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Abstract: Modern electrical grids face increasing demands to serve new or unusual loads, to integrate unconventional new resources, and to transmit power in unforeseen ways. These expanding demands will require utilities to operate existing systems closer to steady-state limits, thus increasing the performance requirements of operation and control systems. In this paper we use the challenges posed by power system stability analysis to motivate a discussion of the technologies required to advance the state-of-the-art in real-time power system control. We consider the computational requirements of system stability analysis techniques (transient simulation, eigenanalysis, time-domain fitting, and frequency-response analysis). Additional requirements are imposed by the necessity that the computational results support either human or automated decision making. We then address the role that critical computer and information technologies must play in addressing these needs. Our emphasis is on high performance computing, where we consider both hardware issues and algorithmic requirements. Data management, user interface, visualization, and expert system technologies are also discussed. We conclude by suggesting elements of a strategic plan for creating the next generation of computer tools for power system analysis, and for their use in real-time control applications.

Key Words:

1.0 INTRODUCTION

The intent of this paper is to identify and recommend courses of action that should be initiated, at national level, to assure adequate electrical power service over the next one or two decades. The focus is upon research needed in the area of real-time power system control and operations, at the higher levels appropriate to an energy control center. We first discuss forces and trends that make this focus appropriate, and which bring a certain urgency to the research planning effort.

Contemporary power system engineers rely heavily upon a physical plant which reflects a recent but bygone era, when cheap resources encouraged both generous safety factors and operating policies which now seem very simplistic. Expanding electrical needs have since produced a power system that is somewhat larger and much more complex. A sustained effort to minimize construction of electrical resources through tighter system operation is compounding that complexity. This, in turn, compounds the likelihood and the possible consequences of equipment or human failure.

This has produced a burgeoning need for more comprehensive information, and better information processing tools, at all stages of the engineering process. This culminates at the system operations center. It is there that all the planning, analysis, design, and facilities development translate into actions, and are adjusted to accommodate the unpredicted and the unpredictable. Given proper facilities, generation sources can be balanced against immediate airshed conditions, reservoir schedules can be fine-tuned to aid migrating fish, power can be routed to serve storm-damaged areas, or emerging system problems can be detected in their early stages.

We project and recommend an expanded role for the system operations center. While there are many aspects to this, the most topical are

- comprehensive, state-of-the-art information systems, featuring

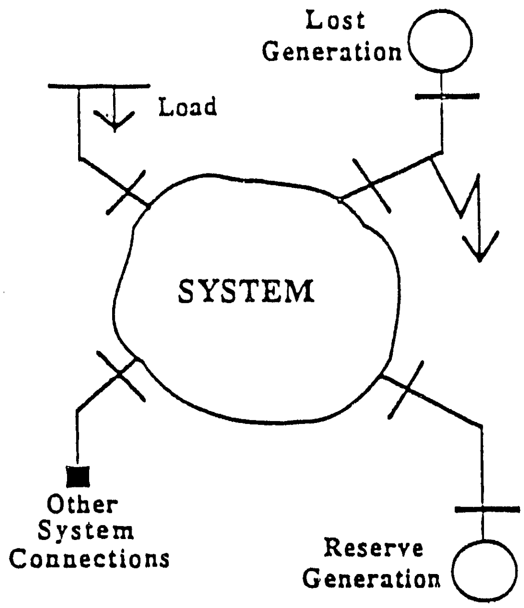

FIGURE 1. Power System Responding to Loss of Generation Capacity

choice would be determined by analysis conducted while the scenario occurred.

In real time, the above scenario could be analyzed as follows. Measurements are made to obtain system data, and two possible operating options are identified. State estimation is performed to obtain initial conditions for the power flow under each option. Because the options are independent, the two power flows are calculated in parallel. Using the power flow results, two eigenanalyses are performed; one for each option. The results are used to evaluate each option for small-signal stability. This evaluation is primarily based on the damping associated with a few key eigenvalues, but the associated eigenvectors may also have to be considered. Decision information is then communicated to the human operator. This information includes a quantitative description of the stability of each option, and a recommended choice. Finally, after the option had been selected the performance of the system would continue to be monitored and compared to model predictions to ensure that the projected system state was actually realized.

