Impacts of Information and Communication Failures on Optimal Power System Operation

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Abstract— **This paper focuses on recognizing the ways in which information and communication network failures cause a loss of control over a power system's operation. Using numerical evidence, it also assesses the specific impacts of such failures on the optimal operation of a power system. Optimal power flow (OPF) is the most prominent method for implementing optimal operation. In OPF, it is assumed that all power appliances are accessible through the communication and information network, and all power devices are set as the output of OPF; nevertheless, the loss of control and operation of the power system's apparatuses may seriously impact the real-time operation of the bulk power system. The control and operation of the power system is dedicated to a modern communication network, in that intelligent electronic devices (IEDs) are connected to apparatuses of the power network. Data communication among IEDs enables both automatic and remote manual control of the power system. Although such a network offers new advantages and possibilities not previously achievable, it intrinsically has its own source of failures, such as the failure of physical components, loss of integrity, software failures and data communication faults.**

Index Terms— **Communication networks, failures, optimal power flow (OPF).**

I. Introduction

THE incorporation and application of real-time communications in power systems enable the dynamic flow of both power and information to accommodate the efficient delivery of power system services [1]. Power system operation takes advantage of data communication among power system apparatuses to transfer the power from the source to the end-user reliably and optimally [2].

Optimal power flow (OPF) is the most prevalent method by which to find the power system's operating point. In general, OPF is an optimization problem based on the power system's power flow solution [3]. Power flow is a process by which the amount of voltage and the angles of all buses of the power system are calculated when generations and loads are given. Compared with power flow, the OPF algorithm aims to find the steady-state operating point that optimizes the objective function while fulfilling power flow equations and all network requirements and constrains [4]. Objective functions can be either minimizing generation costs or maximizing benefits [3]. Network requirements for a power system encompass all logical and physical constrains, such as the capability curve of the generators, and the capacity and bus voltage limits of the transmission lines.

Coordinating the power system with the OPF results, however, requires the availability of not only generation units, capacitor banks, transmission lines and circuit breakers, but also the information and communication network [5]. Nonetheless, OPF presumes that such a result can be implemented with a probability equal to one, implicitly supposing that the entire information and communication network always works perfectly [2]. It is also infers that all power appliances are accessible through the communication and information network and that all power devices are assigned as the output of OPF.

In actuality, the vulnerability of the electrical infrastructure is increasing due to the complexity of controls and significant interdependency with information and communication systems [6]. Failure modes of the power system have been studied fully, and remedial actions are well developed. Escalating numbers of smart grid devices and communication networks will introduce modes and consequences of failure that are new to network coordinators. The loss of control and operation of the physical and logical components may seriously impact the power system's operation. These impacts may be localized to an individual load or extended to an entire balancing area [7].

The control and operation of the power system is dedicated to a modern communication network, in that intelligent electronic devices (IEDs) are connected to the power network's apparatuses. Data communication among IEDs enables both automatic and remote manual control of the power system [8]. Although such a network offers new advantages and possibilities not previously achievable, it intrinsically has its own source of failures, such as the failure of IEDs, loss of network integrity, software failures and data communication faults [7].

This paper focuses on recognizing the means by which information and communication network failures cause a loss of control over the operation of a power system. An OPF formulation is presented that intends to minimize system operating costs. The ability of failures to alter the feasible design space of the OPF is investigated, and the specific impacts of failures on power system operation are assessed using numerical evidence. in the paper also investigates how communication and information network failures cause the

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system's operating point to fall short of optimal. Failure to dispatch a unit, failure to adjust the automatic curtailment of adjustable loads and the loss of control of the entire network are investigated and discussed as three possible failure modes.

II. Centralized Operation of Power Systems

Operating requirements usually demand a balance between the generated power and the demand load according to certain criteria. Optimal operation intends to deploy all available assets to satisfy the requirement of minimum cost or maximum benefit. In the smart grid environment, this optimal decision is delivered to all physical power devices through an information and communication network. The key challenge for power system operation in a smart grid infrastructure is to integrate smart grid devices and communication networks in order to obtain optimal results. Careful study is required to predict the impact and consequences of any failures in these smart appliances. In the following subsection, the concept of OPF is introduced, and the required communication infrastructure is discussed.

A. Optimal Power Flow

The OPF algorithm is an optimization problem that aims to find the power system's best operating point regarding an objective function. While optimizing the objective function, the OPF simultaneously solves the power flow equations and keeps the operating conditions within specific constraints [3].

