Evaluating the Effects of System Operators' Response on the Propagation of Power System Cascading Failures

by
Conor F. Hennessy

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science OR Electrical & Computer Engineering
Honors Scholar

Presented May 5, 2017
Commencement June 2017

AN ABSTRACT OF THE THESIS OF

Conor Hennessy for the degree of Honors Baccalaureate of Science in Electrical & Computer Engineering presented May 5, 2017. Title: Evaluating the Effects of System Operators' Response on the Propagation of Power System Cascading Failures

Abstract approved:_Eduardo Cotilla Sanchez

The majority of power system cascading models assume that system operators will react perfectly and timely to an electrical event. However, as evidenced by several blackouts in the last decades, the inadequate system operators' situation awareness and response can contribute significantly to the severity of an electrical disturbance. Under these premises, this paper proposes an approach for considering the effect of operators' response in the cascading modeling of power system blackouts. Particularly, the impact of a delayed reaction by the operator on the number of customers disconnected is investigated. This is achieved by modeling different levels of operators' response time into the protection device responses (such as relays) and simulating cascades with an open source quasi-steady-state (QSS) simulator. The method is illustrated using the IEEE RTS-96 and Polish Grid networks to quantify the impact of delayed operators' response and to demonstrate the effectiveness of the proposed methodology.

Key Words: ***Cascading failures, power system reliability, situation awareness, system operators, transmission networks***

Corresponding e-mail address: hennecon@oregonstate.edu

I. INTRODUCTION

Electrical power system blackouts are usually caused by a combination of electrical events, which stress the system beyond its limits leading to a series of cascading outages and consequently to customer disconnection. In the majority of existing literature on the cascading modeling of power system blackouts, only the effect of electrical events, such as loss of transmission lines or generation units, on power systems reliability is considered, whereas the effect of the human factor on the operational reliability and resilience of power systems is usually ignored.

However, as evidenced by large blackouts in the last decades, such as the North American and the Italian blackouts of 2003 [1], the Arizona-Southern California blackout of 2011 [2], and the 2006 European Blackout [3], system operators' situation awareness (SA) and timely decision-making are significant contributing factors to the size and duration of electrical disturbances. The growing operational complexity of power systems, in combination with increasing number of human-machine interactions and dependability on information systems [8], show that system operators are still a key element for the robustness of the electrical infrastructure. Therefore, since there is still an operator in the loop, a high level of uncertainty remains upon modeling power systems, and in particular when modeling the cascading behavior leading to large-scale power system blackouts.

Based on experiences from past blackouts worldwide (such as [1-4]), the response by the system operators affects significantly the development and severity of an electrical disturbance. Operators' response can refer to any actions taken by the operator to keep or return the system to a reliable and stable state, e.g. restoring into service faulted components, operational actions such as generation re-dispatching to control power flows, etc. Depending on the level of SA developed by the operators, there are four main reactions to an electrical event: (a) effective response, (b) delayed response and (c) incorrect action.

A delay in operators' response can range from minutes to hours depending on several factors, such as network complexity, the severity of the disturbance and the state of the ICT infrastructure. The latter, in particular, resulted in a delay in the magnitude of hours during the Northeast USA blackout of 2003 [1], where malfunctions in the information and alarm processing systems of FirstEnergy's control center kept the operators in the dark and unaware of the evolving conditions for several hours. In order thus to capture the effect of these factors on the effectiveness of operators' response and to model the impact of a wide range of operators' response time on the reliability of a power system during an electrical disturbance, a delay of up to four hours in steps of fifteen minutes is used in the simulations carried out here. A delay of up to several hours has been used in past studies for evaluating the impact of operators' response time on the load not served (LNS), such as [5].

The next form of operator response investigated is incorrect action. Insufficient or inaccurate SA can result in incorrect action being taken by operators; for example, different dispatch solutions that are equivalent from the optimization point of view have different long-term statistics.[13] In addition, certain transmission lines have been shown to be more critical to stability than others in given systems [13]. A lack of operator SA regarding which lines are critical could lead to incorrect response actions.

