

REAL-TIME CONTROL AND OPERATION OF POWER SYSTEMS

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INTRODUCTION

The industry is nearly a generation into a period of profound change, technical, financial, and sociological. Conventional power system operation and control practices evolved in an environment of generally robust systems, with the challenge being to minimize production costs. Now, the theory, experience, and practice that were developed and have sustained the industry during its first century of existence are becoming inadequate to new and still evolving circumstances. New challenges are being imposed, associated with secure operation of systems that are less robust, with the imposition of new demands, and perhaps most importantly, with radical restructuring of the industry. These challenges reflect a need for devising new strategies relevant to a restructured industry and increased environmental and economic constraints.

AGC presents the appearance of a mature practice, comprising a more or less standard package of basic algorithms reflecting its evolutionary growth. The basic paradigm is control of active power, rather than of energy; operation planning functions are not fully integrated with on-line control, and dynamic dispatch is only recently being offered. Direct control of load is still experimental. "Static" security constrained dispatch, which is restricted to active power only, is possible, with several suitable linear programming techniques being available. Such an approach can be effective in systems subject to thermal limits on line flows, so long as they have VAR support adequate to maintain their voltage profile. On many systems, however, VAR resources are no longer completely adequate, and *if* security control is to include the consideration of bus voltages and the dispatch of reactive power, as it should, the problem's complexity is increased significantly, to the extent that real-time application is still a future goal for large systems. System restoration practices are still embryonic.

CONTROL OBJECTIVES AND ALGORITHMS

AGC refers to the full range of control actions that are comprehended within the control signals that are sent to individual generating units by the system energy control center, or energy management system, including not only the conventional economic dispatch and load-frequency control, but also the other controls which are becoming more necessary. Its objectives include satisfaction of demand, observance of security, minimization of cost, and protection of environment. During normal conditions, cost minimization is predominant subject to security constraints.

Improvement of Operating Efficiency

Interregional transfers exceeding a few percent of regional generation are both technically and economically infeasible. Moreover, holding even a local disparity of generation and demand within certain bounds is often necessary because of limited transmission capacity. To be worthwhile, any proposed improvements of operating efficiency must

recognize these constraints. Due to a disparity of unit fuel types and transportation costs, as well as differing generation efficiencies, total fuel cost expenditure can be significantly affected by the distribution, within the constraints already mentioned, of the total generation requirements among individual sources.

Economic dispatch. Economic dispatch is the disbursal of total generation requirements among available sources in such a way that the total operating cost (\$/hr) is minimized. Prevailing transmission conditions for the subject system, determined by foreign party interchange transactions and the current native load pattern, are obtained as data (typically by on-line telemetry) for the dispatch calculations. The dispatch algorithm may also include the effects of transmission losses varying implicitly with the candidate solution. The computations are typically performed every few minutes, and in the interim periods unit generation is maneuvered around the economic base point to satisfy the changing power demand. Interutility or interarea opportunity transfers, within interchange capability bounds, are regularly assessed and scheduled as appropriate to achieve better overall economies. In this way then, the realized interconnection-wide economy approaches its feasible minimum.

Static versus dynamic optimization. In static dispatch the fuel cost and operating conditions at each unit can be considered independently of operation at other units. In dynamic dispatch the fuel cost and operating conditions at any unit may be functionally related to its, or another unit's, past and/or future operating scenarios. Static dispatch algorithms are suitable under certain conditions, e.g.: when unit fuel costs can be assumed constant up to the unit commitment time horizon, the operating parameters of each unit are independent of those at any other unit, and incremental unit fuel cost is a monotonic function of net generation. Relaxing any of these conditions calls for the use of dynamic dispatch algorithms. -Dynamic dispatch may also be suitable for jointly owned units where the incremental cost to each party is related to the generation share of other parties.

Sensitivity to data accuracy. As in many processes, the effects of data accuracy should be a consideration in economic dispatch. Most important, of course, is the accuracy of fuel cost, but the veracity of unit efficiency also depends on many parameters of subjective precision.

The ratio of a thermal unit's input to output, called "heat rate," is the reciprocal of its efficiency. The derivative of input with respect to output is called the "incremental heat rate." Note that economic dispatch minimizes total \$/hr by scheduling each unit to the same incremental \$/hr operating cost. Because of difficulty of in-service measuring of heat input, knowledge of incremental heat rate for current operating conditions is particularly subjective and imprecise for coal fired units.

Reactive power dispatch. The dispatching of reactive power (VARs) is a means of adjusting a generating unit or other VAR

controlling device to hold desired voltage level in its vicinity. To hold voltage levels within desired bounds first of all requires adequate circuit and supply capability to serve the prevailing load. The majority of loads are inductive in nature, and if their required VAr inputs are not locally supplied they must be delivered by a higher network amperage with two adverse effects: increased load voltage regulation, and increased network losses.

Depending on load power *factor*, there is an economic trade-off between the alternatives of providing local VAr supply or an increased network amperage capability. For lower power factor loads, a local VAr supply can reduce network amperage and realize economic benefits by reducing losses and operating cost. However, because loads vary with customer usage it is not usually practical to adjust VARs continuously seeking to always maintain a near unity power factor network load.

