On the Role of Power-Grid and Communication-System Interdependencies on Cascading Failures

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***Abstract*—The mutual functional dependencies between a power grid and its supporting communication system demands that smart grids be studied as a single, electric-cyber system, especially when the reliability of the system is of concern. In this paper, we consider two functional dependencies of power grids on communication networks, namely, state estimation and transmission of critical control signals. Conversely, we consider the dependency of the communication system on the power grid for its power supply. By embedding the coupling effects in the DC power-flow optimization problem, we model the dynamics of cascading failures using successive changes in states of both systems. We show that as the level of dependencies increases severe cascading behavior is observed. Further, we show how the connectivity of the communication system affects the reliability of the power grid.**

***Index Terms*—Power Grids, Communication Systems, Interdependency, Cascading Failures, State Estimation**

I. Introduction

As we move toward a smarter grid the role of the communication network becomes prominent in efficient and reliable operation of the power grid. Power grids use modern communication techniques to communicate measurements and control signals. Due to the extensive integration of the power grid and its communication system, it is critical to study smart grids as a single, electric-cyber system, especially when the reliability of the system is of concern [1].

Despite the fact that today's power grids are reliable and the control and communication systems have been deployed to further enhance their reliability, historical data shows that power grids are yet conspicuously vulnerable to cascading failures and they have experienced large blackouts at an enormous cost. Cascading failures can be defined as successive interdependent component failures in the system. The historical data of the August 2003 blackout occurred in Eastern Interconnection suggests that failures in the information and control systems contribute to cascading failures [2]. Moreover, in the blackout of Italy in September 2003 the shutdown of power stations resulted in failures in the Internet communication network [3]. The available historical data suggests that the power system and its communication network have bi-directional functional dependencies. While such dependencies can increase the reliability and efficiency of both systems, it can also increase the risk of failures in the individual systems. In this paper, we consider the functional dependencies that lead to propagation of failures between the two systems. Considering such dependencies are specifically important in analyzing the reliability of the whole system.

Due to the intrinsic complexities involved in the modeling of interactions between interdependent systems, modeling the coupled power-grids and communication systems has not been widely studied in the literature. Here, to simplify the analysis, we consider two key functional dependencies of power grids on the communication network, namely, state estimation and transmission of control signals for remote load shedding. Conversely, we consider the dependency of the communication system on the power grid for its power supply.

We build upon our earlier work [4] to capture the effects of bi-directional, functional dependencies between the two systems using the DC power-flow [5] optimization problem. Using this approach, we model the dynamics of cascading failures using successive changes in the states of both systems due to propagation of the effects of failures between the two systems. We further study the extent to which the coupling between the two systems affects the reliability of the whole system. We show that as the level of coupling between the two systems increases failures propagate faster in the individual systems and severe cascading behavior occurs. We argue that studying the power grid individually may not clearly illustrate the reliability of the power grid in the case of contingencies due to the actual dependency of the two systems on each other to mitigate the effects of contingencies. Further, we investigate how the connectivity of the communication system affects the reliability of the power grid. One can use the approach presented here to characterize the criticality of nodes and links in communication networks. These findings have practical applications in identifying the critical regions of the communication network that should be strengthened by, for example, adding more links so as to enhance the robustness of the power grid to cascading failures.

II. Related work

The majority of research in cascading failures in smart grids have focused on single, non-interacting power grids. The examples of such efforts are [6], [7] (see [8] for a review). Recently, researchers have also exerted considerable efforts in studying smart grid communications [9]. A considerable subset of such efforts emphasize only on the distribution level; however, as the large blackouts and cascading failures are attributes of the transmission network, in this paper we study the communication system in the transmission level [10]. Besides individual-system studies, there have been few efforts in modeling the interdependent power grids and communication systems. We categorize such efforts into three classes as described bellow.

Graph-based models– These models consider the graphs representing the interdependent systems. They study the effects of graph characteristics, such as degree distributions and the clustering coefficient of the graph on cascading failures using tools such as graph theory and percolation theory. Examples of such models are [3], [11], [12].

Hybrid simulations– These approaches aim to build accurate synchronization mechanisms, between power-system simulators and communication-system simulators. The challenge here is to synchronize the continuous time power-system simulators with the discrete-event communication-system simulators. Examples of hybrid-simulation approaches are [13] and [14].

