An Information Architecture for Future Power Systems and Its Reliability Analysis

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***Abstract*—Analysis of 162 disturbances from 1979 to 1995 reported by the North American Electric Reliability Council (NERC) indicates the importance of information systems under the regulated and competitive environment. This paper points out the major deficiencies in current communication and information systems and proposes a new power system information architecture aimed at correcting these deficiencies. The proposed architecture includes automation and control systems at all levels, from substation control system to independent system operator (ISO) operating center, taking into account the requirements of real-time data, security, availability, scalability, and appropriate Quality of Service (QoS). It uses multiple communication channels employing a wide variety of technologies to transmit real-time operating data and control signals. The real-time operating and control system is modeled with various redundancy configurations; the reliabilities of different configurations are studied and compared for practical values of component failure rates and repair rates.**

***Index Terms*—Communication technology, EMS/SCADA, failure rate, fault-tolerance, information architecture, internet, multi-protocol label switching (MPLS), power system, real-time, reliability, repair rate, virtual private network (VPN).**

I. Introduction

DEREGULATION and competitive markets for electricity have changed the organizational structures of the electricity supply industry as well as the operation of power systems. Interoperability between different entities requires adequate information to be brought to operators in a timely manner.

All these requirements brought about by the electric market restructuring together with the unanticipated events that may occur indicate that the communication and information systems are becoming critically important for reliable and economic operation. However, the traditional isolated communication and information systems are not adequate for large amount of intercompany information exchanges and interoperation due to horizontal mergers and consolidation of many existing utilities. Poor coordination caused by lack of timely and adequate information exchange can exacerbate the effect of disturbances. A need exists for a better design of the communication and information architecture accommodating large information flow to facilitate smoother control and efficient decision making.

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To understand and analyze the cause and impact of failures, we have carefully examined 162 disturbances reported by the North American Electric Reliability Council (NERC) from 1979 to 1995 [1] based on 11 possible contributing factors and damage assessment criteria. The analysis of these disturbances clearly indicates that problems in *real-time monitoring* and *operating control system*, *communication system*, and *delayed restoration* contribute to a very high percentage of large failures.

Based on this analysis, an alternate architecture for the communication and information network is proposed. This architecture adopts suitable computing and communication techniques to take into account the requirements of real-time data, security, availability, scalability, and appropriate Quality of Service (QoS).

In order to evaluate and compare the benefits of the different fault tolerance mechanisms proposed, the real-time operating and control system is modeled with various redundancy configurations using the HIMAP [2] software package. The reliabilities of different configurations are studied and compared for practical values of component failure rates and repair rates. Configurations that offer a high level of reliability are identified.

This paper is organized as follows. After a brief introduction, Section II presents the analysis result of disturbances and identifies bottlenecks in current information systems; Section III presents the proposed information architecture and brief review of its key features, while detailed discussion can be found in [3]. Following the reliability analysis in Section IV, some conclusions and observations are made in Section V.

II. Disturbances Analysis and Bottleneck Identification

NERC has published its findings on bulk electric system disturbances, demand reductions, and unusual occurrences since 1979–1995 [1]. In order to understand and analyze the cause and impact of failures, we have carefully examined reviews of selected electric system disturbances in North America reported by NERC from 1979 to 1995. Our analysis provides detailed information for every disturbance from the initial faults that initiated the disturbances to the contributing factors that amplified the effect of the disturbances following the initial faults; a damage assessment is also given for each disturbance. Contributing factors are divided into ten analysis categories based on the NERC Operational Guides and Planning Policies [4]. Problems in each analysis category that contribute to the severity for every disturbance are also identified.