OPF schemes can be either centralized or distributed depending on the network's structure and the relationship among devices. In centralized OPF, all information is collected and analyzed in a central unit. The substantial difference between centralized and distributed schemes is that in the former, an individual problem is solved, and all network participants follow that solution, while in the latter, multiple decision makers solve their own optimization problems with customized cost functions and constraints. Classical optimization methods are well suited to solve OPF in centralized environments; however, distributed environments demand more sophisticated methods, such as game theory, stochastic programming and dynamic programming [9]. From a communication perspective, in centralized operation, each individual device requires only bidirectional communication with the server; however, in distributed systems, each IED must communicate directly with a subset of peer IEDs in order to take action. Therefore, communication in a distributed system is more important and complex than in a centralized system, and the failure of the communication system impacts the operation of the power system more severely.

In this paper, centralized power system operation is studied. Thus, a unique server runs the optimization problem and provides the generation, load adjustment and status of breakers to the generation units, end-users and circuit breakers, respectively. Here, the objective function of the OPF problem is to minimize operating cost, which is a sum of the cost of the power provided by the generation units and the load shedding cost.

$$Min. \quad C=\sum_{\forall j} Cost(P_j)+\sum_{k\in load} Cost(P_{sk}) \tag{1}$$

Subject to:

$$P_{gi}-P_{di}=P_i(\theta_i,V_i) \quad \forall i\in bus \tag{2}$$

$$Q_{gi}+Q_{ci}-Q_{di}=Q_i(\theta_i,V_i) \quad \forall i\in bus \tag{3}$$

$$P_{gj}^{min}\le P_{gj}\le P_{gj}^{max} \quad \forall j\in generator \tag{4}$$

$$Q_{gj}^{min}\le Q_{gj}\le Q_{gj}^{max} \quad \forall j\in generator \tag{5}$$

$$Q_{cj}^{min}\le Q_{cj}\le Q_{cj}^{max} \quad \forall j\in capacitor\,bank \tag{6}$$

$$P_{dk}=P_{dk}^{prim}-P_{sk} \quad \forall k\in load \tag{7}$$

$$P_{sk}\le P_{sk}^{max} \quad \forall k\in load \tag{8}$$

$$V_i^{min}\le V_i\le V_i^{max} \quad \forall i\in bus \tag{9}$$

$$\left|S_{ij}(V,\theta)\right|\le S_{ij}^{max} \quad \forall i\ j\in bus \tag{10}$$

where P_{gi}, Q_{gi} stand for the active and reactive power generated at the i^{th} bus, respectively. Likewise, P_{di}, Q_{di} are the active and reactive power demand at the i^{th} bus, and Q_{ci} is the reactive power generated by the capacitor located at the i^{th} bus. P_{dk}^{prim} is primarily a value of the real power consumed by the k^{th} load. P_{dk} is the real power demand of the k^{th} load used in power flow equations. P_{sk} is the amount of load shedding of the k^{th} load. V_i is the voltage magnitude of bus *I*, θ_i is the angle of bus *i* and S_{ij} is the MVA of the line between buses *i* and *j*.

In the above OPF formulation, (2) and (3) are active and reactive power flow equations. Limits to the amounts of active and reactive power provided by the generation units and the reactive power produced by the capacitors are imposed by (4)-(6). Equations (7) and (8) are load shedding restrictions. Finally, (9) and (10) relate to the limits of bus voltage and power flow in the transmission line, respectively.

B. Implementation of the Control Network for Operation

In order to operate the power system successfully, communication networks carry out various tasks. The primary tasks of a communication and information network are to protect, control and operate the power system. Digital communication networks usually are categorized into one of the following three levels:

- LANs: Local area networks (LAN) usually are implemented in buildings in which the various pieces of equipment are situated close to each other. LANs typically connect workstations, personal computers, printers, servers and other devices. In a LAN, communication is based on the MAC address, a constant code for each network appliance. Switches also constitute key elements of communication.
- MAN: A metropolitan area network (MAN) is a large computer network that usually spans a number of buildings

and interconnects a number of LANs through a high-capacity backbone technology. For example, a large power plant may use a MAN to integrate all units, the substation and the control room and to interconnect all LANs with fiber optic technology.

