (d) Transmission constraints, and (e) protection and control systems.

The payoffs of reliability analysis is system optimization. Specifically, it can provide cost/benefit evaluations, estimates of interruption costs, and optimization of maintenance schedules.

In view of increased public awareness, it is necessary to communicate reliability analysis results among engineers, management, and the public and to educate the public on the tradeoffs.

The introduction of power electronics is adding another dimension to the controllability of the power system with substantial impact on power system planning procedures. Flexible AC Transmission Systems (FACTS) as have been coined by EPRI require new adaptations of planning procedures. New formulations more powerful than existing analysis models will be required to deal with increase controllability of the power system.

The research community has the responsibility to address these problems and to provide models and tools which will increase our understanding of the interrelationships between power system expansion options and the national economy and the environment.
EMERGING TECHNOLOGIES
RESEARCH OPPORTUNITIES AND NEEDS

Despite its conservative image, the U.S. power industry has not been too reticent about adoption of new technologies. Certainly power utilities have been at least as aggressive as other segments of industry incorporating computer technology into many aspects of system operation and design, and are anticipating new technological advances in computing to enhance system control and monitoring.

Advances in computer technologies are, however, not necessarily driven by power system needs. Research to achieve increased computation speed and parallel processing architectures which can be readily utilized in power systems will be supported by a variety of constituents. There are emerging technologies whose primary application is in the power arena and must derive primary research support from agencies dedicated to the support of such research. This workshop addressed four such technologies ranging from already established technologies with fairly predictable evolution to areas which cannot yet be classified as technology but which could lead to revolution. All four are characterized by the need for basic materials research. Power semiconductors are already making significant impact in many aspects of power system operations. Additional potential applications, and the attendant required technological advances, are identifiable. Photovoltaics have survived the initial euphoria and irrational advocacy to become a solid area of technological development which has potential for significant impact on the power system. Superconductivity has undergone a more recent transient. High temperature superconducting materials have now become sufficiently understood that reasonable technological and economic assessments are possible. At the
same time, existing low temperature superconducting materials and technologies warrant continual evaluation.

Cold fusion gives the appearance of having been stillborn. It's true, appearance is in part distorted by factors not altogether scientific, and the potential impact of the phenomena certainly warrants rational assessment by the electric power community.

The identification of research opportunities and needs of these "emerging technologies" are products of this workshop and are outlined below.

POWER ELECTRONICS

Application Opportunities

- Bulk Power Transmission
  - HVDC Transmission
- Bulk Power Control
  - Voltage/Var Control
  - Power/Angle Control
- End Use Applications
  - Continuous Motor Speed/Torque Control
  - Modulation of Electric Heating and Drying
  - Uninterruptable Power Supplies, UPS
- System Protection
  - Solid State Switching/Circuit Breaking
  - Current Throttling
  - Harmonic Mitigation
Research Needs

- Research development is needed in the area of integrated "smart power" modules that can be used across a broad range of power generation, power conditioning, power delivery, and power processing systems. Such modules would contain all needed functions of drive interface, electrical isolation, conditioning, control, etc. - all integrated with the power semiconductors.

- An integrated effort to the development of power electronic devices - starting with materials and components and incorporating new technologies into devices and systems (as suggested in 1).

- In the device area, development of improved low-cost power switching semiconductors that would operate at higher frequencies and with higher efficiencies than current devices. Although new developments are very high cost in this area, it may be possible to leverage on-going developments and the benefits would accrue to several energy system concepts.

- Power electronics are bound to impact the power utility industry in several areas: dispersed generation and cogeneration - interfacing, power conditioning, etc.; industrial applications - separation techniques, adjustable speed drives, etc.; remote power requirements; dc transmission.

PHOTOVOLTAICS

- Introduction: Projections for additional U.S. utility capacity needs range from 100 GW by the year 2000 to 250 GW by 2010, and much of this is projected to be demand for peaking units. Photovoltaics is expected to play an appreciable role by tapping the unlimited natural resource of
sunlight. The basic power element of a PV system is the solar cell which converts sunlight directly into electricity and the energy conversion is pollution free. Solar cells made from materials like single crystal silicon and GaAs have been shown to be stable and reliable with a 30 year lifetime.

**Cost Consideration:** The cost of producing electricity from PV has come down very rapidly from $15/kWhr in 1975 to about 30¢/kWhr today. DOE's long term goal is to bring the cost down to 6¢/kWhr so it can compete with conventional energy sources. This can be achieved by module conversion efficiencies of 15% at a production cost of $100/m² with a 30 year module life.

**Recent Accomplishments:** Some of the recent PV accomplishments include the development of 23% efficient one sun silicon cells, 28% efficient silicon concentrator cells, 29% efficient GaAs concentrator cells, 15-17% efficient sheet silicon cells, 17-18% efficient polycrystalline silicon cells, 10-11% efficient amorphous silicon cells, 12% efficient CdTe cells, and 14% efficient CuInSe₂ cells. It will be a few years before these laboratory cell efficiencies can be realized in production. Recently Sandia Labs reported a conversion efficiency of 31% using a combination of GaAs and silicon cells. Boeing has announced 37% concentrator cell by a combination of GaAs and Ga₃Sb₅.

**Research Needs:** No material or technology has yet met this cost and efficiency goal simultaneously. Research is being conducted on various materials including high-cost high-efficiency silicon and gallium arsenide and low-cost low-efficiency materials like amorphous silicon and polycrystalline CuInSe₂ and CdTe. Advanced concepts like concentrator
and cascade solar cells also need to be investigated to boost the output power. Specific needs are listed below:

- Basic research is needed in the area of semiconductor materials to identify loss mechanisms which reduce the output of solar cells.

- There is a need to develop better models to design high efficiency devices. This is especially true in the area of thin film solar cells where carrier transport and recombination mechanisms at the interfaces are not well understood.

- Advanced concepts like concentrators and tandem solar cells using single crystal and thin film materials need to be investigated more thoroughly to increase solar cell performance.

- Process of transferring laboratory cell technologies to production needs to be streamlined and expedited. Manufacturability should be stressed.

**Other Issues**

- There is a need for policies and programs to provide partnerships between universities, PV industry, government, and utilities.

- There is a need for a total systems approach to PV, and to develop more reliable power conditioning equipment, storage devices, and the support structure for PV modules.

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**SUPERCONDUCTIVITY**

Superconductors allow the flow of electrical current with zero energy loss to resistance for DC transmission below a critical current density. Thus, they promise ideal energy transmission and new technologies including high field magnets which may be used to store energy or to confine charged particles.
particles in a fusion reactor. The 1986 discovery of high temperature superconductivity in an unlikely group of copper oxides generated intense excitement and a rush to find new alloys which may superconduct even closer to room temperature. Now, despite international scrutiny of high grade samples and publication of more than 4,600 papers on the rates, the origin of their superconducting character remains a mystery. Even the nature of the current carriers remains in doubt: holes, electrons, and more exotic species have been proposed, but the key ingredient is not yet established. Large scale power applications of the oxide alloys are not hopeful at this point, in part because of their brittleness, extreme corrosion difficulties, and fundamental obstacles to the transport of large current density $j_c$ in wires, cables, and coils which may be appropriate for magnets and transmission lines. Alternating current creates a power loss inversely proportional to $j_c$, and presently available oxide materials are unable to surmount this obstacle. Hence, a search for new duct-like, corrosion-resistant alloys which may retain superconductivity properties at even higher temperatures is warranted by technological needs and scientific optimism. Theoretical suggestions for a variety of mechanisms often point to room temperature superconductivity although predictions for specific materials are rare.

COLD FUSION

Much more experimental data is needed to establish the claimed cold fusion results as scientific fact. Even if they prove to be true, it is not clear at this stage that cold fusion will be an efficient source of electric power production through a Carnot cycle because the fusion rate may drop with increased temperatures. Nevertheless, it may serve as a moderate temperature
distributed heat source. More importantly, cold fusion has the potential of being a significant source of tritium for both civilian and military applications. In its civilian application, cold fusion production of tritium may play a significant role in making hot fusion practical, since the d+t reaction is significantly more energetic than the d+d reaction.
NSF WORKSHOP ON
RESEARCH NEEDS IN POWER SYSTEM
OPERATIONS AND PLANNING
Georgia Institute of Technology
Atlanta, Georgia 30332
September 5-8, 1989

WORKSHOP ORGANIZERS

Dr. Sarosh Talukdar
Department of Electrical and Computer Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

Dr. Felix F. Wu
Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, California

Dr. Roger P. Webb
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia

Dr. A. P. Sakis Meliopoulos
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia
<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Address</th>
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<tr>
<td>ANDO L. ALVARADO</td>
<td>ASSISTANT PROFESSOR</td>
<td>UNIVERSITY OF WISCONSIN</td>
</tr>
<tr>
<td></td>
<td>JOHNSON DRIVE</td>
<td>SON, WI 53706</td>
</tr>
<tr>
<td>MARTIN BAUGHMAN</td>
<td>ASSOCIATE PROFESSOR</td>
<td>UNIVERSITY OF TEXAS</td>
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<td>SLAV M. BEGOVICH</td>
<td>STANT PROFESSOR</td>
<td>OKLAHOMA UNIVERSITY</td>
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<td>JIA INSTITUTE</td>
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<td>NORMAN, OK 73072</td>
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<tr>
<td>ARTHUR M. BREIPOHL</td>
<td>OG &amp; E PROFESSOR</td>
<td>UNIVERSITY OF OKLAHOMA</td>
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<td>GEOREGIA INSTITUTE</td>
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<td>O. E. CARLSON</td>
<td>PRESIDENT</td>
<td>GEORGIA INSTITUTE</td>
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<td>WASHINGTON</td>
<td>P. O. BOX 35034</td>
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<td>J. D. CHIANG</td>
<td>STANT PROFESSOR</td>
<td>GEORGIA INSTITUTE</td>
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<td>ILL UNIVERSITY</td>
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<td>CAROL S. CHENG</td>
<td>GRADUATE STUDENT</td>
<td>GEORGIA INSTITUTE</td>
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<td>K. DONG CHIANG</td>
<td>STANT PROFESSOR</td>
<td>GEORGIA INSTITUTE</td>
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<td>NEWTOWN-YARDLEY ROAD</td>
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<td>GEORGIA INSTITUTE</td>
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<td>R. D. CHRISTIE</td>
<td>STANT PROFESSOR</td>
<td>GEORGIA INSTITUTE</td>
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<td>SOUTH CAROLINA</td>
<td>P. O. BOX 32666</td>
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<tr>
<td>M. DANESHDOOST</td>
<td>ASSOCIATE PROFESSOR</td>
<td>SOUTHERN ILLINOIS UNIVERSITY</td>
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<td></td>
<td>DEPARTMENT OF ELECTRICAL ENGINEERING</td>
<td>CARBONDALE, IL 61901-6603</td>
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NSF WORKSHOP ON RESEARCH IN POWER SYSTEMS OPERATIONS
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PAUL WEBER BUILDING
FINAL ROSTER

S. DEBS
ESSOR
GIA TECH
OL OF ELECTRICAL
NEERING
NTA, GA 30332

ALI FELIACHI
ASSOCIATE PROFESSOR
WEST VIRGINIA UNIVERSITY
P. O. BOX 6101
MORGANTOWN, WV 26506-6101

ER H. FINK
IDENT
SEN AND FINK
CIATES, INCORPORATED
4 WAPLES MILL ROAD D-2
FAX, VA 22030

A. A. FOUAD
PROFESSOR
IOWA STATE UNIVERSITY
122 COOVER HALL
AMES, IA 50011

A. GIRGIS
ESSOR
SON UNIVERSITY
DEPARTMENT
SON, SC 29634-0915

HANS M. GLAVITSCH
PROFESSOR
ETH ZURICH
ETH ZENTRUM
ZURICH, CH8092

IE S. HECK
STANT PROFESSOR
HIA INSTITUTE OF
NOLOGY/SCHOOL OF
RICAL ENGINEERING
NTA, GA 30332

GERALD T. HEYDT
PROGRAM DIRECTOR
NSF
ECS-1151 - NSF
1800 G STREET, N.W.
WASHINGTON, DC 20550

L. HUBAND
SION DIRECTOR
RICAL SYSTEMS
GROUP
1800 G STREET, N.W.
INGTON, DC 20550

BARRY HYMAN
ASSOCIATE PROFESSOR
IVERSITY OF WASHINGTON
FU-10
SEATTLE, WA 98195

JA ILIC
T.
DING 10 - 059
ASS AVENUE
RIDGE, WA 02931

R. JOHN KAYE
VISITING ASSOCIATE ENGINEER
U. C. BERKELEY
231 CORY HALL
BERKELEY, CA 94720
LD L. KLEIN
ESSOR AND CHAIRMAN
VIRGINIA UNIVERSITY
BOX 6101
ANTOWN, WV 26506-6101

K KUMAR
CIATE PROFESSOR
C CAROLINA A & T
2 UNIVERSITY
EAST MARKET STREET
NSBORO, NC 27411

SAKIS MELIOPoulos
CIATE PROFESSOR
IIA INSTITUTE OF 
VOCOLOGY/SCHOOL OF 
TRICAL ENGINEERING
VTA, GA 30332-0250

3 A. MOMOH
CIATE PROFESSOR
4D UNIVERSITY
6TH STREET
INGTON, DC 20059

PAI
RTMENT OF ELECTRICAL 
COMP. ENGINEERING 
RSITY OF ILLINOIS 
EST GREEN STREET 
VA, IL 61801

J V. F. PEREIRA 

275Y 
OE JANEIRO 
0001 
IL,

FRANK LEWIS
ASSOCIATE PROFESSOR
GEORGIA INSTITUTE 
of TECHNOLOGY
ATLANTA, GA 30332

HYDE M. MERRILL
MANAGER - PLANNING 
POWER TECHNOLOGIES, 
INCORPORATED
BOX 4058 
SCHENECTADY, NY 12301

SHMUEL S. OREN
PROFESSOR AND CHAIR, IEOR 
IVERSITY OF CALIFORNIA 
AT BERKELEY 
ETCHEVERRY HALL 4143 
BERKELEY, CA 94720

ALTON DeWITT PATTON 
PROFESSOR 
TEXAS A&M UNIVERSITY 
LECTRICAL ENGINEERING 
PARTMENT 
OLLEGE STATION, TX 77843

MARIO RABINOWITZ 
ENIOR SCIENTIST 
PR 
PO. BOX 10412 
PALO ALTO, CA 94303
NSF WORKSHOP ON RESEARCH IN POWER SYSTEMS OPERATIONS
09/06/89 - 09/08/89
PAUL WEBER BUILDING
FINAL ROSTER

UR RAHMAN
ESSOR
INIA TECH
TRICAL ENGINEERING DEPARTMENT
WHITTEMORE HALL
KSBUY, VA 24061

A. ROHATGI
PROFESSOR
GEORGIA INSTITUTE
OF TECHNOLOGY
ATLANTA, GA 30332

RUVALDS
ESSOR
ERSITY OF VIRGINIA
ICS DEPARTMENT
LOTESVILLE, VA 22901

SETH R. SANDERS
ASSISTANT PROFESSOR
U. C. BERKELEY
DEPARTMENT EECS
CORY HALL
BERKELEY, CA 947210

LD B. SHELBE
CIATE PROFESSOR
RN UNIVERSTY
RTMENT OF ELECTRICAL
NEERING
RN, AL 36849

CHANAN SINGH
PROFESSOR OF ELECTRICAL
ENGNEERING
ERTAS A&M UNIVERSTY
DEPARTMENT OF ELECTRICAL ENGNEERING
COLLEGE STATION, TX 77843

RT L. SULLIVAN
RAM AND PROFESSOR
ERSITY OF FLORIDA
LARSEN HALL
ESVILLE, FL 32611

SAROSH N. TALUKDAR
DIRECTOR DESIGN SYSTEMS
ERNEGIE MELLON UNIVERSTY
DOHERTY HALL - A219
PITTSBURGH, PA 15213

GE J. VACHTSEVANOS
ESSOR
GIA INSTITUTE
ECHNOLOGY
NTA, GA 30332

PRAVIN P. VARAIYA
PROFESSOR
EECA DEPARTMENT
U. C.
BERKELEY, CA 94720

. VENKATA
ESSOR
ERSITY OF WASHINGTON
0
TLE, WA 98195

BRUCE F. WOLLENBERG
PRINCIPAL CONSULTANT
CONTROL DATA CORPORATION
2300 BERKSHIRE LANE, NORTH
PLYMOUTH, MN 55345
J. WOOD
ENER-PLANNER
TECHNOLOGIES, INCORPORATED
1058 POST ST.
TECTODY, NY 12301

FELIX WU
PROFESSOR
UNIVERSITY OF CALIFORNIA
231 CONY HALL
BERKELEY, CA 94720
NSF Workshop on Research Needs in Power System Operations and Planning

Tentative Schedule

pt. 5, 1989
7:00 - 9:00 p.m. Welcome Reception

pt. 6, 1989
8:00 - 8:30 a.m. Registration - Paul Weber Building
8:30 - 9:00 Organizational Meeting
9:00 - 12:00 Caucus Meetings
   Security Assessment Group: Room 1
   Power System Economics: Room 2
   Strategic Planning: Room 3
   Emerging Technologies: Room 4
12:00 - 1:30 p.m. Lunch
1:30 - 3:00 Security Assessment Session A
   Chairman: Dr. Sarosh Talukdar
   "Analytical and Rule based approaches in security assessment and enhancement"
   Prof. Hans Glavitsch, ETH Zurich
   "New approaches to Dynamic Security Assessment"
   M.A. Pai, P. Sauer, University of Illinois
   "Dynamic Security As Affected by a Changing Electric Utility Environment"
   A.A. Fouad, Iowa State University
   "Problems in Power System Security"
   Rich Christie, University of Washington
3:00 - 3:30 Break
3:30 - 5:00  Security Assessment Session B

Chairman:  Dr. Sarosh Talukdar

Round Table Discussion

5:00 - 7:00  Open
7:00 - 9:00  Dinner

Keynote Speaker:  Dr. Frank Hubbard, NSF

Sept. 7, 1989

8:30 - 10:00 a.m.  Power Systems 2000 and Beyond
Session A

Chairman:  Dr. Felix Wu

"Organizational Issues"
Marty Baughman, sub-area coordinator
Contributors:  S. Oren
              M. Caramanis
              J. Kaye

"Operational Issues"
Bob Thomas, sub-area coordinator
Contributors:  M. Ilic
              C. DeMarco
              B. Fischl
              J. Grainger

"Technological Issues"
Pravin Varaiya, sub-area coordinator
Contributors:  J. Thorp
              F. Alvarado
              C.C. Liu
              K. Clemens

10:00 - 10:30  Break

10:30 - 12:00  Power Systems 2000 and Beyond
Session B

Chairman:  Dr. Felix Wu

Round Table Discussion
12:00 - 1:30 p.m. Lunch

1:30 - 3:30 Strategic Planning Session A

Chairman: Dr. Robert Sullivan

"System Reliability Modeling Issues"
A.D. Patton, Texas A&M University

"Evolution of Power System Reliability Analysis"
R.L. Sullivan, University of Florida

"The Need for a busy signal and Risk and Uncertainty in Strategic Planning"
H.M. Merrill, and A.J. Wood, Power Technologies, Inc.

"Modeling and Optimization issues in Expansion Planning Studies"
A.P. Meliopoulos, Georgia Tech, and G.J. Cokkinides, University of South Carolina

"On the Treatment of Uncertainty in Power System Planning"
A.S. Debs, Georgia Tech

"Reactive Power Planning for Voltage Control"
J.A. Momoh, Howard University

3:30 - 4:00 Break

4:00 - 5:00 Strategic Planning Session B

Chairman: Dr. A.P. Meliopoulos

Round Table Discussion

5:00 - 7:00 Open

7:00 - 9:00 Dinner
8:30 - 10:00 a.m. Emerging Technologies Session A

Chairman: Dr. R.P. Webb

"Present and Future Impact of Power Electronic Systems on the Electric Utility Industry"
H.B. Puttgen, Georgia Institute of Technology

"Recent Trends in Photovoltaics"
A. Rohatgi, Georgia Institute of Technology

"Photovoltaic Technologies for Power Generation"
David E. Carlson, Solarex

10:00 - 10:30 Break

10:30 - 12:00 Emerging Technologies Session B

Chairman: Dr. R.P. Webb

"A Comparison of Cold Fusion and High Temperature Superconductivity"
M. Rabinowitz, Electric Power Research Institute

"Prospects for New Superconductivity Materials"
J. Ruvalds, University of Virginia

12:00 - 1:30 p.m. Lunch
POWER SYSTEM OPTIMIZATION USING AI-TECHNIQUES TO INTEGRATE ANALYTICAL SOFTWARE

by

D. Reichelt and H. Glavitsch
Swiss Federal Institute of Technology
Zürich, Switzerland
Power System Optimization Using AI-Techniques to Integrate Analytical Software

D. Reichelt, H. Glavitsch
Swiss Federal Institute of Technology, Zürich, Switzerland

ABSTRACT

Beyond the individual use of optimization programs in power systems a next step in the optimization is seen in the combined use of knowledge-based and analytical programs. The problem of assessing the security of a system is considered (OPF, short circuit current, overload). Thereby the approach adopted by an operator is attempted to reproduce. A key feature is the search along a tree and the observation of several objective functions. The control of the search is realized by a knowledge-based program. Two examples of networks optimized with respect to losses, overloads and short circuit duties are investigated.

INTRODUCTION

System Optimization with the objective of minimizing losses, cost, voltage deviations as well as improving security is conceived in such a way that within an energy management system a package of programs is at the disposal of the operator which he employs at regular intervals following an event. The load flow, the optimal power flow, the short circuit program, the contingency analysis program and the unit commitment program - to name the most important ones - are analytical routines based on a particular model and oriented towards a specific objective. Employing such a program will yield a system state which is momentarily of interest to the operator or an optimal state within the framework of the model and the operational conditions (security).

In the operation of a power system it is not a singular optimal state as determined by one of the analytical routines which is aimed at but the "best" state from a global point of view. Thereby the system is considered under various aspects and by applying different criteria. Ideally, a system should be optimal with respect to losses and cost, it should be secure - there are various options - and should not exceed given limits of short circuit currents. Approaches like the ones in [1,2] tend in this direction.

However, a global optimum in the ideal sense is not available neither in reality nor within the mathematical model. Although, an exact optimum is reached by the individual routine it is either the model or the method which is responsible for the fact that only a part of the objective of the practical system operation is covered.

The operator based on his experience will check the system by several routines and will finally decide on the system state to be realized.

Complementary to the analytical routines there are techniques which employ heuristic procedures, e.g. expert systems or general AI-techniques. They process accumulated knowledge. Hence, expert systems need a knowledge base and draw conclusions with the help of an "inference engine". In special areas where data are given mainly in qualitative form such techniques have proven successful, e.g. alarm processing, fault diagnosis [3,4]. In problems where these techniques compete with exact analytical algorithms it will, however, not be possible to replace the latter.

On the other hand a synthesis of both these techniques in a hybrid system seems promising. The application of analytical programs has to be coordinated on a high level. Thereby heuristic concepts are to be considered. Since it is usually a search which must be carried out the existing knowledge will speed up the process whereas a complete analytical search would be too cumbersome and too slow.

It is the objective of the paper to show the way for combining analytical techniques and AI-techniques for the purposes of system optimization, in particular for the benefits of cost and security.

HIGH LEVEL SYSTEM OPTIMIZATION

When aiming at a system optimization under several objectives analytical methods alone are not sufficient since one goal is being followed at a time and the methods are not able to decide if and where the "best" system state with respect to the criteria considered may lie. Only when a synthesis of AI-techniques together with conventional programs is realized the advantages of both approaches can be exploited. The idea is that the hybrid system utilizes data sets which are produced by exact procedures and which form part of the knowledge base. Beyond that it reproduces the heuristic approach of a system planner who
includes several criteria in his optimization process. This way a system can be optimized more comprehensively than it is possible with singular, isolated optimization methods.

The envisaged hybrid system in this paper treats a power system in an optimal way such that an operating state is found which satisfies different requirements. Thereby it is clear that the system state cannot be optimal with respect to all criteria since the various objective functions will have their extremum in different system states. In the course of an optimization the objectives may be even contradictory. Despite that the final system state should fulfill the objectives as comprehensively as possible. In conventional system operation it is the operator’s judgement which determines the performance of the system with respect to the objectives. In a systematic approach the grading of objectives has to depend on certain chosen priorities. These have to be selected depending on the respective system state and may be varied during the course of the optimization.

It has been observed that non-convex objective function appear in those optimization programs where control variables and parameters are varied in discrete steps. In such cases the high level control system has to recognize the local minima and has to extend the space for the search accordingly in order to assure the continuation.

EMPLOYED NUMERICAL TOOLS

Today system planning and operation relies on a series of sophisticated numerical programs for the analysis, simulation and optimization of the power system. The underlying models are deterministic as well as stochastic and their orientation can be static or dynamic. System planning employs these tools depending on the prevailing needs and the required details. In system operation the set of programs, e.g. within an energy management system, is limited. Within system planning the present development is far away from a concept which could be considered as a global approach. In system operation tendencies are recognizable which attempt to assess and determine a system state which obeys several criteria at the same time. It is still the quasi-steady state which is considered. Security assessment and optimization is the example in which such an approach is exercised and in which “multi-objective” searches can be demonstrated the best way.

This is the reason for considering this domain as a field of application for the considered combined techniques. The numerical routines in this area include the load flow as a basic tool. For the control of variables in a continuous manner the so-called optimal power flow is becoming a classical element. Beyond that a discrete version of an OPF is emerging which optimizes the system topology, i.e. switching operations [5]. Both routines are suitable for loss minimization and for overload relief and both can be complemented by an outage calculation to lead to a comprehensive security enhancement routine [6]. Further, a program is available which minimizes short circuit currents whereby again topological changes are achieved by means of switching operations.

The programs which employ switching operations, i.e. OPF with discrete controls and the minimization of short circuit currents, are based on a linear set of equalities, i.e. a tableau, consisting essentially of distribution factors. The switching operation itself is modeled by injected currents at the switched element and is reflected in the tableau by a change of base which is similar to linear programming (LP). The tableau produces a linear approximation to the new system state and to the objective function after the switching operation [5].

The tableau necessary for short circuit current minimization differs from that for the OPF with discrete controls in the distribution factors and in the dimension. The distribution factors are different because the admittances of the generators have to be included in the setup of the admittance matrix for the short circuit. The dimension is higher since there is no slack node and since the possible short circuit locations have to be accommodated as connections in advance.

Both discrete optimization programs determine a sequence of switching operations according to the method of steepest descent which leads to an optimum. Since the controls are discrete there is no guarantee that a global optimum will be reached. Hence, additional switching operations have to be considered as will be shown in a later chapter.

On the other hand it must be possible to change and optimise variables of generators in a continuous fashion following each switching operation, i.e. to employ a conventional OPF. For both reasons the discrete optimization programs have been split up into functional blocks. Thus any switching operation can be controlled from outside and also be reversed again. Thereby the short circuit current minimization and the OPF with discrete controls are executed within the same framework of programs. The organization and execution of changes of topology is handled similarly in both cases, only the objective function controlling the course of the optimization is different in each case.

In more detail the following procedure is adopted. After the system matrices and the corresponding tableaus have been set up the block for loss minimization / overload relief and the block for short circuit currents will determine a selection of switching operations each of which will improve the respective objective function. The switching operations which are proposed by the block loss minimization / overload relief fulfill the given constraints. Since in the minimization of short circuit currents the effects of a switching operation on the load flow cannot be modeled in a linear fashion it is necessary to test the observation of constraints separately. Hence, there is a block which checks switching operations with respect to maintaining constraints only. It is active when short circuit currents are the objective, and the block loss minimization / overload relief is not in use.

Fig. 1 shows the sequence of steps in this type of optimization in a schematic way.
Modules based on linear programming appearing in this figure are the following:

Module A: generates a selection of switching operations which will improve objective function 1 (losses / overload reduction)

Module B: generates a selection of switching operations which will improve objective function 2 (short circuit current)

Module C: generates all those switching operations which fulfill the given constraints

Module D: reverses switching operations without considering objective functions or constraints

It is emphasized that switching operations once executed can also be reversed again. Module D takes care of this function.

Thus a series of tools for switching is available which allows the comprehensive search for optimal system states.

A few indications for the better understanding of the schematic are appropriate. The decision which of the proposed switching operations is to be executed has to be taken externally (see arrow 2 in fig. 1). The reason is that the two objective functions (short circuit current and losses / overload) are on a contrary course in certain cases and lead to opposing switching operations. Hence, priorities have to be given for the prevailing system state. This is a point where a new level of decision making enters the picture and where an expert system has its place.

In the course of the process local minima have to be recognized as such without stopping the search. Thereby switching operations can be reversed again. This also has to be controlled from the outside (see arrow 1).

In principle, the control from the outside can be done by the system planner or by the operator. In the following the approach will be described which optimizes the system with the aid of AI-techniques and which resembles the heuristic procedure of an operator or planner.

INTEGRATION INTO A LISP ENVIRONMENT

LISP has been chosen as the environment in which decision making by means of AI-techniques is to be embedded. Thereby the version VAX LISP/VMS, a COMMON LISP implementation, is used which is supported by the operating system VMS. The analytical procedures were available in FORTRAN. Hence the level structure determines in which way FORTRAN programs, data sets, etc. are used by the LISP environment, see fig. 2.

Two different approaches are in use in order to call FORTRAN programs from the LISP environment. They can either be implemented as external routines which are directly called or they can be called as individual programs from LISP via the operating system. Both approaches are actually employed since the available FORTRAN programs have different requirements.

Integration as external routines:

Routines written in FORTRAN have to be defined as external routines to LISP. They can be directly called from the LISP environment via the "call-out" facility. Data are passed in both directions by using the function arguments. The actual LISP version recognizes the data types commonly used by FORTRAN, including Arrays.

LISP does not create object modules that can be linked. Due to the special nature of LISP, the compiled FORTRAN routines must be linked into a VMS shareable image which
is position independent. The names of the referenced sub-routines in this shareable image that are available to LISP through the call-out facility must be listed as entry points by a linker option.