Effect driven models– These approaches concentrate on a specific effect of the control and communication system on the power grid and model the effects directly in the power-grid dynamics and equations. Examples of such models include [15] and [4]. In [15], for example, the role of information exchange is investigated in the transient stability of generators and the loss of generator synchronism in power grids. In our earlier work [4], we showed the effects of communication irregularities in transmitting the load-shedding control signals on cascading failures. The effects of these irregularities is embedded as a constraint in the power-flow optimization problem. Here, we extend our earlier work [4] to study the bi-directional interdependencies in the system.

III. Communication system characteristics

The control and communication systems of power grids are hierarchical systems, where the communication network for the transmission and distribution systems are two levels of such hierarchy. Power grids are also decomposed into regional sub-systems (including both the transmission and distribution systems) termed balancing authorities (BA). In this paper, we use the IEEE 118 bus system as the transmission system of our BA. Each BA has a primary control center (and a set of backup control centers) responsible for maintaining the stability of the region. We choose the marked substation shown in Fig. 1 as the control center of the IEEE 118 bus system. The control center monitors the system e.g., by employing supervisory control and data acquisition (SCADA) systems, and makes control decisions for the BA (e.g., finding solution to the optimal power flow distribution for the transmission system).

In this paper, we consider the communication network at the transmission level. We assume that power grid components utilize intelligent electronic devices (IEDs), which host the control and measurement agents. The control agents have actuators that enable the implementation of the remote control signals e.g., breaker tripping. Here, we assume that the control agents at substations implement remote load-shedding control signals by sending appropriate signals to the distribution network connected to them. We also assume that measurement agents measure the temperature of high voltage cables and send the measurements to the control center so that the control center has an estimate of the actual transmission capacity of the grid for safely utilization of the full grid capacity. The agents communicate with the control center using the communication network.

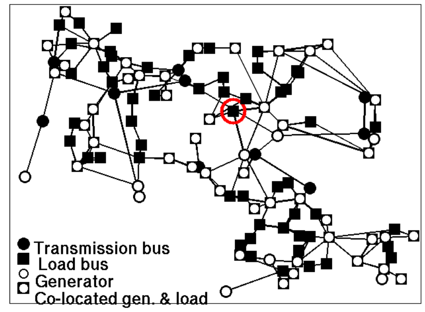


Fig. 1: The IEEE 118 bus system topology with its control center marked with a circle.

Various communication technologies have been recognized to be appropriate in supporting the communication network in the transmission level [9]. Depending on the technology and how they have been employed, the communication network may have different topologies. We consider the average degree of nodes in a topology as a measure of the connectivity of the network. We investigate the effects of the connectivity of the communication system on the reliability of the power grid by considering a set of candidate topologies. This set includes a network with the same topology as the power grid connectivity, termed the base topology, which is a communication network with a node at each substation and communication links along the transmission lines (e.g., due to employment of optical ground wires along the transmission lines). We also consider random variations of the base topology by generating two random sets of topologies based on the base topology; one set with randomly removed links while maintaining the connectivity (smaller average degree of nodes) and one set with randomly added links (larger average degree of nodes).

IV. Modeling Functional Interdependencies

A key solution in reacting to contingencies in power grids is to safely utilize the existing transmission capacity to its maximum in order to avoid over-curtailment of loads and limiting power delivery. Clearly, monitoring the transmission capacity is critical for carrying out this solution. A transmission line has a power-flow capacity that can be defined as the thermal limit, the voltage drop limit, or the steady-state stability limit [16]. In this paper, we consider the thermal limit of the line. The power-flow capacity of a transmission line may vary due to the temperature of the environment and weather conditions [17]. The measurement agents send the measured temperatures to the control center. Estimating the temperature from the measurements and accurately estimating the capacity of the transmission lines can help in reacting to emergency scenarios more efficiently. However, error in these estimations due to error, delay, and interruption in communication networks can result either in underutilization of resources or in overloading of lines, which can severely affect the reliability of the power grid. We consider the effects of overestimation of the transmission line capacity. For each line, we define $e \in [0,1]$ as the parameter quantifying the error in the estimated transmission capacity of the line. The amount of overestimation is $C^e = eC^a$, where C^a is the actual capacity of the line. Thus, the control center may overload the line as it erroneously assumes $C^a + eC^a$ for the line capacity. In this paper, we simply assume that e depends on the connectivity of the communication network and increases with the hop distance from the control center due to the delay.

