

# Impacts of Control and Communication System Vulnerabilities on Power Systems Under Contingencies

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**Abstract**—Modern power grids rely heavily on their control systems operating over communication networks to mitigate the effects of stresses in the grid. However, the cascading phenomenon and blackouts remain possible if the initial disturbances in the power grid are accompanied by other system vulnerabilities such as failures of the communication and control systems that transmit and implement critical control signals. Understanding the effects of such vulnerabilities are important in the design of future smart grids. In this paper the vulnerabilities in the control and communication system are coupled with the load shedding mechanism and their effects on power-grid cascading behavior are revealed by means of simulation. In particular, the cascading failure behavior of the grid is investigated considering the effects of failures in the control and communication systems, as well as the topological location of the failures.

**Index Terms**—Power system control, power system communication, vulnerabilities, cascading failures, load shedding

## I. INTRODUCTION

Control and communication systems are the key elements of reliable power grids. The design of these systems aims at enabling power grids to endure disturbances and mitigate their effects. However, the cascading phenomenon and blackouts may remain a threat to the reliability of power grids if the initial disturbances are accompanied by other vulnerabilities in these systems. Examples of such vulnerabilities include failures in the control systems which may cause problems in implementing critical control signals, communication system failures resulting in inability to transmit critical control signals, missing or uncertain information in decision making, and limitations dictated by physical components and/or marketing policies of the power grid, which can affect the ability to implement the control signals. Examples of sources of vulnerabilities in the control/communication systems are natural disasters and malicious physical or cyber attacks on these systems. Such scenarios may cause failures of communication components, such as optical fibers and communication routers, as well as failures of control agents of control systems. Failures of critical communication components can lead to loss of controllability and observability in the control system and may disable control agents.

The trend seen in recent decades in operating the grids close to their limits of transmission and generation capacities have

made the role of control systems more important than ever. As such, understanding the effects of vulnerabilities in the control systems and the communication systems that they rely on is important in the design of future smart grids. However, these effects has not been extensively studied to the best of our knowledge due to the challenges associated with coupling the models available for power grids and control/communication systems. Some of these efforts can be found in [1]–[3].

Load shedding is a critical control action when the system must be reconfigured to accommodate the disturbances on the power grid. It is the process of reducing certain amount of load with lower priority in a controlled way to maintain the stability of the remaining portion of system [4]. As a real example, some experts believe that if 0.4% of the load had been shed for 30 minutes, the widespread power outage in the Western United States on August 10th, 1996, could have been avoided [5].

In this paper we model the vulnerabilities in the control/communication systems (communication system failures, control system failures, and physical and policy-based limitations) simply by formulating an optimization problem for the load-shedding control with new constraints to capture these vulnerabilities. This approach relies on the direct modeling of control/communication system vulnerabilities within the load-shedding formulation. It is a simple and efficient approach for coupling the power grid with the control/communication systems without dealing with the complexities associated with integrating communication system and power-grid simulators. Our work reveals certain effects of the vulnerabilities in the control/communication systems on the cascading failure behavior of the power grid. In particular, we investigate the cascading failure behavior of the grid considering the effects of failures in the control/communication systems, as well as the topological location of the failures. Simulations show that vulnerabilities in the control/communication systems can increase the probability of large cascading failures initiated by small disturbances over the power grid. We will also show that the location and characteristics of the failures affect the cascading behaviors in the power grid.

The remainder of this paper is organized as follows. In Section II we will briefly review two categories of prior works that relate to this paper. The control and communi-

cation system structure is described in Section III and our model of vulnerabilities in the control/communication system using load-shedding formulation is also presented in the same section. In Section IV we present our simulation methodology, and in Section V we present the results on the effects of vulnerabilities in the control/communication systems on the cascading behavior of the grid. Finally, our conclusions are presented in Section VI.

## II. RELATED WORKS

In this section we review two categories of the works that are related to this paper. The first category is on the coupling between control/communication systems and power grids and the second category includes load-shedding mechanisms.

A communication system of any power grid aims to serve the control system, and they both help in enhancing the reliability of the power grid. Clearly, any degradation in the control/communication systems that serve the power grid is expected to negatively impact the reliability of power grids. The dependence of power grid's operation and reliability on control/communication systems has been receiving great attention recently due to its importance in designing future smart grids. A power grid and its communication system are commonly treated as coupled, interdependent networks. For example, Buldyrev *et al.* [6] modeled the power grid and its communication network as interdependent systems, where each node in the power grid has a corresponding node in the communication network. It is argued in [6] that for any pair of nodes, the functionality of one node depends on the functionality of the corresponding node in other network. Analytical solutions were presented on the critical fraction of nodes whose removal would result in cascading failures and a complete fragmentation of two interdependent networks [6]. Their approach is based on graph theory and does not capture the power system characteristics and power flows.