- WAN: Wide area networks (WAN) apply to data communication networks that cover geographically wide areas; they generally connect smaller MANs and LANs. For applications in wider areas, such as wide area monitoring, devices usually use WAN to connect to other devices located in other regions.

A typical digital communication network consists of intelligent electronic devices (IED), a server, a human machine interface (HMI), network switches, network connections, and other apparatuses. IEDs, acting as interface devices between the power network and the communication network, include measuring units, protective relays, and controllers. IEDs collect data from the electrical equipment and send them to the server; they also apply the commands received from HMIs to the electrical equipment. Network connections create paths for linking IEDs together. Network switches select paths along which to transfer information inside the communication network through network connections [10].

A simple power system and its corresponding communication network, shown in Figs. 1 and 2, are used to exemplify and clarify the implementation of optimal power system operation. The power system has six buses, three generation units, two critical loads, and one adjustable load located at bus 4. It also has a specially designed communication network that connects data and provides peer-to-peer communication among IEDs. The communication network is a star-wired ring topology Ethernet network to which devices are integrated through switches. Ethernet is the most popular LAN architecture in the world due to its flexibility. Several architectures, such as star, ring and hybrid schemes, can be implemented in Ethernet networks [11].

A centralized control and operation scheme is considered for the network shown in Fig. 1. All network information is collected in the server, and the server periodically executes the optimal operation problem. The server is the main component of that network, and arithmetic and logical subroutines are performed on it. In a centralized configuration, the availability of the server is vital; its failure will halt the entire network [12]. Thus, redundancy in servers and their integration architectures is critical. In Fig. 2, SR is a single server connected to redundant switches through two unshielded twisted pair (UTP) cables. The ring topology used here offers redundant paths from two sides of the loop in order to mitigate the risk of switches malfunctioning or not functioning at all.

The optimization problem solved in the server provides information regarding the amounts of both the generation of each generating unit and the load shedding for each load point, if available. Based on the results of the optimization problem, proper commands are issued to open/close the breakers and adjust the generation units and adjustable loads.

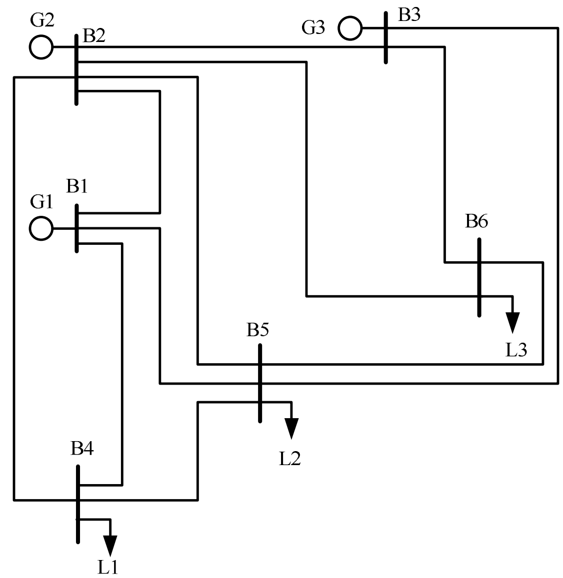

Fig. 1. Power network schematic diagram

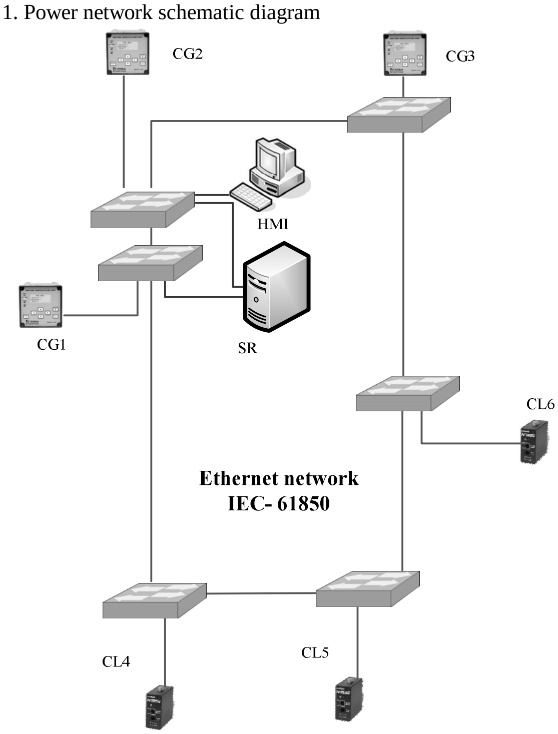

Fig. 2. Communication network schematic diagram

III. Degraded Operation under Loss of Control

From a power system standpoint, information and data are gathered from multiple distributed points, such as generation units, substations, distribution systems and load points. This information is available from various digital devices installed along the power system [1]. Integrated smart grid devices and communication networks, both hardware and software, increase the complexity of the power network and may have various impacts on different parts of the system. The failure of any integrated hardware or software may cause a situation known as *Loss of Control*, which can emerge in different forms, such as:

- Inability to open and close circuit breakers;

- Inability to send generation request signals to generation units;
- Inability to send load adjustment signals to adjustable load units;
- Inability to communicate with control center unit.

Communication network device failures might cause a loss of control over some variables involved in a power system's operation. Failures change the design variables of the optimization problem and therefore change the objective function and optimization constraints. Consequently, the feasible design space of the optimization problem might be altered due to failures inside the communication network. Changes in the design space might result in a less than optimal power system operating point. In order to amend the OPF based on new conditions, some additional conditions must be added to the optimization problem, as will be illustrated.

Equations (2) through (10) delineate the feasible design space (Ω_0) of the OPF problem. Solving this optimization problem yields the minimum accessible value for the objective function, ω_{opt}. The definition of the optimality of point ω_{opt} immediately results in a situation in which, if any point ω_0 satisfies (2) to (10) and belongs to Ω, then:

$$\forall \omega_0 \in \Omega_0 :: C(\omega_{opt}) \le C(\omega_0) \quad (11)$$

In other words, if ω_0 is found such that $C(\omega_{opt}) > C(\omega_0)$, then ω_0 cannot be inside the Ω_0:

$$\exists \omega_0 \mid C(\omega_0) < C(\omega_{opt}) \Rightarrow \omega_0 \notin \Omega_0 \quad (12)$$

As Fig. 3 shows, failures in the control network can change the feasible design space Ω_0 to the new, smaller design spaces (Ω_1 and Ω_2).

$$\Omega_0 \xrightarrow{\Phi_1} \Omega_1 \quad (13)$$

$$\Omega_0 \xrightarrow{\Phi_2} \Omega_2 \quad (14)$$

where Ω_0 is the feasible design space; and Ω_1 and Ω_2 are the modified feasible design states caused by failures Φ_1 and Φ_2, respectively. When the entire communication functions properly, ω_{opt} is the optimal operating point of the power system. If failure Φ_1 occurs, the feasible design space changes to Ω_1, but ω_{opt} remains inside Ω_1. Hence, failure Φ_1 does not change the optimal solution. If failure Φ_2 occurs, the feasible design space changes to Ω_2. As Fig. 3 depicts, ω_{opt} is not inside Ω_2. Therefore, based on (12), ω_{opt} is no longer a feasible solution, and the optimization problem does not converge to it. Assuming that the optimal point of Ω_2 is ω'_{opt}, (11) results that $C(\omega_{opt}) \le C(\omega'_{opt})$. The resulting degradation improves from Φ_2, moving the optimal solution from ω_{opt} to ω'_{opt}, calculated as:

$$\delta_{\Phi_2} = \frac{C(\omega'_{opt}) - C(\omega_{opt})}{C(\omega_{opt})} \quad (15)$$

where *C(ω)* is the cost of point *ω*, and *δ* is the degradation from the optimum operating cost. If the feasible design space does not change, or if ω_{opt} remains inside the feasible design space, the value of δ is zero. For the failure Φ_1, $\delta_{\Phi_1} = 0$.

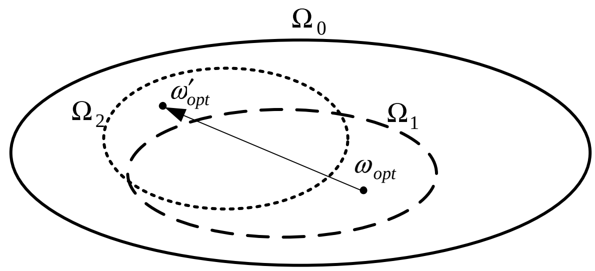

Fig. 3. Modified feasible design space under failures

In the following subsections, three different types of failures are discussed, and in each case, the impact of the failure on optimal operation is investigated.