Maintenance of System Security

State of the Art. Maintenance of system security is a fundamental responsibility of power system operation. The historic objective of minimizing system production cost was based on the tacit assumption that continued reliable operation in the face of all credible circumstances was assured by system design. However, over the past generation, it has become apparent that this assumption can no longer be maintained, and attention has been shifting to the operational maintenance of system security in the face of an inconstant, often uncertain operating environment. Maintenance of system security requires security-related monitoring, assessment, and enhancement, all of which may be subsumed under security control [1].

Security monitoring is generally confined to data provided by a supervisory control and data acquisition (SCADA) system, massaged by topology processing and state estimation. Security assessment, based on analysis of this data, comprises basically “static” security assessment. Current practice for both dynamic and voltage security is based on the use of guidelines derived from off-line studies. Currently, there appears to be no software commercially available that is adequate for on-line analysis of dynamic or voltage security.

A measure of control that has been implemented on some systems is sometimes referred to as “emergency-constrained” dispatch, in distinction from “contingency-constrained” dispatch. The former is after-the-fact, corrective redispatch to remove constraint violations already incurred; in our terminology this is an element of emergency control. The latter type, “contingency-constrained” dispatch, is herein considered as security constrained dispatch proper: before-the-fact actions taken to preclude violations that would be caused by certain credible contingencies. Security dispatch is an open-loop, or at best an open-loop feedback, type control, and as such is limited in its ability to stay on top of rapidly varying system conditions.

Security control. Dy Liacco’s original Adaptive Reliability Control System concept [2] incorporated three levels, the direct, optimizing, and adaptive levels. The evolution of automatic power system controls in the succeeding years has been within the framework of the first two of these levels. The time has now come to consider seriously the importance of the neglected third level. If we consider the “optimizing” level as the generation control (AGC) level, and the

“adaptive” level as the security control level, the latter is then charged with monitoring the system’s level of security, on the basis of which it determines which control objectives are dominant. It thus provides the necessary multimodal coordination between the several system modes (normal, alert, emergency, in extremis, and restorative). Implementation of this far-sighted scheme of Dy Liacco’s will still, a quarter-century later, require substantive research in a number of areas.

A probabilistic framework. The Emergency State is defined as that state in which one or more inequality constraints are violated; the Alert State as that state in which the probability of such violation within a given time horizon (or more ideally, over a regressed horizon giving more weight to the nearer term) exceeds an acceptable level. The inequality constraints to be observed need not be confined to conventional equipment ratings, but might include requirements for minimum reactive reserves, limits on power transfers across critical system boundaries, etc.

The likelihood of leaving the Normal State, i.e. of violating an operating constraint in the near term, requires an assessment of the rates of component failure or subsystem breakdown due to maturity, ambient conditions (e.g. weather in its various aspects), etc., together with an evaluation of control policies available to restore or enhance security. Under ideal or elementary circumstances, then, security assessment reduces to calculating the probability that the power system state will move from the normal operation state to the emergency state, conditioned on the current state, projected load variation, and ambient conditions [3].

Security assessment requires calculating the probability S that the power system state will move from the normal operation state to the emergency state, conditioned on the current state, projected load variation, and ambient conditions. This may then be compared to a security threshold d , defined as a function of the time-varying disturbance forecasts. The ratio S/d becoming less than 1 then indicates system transition from Normal to Alert status, triggering appropriate security enhancement procedures to restore the system to Normal. The (in)security level of the operator’s system is a very dynamically varying condition, and at least for the some time it may have to be estimated, not directly, but crudely for the direct formulation, or by means of such secondary conditions as reserve margins for the indirect formulation.

Security monitoring. System security is affected by variables other than the conventional system state vector. Contingency probabilities change with weather, system load (so that load prediction is of importance), system conditions (e.g. some types of contingencies are more probable during maintenance), and conditions on neighboring systems. System security is also a function of reserve margins, including the current level (and distribution) of reactive reserves, and of dynamically updated emergency ratings of both overhead and underground transmission lines. Such considerations have been ignored by academic research, but system operators cannot ignore them. For instance, the east coast lightning detection network [4] has been developed to give operators advance information about the approach of electrical storms. The point is that conventional state estimation is not sufficient for security monitoring. Non-conventional “state variables such as reserve margins, near term load forecasts, and forecasts of environmental conditions need to be considered in the context of security control.

Voltage Security Assessment. Improved understanding of relevant dynamic phenomena are prerequisite to advances in control effectiveness. This is specially true of voltage control because of the previous noncritical status of voltage phenomena, which led to neglect of careful study.

While assurance of a reactive supply/demand balance across the whole system is necessary to system security, it is not sufficient. At the same time, while assuring a reactive reserve at all individual generators is not necessary (since deficiencies can often be made up by neighboring generators), it is sufficient, in a well designed system, to assure system security. It seems that there are intermediate groups of generators and load buses - *voltage zones* - within which supply/demand balance (and therefore VAr reserve margins) are both necessary and sufficient to system security [5]. Thus, a basic issue for voltage control is that of local imbalances between reactive demand and supply, whether contingency related or “merely” resulting from increased loading of the system. Hence, while determination of proper VAr controls requires the monitoring of local VAr demand and local VAr reserves, the purposes of security control require an estimation of the contingent changes in local reactive load that would be caused by defined disturbances. Monitoring the minimum of the contingent VAr margins of all the zones within a given system will provide an unambiguous indication, under precontingency conditions, of secure precontingency operation of that system relative to postcontingency conditions.

Other Control Issues

Control of network flows. It has been recognized that power systems could realize various benefits with the addition of power flow control (PFC) devices at selected locations. Such benefits come about by forcing power flows onto alternative paths than those resulting from free-flowing conditions. Fortunately new control device technology is rapidly making such devices economically feasible and several are already in service.