TABLE I
STATISTICAL RESULTS FOR INITIAL FAULTS

Initial cause	Severe weather	Fault	Accident	Equipment failure	Human error	Relay malfunction	Sabotage	UO	VR
1979		3	1	2	2				
1980	2	2		2	2	2			
1981	1	5		2		1	1		
1982	2	1		3	2	1			
1983	2	3	1	1					
1984	2	1	1	3	2	4			1
1985	1	2	3	3	3				
1986	1	4			1			1	
1987	1	1		2					1
1988	1	4		1		3	1		1
1989	4	3		1				1	1
1990	6	1		3		1			1
1991	8	1		3					
1992	1	4	2	4		1			
1993	4	3		1			1		
1994	2	1	1	2	1			1	
1995	3	1		1		1			
Total	41	41	8	34	13	14	3	3	5
Percentage	25.31%	25.31%	4.94%	20.99%	8.02%	8.64%	1.85%	1.85%	3.09%

Fault: Phase-to-ground or Phase-to-Phase faults of bus and line.
UO: Unusual Occurrence such as earthquake, solar magnetic disturbances, etc.
VR: Voltage Reduction.
Accident: Uncontrollable factors such as fire, birds, etc.

A. Disturbances Analysis Based on Initial Faults

We divide the initiating events of power system disturbances into nine categories that could represent all possible causes and examine the percentages for each of the categories among the considered disturbances. The results are listed in Table I.

From Table I, it can be observed that severe weather, unanticipated faults, and equipment failures are among the most common initial causes of disturbances. Stresses in the transmission system due to the increase in the number of transactions under competitive markets that were not foreseen and planned for will lead to more vulnerable systems if careful operational strategies based on real-time network analysis are not available.

With the transmission system operating closer to its security limits, the ability to obtain better-controlled systems with the presence of predictable or unpredictable events becomes more critical. This requires accurate, fast, and reliable on-line security analysis to accurately determine the security limits and provide the operators timely and adequate operation and restoration guidelines.

The proposed architecture suggests efficient on-line security analysis tools to be available at every level from the operations control center to the independent system operator (ISO) operating control center. Besides traditional state estimator (SE) and contingency analysis functions, these tools should also include some new applications such as voltage stability analysis (VSA), dynamic security assessment (DSA), and calculation of available transfer capability (ATC) [5] for evaluating real-time security and determining transmission system limits. With these security analysis tools, a better-controlled transmission system that can work closer to its limits without increasing the risks involved can be designed.

B. Disturbances Analysis Based on Contributing Factors

Following the initial faults, some system components may fail or malfunction, and potential deficiencies could be triggered. These deficiencies and failures definitely amplify the effects of the disturbances. In order to analyze these contributing factors, we have divided them into ten analysis categories based on the NERC Operational Guides and Planning Policies [4]. The percentage for each of these contributing factors among the considered disturbances is presented in Table II.

The results show that problems in *real-time monitoring* and *operating control systems (37.04%)*, *communications and information systems (32.10%)*, and *delayed restoration (38.27%)* contribute to the highest percentage of considered disturbances other than protection systems. We did not rank power system facilities since almost all disturbances were exacerbated by either equipment failures or forced and planned equipment outages. These three aspects are closely related to power system performance and operation. They critically depend on a robust information infrastructure and real-time monitoring and analysis tools. Therefore, the need for efficient architectures, techniques, and tools for network contingency analysis, real-time operation, and future operational planning to deal with equipment outages gains significance.

C. Identification of Bottlenecks

Having identified the three key contributing factors in Table II, we further analyzed the disturbance data in [1] and identified the following key bottlenecks in the communication and information systems that led to the operation and restoration problems found in many disturbances:

1) inadequate exchange of real-time operating information and real-time coordination among control centers;

TABLE II
STATISTICAL RESULTS FOR CONTRIBUTING FACTORS

Contributing factor	1979-1985	1986-1990	1991-1995	Total	Percentage
Power system facilities	59	38	36	133	82.10%
Real-time monitoring and operating control system	**31**	**11**	**18**	**60**	**37.04%**
Communication and information system	**18**	**15**	**19**	**52**	**32. 10%**
Personnel performance	28	10	11	49	30.25%
Operational planning	26	14	9	49	30.25%
System reserve & generation response	15	5	7	27	16.67%
Preventive maintenance	17	4	9	30	18.52%
Load relief	15	2	4	21	12.96%
Delayed restoration	**31**	**12**	**19**	**62**	**38.27%**
Protection systems	51	25	26	102	62.96%
Disturbance considered	70	45	47	162	