Although this example indicates the need for high-speed advanced computing to conduct real-time system analysis, this may be the least challenging problem. In a more realistic scenario, many more factors besides small signal stability would have to be considered in making decisions. Data acquisition and pre-processing would require the management of considerable data and some form of intelligent decision making to determine the contingencies to be studied. Possibly the most challenging need would be the evaluation of analysis results to inform operators of possible problems and recommended control actions. This would require considerable machine intelligence to interpret system history as well as analysis results. How information is communicated to the operator is extremely critical. Extensive man machine interfacing would be required in order for the computer and operator to effectively communicate. Because the human operator is an important component in the control and decision making process, it is important that the computer educate operators as they use the system, as well as vice versa.

2.1 What Has to Change?

Realization of the above scenario for real-time control requires several technology advances. First, computational resources adequate to carry out the stability calculations in the time available for decision must be incorporated into the operational environment. As now typically executed by system planners, the required power-flow computations take only a few minutes on a mid-range minicomputer. However, the eigenanalysis for a model of reasonable complexity could take hours. Clearly, significant improvements in performance are required.

Data management also will require attention. To realize our scenario, an appropriate system model for the power flow computations must be available, the output data from the power flow computation and the system model must be made available for use in the eigenanalysis, and the final results of the computations must be presented so as to be useful in selecting among alternative actions. In addition, model results and data obtained from system monitoring must be placed in formats suitable for comparison. In a more realistic scenario, results must be compatible with multiple computational models. These requirements contrast with the current state-of-the-art in the planning environment, where management of models and results from even a single application can be a challenge.

- high-volume information sharing with other operation centers
- direct surveillance over critical equipment, especially that involved in large-scale automatic control
- "intelligent" displays and operator alerts

• access to standard, high performance modeling and analysis software, with appropriate increases in staff levels and skills

• direct involvement with and support from a wider range of planning staff, probably through computer networks.

Within the operations center, distinctions between real-time control and real-time operation will become more a matter of emphasis and time-scale than of function. It is useful to treat them together as "man in the loop" control processes or, alternatively, as partially automated decision processes. This model is readily extended to include longer-range planning, for use in overall workflow analyses.

The motive forces in this scenario are societal need and technological opportunity. Advanced computers can support software tools that are much more powerful, generic, and "user-friendly" than those now used. This in turn permits

• faster and more comprehensive treatment of large-scale problems

• better access to software packages developed outside the power industry

• more flexible use of individual and collective staff skills.

Technology advances with respect to sensors, communications, computer networks, man/machine interfacing, and various system sciences add further dimensions to these opportunities and potential benefits.

The power industry has a massive technology transfer within reach. Effecting it may be rather more urgent, difficult, and slow to achieve than is generally recognized. Economic expansion or environmental factors can readily absorb the operating margins which are directly available on the power system, and do so much more rapidly than new physical plant can be developed. Whether the demands, the constraints, and the resources can be predicted with a degree of confidence appropriate to the services and the risks involved is an open question.

2.0 SCENARIO

In this section we present a simple scenario illustrating the potential role of computationally intensive modeling in real-time control applications. The scenario focuses on a particular class of calculations (computation of system small-signal stability profile). However, comparable scenarios involving other modeling techniques can easily be constructed. We then consider the advances in technology and changes in procedures necessary to realize this scenario, and identify critical computing and information requirements for that realization.

The standard method of analyzing a system's small-signal stability profile is to conduct transient simulations to explore system response to various events. These simulations cover time periods of approximately 10 seconds and require extensive computer time. Modal analysis is another approach to analyzing a system's small-signal stability profile. Eigenanalysis is a method of modal analysis that provides detailed information about a system's small-signal stability characterization [3]. System experts have shown the value of eigenanalysis as a design tool [ref.]. Because of the extensive information it provides, eigenanalysis shows considerable potential as a planning and real-time operations tool. Therefore, in this scenario, eigenanalysis is used as the basis to analyze the system's small-signal stability characteristics.