Generally, modeling and simulating the dynamics of power systems that are coupled with control/communication systems is challenging. Power system dynamic simulation is commonly modeled as a continuous time simulation, where the dynamics of the generation and load in the power grid follows general rules of electricity. Meanwhile, communication networks are usually modeled as discrete-event systems to account for the stochastic nature of packet generation and transmissions [2]. To analyze the coupled systems, hybrid simulation tools combining power system and communication-network simulation are needed. Certain hybrid schemes are available in [1]–[3]. Nataro *et al.* [1] provide a NS2/ADEVs implementation of the hybrid simulation scheme and study load-shedding scenarios to investigate the effect of bandwidth and base-line delay in the communication system on the network performance. As an improvement of the ADEVs approach, Lin *et al.* [2] proposed a co-simulation framework with an accurate synchronization mechanism between continuous-time and discrete event simulation. The proposed framework is used to improve the practical investigation of smart grids and evaluate wide-area measurement and control schemes. In [3], Hopkinson *et al.* present the electric power and communication

synchronizing simulator (EPOCHS). The effects of loss in the communication links on agent-based protection system is shown. The defined loss affects the information used to calculate the disturbance size and load-shedding amount as the control action. Communications bandwidth, loss, and latency are topics of high interest in modeling integrated power, control and communication systems. However, the focus of these works are on providing a simulation framework rather than discovering the effects of the interaction between these systems. Furthermore, to the best of our knowledge, the effects of failure and limitations in the control/communication systems have not been investigated in the cascading failure behavior of power grids.

In the case of contingencies in the power grid, the generators are re-dispatched to stabilize the network. If the network violations (e.g., frequency stability problems) cannot be alleviated by the generation re-dispatch, loads have to be curtailed. A load-shedding scheme must specify where and how much load to shed. In the works described above load shedding has been recognized as an acceptable control action that can help in understanding the effects of control/communication vulnerabilities on power grids. Hence, in this paper we couple the communication/control vulnerabilities with the load-shedding mechanism.

There has been extensive research on different load-shedding schemes and their formulations. One approach is to formulate load shedding as an optimization problem. In the optimal load-shedding problem formulation, the goal is to find the minimum amount of load to shed while satisfying load flow equations and static constraints like line flows, voltage, angular limits, and shedding constraints [7]. Example of such works are [8]–[11]. There are other approaches for load shedding based on heuristic methods [12], neural networks [13], etc. All these works attempt to formulate the load shedding to mitigate the effects of contingencies over the system and stabilize the network. Contrary to our work, these works assume that there is no vulnerabilities in the control/communication systems. In other words, the load-shedding solution is efficient and the solution is completely implementable over the grid. Timing is another critical issue in performing the load shedding. As an example the work presented in [7] combines nonlinear mathematical programming and discretized differential-algebraic power systems equations to estimate the optimal amount of load to be shed as well as the best time to shed it.

## III. MODELING CONTROL AND COMMUNICATION SYSTEM VULNERABILITIES COUPLED WITH LOAD SHEDDING

In order to model vulnerabilities in the control/communication systems we use a direct approach to couple the vulnerabilities with the load-shedding mechanism. We consider load shedding as the critical control action to mitigate the effects of disturbances over the grid and we assume that other typical control actions, such as tripping overloaded lines by the protection relays and adjusting generator set points, will be performed when needed. In this section, we first describe the control and communication structure of the power grid that we have considered in this

paper. Next, we define the vulnerabilities of these systems through this structure. Finally, we use the optimization approach to formulate the load-shedding problem and embed the defined vulnerabilities in this formulation.

#### A. Control and communication system

We can consider the control and communication system of the power grid as a hierarchical system. Control and communication systems of the transmission network and the distribution network of the power grid are two levels of this hierarchy. Since large blackouts and cascading failures are attributes of the transmission network in power grids, we study the cascading behaviors in this level. We assume that the control over the distribution network, placed below the substations of the transmission network, will perform the local control actions as well as implementing necessary remote control signals. The transmission grid can be decomposed into sub-systems based on the control regions defined over it. This facilitates the application of optimal control to large-scale systems and finding the solution for the optimization problems defined for control. Another level of the hierarchy in the control system of the grid is the control layer between the control regions whose role is to manage the grid as an interconnected network. This layer can be defined as a set of policies for interaction of these regions.