As development proceeds along this line it is necessary to consider other potential impacts of PFC facilities. Many benefits of an interconnected system are realized because an area or utility is assisted in its times of difficulty. If the difficulty is sudden loss of generation or load, free-flowing tie power, responding to system wide governor action and occurring within seconds, can maintain system frequency within satisfactory bounds. Should PFC devices become ubiquitous and implemented in such a way that they constrain tie flow dynamics, the benefits of an interconnected system could be degraded. There should be investigation of various scenarios considering these aspects. When an area suffers the sudden loss of generation or load, tie-line flows must provide a rapid make-up of area imbalance until generation control has time to do so. Inhibition of tie flow dynamics could be disastrous if the internal area balance cannot be reasonably reestablished on the same time scale as PFC action.

Direct load control. In addition to PFC, developments are proceeding in the areas of distribution automation and demand side load management. With these in place we should have control opportunities for load generation balance available through the manipulation of customer load. Properly implemented, we might expect to have at any moment the opportunity of either increasing or decreasing area load. Carefully designed demand-side load management might

potentially mitigate the effects of any inhibition of tie-flow dynamics by PFCs.

In the extreme, with fast PFC in-place, all tie-lines become non-synchronizing circuits, all inter-utility flows follow their contractually scheduled paths, and AGC is a local utility operations process. This described scenario is an extreme that will not be reached for decades, if ever. Nonetheless, it is not unlikely that some evolution of power systems will occur in this direction. Each new PFC incrementally decreases the benefits of interconnected operation. On the other hand, direct load management can have an offsetting effect. The future looks interesting.

Multicriteria Optimization. AGC conventionally has dealt with load-frequency control and economic dispatch. However, the objectives associated with the variety of other non-conventional system control objectives that have been achieving prominence are not always compatible with conventional AGC objectives. As the criteria for satisfactory system operation proliferate, the region of feasible solutions, satisfying all constraints simultaneously, may shrink to non-existence, and a new problem emerges, of criteria for establishing relative precedence among the constraints. This leads us directly to the heart of the problem of multicriteria optimization (MCO).

In general, MCO formalisms provide guidance in the formulation of the problem, but no solution. The guidance provided by MCO involves the identification of “non-inferior” (or Pareto optimal) sets (surfaces or loci) of solutions within which no one criterion can be improved without consequent degradation of others. Japanese engineers have reported a methodology for “multiobjective optimal generation dispatch.” For dealing with the final subjective choice among the set of Pareto optimal solutions, they develop a “preference index,” which is formulated to minimize postcontingency line overloads due to generator outages [6].

Control of Energy vs. Control of Power. Conventionally, power system control has been characterized by continuous, proximate (on-line) control of power generation in response to changing load demand, supported by prevenient (off-line) operation planning functions such as unit commitment, maintenance scheduling, etc. As needs for other-functions have emerged, most notably security control and more recently reactive control, operation planning (or even system planning) studies have provided guidelines to be used by system operators in manually augmenting the on-line control of the system. Most recently, increased computational capabilities have resulted in some security functions being performed by PCs available to system operators.

Of late, the line between the two sets of functions (proximate and prevenient) has begun to blur, under the impact of a variety of influences. Dynamic dispatch has emerged as a practical step beyond static optimal dispatch, with capabilities for accommodating non-monotonic cost relationships, response constraints, energy limits, etc. Disparities in fuel supplies, including contract restrictions, quality differences, etc., impose a need for control of energy rather than power. Similar needs will likely arise from generation contracts with IPPs, co-generators, etc., and from the need for optimal use of direct load control.

These emerging practices impose a need for integral control of energy over a time-horizon, rather than just instantaneous

control of power. The result is that the prevent control formerly effected off-line by operations planning functions is merging with the proximate, on-line control of the system, from which a new control paradigm may be expected to emerge. This evolution, which is driven by system needs, is becoming possible, not so much because of the use of more powerful mathematical tools, although these play an important role, as because of the availability of vastly increased computational power, and of information handling capabilities, in the form of more powerful data base structures and management, wider bandwidth data transmission, etc.

Additional research needs. There has been a resurgence of interest in nonlinear power system dynamics due to their importance for voltage phenomena. Over the past several years, understanding of these phenomena has been markedly advanced by the work of investigators at a number of universities. One example is a taxonomy of phenomena determined by system parameters and variables [7].

The state of the art in security assessment suffers from some serious deficiencies that will prove increasingly troublesome as current industry trends continue. These deficiencies include the artificial distinctions (for mathematical convenience) between various classes of security (e.g. static, dynamic, voltage, etc.), and deterministic analysis of probabilistic phenomena. As system operating conditions become more volatile, and the system itself less robust, the lists of "credible" contingencies will become longer and more mutable in response to numerous system and environmental conditions. Improving hardware capabilities may prolong the reign of the current approach, but it may be expected ultimately to become non-viable.

