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- CONCEPTUAL DESIGN

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Memorandum No. UCB/ERL M85/70

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ANALYTICAL TOOLS FOR POWER SYSTEM RESTORATION - CONCEPTUAL DESIGN

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Abstract

A conceptual framework for computer-aided monitoring and assessment during system restoration using analytical tools is proposed. The basic structure is similar to the one for security monitoring and assessment. State estimation and the related functions, such as observability analysis, bad data identification, external network modeling, that are used in security analysis, can be modified for application to system restoration monitoring. The work in this area is reported. For restoration assessment, in addition to load flows and optimal power flows that are used in security assessment, a host of analysis/optimization programs is required. These analytical tools are identified and categorized. To synthesize possible control sequences and to select and coordinate analysis procedures for assessing restoration plans is a very complex task. A knowledge-based expert system architecture for this task is suggested. The conceptual design of the knowledge-based system and its interface with the analytical tools are presented.

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I. INTRODUCTION

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Power systems are operated under two sets of constraints; load constraints and operating constraints [1]. The load constraints impose the requirement that the customer load demand be met, whereas the operating constraints require that the system variables such as line flows, voltages be within acceptable limits. The system is said to be in a normal state if both the load constraints and the operating constraints are satisfied. The system is said to be in an emergency state if there is a violation of the operating constraints. The system is said to be in a restorative state if some load has been lost, i.e., there is service interruption. (See Fig. 1). Since disturbances or contingencies such as lightning strikes on transmission lines and generator failure occur frequently, power systems have been planned and operated so that it has the ability to withstand most contingencies. This is called system security. In the last twenty years, great progress has been made in developing analytical tools for security analysis. Sophisticated network analysis software is now installed in modern real-time computer controlled energy management systems (EMS) to perform security monitoring and assessment (Fig.2). These analytical tools contribute to the improvement of system security.

Even for systems designed to be highly secure, unpredictables do happen and cause service interruptions and customer outages. It is therefore imperative to develop strategies to handle service interruption by minimizing its impact and to restore service to customers. Most utilities have system restoration plans [2]. For example, one company has developed system restoration guidelines based on operator-analyst discussions and simulations [3,4]. Their proposed strategy calls for:

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Figure 1. Operating states of power systems.



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Figure 2: Functional blocks of monitoring and assessment.

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- sectionalization of power system into islands
- restoration of each island
- synchronization of islands

The idea behind their proposed strategy is that simultaneous restoration will result in speedy restoration.

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In contrast to the rapid advancement in the area of security analysis and control, very little work has been done in providing analytical tools to assist operators during the restoration process. In Japan, an interactive restoration control system has been proposed [5] and an expert system approach has been suggested for restoring a section of a feeder [6]. In a recent survey report on current operational problems in power system [7], it is found that most respondents consider the present approach to system restoration is unreliable, work is needed in problem analysis for system restoration and the new approach should have monitoring/assessment capability. We believe that computer-aided analysis for restorative control can be of great assistance to the operator, the same way as security analysis has demonstrated in normal operation.

In this paper, we

- present a conceptual framework for performing monitoring/assessment functions during system restoration
- identify analytical tools in system security monitoring that, after necessary modifications, can be transported for use in system restoration monitoring
- survey the analytical tools that can be used for system restoration assessment
- identify their effective areas of application
- propose a knowledge based expert system for coordinating the analytical tools for restoration assessment

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Some of the ideas of this paper was outlined in [8] and benefited from [9].

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II. A CONCEPTUAL FRAMEWORK FOR SYSTEM RESTORATION

The problem of restoration after service interruption is a complex decision and control problem for the system operator [10]. The problem may be viewed conceptually as a multi-objective, multi-stage, combinatorial, nonlinear constrained optimization problem. The objective of restorative control is the speedy restoration of all customer service, which involves the minimization of restoration time and the maximization of customer load restoration at each stage. The constraints on the system involved in the restorative control include:

• power flow constraints

(power balance between generation and load, line flows and voltage limits)

• stability constraints

(transient and dynamic stability of system response frequency and synchronization considerations)

• generator restart constraints

(cold restart or hot restart)

- gennerator load pick-up capability constraints
- transmission and tie line switching sequence constraints

The control variables in the restoration problem are the generation schedule of the generators and switching sequences. The decision-maker during restoration is the system operator. The operator's decisions during restoration are based on his knowledge of the

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- current state of the system
- availability of viable alternatives
- consequences of each alternative

Computer/communication systems of an energy management system, together with analysis software can assist the operator greatly in the monitoring and assessment functions. Energy management systems have been effective in assisting system operators during normal operation for cost minimization and security enhancement. Additional analytical capability added to the EMS can certainly assist system operators during restoration.