We assume that in each sub-system, the control regions utilize controlling and monitoring agents. These agents are located on top of the communication nodes and operate and communicate over the communication system spanned over the control region. Examples of controlling agents are control relays and remote terminal units (RTUs), which perform local control/automation and execute remote control signals from system control center (SCC). The SCC is the critical control center which make region-wide decisions and may have backup centers to solve the single point of failure problem. However, at each time only one SCC is the responsible control center for the region. Monitoring agents such as phasor data concentrator (PDC) and phasor measurement unit (PMU) gather information on the health of the system devices and control agents, the amount of load on each bus, as well as the information on the control capabilities of the control agents such as the load amount that can be controlled by the them and the response time to perform load-shedding control signal. They also provide the information on the load shed cost (marketing information) at each bus and their priority in performing load shed in the urgent cases. These agents communicate through the communication infrastructure with the SCC. We assume that the SCC performs the optimal control based on the information provided by the agents and calculates the optimal power flow and optimal load shedding if it is necessary in the sub-system region. The SCC sends control action messages to control agents associated with the buses of distribution regions during urgent situations through communication network for load shedding or other control actions. These actions will modify the operating point of the system to a more secure state. Note that based on our assumptions about the monitoring agents, SCC will have the

information on the failures and capabilities of the control agents. It may also utilize the sent and received information using communication network to decide whether a control agent is reachable or functional, and whether it can receive the control signal. Therefore, the SCC considers the vulnerabilities in the control/communication system in the decisions it makes.

At this point we define the vulnerabilities in the control/communication in the context of load shedding based on the structure defined above. Here vulnerabilities are defined as the inability of control agents to implement the load shedding efficiently. Sources of such inabilities includes the failure of communication system to send the load-shedding control signal from SCC to control agents, and failure of protection/control system at the control agent itself. Another source of the inability to implement load shedding is system constraints dictated by the physics of the components and marketing policies of the power system that may restrict the application of the optimal load-shedding controls. For example, different customers may have different interruption costs for the load curtailment; alternatively, there may exist critical loads that cannot be curtailed from the grid (based on policy or physical constraints) or the priorities that may apply to load shedding.

In the next subsection, we embed the vulnerabilities in the optimal load-shedding formulation.

#### B. Load shedding formulation

The electric power transmission network is described as a set of nodes interconnected by transmission lines. Generally in the transmission network, the network nodes represent load buses (substations)  $\mathcal{L}$ , generators  $\mathcal{G}$ , combinations of load and generation buses, and transmission buses that do not have any loads or generators (they only help in transmitting power in the transmission network). We use the notation  $L_i$  to represent the total initial demand or load on a load bus  $i$ . By definition, a load value at a load bus is a non-positive real number representing the energy that is being consumed at the bus. We consider the parameter  $c_i$  representing the ratio of the controllable load over the total load of a load bus, say  $i$ , where  $0 \leq c_i \leq 1$ ,  $i \in \mathcal{L}$ . Here,  $c_i = 0$  means that no load shedding is possible on the bus  $i$ ;  $c_i = 1$  means that all the loads in bus  $i$  can be controlled by the SCC and that bus  $i$  cooperates fully in the load-shedding control action. We decompose the load of a bus into a dispatchable part (controllable load of the bus) with value  $L_i^d = c_i L_i$  and a fix-load part with value  $L_i^f = (1 - c_i)L_i$ . Similarly to [11], we calculate the optimal power flow and the optimal load shedding by minimizing the cost defined as

$$Cost = \sum_{i \in \mathcal{G}} w^g_i g_i + \sum_{i \in \mathcal{L}} w^\ell_i \ell_i. \quad (1)$$

A solution to this optimization problem is the pair of  $g_i$  and  $\ell_i$  values that minimize the above cost function. 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 are listed below.

- (a) Limits on the generator power:  $0 \leq g_i \leq G_i^{\max}$ ,  $i \in \mathcal{G}$ .
- (b) Limits on the controllable loads:  $L_i^d \leq \ell_i \leq 0$ ,  $i \in \mathcal{L}$ .
- (c) Power flow through the lines is limited:  $|F_{ij}| \leq F_{ij}^{\max}$ .
- (d) Power balance constraints (power generated and consumed must be balanced):  $\sum_{i \in \mathcal{G}} g_i + \sum_{i \in \mathcal{L}} (\ell_i + L_i^f) = 0$ .

