MODELING AND SIMULATION FOR CASCADING FAILURE CONSIDERING AN AC FLOW POWER GRID

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ABSTRACT

These days, there has been a growing interest in the importance of electricity in the human daily life. Importance of providing steady electricity from a power grid infrastructure has been continuously increased. However, the power grid infrastructure can fail by several reasons. The breakdown of a small part of the network can affect the whole. The electrical failure can spread in sequence while causing blackouts, and this process is called Cascading failure. Although extensive research has been carried out on this with DC approximated model, little attention has been paid to AC models. In this paper, we propose an AC flow model to conduct a simulation for cascading failure of an electrical power grid. South Korea's peak amount of electricity demand data is used for simulation. In conclusion, the flow of a power grid is calculated by the AC model which gives more realistic results than the DC model.

Keywords: cascading failure, blackout, AC flow, power grid

1. INTRODUCTION

Nowadays, there has been an increasing interest in the importance of electricity in human daily life. Electricity is used for almost all activities in life and inevitably, there is constant growth of the electricity demand. Hence, importance of providing steady electricity from a power grid infrastructure has been continuously increased. A power grid infrastructure is strongly connected with other infrastructures. For example, communication and railroad networks, and medical systems, are operated by electricity and can have negatively effects if the Power Grid Infrastructure encounters a problem.

The power grid infrastructure can break down due to several reasons. For example, natural disasters can physically damage a power plant or an electrical cord. Moreover, excessive power demand can overload power transmission, and this might cause failure in the overall infrastructure. An initial failure at one infrastructure can result in chain reaction of other failures of dependent infrastructures. The electrical failure can spread sequentially causing blackouts, and this process is called cascading failure. A failure might increase the amount of loaded electricity onto particular power transmission which can result in a situation of cascading failure.

There are several blackout examples caused by cascading failure. In 2012, the power grid of South Korea had been damaged because of typhoon Bolaven and cascading failure on power grid made blackouts on 2 million households. In August 2003, approximately 100 power plants and 50 million people experienced major blackouts due to one transmission line problem near the east coast of North America. This paper seeks to remedy cascading failure problems by forecasting the component that can influence the whole power grid when failure happened.

Forecasting the size of the cascading failure has been widely studied so far. First of all, Bienstock and Verma (2010) proposed a model that can calculate the survival time of the power grid when k components were deleted out of N grid components. Although, this model is not directly related to the cascading failure problem, however, many other researchers have developed cascading model based on it. Carreras and Dobson (2004) proposed a model that can calculate the amount of failures caused by an initial failure. An arithmetical model was developed by Kim, Bae, Bae, and Lee (2013) that can calculate a new power flow when a failure happens.

According to these studies, failures of a few components of a power grid cause serious cascading failure. To avoid the huge cascading failure, demand shedding policies were suggested by Kim, Bae, Bae, and Lee (2013). In addition, other researchers (Bienstock 2011; Pinar, Meza, Donde, Lesieutre 2010) have considered methods that shed load.

There is a large volume of published studies considering cascading failure with DC approximated model (Kim, Bae, Bae, Lee 2013; Pfitzner, Turitsyn, Chertkov 2011; Bernstein, Bienstock, Hay, Uzunoglu, Zussman 2011; Bienstock 2011; Dobson, Carreras, Lynch, Newman 2007; Dobson, Carreras, Newman 2005; Chen, Thorp, Dobson 2005; Carreras, Lynch, Dobson, Newman 2004; Bernstein, Bienstock, Hay, Uzunoglu, Zussman 2011). The DC model is able to provide solution, which contain flows of transmission lines and phases of power plants by using the linear programming or other methods. However, one of the critical constraints of the DC model is that the phase difference between the two-linked-plants that should converge to zero. The model cannot provide any solution when the difference has a value which is not close to zero. One of the major issues in DC model is that it does not reflect the flow that varies based on time series.