The power grid also depends on the communication system for transmitting load-shedding control signals to substations in the case of contingencies. In [4], we showed the role of communication irregularities in implementing load shedding and their effects on cascading failures. For a load substation, we say the substation load is *controllable* ($c = 1$) if the load shedding control signal can reach its control agent through the communication network and is *uncontrollable* ($c = 0$) otherwise. The controllability of the loads at substations depends on the connectivity of the communication network.

Similarly to [3], we assume that a communication component fails probabilistically (with probability q) if the power component in its geographical proximity fails. This dependency leads to propagation of failures from the power system to the communication network.

V. System model and Flow distribution

Consider the transmission system of a power grid with n nodes (substations) interconnected by m_1 transmission lines. Suppose that functionality states of the lines are denoted by $\mathbf{R}^P = (R_1^P, R_2^P, ..., R_{m_1}^P)$, where $R_i^P = 0$ represents the state that the line is tripped, and $R_i^P = 1$ otherwise. We assume that the communication network has a node (router) at each substation of the transmission system. Communication nodes are interconnected by m_2 communication links with functionality states denoted by $\mathbf{R}^N = (R_1^N, R_2^N, ..., R_{m_2}^N)$. We represents the capacity estimation error of transmission lines by $\mathbf{E} = (e_1, e_2, ..., e_{m_1})$ and the controllability status of the substations by $\mathbf{C} = (c_1, c_2, ..., c_n)$. The interdependencies between the two systems result in a cycle in the propagation of the effects of failures between the systems (see Fig. 2). We embed such interdependencies in the DC power-flow optimization problem.

The DC power-flow equations [5] can be summarized as

$$F = AP, \tag{1}$$

where P is a power vector whose components are the input power of nodes in the grid (except the reference generator, P_0), F is a vector whose m_1 components are the power flow through the transmission lines, and A is a constant matrix whose elements can be calculated in terms of $\mathbf{R}^P$ and the impedance of the lines. This system of equations does not have a unique solution. Therefore, similarly to [7], in order to find the solution to this system we use a standard optimization approach with the objective of minimizing the simple cost function below:

$$Cost = \sum_{i \in \mathcal{G}} w^g{}_i g_i + \sum_{i \in \mathcal{L}} w^\ell{}_i \ell_i. \tag{2}$$

A solution to this optimization problem is the pair of g_i and ℓ_i values that minimize the above cost function. The sets $\mathcal{L}$ and $\mathcal{G}$ are the set of load buses and generator buses, respectively. In this function, $w^g{}_i$ and $w^\ell{}_i$ are positive values that represent the generation cost for every $i \in \mathcal{G}$ and the load-shedding price for every $i \in \mathcal{L}$, respectively. We assume a high price for load shedding so that a load is to be curtailed only when there is generation inadequacy or transmission capacity limitations. The constraints for this optimization, which capture the effects of the interdependencies between the power-grid and its communication network, are listed below.

(a) DC power flow equations: $F = AP$.
(b) Limits on the generators' power: $0 \le g_i \le G_i^{\max}$, $i \in \mathcal{G}$.
(c) Limits on the controllable loads: $c_i L_i \le \ell_i \le 0$, $i \in \mathcal{L}$.
(d) Limits on the power flow through the lines:
$|F_i| \le C_i^a + e_i C_i^a$ for $i \in \{1, ..., m_1\}$.
(e) Power balance constraints (power generated and consumed must be balanced): $\sum_{i \in \mathcal{G}} g_i + \sum_{i \in \mathcal{L}} (c_i \ell_i + (1 - c_i) L_i) = 0$.

Note that in the above formulation ℓ_is are negative and g_is are positive based on the definition and L_i is the demand at the load bus i. The solution to this optimization problem determines the amount of load shed and the power flow through the lines. If failures occur in the power transmission system, we assume that the control center redistributes the power in the grid by solving the above optimization problem. If the new power redistribution overloads lines, more failures will occur in the power grid, which may lead to failures in the communication system. Failures in the communication system affects the power flow redistribution decision at the control center through $\mathbf{E}$ and $\mathbf{C}$ and this cycle will go on until no more failures occur in the grid. The end of cascading failures can occur as a result of successful control actions or formation of the operational islands in the grid. To summarize, $\mathbf{R}^P = (R_1^P, R_2^P, ..., R_{m_1}^P)$ affects $\mathbf{R}^N = (R_1^N, R_2^N, ..., R_{m_2}^N)$ through q and conversely, $\mathbf{R}^N = (R_1^N, R_2^N, ..., R_{m_2}^N)$ affects $\mathbf{R}^P = (R_1^P, R_2^P, ..., R_{m_1}^P)$ through $\mathbf{C}$ and $\mathbf{E}$. Thus, cascading failures can be described by a sequence of successive changes of states of both systems.