Our proposed conceptual framework for system restoration is centered around an EMS control computer and is shown in Fig. 3. The EMS serves as the interface between the system operator and the power system. The monitoring and assessment functions are divided into three tasks: modeling, analysis/optimization, and synthesis. Here we use the term *modeling* in a more general sense than monitoring. By modeling, we mean the process of assembling from on-line data acquisition and off-line information necessary data regarding the present and future system for use in analysis and assessment. The assessment function is splitted into *analysis/optimization* and *synthesis*. The details of these tasks are described below.

III. MODELING

Current capability of EMS is confined to the use of steady-state analysis of power systems using load flows. Recognizing this practical limitation, we propose to formulate the constraints in system restoration as a multi-stage load flow problem. The network configuration and the power flow constraints are represented directly in the load flow model. The stability constraints and the constraints on generator re-start, load pick-up, etc., are transcribed into load

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Figure 3: Conceptual framework for system restoration analysis.

flow constraints. The load flow is the workhorse of the monitoring/assessment functions during restoration. The modeling task concerns with the establishment of the load flow model for monitoring/assessment.

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Real-time data are obtained through RTU's, SCADA, and communication facilities typically used in EMS. Because there are two networks in the system, one is the electric network and the other is the information (communication) network, we shall carefully distinguish the concepts of *electrical islands* and *observability islands*. During restoration, the system may be splitted into several islands that are electrically unconnected. Depending on the availability of measurements, state estimation can be performed only for a part of the system. This part may contain several islands that are topologically unconnected. The former are called electrical islands and the latter observability islands. For a given system the breakup into electrical islands may not coincident with its observability islands.

The monitoring function during restoration follows closely the same components in the security analysis (Fig. 2) except that the detail requirements are different, as noted below (See Fig.4).

3.1 Observability

We say a network is observable if there are sufficient measurements to make state estimation possible. Communication facilities used during restoration, such as telephone circuits, may be susceptible to overloading during an electrical outage. If the outage is widespread, resulting from natural causes such as severe storms, then certain communication links may be lost to service. Therefore loss of observability is not to be unexpected during restoration. The observability analysis should be able to test observability of the system and in the event it is not observable, to identify *all* observable islands in the system.

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Figure 4: Functional blocks of restoration monitoring and control.

This is because during restoration it is important to monitor every part that is monitorable. Any observability program that identifies only the largest island is inadequate. We have developed a numerical approach to observability analysis that is capable of simultaneously identifying all observable islands [11-13].

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The basic ideas of the multi-island observability analysis method are the following. A network is observable if and only if all measurements are zero implies all line flows are zero. Consider first the case that a network is observable. When all the measurements are set to zero, no matter what reference angle is assigned to the slack bus (ϑ pseudo measurement), the state estimation equation can be solved with a unique solution. This solution should have all angles the same, so the line flows are all zero. When the network is not observable, the fact that all measurements are equal to zero only forces *some* angles to be the same. The result will be several groups of nodes having the same phase angles. Each group of identical phase angle is an observable island. Efficient algorithms have been developed based on these ideas [11-13].

3.2 State Estimation

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State estimation processes a set of real-time measurements to give the best estimate of the current state of the system. During restoration, the state estimation is required to handle

• multiple electrical islands

multiple observability islands

Most state estimation programs can handle multiple electrical islands but not multiple observability islands. The introduction of pseudomeasurements to make unobservable part observable has been suggested, but it may degradate the quality of state estimation results. We have

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developed a scheme that is capable of performing state estimation for a system with multiple observable islands [11-12]. The process starts from identifying observable islands. The lines flows on the branches crossing two different observable islands will not be observable from the measurements, hence they are unobservable branches. Those injection measurements into the buses that have unobservable branches connected to them are irrelevant in the sense that they are not contributing to the state estimation of the observable part of the network. Once the irrelevant injection measurements are removed and a reference angle is introduced into each observable island, the state estimation program can return the estimated state of all observable islands.

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3.3 External Network

The control center receives telemetered data of real-time measurements. The monitored part of the power system that these measurements cover normally consists of one's own system and is usually called the *internal system*. The rest of the interconnection is called the *external system*. Since the division into internal and external systems are for the purpose of state estimation, a better way of defining internal and external systems is via the state-estimation process. The internal system in this context is actually the observable part of the system with respect to the state estimator in one's energy control center. During the restoration process, due to loss and recovery of communication links, the boundary of internal and external systems is constantly changing. Therefore we need an external network model that

- is flexible to changing boundary between internal and external systems
- does not corrupt the internal system state estimation

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We have developed a method that performs internal state estimation and external network modeling simultaneously [14]. It uses one state estimation covering both internal and external systems. The set of pseudomeasurements in the external system is so selected that it makes the external system barely observable. This way the two requirements mentioned above are all satisfied.