When using VMS as the operating system attention has to be paid to several items which are specific to the way of implementation. Thus, it has to be observed that the data types of the transferred variables have to be implemented the same way in both languages.

When arrays of integer variables are used the format INTEGER*4 in VAX FORTRAN corresponds to the format (SIGNED-BYTE 32) in VAX LISP for which storage of fixed length is allocated. The LISP format INTEGER cannot be used, since in principle it is not limited in length and thus storage is automatically allocated as necessary.

Arrays of real variables in double precision which are implemented as DOUBLE-FLOAT in LISP must be specified as G-FLOATING in VAX FORTRAN. In case of default VAX FORTRAN would take the D-FLOATING format which also uses 8 bytes (64 bits) but has an other ratio of mantissa to exponent in the storage allocation.

Further special attention has to be paid to COMMON-blocks in FORTRAN routines. They have to be provided with special attributes in the link process (writable, not shareable). In the generated shareable image they appear in full length.

Integration via the operating system: Autonomously running programs can be treated in a simpler way. They are called from the LISP environment through the VMS operating system. As in normal usage input and output are transferred by files. This deviation through the operating system is slower, however, it requires less storage in the LISP environment since no additional shareable image is generated.

As employed in the actual program the numerical tools used are integrated into the LISP environment in both ways. An important item is the extended optimisation program as described in the chapter above. This program starts from the actual system state and performs changes in topology as exhibited schematically in fig. 2. The procedure is controlled externally. The system matrices are adapted in each run through the main loop. The individual modules refer to the previously calculated data whenever the former are called. In order to realize this external control of the extended OPF from the LISP environment the whole program is split up into its functional blocks which are introduced as external routines in LISP and which are called directly by the "call-out" facility. The required system matrices should only be increased to the point where it is absolutely necessary since COMMON-blocks show up in the shareable image in their full size. To give an example of the storage requirement it is mentioned that the optimization of a 83-node system with about 20 switchable nodes needs a shareable image file of nearly 4 megabyte.

Programs which compute distribution factors and prepare data files before the optimization proper are treated differently. They are called from LISP via the VMS operating system. Also the OPF being a program of its own is called via the operating system. Thereby the classical OPF (continuous control) can be combined with the extended optimization program (discrete control). The data transfer, however, is done via files.

Since these programs run autonomously and since they are not time critical besides the OPF they can be employed in this way thereby avoiding an increase of the shareable image. In the extended optimization program this was not possible because the program is interrupted and reactivated by the LISP system itself.

ORGANIZATION OF THE SEARCH PROCESS

The high level control program performs a comprehensive optimisation of the system. The framework where the optimization takes place is supplied by the realizable system states. They form a discrete search space which is structured in the form of a search tree.

Each of the possible system states which can be reached from already evaluated states will be represented as a node. Control actions which cause a transition from one state to another form the links between the nodes.

At the root of the tree there is the initial state from where the optimization is started. This node is expanded whereby those states will be evaluated which can be reached by a single control action from it. The new states will be attached to the nodes being processed as extensions of a node (children of a node) and form the starting point for further expansions. The analytical programs determine to which children of a node a given node is expanded. They provide a selection of control actions which lead to improved states. Each state in the tree is assessed by means of the values adopted by the objective function there. In this way the search tree is formed in the course of the optimization.
In order to avoid the complete storage of each system state the transition from one node to a derived node will be represented by a pair of forward/backward control actions. The actual search follows the principle of depth-first. At each node the search process takes the derived node where the dominant objective function changes most and follows the tree along the steepest descent until a terminal node is reached. Even though one of the objective functions might not change anymore at this point it is not necessarily the absolute minimum. Due to the discrete nature of the control actions the dominant objective function need not be convex and therefore the process may stop at a local extremum. Further, it is not certain that the system state satisfies the additional criteria.

It is at such a point where the backtracking begins. The process follows the search tree back to a node which allows to consider further derived nodes and evaluates the criteria from there.

In a complete search along the tree the number of states to be evaluated would grow immensely. Therefore the information extracted from the analytical programs is used to prune the search tree.

Most of the analytical programs employ a linearization of some sort or as for switching operations linear programming is used and, hence, the effects of control actions on the objective function can be estimated. So promising control actions will be considered only and included in the search and hopeless operations are excluded from the start. In the literature there are similar procedures for minimization problems that attempt to avoid exploring states that can be predicted to be irrelevant, one of the best known being the alpha-beta algorithm.

The search process was implemented in LISP and the analytical programs were incorporated as described in the foregoing chapter.

**KNOWLEDGE BASED PART**

In order to accomplish an optimization of the system in the way described above the high level control program has to be provided with specific knowledge such that the heuristic procedure of the operator can be simulated.

An essential part of the knowledge is supplied implicitly by the analytical programs either in quantitative or in qualitative form. It comprises information about the state of the system where the optimization should take place as well as numerical results of simulations of the mathematical model. Also included are values of the objective functions which determine the course of the optimization decisively. It is this exact knowledge which forms the strength of a hybrid system.

Further, there are rules which control the course of the optimization. They can be classed into two groups.

The first group consists of rules which direct the way in which the individual programs are called and how their execution is controlled. So far these programs have been used in an isolated manner and have been initiated manually. Now their execution has to be coordinated on a higher level of abstraction. Thus, it has to be known which routines depending on the selected priorities to call in order to lead the search process along the tree further "down". A result is a fixed number of rules representing quite specific knowledge about the structure and the execution of analytical programs in use. These rules remain unchanged and hence are integrated directly in the search process. Since they affect the coordination of the numerical tools only they are independent of the power system under investigation and have a general validity.

The control of the search process can be further refined by a second group of rules. They are more of a heuristic nature. If, for example, the optimization does not progress in the desired manner, an assessment has to be made if a back track should be started such that the search is not unnecessarily lengthened. Further, priorities may change in the course of the optimization. This is also determined by rules.

Rules are added which are power system specific. Thus decisions from the operator are required determining the further course of the search in a situation where in a particular system state certain criteria are violated. An example would be a proposed switching operation which would violate constraints slightly at a geographical distant location. A conventional system would discard this operation which from the view point of the practical operator would not necessarily be required. A rule base will represent this part of the knowledge.

This rule base is not integrated in the hybrid system yet. So far it is realized as an automatic search process. It employs already the knowledge of the analytical programs and that about their execution and their coordination. In a further step it is planned to add a rule base as outlined above.

**RESULTS**

The hybrid system for a high level optimization was tested in two cases. In the first case a search was carried out for the objectives of loss minimization and reduction of short circuit currents. In the second case the objectives were the relief of an overload and the reduction of short circuit currents.

The employed network consisted of 83 buses, 8 among them in the form of double bus bars. Fig. 4 shows a section of this network. Changes of topology are done in this section only. Lines beyond this section are considered as not switchable.

The double bus bar DS1/DS2 takes a central place in this network. It has 9 outgoing lines. In case of a short circuit the duty on the breakers is too high in the given configuration of DS1/DS2. Therefore in both examples a reduction of the maximum short circuit current on these buses is attempted.

**Case 1:**

In this example the network is in an operating state where the base case load flow fulfills the constraints. The losses in this initial state are 34.57 MW. Their minimization is one
objective of the optimization. The value of the transient short circuit current is 13.2 p.u. at bus DS2. This is considered to be too large, the short circuit current should not exceed 10 p.u. at any of the buses of double bus bar system DS1/DS2. Thus, the optimization will have to achieve two goals, minimizing the losses and decreasing the short circuit currents to keep them within the given limit.

The optimization starting at the initial state determines three switching actions which improve both objective functions. Two of them lead to further system states as shown in fig. 5.

The hybrid system offers the operator a choice of three possible switching sequences each of which has its advantages. The operator will have to take the final decision which of the proposed switching sequences will be executed.

Case 2:
In the second example the network with the same topology as in case 1 but with higher loads is used. The resulting base case load flow indicates an overload on line 4-23. The relief of this overloaded line is one goal of the optimization. The other objective is to decrease the short circuit currents under the limit of 10 p.u. similarly as done in case 1. The optimization determines system states which fulfill both criteria. However, the priorities had to be changed in the course of the optimization.

The short circuit currents of certain buses are mainly influenced by switching actions performed in the immediate neighbourhood of these buses. On the other hand the effects of switching actions on the load flow are hard to predict. Thus, the dominating objective function in the initial state was the reduction of the maximal short circuit current, see table 2. Having achieved this goal the priorities were changed. In the subsequent optimization system states were evaluated which decreased the overload without violating the limit for the short circuit currents which is already achieved. The hybrid system offered a choice of switching sequences that fulfilled both criteria, an example is shown in tab. 2.

After employing this sequence of switching actions the load on line 4-23 will be decreased from 145% in the initial state to 94% in the final state. The short circuit currents in this final state are within the given limit. Thereby it has to be mentioned that these topological changes cause

### Table 1: System states in detail

<table>
<thead>
<tr>
<th>System state</th>
<th>Performed switching action</th>
<th>Objective functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>line DS2-5A out, line DS1-5A in</td>
<td>loss red. -12.48%, max. I_{SC} = 9.83</td>
</tr>
<tr>
<td>B</td>
<td>bus coupler, 26A-26B closed</td>
<td>loss red. -15.02%, max. I_{SC} = 9.84</td>
</tr>
<tr>
<td>C</td>
<td>line DS2-1 out, line DS1-1 in</td>
<td>loss red. -8.92%, max. I_{SC} = 12.35</td>
</tr>
<tr>
<td>D</td>
<td>line DS2-5A out, line DS1-5A in</td>
<td>loss red. -11.94%, max. I_{SC} = 8.98</td>
</tr>
<tr>
<td>E</td>
<td>line DS2-36 out, line DS1-36 in</td>
<td>loss red. -10.86%, max. I_{SC} = 10.28</td>
</tr>
<tr>
<td>F</td>
<td>line DS2-36 out, line DS1-36 in</td>
<td>loss red. -7.67%, max. I_{SC} = 9.02</td>
</tr>
</tbody>
</table>

Node C: This is a system state where the largest loss reduction (-15%), the short circuit currents are just within the limit of 10 p.u., their maximum value is 9.84 p.u.

Node D: This is a system state in which the loss reduction is smaller (-11.9%), but where the maximum short circuit current is below 9.0 p.u.
higher loads on other lines, two of them will even be loaded to their limit.

<table>
<thead>
<tr>
<th>Switching action</th>
<th>Maximum short circuit current</th>
<th>Load on line 4-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial state</td>
<td>13.2 p.u.</td>
<td>145%</td>
</tr>
<tr>
<td>line DS2-5A out</td>
<td>9.88 p.u.</td>
<td>143%</td>
</tr>
<tr>
<td>line DS1-5A in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bus coupler</td>
<td>&lt; 10.0 p.u.</td>
<td>122%</td>
</tr>
<tr>
<td>line 5A-26B out</td>
<td>&lt; 10.0 p.u.</td>
<td>113%</td>
</tr>
<tr>
<td>line 5B-26B in</td>
<td></td>
<td>105%</td>
</tr>
<tr>
<td>line 3A-24 out</td>
<td>&lt; 10.0 p.u.</td>
<td>101%</td>
</tr>
<tr>
<td>line 3B-24 in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>line 3A-2 out</td>
<td>&lt; 10.0 p.u.</td>
<td></td>
</tr>
<tr>
<td>line 3B-19 out</td>
<td>&lt; 10.0 p.u.</td>
<td>94%</td>
</tr>
</tbody>
</table>

Table 2: Proposed sequence of switching actions

These two examples illustrate quite clearly the way in which a hybrid system performs a search for a best operating state. "Best" has to be understood as the best combination of values of objective functions. The merit of the knowledge based part is the coordination of the analytical programs. This is considered to be similar to the search performed by the human planner or operator.

CONCLUSIONS

The paper has set out to explain the extension of system optimization and the way how it would be realized by a combination of a procedural and a knowledge based approach. It makes an effort to bring to the attention of the reader what is involved when the two types of programs are merged. Another focus is the search directed towards several objective functions the key point being the tree. Thereby the actual search process is described in detail and reflects the needs of the planner and operator. Special consideration had to be given to the fact that continuous and discontinuous controls were employed. In order to avoid a hangup at a local extremum backtracking had to be foreseen. Two example cases give an illustration of the search process and type of results which can be achieved. This is to be considered a first step in this area since several ways for complementing and upgrading the search process are possible.

REFERENCES


NEW PERSPECTIVES IN DYNAMIC SECURITY ASSESSMENT (DSA)

by

M. A. Pai and P. W. Sauer
University of Illinois
NEW PERSPECTIVES IN DYNAMIC SECURITY ASSESSMENT (DSA)

M. A. PAI and P. W. SAUER
UNIVERSITY OF ILLINOIS

- R & D EFFORTS IN DSA HAVE REACHED A CRUCIAL PHASE.

DIRECT METHODS (STATUS)

- DIRECT METHOD (LYAPUNOV/ENERGY FUNCTION) HAS BEEN THE PRINCIPAL TOOL SO FAR.

- SOME OF THE ADVANCES IN THIS DECADE HAVE BEEN

  A. PROPER CHARACTERIZATION OF THE STABILITY BOUNDARY OF THE POST-FAULT S.E.P.

  B. BETTER ALGORITHMS TO FIND THE CRITICAL ENERGY.

  C. USE OF STABILITY MARGIN TO COMPUTE CONTINGENCY-SENSITIVITIES FOR PRE-FAULT OPERATING CONDITIONS e.g. LOADABILITY, FLOWS, GENERATOR LOADING, NETWORK STRUCTURE ETC.

  D. INCORPORATION OF DETAILED SYSTEM DYNAMICS AND LOAD MODELS IN DIRECT METHODS.
NEW PERSPECTIVES IN DSA DIRECT METHODS

- IN SPITE OF THIS SUCCESS STORY OF DIRECT METHODS (ACHIEVED OVER FOUR DECADES!), MORE R&D IS STILL CONTINUING AND MUST CONTINUE.

- THE CENTRAL ISSUE CONCERNING DIRECT METHODS WILL BE THE NEED TO IDENTIFY A RELIABLE ALGORITHM OR A SET OF ALGORITHMS TO COMPUTE THE CRITICAL ENERGY UNDER ALL SYSTEM CONDITIONS. CURRENTLY THERE ARE A NUMBER OF ALGORITHMS PROPOSED.

1. CONTROLLING U.E.P METHOD (ATHAY ET AL).
2. PEBS METHOD (KYOTO METHOD).
3. CANDIDATE U.E.P METHOD (IOWA STATE).
4. AUTOMATIC U.E.P METHOD (IOWA STATE).
5. CANDIDATE CLUSTER AND TWO MACHINE EQUIVALENT METHOD (LIEGE).
6. QUASI-U.E.P METHOD (MIDDLE SOUTH SERVICES).
8. HYBRID METHOD (COMBINATION OF PEBS AND CONTROLLING U.E.P) (BERKELEY, CORNELL)

THIS IS INDEED AN IMPRESSIVE MENU!

- (3)-(6) HAVE BEEN TESTED ON VERY LARGE INDUSTRY-TYPE SYSTEMS.
IMPLEMENTATION IN AN ON-LINE ENVIRONMENT IS AWAITED FROM THE IOWA STATE-ONTARIO HYDRO EFFORT.
• CONTRARY TO POPULAR NOTION, COMPUTATION OF STABILITY MARGINS AND THEIR SENSITIVITIES TO PRE-FAULT OPERATING QUANTITIES WILL OFFER THE RICHEST DIVIDEND FROM DIRECT METHODS.

• USING STABILITY MARGINS, DIRECT METHODS CAN ACT AS A FILTER FOR SCREENING OF CONTINGENCIES JUST AS PERFORMANCES INDICES DO FOR S.S. SECURITY ASSESSMENT.

• STABILITY CONSTRAINED OPF IS A DISTINCT POSSIBILITY.

• USE OF TRAJECTORY APPROXIMATIONS IN THE HYBRID METHOD CAN SPEED UP THE ENTIRE PROCESS CONSIDERABLY.
PERSPECTIVES IN PARALLEL PROCESSING (PP)

- Prospects for using PP technology are indeed very good particularly when very large networks and detailed dynamics are involved. After direct methods have identified the critical contingencies, high speed simulation for these contingencies will yield better insight into system's vulnerable spots.

- Assessment techniques will have to be developed from the wealth of data available from these simulations. Unlike direct methods, stability margins from simulation are not available.

- In addition to angle stability, voltage profiles can be displayed.

- Some approaches might include

  1. Fine tuning the stability margins from the detailed model energy functions.

  2. Develop a knowledge based expert system (based on planning experience) to make use of the simulations to provide the operator with indices or "road-map" to enhance the security (both angle and voltage stability).
CAN DEVELOP FROM THE SIMULATIONS SOME SORT OF VIPI (VOLTAGE INSTABILITY PROXIMITY INDICATOR).

CAN MONITOR RELAY PERFORMANCE
SOME PARALLEL PROCESSING TECHNIQUES (PP)

- THERE IS ACTIVE RESEARCH GOING ON AT VARIOUS PLACES IN USING PP FOR HIGH SPEED SIMULATION. SOME OF THESE ARE

1. USING ARRAY PROCESSORS.
2. USING HYPERCUBE.
3. USING VECTOR MACHINES (CRAY, CONVEX C-1XP, ETC).

(1) AND (2) TEND TO BE DEDICATED MACHINES FOR A SET OF TASKS WHEREAS (3) IS VERY FAST AND GENERAL PURPOSE BUT EXPENSIVE ALSO AT THE MOMENT. REDUCTION IN COST MAY CHANGE THE SCENARIO. THREE PARALLEL ALGORITHMS HAVE BEEN PROPOSED.

1. WAVE FORM RELAXATION METHOD (WRM).
2. TRAPEZOIDAL INTEGRATION USING BOTH TIME AND SPACE PARALLELIZATION.
3. TRAPEZOIDAL INTEGRATION WITH DENSE PARALLEL LU FACTORIZATION FOR USE IN PIPE-LINE MACHINES.
WAVER FORM RELAXATION METHOD

- ASSUMES A SET OF COHERENT GROUPS.
- EACH GROUP OF MACHINES IS INTEGRATED OVER \([0,T]\) SIMULTANEOUSLY.
- INTEGRATION OF ALL GROUPS COMPLETES ONE ITERATION.
- REPEAT INTEGRATION TILL CONVERGENCE.

COMMENTS

- CONVERGENCE IS AN ISSUE.
- TIME "WINDOWING" WILL IMPROVE CONVERGENCE.
TRAPEZOIDAL INTEGRATION WITH TIME AND SPACE PARALLELIZATION (ARIZONA STATE)

CONSIDER

\[ \dot{x} = f(x, y, u) \quad (1) \]
\[ 0 = g(x, y) \quad (2) \]

(1) CONSISTS OF MACHINE D.E.'S. IT HAS A QUASI-LINEAR STRUCTURE AND BLOCK DIAGONAL. (2) CONSISTS OF MACHINE STATOR AND LOAD FLOW EQUATIONS. IT IS SPARSE. TRAPEZOIDAL INTEGRATION LEADS TO

\[ x_{n+1} = x_n + \frac{1}{2} [f(x_{n+1}, y_{n+1}) + f(x_n, y_n)]h \]
\[ 0 = g(x_{n+1}, y_{n+1}) \quad n = 0, 1, 2, ..., T \]

PICARD ITERATION AT EACH TIME INSTANT LEADS TO

\[ x_{n+1}^{[\mu+1]} = x_n^{[\mu]} + \frac{1}{2} [f(x_n^{[\mu]}, y_n^{[\mu]}) + f(x_n^{[\mu]}, y_n^{[\mu]})]h \]
\[ y_{n+1}^{[\mu+1]} = \hat{g}(x_n^{[\mu]}, y_n^{[\mu]}) \quad n = 0, 1, 2, ..., T \]

FOR \( m \) MACHINE, \( n \) BUS NETWORK WITH SAY 6 D.E.'S FOR EACH GEN. WE WILL HAVE 6m+2m+2m+2n = 8m+4n ALGEBRAIC EQUATIONS IN ALL. WE SOLVE (8m+4n) EQUATIONS IN PARALLEL IN TIME.
THEORETICAL SPEED UP RESULTS ARE AVAILABLE ON A "PARA COMPUTER."
TRAPEZOIDAL COMPUTATION WITH DENSE LU FACTORIZATION
(U OF I)

\[ F_1(x_{n+1}, y_{n+1}) = 0 \]
\[ F_2(x_{n+1}, y_{n+1}) = 0 \]

\[
\begin{bmatrix}
  F_1 \\
  F_2
\end{bmatrix}
= 
\begin{bmatrix}
  J_1 & J_2 \\
  j_3 & J_4
\end{bmatrix}
\begin{bmatrix}
  \Delta x_{n+1} \\
  \Delta y_{n+1}
\end{bmatrix}
\] (3)

\[
x^{[\mu+1]}_{n+1} = x^{[\mu]} + \Delta x_{n+1}
\]
\[
y^{[\mu+1]}_{n+1} = y^{[\mu]} + \Delta y_{n+1}
\]

- \( J_i \)'s ARE JACOBIANS. J IS SPARSE WITHOUT PARALLELIZATION IN SPACE AND TIME, ALGORITHM HAS BEEN TRIED ON A CRAY X-MP/48 WITH A DENSE, STORAGE LU FACTORIZATION SCHEME (SMPAK) FROM YALE UNIVERSITY.

- CURRENT RESEARCH IS ON PARALLEL ALGORITHMS ON CRAY MACHINE. ALSO LOOKING AT DECOMPOSITION METHODS.

NUMERICAL RESULTS

FOR 3 MACHINE 9 BUS SYSTEM WITH 7 D.E.'S AT EACH MACHINE, WE HAVE 21+6+18 = 45 ALGEBRAIC EQUATIONS. IT TOOK 1.97 SEC ON CRAY XMP/48 COMPARED TO 157 SECONDS ON VAX-11/785 FOR TIME SIMULATION UP TO 1 SEC.
CONCLUSION

- More research is needed in direct methods to serve as a reliable screening tool and better use of stability margins.

- Parallel processing offers a rich area for research in high speed simulation of transients for the critical set of contingencies.

- Knowledge based expert systems are needed to make better use of the wealth of information from high speed simulations e.g. voltage profile analysis.

- A critical examination of algorithms in direct methods and parallel processing is needed.

- Can stability margins and sensitivities be obtained from high speed simulation?
POWER SYSTEM DYNAMIC SECURITY AS AFFECTED BY A CHANGING UTILITY ENVIRONMENT

by

A. A. Fouad
Iowa State University
1. Introduction

Dynamic security of power systems has received considerable attention in the literature. Yet, the author's experience indicates that different people use the term to mean different things. Furthermore, the motivation for research in this area is not always clear. To help focus the discussion, we will begin with the current security-related practices in the Northern American Interconnection. We will then examine the trends which are “stretching” these practices to their limits and beyond. The stage will then be set for identifying the research needs and the tools to satisfy them.

First, it should be pointed out that in the electric utility industry security is dealt with as part of system reliability, with no distinction between “static” and “dynamic” security. Reliability is considered to have two aspects: adequacy of the supply which means scheduling enough capacity to meet the demand; and security which is used specifically to mean “prevention of cascading outages when the bulk power supply is subjected to severe disturbances.” Even this distinction is a relatively recent concept in the electric utility industry (since the late 1960s). The distinction between dynamic and static security is not yet totally accepted by the industry.

With the concept of security having been introduced, in the late 1960s, in the “thinking” of the industry (i.e., in the planning and operation of power systems), the task of making the systems secure first focused on identifying the criteria to be met: the type of severe disturbances which must be withstood (before cascading
outages would result) and the system conditions for testing the strength of the
system. This task fell on the shoulders of the system planners; the result was that
transmission planning became a much more complex undertaking than before. Not
only the planning criteria were made difficult by a more security conscious
industry, the task was further complicated by the increased dependence on
controls, e.g., modern excitation controls, fast turbine valving, dynamic braking
resistors, series and shunt compensation, and others.

The 1970s brought with it the high oil prices, as well as the increased
regulatory delays in planning and building new facilities. The net result of these
developments was that, to make certain that the reliability criteria were met at all
times, engineers had to analyze many more possible situations which might be
encountered during system operation. Pretty soon, many studies were being made
to support system operation. These studies were becoming increasingly different in
focus and objective from the studies made to plan new facilities. Thus, the
operations planning function came about, and many electric utilities formed study
and analysis engineering groups to perform the operations planning function.

Until recently (say early 1980s) power system security almost exclusively
meant examining system conditions after the transient (following the disturbance)
had subsided and new steady-state conditions were reached. The concern would be
to ascertain, in the new operating conditions, that “thermal” and voltage limits are
not exceeded. The implied assumptions are that the transition to the new S.S.
conditions will “safely” take place. These assumptions were becoming increasingly
suspect. For some power system, voltage problems, some of which have been
recognized to be “dynamic” in nature, and stability problems were of primary
concern. In other systems, these problems were confronted when the "first line of defense" disappeared (i.e., as a second contingency). Thus, dynamic security, as is presently understood, came about. IT IS AN OPERATING CONCERN.


As explained in the previous section, the North American Electric Reliability Council (NERC) defines power system security as prevention of cascading outages, when the bulk power supply system is subjected to severe disturbances (called contingencies) such as short circuits. The power network is planned to withstand the occurrence of certain disturbances. Security limits are then established and the power system is always operated within these limits.

In North America, NERC establishes the overall philosophy of planning and operating the power systems for reliability. The specific criteria which must be met, however, are established by the individual reliability councils. Each council sets the conditions under which the "strength" of its system must be tested, and the specific "criteria" it must meet. These are translated into the types of contingencies which the system must withstand for cascading outages not to occur.

The central issues in how power system security is dealt with in the North American Interconnection are: 1) how to determine the security limits under all possible conditions, and 2) how to ascertain that system security (based on these limits) is maintained at all times. The answer is conceptually very simple; yet it has become increasingly difficult to accomplish. All possible (and credible) conditions and scenarios are considered; analysis is performed on all of them to
determine the security limits* for these conditions. The established limits are given to the operating personnel in the form of "operating guides," establishing the "safe" regimes of operation. The key power system parameter or quantity is monitored (in real time) and compared with the available (usually pre-computed) limit. If the monitored quantity is outside the limit, the situation is alerted or flagged for some corrective action. Conceptually simple, yet becoming exceedingly difficult (sometimes almost impossible)—why?

The difficulty lies with what I will define as "the data point" problem. The problem arises because analysis of each scenario requires solving a system described by nonlinear equations when subjected to large disturbances. Each scenario, which may involve a complex sequence of switchings and controls, requires a complete analysis run. Operating guides are derived from many such runs (hundreds or thousands?). For large systems this requires a large effort to: collect and maintain the data, set up the scenarios, obtain the runs, interpret the results and translate them into operating guides that are self consistent—a major and very complex undertaking.

3. Industry Trends

Transmission lines bring large quantities of bulk power, in some cases, hundreds of miles from generating plants to population and industrial load centers. But increasingly, these same circuits are being used for other purposes as well: to permit sharing surplus generating capacity between adjacent utility systems, to

* Examples: power loading at a critical power plant; voltage at a particular bus; apparent impedance "seen" by a given out-of-step relay or an important tie-line; power flow at a key transmission interface, etc., (seldom or almost never critical clearing time of a breaker).
ship large blocks of power from low-energy-cost areas to high-energy-cost areas, and to provide emergency reserves in the event of weather-related outages. Although such transfers have helped to keep electricity rates lower, they have also added greatly to the burden on transmission facilities and increased the reliance on control.

Recently, further developments have taken place that could push transmission networks closer to their physical limits than ever before, possibly with a noticeable effect on the reliability of electric service. In addition to the problems created by shutting down oil- and gas-fired power plants, we now have to deal with the aspect of non-utility electric generating entities and uncontrolled transmission access.

Economy energy transactions, reliance on external sources of capacity, and competition for transmission resources have all resulted in higher loading of the transmission system. It has also resulted in heavier loading of tie-lines which were originally built to improve reliability, and were not intended for normal use at heavy loading levels. This trend has increased interdependence among neighboring utilities. With greater emphasis on economy there has been an increased use of large economic generating units. This has also affected reliability.

As a result of the trends mentioned above, systems are now operated much closer to security limits (thermal, voltage, and stability). On some systems, transmission loadings are being operated at or near limits twenty-four hours a day. The implications of these trends are:

1. The industry trends have adversely affected system dynamic performance. A power network stressed by heavy loading has a substantially different
response to disturbances from that of a nonstressed system. For example
while for a robust system the effect of a disturbance tends to be localized if
no additional stimuli are introduced, the effect of a disturbance in a stressed
power network may be felt far away; when they occur, system splits may
take place away from the disturbance location; poor damping may lead to
growing oscillations under small or large disturbances; and soon.

ii. The potential size and effect of contingencies has increased dramatically. On
the one hand, when a power system is operated closer to the limit a relatively
small disturbance may cause a system upset. On the other hand, the largest
size contingency is increasing (today contingencies involving loss of 2000 MW
or greater are possible). Thus, to support operating functions many more
scenarios must be anticipated and analyzed. In addition, bigger areas of the
interconnected system may be affected by a disturbance.

iii. Where adequate bulk power system facilities are not available, special
controls are being employed to maintain system integrity. Overall, systems
are more complex to analyze to ensure reliability and security.

iv. Some scenarios encountered cannot be anticipated beforehand. Since they
cannot be analyzed off-line, operating guides for these conditions may not be
available, and the system operator may have to "improvise" to deal with
them (and often does).

4. The Needs

The present methods of planning and operating the North American
interconnected power network emerged from the days of building robust power
networks, normally operated well below their security limits. Relatively few cases (by today's standard) were needed to be analyzed to test the strength of the system and establish the security limits. Nowadays, thermal-limits and voltage limits are of concern to practically all the power systems in the Interconnection. In addition, several areas of the North American Interconnection are stability limited. It has become increasingly obvious that at present, many power systems in the North American Interconnection are finding that meeting NERC criteria for security is a very challenging task.