There are also several papers assuming deterministic demand quantity (Kim, Bae, Bae, Lee 2013; Bienstock 2011; Dobson, Carreras, Lynch, Newman 2007; Nedic, Dobson, Kirschen, Carreras, Lynch 2006; Dobson, Carreras, Newman 2005; Carreras, Lynch, Dobson, Newman 2004). However, the demand is not deterministic in reality, and it varies by time. Moreover, assuming the demand as a deterministic value might cause failures, and these failures affect cascading procedure. Thus, it is possible that the cascading procedure is misestimated with the assumption.

In the real case, a power plant operates an Alternating Current (AC) motor, and it has its own angular frequency. The frequency might cause a big difference among phases. In addition, the amount of flow changes by time during the rotation of the motor. Although, extensive research has been carried out on DC models, little attention has been paid to AC flow models.

Therefore, to overcome these limitations, a new power grid model is needed to provide solutions regardless of the phase difference. Thus, we suggest an AC flow model for simulating cascading procedure of a power grid.

2. POWER GRID CASCADING MODEL

2.1. AC Flow Calculation

AC flow model has more complicated conditions than a DC Approximation model, because it requires more complex data sets to explain current, voltage, and impedance. Impedance consists of reactance and resistance. We introduce the concept of complex number to deal with these two values independently. Accordingly, impedance is expressed with resistance as a real number and reactance as an imaginary number. This type of impedance influences not only the voltage, but also the flow by Ohm's law, meaning that the voltage and the flow should be expressed by the complex number. Then, the voltage, flow, and impedance have two dimensional values, and the values interact with each other.

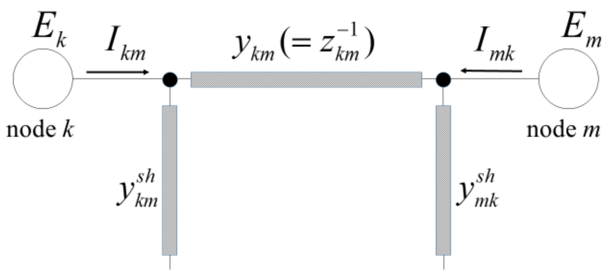

Figure 1: A diagram of node *k*, node *m*, and a transmission lines between these nodes.

The AC power grid model can be constructed by network modeling as shown in Figure 1. Transmission lines of a power gird are expressed by arcs, and other components, such as power plants and transforming stations, are expressed by nodes. The following terminologies can be defined.

E_k *: complex voltage of node k*

V_k *:voltage of node k*

U_k *: maximum voltage of node k*

I_{km} *: complex flow from node k to node m*

z_{km} *: impedance of an arc, connecting node k and m*

r_{km} *: resistance of an arc, connecting node k and m*

x_{km} *: reactance of an arc, connecting node k and m*

y_{km} *: admittance of an arc, connecting node k and m*

y_{km}^{sh} *: admittance of a shunt between node k and m*

g_{km} *: conductance of an arc, connecting node k and m*

b_{km} *: susceptance of an arc, connecting node k and m*

Admittance is inverse number of impedance. Then, the following equations can be found.

$$z_{km} = r_{km} + x_{km} j \tag{1}$$

$$y_{km} = z_{km}^{-1} = (r_{km} + x_{km} j)^{-1} = g_{km} + b_{km} j \tag{2}$$

$$g_{km} = \frac{r_{km}}{r_{km}^2 + x_{km}^2} \tag{3}$$

$$b_{km} = \frac{-x_{km}}{r_{km}^2 + x_{km}^2} \tag{4}$$

However, Andersson (2008) suggested an equation to calculate AC flow. In this equation, voltage, flow, and impedance are expressed with complex numbers.

$$I_{km} = y_{km}(E_k - E_m) + y_{km}^{sh} E_k \tag{5}$$

$$I_{mk} = y_{mk}(E_m - E_k) + y_{mk}^{sh} E_m \tag{6}$$

$$E_k = U_k e^{j\theta_k} = U_k(\cos\theta_k + \sin\theta_k j) \tag{7}$$

$$E_m = U_m e^{j\theta_m} = U_m(\cos\theta_m + \sin\theta_m j) \tag{8}$$

These equations show relationships between the phase of power plants and the flow of transmission lines. And *j* is the symbol of imaginary number. We take the advantage of the suggested equations (5), (6), (7), and (8) to calculate the AC flow.