The indicated alternative consists of (i) a probabilistic framework coupled with (ii) non-simulative analysis based on a deeper understanding of system dynamics. (i) A weakness of the deterministic approach to security assessment is the false sense of security that it may provide. While the response of the system to a contingency may be deterministic, given the proper set of initial conditions, the occurrence of the contingency is not. A number of approaches to probabilistic security assessment have been proposed [3,8]. Development of a consistent, comprehensive framework for probabilistic security assessment will provide a basis for application of advanced AI techniques. (ii) By non-simulative analysis is not meant closed form analytic solutions of specific scenarios. Rather we suggest that the establishment of necessary and sufficient conditions for power system security, both heuristic [5] and analytic [7] based on a deeper understanding of relevant dynamic phenomena, would dramatically reduce dependence on review (whether by simulation or analysis) of the effects of a set of selected contingencies.

POWER SYSTEM RESTORATION

Restoration Problems

In order to reduce the probability, the extent, and the duration of major failures in bulk power supplies, preventive, corrective and restorative actions are required. Restoration problems may be divided into several functional groups: outaged system assessment and preparation; prime mover characteristics and scheduling; load characteristics and coordination; and electrical phenomena [9].

Outaged system assessment and preparation. A large number of initiating causes of interruptions are due to temporary faults that are immediately cleared, leaving the system in an unfaulted condition. However, attempting to restore a faulted line or equipment may cause a larger disturbance or extend the restoration duration. The knowledge that major transmission paths are unavailable would alter the restoration plan.

Assessment of switching status uses up critical time. Some utilities automatically open all circuit breakers upon loss of voltage to simplify and speed up the reintegration process. Others prefer saving the breaker stored energy and minimize breaker operations by judicious selection and operation of breakers, requires assessment of switching status by automatic path finding through the use of an expert system.

During the initial phases of restoration, when the system is primarily under manual control, abnormal frequency and voltage variations are tolerated, and automatically switched capacitors and under-frequency relays (which are designed for and are responsive to small voltage and frequency perturbations) will hinder the restorative process. The problem is whether, and to what extent, these relays should be deactivated during restoration.

In re-starting steam units often it is necessary to supply auxiliary power from a remote station. The problem is to select a feasible and available path between the power source and the unit to be started, using models which can adequately represent the such system under large perturbations, so that the starting frequency and voltage values do not fall below the allowable low limits and, for example, cause locked rotors prior to the start-up.

Prime mover characteristics and scheduling In restoring a power system, operators need to know in advance the amounts of real and reactive generation which will be available at a projected time. These data which are time and temperature sensitive could be used to optimize the sequence of the various restoration operations and allow a significant increase in restoring megawatt-hour of service. Efficient coordination between power plants and power system operations can result in significantly more restored services within a given time.

To maintain system frequency within the allowable limits during restoration, loads are picked up in increments which can be accommodated by the inertia and response of the restored and synchronized system. Load pick-up in small increments tends to prolong the restoration duration. With large increments there is always the risk of falling into a frequency decline and recurrence of the system outage.

Load characteristics and coordination. In starting steam units, it is important to coordinate certain critical time intervals, such as maximum time interval beyond which certain thermal units cannot safely be restarted hot, or the minimum time interval required before a thermal unit can be started. Thus, at the early stages of restoration it is important to know approximately the amount of real and reactive loads to be picked up at any time following an outage. As the outage duration lengthens, the coincident load factor increases. The load-time variation depends on normal peak and light loads, load power factors, power factor corrections, load type, and the total connected loads. The problem is to use these data and to develop a load model as a function of elapsed time.

During early stages of the restoration process, it is necessary to keep system voltages within the allowable, although still lower than normal, range. This is done in several ways: energizing fewer high voltage lines, operating generators at minimum voltage levels, deactivating (over-riding) switched static capacitors, connecting shunt reactors, adjusting transformer taps, and picking up loads with lagging power factors. Improper control actions can cause a reactive power imbalance resulting in, for example, generator self-excitation and runaway voltage rise.

Electrical Phenomena. During the reintegration phase, it is desirable to energize as large a section of high voltage transmission as switching transient voltages would allow, to minimize the restoration process. In energizing a large section, there is always the risk damaging the equipment insulation. Power system equipment are protected against the effect of overvoltages resulting from normal operation by surge arresters which provide a relatively low-impedance path for transient overvoltages. During restoration however, certain line-transformer configurations when energized generate a combination of sustained, transient and harmonic overvoltages which may cause surge arrester failures and thus system faults, or the subsequent flash-over and damage to equipment.

Another problem is at what point in the restoration procedure can the tie lines to the adjacent systems be closed? The present practice is to activate the EHV interconnections in the system being restored when units with large reactive power absorbing capabilities are in service. There is a need for establishing a simple and quantitative guideline, such as the ratio of available reactive absorbing capability to the charging current of the EHV line, which would allow interconnection activation.

During re-integration, system operators often encounter an excessive standing phase angle difference across a breaker which connects two adjacent stations. Closing a power circuit breaker on a large difference can shock the power system, cause severe equipment damage, and the possible reoccurrence of the system outage.

Requisites of Restoration Plans and Training.

Restoration plans. Restoring a power system after a partial or complete collapse in a minimal amount of time presents a very complex problem. Most of the existing restoration plans attempt to solve simpler problems (or sub-problems) in a reasonable manner from a limited number of possible initial conditions. Clearly, there is a need for research into restoration plans which will allow integration of the applicable analytical tools in the real-time operating environment. Many of the dynamic phenomena neglected (or unimportant) during normal operation play a critical role during restoration, and need to be taken into account. Any detailed plan has to be specific to the particular characteristics and requirements of the individual power system in question. A restoration plan consists of: (a) procedures for assessing the power system status following a major disturbance, (b) a strategy for meeting system specific priority objectives, recognizing distinct levels of restoration, (c) guidelines established on the basis of extensive steady state, transient and dynamic simulations, and (d) provisions for coordinating activities at the control center, generating plants and the load centers.