A. Inability to Dispatch a Generation Unit

In this case, the optimization problem finds that a group of generation units generates a certain amount of power to perform OPF with minimum cost. Nevertheless, one or more generation units are not able to be dispatched. This situation may arise for many reasons, including:

- Dedicated bay control unit fails and is not able to close the corresponding breaker of the generation unit.
- Communication network loses its integrity due to a failure inside the network.
- Trip/close signals do not transfer correctly to the correct device, possibly because of the incorrect configuration of network devices or address conflicts among devices.

In such cases, it is assumed that when the control of an intrinsically dispatchable unit, e.g., a thermal unit, is lost, it must be turned off. Therefore, the following equation is added to (2)-(10):

$$P_{G,n} = 0 \quad (16)$$

B. Inability to Adjust an Adjustable Load

The steady-state operation of a power system entails a balance between generation and load. This balance can be maintained through a combination of power generation and load reduction, with the goal of cost minimization. In practice, part of a non-critical load can be considered an adjustable load and can go through the automatic demand response program to alleviate the peak load and flatten the load profile, or to minimize operating costs when overcoming the demand energy is quite expensive due to the necessity of turning on another fast-response, low-capacity generating unit [13].

Load shedding and demand response normally are executed and supervised through the energy management controller of the local network coordinator, e.g., microgrid [13]. In the smart grid, an automatic demand response (ADR) is a novel context that enables network coordinators to adjust a portion of each load, which can be de-energized remotely in a certain amount of time. Network coordinators have permission and access to curtail certain non-critical loads. Thus, OPF includes the load shedding price and the amount of adjustable load as two input variables (See (1), (7).).

However, automatic load shedding requires a bidirectional communication infrastructure to send the “turn-off” commands to loads, to send back a permissive signal and to acknowledge the load shedding to the network coordinators. If the communication network cannot deliver the “turn-off” command to recipients or return the permissive and acknowledgement signals, it will not be able to de-energize the adjustable load; thus, the network coordinator will have to repeat the OPF under new circumstances to find another feasible result in the modified design space. So, an amended OPF would have to be performed with the following additional requirement:

$$P_{S,n} = 0 \quad (17)$$

where $P_{S,n}$ is the load curtailment in bus *n*, and *n* is the index of the bus in which the load adjustment controller failed.

C. Loss of Operation

Under centralized control, the power system is vulnerable to server failures involving the server’s inability to send any signals to the generating units and adjustable loads. However, self-control generating units are key to maintaining the generation-load balance [2]. Local control units regulate the voltage of the output terminal by varying the output reactive power.

To amend the OPF, all generation units are set to their previous values. Only self-control generation units remain as design variables. Controlling adjustable loads is not possible.

IV. Case Study

In this section, a simple numerical calculation for the power system, depicted in Fig. 1, and its dedicated communication network, depicted in Fig. 2, is demonstrated.

A. Input Data

Table I lists the impedances of branches among nodes of the power system shown in Fig. 1. The voltage level of the system is presumed to be 33kV. Table II lists basic information about the generation units. Pr, Qr represent the maximum active and reactive power of the generation units, respectively. Also, the cost functions of the generation units are assumed to be second-order polynomials. If generation unit (*i*) has three constants (a_i, b_i, c_i), then the cost function equals $C_i = a_i + b_i p_i + c_i p_i^2$.

Assumed specifications of the proposed power system’s loads are listed in Table III. Based on the demand response contract, 2MW of L1 is assumed to be an adjustable load that the network coordinator can de-energize upon request.

Four different cases are studied. In the first case, all elements of the communication network function properly. In cases 2, 3 and 4, a failure in some element of the communication network causes a loss of control over the generation unit, over an adjustable load and over the entire network, respectively. In all cases, the sequential quadratic programming method is used to solve the nonlinear constrained optimization problem.