In reality, an admittance of a shunt is a very small value, compared to an admittance of a transmission line. Moreover, there might be no shunt between some nodes. Therefore, a complex flow can be calculated without considering admittance of shunt as below.

$$I_{km} = y_{km}(E_k - E_m) \tag{9}$$

In the equation (7), if a condition $x_k^2 + y_k^2 = U_k^2$ is satisfied, then x_k and y_k can be introduced, instead of $U_k \cos\theta_k$ and $U_k \sin\theta_k$.

$$x_k = U_k \cos\theta_k \tag{10}$$
$$y_k = U_k \sin\theta_k \tag{11}$$
$$E_k = x_k + y_k j \tag{12}$$

Then, the complex flow is presented with x_k and y_k by using (7) and (9) as shown above.

$$I_{km} = y_{km}\{(x_k + y_k j) - (x_m + y_m j)\} \tag{13}$$
$$= (g_{km} + b_{km} j)\{(x_k - x_m) + (y_k - y_m) j\} \tag{14}$$
$$= \{g_{km}(x_k - x_m) - b_{km}(y_k - y_m)\} + \{g_{km}(y_k - y_m) + b_{km}(x_k - x_m)\} j \tag{15}$$

Therefore, an instantaneous value of AC flow i is the real number of the complex flow. A part of imaginary number indicates the phase of flow. In general, the real part is called flow, and the imaginary part is only used to explain the phase of a flow. In this study, we focus on finding out the flow, so that the phase is determined by the flow automatically.

$$i_{km} = g_{km}(x_k - x_k) - b_{km}(y_k - y_m) \tag{16}$$

Equation (16) is real part of I_{km}. Thus, it is the flow between node k and m, and a node mass can be calculated. The mass of node k is expressed with P_k, D_k, and zero. A node is a supply node if it has a positive node mass, which means the amount of supply generated by the node. On the other hand, node k is a demand node when it has a negative value of node mass. In this case, the amount of demand is indicated by D_k, and the node mass is $-D_k$. Otherwise, a node is an intermediate node when its node mass is zero.

$$\sum_{m=1}^{n} i_{km} = \begin{cases} P_k \\ -D_k \\ 0 \end{cases} \tag{17}$$

The number of nodes is n, and the node mass is the sum of flows, which are connected to the node. As a result, an AC flow model is introduced by using (16) and (17).

Maximize $\sum_{k=1}^{n} P_k$

Subject to

$$\sum_{m=1}^{n} i_{km} = \begin{cases} P_k \\ -D_k \\ 0 \end{cases} \tag{18}$$
$$g_{km}(x_k - x_k) - b_{km}(y_k - y_m) = i_{km} \tag{19}$$
$$x_k^2 + y_k^2 \le U_k^2 \tag{20}$$

Objective value of this AC flow model is total amount of power generation in order to conserve a given power demand. Constraints (18) and (19) are equivalent to (17) and (16). However, constraint (20) is slightly different from $x_k^2 + y_k^2 = U_k^2$, because U_k means a maximum voltage generated by node k. This constraints indicates that the node can generate less power than U_k. Therefore, constraint (20) can have the inequality.

The flow finding problem contains both linear and quadratic constraints. The quadratic constraints are used not only due to the flows are expressed with complex numbers, but also due to the constraints related with size of the flow. Moreover, the size of the complex flow is constructed by the combination of the square of real and imaginary parts, which should be less than a flow capacity. Due to the constraint, we cannot solve the problem by linear programming which is used in DC models. Therefore quadratic constraints programming is used to find the flows in the power grid.