The aim of this paper is to incorporate the effect of the level of system operators' SA and response in the cascading modeling of electrical disturbances. This will be demonstrated by modeling the impact of operators' delayed or incorrect response to sets of electrical contingencies due to insufficient SA on the LNS, at several different levels of strain on the test cases modeled. In particular, we will model different levels of operators' response time into the protection device responses (such as relays) and simulate cascades with an open source quasi-steady-state (QSS) simulator. This model incorporates load shedding and generator re-dispatch capabilities into a dc power flow based quasi-steady-state (QSS) time horizon integration scheme that keeps track of thermal overloads over time. We augmented the endogenous events capabilities with scheduled and unscheduled failures that take into account different levels of operators' delayed responses.

The effect of these reactions on the reliability of a power system varies and depends on the evolving power system conditions. For example, the impact of an incorrect reaction by the system operator during highly stressed conditions or during an electrical disturbance would be significantly higher than the impact of an incorrect reaction during normal conditions. For this reason, these experiments will be conducted for different levels of grid strain. This study will help show how the impact of operators' SA and decision-making on the network reliability has critical effects on the propagation of cascading failures. The IEEE RTS-96 and Polish grid networks serve as test cases for these experiments, which will enable the validation of the model using test systems of different size and complexity [5].

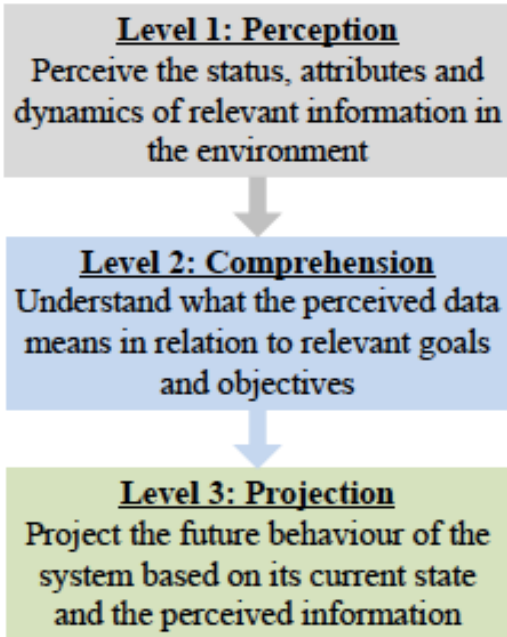
This paper is organized as follows. Section II discusses situation awareness and its importance in operating a power system in a reliable way. Section III presents the cascading failure mechanism, while Section IV provides the proposed operator model during cascading. The simulation results are presented in Section V and Section VI concludes and summarizes the paper.

II. Situational Awareness

SA and decision-making are critical for operating and protecting a power system, during both normal conditions and in the face of an electrical incident. The concept of SA has attracted the interest of several researchers and practitioners in a variety of domains, such as military [6] and aviation [7]. As a result, several efforts have been made to form a clear understanding of what SA is and capture its multi-dimensional aspects. One of the most dominant definitions is the three-level SA model by Endsley [6], according to which SA is composed of the following levels (Figure 1): perception, comprehension and projection. Based on this model, SA is defined as "*the perception of the elements in an environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in near future"*[6].

Due to the increasing size and complexity of modern power systems, system operators often have difficulties developing and maintaining a complete and accurate picture of the system, which will enable the correct decision-making and the implementation of the appropriate control actions. The main sources of operator

FIGURE I: SITUATIONAL AWARENESS



errors are described in [6] and they mainly include failures in the hardware and software applications, missing or incorrect real- time measurements, environmental factors such as data and alarm overload, the increasing automation in power systems (i.e., out-of the-loop syndrome [8]), lack of training, and/or experience and insufficient data and information sharing between neighboring networks.

It is therefore critical to evaluate the impact of system operators SA and response on the propagation and severity of power system cascading failures. However, there is limited literature focusing on this highly important issue, such as [9] and [10]. Therefore, further work is required to adequately model and understand the mechanisms through which insufficient SA and response by the operators can affect the cascading failures in power systems.