Consider a large system where a major generation plant is lost due to a disturbance (Figure 1), and assume the plant cannot be immediately brought back on line. Also assume that system has survived the initial transient, but the new steady-state operating point is unacceptable due to lack of scheduled generation. The operator has two choices: 1) intentionally drop pre- determined loads; or 2) ramp up a set of pre-determined generators with spinning reserve which will cause heavy loading of some key radial transmission lines. This decision must be made within minutes. Naturally, the second option is preferred if the system permits. Under current practice, the choice would be governed by planning studies previously conducted off-line. With an on-line tool, the but only a few eigenvalue-eigenvector pairs are obtained.

All but the last two items in Table 1 are model-based analysis techniques; that is, a detailed mathematical model is required. The last two analysis methods listed use system response data as opposed to theoretical models. Such techniques as the Fast Fourier Transform (FFT), Prony analysis, and frequency domain model fitting have considerable potential as analysis tools especially in the development of accurate theoretical models [2,5].These techniques are primarily based on optimization and curve fitting algorithms (such as singular valve decomposition and search techniques). The computational requirements of these techniques are not as nearly burdensome as model-based methods such as eigenanalysis.

Of the analysis techniques outlined in Tables 1 and 2, the low-frequency simulation methods and eigenanalysis require significant computational speed-up in order to be used in a real-time environment. The results in [6] indicate that significant speed-up is possible by simply employing modern high-speed computers. For example, a 467 state MASS problem would require 36 minutes of cpu time on a VAX 8650 while the same problem requires 26 seconds on a CRAY X-MP EA/232 computer. Also, it is not at all unreasonable to expect additional efficiency from the application of leading-edge numerical analysis techniques. Such techniques as efficient variable-step integration of coupled stiff differential and algebraic equations, and the eigenanalysis of large matrices have received considerable attention in the mathematical community (e.g., see [7-10]. A conservative estimate is that the application of modern high-speed computers and numerical techniques can double the size of problems studied while at the same time reducing the required computation time by one-third.

4.0 CRITICAL COMPUTING TECHNOLOGIES

In this section we discuss the state-of-the-art in the computing and information technologies required for the use of system modeling in real time control. We again emphasize high performance computing, man-machine interface, and data management. In brief, we argue that the necessary computational power to permit real-time system analysis will become available over the next few years. Substantial effort will be required to develop the necessary computational software. In other areas we believe that current technology is adequate to meet power system requirements. However, significant improvements in software engineering tools are required to make these technologies readily available to power system engineers.

We begin our discussion of the state-of-the-art with a cautionary note. Over the last four decades engineers have had access to a rapidly improving computational capability. This has enabled them to continually model larger, more complex systems, with greater accuracy. Although the speed at which floating point arithmetic can be done receives the greatest publicity, increases in memory size and access speeds, size and data transfer speeds of mass storage devices, and software engineering tools are also well-known factors. Perhaps less well publicized is the fact that roughly half the aggregate improvement in computational performance has come from the development of new computational methods. As an example, it has been estimated that over a twenty-year period an effective improvement of five orders of magnitude was achieved in computational performance for aerodynamic simulation. Of that improvement, three orders of magnitude are attributed to numerical methods, and only two to hardware developments [11]. In projecting computational performance, factors other than hardware speed must be taken into account.

4.1 High Performance Computing

Introduction of current generation superworkstations and, for large modeling jobs, vector supercomputers for power system analysis offers significant benefits in terms of reduced turn around time, and increases in model size and complexity. Implementation of analysis tools on these classes of systems is relatively straightforward, and will not be addressed here. In any event, workstations and vector supercomputers are not adequate for the problems discussed here. Real-time system stability analysis will require significant performance increments over the current state-of-the-art. Advances in parallel computing technology may provide the required performance over the next several years. However, extensive effort will be required to realize the prospective gains.

Massively parallel computing is based on the simple idea that large numbers of relatively

Improvements in man-machine interface technology are also required to realize this scenario. Sophisticated planning models, as currently in use, are tools for experts. Development of the required system model, evaluation of the results, and presentation of the results so as to usefully support real-time decision making all must be automated. In addition, the interface will need to embody some "intelligence", so as to be able to select the type of modeling appropriate to a particular analysis, and, perhaps more important, to suggest alternative actions for analysis. Again, these requirements contrast markedly with the relatively primitive interfaces in common use for power system planning models.