2) lack of automatic communication systems to receive rapid, and automatic information;
3) lack of timely communication and failure to use available communication systems;
4) large number of alarms and information overload on computer facilities;
5) inadequate transmission system security and communication facilities;
6) inadequate/improper communication or transmission circuits;
7) power supply failures to communication facilities and circuits;
8) lack of standard procedure and terms used to exchange real-time operating data;
9) lack of advanced communication equipment and emergency communication equipment;
10) lack of real-time security analysis and coordinated operation under adverse conditions, including the effects of simultaneous transfers in transmission interface.

Existing communication and information system architectures lack coordination among various operational entities, which usually is the cause for delayed restoration. Moreover since the various subsystems are isolated, data and information sharing are limited. This is particularly important in the deregulated environment where the merger and consolidation necessitate large information exchange and interoperability. Load sharing between computational resources is of paramount importance during contingency situations.

To overcome these drawbacks, Section III presents the proposed information architecture for power systems together with a brief review of the advantages and new functions of the proposed architecture.

III. PREPOSED INFORMATION ARCHITECTURE

A. Schematic of the Proposed Architecture

The proposed information architecture, shown in Fig. 1, employs a distributed hierarchical computational structure to meet the goals of fault-tolerant and scalability requirements of power systems. The architecture shows a layers of abstraction of which the bottom two layers (substations and control center) are mainly concerned with the operational aspects of the power systems, while the top two layers [control center and ISO/energy trading system (ETS)] are concerned with both the operational and the planning aspects of the power systems. In this layered architecture, the granularity of real-time guarantees is coarse at the top layer (i.e., typical computation and communication deadlines are in hours) and it becomes fine-grain as we go down to lower layers (e.g., at substation, the deadline is in seconds). On the other hand, the amount of data processing involved increases as we go from the bottom layer to the top layer. This clear separation of the computations based on deadline granularity and data processing means that the proposed distributed computing architecture can efficiently integrate diverse algorithms and analysis techniques pertaining to operation and planning of power systems.

The proposed architecture can reduce the communication and computation burden on higher level computer systems through data aggregation. More relevant and critical information is brought to the operators in the control center and ISO operating center, and this is especially important during contingencies for the operators to quickly understand the actual situation and make correct decisions.

B. Key Features of the Proposed Architecture

In the proposed architecture, suitable communication media for level-to-level and peer-to-peer information links are also identified [3]. In order to tolerate communication link faults, redundant communication links are employed using different communication technologies [6], [7]. Multi-protocol label switching (MPLS)-based [8] virtual private network (VPN) [9], [10] services employed in the proposed architecture allow timely and secure information exchange among entities, making it possible to share computational load between peer systems under failure or overload conditions. Local area networks (LANs) are connected to the MPLS-based VPN through firewall [11] while still keeping the traditional links from substation to control center, from control center to ISO