III. CASCADING FAILURE SIMULATION CONSIDERING OPERATORS' SA AND RESPONSE

A number of research groups have recently implemented quasi-steady state (QSS) models using the dc power flow equations to investigate cascading failures [11]. The dc equations include numerous assumptions that could substantially depart from the "real representation off the system". On the other hand, the dc model is numerically stable, relatively fast to compute for larger systems, and the blackout sizes that it produces are statistically similar to historical data. For these reasons, the dc model was used for this paper.

For this model, the time required for the actions implementation is modeled as equal to the time required by the operator to make a decision ($T_{dec\text{-}mak}$) and the time needed for applying the actions ($T_{actions}$):

$$T = T_{dec-mak} + T_{actions}$$

The time for applying actions ($T_{actions}$) depends on the action being implemented. For purposes of modeling operator response to branch failures and protective devices, $T_{actions}$ can be modeled as a times that fall into a range around a mean duration for each branch, with a normal distribution.

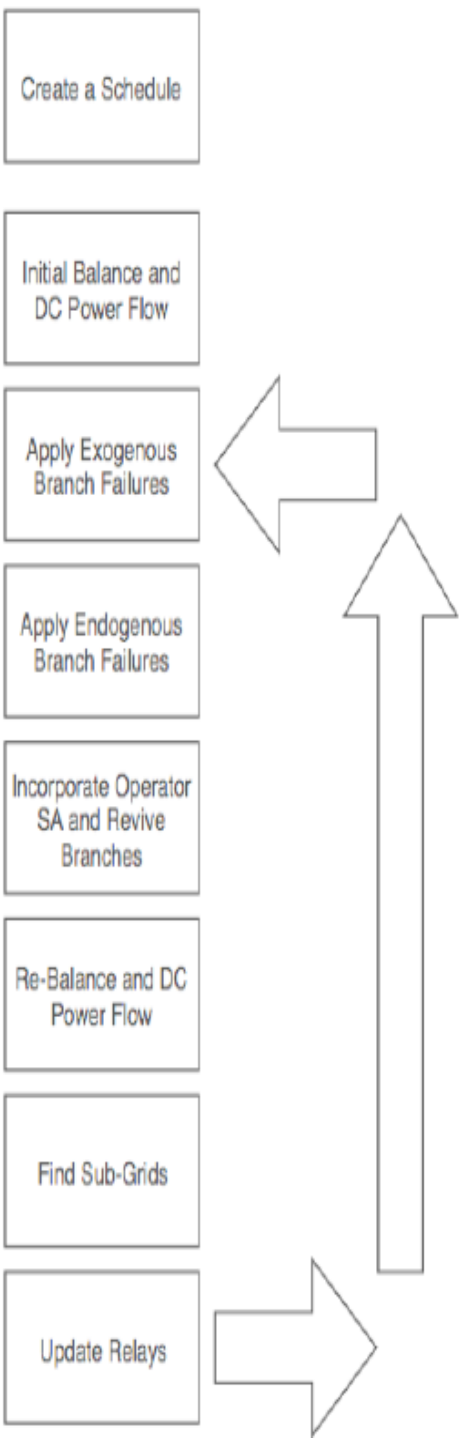
Time for decision-making ($T_{dec\text{-}mak}$) can be approached in a deterministic way; this will demonstrate the impact of operator SA on the reliability of the test systems.

For this model, we consider the delayed response of system operators. An increasing delay duration can be used as different case scenarios. The test cases will be modeled over a constant period of time, with operator delays averaging everywhere from fifteen minutes to three hours, on fifteen minute intervals. For each delay duration, its impact on the chosen reliability indices will be evaluated. Operator response delay length can then be plotted in relation to the reliability indices, which will help determine the maximum allowable time that operators have before the situation and the risk of cascading becomes uncontrollable.

In addition, we will consider the way that operator SA can contribute to a correct or incorrect response being taken. This type of SA will be modeled as the whether or not an operator making a correct decision in a given situation. In our model, a correct decision by an operator results in the repair of the most critical branch being prioritized when multiple braches fail at the same time.