Operator training. In the restorative state, system operators are faced with a state of their system quite different from that to which they are accustomed in day-to-day operation, and for which the EMS application programs at their disposal were not designed and are not well adapted. Most operating companies maintain restoration procedures based on certain operating philosophies and practices, and familiarity with characteristics of their power plant restart capabilities and their power system reintegration peculiarities. The resulting procedures are made available in the form of written manuals which prescribe steps or "rules" to be followed during restoration, along with appropriate checkpoints along the way in order to verify that everything goes according to the plan. The media for training, exercising, and guiding operators range from simple instruction manuals, to audio-visual tapes, to highly interactive simulation.

Since major disturbances occur infrequently, operators receive little experience in restoration. For a simulator to be an effective training tool, it must be highly interactive and provide responses to the operator commands similar to those that the actual power system does. The available generic simulators can provide procedural training in early stages of operator training. However for exercising and preparing experienced operators to cope with system-specific and time-critical emergency situations such as restoration, high-fidelity system-referenced simulators are needed.

Need for Advanced Methodologies. During restoration, a power system often consists of one or two islands, most of the automatic controls have tripped or are deactivated, and the system is primarily under manual control. During these early phases of restoration, wide voltage and frequency ranges are tolerated. Under these large perturbation of long duration, the models and simulations which have primarily been developed for small and transient perturbation will not accurately represent the behavior of the power system and its components. There is a need for simulator models that can represent power system characteristics relevant to restoration.

It appears difficult to analytically formulate generally applicable models for restorative states of a power system, particularly in view of the limited amount of available data. Knowledge-based expert systems, which would allow operators heuristic problem solving capabilities, do seem to be suited to the restoration problem. The need is to find ways to integrate the capability of knowledge-based expert systems with the analytical tools required by restoration. Such an on-line guidance system would be capable of updating the restoration plan and procedure to allow occurrences of unexpected events and verification of operators's commands by on-line simulation prior to its implementation. The technology of expert systems is now fairly mature and the time is right to explore their potential use in system restoration.

MODELING AND ANALYSIS METHODS

Basic Models

Generator modeling The physics of the generator is well understood. Standard mathematical models are available [10]. Nonlinear differential equations are used to describe rotor dynamics, field currents, and the effect of control systems such as exciters and voltage regulators [11]. Applications of control-theoretic methods for estimating machine parameters from actual measurements have been proposed. The complexity of applications is due mostly to the nonlinearity of

the system. A complete generator model with control devices covers a time span from cycles to minutes. Time-domain decomposition is commonly used to simplify the model. There are a few analytic justifications of this heuristic approach leading to improved models. However, a lot more needs to be understood in deriving aggregated generator models.

Load modeling In power system analysis, the load typically represents aggregate demand at a substation or other points of the power system. Being composite in nature, their characteristics are quite complex. However the common practice in power system analysis is to represent the load as a linear function of polynomials of voltage and frequency, sometimes plus a single equivalent induction motor. Due to lack of procedure and data, the determination of parameters is seldom done for a particular load. Generic load models including parameter values are commonly used. Several studies have indicated that results of transient stability analysis and voltage stability analysis are very sensitive to the way loads are modeled [12]; thus load modeling is quite critical in power system analysis, and further research is needed for physically-based load models together with analytic procedures for parameter estimation. Future load research should take into account data from smart meters and the ability of customers (or the utility) to alter load as part of load management.

Basic Analysis Tools

Real-time load flow. The load flow equations describe the power system steady-state response to changes in system generation, load demand, and network topology. A typical power system load flow study may involve up to several thousands nonlinear equations. The set of equations can be solved rather efficiently by Newton's method or the fast decoupled method, with sparse matrix techniques. The solution is used to check whether there is an overload or abnormal voltage condition. Several approximate load flow formulations (decoupled, DC) are also used in applications where a fast and approximate solution is desired. On-line load flow is an essential tool in security assessment (contingency analysis) and LP-based optimal power flow.

In an on-line environment, load flows are often solved many times for different system loading conditions, with each one differing from the others only in certain parameters (generator outage, line switching, etc). Rather than solving a new load flow from scratch, some researchers have devoted efforts to find a computationally efficient method to solve changed cases from a base case. Most approaches are based on the sparse vector method. This is a fruitful line of research.

The accuracy of a load flow result is only as good as the input data. Data uncertainty sometimes casts doubt on the usefulness of studies. The increase in non-utility generation and customer load management further aggravates this problem. Stochastic load flow is a generalized formulation of the load flow in which certain variables (e.g. loads, line impedances) are treated as random variables with given statistics. Due to nonlinearity in the load flow equations, efficient computational methods in stochastic load flow are still lacking.

State estimation [13]. The starting point of secure and economic operation of a power system is the knowledge of

the present operating state of the system. Real-time measurements from time to time are unfortunately contaminated by errors. State estimation is a mathematical procedure to come up with a "best" estimate of the true state of the system from such erroneous data. It is formulated as an optimization problem where one minimizes the weighted least squares of measurement errors. Extensive research in the last decade has led to the development of computationally efficient algorithms and their implementation. However, state estimation is only effective in weeding out random measurement errors that are not obtrusive. Large bad data in real-time measurement or structural error in system parameters may hopelessly bias the result of state estimation. Several bad data detection schemes have been developed. The combined use of state estimation and measurement calibration [14] is an effective way of handling measurement errors. Models for parameter error identification have also been developed.