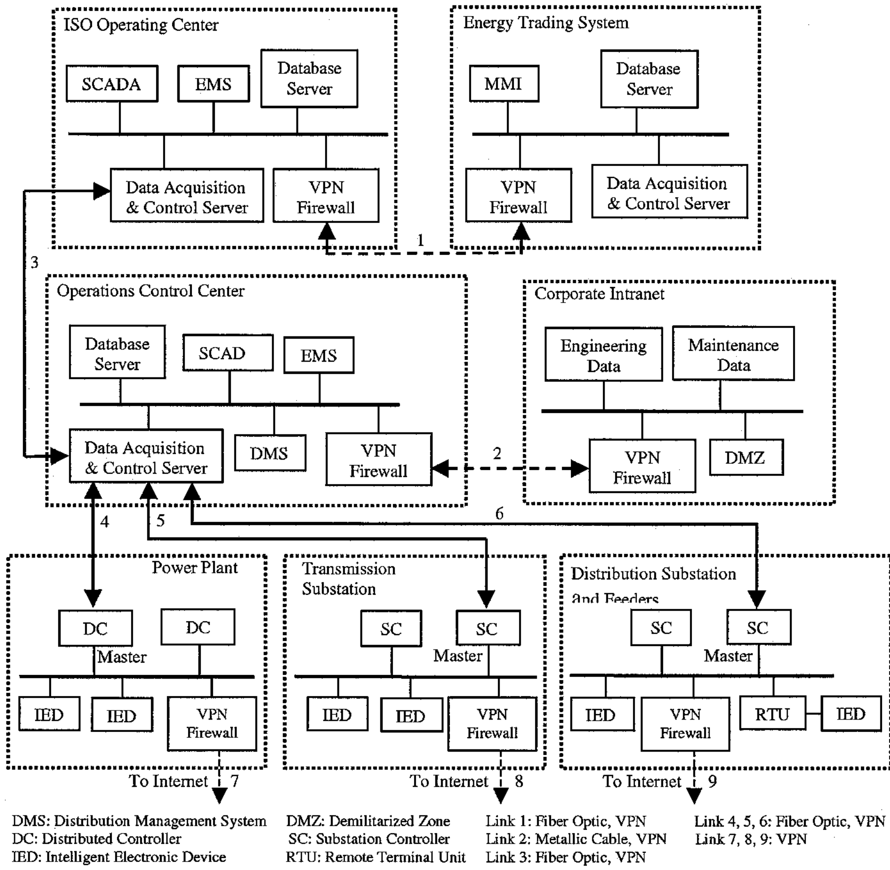


Fig. 1. Proposed information architecture.

operating center, and from ISO operating center to ETS. The demilitarized zone (DMZ) [12] in the corporate intranet is a specific area allowing external partners and customers to access needed information without sacrificing the security of the control center. This is similar to the concept of an "extranet." The load sharing mechanism provides a possible solution for the presence of control system faults and/or large changes in computational loads.

IV. Fault-Tolerant Design and Reliability Studies

The real-time operational and control system of power systems is modeled and analyzed with various redundancy configurations using HIMAP software package [2], for practical values of component failure rates and repair rates. HIMAP is a powerful modeling and analysis tool that allows the designer to specify the system as a fault tree, a fault tree with component repairs, a Markov chain, or a Petrinet. We studied the reliability of the following fault-tolerance designs: 1) operational and control system with varying computing and/or communication redundancies, and 2) operational and control system with different fault-tolerant designs for backup control center. The studies have been carried out with and without taking into account the repair rate. We assumed that the component failure rates are fixed, and the failures are independent, i.e., fault on one component does not induce a fault on another component.

A. Computing and Communication Redundancy Design

For modeling the control center—substation interconnected control system, we assume the control center without fault-tolerance consists of one information/communication bus and two servers with the bus connecting the servers (one SCADA data acquisition server and one EMS database server). The control center is said to have failed if one of the bus, SCADA server, or EMS server have failed. Each substation without fault-tolerance consists of one bus and one server. Each substation is connected to the control center using a wide-area communication link. In our studies, we make the following realistic assumption on the reliabilities of the various system components: control center server has the highest reliability, and then control center and substation bus, followed by substation server, and the last one is the wide area communication link which has the lowest reliability among all the components. The repair rates for computing systems (servers and bus) are assumed to be lower than the repair rate of communication system (wide-area links).

We study four configurations:

1) without redundancy;
2) with wide-area communication redundancy (1 primary + 1 backup link);
3) with computer system redundancy (1+1 bus and 2+2 server at control center; 1+1 bus 1+1 server at substations);
4) with full redundancy (union of design configurations 2 and 3).