The dc model and simulation, incorporating operator SA, was broken down into an iterative process, as described in the following paragraphs and shown in Figure 2.

FIGURE II



Step One: Use branch failure data to create a schedule of failures.
Data on how frequently various branches fail can be used in conjunction with data on the length of time that branch failures typically last to create a schedule of which branches in the test cases are functioning for every time during the simulation. For much of the simulation, the grid will be operating normally, or will be unaffected by isolated branch failures. However, for certain times within the simulation, the grid will experience branch failures that will cause losses, and operator action becomes significant during these times.

Step Two: Initial Rebalance and Power Flow
Provides a baseline for further simulation

Step Three: (begin repetition): Apply exogenous branch failures
The schedule created in step one is checked to see which branches are out of service, and which previously out-of-service branches are once again functional. This information is taken into account for power flow calculations.

Step Four: Apply exogenous branch failures.
The system is checked for thermal overloads, and branches that have overloads will trip.

Step Five: Incorporate Operator SA and revive branches *The simulation will check how much time each out-of-service branch has been dysfunctional for. It is at this point that operator situational awareness can be taken into account; operators with good SA will take action quickly to repair branches, and/or will prioritize the most critical branches. Operator action is incorporated into the DC simulation as operators reviving a branch a certain amount of time after a relay. If enough time has passed for an operator to have taken, and completed, correct action to revive a branch, that branch is simulated as in service once again.*

Step Six: Re-balance and DC power flow
The generation is set to match the load, and the power flow is calculated, using the DC approximation.

Step Seven: **Find sub-grids**
If branch failures separate the grid into discrete sections, that is determined at this point Step Eight: Update relays If the power flow calculations show that any relays should trip on overcurrent, those relays trip and the effects are noted.

IV. Test Network

For the experiments in next section, we build a QSS simulation benchmark that models the time horizon of a given test case. This simulation used system and operational data from the IEEE RTS-96 test case and a snapshot of the Poland power grid. Data regarding the frequency and duration of transmission line failures were used to create a schedule of line failures and repairs, used by the simulator to change the state of the grid. Additionally, the simulator keeps track of thermal overloads over time, which also can cause lines to fail, and need to be repaired. That way, the simulator can take into account endogenous failures caused by overcurrents. Every time the topology of the grid changes due to a new line failure or repair, the simulation updates the power flow, checks for overloads, and checks for and records the time, losses, and load not served. These experiments were performed with the grid operating at a base of 60% & 100% of the full load for each system, to test the effects of operator response at various levels of strain.

Since the RTS-96 grid is small and inherently robust by design, the given failure frequencies of the components are not capable of generating particularly critical scenarios. Therefore, the failure frequencies were scaled by a factor of twenty in order to produce scenarios with nonzero losses. This number was obtained by simulating the RTS96 case with branches failing at the frequencies created for the RTS96 case scaled by an increasing integer factor, and choosing the first scalar that yielded non-trivial results, which was twenty.

The exact same schedule of line failures was simulated twelve times, with a different duration of operator response delay for each simulation, ranging from zero to three hours.

Situation awareness can be modeled as type of action taken as well as time taken to act. To model situation awareness in the Polish grid this way, the lines that were most likely to cause power losses were identified, and designated critical. Situation awareness can be simulated as the operators being aware that those lines are critical, and responding more quickly to these lines relative to noncritical lines

The DC QSS simulator was used to run simulations where we introduced a constant mean response time across all lines (three hours). Simulations were also run where there was a one hour response time to critical lines, and a four hour response time to noncritical lines, resulting in a 3.75 hour average response time across all lines. These simulations were run with the average given frequency of failures at the level of the RTS 96 grid, at half that frequency, and at twice that frequency, in order to understand the importance of situation awareness in grids under various stress levels. We performed an experiment where the average duration of branch failures was varied from zero to three hours, representing up to a 27% increase in the median failure duration of 11 hours, thus simulating delays in operator response time due to poor situation awareness. The percent increase in load not served as response delays increase outpaces the increase in response delays.