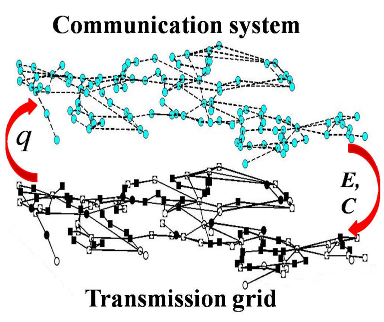
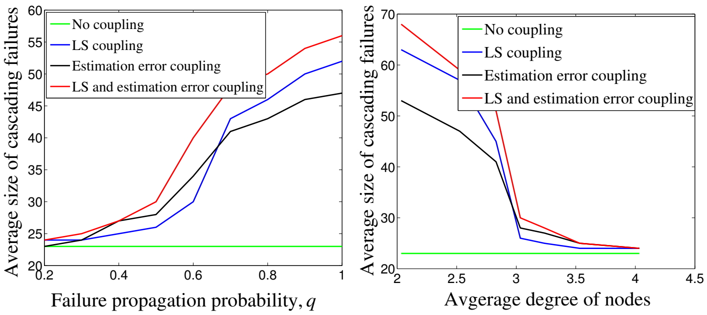


Fig. 2: Schematic depiction of the coupling effect between the power grid and its communication system.

VI. Results

We use MATPOWER [18], a package of MATLAB m-files, for solving the power-flow optimization problem introduced above and simulating cascading failures. We assume that the cascading failures are triggered by three random initial failures of transmission lines and their corresponding communication components. First, we consider various probabilities q for the propagation of failures to the communication system. This facilitates the modeling of various levels of the dependency of the communication system on the power grid. We also consider four scenarios representing different levels of dependencies of the power grid on the communication system. Such scenarios include no-coupling, coupling through capacity estimation error, coupling through the load-shedding controllability, and coupling through both of the last two effects. In the no-coupling scenario, the effects of failures do not propagate between the two systems. Note that considering the no-coupling is similar to considering cascading failures in the power grid alone while assuming perfect communications.



(a) (b)

Fig. 3: Average size of cascading failures (number of tripped lines) a) as a function of q and different levels of coupling between the power system and the communication network, and b) as a function of average degree of nodes in the communication network for $q = 0.5$.

In the coupling scenarios, failures propagate to communication systems with probability q. The results shown for each scenario are obtained by averaging the size of the cascading failures over 500 realizations. We measure the size of cascading failures using the number of tripped overloaded lines in the power grid. As expected, we observe in Fig. 3-a that the size of cascading failures increases with the level of coupling between the systems. Our observations confirm that accurate reliability analysis of coupled systems needs to consider both systems together. We also observe that coupling through load shedding is highly sensitive to connectivity of the communication system and the cascading behavior becomes severe as the communication system becomes disconnected.

Furthermore, from Fig. 3-b we observe that the connectivity of the communication network affects cascading failures in power grids. In the simulations, for each value of the average degree of nodes we used 20 randomly generated topologies with approximately the same average degree. The results of Fig. 3-b suggest for a critical value of average degree of nodes (approximately 3 in this example) for which the size of cascading failures drops sharply. We interpret this value as the minimum connectivity of communication network that can considerably reduce the risk of large cascading failures in the power grid. One can use this approach to identify the critical regions of the communication network that should be strengthened by adding more links so as to enhance the robustness of the power grid to cascading failures.

VII. Conclusions

In this paper, we argued that the bi-directional functional dependencies between the power grid and its communication system affect the reliability of the power grid and its cascading-failure dynamics. By embedding the interdependency effects in the DC power-flow optimization problem, we modeled the dynamics of cascading failures using successive changes in states of both systems. Using the presented model we showed that analyzing the power grid as an individual system may not adequately capture all aspects of its reliability. We conjectured that the level of coupling between the two systems affects the cascading-failure behavior in a substantial way. Moreover, we have shown that connectivity of the communication network, measured by the average degree of nodes, does affect the cascading behavior in the power grid also in a substantial way.

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