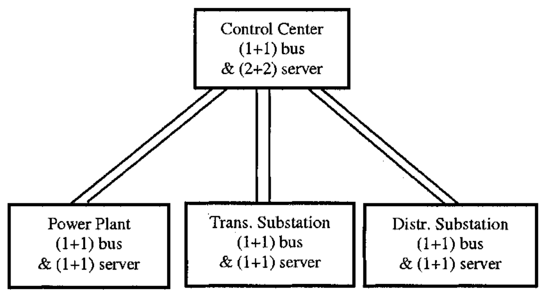
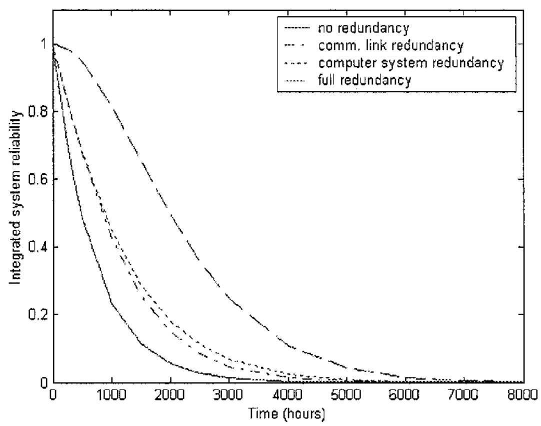
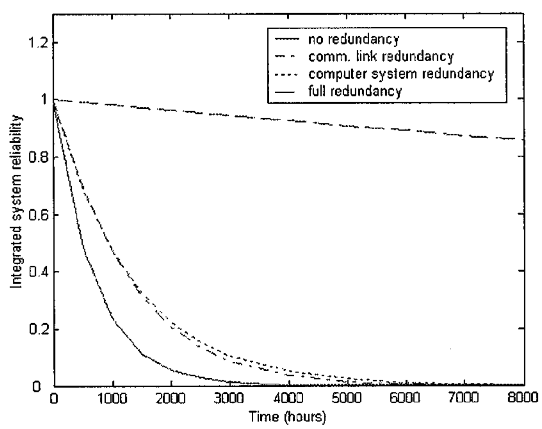


Fig. 2. Full redundancy configuration of operation and control system.



(a)



(b)

Fig. 3. (a) System reliability without repair. Failure rates: control center server (5E-5), Bus (7.5E-5), substation server (1E-4). Communication link (2.5E-4). (b) System reliability with repair. Failure rates are same as in Fig. 3(a). Repair rates: servers and bus (0.1). Communication link (0.02).

Fig. 2 shows the full redundancy configuration of the operation and control system.

Fig. 3(a) and (b) shows the results of the reliability study of the operation and control system without and with repair, respectively. From Fig. 3, it can be seen that full system redundancy configuration offers a very high reliability compared to other configurations. Furthermore, it can be observed that the system reliability can be significantly enhanced with repair.

B. Redundancy Configuration for Backup Control Center

Here, we propose four configurations for backup control centers and study their reliability. We will also evaluate the designs in terms of their load handling capability and cost. It is to be noted that the cost of a given configuration is proportional to the number of computing nodes and communications links it uses. The four backup configurations for connecting two substations to the control centers are as follows.

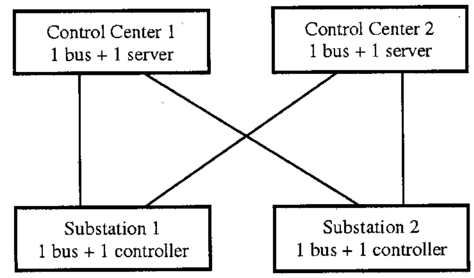
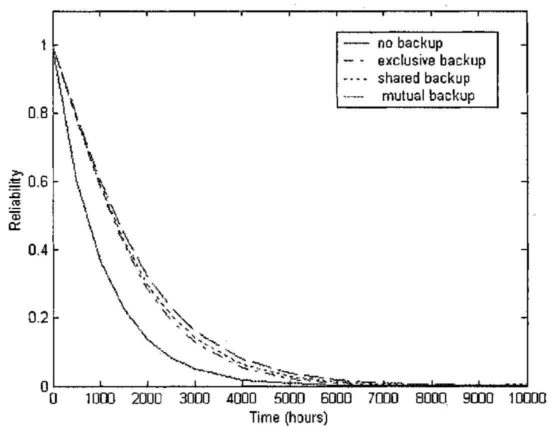


Fig. 4. Mutual backup control center configuration.