2.2. Cascading Procedure

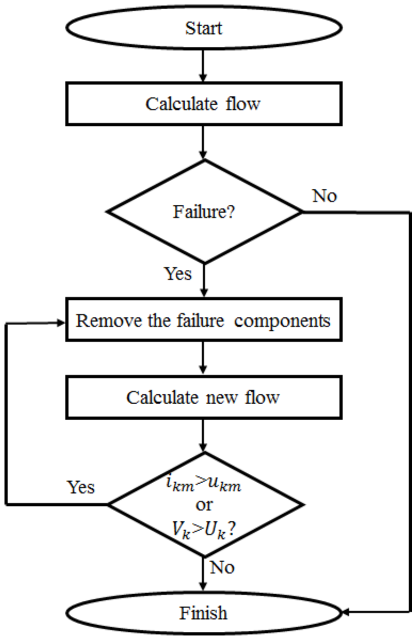

Figure 2: A flow chart for cascading procedure

In order to satisfy the power demand, power plants generate power and transmission lines transmit their flows. However, every component of a power grid has its own capacity. A power plant has a capacity of power generation, and a transmission line can only transmit electric current under its transmission capacity. Therefore, these capacities cause failure when some of the components have values over the capacity, and a failure component cannot work until it is repaired. In this study, the repair process is not considered. Thus, the failure components are removed from the power grid, and the remaining power grid without the failure components is obtained. However, it is difficult to satisfy the demand with the remaining power grid. It is because the demand could not be satisfied with the original power grid even though it has more components than the remaining power grid. Hence, the power grid without failure components is likely to contain additional failure. This procedure continues until finding a power grid which satisfies the power demand. This procedure is called a cascading procedure.

As shown Figure 2, we introduce a flow chart for cascading failure of an electrical power grid. This procedure starts with information about capacities and demands. By using (16), we can get the flow of transmission lines, and the amount of generation of power plants. Failure of a component is determined by checking its capacity. A constraint $i_{km} < u_{km}$ or $V_k < E_k$ means that a component, which is related with this condition, does not violate its capacity. If the conditions are violated by some components of the power grid, then the failure components should be deleted, and new flow and generation will be calculated without those components. This power grid repeats the same procedure until there is no failure.

A number of components is expected to be failed from this procedure, even though the number of initial failure components is very small. As a result, cascading failure can cause huge damage on the power grid. Therefore, analyzing this cascading failure is important to satisfy the power demand stably.

3. DEMAND AND SUPPLY

To calculate the flow, information about the power demand should be known. Most of other studies have been considered the demand as constant and fixed value. This value is given from demand forecasting and it indicates that the forecasted demand is not a real amount of demand. Moreover, the real amount of demand is changed by the time. Thus, calculating flow with the forecasted demand might lead to uncertainty. Furthermore, using the fixed demand can make flow of the power grid infeasible.

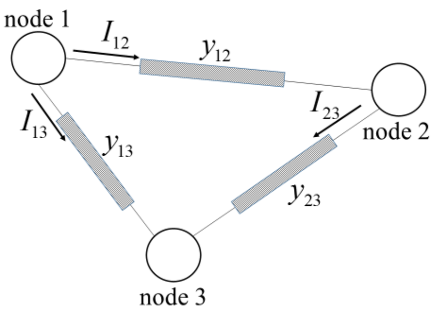

Figure 3: An example of a small power grid

Figure 3 shows a small power grid. Suppose that this power grid requires flow I_{12}=90, I_{13}=100, I_{23}=0, and all of the admittance are same. In this example, the amount of power generation can be calculated by (9).

$$I_{12} = y_{12}(E_1 - E_2) = 90 \tag{21}$$

$$I_{13} = y_{13}(E_1 - E_3) = 100 \tag{22}$$

$$I_{23} = y_{23}(E_2 - E_3) = 0 \tag{23}$$

Equation (23) indicates $E_2 = E_3$, and this relation leads to $y_{12}(E_1 - E_2) = y_{13}(E_1 - E_3)$ because y_{12}=y_{13} is given. Moreover, this relation means I_{12}=I_{13}, which is contradiction to (21) and (22). Therefore, this power grid has no feasible solution under this condition.