TABLE I
BRANCH DATA

From Node	To Node	R_i+jX_i (p.u.)	From Node	To Node	R_i+jX_i (p.u.)
1	2	0.10+j0.20	2	6	0.07+j0.20
1	4	0.05+j0.20	3	5	0.12+j026
1	5	0.08+j0.30	3	6	0.02+j0.10
2	3	0.05+j0.25	4	5	0.20+j0.40
2	4	0.05+j0.10	5	6	0.10+j0.30
2	5	0.10+j0.30			

TABLE II
GENERATION UNIT DATA

Load Name	Connected to Bus	Pr (MW)	Qr (MW)	Cost Function Coeff		
				a	b	c
G1	1	7	6	20	7.5	0.007
G2	2	4	5	29	3.2	0.003
G3	3	4	5	34	6.5	0.004

TABLE III
LOAD DATA

Load Name	# of Bus	Critical Load (MW)	Adjustable Load (MW)
L_1	4	1+j3	2
L_2	5	3+j3	-
L_3	6	3+j3	-

Case 1: *All elements function properly:* This case is the base-case result and is used to calculate δ for the other cases. Table I shows the amount of real and reactive power of the three generation units and the load shedding of L_2 to have minimum operating costs.

TABLE IV
OPERATION IN THE BASE CASE NETWORK

Ω_i	P_1+jQ_1 (MW)	P_2+jQ_2 (MW)	P_3+jQ_3 (MW)	Ls_2 (MW)	$C(\Omega_i)$
Base Case	0	4+j5	3.14+j4.3	2	107.3

Case 2: *Inability to dispatch a generation unit:* According to (16), the generation unit is turned off, and its power output is zero. On the basis of this assumption, results of the system’s optimal operation are found as recorded in Table V.

TABLE V
OPERATION WHEN A GENERATION LOSES ITS DISPATCHABILITY

Ω_i	P_1+jQ_1 (MW)	P_2+jQ_2 (MW)	P_3+jQ_3 (MW)	Ls_2 (MW)	$C(\Omega_i)$
G1 out	-	4+j5	3.14+4.4	2	107.3
G2 out	3.1+j4.4	-	4+j5	2	134.6
G3 out	3.2+j4.5	4+j5	-	2	116.6

Case 3: *Loss of control over an adjustable load:* In Fig. 1, if communication between the load controller CL5 and the Server SE is obstructed, then the SE would not be able to curtail the L_2 as 0.2 p.u. (as shown in Table III). To amend the

OPF, (17) is added. Table VI shows the observed results based on the amended OPF. In this case, the G1, which is an expensive unit, must generate the power.

TABLE VI
OPERATION WHEN SERVER CANNOT CURTAIL LOAD L_2

Ω_i	P_1+jQ_1 (MW)	P_2+jQ_2 (MW)	P_3+jQ_3 (MW)	Ls_2 (MW)	$C(\Omega_i)$
L1	1.4+j2.4	4+j3.6	4+j3.14	0	130.4

Case 4: *Loss of control over the entire network:* In the final case, the complete loss of operation is investigated. It is arbitrarily assumed that G1, G2 are generating 50% of their maximum capacity.

TABLE VII
OPERATION WHEN SERVER CANNOT CONTROL THE SYSTEM

Ω_i	P_1+jQ_1 (MW)	P_2+jQ_2 (MW)	P_3+jQ_3 (MW)	Ls_2 (MW)	$C(\Omega_i)$
Loss of control	2.6+j2.4	2+j3.5	2.5+j3.5	0	152.2

B. Comparison and Discussion

Table VIII summarizes the operating costs in all studied states. The results presented in Table VIII show that the operating failure in G1 did not change the optimum solution for OPF; however, operating failures in G2 and G3 degraded the operating costs by approximately 25% and 9%, respectively. In case 3, when L_2 could not be controlled, the optimal operation degraded by approximately 22%. A server failure is the worst of these scenarios because of the associated lack of control over dispatchable units and adjustable loads.

TABLE VIII
OPERATION IN THE BASE CASE NETWORK

No.	Case	Operating Cost	δ (Degradation)
1	Base Case	107.3	-
2	G1 out	107.3	0%
3	G2 out	134.6	25%
4	G3 out	116.6	9%
5	Load shedding	130.4	22%
6	Loss of control	152.2	42%

V. CONCLUSION

The key challenge for smart grid initiatives is to increase the penetration of smart technologies into the power system while retaining reliable and cost-effective operation.

The impact of the smart grid on the operation of the power system has yet to be determined. This paper investigated the impact of communication and information network failures on the power system's operation and proposed an index to measure degradation from the optimal cost. Three types of failure were studied, and their degradation was calculated.

This study can serve as a benchmark for comparing different communication network architectures on the power system's operation, revealing the best one and diminishing the risk of the communication network experiencing mal-operation.

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VII. BIOGRAPHIES

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