Unless some unforeseen developments take place, indications are that the conditions creating the present security-related problems will not improve in the near future. No one expects the regulatory process to be substantially expedited, or that rights of way to become easy to obtain, or that idle oil-fired and gas-fired power plants to be again put in operation. Realistically we expect the situation to get worse. So, what is needed for the industry to cope? Let us pursue some plausible scenarios.

Scenario No. 1: Maintain the present practice, but improve it.

This scenario calls for a more accurate, and realistic, method of obtaining security limits. The mode of operating would still be the same, i.e., monitor key parameters and compare their values with the limits for the existing conditions. How can this be accomplished?

The one complaint this author hears consistently from system operating personnel is that they often encounter operating conditions which had not been studied by the operations planning engineers. This means that no security limits are available for these conditions! How can this be alleviated? Let us
pursue some suggestions.

i. Limit the number of conditions to be analyzed by moving the analysis closer to real time. It should be stressed here that even if extremely fast analysis tools are available that does not eliminate the need for setting up a number of credible sequences of events to be analyzed.* A host of issues present themselves:

- Which credible scenarios? How to select them? What criteria to use? The old criteria may need to be scrutinized to see if they are applicable.
- What system model to use: for the study system, for the neighboring systems, etc.?
- How soon need the analysis be made? How fast need it be completed?
- What role should the control have? For corrective action, or emergency?

ii. Simplify computation of security limits by some new (yet to be developed) means. Examples:

- Pattern recognition techniques
- Analyze groups (or categories) of disturbances and scenarios, instead of analyzing many individual disturbances/scenarios

* There is no "instantaneous" stability analysis (even if the tool is available); the scenario to be analyzed will not be instantaneous.
iii. Move toward "softer" limits, instead of hard limits to be strictly adhered to. Issues to be addressed:

- Level of risk; how to determine it?
- What level of risk is acceptable?
- Can control take a bigger role in reducing the risk?

iv. Give more emphasis to "trends" in security limits as system conditions change. This is actually how the system operator deals with security, yet it is not something that is usually quantified. Some issues to be addressed:

- Can the sensitivity (of the security-limited parameter) to system changes be determined in near real time?
- Can the security criteria, and hence the operating guides, be modified to put more emphasis on these sensitivities?

The above are not meant to be an exhaustive list of the implications of this scenario. Rather, they are offered as examples of what can be done.

Scenario No. 2: Replace the current practice with an entirely new approach.

There are some reasons why this scenario is very plausible:

i. The deregulation issue, when it comes, will make this scenario very probable.

ii. The present practice, based on enumeration of contingencies, is doomed. Sooner or later it must be replaced. It is important that we start
thinking, and developing, new methods, so that they will be available when we need them.

iii. New technologies and new tools are emerging which may help us develop new practices.

If we cannot rely on anticipating every possible contingency and obtain a security limit for it, how can we proceed? We obviously must assume that we should cope with situations in a faster time frame; we also must assume that we will be able to monitor and detect conditions in the system faster and better than was possible in the past; and we also must not expect that the system can totally "take care" of the effects of all disturbances without "outside" help (too many things can happen, and too much uncertainty in system conditions).

The above seems to indicate that scenario no. 2 will require an innovative approach which is capable of integrating: system monitoring, security assessment, and control.

The technological developments which may support the above are:

- Recent developments in system state vector measurements.
- Direct stability analysis techniques, which look very promising, are at various stages of R & D.
- Impressive developments in computer architecture and hardware.
- New electronically-switched controls which will make integration of controls in the new approach possible.
- Increased sophistication of such tools as: expert systems, pattern recognition, neural networks, etc.
5. Looking Ahead

Having been closely associated with a scheme to develop operating security limits for on-line use, I am impressed with two important factors that affect this discussion: 1) the size of the development effort compared to the effort needed for research I would assign a 10 to 1 ratio as a ball park figure, and 2) the time frame required for this R & D work. This observation is important as we discuss the research needs of the North American Interconnection to deal with Dynamic Security Assessment.

My recent experience would lead me to suggest that we must deal with both scenarios in parallel. In other words, I believe that future R & D efforts should attempt to: 1) improve present methods of dynamic security assessment practices, and 2) develop a new approach which integrates security monitoring, assessment, and control. Although the new approach will be very much needed, the rationale for advocating the dual R & D effort is that to develop the conceptual framework for a new approach, to devise the tools and to bring them to a stage where they can deal with practical issues, a 20-year horizon is a realistic time frame. In the meantime, the interests of the North American Interconnection will best be served if at the same time we address the issues presented under Scenario #1, designed to improve the present practices.

What role can NSF-sponsored research play? I hope the foundation for such a decision has been made.
A FRAMEWORK FOR POWER SYSTEM SECURITY ASSESSMENT

by

Sarosh Talukdar and Richard Christie
Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213, USA
A FRAMEWORK FOR POWER SYSTEM SECURITY ASSESSMENT

Sarosh Talukdar        Richard Christie
Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213, USA

ABSTRACT
This paper develops a discrete approximation to the operating regimes of power systems. The form of the approximation is a transition graph. Nodes in this graph represent certain discrete states of the system; arcs represent planned and unplanned events that cause transitions from one discrete state to another. Real-time operations can be visualized as tracing a path through this graph. Security can be visualized as the distance between the incumbent state and the nearest state of unacceptable quality. Hill climbing and means-ends analysis are suggested as techniques for conducting the multi-ply searches necessary for finding these nearest unacceptable states.

SECURITY IN POWER SYSTEM OPERATIONS
The goals and concerns of operating a power system can be grouped into three main categories: quality-of-service (or quality, for short), cost and environmental impact. This paper will discuss some aspects of the first of these categories.

Concepts
Quality can be viewed from two vantage points: (1) from outside, as seen by the customers and other utilities that deal with the system, and (2) from inside, as seen by the components of the system that are affected by its operating state. From both viewpoints, quality is adversely affected by random disturbances, such as sudden failures of equipment. The study and mitigation of these effects comes under the heading of security. More specifically, a power system is said to be secure if it is providing high quality service and is likely to continue to do so despite the occurrence of random disturbances. Thus, the three main concerns of security are:

1. **risk assessment**: determining the chances that random disturbances will cause quality degradations;
2. **consequence assessment**: determining the magnitudes of these quality degradations and expressing them in meaningful terms;
3. **correction**: synthesizing strategies for changing the existing level of security (expressed in terms of risks and consequences) to a desirable level. As such, the correction problem involves finding good tradeoffs between security and the other two imperatives of power system operations, namely, reducing costs and environmental impacts.
The concepts of quality and security are applied to actual systems through methods that are either automatic (programmed) or manual (that have not, or cannot, be programmed). Of necessity, the automatic methods use only knowledge that is explicit, but the manual methods can use both explicit and tacit knowledge. By explicit knowledge we mean information that is expressed in readily accessible terms, such as equations, diagrams or text, and therefore, is long lasting and open to examination. By tacit knowledge we mean information that is buried in the brains of certain humans. A typical example of the use of tacit knowledge is a human who is exceedingly good at solving some problems but cannot describe how he does it. Tacit knowledge is volatile, difficult to transport and neither subject to scrutiny nor always available when needed.

In the following material we will discuss the amounts of explicit and tacit knowledge involved in the current approaches to transforming the concepts of quality and security into practice.

Quality
The explicit definitions of quality in current use are expressed mainly in terms of tolerance ranges or hard constraints (often called load and operating constraints) of the form:

\[ a_n \leq x_n \leq b_n, \quad n = 1, 2, \ldots, N \]  

where the a's and b's are constants whose values are determined by various planning and regulatory agencies, and the x's are key state variables, such as bus voltages and line flows. If all the constraints are met, the system is said to be in a normal state with an adequate level of quality; otherwise the system is said to be in an abnormal state with less than adequate quality. In other words, the constraints partition the state space of the system into two disjoint regions: normal and abnormal. Often, the abnormal region is further divided into an emergency region, corresponding to conditions under which system components are severely stressed, and a restorative region, corresponding to conditions under which there are significant interruptions of supply to customers.

The main advantage of this approach is that it is conceptually simple and computationally straightforward, once the values of the a's and b's have been determined. The main disadvantages are:

1. It can be difficult to select good values for the a's and b's;
2. Finer gradations of quality are needed to effectively operate a system. However, including these gradations requires the addition of many more constraints. Rather than deal with the computational burdens that would result, utilities leave the making of finer gradations to the judgement of the human operators of systems. Much of the knowledge used is tacit.
3. The magnitudes of violations of load and operating constraints are not, in themselves, meaningful indicators of quality losses. To be meaningful, the violations must be translated into terms such as:
   - external economic impacts (short and long term)
Internal economic impacts and the risk of equipment damage
-safety
-customer dissatisfaction
-effects on future regulatory policy

that can be understood and used by decision makers both inside and outside the utility. There is little explicit knowledge for making such translations and even less in the way of automatic procedures for real-time use.

Security

Security assessments are initiated when a system is in a normal state and providing an adequate level of service. The assessments are made to determine the system's potential for degenerating into an abnormal state with the attendant degradations of quality. Most of the automatic assessment methods in current use are based on an algorithm that was suggested by DyLiacco [5]. This algorithm has the following steps:

1. From the set of all possible disturbances (contingencies) select a subset of critical contingencies;
2. Determine the response of the system to each of these critical contingencies;
3. Check the responses against the constraints (a). If there are significant violations, i.e., if a critical contingency would result in a significant degradation in quality, then the system is insecure; otherwise it is secure.

There exist widely accepted, reasonably accurate, automatic procedures for simulating the responses of systems to given initial conditions and thereby, performing step 2. This is not the case for steps 1 and 3.

The available automatic procedures for selecting critical contingencies suffer from three major flaws. First, they neglect most multiple-event-contingencies, which, though relatively rare, are almost exclusively responsible for the larger losses of quality, such as occur during blackouts. Second, they tend to be weak in identifying those single-event-contingencies that could cause voltage and stability problems. Third, they provide no explicit information on the risks of the contingencies occurring. Instead, the operators must use their judgement to estimate these risks.

With regard to step 3, available automatic procedures suffer from two major flaws. First, they provide no good ways for evaluating the significance of constraint violations. (As has been pointed out, the magnitude of a violation is not, in itself, a meaningful indication of its potential consequences. To assess these consequences an operator must rely on knowledge which is largely tacit.) Second, there is a profound lack of explicit knowledge for synthesizing corrective actions to make good tradeoffs among the conflicting objectives of security, operating cost and environmental impact.

In summary, there are considerable gaps in the explicit knowledge that has been encoded into automatic procedures for security assessment and correction. This conclusion is emphasised by the entries of Table 1 which cover the properties of DyLiacco's algorithm, some of its derivatives and a representative sampling of other
Table 1: A representative sampling of security indices and a subjective evaluation of their usefulness

<table>
<thead>
<tr>
<th>INDEX</th>
<th>INFORMATION CONTENT ON A SCALE OF 0-&gt;5 (0: None; 5: Complete)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DyLiacco</td>
<td>Risk 2 Consequences 1 Correction 0</td>
<td>Widely used</td>
</tr>
<tr>
<td>[1], [5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stott</td>
<td>Risk 2 Consequences 1 Correction 0</td>
<td>Derivative of DyLiacco</td>
</tr>
<tr>
<td>[9]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Security Index</td>
<td>Risk 1 Consequences 0 Correction 0</td>
<td>Derivative of DyLiacco</td>
</tr>
<tr>
<td>[4]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>Risk 2 Consequences 0 Correction 0</td>
<td>Simple and widely used</td>
</tr>
<tr>
<td>Angle Swing</td>
<td>Risk 1 Consequences 0 Correction 0</td>
<td>Computationally expensive</td>
</tr>
<tr>
<td>[11]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Energy</td>
<td>Risk 2 Consequences 0 Correction 0</td>
<td>New and as yet untested</td>
</tr>
<tr>
<td>[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Stability</td>
<td>Risk 1 Consequences 0 Correction 0</td>
<td>Computationally expensive</td>
</tr>
<tr>
<td>[10]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic Impact</td>
<td>Risk 0 Consequences 2 Correction 0</td>
<td>Estimates cost of unserved energy</td>
</tr>
<tr>
<td>[8]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historical Trends</td>
<td>Risk 1 Consequences 2 Correction 0</td>
<td>Extrapolations of past outages</td>
</tr>
<tr>
<td>Planning Indices</td>
<td>Risk 2 Consequences 2 Correction 0</td>
<td>Over 20 in use. Difficult to adapt for on-line use</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>
for on-line use. Security indices in current use. Where can the knowledge to fill these gaps be found? The succeeding material offers some suggestions.

### CQR—AN EXPERIMENT IN KNOWLEDGE ACQUISITION AND AUTOMATION

Utilities have been accumulating knowledge on security for decades. Much of this knowledge is utility-specific, reflecting the structural and behavioral differences among utilities. Much of the knowledge is also tacit and concentrated in the brains of a few experts in each utility, where it is not readily available for dealing with security problems in real-time operations. To see if such knowledge could be translated into more accessible forms, we undertook the development of an expert system called CQR [2]. Specifically, CQR is being built to help answer three questions:

1. Can tacit, security-related knowledge from a representative utility be made explicit and translated into computer programs to aid in the utility's real-time operations?
2. Can the knowledge acquisition and automation techniques developed for the representative utility be generalized to other utilities?
3. Will the resulting improvements in the treatment of real-time security be sufficient for current and future needs?

Work on CQR is still in progress but the answers to all three questions now seem clear. Specifically, general techniques for converting tacit knowledge to automatic, utility-specific programs for real-time issues are eminently possible. Further, existing tacit knowledge alone is far from sufficient for either present or future needs. Rather, new knowledge in the form of new methods will have to be developed.

### POWER SYSTEMS AS FINITE STATE MACHINES

One of the principal difficulties in developing methods for solving security problems is a lack of good tools for visualizing (meaning formulating, representing and conceptualizing) these problems. In the following material we will develop a transition-graph-model of power systems that aids the visualization process. This model is obtained by borrowing ideas from finite element analysis and finite state machines.

In finite element analysis, a large volume over which some quantities vary continuously, is partitioned into smaller volumes over which variations in the quantities are neglected. We will use this idea to develop discrete approximations to the continuous operating variables of power systems.

A finite state machine is any device or system whose behavior can be represented by a directed graph with a finite node set. Each node represents one of the discrete states the device can occupy. Arcs represent events or excitation functions that cause transitions from one state to another.

#### Developing the Model

To obtain a finite state approximation (transition graph) of power system behavior, think of a power network with M devices such that each device can be either on (energised) or off (deenergised), giving rise to a total of $2^M$ different configurations. The continuous variables associated with each configuration can be represented by
Points in a state space whose axes are bus voltages and line flows. Assume that a procedure exists for evaluating the quality of each point in each space. Then, discrete approximations of the spaces can be obtained by the following two step procedure. First, partition each state space into regions such that each region is small enough for quality variations across it to be neglected. Second, select a single point in each region to serve as its representative. We will call this point a discrete state.

As an example, suppose that quality is evaluated by means of the N load and operating constraints of equation (a). Then, each state space can be partitioned into $2^N$ regions, such that each constraint is either off (satisfied) or on (violated) by all the points in a region. It follows that quality is uniform over each region. An arbitrary interior point can now be selected to serve as the region’s discrete state.

To develop the discrete states into a transition graph, let:

$S_{ij}$ be a vector representing the discrete state corresponding to the j-th region of the state space for the i-th configuration.

$Q_{ij} = Q(S_{ij})$ be the quality of $S_{ij}$, i.e., $Q_{ij}$ is a vector whose elements are the values of some set of quality indices, such as constraint violations, and $Q$ is a vector whose entries are procedures for evaluating these indices.

$E_{ij,kl}$ be an event that causes a transition in the state of the system from $S_{ij}$ to $S_{kl}$. Such events can be of two types: planned (scheduled breaker operations, for instance) and unplanned (faults and load changes, for instance).

$R_{ij,kl} = R(E_{ij,kl})$ be the risk of event, $E_{ij,kl}$, occurring accidentally.

$T$ be a transition graph whose node set is $\{S_{ij}\}$ and whose edge set is $\{E_{ij,kl}\}$. Appended to each node is its quality, $Q_{ij}$, and to each arc, its risk, $R_{ij,kl}$.

Thus, each node in the transition graph identifies a discrete state that the power system can occupy as well as the quality of service that would result from the occupancy. Each directed arc represents an event that will cause a transition from one node to another as well as the risk of this transition occurring accidentally.

Using the Model

Because of its size and density, constructing the entire graph for a typical power system would be impractical. To illustrate, suppose that quality is evaluated using the load and operating constraints, as described earlier. Then the graph has in excess of $2^N + M$ nodes. Since $N$ and $M$ are of the order of a thousand for typical systems, this is a very large number of nodes. Also, there are usually thousands of events that would cause a system to change its current discrete state for another. Therefore, the typical node has thousands of arcs emanating from it.

Fortunately, in dealing with real-time security, it is not necessary to consider the entire
graph but only the neighbourhood of the current operating state. As we shall see, even in this neighbourhood, all the nodes and arcs do not have to be constructed.

Power system operations can be thought of as a succession of planned and unplanned events. This succession can be visualized as tracing a path through the transition graph. The quality of this path is determined by the qualities of the nodes through which it passes. In essence, the security problem is to keep unplanned events (random disturbances) from forcing the path through nodes with unacceptably low qualities. Traditionally, this problem has been broken into two subproblems. The first, called assessment, estimates the risk that the incumbent state will transition to a state with unacceptable quality. The second, called correction, seeks to reduce this risk. In the following material we will use the transition graph to develop more specific formulations of these problems.

Let:
- $S^*$ be the incumbent, discrete, operating state of the system;
- $P_j$, $j = 1, 2, \ldots, J$, be a set of discrete states with at least one unacceptable quality flaw. For instance, $P_1$ might be the set of all states with overloaded lines, $P_2$ the set of all states corresponding to blackouts, and so on.
- $R$ and $S_{kl}$ be as defined earlier.

Then, the security assessment problem can be formulated as follows.

\[
\text{(Prob-1)} \quad \max \ R \left( S^*, S_{kl} \right) \\
\text{subject to:} \quad S_{kl} \in P_j, \quad j = 1, 2, \ldots, J
\]

The security correction problem can be stated as follows.

\[
\text{(Prob-2)} : \quad \min \ \left[ \max \ R \left( S^*, S_{kl} \right) \right] \\
\text{subject to:} \quad S_{kl} \in P_j, \quad j = 1, 2, \ldots, J \\
\text{operating cost } < c \\
\text{environmental impact } < e
\]

where constraints on operating cost and environmental impact have been included as a reminder that these quantities are usually in conflict with security and it is desirable to take these conflicts into account in running a power system.

Discussion

The above formulations of the assessment and correction problems provide a useful lens through which to review the disadvantages of available solution techniques. In particular, available techniques for assessment lack:

1. ways to properly characterize quality and therefore, the sets $P_j$;
2. good indices, R, for characterizing risk; and
3. powerful search techniques. As a result, solutions to (Prob-1) are sought only to a depth of one ply (one event or one arc distant from the incumbent state).

Since the assessment problem is a part of the correction problem, the latter suffers from all the difficulties of the former. In addition, there is the complexity of a "mini-max" process and the need to consider conflicts among security, cost and environmental impacts. It is not surprising that there are few good and explicit procedures for solving the correction problem.

In the succeeding material, we will propose ways in which to seek improvements to the assessment problem. In particular, we will illustrate how new risk indices can be constructed and suggest a more powerful search technique than any currently in use. We will not, however, deal with the issues of better characterizing quality or solving the correction problem.

RISK INDICES

The risk of a transition from one discrete state to another can be characterized in a variety of ways of which probabilities are just one. Two of many other possibilities are the "outage distance" and the "load distance."

By the "outage distance" between two discrete states we mean the least number of unplanned outages linking them. Thus, we can speak of operating states that are one, two, three, etc., outages from the incumbent state. To compute this index one would have to find the shortest path through outage arcs that links the selected nodes in the transition graph. Of course, in the security assessment problem, the incumbent node is specified by location (its state is known) but the second node is specified only by quality. Therefore, a search must be conducted to find, from all the nodes with the specified quality, the one that is closest in terms of outages, to the incumbent node.

By the "load distance" between two discrete states we mean the least amount by which system load must change for the first state to transition to the second. This index allows us to speak of states that are 100MW, 350MW, etc., away from the incumbent state.

The two indices described above seem to have a some intuitive appeal for the power system operators with whom we have talked. However, they are not necessarily the best indices and researchers and operators are encouraged to use the idea of a transition graph to develop other indices.

Whatever the index, the assessment problem has the same essential form, namely, a search through two sets. The first set contains the arcs specified by the risk index that is selected. The second set consists of nodes of the quality specified in the assessment problem. The search is for the shortest path through arcs from the first set that links the incumbent node to a node in the second or goal set.

CHOOSING A SEARCH TECHNIQUE

There are a large variety of techniques for searching for paths in graphs and trees. To help describe the main options, consider a tree whose root node is at the top. A node in this tree will be said to have been evaluated when its quality has been determined and said to have been completely expanded when all its children have been identified.
and evaluated. An open node is an evaluated node that not been completely expanded. A goal node can be specified either by quality or location (discrete state value).

Four primary categories of search techniques for finding paths connecting the root (given) node to goal nodes are:

Breadth-First: all nodes at a level are completely expanded before undertaking the expansion of any nodes at the next lower level. Breadth-first search guarantees that the first goal node found will be on a minimum-length path, but is inefficient when the branching factor is large.

Depth-First: only one node at each level is evaluated. This node is a child of the node that was evaluated at the next higher level. Depth-first search works well when all the goal nodes are at similar depths and most paths lead to them.

Hill-Climbing: a variation on depth-first search. One node is completely expanded at each level. The best child of this node is chosen for complete expansion at the next level. Hill climbing is usually much more efficient than either breadth-first or depth-first search.

Beam Search: a variation of hill-climbing. If several children of a node have similar quality, then the best n of them are chosen for expansion.

In addition, search techniques can be classified by the direction of their progress into the following groups:

Forward Chaining: the search proceeds from a given starting node to a goal node.

Backward Chaining: the search begins from one or more goal nodes and works backwards to a starting node. This technique is effective when the branching factor in the backwards direction is lower that the branching factor in the forwards direction. Of course, it requires that the locations of the goal nodes be known in advance.

Bi-Directional: the search for a connecting path proceeds simultaneously from both a starting node and a goal node.

Existing assessment schemes use breadth-first search. Because of the computational burden involved, they look only one level down from the starting node, that is, they confine their exploration to single-event-contingencies. For deeper searches we need a more efficient technique. Our choice is hill-climbing with forward chaining and means-ends analysis (MEA). The reasons are as follows.

Hill-climbing was chosen because we need more efficiency than depth-first would seem able to provide, and because the implementation of beam search would be difficult. Forward chaining was selected because the goal nodes are not known by location at the beginning of the search. MEA was chosen to provide the criterion for determining which child is best in hill-climbing. In essence, the MEA criterion is to pick the child whose quality is closest to the goal quality. (Recall that the goal nodes are specified by quality not location.)
IMPLEMENTATION STATUS

A simple prototype [3] for proof-of-concept purposes has been developed for a single processor, a uVax II, with a Unix operating system. The control structure, result storage and report generation portions of the prototype have been written in OPS83; the number crunching parts have been written in C.

The prototype calculates the outage distance and the load distance to line overloads and bus undervoltages with user specified magnitudes. For instance, the user can specify a line overload of 20% over the normal rating and a bus undervoltage of 10% below nominal. The prototype will then identify the minimum number of outages and the smallest increase in system load that will produce the overload or undervoltage conditions in at least one of the system's lines or buses. (At present we are using the IEEE 118 bus test case as our system). Moreover, the prototype appears to be faster than a conventional, one- ply, breadth-first search for security assessment.

CONCLUSIONS

Assessing and correcting the security of a power system are computationally hard problems that involve a very large number of alternatives. Existing methods for real-time assessment conduct, at best, a one ply search of the alternatives, and therefore, provide incomplete assessments. Explicit methods for real-time correction are virtually nonexistent.

More powerful methods of assessment and correction exist for off-line (non-real-time) problem solving. Some work with an expert system called CQR indicates that there are good prospects for capturing and adapting the knowledge used by these methods for real-time operations. However, the improvements so achieved will not meet all the needs of power system operators. New methods need to be developed.

The transition graph described in the paper seems to provide a promising way of visualizing power system operations, particularly for the design of new methods. Means-ends analysis seems to be a good way of organizing computations, particularly for the multi-ply searches required by these new methods.

The transition graph and means-ends analysis have been used to develop and demonstrate a pair of new and relatively simple indices for risk assessment, namely, outage distance and load distance. These indices represent a small step towards meeting the needs in the area of security. Much more work needs to be done in its three basic subareas, namely:
1. defining and evaluating better risk indices;
2. defining and evaluating better quality indices; and
3. developing explicit methods for correction.

ACKNOWLEDGEMENT

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Electric Power Systems
SECURITY ASSESSMENT

PROBLEM

Find the nearest bad state

TWO SIMPLE, INTUITIVELY APPEALING RISK INDICES

1. Outage Distance: Minimum number of outages to a bad state

2. Load Distance: Minimum increase in system load to a bad state
SYSTEM RELIABILITY MODELING ISSUES

by

A. D. Patton
Texas A & M University
College Station, Texas
SYSTEM RELIABILITY MODELING ISSUES

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A. D. Patton
Texas A & M University
College Station, Texas

Introduction

The purpose and intent of this paper is to describe and discuss outstanding issues of electric power system modeling and interpretation and use of reliability performance measures which are sufficiently accurate to support their use as absolute measures of reliability performance. Clearly, of course, the assignment of economic consequences to computed system reliability indices immediately implies that these indices are being viewed in a physical and absolute sense rather than in a relative sense.

Most existing reliability models serve reasonably well when their computed indices can be viewed in a relative sense, but must be questioned when absolute significance is demanded of their computed indices. Sources of error in reliability models arise from idealizations, simplifications, and omissions in the mathematical models as well as from uncertainties in the data required by the models. Some of the modeling issues which are believed to influence accuracy but which have not been explicitly incorporated in models (in common use at least) are summarized as follows.

1. Unit duty cycles. Most models assume that generating units and transmission components are continuously subject to failure (at the same rate) and do not experience periods of economic shutdown. This assumption is probably valid for most transmission lines and for generating units in base-loaded service, but is clearly not true for peaking and cycling generating units. Clearly, generating units which cycle in and out of service also experience two general types of failures which should be separately recognized: running failures and starting failures. Further, generating units which are on economic shutdown are not immediately available to supply load and hence start-up times need to be appropriately modeled for cycling units.

2. Unplanned outage postponability. Most generating unit unplanned outages are postponable to some degree if such postponement is desirable to avoid load loss, significant excess production costs, or other operating difficulties. The modeling of unplanned outage postponability in generating units is usually done by assuming that those outages with relatively small postponability (up to the weekend) occur instantaneously while those outages with greater postponability (beyond the weekend) are typically ignored altogether for reliability purposes. It is believed that this ad-hoc treatment of unplanned outage postponability is the single greatest source of inaccuracy in generation reliability models. Clearly, a superior approach would be to deal directly and explicitly with outage postponability.

3. System dynamics. Some preliminary work has been done to include system dynamics in the computation of reliability indices, but all reliability models in practical use limit themselves to steady-state treatments only. Therefore, no practical models exist for predicting the consequences of system dynamics on actual system reliability performance. This, clearly, should be an area of further research.

4. Protection and control systems. The operation of protection and control systems has a profound impact on actual system reliability performance and must be accurately reflected if computed reliability indices are to bear much resemblance to reality. It is observed that many, if not most, load loss events associated with bulk system failures are attributable in some sense to protection or control system malfunctions.

The issues of reliability model verification and the collection of data for reliability models go hand-in-hand with the development of more sophisticated, and hopefully more accurate,
means for estimating the parameters needed in the model. Therefore, reliability data collection systems need to keep pace with the needs of models. Presently, the NERC GADS dataset seems to provide most of the raw statistics needed for these advanced reliability models for generating systems. However, data collection systems for transmission components are much less advanced. Certainly a key to more accurate model methods for computing reliability indices is historical validation of model results. Without careful and substantial verification efforts, model accuracies will remain suspect.

Interconnected and Composite System Models
Interconnected and composite system models deal jointly with generation and transmission (bulk) and are therefore able to evaluate the relationships between generation and transmission and the tradeoffs that may exist. Generally, interconnected system models aggregate the generation resources of areas (or companies) and represent the transmission ties between areas by equivalents of physical transmission lines. Thus, interconnected system models are suitable for identifying the adequacy of generation resources within areas and transmission ties between areas. In contrast, composite system models usually maintain the identity of individual generating units and transmission lines and are therefore suitable for studying detailed relationships between generation and transmission in a given part of the network. Both types of models require modeling of both generation and transmission for reliability evaluation.

Direct treatment of generation and transmission with many areas and a general network topology in very complex form is demanding. Hence, research has focused on methods usually called distributed level - often at the expense of modeling detail. Research has been pursued and has been developed based on (1) analytical methods, (2) Monte Carlo simulation methods. Analytical methods generally classified as the method used to identify mission constraints: decomposition or contingency selection followed by a network flow calculation of some type. Computation effort for analytical studies tends to rise rapidly with the number of areas or nodes in a network; hence resourcfulness is needed to maintain computational feasibility for large networks. Computer time limitations have limited the number of load levels which could be considered in analytical methods. However, new work using the clustered load model now seems to offer a reasonable alternative to analytical methods. This approach is being applied successfully to interconnected system models with 30 or more areas or nodes. Carlo simulation models offer the advantage of great detail (as compared to existing analytical models), ways that face the issue of statistical convergence of results as the number of replications (and hence computer time) required to achieve desired or acceptable levels of statistical confidence. Here, research into methods for enhancing the statistical convergence of results by variance reduction or methods is needed.

Demand-Side Strategies
Current emphasis on demand-side strategies including various forms of load management indicates a need for improved modeling methods for evaluating these strategies in the system context. In general, load management can take two forms: (1) the load is modified indirectly through incentives and constraints, and (2) the load, or some fraction of the load, is under the direct control of the system. In the first case, the exogenously modified load re-independently of the available generation and transmission resources can be modeled in the usual way, providing that changes in the load cycle can be properly reflected in generation and transmission models as discussed previously.