V. RESULTS

For both grids, the load not served grows with operator response time, and grows much faster than response time does (although this depends on occurrence; if branches fail at a low enough rate that they never or rarely cause any power losses, this is not true). The increase is due to additional lines failing during the response delay. When lines are already down, additional line failures are more likely to increase the load not served; in addition, due to thermal overloads causing endogenous failures, lines are more likely to fail after other lines have already failed. Thus, the hours most affected by operator SA - the hours after line failures, are especially critical.

An analogous simulation was performed using the RTS-96 grid, the results of which are shown in Figure IV. Once again, the increase in load not served outpaces the increase in the duration of line failures due to operator response delays.

For the RTS 96 Test Case, the amount of LNS does not increase to the same extent that it does in the Poland Case, likely due to the robust nature of the grid in the RTS 96 test case. However, the LNS still increases significantly more rapidly than the failure durations do, due to operator response delays.

FIGURE III

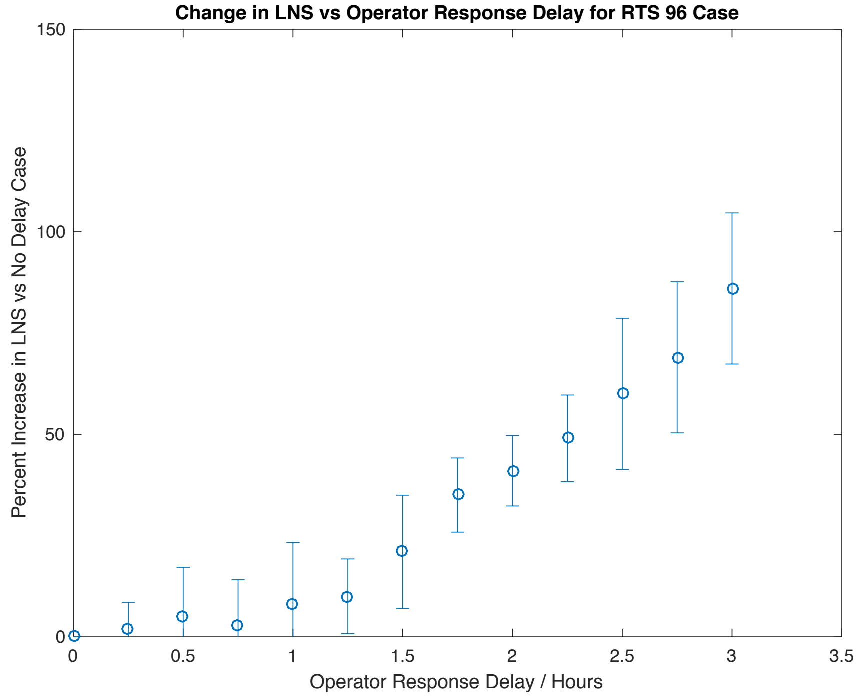
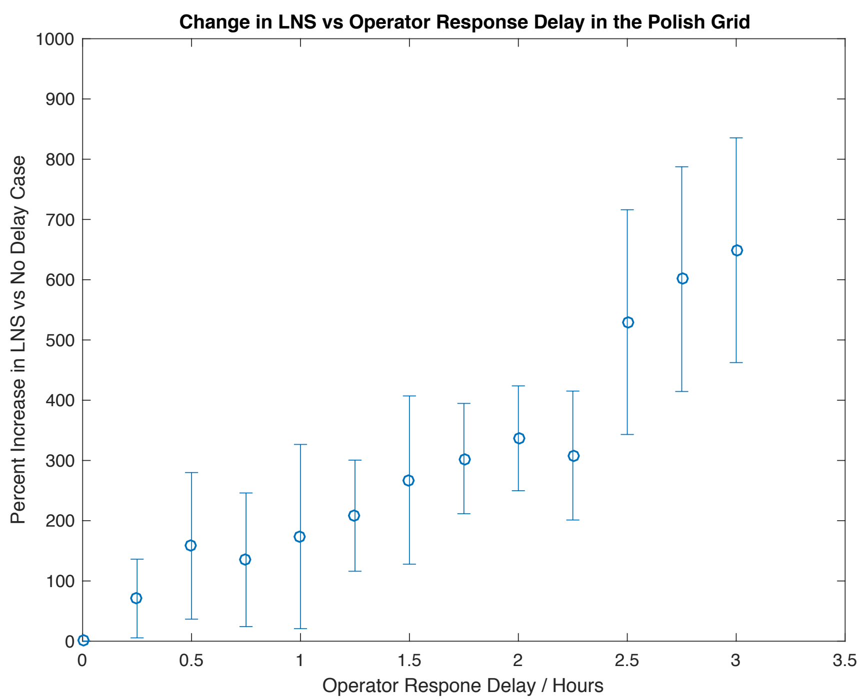