Since the solution to the above optimization problem  $\ell_i$  falls in  $[L_i^d, 0]$  for  $i \in \mathcal{L}$ , we observe that when the solution has  $\ell_i$  values closer to  $L_i^d$  for every  $i \in \mathcal{L}$  the cost function (1) is smaller than that when  $\ell_i$  is near zero. Hence, the more load shedding we perform the larger the cost function becomes. Therefore, this approach works to find the minimum necessary load shedding considering the vulnerabilities defined through the constraint (b).

Based on the model presented in this section we study different scenarios of power system under contingencies which are accompanied with vulnerabilities in the system defined through the ability of the buses to do the load shedding.

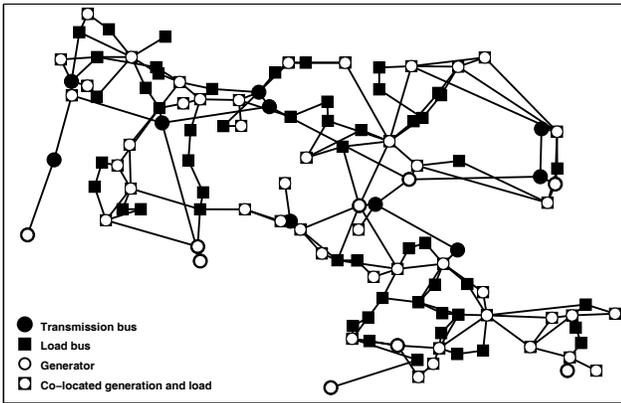


Fig. 1. IEEE 118 topology with its loads and generations.

#### IV. SIMULATION METHODOLOGY

In this section we study scenarios where we encounter transmission-line failures in the power grid, in the presence of vulnerabilities in the control/communication system, which together trigger subsequent cascading failures in the power grid. We investigate the cascading-failure behavior by simulating the power system and optimal load shedding with the constraints defined in Section III. We use MATPOWER [14], a package of Matlab M-files, for simulating the power system and solving optimal power flow problems. The new load-shedding optimization constraint is implemented in the MATPOWER solver using dispatchable loads [15]. We consider different scenarios of contingencies and vulnerabilities on the IEEE 118-bus network shown in Fig. 1. Different types of nodes (load buses, generators, co-located generations and loads, and transmission buses) in the IEEE 118-bus network

are shown in Fig. 1. To accommodate the power flow and use dispatchable loads in MATPOWER solver, additional buses were added to the IEEE 118-bus model in order to separate buses with both loads and generations. (The reason for taking this step is to accommodate the added negative generators that result from dispatchable loads since the MATPOWER solver does not permit two generators at the same bus.)

We embed the vulnerabilities in the control/communication system in the  $c_i$  values defined in Section III. For instance we assume that if SCC recognizes that there is a failure in the control system of the load bus  $i$  or failure in the communication system (load bus becoming unreachable), then it sets the  $c_i$  value of that bus to zero. Note that the condition  $c_i = 0$  means that the load bus has only a fixed load and it cannot cooperate in load-shedding control. However, to implement vulnerabilities other than a complete failure of control agents e.g., limitations due to marketing policies or physics of the system, we assume that the  $c_i$  values of load buses can take any value in the interval  $(0, 1)$ . Furthermore, we assume that the SCC has also the information,  $w_i^l$ , on the cost of load shedding, as well as the cost of generation,  $w_i^g$ , at each bus  $i$ . In our simulations we have assumed equal costs for generation on buses. In addition, we have assumed equal load shedding prices on load buses which are 10 times larger than the generation costs.

We consider two scenarios based on the  $c_i$  values in our simulations. In the first scenario, we consider the realization of vector  $\bar{c}$  for which the  $c_i$  values can assume *any* value in the interval  $(0, 1]$ . This scenario corresponds to the case where the only vulnerability in the control/communication system is due to limitations (e.g., system policies) in implementing load shedding. In this scenario we assume that there is not any load bus with totally uncontrollable in the system; for example,  $c_i = 0.5$  means that only half of the load in the  $i$ th bus is controllable. The second scenario addresses a boolean load-shedding capability, where the values of the  $c_i$ s are restricted to assume the binary values 0 or 1. In this scenario,  $c_i = 1$  means that the  $i$ th load bus can implement the load shedding fully while  $c_i = 0$  means it cannot implement load shedding at all. The ratio of the total controllable load over the total load in the grid,  $r_{c/t}$ , can be calculated using the following equation,

$$r_{c/t} = \left( \sum_{i \in \mathcal{L}} c_i L_i \right) / \sum_{i \in \mathcal{L}} L_i. \quad (2)$$

To implement the initial triggering contingency over the power system, we consider three transmission line failures randomly selected among all the transmission lines in the grid. A cascading phenomenon can occur due to the ineffectiveness (sub-optimality) of the load-shedding control action due to the degradation (inability to implement full load-shedding on certain buses) in the control/communication system. It is reasonable to anticipate that the sub-optimal solution of the optimization results in more line overloads compared to the case where load-shedding can be implemented fully. In the simulations we assume that control relays trip the lines with a probability proportional to their amount of overload once the

power flow through the line reaches 90% of the line's tolerable flow. On the other hand, once the load of a line surpasses the tolerance level of the line, it will fail with probability one.