Recognizing the benefits of state estimation, many utilities are pushing for the extension of it to cover larger networks and lower voltages. State estimation relies on the availability of a set of simultaneous measurement data reaching the control center in time for processing. Occasional failure of communication channels or remote terminal units may render parts of the system without sufficient measurement for state estimation. They become "unobservable islands" in the system. Current practice is to use "pseudo-measurements" for these islands. The issue of observability will undoubtedly intensify as a result of the increase in non-utility generation. Better approaches for handling unobservable islands in state estimation are needed.

Optimal Power Flow. The purpose of an optimal power flow (OPF) function is to schedule power system controls to optimize an objective function while satisfying a set of non-linear equality and inequality constraints. The equality constraints are the conventional power flow equations; the inequality constraints are the limits on the control and operating variables of the system.

Practical constrained active and reactive power dispatch problems have complicated non-analytical, non-static, and partially discrete formulations. At the same time, however, most OPF development efforts have centered on the mathematical optimization of very simple classical OPF formulations, expressed in smooth nonlinear programming form. As they stand, these formulations are far too approximate and incomplete descriptions of the real-life problems to be adequate for on-line use. Furthermore, at the present time they cover only a very limited area of system operations.

Optimal power flow programs today, even though they have obtained a fair level of maturity and have overcome some of their limitations in terms of flexibility, reliability and performance requirements, are too plagued by weak convergence, unrealistic assumptions, poor input data and inadequate models of the power system to be able to solve real life operational problems. These are some of the reasons that optimization functions suitable for on-line control have not yet been accepted as standard packages in the industry.

Great attention needs to be given to the entire modeling and formulation of the power system optimization problems. In what follows, we will attempt to outline and briefly describe the areas that future research is mostly needed.

The main role of on-line OPF is seen as a tool helping to maintain viable system operation (i.e., no limit violations), while tracking the unreachable moving target of optimality. The OPF function has to calculate practically implementable control moves that steer the power system as reliably and as far as possible in the direction of the optimum, while avoiding and alleviating limit violations. The main emphasis on rigor should be devoted to the operating-constraint and implementability issues. All relevant constraints (more than is now typical) must be included in each OPF formulation; “optimal” solutions respecting many but not all important constraints could be worse than useless. These additional requirements include: better automatic strategies for infeasible or nearly infeasible problems; more flexible control and constraint priority strategies; incorporation of control and load dynamics; and inclusion of start-up/shut-down constraints of certain controls and other operating constraints that meet specific practical requirements.

The need to often update and maintain accurate external models is recognized and understood. However, the use of existing equivalents in conjunction with OPF problems can cause serious errors in the OPF solutions, resulting from poor accuracy of loss modeling in the equivalents and inability to monitor or enforce inequality constraints of the external system represented by the equivalent.

Existing OPF algorithms use all of the potential control actions in obtaining an OPF solution, but for many applications it is not practical to execute more than a limited number of control actions. More research is needed to develop workable methods of selecting the most effective reduced set of controls.

No serious attempts have been made yet in implementing a “trajectory” of the OPF control shifts that does not exacerbate existing violations or cause additional ones. The sequence in which the different control settings are altered may inadvertently create new problems. The time constraints of the regulating apparatus will have an effect in implementing any new schedule.

To reduce the discrepancy between idealized and realistic OPF problems, emphasis should be focused on establishing consistency between daily scheduling and static optimal solutions produced by the OPF. This calls for inclusion of dynamic constraints spanning an entire time period that are not accounted for in the existing OPF formulations and development of interfaces with other on-line processes such as daily commitment, economic dispatch, AGC, etc.

Expert systems can help resolve some of the deficiencies mentioned earlier, in particular, OPF case setup, interpretation of the OPF results, and optimization solution process.

Transient Stability; Simulation Methods. Power system security analysis is used to define how well a system can withstand those contingencies for which it was designed. When dynamics is the main concern, the dynamic behavior traditionally is examined off-line by transient stability programs. These programs, in the very least, model the dynamic behavior of the machines together with their interconnection through the electrical network. These models are simulated in time using some integration algorithm. If instability (loss of synchronism) is detected the exact mode of instability (the separation boundary) can be identified.

The main thrust of future work regarding the simulation methods should concentrate in the area of computational efficiency. Specifically, the following areas need further research: efficient step size control; handling of discontinuities; selection of “optimal” system and model sizes; dynamic equivalencing techniques; efficiency of contingency screening; determination of remedial actions; development of adequate indices of security.

Direct Methods. Direct methods of transient stability represent a powerful tool for system operations [15]. These methods attempt to minimize the need for time domain simulation of post disturbance system response. They express the degree of system stability in terms of a quantified index (Transient Energy Margin). They can also produce sensitivity information for the simulated contingencies and some corrective/preventative remedial plans to maintain security. Much remains to be done in many areas including: development of reliable algorithms to compute the critical energy under all system conditions; incorporation of line switching capability; development of hybrid techniques; development of direct methods for improved screening tools that employ different stability indices; development of stability indices for transient problems and voltage collapse conditions; development of stability indices capable of measuring the extent of a disturbance; development of parallel processing technologies to speed up simulation of critical contingencies identified by direct methods; development of knowledge-based expert systems to provide the operators with meaningful stability indices that produce a “road map” to enhance stability.