FIGURE IV



Operator response is especially important when the grid is strained. Figures V and VI are CDF plots showing the likelihood that a power outage results reaches a certain size, measured MegaWatts of LNS. In Figure V, the simulated Polish Grid is loaded at 60% of peak load, and there is little difference caused by operator response delays. However, in Figure VI, showing the results of a simulation conducted using peak load, the operator response delays make large outages far more probable. This is likely because, at that level of strain, a short delay is unlikely to cause further equipment damage and cascading. It can be insinuated from these results that a strained grid is more prone to cascading, making timely operator responses more imperative, to keep problems small and isolated.

FIGURE V

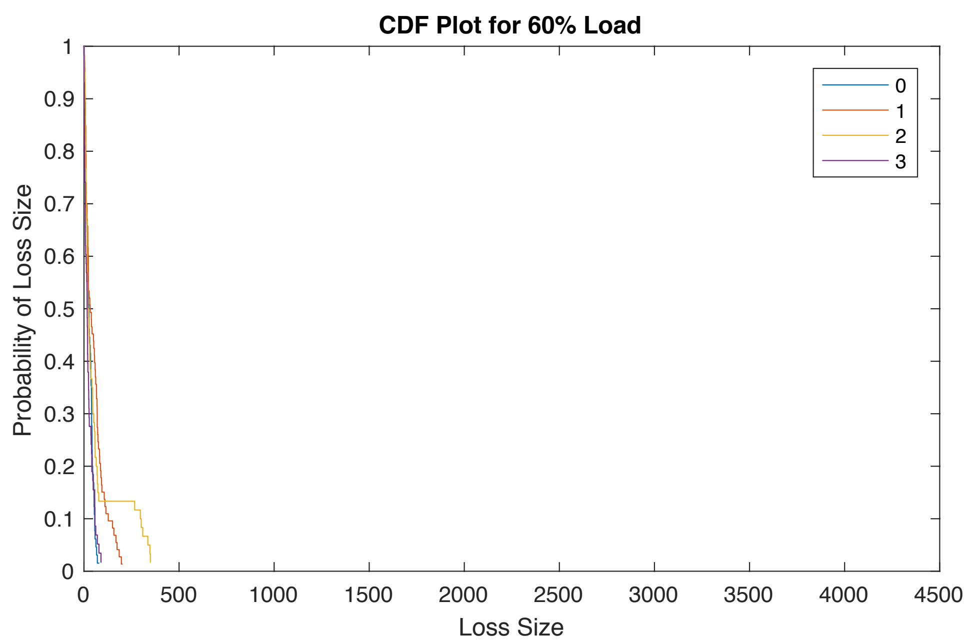


FIGURE VI

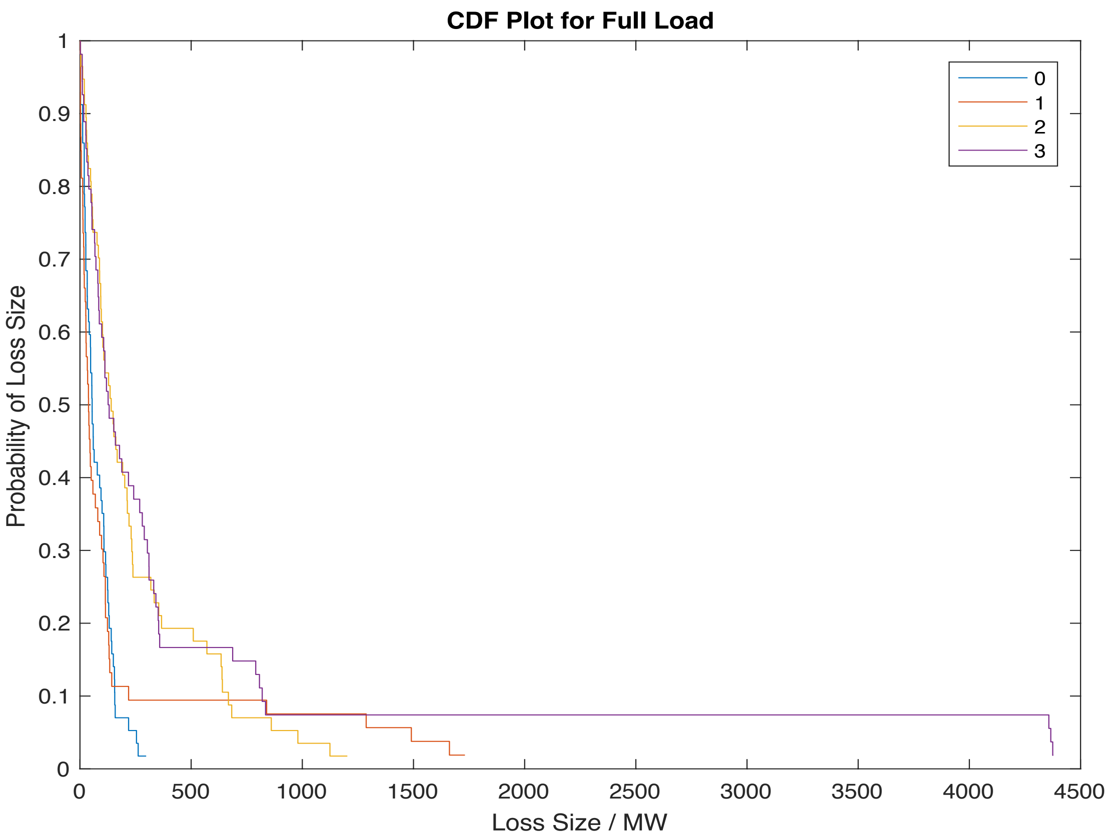


TABLE I

Table I summarizes the results of simulating operators responding more quickly to critical lines than other lines, compared with an even response across all lines. The results suggest that targeting critical lines at the expense of other lines is actually a slight detriment at low failure frequencies, most likely because of the overall increase in delay time. However, at the high failure frequency, targeting critical lines for repairs had a very