## V. RESULTS

### A. Experiment 1

The goal of this experiment is to study the effects of partially or fully losing control over the load buses to perform load shedding on the cascading behavior of the grid. We have generated approximately 10,000 realizations of the vector  $\bar{c}$  of the ratios of the controllable load over the total load for the load buses. For each realization we have calculated the ratio of total controllable load over the total load in the grid,  $r_{c/t}$ , using the equation in (2). Next, we categorized the realizations based on the calculated  $r_{c/t}$  values into 10 equal-length sub-intervals in  $[0, 1]$ . In order to have the same number of realizations in each interval we selected 200 realizations in each interval. For each of the realizations we ran Monte-Carlo simulation 200 times, where in each simulation we select three transmission line failures randomly.

The average number of failed lines due to cascading failures is shown in Fig. 2 as a function of  $r_{c/t}$  for both scenarios of binary  $c_i$  values and the  $c_i$  values in the interval  $(0, 1]$ . From the results shown in Fig. 2 we observe that when full control is achievable over the loads in the grid (e.g., when there are no vulnerabilities in the control/communication system), control actions can mitigate the effects of initial disturbances and prevent the occurrence of the cascading failures. Therefore, there are only few (e.g., less than 5) failures on average when  $r_{c/t} = 1$ . However, losing control over the load buses results in an increase in the number of failures (on average) and a high probability of cascading failures. In addition, we observe that when the power grid is operating near its maximum capacity, vulnerabilities in the control/communication system can have drastic effects. In Fig. 2 we show the cascading-failure phenomenon, measured by the number of transmission-line failures in the system. Our simulations show a similar trend in the cascading behavior if we consider the amount of unserved loads in the system, as shown in Fig. 3. The reason for the similarity in the trends in cascading behavior in both cases (when considering the number of transmission-line failure and unserved loads) can be explained as follows. In the presence of control/communication vulnerabilities, lines have increased chance of becoming overloaded and hence fail, which causes the load buses to be disconnected from the grid. Therefore, the total amount of unserved loads in these cases are larger than that in the case when controlled load reduction (necessary load shedding) is performed.

Another intuitive observation made from Fig. 2 is that for a fixed amount of uncontrollable loads over the grid, the scenario for which we totally lose control over certain load buses results in a more severe cascading effect compared to that for the scenario where we lose control over a portion of the loads in the load buses.

### B. Experiment 2

The goal of this experiment is to understand how the topological distribution of load buses with uncontrollable loads

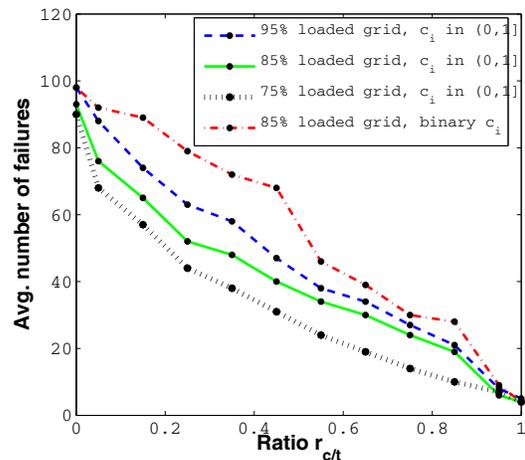


Fig. 2. Average number of failed lines due to cascading failures as a function of the ratio of total controllable loads over the total load in the grid.