Therefore, direct load control effects cannot be accurately modeled by any load model which assumes that the load is independent of the supply resources - the usual assumption. One modeling approach which is obviously possible is Monte Carlo simulation. Here the necessary temporal correlations between load and supply resources can be preserved.

Evidently additional research is needed to fully explore the possibilities of modeling of direct-load control and other forms of demand-side management. This research should explore both Monte Carlo simulation as well as analytical solution techniques.

Reliability Performance Measure

<table>
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<tr>
<th>Most reliability performance measures or indices are expected values. Examples are:</th>
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<tr>
<td>1. LOLE, expected number of days or hours of capacity insufficiency per year or other time period.</td>
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<tr>
<td>2. Frequency, expected number of load interruption events per year or other time period.</td>
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<tr>
<td>3. Duration, expected duration of a load interruption event when one occurs.</td>
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<tr>
<td>4. EUE, expected unserved energy per year or other time period.</td>
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</table>

As expectations the above and similar indices measure long-term average reliability performance, but shed no light on possible variations in performance from year-to-year or from event-to-event. Therefore, the expected values of reliability performance measures are incomplete descriptors of performance and may even be misleading in some cases. Expected values are particularly inadequate (as sole measures of performance) when year-to-year or event-to-event variances are large or when expected values are small.

As an example suppose a system has an LOLE (expected value) of 0.1 days per year. How physically meaningful is this index (to a consumer or to a PUC lawyer) when in most years, the number of days of shortfall is zero with occasional years in which 1, 2, 3 or more days of shortfall are experienced? A more complete description of performance would be provided by the variance of the performance measure or, if possible, the probability distribution of the performance measure. As a further example suppose two systems, each has an LOLE of 0.1 days per year, but performance index variances are different for the two systems. In this case the two systems experience different reliability performance, perhaps significantly different, but this fact is obscured if only the LOLE (expected value) index is computed.

Some research has been conducted on the probability distributions and variances of reliability performance measures but it appears that much more need to be done in this area both in terms of calculation methods and in terms of interpretation and use of the expanded statistical measures. Monte Carlo simulation methods (which do not employ variance reduction techniques) readily yield probability distributions of reliability performance measures as a natural by-product of the simulation process. The calculation of variances and probability distributions in analytical methods will be more difficult but seems a worthy objective.

It also seems appropriate to point out that reliability indices as commonly computed are not only expectations only, but are further point estimates of such expectations. That is even though the data used in reliability studies is usually crude and uncertain, no general methods exist to make confidence or other accuracy statements about computed system reliability indices. This is regarded as rather curious deficiency since it can lead to inappropriate interpretation of the computed reliability indices. Accordingly, the treatment of reliability index uncertainty arising from data uncertainty would seem to be a fruitful area of research.

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EVOLUTION OF POWER SYSTEM RELIABILITY ANALYSIS

by

R. L. Sullivan
Department of Electrical Engineering
University of Florida
Gainesville, FL 32611

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Abstract - This paper presents the evolution of power system adequacy analysis including a discussion of available data, systems simulation tools, and measures of system adequacy. It elaborates on the salient benefit of graph theoretic approaches in addressing such issues as bulk supply adequacy. Future research areas are described in the conclusion.

INTRODUCTION

Power system reliability has two primary components. One component is more accurately termed system adequacy and the other system integrity. This paper will deal primarily with system adequacy issues which focus on the ability to meet demand under both normal and the most plausible multiple contingencies. Security analysis addresses the issue of system performance degradation as a result of dynamic events in a system.

Power system adequacy analysis has been of interest to systems engineers for many years. Early deterministic measures have given way to probabilistic techniques using repairable component models coupled with state space simulation, convolution, and graph theoretic methods for determining the various measures of adequacy. Although very useful, power system analysis and related studies should be viewed realistically. To quote from a text on the subject "Adequacy studies do not produce spectacular results. It is reasonable to expect, for example, that such studies can accurately predict or assist in assessing the unique catastrophes which occur at time to time and which are all due to perhaps single set of causes. One should exercise reasonable judgment and provide useful insights." Statement notwithstanding, this paper discusses the evolution of adequacy analysis, availability, component and system models, and computational algorithms and will conclude with a road map for future research.

The first use of deterministic measures of adequacy dates back to the 1930's, but significant advances were made in the 1940's leading to the use of simple probabilistic models to plan the expansion of generation facilities using a measure of adequacy called LOSS-OF-LOAD PROBABILITY (LOLP). In the 1960's, others extended the methodology to include the determination of adequacy measures of adequacy called FREQUENCY OF FAILURE (f), DURATION OF FAILURE (d), and VALUE OF DEMAND NOT SERVED (EDNS), and VALUE OF UNSERVED ENERGY (EUE). Thus these three measures were used to define generation system adequacy and were later applied using state space techniques to simplified overall power system adequacy assessment.

Interestingly, the approach to adequacy analysis in Europe evolved along different lines. The European electric utilities preferred simulation-based techniques based on Monte Carlo methods in which actual system operation is simulated and failure events are handled by calls to random number generators that contained component capacity states that changed randomly in accordance with predefined probabilistic rules. This is, of course, quite different than the model base approach used in American industry. One approach is not necessarily better than the other. Salvaderi in a 1985 paper (1), compared the two approaches and found they produced very different results and that they both had their own biases. However, they both provided insight into the relative response of systems to random disturbances in a complex power system. In view of the interest in technologies with significant temporal characteristics, one possible advantage of simulation-based techniques is the ability to better capture these characteristics in expansion planning.

In the 1960's, interest in better production costing tools emerged which gave rise to the use of convolution techniques and the marriage of generation system adequacy and production analysis. Convolution techniques were very effective in solving both the adequacy and production costing problem in a very computationally attractive way. By modeling the system load over an interval of time using a so-called load duration curve, not only could LOLP be calculated but a whole host of other new measures like EXPRESSED VALUE OF DEMAND NOT SERVED (EDNS), EXPRESSED VALUE OF UNSERVED ENERGY (EUE), and the like could also be calculated. These measures became quite useful to system planners as they attempted to quantify the value of interconnections with neighboring utilities based on some known cost of emergency energy.

In the mid seventies, the research community began turning its attention to methods for bulk power system adequacy analysis. Two works opened up a decade of new initiatives. The Ph.D. dissertation by P. Doulliez (2) put forward graph theoretic ideas for capacity planning in multi-terminal networks. H. Baleriaux et. al in a CIGRE paper written in 1974 (3) capitalized on these network concepts to produce a software code called TRANQUEL which loosely stands for transmission quality evaluation. Using these concepts, the standard measure of LOLP, EDNS,
EUE could be calculated for the entire system. Other investigators extended these concepts and developed a technique for determining the relative importance of transmission elements in determining overall system adequacy. Pang and Wood in their 1975 paper applied graph theoretic methods to area adequacy analysis which has been extended by a number of investigators with varying success. A number of the uniquenesses that model the power system as a directed network is that they do not produce accurate powerflow results and contain voltage information. The poor performance is from the inability of the so called flow algorithms to account for how measures of system adequacy can be determined.

**ADEQUACY DATA**

A concerted effort has been made throughout the industry worldwide to collect data to be used in adequacy analysis. In the United States, one source of aggregated data is the Edison Electric Institute. Further, many individual companies keep extensive records on component failures and service interruptions. Other major data collection efforts around the world include: CEA-ERIS (Canada), EDF (France), ENEL (Italy), NERC (US), CEGB (UK), and UNIPEDE and VDEW (West Germany). In this section, some of the data will be presented just to put the data issue in perspective.

**What can we measure?** Clearly, power system components either work as they were designed to work or they do not. This is a measurable quantity, even if the cause of a component outage is not always clear. Components fail for internal and external reasons—and the failure may not always be a correctable design flaw but misuse of the equipment. The fact that we feel that component failure can be accurately measured is the basis for using so-called repairable component adequacy models in adequacy analysis. In one way or another, all model based adequacy analyses use such models. Implicit in such models are the assumption that the probability of failure and repair is exponentially distributed and that the failure and repair rates are constant. In more mathematical jargon, the component failures can be modeled as discrete state, continuous transition, Markov processes. And usually, the failure and repair of system components are assumed independent. Relaxation of any of the assumptions can result in very intractable modeling and simulation problems. Of course, most researchers have tried to develop clever schemes for removing these assumptions—but they have had very limited success. Since the Markov chain models are really dynamic models, another very important assumption is made, and that is it is valid to assume a system reaches a steady-state mode of behavior in terms of its adequacy i.e., the probability of failure to perform its intended function is independent of time.

**Generation Component Data**

Examining the type of data that is available on generating units, there are six major data quantities:
Service Hours is simply the number of hours a unit or group of units if the data is aggregated by unit class and type that the full capacity is available to serve load. A typical number for service hours would be 7000 hrs.

Forced Outage Hours is the number of hours a unit or group of units are unable to provide any capacity due to component outages. A typical number for forced outage hours would be 400hrs/yr.

Number of Forced Outages is the number of times each year that a unit or group of units is unable to serve load. A typical number for the number of forced outages would be 8 outages/yr.

Forced Partial Outage Hours for State i is the number of hours a unit or group of units is forced to operate in a derated state with available capacity less than full rated capacity. A typical number for a forced partial outage where say 10% of the capacity is unavailable is 15hrs/yr.

Number of Forced Partial Outages for State i is the number of times each year that a unit or group of units is unable to serve load. The corresponding number of outages where 10% of the capacity is lost would be 1.

Number of States is the total number of derated states used for a unit or group of units to describe their adequacy characteristics—five state models are typical. Five is the typical number of states used to describe a unit or group of like units.

Transmission Component Data

Transmission component adequacy data is more difficult to obtain because of the number of elements in a transmission system and the fact that the system is geographically distributed across thousands of miles. Also, common mode outages, adverse weather events, station originated outages, and section system failures can be difficult to characterize properly. In fact, these data collection and assessment weaknesses contribute to poor correlations between actual and modeled results. It is fair to say however, that a concerted effort has been made by most major utilities to collect outage data for use in transmission component models of bulk power system adequacy analysis [11]. Since each utility collects and analyzes data differently, the data from a typical investor owned utility will be presented to give the reader a feel for the type of activity underway in the industry.

The categories of data collected on a transmission system would include the frequency of failure, forced outage hours or repair time, service hours or time available for service for selected components or collections of components. Typically, the components or collection of components involved in the data collection process range from very simple to more detailed as the following list of categories reflects.

1. An entire transmission line segment including the line itself plus all protection equipment.
2. A line segment with one breaker identified as a separate component. This is more detailed than one and requires more data.
3. A line segment with two breakers identified as separate components. This representation is even more realistic as line segments are usually protected with receiving and sending end breakers.
4. A line segment with two breakers and a transformer as separate components. Since many line segments interconnect subsystems operating at different voltage levels, this representation is very significant.

Using data collected on line segments for various voltage levels the frequency of failure as a function of line length and average repair times are as follows:

Line Segments Only

A. 69kV (based on 25,000 mile-years of data)
   \[ f(x) = 0.013X \quad X = \text{miles of line} \]
   \[ R = 4.05 \text{ hours} \]

B. 115kV (based on 16,000 mile-years of data)
   \[ f(X) = 0.006X \]
   \[ R = 5.90 \text{ hours} \]

C. 230/500kV (based on 15,000 mile-years of data)
   \[ f(X) = 0.002X \]
   \[ R = 6.57 \text{ hours} \]

From this data it is clear that the lower subtransmission and distribution networks experience the highest frequency of failure but can be repaired more quickly.

Breakers

A. 69kV (based on 3770 unit-years of data)
   \[ f = 0.04/yr \]
   \[ R = 4.6\text{hrs} \]
B. 115kV (based on 2308 unit-years of data)
   \[ f = 0.03/yr \]
   \[ R = 3.2\text{hrs} \]
C. 230/500kV (based on 1456 unit-years of data)
   \[ f = 0.03/yr \]
   \[ R = 4.4\text{hrs} \]

Similarity in the data reflects the lack of geographical effects associated with user performance. This data strongly suggests the commonality between breaker unilities; the outages are due to unological problems and not external uts.

Two Breakers and Bulk Transformer (based on 924 unit-years)
   \[ f = 0.05/yr \]
   \[ R = 4.57\text{hrs} \]

This data exhibits the same characteristics as other line segment
ents.

One solution to overhead line segment ics is to construct underground cables. The following data for 115/230kV ground cables echoes this statement:
\[ f(X) = 0.0025X \]
\[ R = 120\text{hrs} \]

Even though there are some adequacy fits associated with underground cables, repair times are twenty times higher than equivalent overhead facilities. Further, cost disadvantage of underground versus head can be as high as ten to one. This is a typical dilemma faced by system ners. When does the higher adequacy ant the higher cost? Obviously, the er is wrapped up in the value of adequacy specific instance. Assessing the value adequacy is a very complex socio-economic blem that has no solution even today.

3. Cause of Interruption
   a. Lightning-------------------5.15
   b. Trees/Vegetation-------------22.20
   c. Conductor Failure-----------2.44
   d. Equipment Failure----------14.43
   e. Transformer----------------.66
   f. Animals---------------------33.55
   g. Underground Cable---------1.78
   h. Accident-------------------7.40
   i. Unknown-------------------10.03
   j. Other---------------------2.34

4. Duration of Interruptions

<table>
<thead>
<tr>
<th>Hours</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>.5</td>
<td>32.52%</td>
</tr>
<tr>
<td>1.0</td>
<td>23.90%</td>
</tr>
<tr>
<td>1.5</td>
<td>12.93%</td>
</tr>
<tr>
<td>2.0</td>
<td>8.34%</td>
</tr>
<tr>
<td>2.5</td>
<td>5.15%</td>
</tr>
<tr>
<td>3.0</td>
<td>4.97%</td>
</tr>
<tr>
<td>3.5</td>
<td>2.53%</td>
</tr>
<tr>
<td>4.0</td>
<td>2.72%</td>
</tr>
<tr>
<td>4.5</td>
<td>1.69%</td>
</tr>
<tr>
<td>5.0</td>
<td>1.22%</td>
</tr>
<tr>
<td>5.5</td>
<td>.84%</td>
</tr>
<tr>
<td>6.0</td>
<td>3.19%</td>
</tr>
</tbody>
</table>

Further, 40% of all interruptions occurred between 7:00a.m. and 11:00a.m.. In summary, 80% of the interruptions were unrelated to weather conditions; 87% of those were due to the operation of either transformer fuses or lateral fuses—which is normal operation for protective devices such as fuses, and 55% of the interruptions could be tracked to animals and trees/vegetation. Only 16% occurred due to equipment failure. Note that no interruptions were directly attributable to excessive customer demands, but it is reasonable to assume that a portion of the interruptions due to equipment failure and fuse operations could be related to customer load requests. Needless to say the database from which to extract the impact of customer demand requirements on system adequacy is nonexistent.

ADEQUACY MODELS

A quick glance at the papers written in the last ten years, one notes that the tenor is one of "What is wrong with the adequacy models being used in current studies?". Concerns over common mode failures, weather effects, non-markovian failure mechanisms, failure bunching, non-independence, station originated outages, effects of terminal complexity, and comparisons between different models and techniques clearly suggests a dissatisfaction with the state of the art. In fact, there seems to be no aspect—data, models, simulation tools, and measures—that has escaped investigation. The consensus seems to be that the state of the art is certainly not mature and that only a well organized attack involving government, industry, and the universities will be effective. These are fundamental problems which when overlaid with the changing structure and operation of modern power systems paint a very challenging research picture.

As background, a brief discussion of the often used, but unrealistically simple, models used in adequacy analysis is presented.
Using the data collected on individual system components; namely service hours forced outage hours, the frequency of failure f and forced outage rate q can be calculated. Knowing f and q, component availability p can be calculated. These four parameters can be used to describe the adequacy model of the system in very simplistic terms.

Since components are electrically interconnected, their adequacy models are also interconnected to form a network adequacy model. Models can be connected in series or parallel depending on the capacities of the interconnected areas that require analyzing an enormous number of capacity states, of course, is out of the question. Thus using the forced outage rate f and availability p, crude capacity functions could be defined and used through convolution techniques to form the effective probability distribution for the available capacity in a ration system. More complicated models allow partial outages to be modeled to realistically reflect actual system operation. Implicit in this approach is the fact that the load over some interval of time be represented, thus resulting in an assessment of system adequacy for more than one load level.

The beauty of the above so-called load duration curve approach was appreciated even earlier when work on demand side management surfaced. There have been countless studies conducted to determine the impact of various technologies on load shapes. Of current interest is the effect of real time on load shapes. Although useful, it is not experience suggests that the load duration curve model of a system hides some temporal characteristics that influence the success of a demand side management strategy. Examples where such approaches did not capture the dynamic nature of a modern power system weakness has given rise to special codes for assessing the impacts of the new demand side management strategies.

Computational solution techniques created the need for analytical methods. Stremel in 1981, Schenk in 1984 (13), Mazumdar in 1985, and Gross (15) and Wang (16) in 1988 tackled this problem in a variety of ways. Approximation techniques that better simulates the flexibility operators have in avoiding outages or troublesome operating states. Redispatching generation to avoid line overloads is a typical example of such flexibility. Although the code was originally restricted to consider the network down to subtransmission levels, it is being expanded to include the distribution results are desired or operational details are to be included, powerflow based techniques are in order.

One successful powerflow based adequacy analysis method that includes the effects of both the transmission and generation systems is call GATOR, and was developed at Florida Power Corporation. In effect, it combines the advantage of standard powerflow analysis with simple component adequacy models as described in the previous sections to produce very useful adequacy measures for the entire system. Further, the code has built-in logic that better simulates the flexibility independent power producers. Because GATOR calculates the complete power flow distribution for each capacity state considered using a very detailed electrical model of the bulk system, it is computationally very demanding, and not particularly well suited for complex interconnected areas that require analyzing an enormous number of capacity states to estimate the level of system adequacy. Stated more properly, there is a tradeoff between computational effort and powerflow accuracy that must be considered in choosing analysis tools.

As stated earlier, distribution systems tend to be very radial in structure, thus facilitating the use of serial and some parallel component models to create an entire feeder adequacy model. Perhaps the biggest impediment to increasing the accuracy of such techniques stems from the ability of the protection system to automatically reconfigure the network to avoid service interruptions. Substation switching schemes can often mitigate the effects of a component outage on service.
Distribution system adequacy models are important because component outages at a level usually result in service interruptions. The higher up in the system an outage occurs, the less likely a service interruption will occur; however, some of the most catastrophic system failures, like the 1965 Blackout, was initiated by outages of the bulk transmission system. As the data presented in the previous sections suggests, distribution component outages are caused both by trees and squirrels and not by normal component failures per se. The solution to this type of adequacy problem is feed tree trimming programs, and, for the sake of a better phrase, what might be called "network proofing" distribution system components.

MEASURES OF SYSTEM ADEQUACY

Over the years, a number of measures of system adequacy have been defined and used. The earliest measure is of course "reserve margin". Reserve margin is a deterministic measure that defines the amount of excess generating capacity in a generation system. The larger the reserve margin, the less likely a given unit outage would result in service interruptions. In the fifties when probabilistic techniques began to be used, a measure of adequacy called "loss-of-load probability (LOLP)" was defined. Because probabilistic techniques were constrained by the lack of computational resources, the calculation was made only for the annual peak load. A stable level of adequacy was one failure to load event in ten years. Some interpretations of this measure lead to the famous one day in ten year level of adequacy. There is little difference in the usefulness of these two quantities since they are only in what assumption was made about system adequacy curve.

As load models and algorithms became more comprehensive and therefore realistic, LOLP measure became more the average level of operating the system. The most important of the adequacy measures is "reserved generation capacity". The LOLP technique allowed the straightforward calculation of LOLP: it is determined by evaluating the expected system load distribution at a point corresponding to the peak in the interval being modeled. Furthermore, EDNS due to the component outages was only determined as it is the area under the load duration curve.

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Graph Theoretic Approach

1. Represent each network element as having random capacity states—usually two.
2. Using the Ford Fulkerson algorithm for determining the maximum flow through a network (maximum flow is equal to capacity of the minimum cut through the network) and set theory to classify sets of states as either acceptable or unacceptable—thus avoiding complete enumeration of all capacity states. If unacceptable, determine the associated probabilities and unserved energy at each bus of interest.

Many changes in the electric utility industry have led to greater interest in multi-area adequacy analysis. Perhaps the most important force behind the need for such analysis is the need to evaluate the cost/benefit of reserves that are distributed throughout a pool of interconnected utilities. In general, transmission systems are playing a greater role in the day to day operation of utilities than ever before which is particularly true when reserves must be available to pool members to be of any value in maintaining system adequacy. It is very difficult for planners and decision makers to justify interconnections based on capacity deferment grounds. The cost/benefit of a given interconnection is very much a function of how much capacity it displaces in the receiving system and the cost of energy being received. Although the capacity of a transmission line is a known quantity, the availability of the line is very much a random variable as discussed in a previous section. Interconnections that have adequate capacity to insure acceptable levels of supply are only valuable if they are in service. Analysis tools used for composite system analysis therefore must have two major characteristics: they must be able to model the interconnected networks of member utilities and they must be able to represent the random failure and repair of the network elements. In some applications, it is even important to use network models that can accurately reflect the distribution of powerflow through the network—as Gator does. However, if one is interested in obtaining more insight into adequacy characteristics of individual load centers or even buses for a large number of capacity states, such tools are computationally unattractive.
Repeat step 2 until all states have been classified for the load level assumed.

Multiply results times probability that the load level assumed will occur--using forecasted data.

Repeat steps 2-5 for each load level if load is assumed to vary randomly over the period being analyzed.

i-area Adequacy Analysis

For multi-area composite system adequacy analysis, it is desireable to only evaluate in all the area of interest rather than the entire system. Thus equivalencing techniques developed by Kumar can be used to valence pool members whose adequacy is not directly of interest. This overcomes two problems. One, it reduces the computational effort but yet it retains the effects of the adequacy of other pool members on the area of interest. Referring to Kumar's paper in all, so as to not duplicate or misrepresent findings, he demonstrates the technique using several systems—the IEEE Reliability Test System (RTS) and the 41 bus Saskatchewan Hydro Corporation (SPC) system. The paper discusses three separate studies to demonstrate the technique:

Comparison of adequacy indices for a two interconnected RTS network obtained by:

a. developing an equivalent for one RTS and using it to calculate the adequacy indices for the other network.

b. solving the entire network consisting of the two RTS networks.

Analysis of the effect of load variation on adequacy indices for the south region of the RTS.

Analysis of the effect on the adequacy indices of interconnecting the SPC and the RTS power networks.

Indices of adequacy are used in the cases including Probability of Failure, Frequency of Failure, Expected Load Ailment, and Expected Energy Not Supplied. of these were discussed in a previous ion.

Study II This study was conducted to demonstrate that the equivalencing concept works. As the paper illustrates, not only does it work but it works quite well. On the basis of this result, equivalencing was used by Kumar in the other two studies.

Study III This study demonstrates the use of the technique in assessing the benefit of interconnections on load point adequacy.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research programs should methodically include all aspects of system adequacy including data collection and analysis, component and system models, simulation tools and environment, and useful measures of system adequacy. These topical areas are interrelated and thus should not be addressed independently. Measures of system adequacy are only valuable if there exists data, models, and simulation tools to compute them. Further, in view of the changing nature of the industry and the interest in marginal cost pricing, reliability differentiated rates, load control, etc., there is a need for a more comprehensive and consistent set of adequacy measures down to the bus levels. Because it is well recognized that the classical assumptions are not valid and that common mode outages, station originated outages, protection system failures, and even system control functions influence system adequacy, much more data is needed to build a realistic reliability model of a bulk power system. The simulation environment issues should take into account advances in computing speed, storage, display, networking, and distributed processing. Perhaps adequacy analysis should be driven more by real time system data than simplistic reliability models of components for which there is little data.

REFERENCES


THE NEED FOR A BUSY SIGNAL

by

Hyde M. Merrill and Allen J. Wood
Power Technologies, Inc.
Schenectady, New York
This morning Norman U. Gigawatt tried to call home to remind his wife to pick up orange juice. The line was busy. He knew that there was only one line going into his house, and that only one conversation could be carried on at once. With no teenagers, and knowing his wife's habits, he figured that if he tried again in ten minutes he had a good chance of getting through, and sure enough, he did.

Incidentally, he had little doubt that, if he got a busy signal, the line was truly busy: several times, when it seemed to be tied up for an inordinate time, he had the phone company verify it. They usually reported that, yes, someone was talking. Once, when he hadn't been able to get through for hours, they told him that there was something wrong with the line. It was fixed that afternoon. But that had only happened once, so he believed the busy signal unless he had evidence to the contrary.

N. U. Gigawatt ate lunch at McDonald's. The milkshake machine, the kid told him, was kaput, so he had a Sprite instead. (He had no reason to disbelieve the kid. It was in McDonald's interest, after all, to sell him a milkshake.)

That afternoon Favorite Light and Power Company (FLAPCO), one of N. U. Gigawatt's best customers, called and asked for 75 MW from his pulp mill cogeneration plant for two weeks. FLAPCO was willing to pay a good price -- a few more like this and he could afford the down payment on the Porsche.
Unfortunately, MUG would have to wheel through Big Bad Company (BBP), and he had problems making those gents in the past. Dealing with BBP was always difficult. Sometimes they told him that they didn’t have capacity available to do the wheeling. He got the impression they were worried about overloading lines. Although he was aware of occasional local blackouts and they were worried about overloading lines, he knew that his power was moving on the network. This made MUG wonder how real BBP's claims really were. When he tried to press BBP on how their engineers started by throwing jargon around and defining and applying measures of network capacity. There was a lot of "engineering judgment" involved in determining reliability criteria than eastern utilities like BBP, and MUG contrasted the various service interruptions Mr. Gigawatt experienced on this typical day.

### Table 1

Service Interruptions for Norman U. Gigawatt

<table>
<thead>
<tr>
<th>Physical Process</th>
<th>Signal</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obvious</td>
<td>Visual - no juice</td>
<td>None of consequence</td>
</tr>
<tr>
<td>Obvious</td>
<td>Clear - visual</td>
<td>Minor delay, but preferable to no light at all</td>
</tr>
<tr>
<td>Obvious</td>
<td>Auditory - clear</td>
<td>Temporary and acceptable delay in communications</td>
</tr>
<tr>
<td>Obvious</td>
<td>Auditory - clear</td>
<td>Acceptable substitute available on demand</td>
</tr>
<tr>
<td>Obscure</td>
<td>Ambiguous - reluctance to commit to service</td>
<td>Incomprehensible delay in essential service. No substitute offered. Major profit implications.</td>
</tr>
</tbody>
</table>

### The Transmission Network

It is useful to describe and differentiate two models of a transmission system.

### Model 1: Transmission as Moving a Commodity

This model, which is almost everyone's implicit or explicit mental model, treats electrical energy as a commodity which is produced at point A, moved to point B, and used there. In model 1, the three processes (generation, transmission, and use) are quite different and can be dis-integrated in terms of physical mechanics, ownership, regulation, costing, pricing, etc.

### Model 2: Transmission as a Function of an Integrated Machine

The physical reality which conflicts with model 1 is that transmission moves nothing from point A to point B. Not even electrons (if there still is such a thing) move from A to B. In model 2, transmission is a force-at-a-distance function which is part of an integrated energy-conversion machine. One analogy is the transmission of a car, which connects the engine to the wheels. Another is a belt drive which couples a steam engine to a gear which raises or lowers an elevator. In fact, it is instructive to think of a complicated belt system, driven by one or more steam engines, which runs a lathe in one room, a drill press in another, and an elevator at the end of the hall. Voltage, VARs, electrical losses, etc., all have their analogs in this system.

### The Practical Differences between Model 1 and Model 2

All of the challenges and difficulties associated with the busy signal problem are due to the differences between model 1 and model 2. In model 2, the operation of the transmission system cannot be separated from the operation of the engines and the wheels, lathes, elevators, etc. In model 2, it is the transmission system as a whole, not a piece of the driveshaft or one of the idler wheels, which allows potential energy at one location to be transformed into kinetic energy elsewhere. Although it is the transmission system as a whole that makes this happen, in some sense some parts of the transmission system contribute more than others to this force-at-a-distance. (For example, in a hoist made of a rope and several pulleys, the tension in the rope varies from point to point, but if the rope is cut anywhere, the hoist fails.) In model 2, there is little control over which portion of the system contributes the most leverage: it is dictated by physics.

Although model 2 is more consistent with physical reality than is model 1, much of the language and many of the concepts used in transmission engineering have their roots in model 1. Edison found the model 1 power-flow concepts handy, and one of the important contributions of the pioneers was to develop a practical way of measuring and integrating flow -- the watthour meter. We will use these existing constructs, but keeping in mind the fact that they are reflect reality only crudely.

### MEASURING TRANSMISSION CAPACITY

#### How Transmission Capacity is Measured Today

There is no simple equivalent of the telephone company's busy signal on a power network. Transfer capacity is not the rating of a single line or a few lines. It is a function of the strength of the network as a whole. It is defined in terms of reliability criteria, which themselves are subjective and somewhat imprecise. It
1. As switching operations occur and as demand, location, and wheeling patterns change, even loop actions taken by operators of other systems, the available transfer capacity.

Of these realities, even explaining transfer capability limits between only three interconnected systems becomes confusing.

2. Attempts to define how much power system X can send to system Y, with simultaneous transfer from Z, for instance, if X is transmitting 1300 MW to Y, and the transfer capability between X and Z is 2600 MW, to X) or 2000 MW (X to Z).

Such diagrams are required to represent transfer capabilities for a three-area (X, Y, and Z) system. If these diagrams are developed using load flow programs, simulate the flows on the network. Developing these diagrams for even a three-area system, for a range of operating conditions, takes a lot of engineering time and inter-utility cooperation, or capabilities for systems with more connections (due to a variety of possible wheeling actions, for instance), are much harder to model.