Effects of Awareness of Critical Lines	**Operator Response**			
	Mean 3 Hour Response Delay for All Lines		***Mean 1 Hour Response Delay for Critical Lines, 4 Hours for Noncritical (3.75 Overall)***	
	Mean Load Not Server Per Month (MWHrs)	***Mean Outages Larger than 10% of Total Load Per Month***	***Mean Load Not Server Per Month (MWHrs)***	***Mean Outages Larger than 10% of Total Load Per Month***
Half Failure Frequency	5.55*10^5	0	5.60*10^5	0
Regular Failure Frequency	3.45*10^6	0.167	3.48*10^6	0.167
Double Failure Frequency	1.22*10^7	0.778	9.25*10^6	0.625

significant effect, driven mostly by the prevention of large losses. An explanation of this is that large losses are often driven by concurrent failures of critical lines, so quicker repairs to those lines reduce the likelihood of concurrent failure. However, at low failure frequencies, the likelihood of concurrent failure of critical lines low enough that the overall increase in failure duration causes losses greater than those saved by quick responses to critical lines

VI. CONCLUSIONS AND FUTURE WORK.

This paper has presented a methodology for incorporating the effect of the level of system operators SA and response in the cascading modeling of electrical disturbances. This was achieved by modeling the delay in operators' response into the protection device responses (such as relays) and simulating cascades with an open source QSS simulator