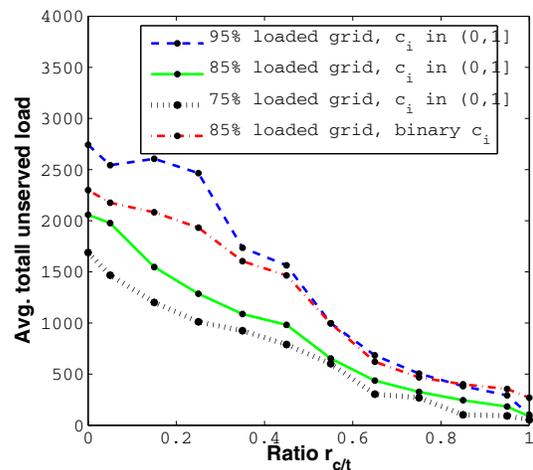
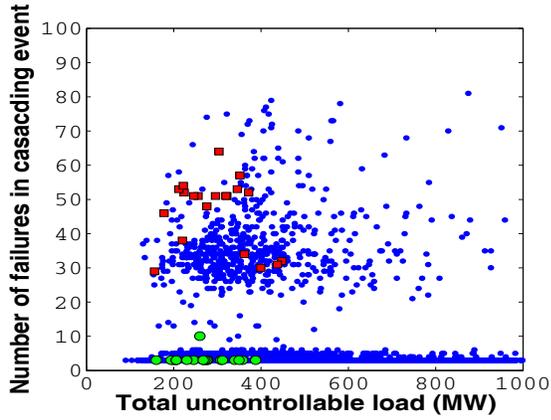


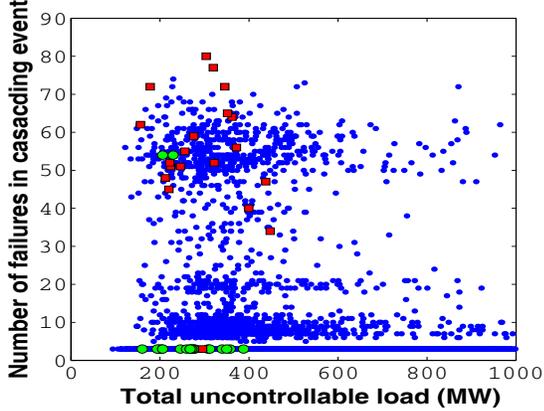
Fig. 3. Average total unserved load due to cascading failures as a function of the ratio of total controllable loads over the total load in the grid.

affects the cascading behavior. Understanding the effects of the distribution and topological location of control/communication system failures is useful in designing reliable coupled control/communication system with power grid. To this end, we consider the special case when load buses are either fully capable or totally incapable of implementing load shedding (i.e.,  $c_i$  values are binary). Similarly to the previous experiment, we assume that the occurrence of three initial transmission line failures triggers a disturbance over the grid. We consider realizations with five load buses that are incapable of load shedding. The  $r_{c/t}$  values for these realizations lie in the interval  $[0.9, 1)$ . In other words, in this experiment we have zoomed in the interval  $[0.9, 1)$  for the values of  $r_{c/t}$ .

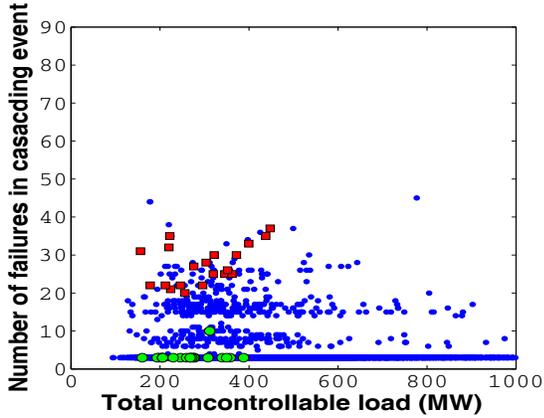
We consider scenarios with five load buses with uncontrollable loads randomly selected over the grid. We ran the Monte-Carlo simulation on 100 realizations of three initial transmission line failures (randomly selected). In addition, for each of the 100 realizations we carried out 10,000 iterations, each with a realization of random selection of load buses with uncontrollable loads over the power grid. For better observability, the results obtained on four of the 100 realizations



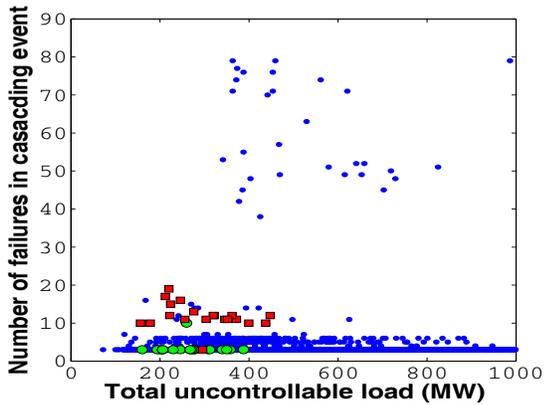
(a)



(b)



(c)



(d)

Fig. 4. Cascading behavior of the grid for various distributions of load buses with uncontrollable loads over the grid. Four scenarios, each shown in a sub-figure, are considered for the initial three transmission line failures.