Finally, we note that as sophisticated planning tools migrate from the planning to the operations environment, the distinctions between the planning and operations functions will begin to blur. To give just two examples, contingency analyses conducted by planners will be used in the operations environment as starting points for calculation of system response to observed disturbances, and monitoring data will be compared in real-time to planning predictions to permit improvements in the models, and to provide early warning of operational conditions that may be outside the envelope considered in system design. In consequence, distributed computing technology, and in particular distributed data management, will be of substantial importance.

3.0 COMPUTATIONAL REQUIREMENTS

Many analysis techniques have been developed to study power system characteristics. In order to evaluate the possibility of incorporating these techniques into a real-time environment, one must understand the computational and numerical requirements. In this section we briefly examine the mathematical requisites of some common and potentially very useful analysis methods outlined in Tables 1 and 2.

The first item in Table 1, power flow, is not only used in steady-state analysis, but is required by many dynamic analysis methods to provide initial conditions. The most common solution algorithms are based on iterative methods such as Newton-Raphson and Gauss-Seidel [1]. Well established sparse matrix algorithms have provided relatively fast and efficient computational techniques on conventional computers. A standard 2000 to 3000 bus problem only requires a few minutes on a conventional mid-range computer.

Low-frequency time simulation (termed transient and mid-term simulation in Table 1) is employed to study system dynamic characteristics. Transient and small-signal stability studies include transient simulation while a voltage stability study benefits from mid-term simulation. Network modeling for low-frequency simulation is done in the phaser domain which limits the modeling bandwidth to below 10 Hz. System models for generator exciters routinely have time-constants in the 0.01 second range, and speed-governor models can have time constants on the order of 50 seconds. Such dynamic range results in a stiff set of coupled differential-algebraic equations.

There are many transient simulation programs in the industry including the Electric Power Research Institute's (EPRI) Extended Midterm Stability Program (ETMSP) [2]. Also, ETMSP is one of a few simulation programs that incorporate mid-term stability models. The solution techniques incorporated by ETMSP include Runge Kutta and Trapezoidal integration methods. As can be seen from Table 2, mid-term simulation typically requires considerably more computation time than transient simulation. This is due to the longer simulation time and additional models.

The last three items in Table 1 are classified as modal analysis methods [3]. Of all the modal analysis techniques, eigenanalysis provides the most extensive information. Presently, the primary eigenanalysis package in the industry is the EPRI/OH Small Signal Stability Package (SSSP) [4]. SSSP consists of two eigenvalue programs: the MultiArea Small Signal (MASS) program; and the Program for Eigenvalue Analysis of Large Systems (PEALS). MASS computes the system state matrix, and then uses the standard non-symmetric QR algorithm to compute all of its eigenvalues and eigenvectors -- both left and right. Because the QR algorithm requires N^3 computations, MASS is limited to relatively small systems (see Table 2). PEALS computes only a select few eigenvalues and eigenvectors using either the AESOPS algorithm or a modified Arnoldi algorithm. Both methods require the user to specify a point in the complex plane, and then computes the eigenvalues and eigenvectors nearest that point. As indicated in Table 2, PEALS is much less computationally expensive than MASS,