Figure 2

![Typical Bi-Axis Transfer Capability Polygon](Source: EPRI EL-3425)

Reliability and security issues are closely related to transfer capacity. Today's recommended criteria are established by NERC, by each reliability area, and in some by power pools. The criteria are interpreted and applied by each individual utility. These criteria are specialized for different parts of the system. For instance, the reliability of satisfying expected loads by a utility's set of power plants is expressed as loss-of-load probability, expected unmet demand, reserve margin.

The reliability of the transmission network is measured in terms of the number and type of contingencies designed to withstand. There is no accepted method for expressing generation reliability and transmission reliability in equivalent terms.

Methods for measuring transmission capacity but only because:

- the parties all have large engineering staffs,
- they are willing to exchange data and cooperate in studies, and
- they are not in serious competition, so utility-to-utility differences in defining transfer capabilities are not seen as competitive plays.

Under evolving conditions when IPPs and QFs play a larger role, only the first of these conditions is likely to hold for the large IPPs. The cooperative nature of today's environment will be lost.

Since the entity owning the transmission may compete with IPPs and QFs who want to wheel, the definition of transfer capacity may be a bone of contention. Accordingly, today's methods for measuring transmission capability will probably not work under deregulation. Signs of this are already occurring.

A BUSY SIGNAL: SPECIFICATIONS

Under deregulation and increased wheeling, a new method for defining transfer capacity is needed, with the following characteristics:

- It should require straightforward calculations,
- It should represent an objective, defensible, standard,
- It should be compatible with today's regulated industry structure, and with likely evolutions thereof,
- It should not be so conservative as to unduly limit wheeling,
- It should represent variations in operating conditions and network changes due to maintenance, switching, etc., and
- It should lend itself to on-line use in control centers as well as consistent application in planning.

It is particularly important that this method be so clearly acceptable to all parties that the courts and commissions will not have to spend inordinate amounts of time reviewing and redefining transmission transfer capability. Such a method is not available today. The Norman Ulysses Gigawatts of the world do not get busy signals -- they receive a minor and probably irritating dissertation on transfer capability calculations.

TOWARD A BUSY SIGNAL

The busy signal specifications make it hard to set down a simple process for developing a busy signal. If it were easy, it would have become a solved problem by now. We will suggest four possible busy signals. Each will have its own unique development path. It is obvious that others are possible.
Gas Pipeline Approach

First idea is to ignore all those (including the authors) who cry out that the transmission work is not a gas pipeline and pretend that it is. "Model 1" approach is actually quite good in many situations where there is only one transmission line in the US and dynamic-stability limited or thermally limited rather than limited by transient stability, and congestion issues are irrelevant for radial lines. Dynamic-stability limits are easy to calculate, so a busy signal based on them would satisfy all specifications listed above.

Unfortunately for this approach, most of the EHV is not radial. But maximum line capabilities are reduced to something below thermal limits to be a safety margin for voltage problems and IC limits plus leaving a margin to accommodate the fact that the analytical methods used to determine flow will direct flows at will, using all available capacity. Determining the appropriate limits for radial elements will be an exercise in itself. But no fear, even if we don't want to do it, some intrusive judge or regulator will argue long enough to several hours of testimony. (Similar events have already occurred.) We could then develop models of the table flows and transfer limits based on linear-flow analysis. The methods are available, are simple to implement and provide a definite limit. They can reflect changes in system configuration and would be easy to implement in an on-line environment.

Approach fails to meet at least two of the specifications given above. First, there would have to be a margin of conservatism built into the ideal line capacitors, so the operation of the hospital would be far from optimal. Second, defining the appropriate limits for individual lines will be quite difficult computationally, in most general situations.

Enhancing Today's Methods

Concerns that power system engineers about cascading failures and blackouts, one such would be to keep the basic notions involved in techniques and search for simplifying methods present them. These current analytical techniques differ in the analysis of N-1 and N-2 cases (where one or both elements are considered to be out of service) to nine transfer limits. Regions for safe operation are determined using some means for searching for operating conditions. (A linearized model using a dc flow might use linear programming; an ac model use an OPF.)

A technique that might work and be a useful tool is to develop the maximal regular sphere (or sphere) that could be enclosed in the region of operation. This would mean that the region would be bounded by the coordinates of the center and the radius. The behavior of this regular bounding sphere (RIBS) (UREKAI! We've coined an acronym) for different initial conditions might be to develop a way to make the RIBS a simple system of load, interchange, etc.

If a RIBS could not be found, it would be possible to work with a transfer capability polyhedron (an extension of Figure 2). It is quite easy to use a linear program to determine if a particular operating point is inside or outside such a polyhedron. The challenge is in finding the hyperplanes that define the sides of the polyhedron.

This general approach is likely to be quite acceptable to experienced power engineers. It represents no philosophical change from what they are doing. Only incremental steps will be necessary to implement it.

Unfortunately, it is not clear that significant simplification will be possible. This means that these methods will continue to be too burdensome computationally, and too complex conceptually, to meet the specifications given above.

Traffic Cop

A third approach is to get around the first and second specifications by creating a totally independent, unbiased entity to control grid access in real time and to plan for transmission additions. Whatever this entity says is the transfer capability of the network is, by definition, true.

At one extreme, the entity could use relatively simple methods in making its decisions. This would lead to an under-exploited network. At the other extreme, the entity could use very complex analysis, doing the same calculations as under "Enhancing Today's Methods." The difference in this approach is that the cop is given complete authority to say who can go and who must stop, so there is no need for other parties to understand or duplicate the analysis.

This approach is quite simple conceptually. A major difficulty is that it is inconsistent with today's US utility industry structure and with likely evolutions thereof.

Integrated Network Approach

The first three methods are based on model 1 of the transmission network. Using model 1 to develop a busy signal is a source of significant difficulty. This is reminiscent of what pre-Copernican astronomers had to do to make their earth-centered model agree with the astronomical data they were collecting.

A model 2 method would not attempt to model flows through the network, but would treat it as an integrated system, with energy injected at some points and removed at others.

Unfortunately, we do not have accepted models of this type available, nor do we know how to develop them. More than the other three methods, developing a model 2 solution would require some very sensitive and basic research.

Conclusions

The current techniques for evaluating available transfer capability in power systems are based upon the natural fear of repeating the widespread blackouts that occurred in the 60's and later. The methods are analytical techniques based on contingency analysis. They are difficult to apply and require cooperative
eering studies by interconnected utilities. They are difficult to explain to the non-specialist, and likely impossible to explain to anyone other than an electric power engineer.

The growth of a competitive generation industry is a need to develop a simpler and more understandable approach to the determination of able transfer capability. The method should be simple to understand and apply and should provide unambiguous answers. It must be conservative enough to accommodate concerns over system security and yet must not unnecessarily restrict the flow of wheeled power.

The paper has suggested four possible evolutionary approaches. Others are undoubtedly feasible. Our intent was to give a push to this as a problem that warrants further effort.
MODELING AND OPTIMIZATION ISSUES IN EXPANSION PLAN EVALUATION METHODS

by

A. P. Sakis Meliopoulos
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

and

George J. Cokkinides
Department of Electrical Engineering
University of South Carolina
Columbia, South Carolina 29208
Recent trends in the electric power industry have led to changes in operating and optimization practices. These must be reflected in planning studies. In this paper, optimization and modeling issues arise. This paper discusses recent trends and developments in the electric power industry. It presents a new electric load model and a new power flow/optimization formulation. Sensitivity analysis of system attributes with respect to expansion options, and effects of policies and practices on power system attributes are discussed. The sensitivity analysis serves as the basis for incremental cost/benefit analysis. The proposed modeling and optimization methods are embedded in a composite power system simulation method based on the probabilistic simulation. Within this framework, a sensitivity analysis is embedded which computes sensitivities of operating costs, security measures, and transfer capability with respect to specific expansion options. This paper presents the electric load modeling, the new power flow/optimization formulation, and the composite power system simulation methods. Typical results are discussed.

2. ELECTRIC LOAD MODELING

Traditionally, the electric load has been thought of as an exogenous process to the electric power system. Planners will design the system to satisfy the electric load with a certain degree of reliability. Load management programs have changed this assumption many years ago. Recent trends will further change the...
mess which represent positive electric load at Argos customers with non-utility generation and energy capabilities. The electric load of these investors and its time variation depends on electricity production costs. (4) Small independent areas responding to spot prices and others.

The trends of these changes on electric load are twofold: the uncertainty associated with the electric load will increase. Second, the electric load is not a stationary process anymore but a process which affects the operating cost of the power system. It is, therefore, reasonable to assume that they are generated as a linear combination of a small number of independent stochastic processes.

Figure 1. Electric Load Model Based on Small Number of Independent Processes

The proposed electric load model is illustrated as an ARMA model. Specifically, the bus electric load, denoted with the vector $S(t)$, is constructed from a vector of independent white noise processes $n(t)$. The white noise vector $n(t)$ is then transformed into an $m$-vector of stationary stochastic processes $z(t)$. Next, the vector $z(t)$ is transformed into an $m$-vector of nonstationary stochastic processes $x(t)$. Finally, the vector $x(t)$ is translated into bus electric loads using the linear model $L$.

The following formulation is proposed which achieves this goal. Consider an electric power system and an arbitrary state defined with the vector $x$ (the vector $x$ is defined in terms of bus voltage magnitudes and phases). For the assumed state $x$, let $v_i, w_i$ be the real and reactive power mismatch, respectively, at bus $i$. Then consider the following optimization problem:

$$\phi_1(\cdot), \phi_2(\cdot), \phi_3(\cdot)$$ are vectors of arbitrary polynomials of the argument

$B$ is the backward operator

$Z$ is an $m \times m$ matrix, $m << n$.

ARIMA models have been extensively used to represent the electric load. It is well known that they are capable of representing the periodicity as well as the nonstationary property of the electric load. The innovation introduced here is the linear model $L$ which translates the low order nonstationary stochastic process vector $x(t)$ into the high order vector $P(t)$ of the bus electric loads. This innovation is justified on the basis that bus electric loads are typically strongly correlated. It is, therefore, reasonable to assume that they are generated as a linear combination of a small number of independent stochastic processes.

The optimal order of the ARIMA model (order of functions, $\phi_1, \phi_2,$ and $\phi_3$) and the number of independent white noise processes (vector $n(t)$) is system dependent.

The Non-Utility System Model. Non-utility systems, such as customer owned generation, power "wheeling" schedules, etc., are represented as electric power injections at specified system buses. These injections are assumed to be stochastic processes. The use of ARIMA models is proposed for this purpose. The advantages of the ARIMA models are (1) they can accurately represent the periodic nature of power "wheeling" schedules, customer owned generation patterns, etc., and (2) they provide a good model to represent the uncertainties associated with customer owned generation, power "wheeling" schedules, etc.

Another advantage of the ARIMA model relates to the possibility that the operation of non-utility systems may be controlled by the utility under certain conditions and constraints. In this case, the customer owned generation patterns, power "wheeling" schedules, etc., may be altered in order to optimize a given operational objective subject to specific constraints. In this case, the ARIMA model parameters can be selected by a proper constrained optimization problem. The resulting ARIMA model will describe the statistics of the non-utility generation and/or the statistic of electric loads responding to specific rate structures. The same approach is applicable to modeling of load management programs.

3. POWER FLOW/OPTIMIZATION MODEL

The power system of the future will rely on FACTS elements to attain an acceptable operating condition. This means that standard power flow algorithms may diverge. A new approach is proposed for power flow analysis which within its algorithms will be able to dispatch FACTS elements as necessary. Utilization of FACTS elements is viewed as remedial actions which are applied by an optimization model within the power flow solution algorithms.

The following formulation is proposed which achieves this goal. Consider an electric power system and an arbitrary state defined with the vector $x$ (the vector $x$ is defined in terms of bus voltage magnitudes and phases). For the assumed state $x$, let $v_i, w_i$ be the real and reactive power mismatch, respectively, at bus $i$. Then consider the following optimization problem:
The proposed approach has several advantages. It combines the remedial actions with the power solution and, thus, increases the efficiency of the overall model as compared to performing a power flow solution and then a remedial action computation separately. Second, it eliminates the necessity of adjustments during the power flow solutions such as net MW export adjustments, capacitor/reactor switching with local logic, etc. These adjustments may require several power flow iterations. Third, and most important, it will guarantee that severe power mismatches will not result in nonconvergent power flows.

Efficiency-wise, the proposed power flow/optimization algorithm requires overall less execution time than the usual power flow with interchange adjustments, capacitor/reactor switching, etc. In addition, the proposed formulation results in an operating condition which is optimized by taking advantage of the controllability of FACTS elements.

4. COMPOSITE POWER SYSTEM SIMULATION

Power system simulation has been the central methodology for planning studies and reliability analysis. Traditionally, the generation system is separably simulated from the transmission system. In the past, the design of a power system and its operating practice, however, and in the future, this decomposition is not justified. Recent trends have resulted in transmission constrained systems which means that there is a substantial impact on reliability, security, and costs due to the interaction between generation and transmission systems. The interaction cannot be ignored anymore, thus the need for composite power system simulation methods.

Efforts to develop composite power system simulation methods date almost 15 years ago. Three distinct approaches are identified in composite power system simulation:

1. The enumerative approach
2. Monte Carlo simulation

Description and discussion of these approaches follows.

4.1 The Enumerative Approach

The enumerative approach has been extensively used in North America for adequacy evaluation/reliability analysis. The basic idea is to enumerate all possible states of an electric power system, to analyze the state and store the results for subsequent processing. Because of the extreme large number of contingencies, the conceptual and computational problems are serious. As an example, a very large number of multiple generating unit outages must be considered for an individual event. The problem of a priori determining the severity of multiple unit outages is a challenging problem. An effort toward this goal is the wind-chime method developed by PTI for EPRI. The method is illustrated in Figure 3. The method considers a number of contingency levels. At each level the "binding" contingencies (states) are identified with a multiplicity of contingency ranking methods. The enumerative method is extremely time consuming. It is our strong belief that state enumeration methods are at best ineffective in addressing the present day needs for composite power system simulation (which is the basic tool for reliability analysis). On the other hand, they provide useful and complete information for the enumerated states. As the systems become increasingly complex and stressed to the limits, the need for effective composite system simulation becomes relevant.

Aggregate (macroscopic) simulation methods of the composite power system are needed.
Monte Carlo Simulation

Monte Carlo simulation is easily implementable and offers a great tool for validation of other methods. The method is illustrated in Figure 4. It is imperative that the Monte Carlo simulation be based on comprehensive models of electric load, generation, transmission, etc. In this way the results of the proposed simulation method are directly comparable to the results of the proposed simulation method. Note that the Monte Carlo method, the number of trials must be adequate to capture all possibilities of adverse effects on the system, and for meaningful results. This requirement hinders applicability of this method to large scale power systems. The Monte Carlo simulation is typically suited to small or medium size power systems.

The basic Monte Carlo approach can be applied for hour in a year in chronological order (sequential approach) or the hours of the study time can be considered at random (random approach). The method requires a stochastic model of the electric load and a stochastic model of component availability. The models can be simple or sophisticated inclusion of exogenous effects, econometric parameters, etc.). The simulation of the randomly selected system conditions is done with the use of power system analysis methods, such as load flows, dispatch algorithms, optimization algorithms, and models simulating operating policies. The result of the simulation are probability distribution functions of power system outputs (circuits flows, voltage levels, energy curtailment, etc.). These results are utilized in the computation of appropriate production quantities or reliability indices. The key issues in this approach are: (1) the number of trials must be large enough to adequately capture all possibilities of adverse effects on the system, and (2) the analysis of the effects for a specific trial must be as close to real world as possible and as efficient as possible.

The Monte Carlo approach has several advantages and disadvantages. Consider, for example, the application of this approach for reliability assessment. For meaningful results, it is imperative that a sufficiently large number of problematic system conditions be captured and simulated. However, the majority of the selected trials are problem free. This implies that the Monte Carlo method calls for the expenditure of considerable computing time in order to obtain sufficient confidence in the results. On the other hand, the method allows the analysis of complex systems without forcing the system model to become unrealistic. In addition, it offers a synthesis of final results and a detailed description of the events that caused the results.

4.3 Probabilistic Simulation

The probabilistic simulation involves the utilization of a probabilistic model for the generation and transmission systems which are coupled with a probabilistic power flow method. The overall procedure is described as follows:

Consider the proposed stochastic load model and the Markov model of generating unit availability. Further, consider the operation of the system during a specified period of time. This period of time may be contiguous or noncontiguous (for example, 1 pm to 3 pm each day for a period of one year). Utilizing the proposed electric load model, the electric load of a bus, during the period of simulation, can be characterized as a random variable with a probability distribution function and correlation to other bus loads. The total electric load can be characterized as a random variable, L, with a probability distribution function, F_L (x). Similarly, utilizing the Markov model of generating units, the unit availability is represented as a discrete random variable. Assume that the n units of the system operate at levels x_1, x_2, ..., x_n, respectively, while the total electric load is l. If unit k is not in operation, then obviously x_k equals 0. Since there is a finite probability that any unit can be forced out, the output of unit j, x_j, is considered to be a random variable with probability of forced outage equal to q_j. We write

Pr(A_j = x_j) = 1 - q_j , \quad x_j \neq 0 \quad (5)

Pr(A_j = 0) = q_j \quad (6)

where A_j is a random variable representing the available capacity of unit j, q_j is the probability of unavailability. The above relationships state that the probability that the output generator j is x_j equals
For the condition that has been considered, the net load \( l_a \) will be

\[
l_a = l - x_1 - x_2 - \cdots - x_n \tag{7}
\]

where \( l \), \( x_1 \), \( x_2 \), \( \ldots \), \( x_n \) are not deterministically known, above equation can be replaced with its equivalent in terms of the corresponding random variables

\[
l_a = l - A_1 - A_2 - \cdots - A_n \tag{8}
\]

\( l \) is a random variable representing the total demand and \( A_i \) is a random variable representing output of unit \( i \). Since the probability distribution functions of the random variables \( l, A_1, \ldots, A_n \) are known and since these random variables are independent, probability distribution function of the random variables \( L_a \) is easily computed with a series of simulations [9].

If we assume that \( l > 0 \) (that is, load exceeds ration), then another unit should be brought into action or one or more of the operating units should raise their output. Assume that unit \( i \) is operating \( l \) and that it is selected according to a criterion to respond to any increases in the load. We shall refer to this criterion as the dispatch criterion. A definition is to satisfy operational practices and constraints. The dispatch criterion can be arbitrary and is assumed to be the unit incremental cost. To begin with, \( x_i \) may be equal to zero. In general, if \( l > 0 \), the output of unit \( i \) will rise from \( x_i \) to \( x_i + \Delta x_i \), where \( \Delta x \) is a small increment (1-2 MW). We shall refer to this increment as block \( \Delta x_i \). The described formulation and directization of probability theory yields expressions such as expected energy, cost of operation, etc., from the \( \Delta x_i \) increase in the output of unit \( i \). The detailed mathematical formulation is in [23].

Upon completion of the simulation algorithm, the probability that unit \( i \) operates at level \( x_i \) or the probability density function of power injection at the system buses as well as the joint probability of any generating unit pair has been computed. Thus, the power injections to the electric power network are characterized as random variables with known probability distribution functions and correlations. This is illustrated in Figure 5. It should be noted that the probability distribution functions at generation buses cannot be approximated by Gaussian distributions. This basic result can provide the performance parameters for each generating unit, such as (1) expected lifetime, (2) expected produced energy, (3) expected operation cost, etc. [23].

The proposed method is also capable of simulating operating practices and constraints of a power system. This objective is achieved by appropriate formulation of the dispatch criterion mentioned in the introduction. Specifically, the dispatch criterion is defined as the sum of the actual operating cost of the generating unit plus a nonlinear penalty function of generating unit output defined with parameters. The definition of the dispatch criterion illustrated in Figure 6. The proposed method accommodates an arbitrary dispatch criterion. The parameters of the penalty function are selected with a probabilistic optimization method which is described by [23].

The solution of the optimization problem is the parameters of the penalty function, such as the operational practices and constraints will be satisfied with maximum probability. Note that if the nonlinear penalty function is neglected, then the dispatch criterion equals the actual operating cost of the generating unit. This selection amounts to simulating the economic dispatch only, neglecting other operation practices, such as interchange schedules, etc., and operating constraints, such as load energy limitations, transmission limitations, etc.

Once the power injections at the system buses have been probabilistically characterized with the above method, the probabilistic power flow is used to compute the probability density function of system output.
Typical results of this method have been presented in Reference [23]. Figure 7, taken from Reference [23], illustrates the utilization of the method for computing the probability distribution function of circuit 14–16 flow of the IEEE Reliability Test System.

4. Flow in MVA

Presently, an effort has been undertaken to incorporate transmission system operating constraints and practices in the probabilistic power flow. A concise description of this method follows. Recall that the proposed simulation method has been described in such a way that the effects of transmission system constraints on the operation of the system subject to transmission and other operating constraints. The optimization problem is postulated as follows: Determine the required adjustments to the generation bus power injections, such that the probability that an operating constraint violation is minimized. The operating constraints may be: (1) circuit loading constraints, (2) bus voltage allowable range, (3) net power interchange constraints, etc. The mathematical

A difficulty associated with the described probabilistic simulation is the incorporation of transmission system optimization processes or security functions related to transmission limitations. Specifically, probabilistic network models, such as the probabilistic power flow, have not incorporated operating constraints in the formulation. Presently, an effort has been undertaken to incorporate transmission system operating constraints and practices in the probabilistic power flow. A concise description of this method follows. Recall that the proposed simulation method has been described in such a way that the effects of transmission system constraints on the operation of the system subject to transmission and other operating constraints. The optimization problem is postulated as follows: Determine the required adjustments to the generation bus power injections, such that the probability that an operating constraint violation is minimized. The operating constraints may be: (1) circuit loading constraints, (2) bus voltage allowable range, (3) net power interchange constraints, etc. The mathematical
ulation of the probabilistic optimisation problem presented next.

The formulation of the probabilistic optimisation based on modeling the probabilistic operating constraints with deterministic constraints. As an example, consider the power flow $T_k$ of circuit $k$:

$$T_k = g(x_j; j = 1, 2, \ldots)$$  \hspace{1cm} (13)

$x_j$ is the power injection at bus $j$.

$T_k$ be the rating of circuit $k$. Then the probability of overload is defined as:

$$Pr[T_k > T_k] = probability\ that\ circuit\ k\ is\ overloaded$$

that the probability density function of the $x$ variable $T_k$ depends on the probability density function of the power injection variables $x_j$. The probability density function depends on the parameters of the penalty function for the generating and load shedding if load shedding is viable. For a mathematical formulation of the above modeling methodology is repeated to other power injection variables $x_j$.

Subsequently, an optimization problem is defined which addresses the following concerns:

1. Power wheeling schedules
2. Customer owned generation ( cogeneration, etc.)
3. Electric load modulation due to specific rate structures.

The formulated optimization problem can be written as:

$$J_v = \sum w_i (V_i - V_{imin})^2$$

$$J_p = \sum w_i (T_i - T_{imax})^2$$

where

$V_{imax}$ is the maximum voltage at bus $i$

$V_{imin}$ is the minimum voltage at bus $i$.

$V_i$ is the actual bus $i$ voltage magnitude

$T_i$ is the actual circuit $i$ power flow

$T_{imax}$ is the circuit rating

$w_i$ are weight factors

$J_v$ is a voltage security index

$J_p$ is a flow security index.

The sensitivity analysis comprises three components. The first component is the optimization analysis, the second component is the sensitivity analysis for a specific condition, and the third component is the simulation process which may be based on Monte Carlo simulation or the enumerative approach. The objective of the optimization analysis is to optimize the operation of the system for a specific load condition. Next the sensitivity analysis computes the sensitivity of the power system attributes (operating cost, security, and transfer capability) with respect to FACTS elements parameters. This analysis provides useful information but only at the specified conditions. To obtain the impact of FACTS elements over a representative range of power system operating conditions, a Monte Carlo simulation or the enumerative approach is used to provide the statistical distribution of the information obtained from the optimization/sensitivity analysis.

The overall procedure is embedded in the Monte Carlo simulation as it is illustrated in Figure 4.

6. SUMMARY AND CONCLUSIONS

Modeling, optimization, and simulation issues have been discussed pertinent to expansion plan evaluation methodologies. Methods have been proposed which favorably address the needs as they are shaped by recent trends in the electric power industry. Specifically, an enhanced model of the electric load is proposed which addresses the following concerns:

1. Power wheeling schedules
2. Customer owned generation ( cogeneration, etc.)
3. Electric load modulation due to specific rate structures.

A new power flow/optimization formulation is proposed which favorably addresses the needs of a power system with increased number of controllable devices (FACTS). A sensitivity analysis embedded in a composite power simulation method provides measures of controllable device effectiveness on any pertinent power system attribute such as operating cost, security, and transmission losses.
Composite power system simulation methods have reviewed. The enumerative approach and Monte Carlo simulation are the well-developed methods. However, both these methods face some practical limitations due to increase uncertainty in electricity and availability of non-utility generation. Promising approach has been recently introduced based on the probabilistic simulation method. The method implies the probability distribution function of system attributes by incorporating modern techniques. Much work needs to be done on the optimization criteria and transmission constraints. 

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BIOKETCHES

A. P. Bakis M. P. Meliopoulos, (N '76, M '83) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1977, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a Professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the book, Power System Grounding and Transients, Marcel Dekker, June 1988, and the forthcoming monograph, Numerical Solution Methods of Algebraic Equations, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineers and the Sigma Xi.

George Cokkinides (IEEE member 1985) was born in Athens, Greece, in 1955. He obtained the B.S., M.S., and Ph.D. degrees at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineer at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina as an Assistant Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE Power Engineering Society and the Sigma Xi.
ON THE TREATMENT OF UNCERTAINTY
IN POWER SYSTEM PLANNING

by

Atif S. Debs
Georgia Institute of Technology
Atlanta, Georgia
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Abstract

Because planning deals with the future, uncertainty, its sources, causes, and how to deal with it will always remain with us. It is argued that the need to reduce the effects of uncertainties in planning has resulted in great innovations in the modeling of various aspects of the system, in the development of interconnected hierarchies of models, and in the development of “feedback” decision strategies to minimize the effects of uncertainty. This is used to pave the way for future research directions based on primary concepts from stochastic control theory, and the use of innovations like expert systems within the framework of feedback control.

Introduction

Uncertainty has been considered at various levels of importance and/or sophistication from the early days of the electric utility industry. Since our focus is on the most recent trends and developments we shall point out that perhaps the two most significant factors affecting the development of sophisticated forecasting and end-use models in the late sixties and early seventies were: (a) the influx of air conditioning and electric space heating demands in the residential and commercial sectors obviating the need for weather-sensitive models, and (b) the 1973 energy crisis that caused eventually a “structural change” in energy use patterns. The former factor was perhaps predictable, and if not, then noticeable as the load patterns started to show steady increases of electrical demands for space conditioning purposes. However, the latter factor was not predictable, except under the scenario of full awareness by the utility industry of the international political factors surrounding the energy issue.

In our thinking, the above factors may contain some clues as to our eventual ability to deal with uncertainty. The first factor, being strictly related to economic growth, technological developments, and overall prosperity, links the growth in electrical demand to basic economic and social concerns. In this regard, a basic concern is whether there is a causal link between electrical demand and economic growth. Here one argues that technical change and the resulting increase in productivity causes economic growth, which in turn, causes higher demands for electrical energy. For one the statistics prove that point since the GNP/Electrical Energy
Demand curve has been essentially a linear one for over 90 years [H7]. The second factor which is associated with drastic shock events, is harder to come by and analyze. Yet it exists and must be accounted for. For one it caused conservation measures to be fully accepted on their own merit and to become proven opportunities for cost-effective investments.

The theme of our paper is based on a "control theoretic" background. The fundamental planning model for any electric utility to be used as the starting point, is one that focuses initially on the role of electrical demand and service in the economy and society. This immediately poses issues of the "value" of electricity in every economic/social function relative to levels of economic well-being and relative to competing energy sources. The uncertainties at this level are enormous and cannot be easily modeled and quantified. However, even very approximate models in this arena are very useful in designing data collection procedures for model calibration, and eventually for predicting the impact of external variables (e.g. price of electricity) on load extent and load shape.

Once the "demand model" is understood, one has to comprehend the production and delivery models. Here, the uncertainties are of a different nature, but are growing in complexity. For one, we do not fully understand the behavior of the transmission system under seriously stressed conditions. The various "voltage collapse" phenomena are posing new concerns about the validity of existing power system models. And with "wheeling" entering the picture with full force, the allocation of responsibility due to system insecurities will become quite a complex exercise.

Finally, given all of the uncertainties associated with these models, one has to establish an overall strategic approach to deal with them. An element in our proposal is to be borrowed from the concept of "adaptive control" in the broadest sense of that term. Another element has to do with the proper "hierarchical structure" to be used in evolving the overall strategic approach.

**Approaches to Modelling**

For a long period of time, most approaches to demand forecasting dealt with extrapolation of trends or fitting to prescribed time functions. With the advent of time-series analysis techniques and parameter identification techniques, the attempts have been and continue to fit observed data to a postulated model. Validation is established on the basis of the stability of the estimates of model parameters over different sets of variables. The theory here is that if the model structure is correct, then a sufficient set of observations can identify its parameters. What is missing here, however, is a clear understanding of causal relationships which are so significant in predicting future behavior. This is particularly evident in the energy-economy relationships of Reference [H7], whereby the authors could not conclude in which direction did the causal relationships occur. It is interesting, that in most time-series models the analysis does yield measures of uncertainty over certain time...
horizons — and that is usually quite useful.

The alternative to time-series based models, are the so-called “physically-based models.” Typically the modeler starts from primary assumptions on system composition and dynamic interrelationships that govern its behavior with an allowance for the sources of uncertainty. The result is a family of models with built-in causal relationships which need to be confirmed by observations. The basic difficulty here is in the domain of model validation and estimation. Usually, giant simulation models are constructed to emulated the underlying processes. Even here, the uncertainties could be quite significant when it comes to forecasting future systems and behaviors.

Model and Uncertainty Classifications

In this section we shall provide a classification of models, uncertainties, and control (decision) measures, based on the above basic arguments.