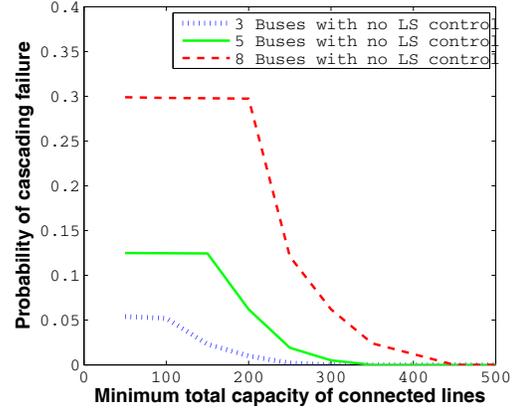


Fig. 5. Probability of cascading failure as a function of the minimum total capacity of the connected lines for three different number of load buses with uncontrollable loads over the grid.

of the initial transmission-line failures are shown in Fig. 4. Similar behavior can be seen in the rest of the samples as well. In each sub figure of Fig. 4 we show the results on the number of failures due to cascading phenomenon for each of the 10,000 realizations of the randomly selected load buses with uncontrollable loads. Note that each point in each of the plots corresponds to one realization (from all the combinations of 5 buses chosen from all the load buses in the grid) of the five randomly selected load buses with uncontrollable loads. As detailed below, the results show that both the topological location of the transmission line failures and the topological location of the failures in the control/communication system affect the cascading behavior of the power grid. For example, the initial triggering disturbance in Fig. 4(b) resulted in a more pronounced cascading phenomenon compared to that in the Fig. 4(d). Similarly, for a fixed distribution of the three initial failures (fixed sub-plot), we observe a clear change in the cascading behavior as we change the combination of uncontrollable buses.

We have also looked at the effects of spatial inhibition and clustering among the uncontrollable load buses. These effects can be important due to the nature of certain disaster events that may affect the power grid and their control/communication systems. For instance, earthquakes and their aftershocks exhibit clustering effects [16] while stress resulting from weapons of mass destruction may exhibit clustering or inhibition effects. Inhibition refers to cases where the load buses with uncontrollable loads cannot be close to each other (e.g., closer than 50 miles) in a geographic sense, and clustering refers the cases where load buses with uncontrollable loads are close to each other (e.g., within a radius of 20 miles). We have assumed that IEEE 118-bus network is spanned over a 100 miles by 150 miles area. We tested the cascading failures with 20 realizations with clustering effect and 20 realizations with inhibition effect. These realizations are shown in Fig. 4: the square markers correspond to scenarios with inhibition and circles correspond to the scenarios with clustering. We observe that when there is clustering effect in the distribution of the uncontrollable load buses the occurrence of cascading failures are less likely compared to the case in which there is inhibition effect. This may be attributed to the ability of the power grid to isolate

the problem locally in the case when the uncontrollable buses are within close proximity of one another, which may impede the propagation of subsequent failures through the grid.

Next, we examine other characteristics of load buses with uncontrollable loads in the power grid that may affect the cascading phenomenon. These characteristics include the amount of loads on buses, the capacities of the lines connected to buses, and the degree of buses in the network (number of transmission lines connected to each bus). Notably, among all these, we were able to identify the capacity of the lines connected to the load buses as the feature with the most influence on the cascading behavior. Based on our simulations, when the minimum total capacity of the lines connected to load buses with uncontrollable loads is above a threshold, then the probability of having cascading failures drops sharply. This phenomenon is shown in Fig. 5, where we show the probability of having ten or more failures beyond the initial three failures for three values for the number of load buses with uncontrollable loads. This can be explained as follows. Since it is assumed that the loads on the buses with uncontrollable loads are fixed if they have lines with lower capacities, there is a higher probability of overloading such line in the case of contingencies. Moreover, it can also be seen from Fig. 5 that the probability of having cascading failures increases with the number of uncontrollable load buses.