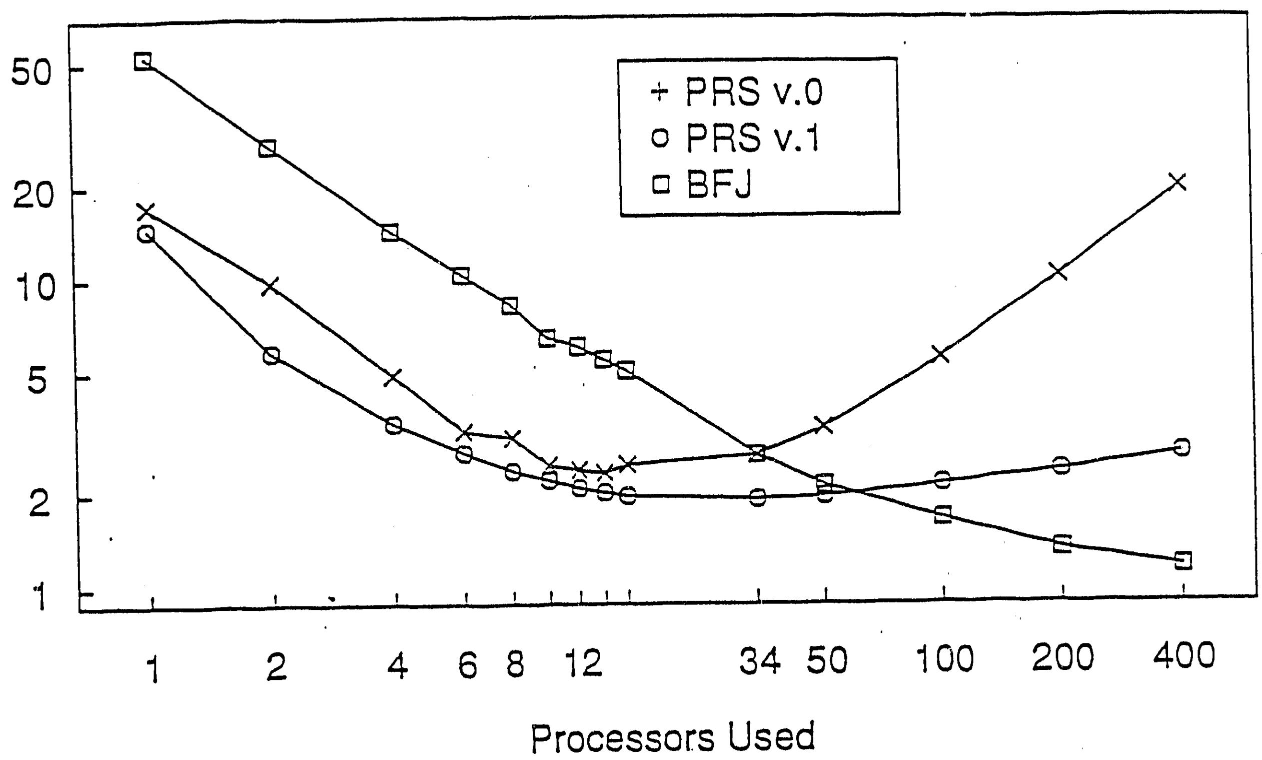

FIGURE 2. Solution Time for 200 X 200 Type 2 Matrix

in which expert system technology has been applied in power system engineering include fault diagnosis and remediation, situation assessment, prediction of the consequences of alternative actions, planning and scheduling, control (comprising many of the previous items), and teaching. To oversimplify slightly, most efforts have been in the form of research prototypes. Only relatively simple systems tend to reach production status. In addition to improve software engineering tools, a number of technical problems require resolution before sophisticated expert systems can be widely applied. Zhang and colleagues list the need for standard paradigms for interfacing the expert system and underlying computational models, slow execution speeds, capturing expert knowledge, maintenance of consistency in the system's rules, and ease of maintenance. To these we would add that the general approach of specifying and executing ambitious expert system projects has weaknesses. We recommend the gradual incorporation of expert assistance in existing user interfaces as more likely to provide useful application tools.

Finally, we turn to the subject of information management. Under the scenario that we have outlined, access to a variety of planning and operational data is required. In particular, a current system model, the results of previous planning calculations, and current operational data may be required. Currently these data are likely to reside in multiple data bases, be in incompatible formats, and, in general, lack consistency. Integration of the planning and operations environments represents a significant challenge, of a type common in engineering applications (e.g. aircraft design, where multiple systems must be combined). One possible starting point is to provide joint access to system and model data in the planning and operations environment. Underlying software tools (e.g., NetCDF [17] to support this sort of integration across multiple data bases and platforms exist, but, again, adequate software engineering tools are lacking. In addition, consensus decisions regarding representation of various types of data (e.g., description of system components) are required.

inexpensive processors can cooperatively complete a computational task more rapidly than a small number of high end processors. The peak speeds of current generation supercomputer processors are on the order of a few hundred megaflops (million floating point operations per second) to a gigaflop (billion floating point operations per second). In contrast, prototype parallel computers with peak speeds as high as 30 gigaflops have been delivered, and teraflop (trillion floating point operations per second) machines are on the drawing boards. It seems reasonable to predict that commercial machines offering two to three orders of magnitude improvement over current generation supercomputers will be available within a few years time.