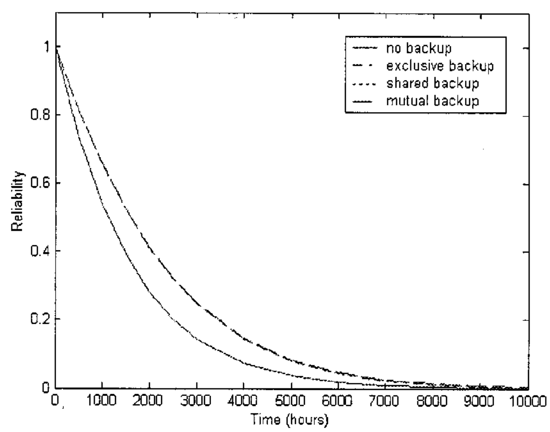
1) *No backup design*: Each substation is connected to only one control center. Here, the number of substations and control centers are 2 and 2, respectively.
2) *Exclusive backup design*: Each substation is connected to a primary control center and an "exclusive" backup control center. Here, the number of substations and control centers are 2 and 4, respectively.
3) *Shared backup design*: Each substation is connected to a primary control center and a "shared" backup control center. That is, the backup control center is being configured as a backup for two substations. Here, the number of substations and control centers are 2 and 3, respectively.
4) *Mutual backup design*: Each substation has a primary control center that is also being configured as the backup control center for the other substation. Here, the number of substations and control centers are 2 and 2, respectively. Fig. 4 shows the mutual backup configuration.

Fig. 5(a) and (b) shows the results of the reliability study for these four backup center designs. From Fig. 5, it can be observed that all the three fault-tolerant backup configurations indeed improve the overall system reliability, while the reliability of mutual backup configuration is the best with the least redundancy employed, and the reliability of exclusive backup configuration is the worst with the most redundancy employed. This study shows that higher redundancy does not necessarily offer high reliability. Therefore, the fault-tolerant configuration plays a crucial role in determining the overall reliability of the system as evident from our studies.

It is important to point out that the difference in reliability among the three fault-tolerant configurations is very small for the failure rates studied; this is especially true when the reliability of subsystems is very high. Moreover, higher redundancy means higher service level with the presence of "certain failure scenarios." For example, if both control centers fail, then the mutual backup can serve no applications, while shared backup with 50% the exclusive backup with 100% service; if one control center fails, then the mutual backup can serve 50% applications, while shared backup with 100% service and the exclusive with 100% service. Of course, higher redundancy also means higher cost.



(a)



(b)

Fig. 5. (a) System reliability without repair. 1 Server and 1 Bus in both control center and substation. Failure rate of components: 1E-5. (b) System reliability without repair. (1+1) Server in both control center and substation. Failure rate of components: 1E-5.

V. Conclusions

The proposed information architecture is capable of providing timely, secure, reliable information exchange among various entities in the system and is also scalable. The distributed nature of the computation in the proposed architecture reduces the burden on the higher level computer systems through data aggregation, providing better operation and restoration guidelines for operators with more relevant and critical information. The proposed information architecture can overcome most of the deficiencies of the current communication and information systems, it will promote the process of data integration and lead to standardization of data exchange for all power system entities.

Reliability analysis of the different redundancy configurations indicates that for computation and communication redundancy design, high component failure rate implies lower system reliability, while the fully redundant system can use less reliable components without sacrificing much system reliability with repairable components. The reliabilities provided by the three backup control center schemes are very close with highly reliable subsystems, but schemes with higher redundancy can provide better service level with more cost.

Our future work will focus on the reliability studies of operation and control system under common-mode failure model, hidden failure analysis, and techniques for intrusion detection and infrastructure security.

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