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3.4 Variable Limit Update

Strictly speaking, system dynamic models are required for analyzing stability and synchronization. With current knowledge and computational capabilities, it is rather impossible to include explicitly the dynamic models for realtime system restorative assessment. In real-time security analysis and control, certain transmission lines loading limits are established based on off-line stability simulations. Similarly for system restoration, the stability constraints and the constraints on generator re-start, load pick-up, etc. are transcribed into limits on line flows and voltages. These limits are generally functions of the current network topology, generator and load pattern. Therefore during restoration these limits need to be updated from time to time. A viable approach to variable limit update is perhaps through table look-up established based on off-line studies.

IV ANALYSIS/OPTIMIZATION

There are many facets to system restoration. The problem has all the characteristics, and more, of a complex decision and control problem: multiobjective, multi-stage, large-scale, combinatorial, nonlinear, etc. The overall problem defies an analytical solution. However solution techniques are available for some subproblems. Here we categorize the subproblems according to their

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• number of stages applicable (single or multiple)

- number of islands applicable (single or multiple)
- control variables (generation rescheduling, load control, line switching)
- linearized (dc) or nonlinear (ac) load flow

Each subproblem can be used naturally as a building block for a more general subproblem (e.g., single-stage for multi-stage) or, when used in a standalone mode, is applied to solve one or more particular aspects of the system restoration problem. We have identified the step-by-step build-up of these subproblems in Table 1. Table 1 also shows the characteristics, the applications areas, and the mathematical formulation of these subproblems.

4.1 Load Flow

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The load flow the workhorse in the stable of program is analysis/optimization programs. It is used for checking feasibility of the intermediate steps in a restoration plan and also served as building blocks for other programs. Approximate models to the nonlinear ac load flow may be used advantageously for restoration analysis because when the case is not feasible the ac load flow will fail to converge without giving the source of the nonconvergence, whereas the approximate models do. The most well-known approximations to the load flow are the dc load flow and the transportation model in which only the Kirchhoff current laws are considered. The solutions to the approximate load flow models can indicate the source of infeasibility. There is a family of approximate models lying between the dc load flow and the transportation model. The dc load flow is equivalent to the optimization problem of minimizing a quadratic function subject to the transportation model constraint [20]. Approximating the quadratic cost by piecewise linear functions gives an approximation to the dc load flow [17].

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· .	ions Relevant References	ocen- interactive mpiled load flow BBIB	load optimal power red flow n an d a seance	con- line on switching n	k-up multi-stage ty generation	al none a	ing ds in malization none ting abring	etton ation
	Applicat	testing arios co by synth	1. max. 7 resto within islan islan islan volta maint	network (figuration selection	load pic capabili	sequentia restorat: within an island	1. defin: 1sland sectio 11.connee	compre restoi contre
oration	Mathematical Problem Formulation	staultaneous linear or nonlinear equations	linear or nonlinear programming	mixed integer programming	dynamic programming	dynamic programming	dynamic programning	dynamic programming
n system rest	Load Flow Model	linear or nonlinear	linear or nonlinear	linear ie	linear	linear	linear	nonlinear
Subproblems tr	Control Varíables	continuous (gen/load dispatch)	cont fuuous (gen/load dispatch)	continuous (gen/load dispatch) discrete (lin switching)	continuous	continuous + discrete	continuous + discrete	continuous + discrete
Table 1.	Number of Stages	single	single	single	multiple	multiple	multiple	single or multiple
. •	Number of Islands	stngle	single	single	single	single	multiple	single or multiple
	Problem	l. Basic load flow	 Generation/ load scheduling 	 Generation/ load scheduling with line switching 	4. Multi-stage version of 2	5. Mult1-stage version of 3	6. Multiple feland versions of 4,5	 Nonlinear versions of 4,5, 6

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During restoration the network is frequently splitted into islands. For some studies, the load flow model cannot be applied directly. For example consider the case where one wants to determine the optimal strategy of connecting two islands so that the load in one island can be picked up by increasing the generation in the other island. Transportation model or dc load flow model can be used in this situation by connecting the islands with very high reactance fictitious branches. The resulting sensitivity factors provide the indication of the effectiveness of various connections.