Unfortunately, the availability of massively parallel machines with very high peak speeds does not guarantee that speed can be effectively applied to complex engineering calculations. The relationship between problem, machine architecture, and numerical procedure is quite complex. However, it is fair to say that presently one can expect to obtain only a fraction of the peak speed for most practical calculations. Major factors restricting performance include the need for interprocessor communication, lack of software engineering tools for developing efficient parallel programs, and lack of efficient parallel algorithms for many problems. We can anticipate improvements in communications speeds and operating system software. However, compilers capable of taking a current code and converting it into an efficient parallel code are not likely to be available in the foreseeable future. Software engineering tools to assist engineers in developing parallel codes are primitive at best, although we can anticipate improvements with time. Finally, significant work will be required to develop efficient parallel algorithms in areas of interest to power system engineers.

To illustrate some of these points, Figure 2 [12] shows the performance of a number of parallel eigensolvers on a prototype parallel supercomputer, the Intel Touchstone "DELTA". This machine has a peak performance in excess of 30 gigaflops, and performs at close to 10 gigaflops on the LINPAK benchmark suite (a standard benchmark). When a number of hardware and software problems are overcome, we anticipate obtaining 5-10 gigaflops on a variety of scientific and engineering problems. The figure shows that current observed performance on eigenanalysis of intermediate order matrices is much lower. The figure clearly illustrates our point that the relationship between problem size, selected numerical method, and solution time can be quite complex.

4.2 Other Technologies

The distinctions among man-machine interface, visualization, and expert system technologies have blurred over the last several years. Modern interfaces may include facilities for problem definition, diagnostics, display of results, and intelligent guidance for both problem setup and analysis of the results. In brief, our view is that the current state-of-the-art in these areas is adequate for the sophisticated systems needed for real-time control applications. Unfortunately, current generation software engineering tools are inadequate for developing and maintaining such systems without prohibitive effort. However, these tools are the focus of active commercial development efforts, and there are active government and university research programs in these areas as well. It seems reasonable to anticipate that significant improvements will be made over the next several years.

There are a number of software tools available for development of man-machine interfaces. NASA's TAE+ [13] is an example of the current state-of-the-art with which we are familiar. This toolkit supports development of multiple window, multiple menu interfaces with various widgets (dials, knobs, etc.) for entering or retrieving information and communicating with applications programs. However, the software engineer retains a significant burden for managing the elements of the interface (which can number several hundreds for a complex application), and for managing the communication between interface and application [14]. In addition, graphics and visualization tools are not integrated with the tool kit. Various other toolkits are available, but offer roughly equivalent combinations of strengths and weaknesses. The bottom line here is that good interfaces for complex models can be built, but significant effort is required, and maintenance is a serious problem.

EPRI has recently reviewed the application of expert system techniques in the power system engineering [15], and a fairly recent bibliography and review is available in the literature [16]. Areas

5.2 Other Information Technologies

We believe that exploitation of modern information technology can provide immediate and substantial benefits for system planning, and is critical in several respects for real-time control. However, we do not recommend the initiation of large scale development projects aimed at real time control. Rather, we believe that the most effective approach will be the evolutionary development of integrated analysis systems in the planning environment, with migration of selected capabilities to real time control application. In addition to the improvements in numerical methods and preparation for the use of massively parallel computers outlined above, such an approach could include the following elements:

1. development of man-machine interfaces for power systems analysis codes that, initially, provide increased ease in the development of models and the display and analysis of computational results, and, eventually, incorporate "expert system" functionality

2. implementation of integrated data management environments, initially for single codes, and eventually coupling a suite of modeling capabilities; required facilities include the management of model inputs and results (e.g., allowing the generation of a new model from the closest analog among cases previously simulated), the communication of data from one model to another, and the automatic update of control procedures from planning studies

3. application of distributed data management technology, starting with implementation of integrated environments based on software tools like NetCDF.

6.0 CONCLUSIONS

In this paper we have considered the application of power system planning tools in real-time control applications. We believe that use of these tools is likely to have significant benefits in real-time control, but also note that numerous technical challenges must be overcome to realize those benefits. In our opinion, migration of tools to the operations environment will come about in concert with a blurring of the distinction between planning and operations. There will be a strong necessity for sharing data and computational tools between these functions. Further, we believe that incorporation of critical technologies into the planning function will come incrementally. Successive generations of planning tools incorporating new developments in computational methods, and improvements in user interface technologies must be developed in concert with their application to real problems in the planning process. Integration of system data required to generate models, of results from planning studies, and monitoring data will be required to support effective application of those tools.