## VI. CONCLUSIONS

Understanding how vulnerabilities in the control/communication systems of a power grid affects its reliability and cascading behavior is important in the design of future smart grids. However, coupling the models that are available for power grids and control/communication systems is challenging. In this paper, we proposed a direct modeling approach for control/communication system vulnerabilities within the load-shedding formulation of the power grid. We considered vulnerabilities such as the failure of control agents, failure of communication systems, and the limitations due to physics and marketing policies of the grid. We investigated how such vulnerabilities affect the efficient load-shedding control actions necessary to mitigate the effects of disturbances over the grid. We used a standard optimal-load-shedding formulation and embedded the vulnerabilities of control/communication systems by considering added constraints to the optimization problem. We simulated various scenarios of failures in the power system accompanied with such vulnerabilities in the control/communication systems. The results confirm our intuition that by losing full or partial control over the load buses in performing load shedding the power grid becomes prone to cascading failures. It is also seen that the location of the failures in the power grid as well as the location of the control/communication system failures affect the cascading behavior of the grid. We also considered scenarios in which the locations of load buses with uncontrollable loads exhibit clustering or inhibition interactions. We have observed that in the presence of inhibition the cascading failures is more likely than that for the clustering scenario. Furthermore, we identified the capacity

of the lines connected to the load buses as the feature with the most influence on the cascading behavior. The approach presented here is a simple and efficient approach for coupling power grids with control/communication systems without dealing with the complexities associated with integrating communication and power systems simulators. This approach enabled us to identify and study effects of such vulnerabilities in the cascading failure behavior of power grids.

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## REFERENCES

- [1] J. Nutaro, P. Kuruganti, L. Miller, S. Mullen, and M. Shankar, "Integrated hybrid-simulation of electric power and communications systems," in *Power Engineering Society General Meeting, 2007. IEEE*, June 2007, pp. 1–8.
- [2] H. Lin, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, "Power system and communication network co-simulation for smart grid applications," in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, Jan. 2011, pp. 1–6.
- [3] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman, and D. Coury, "Epochs: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components," *Power Systems, IEEE Transactions on*, vol. 21, no. 2, pp. 548–558, May 2006.
- [4] F. Shokooh, J. Dai, S. Shokooh, J. Taster, H. Castro, T. Khandelwal, and G. Donner, "An intelligent load shedding (ils) system application in a large industrial facility," in *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005*, vol. 1, Oct. 2005, pp. 417–425.
- [5] C. C. Liu, J. Jung, G. Heydt, V. Vittal, and A. Phadke, "The strategic power infrastructure defense (spid) system: a conceptual design," *Control Systems, IEEE*, vol. 20, no. 4, pp. 40–52, Aug. 2000.
- [6] S. Buldyrev, R. Parshani, G. Paul, S. H. E., and S. Havlin, "Catastrophic cascade of failures in interdependent networks," *Nature* 464, pp. 1025–1028, Apr. 2010.
- [7] E. Aponte and J. Nelson, "Time optimal load shedding for distributed power systems," *Power Systems, IEEE Transactions on*, vol. 21, no. 1, pp. 269–277, Feb. 2006.
- [8] P. Wang, Y. Ding, and L. Goel, "Reliability assessment of restructured power systems using optimal load shedding technique," *Generation, Transmission Distribution, IET*, vol. 3, no. 7, pp. 628–640, July 2009.
- [9] W. Li-yong, Z. Bao-hui, T. Lun-nong, R. Jin-feng, Z. De-cai, Y. Feng, Z. Wen-hao, X. Han, and Y. Gang-liang, "Study on load-shedding based on economic equivalent in power market," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1–5.
- [10] L. Hajdu, J. Peschon, W. Tinney, and D. Piercy, "Optimum load-shedding policy for power systems," *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-87, no. 3, pp. 784–795, march 1968.
- [11] B. A. Carreras, V. E. Lynch, I. Dobson, and D. E. Newman, "Critical points and transitions in an electric power transmission model for cascading failure blackouts," *CHAOS*, vol. 12, no. 4, pp. 985–993, 2002.
- [12] Y. Zhao, N. Zhou, J. Zhou, K. Xie, Y. Liu, and J. Kuang, "A heuristic approach to local load shedding scheme for reliability assessment of bulk power systems," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1–5.
- [13] D. Novosel and R. King, "Using artificial neural networks for load shedding to alleviate overloaded lines," *Power Delivery, IEEE Transactions on*, vol. 9, no. 1, pp. 425–433, Jan. 1994.
- [14] R. Zimmerman, C. Murillo-Sanchez, and D. Gan, *MATLAB Power System Simulation Package*, version 4.0b4 ed., May.
- [15] R. Zimmerman, C. Murillo-Sanchez, and R. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *Power Systems, IEEE Transactions on*, vol. 26, no. 1, pp. 12–19, Feb. 2011.
- [16] L. Holden, S. Sannan, and H. Bungum, "A stochastic marked point process model for earthquakes," *Natural Hazards & Earth System Sci.*, vol. 3, pp. 95–101, 2003.