Long-Term Dynamics. Practically all long-term dynamics (LTD) models have resulted from the outgrowth of transient stability models, with developers adding and improving device models and the numerical integration methods. EPRI has sponsored two LTD models, LOADS YS, and a newer version with enhanced models, ETMSP. Dispatcher training simulators are also being adapted for long-term dynamics analysis. Due to numerical constraints and some modeling limitations, the ETMSP period of simulation has been limited to a few minutes. In Europe, a program, EUROSTAG, has achieved impressive speed advantages and analysis flexibility by exploiting variable step-size integration algorithms [16]. Simulations may extend out to several hours without ignoring fast transients.

In order to enhance the functionality and efficiency of LTD models, research is necessary to improve/introduce modeling of generating units control and protection; improve/introduce modeling of frequency effects in network islands; improve simulation efficiency. Potential research work in small signal stability analysis appears to be in approximating network dynamics and simulation speed up.

Simultaneous Transfer Capability Analysis. Recent developments in the electric utility industry have pushed transmission networks closer to their physical limits, possibly with a noticeable effect on the reliability of electric service. These networks are currently being used not only to deliver power to customers, but also to permit sharing surplus generating capacity between adjacent utilities, to ship large blocks of power from low-energy-cost areas to high-energy-cost areas, and to provide emergency reserves in the event of a contingency. Economy energy transactions, reliance on external sources of capacity, and competition for transmission

resources have all resulted in higher loading of the transmission system.

A simultaneous transfer capability program which would determine transfer capability between areas and allow the user to optimize either transfer capability, system economics, or losses is greatly needed. At the minimum, this capability should provide the following: optimum transfer based on the economic use of the existing system; evaluation of requests for transmission services from other entities while including the effects of other transactions; insight into the system strength and weaknesses (bottlenecks in the system); requirements to accommodate increase multiple transactions; impact of multiple transactions on the reliability and security of the system; documentation for use with regulatory bodies and governmental entities.

MATHEMATICAL AND COMPUTATIONAL INFRASTRUCTURE

Analytical Needs and Mathematical Challenges

Traditional power system operation relies extensively on the decisions made by operators based on their experience. Simulation studies using load flows and transient stability analysis are employed by transmission planners to provide guideline to assist operator decision making. But experienced operators are dwindling, and massive changes in the power system operating environment have made nugatory much of the experience of those who remain. This increases the need for and importance of analytical tools and mathematical solutions.

Electric power systems are extremely large and highly nonlinear. There are analytically complex phenomena associated with the nonlinear nature of the system and there are computational difficulties associated with the large-scale nature of the system relative to its analysis and control. Both impose tremendous challenges.

Power system analysis can benefit a great deal by judicious application of the results of modern systems theory. At the same time, the power industry should guide the development of systems theory to its advantage. Compared to other large industries, electric utilities have had little influence in shaping theoretical developments in mathematical system theory, computer science, numerical analysis and such disciplines which could be of benefit.

Until recently, the theory of nonlinear systems has focused primarily on stability. Two types of stability are defined mathematically: Liapunov stability, which is the stability of the system with respect to disturbances, and input-output stability, which is the stability of the system response to its inputs. Both types have relevance in power system applications. Transient stability and dynamic stability belong to the first type, and the study of nonlinear oscillations belongs to the second type. In all these analyses, there is a fundamental assumption that the system will respond to disturbances or inputs "smoothly." Only in the last decade or so have systematic studies been conducted and theory developed for nonlinear systems that exhibit "non-smooth" response, i.e. small changes in system parameters resulting in qualitative changes in system output. Such "structurally unstable" systems may result in "bifurcations" or "chaos." Recent studies have shown that under certain conditions

power systems may display chaotic behavior [17] and bifurcation behavior has been related to voltage stability problems. Research in this area is important to further our understanding of power systems, especially certain strange, sometimes non-repeatable phenomena.

Numerical Algorithms

The application of numerical analysis and computational complexity theory to power system applications has been slow, apart from sparse matrix techniques. Software in traditional power system analysis is application oriented, i.e. unique software design, data structures, and access routines, and specific abstract models are used for each application. With the increasing complexity of application software and its shortening life cycle, it should be designed to standards of greater flexibility and openness. One of the recent revolutionary developments in software is the introduction of object-oriented programming.

In object-oriented programming, a hierarchy of objects is defined. Each object is a fundamental unit and contains private data and methods (procedures). The interaction between objects is through message passing; thus everything internal to an object is encapsulated and objects can be replaced easily so long as the same external interface is maintained. Inheritance in object hierarchies facilitates the sharing of the same structure.

Artificial intelligence

Artificial intelligence is being developed through two disciplines: expert systems and artificial neural networks. Of the two, expert system technology has had earlier commercial acceptance. Within the last decade however there has been an explosion of interest in the neural network technology. As more insight is gained in the strengths and weaknesses of each, it becomes more and more evident that neither technology is going to displace the other.

Expert Systems. Expert system technology is now a mature field of artificial intelligence. It is concerned with acquisition of experts' knowledge within a certain domain, in the methods of knowledge representation in a knowledge base, and in development of efficient inference engines that can apply the knowledge to a sample data within the problem domain.

Power system problems usually are well understood at the modeling level. The solution of the problem (including interpretation of the results) very often entails a judicious judgment, or many combinatorial searches. Naturally the problems with these attributes have been attacked by the researchers from the expert system field. Examples are security applications [18], alarm processing [19], fault diagnosis and restoration [20], restoration [21], and many others [22].