4.2 Other Analysis Programs

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The optimal power flow has been used in security analysis for generation/load scheduling. It is also applicable for system restoration analysis. In Europe, the use of line switching as an additional means for security control was proposed [15-18]. We believe that the problem can be more appropriately formulated for system restoration. An LP approach for multi-stage generation scheduling was proposed [19], which is very relevant in restoration analysis. Possible extensions of these methods for restoration analysis/optimization are listed in Table 1.

V SYNTHESIS

During restoration, the operator makes a sequence of decisions concerning

- switching sequence
- load pick-up sequence
- generation/load schedule

form a library of analysis software. In order to make this collection of

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- analysis software useful for the operator, an interface between the analysis software and the operator is needed that can
 - synthesize appropriate sequences of actions for assessment
 - select proper subproblems
 - organize and control the analysis procedure

Such a task can best be accomplished by the employment of a knowledgebased system. The knowledge-based, or expert system, is a software consisting of a collection of facts, rules of thumb, and other knowledge about a given field, coupled with methods of applying those rules, to make inferences [21-22]. There are three key components in the construction of an expert system: knowledge base, an inference engine, and a user interface. The knowledge base is the repository of specific knowledge about the problem, usually acquired from an "expert", hence the name "expert system". However this does not have to be so. In fact in the present case, there is no human expert who has the experience serving as an interface between the analysis software and the operator. The knowledge base here is more likely acquired through analysis, heuristics and the understanding of the problem.

A knowledge-based system similar to the one for computer-aided control engineering [23] is suggested (Fig. 5). Central to this knowledge-based system is a "list of facts" or a "blackboard." The information in the blackboard may be organized into three categories: objectives, constraints, and status. There are several rule bases in the system. The rules in RB1 suggest appropriate sequences of actions for assessment. The rules in RB2 define an analytical problem and select software in the library for analysis. The rules in RB3 deal with validation of the assessment results through load flow simulations. For example,



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from RB1, it is suggested that at the present stage to energize a portion of the network. The knowledge-based system writes the following information on the blackboard:



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The problem is then translated into mathematical form using rules in RB2 and appropriate analysis software is selected. This step is recorded on the blackboard:



Suppose that in the load flow simulation of the switching sequence suggested by the optimal switching program, it is found by RB3 that a ramp constraint of the generator is violated. This information is then used to redefine the analytical problem. During the analysis/synthesis process, the current status is always recorded on the blackboard to facilitate the application of the rule bases. An important aspect of the knowledge-based system is its ability to explain the reasoning or inference process. Therefore when the analysis/optimization of a possible control sequence is complete, the knowledge-based system will send the assessment report to the operator. In the proposed knowledge-based system architecture of Fig. 4, there are two types of programs. The analysis programs perform mainly numerical computations and are coded in an imperative language such as FORTRAN. The decision-oriented programs perform symbolic computations and are coded in a declarative language such as PROLOG. It is reported [24] that research is currently underway in computer science for high performance architectures that support a mixture of numerical and symbolic computations. Our proposed system will profit from any such advance.

VI CONCLUSION

Recent research progress in the development of analytical tools for system security monitoring/assessment has been remarkable. As systems operating closer to their limits and the threat of blackouts increases, system restoration becomes more important and the need for analytical tools assisting the operator for monitoring/assessment during restoration increases.

In this paper we propose a conceptual framework for computer-aided monitoring and assessment during system restoration. The basic structure is rather similar to the one for security monitoring and assessment. State estimation and the related functions, including observability analysis, bad data identification, external network modeling, have been used in security monitoring. They can be modified for application to system monitoring during restoration. For security assessment, the analytical tools used are simply the load flow and the optimal power flow. For system restoration, a host of analysis/optimization programs is required. They are identified and categorized in this paper. The problem of synthesis of possible control sequences and the selection and coordination of analysis procedures for assessing restoration plans is much more complex. A

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knowledge-based system is suggested to handle this task. To summarize, the same functional diagram for security monitoring/assessment (Fig. 2) can be used for monitoring/assessment during restoration by replacing two blocks. The contingency evaluation block is replaced by a library of analysis/optimization programs and the contingency selection block is replaced by a knowledge-based system (Fig. 4).

Of the components in the proposed framework, the synthesis using the knowledge-based system is the one requires basic research. Currently we are actively working on this problem.

We envisage that the integration of the analytical tools for system restoration into system operation can take place in three levels:

• off-line planning studies

operator training simulator

• real-time operating environment

ACKNOWLEDGEMENT

The authors wish to thank P. Varaiya for his helpful discussions.

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