1. Energy/Economy Models: At the macro level, the energy/GNP relationships will provide a basis for historical analysis. They are obviously a bit risky if used in any form for long-term forecasts. The historical data can be used to tune more detailed micro models. For example, the historical growth in electrical industrial drives has been used as the major reason for productivity growth prior and during the 2nd World War. Micro models have been used to verify this theory [H7]. Thus, at the micro level, one may be able to build causal relationships between various investments in electrotechnologies and the resulting electrical use patterns. Yet these should be viewed from within the framework of competitive markets, both nationally and internationally. The case of the steel industry should illustrate the point.

In order to make such models useful to the planner, two requirements are in order. The first is the sensitivity of changes in electrical demand due to various economic changes - e.g. prices, interest rates, currency exchange rates, etc. And the second is an assessment of random variability associated with these changes.

Perhaps the most crucial question at this level is related to ability to predict changes in electrical demand due to abrupt major changes. Some of the recent developments in energy modeling have attempted to do that with relatively good success.

2. Demand-Side Models: The major components of these models relate to predicting the potential effectiveness of demand-side programs on the renowned six classifications of load-shape control [D15]— peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape. The “control” mechanisms involved include such items as: load management, time-of-use rates, spot pricing, marketing efforts for increased selective electrical uses, as well as, conservation, interruptible and/or preferential rates, use of storage devices, etc. The key issue here is to predict the overall impact of these measures on load shape and overall load growth. The various models used so far (REEPS, INDEPHT, etc.) do provide some insight into the
uncertainties involved. The bottom line, however, is the development of detailed monitoring programs to study the cost effectiveness of various programs and to integrate the information into end-use forecasting models.

Alongside the Demand-Side models are the various cogeneration models. Although these deal with the supply of electricity, cogenerators are in many respects modifiers of the load shape of a utility. The use of spot prices, or some form of long-term contracts for the timing or amounts of electrical sales, will produce benefits to both the utility and cogenerators [D24]. The uncertainties here relate to the reliability of service from an independent producer, and the predictability of his production schedules based on some basic rule like spot pricing.

3. Supply-Side Models: For existing power plants the uncertainties associated with electric energy production are related to (a) Reliability and (b) environmental considerations. In the reliability domain the uncertainty factors include the standard ones of forced-outage rates (as functions of plant life), and maintenance requirements. The environmental considerations are dependent on existing and potential regulations associated with emissions and nuclear safety. Long-term environmental forecasts will provide the bases for potential strict regulations. Another key issue associated with existing power plants is the cost of refurbishing them to extend their life in a competitive environment [B18].

For planned and future plants the uncertainties abound. For one, perhaps the most critical uncertainty is that associated with construction schedules and delays due to regulatory and other factors. Yet other uncertainties are associated with the penetration levels of new technologies, cogeneration, fuel prices and availabilities, and interfuel substitution.

4. Production Cost Models: As an intermediate step toward full corporate models, production cost models attempt to predict the cost of production given a variety of uncertain futures. The difficulty here is associated with the ability to obtain multivariable probability distributions of production costs and related attributes without excessive computational efforts.

5. Transmission Planning Models: Aside from the normal uncertainties of line outages due to a variety of factors involving weather (normal vs severe), aging of insulators, and other effects, there are now the uncertainties associated with VAR support and voltage stability, simply because the available models for voltage stability prediction are yet to be fully developed. In that same category are the variety of models for on-line dynamic security assessment. With improved EMS software for these purposes, higher use levels are expected of all transmission facilities. These, however, have to be analyzed against an evolving technological breakthrough in solid-state devices with the potential of further increases of such uses. This is going to be particularly significant in the era of "wheeling."

In analyzing uncertainty in these cases the models can get quite complex. In the planning mode long
term probabilities, frequencies, and durations are normally computed. The use of full AC network models will produce more accurate results at high computational costs. Graph theory models produce less accurate power flow results but can account for a much larger event space.

6. Financial Models: The most challenging situation in the future will revolve around the levels of regulation (or deregulation) a utility system will encounter. In the fully regulated environment, the financial models will have to account for all the uncertainties in fuel prices, discount rates, regulatory provisions, construction cost uncertainties, among others. In the deregulated environment in a competitive regime of economy interchanges, spot pricing, and demand-side management, the financial models will be quite different. In either sets of cases, the requirement is to generate probability distributions of financial variations based on the estimated uncertainties.

7. Corporate Models: In these models the planner is supposed to integrate all of the individual models: supply-side, demand-side, transmission, and perhaps distribution, together with the financial models. Critical to such a model is the ability to quantify elasticities of energy demands to a host of decision variables — and in a stochastic sense.

State-of-the-Art in the Treatment of Uncertainty

Many approaches are employed at present in the treatment of uncertainty. We shall use the following classification which seems to be practical although it may leave some room for overlap: (a) Simulation, (b) Risk Analysis, (c) stochastic Optimization, and (d) Multiple Objective Optimization. These are discussed in the sequel.

(a) Simulation Approaches: These are divided into two classes — analytic and Monte-Carlo approaches.

In the analytic approaches probability theory methods are employed to model the uncertainties in the inputs and model parameters to yield either the expected values of the outputs and attributes or their full statistical distributions. The latter is usually much harder to come by since this may require the solution of complex partial differential equations. Because of theoretical limitations, the tendency is to use simplified models of the system and the driving random processes. This is evident in the various “probabilistic production costing” programs that are extensively used. It is also evident in the various reliability models which are limited to special forms of steady-state Markov models and state aggregation procedures.

The Monte Carlo approaches are gaining some popularity because they are free of too many modeling restrictions, e.g. linearity, steady-state, etc. They yield highly desired outputs in terms of probability distributions of system attributes that are used in the decision processes. Thus, they are extremely useful is the assessment of risk in a given situation.

An important use of simulation approached is the development of simplified models (usually
nonlinear but algebraic in nature) which relate desired attributes to decision variables. Such simplified models can be used in obtaining the probability distributions of the attributes over a wide range of variations among the decision variable. They are also very useful in multiple objective optimization (see below).

(b) Risk Analysis: There are many approaches to assess the risks of given decisions. As stated above, Monte Carlo simulations will provide estimates of risk for a given situation. Other forms of risk analysis involve decision trees, scenarios, and the use of experts in the context of decision analysis theory. Risk analysis is used heavily in the financial modeling analysis context. However, the same theories and methods apply to strictly engineering considerations as is the case in reliability evaluation.

(c) Stochastic Optimization: Most planning submodels are posed as optimization problems -- e.g. generation mix, generation capacity addition planning, transmission planning, VAR planning etc. The optimization is performed against a single criterion with desired attributes either included in that criterion or accounted for in the constraints. Here stochastic dynamic programming plays a major role [A1-A2]. The methodology here is flexible and useful if the state space is severely restricted. Since this may be possible through various forms of aggregation of the state space, the methodology will end up to be computationally quite efficient. In this arena one distinguishes among three approaches: Certainty Equivalence, Closed-Loop SDP, and Open-Loop/Closed-Loop SDP. Certainty equivalence reduces the problem to a deterministic one by using the statistical means of all random variables only. In the other two approaches future decisions are based on the random evolution of the system, and are far more effective than the certainty equivalence approach. One immediate use of the stochastic optimization approach is to study the cost of uncertainty. In other words, if one can determine the extra costs associated with various uncertainties, then one has an idea on how much to spend of data collection and modeling efforts to reduce the uncertainties.

(d) Multiple Objective Optimization: Since most planning issues are of the multiple objective type, several approaches have been developed to that end. The simplest approach is based on model simplification and the incorporation of all objectives in a single performance measure with relative “weights” associated with the individual objectives. The difficulties here relate to the fact that different objectives are entirely different from one another. It is usually difficult to lump engineering, social, economic, and environmental objectives under one performance index. The alternative is the use the techniques of “pareto optimization” over the vector of objectives. Analytically, this is hard to achieve. However, the recent techniques of trade-off analysis using simplified models that are empirically generated through many simulations has proven to be quite effective in strategic planning and also in transfer capability planning. Such approaches are amenable to considerations of uncertainty through sensitivity
analysis, Monte Carlo simulations, and even analytic probabilistic approaches.

Framework for the Future

As stated earlier, our proposal is to simply dig deeper into the treasure of modern control theory through its resounding success in reducing the effects of uncertainty through feedback. If simple but well thought-out forms of feedback like Automatic Generation Control can yield a well-regulated system, then why not apply the same principle for planning under uncertainty? Although the analogy is worthwhile to consider from a conceptual standpoint, its application in the planning environment is fraught with difficulties. Some of these include:

- The set of “control decisions” or “control variables” in the planning environment is an ever-expanding one. Only in the past 10-15 years that utilities started to think in terms of “demand-side options” and new energy sources, etc.

- The system being planned is not a closed one. There are always dependencies on external factors: the economy, population growth and distribution, new technological changes, etc.

- Implementation of “control decisions” in the planning environment is not certain. The financial, regulatory, and environmental risks of nuclear generation has all but eliminated this option from consideration for many years to come.

- Planning decisions are heavily dependent on research, development and demonstration efforts. Investments in those efforts should be considered as part and parcel of the entire planning decision process itself. The risks here are very high. Hence the burden of these risks must be distributed, and so should the benefits.

- The theory of planning with many objectives is still at its infancy. Such a theory should consider all the complexities that we have alluded to plus many others.

- Deregulation and competition create opportunities for digging deeper into cost-effective strategies. Hence, they provide more information about market behavior. The result is a “more” rather than “less” certain environment for system planning decisions.

In what follows we shall provide some thoughts as to a reasonable framework for dealing with planning under uncertainty:

(a) Hierarchical/Decentralized Planning Structure

Global Level

There are natural hierarchies in the planning process as can be derived from our earlier discussions. At one level is the overall global economy where energy/economic/environmental interactions need to be modeled to yield scenarios of expected long-term futures. What is usually missing from most of the
published scenarios are those involving potential "shock events" like wars, embargoes, sudden energy shortages, depressions, and others. In the planning jargon, these should be considered as "contingencies" not unlike what is done in the field of "security analysis and assessment." Such models will have to yield the spectrum of expectations regarding fuel sources, prices, and availabilities; structural economic changes; variations in discount rates; and many others. What is critical here is the level of future variability due to uncertainties, and the decision processes that will tend to reduce the levels of uncertainty, e.g. role of international agreements to reduce fluctuations in currency exchange rates.

National Level

The global economy/energy/environmental modeling effort should be repeated, with a lot more detail, at the national level. What is critical here is a model that can factor in issues like:

- Impacts of environmental regulations on expected fuel mixes
- Impacts, from a probabilistic point of view, of regulation, deregulation, and possible new legislation.
- Relationships between economic growth and electricity consumption with considerations of issues of productivity, technical change, conservation, structural economic changes, and interfuel competition.

Regional/Interconnection Level

Traditionally, planning at this level has involved the setting of reliability standards for the region/interconnection with rules regarding emergency assistance, rules for the allocation of spinning reserves, stability criteria, and possibly others. With the advent of energy control centers, the issues are being extended to those of interutility on-line data exchange, regional security assessment, VAR support, and others. With deregulation around the corner, the regional issues will have to involve new strategies for regional generation and transmission planning, on-line pricing mechanisms like spot pricing, and the pricing of wheeling, and the impact of all of those on long-term reliability, as well as, on-line operational security.

Utility Level

From a strategic perspective, the local utility has to consider its future risks in light of:

- Its relationships to all of the above factors at the global, national, and regional levels.
- Its implementation of planning strategies to achieve its objectives with serious considerations of uncertainties.

In essence, minimization of risk at the utility level, will have to involve both investments in: (a) Demand-side options, (b) Communication/Control/Computer systems for
improved on-line strategies and the tuning of models of consumer behavior through feedback.

(b) Role of Feedback Mechanisms

In all of the above discussions we kept emphasizing the concept of feedback to reduce uncertainty. Here we would like to elaborate on some of the issues involved. The feedback process we are alluding to in the context of planning involves the following:

- The implementation of “measurement” schemes for “observing” the progress of the entire planning process. These will range from automated data collection efforts, to the collection of relevant statistics, as well other factors like technological forecasting. It is critical that in all such schemes, detailed models of uncertainty be developed.

- Use of the obtained data in: (a) improved system modeling efforts, and (b) improved operational efforts, e.g. DSM programs.

- Study efforts which compare the evolution of risk relative to different feedback decision processes, e.g. the relative evolution of risk given two different generation expansion plans, with all the uncertainty factors included. The key issue is to evaluate the “robustness” of planning strategies.

- Use of existing and emerging tools for the development of options and the study of strategies under uncertainty including analytical, as well as, the less analytical but extremely useful expert system tools.

(c) Investment Strategies

The ultimate goal is to devise strategies for investment. The above efforts should pave the way toward that goal. In the final analysis, most investments should be considered on their own merit within the overall context and with clear measures of return on investment and the risks involved. In a strongly decentralized and even competitive environment, an ever increasing assortment of investments will emerge at the supply and demand sides to “optimize” system behavior. Again, optimization here is perhaps more along the lines of healthy financial returns at low risks.

Future Research

In this final section we shall propose three general areas for future research:

(a) Modeling Theory: Although physically-based models may yield the ultimate results for the planner, their development and validation in a stochastic sense, is still very difficult, if not impossible to perform. Thus there is a need to develop the methodologies and basic theories for establishing causal links given streams of related data and information. This causality, at some point, should be amenable to interpretation by experts, rather than another form of abstraction.

(b) Integration of Models: In this process, the explicit role of feedback decision strategies should be present with the ability to provide
performance estimates, given postulates of possible future uncertainties and shock events. In essence, there is a need to go beyond the "scenario philosophy" which tends to hide some critical dynamic interrelationships.

(c) Use of Expert Systems: The complexities of marketing strategies, financial analysis approaches, expert judgment, analytical but uncertain approaches, "fuzzy" reasoning, etc.—all of these are ingredients for the development of new expert system tools to be employed in the planning environment.

References

A. Planning Under Uncertainty


B. Generation Planning


C. Transmission Planning


D. Demand-Side Planning


E. Forecasting


F. Reliability


G. Recent Approaches to Planning


H. General


SHUNT VAR SUPPORT PLANNING
FOR VOLTAGE CONTROL

by

James A. Momoh
Department of Electrical Engineering
Howard University
Washington, DC 20059
SHUNT VAR SUPPORT PLANNING FOR VOLTAGE CONTROL

James A. Momoh, Ph.D
Department of Electrical Engineering
Howard University
Washington, DC 20059

ABSTRACT

Currently, shunt VAR planning algorithms are available to system planners to optimally allocate VAR support for vulnerable uses in a given power system. The overall economic objective is generally formulated to include the capital investment cost and the operational cost due to losses. These algorithms usually make some assumptions which facilitate solution methods but lead to other problems, such as speed of solution and application to large networks. This paper reviews the progress in this technology, discusses industry needs, present-worth, new formulations and proposes global optimization method for the problem. New search directions and potential of modern technologies are also discussed.

I. INTRODUCTION

Reactive power (or VAR) planning is one of the most important problems in power systems. Its objective is to determine the minimum cost expansion pattern of new reactive sources to be installed in the system to ensure secure and economic operations. This expansion decision can have direct influence on the operation of the system because the dispatch of active power can be effectively used to maintain acceptable voltage levels and to minimize active power transmission losses of the system. The availability of the optimum shunt VAR is considered a viable alternative to alleviate low or high voltages which may lead to voltage instability or voltage collapse. For ng-term Var planning the question of when, where and how much compensation to install in a power system is desirable. It is a difficult problem that must consider several technical and economic factors. These factors are:

- to maintain voltage and Var within physical and operating limits for the entire system under normal and contingency conditions.
- to coordinate the expansion from the base year towards the horizon (non zero-based) recognizing the expected changes in load, generation, and the network.
- to discretize the number of capacitor and reactor banks and interaction between controllers.

The current methods for VAR planning have advanced from trial-and-error techniques to more sophisticated mathematical programming techniques. The methods are nonlinear programming, linear programming, mixed integer programming, dynamic programming techniques or heuristic methods. However, these methods have failed to meet utility specifications to provide an optimal plan. This is essentially so because such plans are usually only optimal in a very limited sense, in that they do not take into account all the dominant constraints, utilize adequate modeling and other technical issues. Thus, since this is a difficult problem from a purely analytical perspective, new tools such as enumeration lists coupled with knowledge-based support is desirable.

The Electric Power Research Institute, EPRI, has been in the forefront in pioneering the optimal VAR planning technology and the program developed by Lebow, Usoro et al. under EPRI contract number RP 2109 is one of the existing landmark packages in this field. However, further work is being solicited by industry users to enhance the capability of the existing technology. Our objective in further research is to satisfy these needs. The classification and discussion of some specific approaches are discussed briefly.

In the trial-and-error approach, the system is compared with the normal specified condition and the additional VARS are determined by engineering judgment, based on repeated power flow analysis. This method provides extra VAR capacity, but does not optimize it.

Most nonlinear programming techniques as discussed in [1, 2, 3] use a gradient method to schedule real and reactive power generations, shunt reactive powers, voltage levels and transformer taps to minimize operating costs and transmission losses and to improve voltage profile. Usually, these methods have convergence problems and require large computational effort, therefore the method may not be suitable for practical-sized power systems.

In the linear programming approach discussed in [4, 5, 6, 7, 8, 9], an incremental model of the power system is developed about some initial operating state. The required additional VARS are determined sequentially using linear programming. Application to practical-sized power systems has always proved difficult with this method, and a complete optimum solution may not be guaranteed for all types of system configuration.

In dynamic programming [10], a bus is selected for capacitor installation using a voltage sensitivity relation of maximum change in total system voltage by unit injection of reactive power. A capacitor unit is then added and the augmented voltages at various buses are calculated by a linearized change in voltage versus reactive power relationship. In this way, a new system state which is optimum compared to the previous state is found, and the process of bus selection and unit capacitor addition is repeated. Dynamic programming approach is not suitable due to the dimensionability and storage requirement.

Integer programming techniques used in [4, 11, 12] have been employed in order to treat capacitor/reactor, units and transformer taps as discrete variables. Branch and bound techniques with heuristics have also been employed to size and site the VAR sources. A branch and bound technique may guarantee an
optimal solution but is impracticable for large systems. Inclusion of suitable heuristics can improve the branch and bound search technique.

Assessment of Current Methods for Voltage Planning

The sizing and siting of shuntVars has traditionally been by trial and error approach utilizing power flow programs. However, in today's planning environment, sophisticated tools are being used based on the mathematical programming techniques. The tools attempt to minimize the installation cost and seek to determine efficient coordination scheme of Var sources to improve system performance. The engineering review of these specific approaches are divided into three summary tables 1, 2 and 3 according to the mathematical programming methods. These summaries highlight some major works in Var planning. Their potential as a research tool and the need for further improvements are discussed. The validation of these methods to provide answers to industry needs require some additional work in formulation, analysis as in research and development activities.

Based on these reviews and acknowledgement of work done o date in Var planning, a new formulation that includes fixed cost and piece-wise linear cost, coordinate multiple objective function composed of capital investment cost, MW and MVAr losses will be included. The methodology should be able to optimally allocate sizes and sites for shunt vars and reactive sources. The new methods being considered should include innovative engineering insights to address industry needs. The method being suggested should include best case power flow that solves or gives reasons or not yielding a solution, evaluate the impact of critical contingency as it affects overall costs of energy in the planning process, and yields optimal allocation of Var sources. The method suggested for this purpose are discussed.

Table 1. Summary of Major Papers on VAR Planning Using Linear Programming

<table>
<thead>
<tr>
<th>Author</th>
<th>Engineering Elements and Features</th>
<th>Mathematical Techniques</th>
<th>Validation of Algorithm</th>
<th>Remarks</th>
<th>Problems as a Tool</th>
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<td>R. C. and D. (1981)</td>
<td>* Linear programming technique</td>
<td>Linear programming technique</td>
<td>* Limited to small systems, suitable for research use</td>
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<tr>
<td>B. C. and D. (1980)</td>
<td>* Non-linear programming technique</td>
<td>Linear programming technique</td>
<td>* Limited to small systems, suitable for research use</td>
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<tr>
<td>M. O. and D. (1980)</td>
<td>* Linear programming technique</td>
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</table>

Table 2. Summary of Major Papers on VAR Planning Using Non-Linear Programming

<table>
<thead>
<tr>
<th>Author</th>
<th>Engineering Elements and Features</th>
<th>Mathematical Techniques</th>
<th>Validation of Algorithm</th>
<th>Remarks</th>
<th>Problems as a Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. O. and D. (1980)</td>
<td>* Non-linear programming technique</td>
<td>Non-linear programming technique</td>
<td>* Limited to small systems, suitable for research use</td>
<td></td>
<td></td>
</tr>
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<td>* Limited to small systems, suitable for research use</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

II. INDUSTRIAL NEEDS

The general review of planning problems and application to shunt Var allocation problems in large-scale systems is given by several researchers discussed in our review of literature. Several discussions and utility needs were also evaluated by the author. The IEEE power engineering special publication [22] on reactive power planning suggests the importance of this topic to the industry.

Due to recent environmental concern and the Clear Air Act, utility companies in North America have been seeking an efficient and economic method to replace PCB-based capacitor banks which are considered to be toxic and harmful to the environment. The tools currently available are not able to provide a global optimization for sizing and siting of shunt Vars. From budgetary consideration, the method desired should include fixed cost of installation of equipment, site and piece-wise cost of switchgear and other auxiliary equipments. The interfacing of optimization
Igorithms to existing power flow tools is essential for engineering practice and other consideration should be embedded in the large-scale production grid evaluation tool such as power ow. The newly emerging tools for Var planning should meet specific data input and output requirements of a client with minimum changes. Finally, the method should satisfy hard constraint limits and meet budgetary constraints. In addition, the proposed methods should coordinate the expansion plan from base ear towards the non-zero-based planning recognizing expected changes in load, generation and the network. The modelling of components must include practical engineering consideration.

lead for Research and Development

The need for an adequate overall objective function that coordinates capital investment, losses and other planning objectives should be assessed. The methodology should be efficient and meet industrial needs. The method must upgrade existing tools to solve both Var planning problems as well as detect and prevent voltage collapse problems. It should accommodate base case power ow evaluation, use of an enumeration list for achieving optimal allocation. The proposed tools must be well-structured to accommodate future changes and maintenance. It should take into account the physics of the problem in the modelling and also utilize new engineering decision tools such as knowledge engineering to enhance the robustness of the algorithm. The effectiveness of these improvements should be demonstrated on production grid power ow with real system data.

Outstanding Problems and Short-Comings of Current Methods

From the review of outstanding work in voltage planning, industry is faced with looking for alternatives to existing methods. The major problems with the existing techniques are their inability to yield optimal and feasible plans. The methods that are being used do not include the fixed cost and piece-wise linear models. These limitations result in uneconomic plans and, at worse, cannot assure secure system operation. Review of work and industry surveys suggests that the system components being used to not account for discretization of capacitors, transformer taps and other system components. The methods do not account for a base case power ow that does not exist. The objective function used should be properly formulated to account for revenue resulting from a reduction in power losses, and expenditure to meet the interest rate and depreciation on the installation of capacitors and inductors. The software product should be user-friendly and should guarantee optimal choices of sizes at specified and unspecified locations.

III. FORMULATION OF VOLTAGE PLANNING PROBLEM

Assuming the overall objective function is defined as follows:

\[
Z = \sum_{j \in C} (d_j + m_{c_j} q_{c_j} + m_{r_j} q_{r_j}) + W(\text{Loss}) \quad (1)
\]

where:
- \(d_j\) is the fixed cost (or fixed charge)
- \(m_{c_j}, m_{r_j}\) are unit cost of capacitive and inductive sources respectively
- \(q_{c_j}, q_{r_j}\) are respectively the capacitive and inductive vars
- \(C\) is a set of buses which are candidates for var expansion sites

\(W\) is a weighting factor
\(\text{Loss}\) is the real power loss in the network, and
\[\Sigma d_j + m_{c_j} q_{c_j} + m_{r_j} q_{r_j}\] is the capital cost

Therefore, the resulting objective is mixed integer programming problem with the constraints.

Thus we minimize

\[
Z = \sum_{j \in C} (d_j + m_{c_j} q_{c_j} + m_{r_j} q_{r_j}) + W(\text{Loss}) \quad (2)
\]

subject to:

1. Network power flow constraints on
   - Voltages at nodes
   - Current branches
   - Resource utilization and
   - Contingency outages

2. Others
   \[q_{c_j} \leq M_{c_j}\] \quad (3)
   \[q_{r_j} \leq M_{r_j}\] \quad (4)
   \[Z_j \leq 1\]

\(Z_j\) is an integer, and \(M_{c_j}\) and \(M_{r_j}\), the upper bounds on decision variables

and

\(q_{c_j}, q_{r_j}\) are discrete variables

From equation (2), \(W\) is a present worth factor over capital defined for the program in discrete enumeration space of the decision variables \(Z_j, q_{c_j}, q_{r_j}\). We must therefore look for the branching rules, bounding rules and program stopping rules. Since this is a minimizing program, the bounds at any stage of the program must be an upper bound.

The calculation of \(Z_j, m_{c_j}, q_{c_j}\) and \(d_j\) are user specified. They are parameters of site economics. The value of \(W\) can be set to market index cost in dollars/megawatts.

Using financial principles, the value of \(W\) can also be set at the present worth factor for an annual series of dollar value of energy loss is dollars/megawatts years for the applicable interest rate is

\[
W = \frac{m((1 + i)^n - 1)}{(1 + i)^n} \quad (6)
\]

where
- \(m\) is market index of power loss
- \(i\) is the interest rate
- \(n\) is the life of equipment
Using this formulation, a branch and bound with enumeration list is designed to solve the problem. The algorithm essentially consists of three building blocks. The first being intelligent decision support for evaluating base case power flow that solves and varying inadequacy of transmission line is developed. Several rules of thumb are used to detect the causes, evaluate the control parameters such as transformer taps, shunt vars and system configuration.

The second level consists of outage simulation of critical contingencies. The impact of contingencies are also evaluated using present worth economics. The energy equivalent for contingency is included in the objective function.

The third level of the algorithm consists of the optimization strategy to coordinate multiple objectives, account for discrete modeling of decision variables and strategy for allocating Var optimally. An improved branch and bound technique which handles both linear and nonlinear objectives with discrete decision variable is proposed. It selects candidate buses according to starting rules, branching rules, bounding rules and stopping rules. The rules for branching is based on an index that computes minimum or maximum loss for minimum or maximum rules. The rules for branching is based on an index that computes minimum or maximum loss for minimum or maximum rules. The rules for branching is based on an index that computes minimum or maximum loss for minimum or maximum rules. The rules for branching is based on an index that computes minimum or maximum loss for minimum or maximum rules.

The enumeration list selects candidate buses according to site economics record. A suitable selection index will be used to size and site the required Var sources. A stopping criteria based on satisfaction of hard limits guaranteed optimality during the allocation and increased system performance and reliability. The proposed algorithm is highlighted in Figure 1.

Each decision variable selected is compared to a given objective function. The sensitivity of the objective function with respect to changes in components, hard limits and other constraints are evaluated to yield an optimum. The details of this process are discussed in our algorithm proposed in Figure 1.

IV. ADAPTATION OF NEW METHODS

In order to improve Var allocation methods, these basic concepts have been suggested in the paper. For the power flow evaluation tool, we suggest the use of knowledge based support to provide a diagnostic on why certain power flow runs do not converge and which parameters are responsible for unacceptable power flow results. Thus the new power flow engine for planners should be intelligent enough to take corrective measures and guide planners to achieve an economic decision in the planning process. The results of the base case power flow with the aid of the knowledge based support should advantage of new emerging tools for voltage collapse identification and prevent collapse. The voltage collapse identification and prevention should take advantage of new analysis tools such as the bifurcation approach, multiple solution and the energy function method. These methods can be improved by using knowledge based support to select candidate buses and discriminate between contingencies. Finally, the statistics of load profile can be estimated using new decision tools like neural network analysis. The information trained data via neural network can be included in future algorithms for voltage planning. The prevention scheme will be evaluated via the Var planning management method based on improved optimization scheme.

Planners rarely experience multiple loss of lines and the occurrence of outage of lines or unit outages are rare. Future Var planning scenario should include the energy equivalent of a unit outage which gives the duration, frequency of occurrence and the equivalent impact in energy cost. This value should be included in the overall economic objective if important. The experience from engineering economics should be included in the study so that over one year we can estimate the equivalent impact on capital cost.

Recent emerging technologies in transmission systems include the flexible AC transmission systems (FACTS) developed under an EPRI contract. This technology employs many more control devices such as phase-shifter, taps and capacitors (series and shunt). Future shunt Var expansion planning programs will be enhanced using this technology.

The approach to realize an optimum Var planning scheme has been discussed. We hope that improvements on the existing mathematical programming techniques coupled with the enumeration list will be useful.

V. RECOMMENDATIONS

1. There is need for transfer of research results in Var planning and voltage instability to industry. This will require some improvements on currently available tools.

2. Industrial data to validate the new method and program design to meet given specification and problems of utilities should be addressed. Future work should include suggested technology tools in new and existing algorithms.

3. Improvements on analysis for planning and operation should be developed around the production grid programs.

4. Adequate software tools that are easily integrated into standard data format is needed.

5. The impact of emerging technologies such as FACTS should be investigated for future Var planning programs.
There is need for a data bridge that links various types of data formats such as those of GE, PTI, WSCC, and PEPCO.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

UNCERTAINTY AND RISK IN STRATEGIC PLANNING

by

Hyde M. Merrill and Allen J. Wood
Power Technologies, Inc.
Schenectady, New York
UNCERTAINTY AND RISK IN STRATEGIC PLANNING

Hyde M. Merrill and Allen J. Wood
Power Technologies, Inc.
Schenectady, New York

New methods are needed for dealing with uncertainty and risk in power system planning. This paper demonstrates what the real issues in uncertainty risk analysis are, and presents a new framework for analysis. Although the emphasis is on electric utility strategic planning, the structure is valid for any problem of choosing among a set of possible decisions, the presence of uncertainty, with one or many objectives. Areas needing further research, development, and demonstration are identified.

INTRODUCTION

DEFINITIONS

Attributes are measures of the goodness of a plan: revenue requirements, earnings per share, loss of load expectation, etc. Attributes are functions of options and uncertainties. The objectives are to minimize or maximize each attribute.