Based on these considerations, we believe that, in the near term, research and development support can most productively be invested in continuous improvement and integration of power system modeling tools. Attention must be devoted to improvements in computational methods, to application of current generation supercomputers, to the man-machine interface, and to data management. Longer lead time efforts to prepare for the use of advanced architecture supercomputers and to provide integrated data management to the planning and operations functions should also be initiated.

Acknowledgements

We would like to thank Dave Elwood for his helpful discussion and comments.

References

1. G. L. Kusic, POWER SYSTEMS ANALYSIS, Prentice Hall, 1986.

2. Users Manual, Extended Transient Mid-Term Stability Program Package (ETMSP), EPRI Research project 1208-9, FACTS version, September 1991.

3. IEEE/PES Symposium. "Application of Eigenanalysis and Frequency Domain Methods for System Dynamic Performance," C. W. Taylor (Chairman), IEEE/PES 1989 Summer and 1990 Winter meetings.

4. P. Kundur, et. al., "A Comprehensive Computer Program Package for Small Signal Stability Analysis of Power Systems," IEEE TRANSACTIONS ON POWER SYSTEMS, Vol. 5, No. 4, pp. 1076-1083, Nov. 1990.

5.0 R&D AGENDA

In this section we enumerate research and development activities that we believe will enable the utility industry to rapidly exploit advances in computing and information technologies for real time power system control. We would like to start with two general points. First, we must be careful to avoid making too strong a distinction between planning and real-time control. We expect a natural progression of tools from the research world into planning groups, and, from planning, into operational use. At any given time we would expect planners to be employing more detailed or more accurate models than are used in control applications, but expect that improvements in computational performance will allow a subset of these capabilities to migrate into use for real-time control.

Second, we believe that introduction of new computing capabilities into both planning and real-time control applications will in general be an evolutionary process. As just one example, we believe that ambitious projects to develop (say) expert systems that replace human judgement in a particular area in a single step are highly likely to fail. Rather, we anticipate that expert system technology will make its impact in steps, starting with increasingly powerful expert "assistance" appearing as part of the "man-machine" interface for both computational modeling and power system operation.

5.1 High Performance Computing

Exploitation of high performance computing for power system planning and control requires two kinds of activities:

- incorporation of the current state-of-the-art in computing and computational methods in existing power system applications
- activities designed to hasten the application of massively parallel computing to power system problems.

To make use of the current state-of-the-art, the numerical methods in major power system analysis codes should be reviewed for currency, and updated. Methods for solving stiff sets of differential algebraic equations [7] for eigenvalue calculation [8-10] and, in general, sparse matrix methods, are all of interest. Optimization techniques are also of substantial interest for planning and component design, although they are probably of less pertinence for real time control applications. There is no reason why improvements in numerical methods should not be provided to system planners in the near term.

In addition, power system codes should be implemented on current generation supercomputers and high performance workstations. Such implementations will allow planners to investigate more complete system models in reasonable time. Experience suggests that substantial improvements in performance can be obtained with relatively modest effort [6]. By providing faster turnaround on system simulations, these implementations will also be a step towards use of computational models in real time control. Again, assuming access to vector supercomputers and/or high performance workstations can be made available, this work should also provide immediate benefit.

Development activities aimed at enabling the use of massively parallel supercomputers in power system analysis and control are likely to have a very different flavor. It will be several years before such machines can reasonably be expected to be available to system planners or can be used for system control. Competing designs, the lack of software engineering tools, and the lack of efficient massively parallel algorithms for important numerical procedures all complicate the issue. We believe that modest research efforts aimed at evaluating competing architectures for power system applications are appropriate; the performance modeling approach outlined above is one possible approach. However, efforts to create complete parallel implementations of power system analysis codes may be premature.

Finally, we recommend that consideration be given to holding a topical workshop on computational methods for power system analysis, similar in content and format to a 1980 workshop sponsored by the Society for Industrial and Applied Mathematics (SIAM) [18] Such a conference could focus the attention of the applied mathematics community on power system problems, and provide communication between power system engineers and specialists in numerical methods and scientific computing. Potential sponsoring agencies include SIAM, DOE, EPRI, and the utility industry.