The proposed methodology was illustrated using the IEEE RTS-96 and Polish grids, which enabled the demonstration and validation of the proposed simulation tool using networks of different sizes and levels of complexity. The simulation results clearly show that a delayed response by the system affects significantly the probability of additional line outages, which leads to higher LNS during a disturbance. Using the proposed approach, a threshold of operators delay can be effectively defined, for which a steep increase in load not serve is observed (i.e. 2 hours in the case of the test systems used here). Further, as previous works, it is shown that power loss sizes fit a power law distribution and that longer response delays result in larger losses. In addition, it is demonstrated that rather than assigning the same restoration time to all the branches, prioritizing the restoration of the critical lines results in lower LNS.

REFERENCES

[1] U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, 2004.

[2] UCTE, Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy, 2003.

[3] UCTE, Final Report System Disturbance on 4 November 2006, 2007.

[4] FERC, NERC, Arizona - Southern California Outages on September 8, 2011: Causes and Recommendations, 2012.

[5] M. Panteli, and D. S. Kirschen, Situation awareness in power systems: Theory, challenges and applications, Electric Power Systems Research, Vol. 122, May 2015, Pages 140-151

[6] M. R. Endsley, Theoritical Underpinnings of Situation Awareness: A Critical Overview, in: M. R. Endsley, D. J. Garland (Eds.), Situation awareness analysis and measurement, Lawrence Erlbaum Associates, Inc., New Jersey, 2000, pp. 1-24.

[7] J. Keller, C. Lebiere, R. Shay, K. Latorella, Cockpit System Situational Awareness Modelling Tool, in: Proc. of the 5th Human

[8] M. R. Endsley, Automation and Situation Awareness, in: R. Parasuraman, M. Mouloua (Eds), Automation and human performance: Theory and applications, Lawrence Erlbaum Associates, Inc., New Jersey, 1996, pp. 163-181.

[9] M. Panteli, P. A. Crossley, D. S. Kirschen, and D. J. Sobajic, ”Assessing the Impact of Insufficient Situation Awareness on Power System Operation,” IEEE Trans. Power Syst., vol. 28, no. 3, pp. 2967-2977, 2013.

[10] M. Schlpfer, T. Kessler, and W. Krger, ”Reliability Analysis of Electric Power Systems Using an Object-oriented Hybrid Modeling Approach,” in Power Systems Computation Conference (PSCC), Glasgow, Scotland, 2008.

[11] Eppstein, M.J.; Hines, P.D.H., ”A Random Chemistry Algorithm for Identifying Collections of Multiple Contingencies That Initiate Cascading Failure, IEEE Transactions on Power Systems, vol.27, no.3, pp.1698- 1705, Aug. 2012.

[12] A. Clauset, C.R. Shalizi, and M.E.J. Newman, ”Power-law distributions in empirical data” SIAM Review 51(4), 661-703 (2009). Available: http://tuvalu.santafe.edu/ aaronc/powerlaws/plfit.m

[13] D. E. Newman, I. Dobson, and B. A. Carreras, The Interplay of Network Structure and Dispatch Solutions in Power Grid Cascading Failures Nov-2016.

This work is in preparation to be submitted as a journal article to the IEEE Transactions Journ

Evaluating the Effects of System Operators' Response on the Propagation of Power System Cascading Failures

by
Conor F. Hennessy

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Electrical & Computer Engineering
Honors Scholar

Presented May 5, 2017
Commencement June 2017

Honors Baccalaureate Science in Electrical & Computer Engineering project of Conor F. Hennessy presented on Enter date of defense in format May 5, 2017.

APPROVED:

____

Eduardo Cotilla Sanchez, Mentor, representing Electrical & Computer Engineering

____

Ted Brekken, Committee Member, representing Electrical & Computer Engineering

____

Adam Mate, Committee Member, representing Electrical & Computer Engineering

____

Brandon Johnson, Committee Member, representing Electrical & Computer Engineering

____

Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

____

Conor F. Hennessy, Author