A utility chooses from a set of options: build a new coal fired power plant, or upgrade an interconnection, etc. Each option has parameters (e.g., year or size) to be specified.

A plan is a set of specified options - for example, "build a 600 MW coal plant in 1994 and add 350 MW of transfer capability to the west."

Uncertainties are beyond the utility's foreknowledge or control: load growth, fuel prices, regulatory changes, etc. Each has parameters representing a realization, like "3% per year" for load growth. Uncertainties can be modeled probabilistically or as "unknown but bounded" variables without a probability structure. All concepts in this paper apply to both models.

A future is a set of realized uncertainties, for example: "3%/year load growth and 1%/year real oil price increase."

Risk is the hazard to which a utility is exposed because of uncertainty. Risk has to do with attributes, but there is considerably more to risk than how these might vary. This will be explored in this paper.

TWO UNCERTAINTY MODELS

Two useful approaches to modeling uncertainty are:

- Probabilistic: all uncertainties are assumed.
- Unknown but Bounded: upper and lower limits on the uncertainties are assumed, with no assumption about probability distributions.

Probabilistic models usually contain more information than unknown-but-bounded models. The latter are more appropriate, however, if the probability distributions are not known.

Probabilistic models can be misleading if the uncertainty represents an event that either will or will not occur rarely -- for instance, a major mid-East war or a major nuclear accident. For such uncertainties, the law of large numbers says that the frequency with which each outcome occurs will not be.
illy related to the theoretical probability of occurrence. For this type of uncertainty, unknown-but-limited models are more appropriate.

The third approach to modeling uncertainty -- totally unknown -- contains little information and is not very useful.

The framework and methods described below can use both probabilistic and unknown-but-bounded uncertainty information.

The next section of this paper develops a description of the decision risk. It is followed by a section which presents a framework which can be used to analyze and reduce risk.

An important sub-problem -- the effect of uncertainties on attributes -- is discussed in the next-to-last section. The paper ends with conclusions and recommendations for further work.

**DECISION RISK**

In the Introduction, we claimed that minimizing the variance or standard deviation of an attribute is the right way to deal with risk. We will now show this is so.

**IPLE-ATTRIBUTE TRADE-OFF ANALYSIS**

In this section, we review briefly the character of decision-making in the presence of multiple attributes [1,3]. If a problem has multiple attributes, there is usually a single solution which simultaneously optimizes all of them. What is sought is a compromise which presents a reasonable trade off among the attributes.

Figure 1, where the objective is to minimize both $SO_2$ emissions and capital requirements, the plans near the knee of the trade-off curve are the most interesting. Concepts extend mathematically (but not graphically) to problems with more than two attributes.

**EXAMPLE 1: ILLUSTRATION OF RISK**

Suppose that four plans (A, B, C, and D) are measured in terms of two attributes (financing required, and present worth of revenue requirements), with three futures, F1, F2, and F3, as follows:

<table>
<thead>
<tr>
<th></th>
<th>Future F1</th>
<th>Future F2</th>
<th>Future F3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financing Required, $ billions</td>
<td>Plan A</td>
<td>Plan B</td>
<td>Plan C</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Present Worth of Revenue Requirements, $ billions</td>
<td>Plan A</td>
<td>Plan B</td>
<td>Plan C</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Suppose our approach to risk was to minimize the expected values, $E(.)$, of the two attributes. Either plan B or plan C (depending on the probabilities of the three futures) minimizes $E$ (financing required). Plan A minimizes $E$ (revenue requirements). So minimizing $E(.)$ leaves us with three of the original four plans as candidates, with no clear winner.

Suppose we now try to minimize the variances of the two attributes. This puts our fourth plan on the ballot: plan D minimizes the variances of both attributes. Incidentally, plan B, which we will show is the best choice, happens to maximize the variances of both attributes.

Figure 2 shows how the four plans are related for each of the three futures. Clearly, plan B is the best choice. It is at the knee of the trade-off curve for each future: no matter how the uncertainties turn out, it represents the appropriate choice. This is true in spite of the fact that B minimizes neither the means nor the variances of the attributes.

A robust plan is a plan which would be selected for every future (no matter how the uncertainties turned out). In example 1, plan B is a robust plan. We will next examine the more common situation, where no plan is robust.

**EXAMPLE 2: DECISION RISK WHEN NO PLAN IS ROBUST**

A utility [4] has a future need for 1700 MW of additional resources. The available options are demand-side management, OFs, and utility-owned plants, all available in various MW blocks. Fifty-four plans (combinations of various blocks of the options) were studied. Two major uncertainties are general economic conditions and environmental standards. These are modeled probabilistically as nine distinct futures. Incidentally, in this example these two uncertainties are not assumed to be statistically independent. So the probability of each future comes from a joint probability density function.
attributes are considered: price of electricity, fings per share, operability index, and romental index.

ow define two new terms. Each future has a tional decision set, which is the set of plans the knee of the four-dimension trade-off surface that future. Table I lists the global decision set all plans that are in at least one conditional sion set. No plan is robust, but plan 22 is in the conditional decision sets for eight of the nine futures, with an accumulated probability of 0.93. Plan 22 is also in conditional decision sets for eight futures, with an accumulated probability of 0.92. Is not listed in Table I are in no conditional sion set for any future.

measure of the decision risk is the probability a decision is wrong. Table I shows that the probability that selecting plan 22 is wrong is 1.00 - 0.07. This probability measure is available if probability models of the uncertainties are.

RISK ANALYSIS

will now describe other ways of measuring risk, lyzing it, and hedging to reduce risk.

ROBUSTNESS

Decision risk can be measured by identifying the futures for which a plan is not in the decision set. In example 2, plan 22 is in the conditional decision sets for all futures except future 3. This measure of decision risk can be used with unknown-but-bounded uncertainties as well as with probability models.

Exposure is another measure of risk. If a plan that is not robust is selected, and if an adverse future materializes, we will regret (after the fact) not having selected another plan. The magnitude of our regret is the difference between the plan we would have selected (had we only known!) and the plan we did select. This difference is measured in terms of attributes.

For example, suppose that in example 1 the present worth of revenue requirements for plan C were $15 billion instead of $30 billion for future Fl, with the rest of the problem unchanged. Then in future Fl we would prefer plan C to plan B. Our exposure by choosing plan B would be $0.4 billion in financing required, and $0 in present worth of revenue requirements. Exposures can be evaluated future by future. Maximum exposures can be identified.

If uncertainties have probability models, then means and variances of exposures can be developed. Measures like "the probability that a conditional decision set will include a plan whose revenue requirements are more than $100 million better than those of plan B" can be used.

CRITICAL AND IRRELEVANT ATTRIBUTES AND UNCERTAINTIES

If adding or deleting an attribute from the trade-off analysis does not affect the decision sets, then that attribute is irrelevant. This may occur if two attributes are affected in the same way by variations
plans and futures. This would happen if the two linearly related. For instance, in one study it found that LOLP and fuel costs were approximately only related. Any plan with low LOLP also had low costs.

In particular, if the decision set does not change for more realizations of an uncertainty, then that uncertainty can be ignored.

That this goes beyond simply identifying an attribute as being insensitive to variations in plans realizations of uncertainties. For example, in case 3 the attributes are very sensitive to changes in load growth and are highly dependent on the plan realized. But the conditional decision sets for both cases are identical: the plans that are close to the at +1% load growth are also close to the knee at. This decision is robust with respect to this uncertainty.

- Options: BUY A CAR
- Ride TAXIS
- Uncertainty: WILL I HAVE AN ACCIDENT?
- Attribute: COST

<table>
<thead>
<tr>
<th>Future 1</th>
<th>Future 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(No Accident)</td>
<td>(Accident)</td>
</tr>
<tr>
<td>Cost</td>
<td>Plan</td>
</tr>
<tr>
<td>HIGH</td>
<td>RIDE TAXIS</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>BUY A CAR</td>
</tr>
<tr>
<td>LOW</td>
<td>LOW</td>
</tr>
</tbody>
</table>

Figure 4

Example of a Hedge

SECOND ITERATION

- Options: BUY A CAR, BUY A CAR AND BUY INSURANCE, RIDE TAXIS
- Uncertainty and Attribute as before

<table>
<thead>
<tr>
<th>Future 1</th>
<th>Future 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(No Accident)</td>
<td>(Accident)</td>
</tr>
<tr>
<td>Cost</td>
<td>Plan</td>
</tr>
<tr>
<td>HIGH</td>
<td>RIDE TAXIS</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>BUY CAR + INSURANCE</td>
</tr>
<tr>
<td>LOW</td>
<td>LOW</td>
</tr>
</tbody>
</table>

Figure 5

Example of a Hedge (Cont.)

Figure 3

Resent worth of revenue requirements versus SO2 emissions for 22 coal conversion plans [1]

ING TO REDUCE RISK

Figure 4 shows a problem with one attribute -- cost -- one uncertainty -- "Will I have an accident?" There is a robust solution.

Adding a third option (buy a car with insurance) solves the problem. That third option is in the decision set for both plans. See Figure 5.

Example 2 illustrates hedging. Suppose we want to buy plan 22 slightly so that it will be robust. Something has to be done to provide protection in case re 3 materializes.

Example 1 shows that the following plans are in the decision set for future 3: 10, 35, 42, 27, 44, 34, 48, 40, 18, 47, and 46.

Inspection of the plans on Table 2, plan 35 is most plan.

A reasonable hedge to explore, then, is one where the utility commits itself to 500 MW each of demand-side generation and utility-owned generation, and to 700 MW of QFs (plan 22), but with options to cancel 200 MW of QFs and increase the utility-owned capacity by 200 MW, changing it to plan 35. This option is exercised if it appears that the economy will be strong and environmental standards tight (which is future 3). This new plan, with these optional terms, is likely to be somewhat more costly than plan 22.

Another trade-off analysis, producing a new Table 1, will be needed to determine if this new plan is robust. Analyses of exposure can also be redone for this new plan.
Production cost programs, the second major class of long-range planning programs, model the operation of the generation system. But in spite of their name, probabilistic production cost programs aren't probabilistic: the only uncertainties they represent as random variables are the forced outages of generating units and the loads. They originally served a useful and limited purpose -- they permitted a more realistic forecast of the operation of peaking units. They don't necessarily produce a more "accurate" forecast of future system operating costs than do other methods. And they handle deterministically such key uncertainties as load growth, fuel costs, bulk markets for purchase and sale, and delays in inservice dates.

Corporate models are the third major class of programs used in strategic planning. Corporate models simulate a utility as a financial system. They are used to generate pro forma income statements, balance sheets, and statements of sources and uses of funds for ten or twenty or more years in the future. Some of them have the ability to toggle through combinations of various realizations of input uncertainties. Some of the most important corporate model uncertainties, however, require modifications which can be extensive.

Methods have been developed [1,3] for deterministically simulating for a limited number of futures and then interpolating to more thoroughly explore a full range of variations in uncertainties.

**TECHNOLOGY NEEDED**

In the isolated context of individual classes of models, there is obviously room for improvement of the ability to model uncertainties. In particular, when probabilistic models are used, we need to face the issue of correlated (non-independent) random variables. It is so easy to assume independence -- but often this assumption is a gross oversimplification. Recognizing the dependencies can require large probability matrices, and coming up with values for the off-diagonal terms is a non-trivial task.

While this problem goes away if unknown-but-bounded models are used, the price paid is reduced information.

But even if models can predict means and distributions of output parameters, this serves a useful purpose in planning only if we know what we are deciding -- and if we have a carefully selected set of attributes, options, and objectives. For example, in investment decision analysis the volatility (variance) of certain financial instruments can play a key role in setting up strategies. Investments in equities usually offer a higher return (a mean value) than investments in senior debt of going concerns. At the same time equity carry a larger risk -- they are more volatile (variance) -- so that the investor must balance his own tolerance for risk and reward in selecting an investment strategy.

The risk analysis framework described earlier in this paper requires more than statistics of output parameters, however. In order to properly analyze robustness and exposure and to develop and explore hedges, it is necessary to have access to detailed relationships among attributes as functions of uncertainties and options. The authors see two ways of doing this.

**Table 2**

<table>
<thead>
<tr>
<th>Year</th>
<th>Gen</th>
<th>QFS</th>
<th>DEM</th>
<th>YEAR</th>
<th>Gen</th>
<th>QFS</th>
<th>DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>300</td>
<td>600</td>
<td>28</td>
<td>200</td>
<td>600</td>
<td>28</td>
<td>200</td>
</tr>
<tr>
<td>1980</td>
<td>600</td>
<td>300</td>
<td>29</td>
<td>300</td>
<td>700</td>
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<td>400</td>
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<tr>
<td>1990</td>
<td>700</td>
<td>300</td>
<td>30</td>
<td>300</td>
<td>700</td>
<td>30</td>
<td>400</td>
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<td>300</td>
<td>31</td>
<td>400</td>
<td>700</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>2010</td>
<td>900</td>
<td>300</td>
<td>32</td>
<td>500</td>
<td>700</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>2020</td>
<td>1000</td>
<td>300</td>
<td>33</td>
<td>600</td>
<td>700</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>2030</td>
<td>1100</td>
<td>300</td>
<td>34</td>
<td>700</td>
<td>700</td>
<td>33</td>
<td>400</td>
</tr>
<tr>
<td>2040</td>
<td>1200</td>
<td>300</td>
<td>35</td>
<td>800</td>
<td>700</td>
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<tr>
<td>2050</td>
<td>1300</td>
<td>300</td>
<td>36</td>
<td>900</td>
<td>700</td>
<td>33</td>
<td>400</td>
</tr>
</tbody>
</table>

**ATTRIBUTE MODELS WITH UNCERTAINTY**

**ENT TECHNOLOGY**

models used in long-range or strategic planning are fundamentally deterministic. This is ture because the real world is truly uncertain. Use of the random nature of exogenous inputs and use of unknown and unknowable parameters and nure of the power system.

use of this basic characteristic of planning, we not even certain that we can define objectives that y represent the purpose of the organization and its ions. For example, a recent paper [5] explored dilemma transmission planners face in trying to slop planning criteria to account for uncertainties. A paper attempts to advance the ability to define objectives in the context of risk.

major class of programs is used to model the transmission network. A recent survey paper [6] orted some 81 papers on probabilistic load flows and sets topics, going back as far as 1974. These ers generally deal with methods for developing stics of line flows, etc., as functions of ability models for input parameters. Theyially involve small-signal variations which permit eartition, but they do explore non-Gaussian random tables and correlated uncertainties. It is prising to the authors, who are not transmission mers, that all of this work seems to have had atively little practical application in the US, ugh at least one application [7] seems to be an option.
and functional relationships measuring robustness to exposure could be developed. We view this as a mundane task, similar to the effort to develop direct measures of stability, which should not be undertaken lightly.

CONCLUSIONS AND RECOMMENDATIONS

Dealing with uncertainty and risk in strategic planning requires a new perspective and different thought processes. In particular, simply minimizing means or variances of attributes is rarely the answer. The key risk is the risk of making the wrong decision, and this must be viewed in the context of other decisions that are available.

This paper presents a framework for evaluating alternative plans in the presence of uncertainties, ensuring robustness in various ways, and assessing measures to adverse realizations of uncertainties -- elements of risk analysis. Currently-available methods based on this framework involve development and empirical analysis of large data bases.

The second research need -- which partly addresses the first -- is to apply these methods in more studies. Though they have been used perhaps a dozen times, this presents a very limited exposure to the real world.

Third, elemental programs (load flow, production cost, corporate model) need improved methods for dealing with uncertainty. In particular, we need better ways to model uncertainties in what are now considered to be system structure and parameters, as opposed to uncertainties in exogenous inputs. This modeling should be consistent with the risk analysis framework described in this paper.

REFERENCES


ACKNOWLEDGEMENTS

Several colleagues contributed ideas either in discussions or by reviewing an earlier draft of this paper. In addition to PTI staff, this list includes Brenton R. Hill, Director of System Planning at Central Maine Power. Our colleagues may not agree fully with our paper, but it is better because of their insights.
COLD FUSION AND HIGH TEMPERATURE SUPERCONDUCTIVITY

by

Mario Rabinowitz
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303
ABSTRACT

Recent developments in cold fusion parallel many similarities, though less well known, occurrences in the field of high temperature superconductivity. These similarities will be pointed out in the process of surveying the newly emerging field of cold fusion. This paper also examines various possible models that can explain why one might expect enhanced fusion rates in the present experiments. A new theory is presented which is related to a decreased effective mass of the using nuclei in the periodic lattice of a crystalline solid, that can account for the reported cold fusion results. A significant finding is made by analyzing the recent Cluster-Impact Fusion experiments.

INTRODUCTION

To many it would appear that the cold fusion revolution started in 1989, and that the revolution in high temperature superconductivity all took place since 1986. Actually, just as the roots of high temperature superconductivity can be traced back to the 1930's, one can trace the notion of cold fusion back to the 1920's. Over 40 years ago, Fritz London speculated that room temperature superconductivity might be the basis for life itself. And, it wouldn't be surprising if someone someday speculates that fusion energy may be part of the life process, such as during the folding of the DNA molecule when hydrogen is forced very close together by very strong electrical forces in the molecule. Though neither speculation as a basis in established scientific fact, it is clear that London's speculation led to the search for high temperature superconductivity. In 1937, he published a paper on "Superconductivity in Aromatic Molecules" [1].

I think that the gist of London's argument was that if the DNA molecule is broken, its life processes cease. If these processes were just chemical in nature, the two halves would continue to function in their usual manner - at least far from the broken ends. Evidently this does not happen, suggesting to London an analogy between the DNA molecule and a series circuit. If the series circuit is broken at any point, current ceases to flow at all points in the circuit.

Because of London's stature as a scientist, many scientists looked for high temperature superconductivity in both biological and non-biological compounds. Over the past ten years, there were numerous isolated reports of findings of high Tc (critical temperature) that faded away due to difficulty in reproduction of the results. This is reminiscent of the confusion that the cold fusion arena found itself in, in early 1989 when thousands of investigators, worldwide, rushed into their labs to try to reproduce the announced results. Prior to Bednorz and Muller's discovery [2] in late 1986 of easily reproduced high temperature superconductivity, many general theoretical arguments had been proposed that high temperature superconductivity is an impossibility. Similarly, general arguments are being proposed that cold fusion is an impossibility. One such argument relates to the abundance of the elements in the universe, which is quite well accounted for on the basis of conventional fusion theory. What is overlooked in this argument against cold fusion is that cold fusion appears to depend on heavy elements which have only been present in the latter stages in the life of the universe. Because of the high materials and processing costs, commercial applications of high temperature superconductivity, as we know it, may be limited. The same may turn out to be true for cold fusion. Oddly, it may be the inexpensive source of tritium that may make the hot fusion machines practical.

On March 23, 1989 Professors Stanley Pons and Martin Fleischman announced their achievement of fusion at room temperature in a palladium (Pd) electrolytic cell using heavy water (deuterium oxide) as the electrolyte. While the high-temperature plasma approach may be likened to a brute-force approach to
If cold fusion proves out, it could be characterized as a finesse approach. Pons and Fleischman's results [3] were particularly surprising to the scientific community because there had been no hint of fusion-type reaction in other circumstances where the same isotopes were involved. Specifically, liquid solutions of deuterium oxide and of tritium oxide have densities comparable to that of the deuterium in the palladium in Pons and Fleischman's experiment. Fusion is not been seen in these liquids. In addition palladium and other metals such as platinum have been used to purify hydrogen and its isotopes from other gases; the hydrogen isotopes move readily through windows of these metals, but other gases do not. However, fusion has not been observed in these circumstances either. Therefore, for the fusion to occur at the reported levels in such metals, it appears that otherwise unconsidered physical mechanisms must be present in the solid that are not present in the liquid. Interestingly, Gilman [4] in 1971 suggested fusion experiments in the highly loaded solid LiD₂F₃.

Providing a reasonable theoretical description of these mechanisms is important to the work at hand. Hence progresses with a good combination of experiment and theory, each giving direction to the other. Present the experimental work appears to be way ahead of the theoretical work. Yet a good theoretical model or framework can do much to guide experimental work and provide it with coherence. The following theoretical framework provides possible explanations for what has been observed in cold fusion experiments to date.

1. BASIC PROCESSES

There are four essential ingredients or processes for sustained controlled nuclear fusion of either the DT or the cold variety: 1. Tunneling Probability; 2. Collision Frequency; 3. Fusion Probability; 4. Sustaining the Reaction. The power delivered by nuclear fusion -- the fusion rate -- is proportional to the product of the first three processes. The fusion Probability is dependent on processes that occur inside the nuclear well and determine the reaction products. The fourth process involves prevention of poisoning the reactions and replenishment of the deuterium and tritium fuel. The ability to achieve fusion at ambient temperature appears to be related most strongly to unexpected increases in tunneling probability and collision frequency in the center-of-mass system.

1. Tunneling Probability

The fusion rate is extremely sensitive to the tunneling probability expressed as the tunneling coefficient. Even small variations in the relevant variables can substantially change this coefficient, which in practical terms is a measure of how easily two atomic nuclei can overcome the barrier of their electrical mutual repulsion. Once this barrier is overcome, the attractive nuclear force dominates. Tunneling is considered to be a quantum mechanical phenomenon in which a particle whose energy is less than the potential energy of a barrier can nevertheless be found on the other side of the barrier. For fusion to occur, the deuterium nuclei (deuterons) and/or the tritium nuclei (tritons) must overcome the repulsive Coulomb barrier and fuse together.

Due to the periodic potential of the lattice ions in a solid and the quantum mechanical wave nature of the particles that move freely in this lattice, it is possible for the effective mass of the particle in the solid to differ from its mass in free space (free-particle mass). Calculations presented later in this paper show that it is possible for the effective mass of the deuterium nuclei in a solid to be sufficiently less than the mass of deuterons in free space to increase the tunneling coefficient by many orders of magnitude. Another very important effect of the solid is to bring deuterons much closer together than they could otherwise get at ambient temperature.

2. Enhancing the Collision Frequency

As stated earlier, the fusion rate is also proportional to the collision frequency of the deuterium nuclei. In three dimensions, the collision frequency per particle is \( n \sigma v \), where \( n \) is the number density, \( \sigma \) is the cross section, and \( v \) is the mean thermal velocity. We expect this number to be roughly the same in the liquid state and in ordinary solid solution as found in palladium (Pd).

There may be preferential pathways in a solid that decrease the degrees of freedom in the solid so that the fusing particle (deuterium or tritium) is confined essentially to two- or one-dimensional motion in the solid, that is, the particles may be able to move only in certain planes or channels. Decreasing the dimensionality or degrees of freedom decreases the number of ways potentially colliding particles can miss each other. We may think of the two-dimensional case as being similar to the collision of marbles on a tabletop. The tabletop need not be flat as long as the marbles are confined to moving on its surface. We may...
ink of the one-dimensional case as similar to
marbles constrained to move in a tube, and the tube
did not be straight. In this one-degree of freedom
the marbles cannot avoid collision.

The actual solid lattice is much more complicated
than this simplified marble example because on the
atomic and subatomic scale, the world is quantum-
mechanical and because it is difficult on this scale
to restrict particles to only one or two degrees of
freedom. However, for the purposes of numerically
illustrating that a significant increase in collision
frequency may be achieved in such cases, let us
consider some very simple equations as crude approxi-
mations of the real situation. In two dimensions the
fusion frequency is \( F_2 = \frac{n^2}{3} \frac{1}{v} \). In one-
dimension the collision frequency is \( F_1 = n^3 \frac{1}{3v} \).

Depending on the particular values of \( n \) and \( \sigma \), when
particles are confined to planar or channel motion
the solid, \( F_2 \) can be roughly up to several orders of
magnitude larger than \( F_3 \), and \( F_1 \) can be as much as
\( \sigma \) orders of magnitude larger than \( F_3 \). Thus we can
see the importance of restricting the motion of the
particles to one or two dimensions. Not all the volume
the solid is available to the deuterons which
increases the effective number density. Similarly not
all the volume of the channels or planes is available
to the deuterons, increasing the effective number
density further. With respect to the collision
frequency, the much bigger effect is due to the
increased cross section. However, the effects of
increasing the number density and reducing the dimen-
sionality also serve to substantially increase the
fusion frequency compared with a free-space plasma,
thus greatly enhance the fusion rate.

1. SURFACE EFFECTS

One of the most basic questions regarding cold
fusion is whether the phenomenon is a bulk effect
occurring inside the solid or whether it is a surface
effect. Based upon conventional mechanisms, quite
eral arguments could be made that it is neither but
is view does not address the available data [3, 10]. To do so, let us explore the sensitivity of
fusion rate to various parameters to shed light on
their respective roles and to hopefully provide
insight to future experiments.

In free space at ambient temperature (300K,
25 eV), the fusion rate between \( d \) (deuterons)
\( 10^{-2666} \text{ cm}^3/\text{sec} \). Even though the rate rises
linearly with temperature, it remains vanishingly small
at \( 10^{-39597} \text{ cm}^3/\text{sec} \) even up to 12,000K (1 eV). The
interface between a solid and an electrolyte
represents a surface where charged particles can
achieve very high temperatures in very localized
regions, for very short times due to high power input
density in regions of high current density.

In an electrolytic cell, sharp asperities (micro-
protrusions) can grow on the cathode [11]. Field
enhancement at their tips, together with the already
present high double-layer electric field, can lead to
very high electric fields \( 10^9 \text{ V/m} \) and the emission of
electrons and high current densities even though the
voltage across the cell is only \( 1 \text{ V} \). Bubble production
can locally separate and unite the electrolyte from
the cathode like the opening and closing of electrical
contacts. Arcing occurs during the separation of two
metal electrical contacts even though the voltage
source is very low \( 1 \text{ V} \), generating high electric
fields and high temperatures as well as a metal vapor
plasma. This and other equilibrium or non-equilibrium
effects involving inductive temperature amplification
(\( L \frac{d}{dt} \) transformer like, producing high energies
microscopically), could be a miniature form of hot-
fusion. However, since no data exist in the literature
for nuclear reactions between \( H \) isotopes at energies
lower than about 1 keV \( (12 \times 10^6 \text{ K}) \), it appears unlikely
that sufficiently high temperatures could be achieved
by this mechanism to account for the claimed fusion
rates.

Another possibility is that a small number of \( d \)'s
can become entrained with high current density elec-
trons that have energies \( >1 \text{ eV} \). The number of such
\( d \) 's would be a small fraction of the number of elec-
trons, and would attain about the same velocity \( v \) as
the electrons. The ratio of the energy of the \( d \) 's
to the energy of the electrons would be
\( \frac{M_d v^2}{M_e v_e^2} = \frac{M_d}{M_e} = 3670 \). Thus a small number of \( d \) 's
might attain energies of about 37 keV.

Surface effects may be able to account for the
large variability of results both for a given
scientist and among the diversity of investigators.
Rate of growth of asperities is a function of crystal-
lographic plane and may be a factor in what is now
thought to be the charging time for loading the
lattice with \( d \) 's. Similarly the method of preparation
of the Pd may well affect the crystal face at the
surface. An experimental test of whether fusion is a
surface or bulk process would be to rapidly cover the
cathode (Pd) with a close fitting tube to see if an
ongoing reaction is quickly quenched or not. The tube
might have to be heavily loaded with \( d \) 's to avoid the
ambiguity of whether it reduced the d concentration in the cathode. Of course this would not rule out the possibility that the surface is an adjunct to a bulk process.

IV. FUSION IN THE SOLID

1. General Derivation of Fusion Rate

Recent publications have postulated effective mass concepts for the electrons in a solid as an analog to muon catalyzed fusion, as well as other mechanisms to account for increased tunneling [17, 12,13,14,15,16]. Even if the electron concepts are not applicable for a bound system to enhance the fusion rate, our fusing particle (d) effective mass concept appears valid [18-20] as it is applied outside the barrier where the inertia of the unbound deuterons (d) is determined by the lattice.

The cross-section, \( \sigma \), for a nuclear reaction between charged particles can be expressed as a product of four factors:

\[
\sigma = \sigma_c G T \rho
\]

where \( \sigma_c \) is the cross-section for collision, \( G \) is the Coulomb tunneling coefficient, \( T \) is the ratio of net flux of particles transmitted into the nuclear potential well compared to that penetrating the Coulomb barrier and \( \rho \) is a function of the strong interaction leading to a given fusion reaction (exit channel).

For nuclei at low energy whose reduced Broglie wavelength, \( \lambda \), is therefore, large compared to nuclear dimensions, \( \sigma_c = \pi \lambda^2 (L+1) \) for interactions by partial waves with orbital angular momentum \( L \). For s-waves (no angular momentum) this is just \( \pi \lambda^2 = \pi h^2 / 2 \).

A very important effect of the solid is to bring deuterons much closer together than they could otherwise be at ambient temperature. Although the average separation of the d's is about 1.4A in heavily loaded Pd, the d's can be in equilibrium at a separation as close as 0.94A [20, 21, 22]. Closer separation is possible in non-equilibrium processes. Various models for the screening potential of the free electrons in the solid lead to roughly similar results. The differences in the models may be important when better experimental data are available and a close correlation between experiment and theory is sought. At this stage a model of a spherical shell of radius \( R \) of negative charge surrounding each d will suffice even though other models such as a uniform cloud of electrons give significantly higher tunneling and fusion rates. This model leads to a shifted coulomb potential with an analytical solution which can account for the present experimental results. The potential energy as a function of radius \( r \), outside the nuclear well is

\[
V = e^2 / (4 \pi \epsilon_0) [(1/r)-(1/R)], \quad r_1 \leq r \leq R,
\]

where \( e \) is the deuteron charge, \( r_1 \) is the nuclear well radius. \( V = 0 \) for \( r > R \). \( V = V_n \) (the square well nuclear potential) for \( 0 \leq r \leq r_1 \).