TABLE 1. Analysis Techniques

ANALYSIS TECHNIQUE	APPLICATION	COMPUTATIONAL REQUIREMENT
Power Flow	solve for system steady-state network conditions	solution of nonlinear algebraic equations
Transient Simulation (e.g., ETMSP)	simulate initial system response to a disturbance, simulation conducted for a few seconds, used to investigate transient stability, modeling accurate below a 10 Hz bandwidth	solution of nonlinear coupled differential and algebraic equations, equations are semi-stiff
Mid-term Simulation (e.g., ETMSP)	time simulate system response to disturbances, simulations are conducted for many seconds to hours, requires more detailed modeling at lower frequencies than transient simulation	similar to transient simulation, but equations are higher order
Eigenanalysis (e.g., SSSP)	used to investigate the small-signal stability characteristics	requires eigenvalues, right and left eigenvectors, in many cases only a few key eigenvalues are needed
Frequency Response (e.g., SIGPAK)	determine frequency content of signals	FFT analysis
System Fitting (e.g., SIGPAKZ)	fit linear rational functions to time-domain and frequency-domain signals	curve fitting and optimization techniques (e.g., SVD and search methods)

TABLE 2. Performance of Specific Codes

COMPUTER CODE	CURRENT PROBLEM SIZE	*REQUIRED COMPUTER TIME	DESIRED PROBLEM SIZE
ETMSP (transient simulation)	3,000 buses 5,000 states	45 minutes	6,000 buses 10,000 states
ETMSP (mid-term simulation)	3,500 buses 5,500 states	many hours	8,000 buses 12,000 states
SSSP (MASS)	500 states	36 minutes	2,500 to 30,000 states
SSSP (PEALS)	3,500 states	**10 minutes	2,500 to 30,000 states

* Approximate required computer time on a VAX 8650.

** This is the time required to find 10 eigenvalues and their eigenvectors.

5. J. F. Hauer, "Identification of Power System Models for Large Scale Damping Control," IEEE Conference on Decision and Control, Paper No. IS-25-2, Tampa, Florida, Dec. 1989.

6. D. M. Elwood, "Eigenanalysis of Large Electric Power Systems," Pacific Northwest Laboratories, Report No. PNL-7632, Richland, WA, Feb. 1991.

7. G. D. Byrne and A. C. Hindmarsh, "Stiff ODE Solvers: a Review of Current and Coming Attractions," Journal of Computational Physics, Vol. 70, pp. 1-62, 1987.

8. J. J. Dongarra, L Kaufman, and S. Hammarling, "Squeezing the Most Out of Eigenvalue Solvers on High-Performance Computers," Linear Algebra Applications, Vol. 77, pp. 113-136, 1986.

9. Y. Saad, "Variations on Arnoldi's Method for Computing Eigenelements of Large Unsymmetric Matrices," Linear Algebra Applications, Vol. 34, pp. 269-295, 1980.

10. D. Boley, R. Maier, and J. Kim, "A Parallel QR Algorithm for the Nonsymmetric Eigenvalue Problem," Compuational Physics Comm., Vol. 53 pp. 61-70, 1989.

11. Erik: Peterson and Ballhaus, 1987.

12. Erik: Littlefield, 1991.

13. M. Szczur, "TAE+: A User Interface Development Tool for Building Graphic-Oriented Applications," ACM Symposium, Aug. 1989.

14. Erik: Adams, 1990.

15. S. Rahman, "Expert Systems in Power System Planning and Engineering," EPRI, Final report for project 2473-41, Jan. 1991.

16. Z. Z. Zhang, G. S. Hoper, and O. P. Malik, "Expert Systems in Electric Power Systems -- A Bibliographical Survey," IEEE Transactions on Power Systems, Vol. 4, No. 4, pp. 1355-1361, Oct. 1989.

17. R. Rew and G. Davis, "NetCDF: An Interface for Scientific Data Access," IEEE Computer Graphics & Applications, pp. 76-82, July 1990.

18. Erik: Erisman, Neves, nad Dwarakanath, 1980.