Because of the very strong mathematical basis of many phenomena of interest in power system control and analysis, the advantages of expert systems in this area are realized by combining capabilities of analytical tools to solve these models with the reasoning capabilities of expert systems to prepare parameters and data for the analytical solution algorithms and to interpret the results.

Neural Nets. Artificial Neural Networks (ANNs) consist of many simple computing elements, called nodes, which are

mutually connected by links of varied strengths forming a network. A remarkable feature of this architecture is that the weights can be tuned through a learning process so that the ANN reproduces (almost) any mapping from a set of given inputs to a set of the corresponding outputs. Once tuned, an ANN can be used to recall this map on request, usually in negligible time.

A result of this ANN architecture is a set of unique properties: fast execution on ANN hardware, robustness with respect to failure of a computing node and to noisy input data, and autonomous learning of complex relationships in a given data set. Successful applications of this technology in different fields take advantage of one or more of these properties. This in turn calls for reformulating problems (which are typically rooted in scalar computer thinking) in order to best take advantage of the ANN parallelism.

ANN technology is still in the development stage, with many open problems still to be resolved. Among these are: canonical network representation for a given problem (the type of the network, number of input, hidden and output nodes), an efficient learning algorithm, determination of representative data, efficient unsupervised learning combining previously learned subnetworks, etc. Another obstacle is that currently neural networks are modeled on scalar machines, precluding them from realizing the computational speed and robustness properties they are otherwise capable of achieving with proper hardware.

Representative categories of ANNs to power system applications are [23]: substation alarm signal filtering; network observability determination; load prediction; power plant model identification; unit commitment; security analysis; power system stability and control.

One common characteristics of ANN applications to power system problems to date has been use of fairly small nets, often a few dozen nodes. For load prediction, power plant model identification, and initial substation alarm filtering applications this has not been a serious limitation, as encouraging results were obtained even with these ANNs. For other, network related applications, the problem of scaling small demonstrations size ANNs to the size needed to represent the full power system network, with the associated problem of "teaching" the big network, is still open. This is perhaps one of the biggest issues facing application of ANN technology to power network related problems.

Genetic Algorithms. Researchers within the artificial intelligence field have taken interest lately in the genetic algorithm technology. This is an optimal search algorithm modeled after the natural process of selection by survival of the fittest [24]. Points in the control space are modeled as strings, which are successively generated and their fitness evaluated according to the principles of natural evolution (evolution, mutation and crossover). It is expected that these algorithms may have a strong, as yet unexplored potential for very fast optimization on parallel computers.

EMERGING COMPUTER TECHNOLOGY

Hardware

In the early seventies, a load flow study on a system of 1000 buses required a big IBM computer; even so it took in excess

of 10 seconds per iteration of a Newton-Raphson load flow [25]. Today the same size system can be solved on a high end personal computer (costing several thousand dollars) with less than one second of computer time per iteration! Thus even personal computers are now becoming a viable tool for a lot of power system computational tasks. Today, and probably for some years in the future, the computing power of work stations is needed for more involved computations, such as large models, contingency analysis, optimal power flow, and stability studies.

Computing power in all price, performance and functional categories of computers has experienced a steady growth. In fact, since the early seventies up to now the computing power of microcomputer chips has been doubling every year [26]. Right now personal computers based on a general purpose microchip i486 from Intel deliver roughly 1 MFLOPS performance. Only a couple of years earlier such performance was reserved for work stations and minicomputers, at the cost of several tens of thousand dollars. This trend in price performance ratio is expected to continue for the entire decade [27]. Performance leaders in the work station category currently offer a little over 20 MFLOPS. One should expect at least similar pace of improvements for years to come, which means that a 100 MFLOPS work station is just a few years away.

Additional performance gains are realized by optimizing compilers and operating systems. For instance, in [28] it was noted that on average, in the supercomputer area, compiler based improvements amount to a roughly 20% speed improvement a year.

Parallel computers attain performance above that of any single CPU chip by designing several CPUs capable of working in parallel. Indeed, research goals are for GFLOPS performance with the already available CPUs.

Candidate Applications

The computing power of the work stations today is sufficient for most load flow, security and optimal power flow computations. With the top performing work stations and an advanced simulation program such as [16], one can expect to spend from a fraction of a minute up to about five minutes (depending on the work station) of computer time simulating a large power system (about 5,000 state variables) behavior through- and for several minutes after a major disturbance. It is estimated that with about 100 MFLOPS performance one can expect a realistic size system simulation in real time.

On-line dynamic security assessment increases the performance requirement by a factor equal to the number of contingencies to be processed. A full scale contingency evaluation may require several hundred contingencies. With a minute per run performance this would take hours to complete the evaluation. There is however unexplored algorithmic potential to bridge the gap between the performance requirements and the available performance.

Lacking necessary computing power on work stations, some researchers have been exploring the use of parallel computers for transient stability studies. A recent report by an IEEE Task Force details the state of the art in this area [29].

Neural network technology is another area in need of a lot of computing power. For neural networks simulated on

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Neural network technology is another area in need of a lot of computing power. For neural networks simulated on

conventional computers, the training time is notoriously slow, especially when the backpropagation algorithm is used. As an example [30] quotes a problem (a “divide by three” problem) which required 1.28 million iterations to train the network.

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