The periodic potential in which d's move in Pd and their interaction with the ionic lattice and its constituents is similar to that of electrons, and the effective mass concept applies to both. A d in such a crystal is subject to forces from the crystal lattice as well as the Coulomb force from another d. The Hamiltonian of two d's contains contributions from the periodic potential of the lattice, electrons, and from interaction of the two d's. Simplification to the two-body (two d) Hamiltonian may be accomplished by using the effective mass for \( r > a \), the lattice spacing. Experiments involving \( r > a \) and time \( t > a/c \), which consider only external forces, will infer an inertia for the charged particle equal to the effective mass. As nuclear distances are approached (\( 10^{-15} \)m), the interaction between the two d's dominates over the lattice contribution, and the free mass is appropriate. Thus we assume the d's have a reduced effective mass \( \mu^* \) for \( r > R \). In the nuclear well the d's have a reduced mass \( \mu \) = their free reduced mass \( (d \text{ mass}/2) \). Inside the barrier (classically forbidden region), their mass varies continuously from the reduced effective mass \( \mu^* \) outside the barrier to the reduced free (true) mass inside the nuclear well, as a two-body approximation of the many body problem. (In the many body approach the free mass would apply everywhere.) To obtain an analytic solution, we have \( \mu \) at \( r_1 \) to \( \mu^* \) at \( r_2 \) the classical turning point:

\[
\mu R (\mu - \mu^*) (r_1/r) + \mu^* \text{ for } r_2 > r_1.
\]

Solution of the Schrödinger eq. yields the tunnelling coefficient

\[
G = K \exp (-2 g(r_1)), \quad \text{where}
\]

\[
g(r_1) = (e / 2 \hbar) [2 e^2 / 4 \pi \epsilon_0 \mu^*]^{1/2}.
\]

Finally, the barrier transmission flux coefficient \( T \), is given by :

\[
T = [4 k/K], \quad K > k.
\]

k is the wave number for the asymptotic region (outside the Coulomb barrier):

\[
k = \sqrt{\mu \hbar} \text{ and } K = (2m \nu_n) / \hbar. \quad \text{Thus}
\]

\[
\sigma = (2 \hbar / \mu^* \nu K) \hbar \exp (-2g(r_1)).
\]

Note that \( \rho \) depends on the specific reaction. When there is no enhancement from nearby resonances like the \( ^{5}\text{He} \) resonance for d-t fusion and where there is no
inhibition of the nuclear events e.g. by requiring a
adiabatic transition as in d-p fusion, $\rho$ is of order
sity for d-d fusion. The dominant nuclear events are
sumed to be the normal isobaric analogues: $d+d= p+t$
and $d+d=n+ 3\text{He}$, with some branching ratio. The measured
blue [15,16,26,28] of the astrophysical $S$ function
or d-d fusion is $108 \text{keV-barn} = 1.73\times10^{-42} \text{J-m}^2$ which
in be combined with Eq. 6 to yield

$$\sigma = (S/E) \exp -2g(r_1).$$ (7)

The number of d-d fusion reactions/cm$^3$/sec is:

$$N = \frac{n^2}{v^2} e^{-2g(r_1)}$$ (8)

where $n$ is the d number density, and $v$ is the mean
eral velocity. Thus

$$N = \frac{[2\pi 2 S/[2\pi E]]^{1/2}}{a} e^{-2g(r_1)}$$ where $E$
is the energy in the center-of-mass (CM) system.

2. Decreased Effective Mass

Let's proceed to examine the effects upon this
ationship of the crystalline environment. These
effects address the d effective mass. To our knowl-
ge this is the first time that these concepts have
en applied to the fusing particles as a possible
lanation for cold fusion.

In a region of periodic potential perturbations,
saged particles behave dynamically as if they
ossess an effective mass, $m^*$ (less or greater than
e free mass), given by :

$$m^* = \frac{\hbar^2}{[d^2 E/dk^2]}.$$ (10)

Just as the electrons see an attractive periodic
ential, the d see a repulsive potential at each of
role metal ions with further periodic potential peaks
 the positions of the octahedral interstitial sites
en essentially all are occupied by d as in the a-
ase Pd$_x$ with $x > 0.75$. Although a band calculation
ot attempted for the d effective mass $m_e$, the
agnitude to be expected can be estimated from the
ple Kronig-Penney model for a unit charge moving
th periodicity, $a$:

$$m^* = \frac{\hbar^2}{2a^2 E}$$ (11)

where $E$ are the eigenstate energies for d moving
etween the interstitial sites. Eq. 11 properly esti-
ates the effective mass of electrons in terms of the
emi energy $-eV$. For d (bosons of spin 1), even
ough their energies are low, being distributed
round thermal, Eq. 11 gives $m_e \approx .01$ times the free d
mass as a lower limit. A decreased mass can profoundly
crease the $G$ factor. A triton (t) should have an
even smaller effective mass than a d because it is a
mi particle and hence has higher $E$. Because of
his, a prediction of this model is that heavy loading
of the lattice with t and d should give even higher
fusion rates. The difference in zero-point amplitude
of d, t, and p in Pd may also be significant.

The effects of d effective mass are calculated in
Table 1 where the number of d-d fusions/cm$^3$/sec is
calculated for Pd$_x$ for $x > 0.75$. The fusion rate is
calculated for a series of values of effective mass
for CM energies 0.025eV, 0.15 eV, and 1 eV, as could
be found in the high energy tail of the thermal energy
distribution.

$E_{\text{Lab}} = E_{\text{CM}}$ corresponds to symmetric collisions of d
in transit between interstitial sites, which may be
ore likely in a lattice which provides preferential
ways of motion, than in a high temperature plasma.
This is another mechanism which can increase the
fusion rate by many orders of magnitude. As Table 1
ows, fusion rates $>10^{10}$/ cm$^3$/sec may be obtained by
these mechanisms which can account for the reported
cess power and radiation attributed to cold fusion.

In addition to accounting for reported fusion
rates[5-10], this theory further predicts two generic
(i.e. for $m^*$) properties of cold fusion in the bulk
of a solid: 1) There is an extremely strong dependence
on d concentration. 2) There is not a strong tempera-
ture dependence of the fusion rate right up to the
melting point. For Pd this is 1828K, corresponding to
$E = 0.152eV$. In free space, a large increase in fusion
rate would be expected with increased temperature.

With a decreased solubility of d in Pd and hence
decreased density, the large difference between the
$R=2.7A$ and $R=0.9A$ cases, indicate that a decrease in
the fusion rate with temperature may be expected.
These predictions could be tested by externally
creasing the temperature of an active fusion cell,
and by adjusting the d concentration.

Thus we see that an effective d mass of only
$-10^{-1} \times$ the free d mass can account for the known
positive experimental observations. The strong
ponential dependence of the fusion rate upon the
centration and effective mass is evident from Table
1. This may in part explain the wide spread in
positive and negative experimental results of
different investigators.
TABLE 1. d-d fusion rate in powers of 10 per cm³/sec of PdDx.

<table>
<thead>
<tr>
<th>R=0.8A</th>
<th>R=1A</th>
<th>R=1.4A</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_CM (eV)</td>
<td>E_CM (eV)</td>
<td>E_CM (eV)</td>
</tr>
<tr>
<td>ν/E</td>
<td>0.025</td>
<td>0.15</td>
</tr>
<tr>
<td>1</td>
<td>-45</td>
<td>-44</td>
</tr>
<tr>
<td>0.1</td>
<td>+11</td>
<td>+11</td>
</tr>
<tr>
<td>0.05</td>
<td>+19</td>
<td>+19</td>
</tr>
<tr>
<td>0.02</td>
<td>+25</td>
<td>+26</td>
</tr>
<tr>
<td>E_CM (eV)</td>
<td>0.025</td>
<td>0.15</td>
</tr>
<tr>
<td>-80</td>
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<td>-75</td>
</tr>
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<td>-1</td>
</tr>
<tr>
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<td>+10</td>
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</tr>
<tr>
<td>+19</td>
<td>+19</td>
<td>+20</td>
</tr>
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</tr>
<tr>
<td>+15</td>
<td>+16</td>
<td>+17</td>
</tr>
</tbody>
</table>

3. Conclusion

Eq. 9 permits us to estimate how close two d's would have to approach at ambient temperature in a lid to account for reported fusion rates [3,5-10], neglecting effective mass or any other special effects. A separation of about 0.144 (R=0.074) would yield 0.1W/cm². Decreasing the separation to approximately 0.12A (R=0.064) yields 20W/cm². Such close partitions are not possible in equilibrium where the closest separation is calculated to be 0.94A [1-23], and would even be very difficult to achieve non-equilibrium. Therefore, if fusion in the bulk to account for this excess power generation, mething extraordinary must be a vital part of the process such as a decreased effective mass of the sing particles as proposed here.

CLUSTER-IMPACT FUSION EXPERIMENTS

This section is being added in the spirit of melliness. A very important paper [24] was published ten days after our GIT-NSF Workshop, and I nd that the analysis I prepared for this workshop quite applicable to it. The paper is important and of itself, and is very relevant to Cold Fusion. If the term "Cold Fusion" is proper for the bent temperature fusion experiments, then this w work may well be called "Lukewarm Fusion." deuter-deuteron fusion at incident energies 100eV has been demonstrated by D2O cluster-impact fusion experiments at Brookhaven National Laboratory. I will analyze their experimental results. This analysis will help in part to resolve a discrepancy which they note to be "more than 10 orders of magnitude". Following their method of calculation, this discrepancy is found to be 25 orders of magnitude, of which 10 orders of magnitude are accounted for by compression and electron reeining. My analysis is presented to show that the remaining discrepancy can be resolved in terms of proximity and energy only by greatly exceeding asonable values for these parameters.

1. The Discrepancy

Beuhler, Friedlander and Friedman (BFF) have made a significant contribution in demonstrating d-d fusion rates of 10⁻¹/d-sec at incident deuteron energies of only 100eV. [24] They note a discrepancy between their experimentally obtained fusion cross section, α_exp, and one which they calculate. They say, "By assuming no compression occurs the experimental results lead to a value of α which is 10 orders of magnitude larger than that computed for 300 eV d impacts..." as will be shown, their method of calculation leads to a α which is 25 orders of magnitude smaller than the value obtained from their experiment. Significantly, even when both compression effects and electron shielding effects are included, a discrepancy of about 15 orders of magnitude remains.

The formula used by the authors is:

\[ \alpha(E) = \frac{S(E)}{E} \exp\left\{ -31.28/E \right\}^{1/2} \]

which is based upon the experimental astrophysical function S(E) obtained for energy measurements above 10keV. Values of S for d-d fusion at low energies [15,16,25,26] are given between 53 and 108 barn-keV. For calculating α and other parameters in this paper, this range leads only to a factor of 2 in the computed values. BFF use 55x10⁻²⁴ cm²/keV, and this value will be used in Eq. 12. E is the energy in the center of mass (CM) system. For d-d fusion, I calculate the exponent to be 31.4 rather than 31.28, but this would only make a 36% difference in the calculated α.

For a (D2O)₅ cluster accelerated to an energy E_N, the energy of the individual deuterons in the lab frame is:

\[ E_{lab} = E_N / N \left[ 2m_D m_p / m_D \right] \]
\[ = E_N / N \left[ 2m_D + 8m_D / m_D \right] \]
\[ = E_N / 10N. \]

For E_N=300keV, and N=100, E_{lab}=300eV in agreement with BFF. E = E_CM = \[ m_{target} / (m_{target} + m_{missile}) \]
cm-[1/2] E_{lab}^{150eV} as m_1=m_2=m_0 here, which gives the largest value of E_{cm} with respect to E_{lab}. Since the kinetic energy received from the accelerator is the dominant energy upon collision, it is unlikely that the CM energy of the deuterons after impact will differ significantly from 150eV. As N gets larger, E decreases so most of the clusters have energy below 150eV.

Thus for 150eV, Eq. 12 yields σ = 3.1x10^{-57}cm^2. An experimental cross section σ_{exp} can be inferred from the BFF paper. They estimate a fusion rate \( N = 10^{-7} \) per sec/cm^2, where n is the number density of impacted neutrons and v is the mean velocity. From their value of 0.8g/cm^3 as 5 times the density of normal solid D_2O, a value of the normal number density \( n_0 = 10^{22} \) cm^{-3} is obtained. An upper limit of the on-dimensional compression yields \( n_0 = 10^{-20} \) cm^{-3}. For the minimum d-d separation, \( 2R = 10^{-10} \) cm and v = 1.70x10^7 cm/sec. Thus, \( \sigma_{exp} = 5 \times 10^{-32} \) cm^2. This produces a discrepancy of \( \sigma_{exp}/\sigma = 10^{-1} \).

2. Attempting to Resolve the Discrepancy

Let us determine the extent to which this discrepancy can be resolved. Let us use Eq. 9 since it incorporates the effects of both compression and electron shielding. Eq. 12 does not include these. The fusion rate per d is \( N_d = N/n \), and the excess energy due to fusion is \( E = 4.03 \text{ MeV} \), since \( d+d+H+H \rightarrow H+H+4.03 \text{ MeV} \) assuming only this branch of the d-d reaction occurs. Since \( N_d, N, \) and \( P \) are all proportional to \( \sigma \), the same discrepancy occurs for these.

Table 2 shows the calculated values of \( N_d \) on the left side, \( N \) in the middle and \( P \) on the right as a function of the center of mass energy and one-half the nearest separation of the deuterons in angstroms (Å).

<table>
<thead>
<tr>
<th>( E_{cm}(eV) )</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
<th>0.02</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
<th>0.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-20</td>
<td>-17</td>
<td>-12</td>
<td>-6</td>
<td>44</td>
<td>6</td>
<td>+11</td>
<td>+18</td>
</tr>
<tr>
<td>300</td>
<td>-14</td>
<td>+2</td>
<td>-9</td>
<td>-5</td>
<td>+9</td>
<td>+11</td>
<td>+14</td>
<td>+19</td>
</tr>
<tr>
<td>600</td>
<td>-8</td>
<td>-7</td>
<td>-5</td>
<td>-2</td>
<td>+15</td>
<td>+17</td>
<td>+18</td>
<td>+21</td>
</tr>
<tr>
<td>1200</td>
<td>-3</td>
<td>-2</td>
<td>-2</td>
<td>0.3</td>
<td>+20</td>
<td>+21</td>
<td>+22</td>
<td>+23</td>
</tr>
</tbody>
</table>

Table 2. Calculated fusion rate per d-sec, total d-d fusion rate per cm^3/sec, and power density in W/cm^3 all in powers of 10.

As can be seen from Table 2, only at the highest energy of 1200eV and the smallest R of 0.02Å, both of which greatly exceed the likely values of 150eV and 0.2Å in these experiments can the BFF value of \( 10^{-1} \) fusions/d-sec be achieved. For 1200eV and 0.05Å, the calculated value of \( 10^{-2} \) fusions/d-sec can be increased to \( 10^{-1} \) if the electron screening were due to a spherical cloud rather than a spherical shell of negative charge as calculated by numerical integration. For the more realistic 150eV and 0.2Å case, N can be increased from \( 10^{-20} \) fusions/d-sec to \( 10^{-16} \) by this method.

Therefore, a discrepancy remains of about 15 orders of magnitude \( (10^{-1}/10^{-16}) \), unless something like the effective mass concept is invoked. But it is not clear that the effective mass concept applies to the likely amorphous state resulting at impact.

3. Further Significance

The relevance of these experiments to cold fusion goes even beyond the need to invoke a novel concept to explain the fusion rates. The branches of the d-d reaction may be much less than unity. This is similar to the inference obtained in cold fusion observation of neutron (n) to triton (t) yields in electrolytic cells [6,11].

As shown by BFF in Figure 2 of their paper [24], \( ^3\text{He} \) should occur roughly between channels 60 and 95 with a maximum equal to the t peak around channel 110. However, even with a contribution from the tail of the gamma background there is a depression in this region indicating that \( ^3\text{He} \) is not present. Furthermore, the area (integrated count) for the 1 MeV t signal is roughly the same as the area of the \( ^3\text{He} \) signal. This would be expected in the absence of \( ^3\text{He} \). For the normally expected approximately equal t and \( ^3\text{He} \) branches, the area under the 1 MeV peak should be roughly double the area for the proton (p) signal since the energy resolution is not sufficient to fully resolve the t and \( ^3\text{He} \) peaks.
Consequently, their experiment provides evidence at the n to p branching ratio is <<1. Iyengar [6] reports 10^-8 for this ratio. If the branching ratio were close to unity, the neutron flux would be much lower and should not be difficult to measure.

Eq. 9 permits us to estimate how close two d's would have to approach at ambient temperature in a liquid to account for reported fusion rates, neglecting effective mass or any other special effects. Even a given deuteron proximity, 2R, the number density for cold fusion, n_c, can be greater than the number density for lukewarm fusion, n_L, which at all R more than makes up for E_c<<E_L. For small R, n_L represents a local rather than a global number density, just as n_L only represents the number density in the impact region. Care must be exercised comparing the cold fusion rate where n_c=(2R)^{-3} and the lukewarm rate where n_L=(n_0)^{2/3}(2R)^{-1}. Hence separation of about 0.14A (R=0.07A) would yield 1W/cm^3. Decreasing the separation to approximately 12A (R=0.06A) yields 20W/cm^3. Such close separations are not possible in equilibrium where the closest separation is calculated to be 0.94A [20, 22], and would even be very difficult to achieve non-equilibrium. Therefore, if fusion in the 1k is to account for this excess power generation, appears that something extraordinary is a vital part of the process such as a decreased effective mass of the fusing particles.

The analysis presented here clearly indicates that the lukewarm and cold fusion investigators report fusion rates that cannot be explained by conventional models. As the temporal power increases, the reported fusion rate per particle per second increases at a rate greater than that expected from the h/2mE, where h is Planck's constant, m is the mass of each B-E particle, and E is the energy of the incident particles.

VI. HYPERMOBILITY

1. Superfluidity

It has long been known that hot fusion is the source of superfluidity. In my opinion, just as tunneling is at the heart of both hot fusion and cold fusion, a Bose-Einstein (B-E) condensation leading to superfluidity of a charged gas is at the heart of both low and high temperature superconductivity.

I'm going to take a look at superfluidity in a way that is both novel and instructive. It will yield a methodology that is applicable to high temperature superconductivity. In a B-E gas, particles should start a B-E condensation into a ground state in momentum space when the quantum mechanical wavelength is much greater than the interparticle spacing (one-fourth the de Broglie wavelength, \lambda, is the approximation here). This occurs at the B-E temperature, T_{BE}. Let's find T_{BE} by this method and see how well it compares with T_{BE} as obtained traditionally.

\[ T_{BE} = \frac{h^2 n^{2/3}}{4mk}, \]  

where n is the number density of B-E particles of momentum p and energy E.

\[ \lambda = \frac{h}{p} = \frac{h}{(2mE)^{1/2}}, \]  

where h is Planck's constant, m is the mass of each B-E particle, f is the number of translational degrees of freedom per particle, and k is the Boltzmann constant.

Combining Equations 14 and 15, we find

\[ T_{BE} = \frac{h^2 n^{2/3}}{4fk}. \]  

Let us compare Equation 16 with T_{BE} that is derived rigorously in a more exact but arduous manner [27].

\[ T_{BE} = \frac{h^2 n^{2/3}}{11.9mk}. \]  

For the three-dimensional case were f=3, T_{BE}/T_{BE} = 0.992. So the heuristic derivation does quite well. A two-dimensional B-E condensation is not expected because of fluctuations. A one-dimensional B-E condensation is not expected because two phases can't be in thermodynamic equilibrium at a point. However, a three-dimensional gas may exhibit reduced dimensionality if degrees of freedom f are limited.

Now that we have established the approximate correctness of the results from this methodology, let us apply it to the arena of superconductivity.
2. Superconductivity

In the case of a superconductor, the conducting particles may be Fermions rather than Bosons. For a degenerate system of Fermi particles such as electrons or protons (also holes) superconductivity can exist if the particles pair near the Fermi level. Then, this happens, the paired particles will have integral spin (singlet state of spin zero for electrons, although the triplet state of spin one also participate) and obey Bose-Einstein statistics rather than Fermi-Dirac statistics. This can lead to the appearance of superconductivity, just as the pairing of $^3$He atoms in the triplet state leads to superfluidity.

For an idealized non-interacting point-particle Bose-Einstein gas, the condensation temperature is considerably higher than the pairing temperature of electrons in a conductor. Thus, there is no manifestation of superconductivity until the electrons pair, because there can be no condensation until bosons are formed. Therefore, calculation of a pairing temperature would be equivalent to determination of the superconducting transition temperature. If the opposite were true and the condensation temperature were less than or equal to the pairing temperature, it would suffice to calculate the condensation temperature to find the critical temperature $T_c$. In this case since superconducting properties could not manifest themselves until the condensation temperature were reached, it would be difficult to ascertain that the electrons had paired.

The spirit of this methodology is that the feature common to superconductivity in all of its manifestations may be the condensation temperature, rather than the pairing temperature. Thus, it may be quite secondary or incidental that there are a variety of pairing mechanisms with a range of pairing strengths.

In the midst of a panorama of coupling mechanisms and diversity of strengths, it may suffice to calculate the condensation temperature and in the process also obtain the pairing strength. It may be possible to do all this without reference to any particular coupling model.

The first objective of this analysis is to derive an upper limit for $T_c$ for different classes of superconducting materials in different dimensionalities. There can be many mechanisms which poison $T_c$ to lower temperatures, but it is of some value to be able to put an upper limit on $T_c$ for a given class of superconductors. The second object is to derive an approximate coupling strength i.e. the energy gap for these classes. As will be shown, the ability of this simple theory to predict general ranges of critical temperatures is particularly striking. In addition, it gives reasonable predictions in areas such as the heavy fermion (heavy electron) metal superconductors and the ceramic oxide superconductors where neither the BCS theory nor other theories do very well.

It is necessary to modify the usual condensation derivation which yields a condensation temperature $T_c > T_{	ext{cond}}$. Superconductivity can occur if the Fermi particles pair near the Fermi level.

At temperature $T = T_c$, we have

$$\lambda = \frac{4\pi n_s^{-1/3}}{3},$$

where

$$n_s = \frac{kT_c}{E_F}.$$

$n$ is the number density of free charged particles, and $n_s$ is the number density of particle pairs whose condensation temperature is $T_c$, and $E_F$ is the Fermi energy.

$$E_F = \frac{h^2}{9m} n^{2/3},$$

where $m$ is the effective mass of the charge carrier.

For a particle pair gas, of momentum $p$, mass $2m$, and incremental energy $E$ near the Fermi level:

$$\lambda = \frac{h}{p} = \frac{h}{[2\lambda(2\pi\hbar)^2]^{1/3}} = \frac{h}{4\pi(f/2)kT_c^{1/3}},$$

where $f$ is the number of degrees of freedom per particle.

Combining Eqs. 18, 19, 20 and 21:

$$T_c = n_s^{-2/3} / (8\pi)^{1/3} = E_F / 64\pi^2 k,$$

where $D_F$ is the density of states at the Fermi surface.

In order to estimate $T_c$ for some materials like the ceramic oxides, we should consider the possibility that the conduction paths for superconductivity may be two- and/or even one-dimensional. The oxide superconductors such as $Y_{1-Ba_2Cu_3O_7-y}$ are not strictly of lower dimensionality, as mechanisms such as Josephson tunneling through nonconducting regions tend to produce in equilibrium a Fermi energy corresponding to three dimensions $E_F$ rather than to two- or one-dimensional Fermi energies $E_F^2$ or $E_F^1$. Eq. 22 is also obtained for lower dimensions, as these systems are three-dimensional with respect to $E_F$ and thermal equilibrium, and only the degrees of

140
Freedom of the paired fermions are restricted to two
id one dimensions [29-31]. Anisotropy may produce a
iciently higher effective mass in some direc-
s as to effectively reduce the dimensionality.
systems may be considered to be of quasi-lower
mensionality where only the degrees of freedom $f_2$
nd $f_1$ of the paired fermions are restricted in
ir nontunneling conduction paths.
For the ceramic oxides Eq. 22 yields 10K, 40K and
10K in three, quasi-two and quasi-one dimensions.
terpreting the ceramic oxide case as one in which
nterchain interactions are equal to the intra-
ain interactions, leads to

$$T_c \approx (T_{c1} T_{c2})^{1/2} \times (300K \times 40K)^{1/2}$$

$\Delta \approx 110K \approx 100K$ (23)

As before, Eq. 26 is obtained for quasi-two and
 quasi-one dimensions [29-31].

Table 3 shows that Eqs. 22 and 26 do well in
representing experimental and calculated results
over a range of $T_c$ and $\Delta$ of nine orders of mag-
nitude. $T_c^*$ is the experimental or literature value
[32-40] of critical temperature. Although only one
significant figure may be warranted for $\Delta$, two are
listed for the purpose of comparing $\Delta$ and $\Delta_{RC5}$.

For Table 3, Eq. 26 is considered independent of
Eq. 22 and only experimental values of $T_c$ should be
used as input into Eq. 26. However, if Eqs. 22 and
26 are combined, then

$$2\Delta = 8(4f_0T_c)^{3/2}(E_F)^{-1/2}$$

$$= 12R(2m)^{1/2}(f_0T_c)^{3/2}n^{-1/2}$$

(26)

As before, in good agreement with the ceramic oxides. Using
experimental values of $T_c$ causes the ratio $2\Delta/kT_c$ to
to vary.

As shown by Table 3, this simple theory does well in predicting critical temperatures and energy gaps
over a range of nine orders of magnitude. The agree-
ment with experiment is good. The theory agrees
well with the RCS predictions where RCS does well.
In addition, this theory makes reasonably good
predictions where BCS does not, as in the case of
the heavy fermion metals and the ceramic oxides.
Eq. 22 is indicative of the $T_c$ that may be expected
for a given class of materials in a given conduction
dimensionality. The experimental and literature data
are presented in support of the estimates calculated
from this equation. Because of the low number
density of electrons, the ceramic oxides are not
likely to be three-dimensional superconductors
except at the lower transition temperatures.

It is both interesting and noteworthy that this
theory does so well without specifying a coupling
mechanism or strength and with only three variables
$f$, $n$ and $m$, which can be determined from experi-
ment. The variation of $m$ from that of a free electron
mass may be able to account for small differences in
$T_c$ within a given class of materials, as would more
detailed knowledge of the Fermi surface in general.
Particularly important are mechanisms which act to
impair $T_c$, i.e. poison the superconductivity.

The mass variation appears to work well for the
heavy electron metals, where $T_c \approx 1/m$, as predicted
by Eq. 22. Crystallographic data can help determine
$f$. The combination of different dimensions, such as
TABLE 3. Comparison of Estimated $T_c$ and $2\Delta$ with Data For Wide Range Matter

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>Dim.</th>
<th>Est. $T_c$,K</th>
<th>$T_c^*$,K</th>
<th>$2\Delta$,meV</th>
<th>$2\Delta_{RC}$,meV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Elec. Metal</td>
<td>$10^{29}$/m$^3$</td>
<td>3</td>
<td>0.5-1.5K</td>
<td>0.5-1.5K</td>
<td>.68</td>
<td>.304</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallic</td>
<td>$10^{29}$/m$^3$</td>
<td>3</td>
<td>50</td>
<td>23.2K</td>
<td>10</td>
<td>7.04</td>
</tr>
<tr>
<td>Supercond.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic Oxide</td>
<td>$10^{28}$/m$^3$</td>
<td>3</td>
<td>10</td>
<td>13K</td>
<td>19</td>
<td>3.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be-H</td>
<td>$5 \times 10^{29}$/m$^3$</td>
<td>3</td>
<td>200</td>
<td>-</td>
<td>160</td>
<td>60.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallic H</td>
<td>$10^{30}$/m$^3$</td>
<td>3</td>
<td>300</td>
<td>125K</td>
<td>110</td>
<td>38.0</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen Star</td>
<td>$10^{43}$-$10^{45}$/m$^3$</td>
<td>3</td>
<td>$10^6$-$10^9$</td>
<td>$10^{10}$-$10^{11}$</td>
<td>$1.8 \times 10^{10}$</td>
<td>$3.04 \times 10^9$</td>
</tr>
</tbody>
</table>

3. Interesting Coincidence

It is interesting to note that whereas Pd is not a superconductor, Pd-H is a superconductor [41]. Superconductivity has not been detected in Pd below .01K. The transition temperature of Pd-H is about .5K. Furthermore, Pd-H has a negative isotope effect i.e., $T_c$ for Pd-D is even higher and for Pd-T is higher yet. It is nevertheless considered a BCS superconductor and the effect is attributed to the zero point vibrational energy differences of each isotope as interstitial gas in Pd. Pd is the only metal I know which becomes a superconductor when hydrogen and its isotopes are added to it.

It is an interesting coincidence that cold fusion as been reported in Pd-D, and as can be calculated from the previous section Pd-D and Pd-T may be ambient temperature superconductors in quasi one-dimensional form. High loading of D in Pd, produces an expansion of the Pd lattice of a few percent per linear dimension corresponding to an internal pressure of $10^5$ atmospheres ($10^{10}$Pa/m$^2$). Such pressures in hydrogen may be expected to bring it near the metallic state. Greater pressures may be expected to result in three-dimensional superconductivity above ambient temperature for metallic hydrogen [38].

VII. ACKNOWLEDGEMENTS

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**BIOSKETCH**

Ciro Rabinowitz was born in Mexico City, Mexico in 1936. He received the B.S and M.S. degrees in Physics from the University of Washington in 1959 and 1960. He was awarded the Ph.D. degree in Physics from Washington State University in 1963. He is a Senior Scientist at the Electric Power Research Institute (EPRI). Prior to joining EPRI in 1974, he was at Stanford University at the Linear Accelerator Center for seven years. Previously, he was a Manager at Atomic Associates, and a Senior Physicist at the General Electric Research Center. He is currently an adjunct Professor at the Georgia Institute of Technology. He has taught at Stanford University, San Jose State University and San Jose City College; and as an adjunct Professor at Boston University and Case Western University. He has over 300 issued patents and has published over 60 scientific papers on such subjects as superconductivity, physical electronics, electrical discharges, surface physics, and vacuum physics. He has written four articles for the Encyclopedia of Science and Technology. Two are mature articles on Advanced Electric Power Transmission and on the Nuclear Electromagnetic Pulse, in the 1981 and 1986 Yearbooks, respectively. Two others are articles on Electrical Insulation (1982 and 1987) and Superconducting Devices (1989).