However, if a condition $I_{12} = 90$ changes to $I_{12} = 100$, then this power grid has a feasible solution with the increased amount of the total demand, because it can satisfy $y_{12}(E_1 - E_2) = y_{13}(E_1 - E_3)$.

This example of small power grid shows that a power grid might have failure components even though it can afford larger amount of the power demand without any failure. Furthermore, there is no reason to stick to the fixed value of the demand, which is not exactly same with the real demand.

Therefore, we introduce a model that the power demand and supply are in some ranges. In this study, the ranges are calculated by using the fixed demand.

$$I_{km} \in [0.9 \times I_{km}^{Fixed}, 1.1 \times I_{km}^{Fixed}] \tag{24}$$

$$I_{km} \in [1.1 \times I_{km}^{Fixed}, 0.9 \times I_{km}^{Fixed}] \tag{25}$$

Equation (24) works when I_{km} is a non-negative number. Otherwise, I_{km} satisfies (25).

4. DEMAND SHEDDING IN CASCADING PROCEDURE

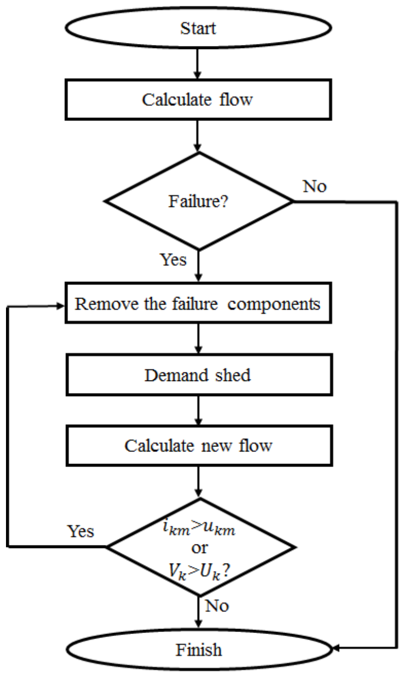

Figure 4: A flow chart of cascading procedure considering demand shedding

As treated in section 2.2., a small size of initial failure can cause huge damage on the entire power grid infrastructure. The huge damage occurs because a power grid cannot find any feasible solution in cascading procedure with a given power demand. Therefore, if the demand is reduced when failure occurs, then the power grid might find feasible solutions. This demand reduction is called demand shedding, and it relaxes the entire problem by reducing the power demand when the flow cannot be obtained to satisfy the power demand after the failure occurred. Therefore, demand shedding process is needed after the failure in cascading procedure. Figure 4 shows an updated flow chart of cascading procedure.

There are many strategies for demand shedding. Demand shedding strategies are suggested by Kim, Bae, Bae, and Lee (2013), and a strategy with the highest demand conservation was founded. The demand conservation indicates that how much demand is left after demand shedding, compare to initial demand. As a result, a proportional shedding strategy is proposed as the best strategy for demand conservation. Thus, in this study, proportional demand shedding strategy is adopted.

Proportional shedding does not give any priority to components of a power grid. When a power grid cannot afford a given total demand, proportional shedding strategy reduces demand of all nodes in same proportion. For example, there are two demand nodes, called A and B. Demand of these nodes are100 and 200, respectively. However, 30 of total demand should be reduced by proportional shedding. Then, the demand of A becomes 90, and the demand of B becomes 180. This is because proportion of reduced demand should be same on every node.

5. SIMULATION

In this study, a cascading simulator, which was developed by Kim, Bae, Bae, and Lee (2013), is used. It is extended with the AC flow model. Demand conservation and cascading procedure are results of the simulator. In addition, this simulation is replicated 30 times, with South Korea's peak amount of electricity demand data on year 2013. It contains information of 837 nodes and 1148 arcs.

5.1. Failure model

A failure model should be defined before starting the simulation. Failure model determines whether a component of power grid fails or not. Exponential smoothing method is one of the ways, suggested by Kim, Bae, Bae, and Lee (2013), to calculate *effective flow* of an arc, and compare it with its *effective capacity*. If effective flow is bigger than effective capacity, then the arc fails.

$$\hat{f}_{km}^{r} = \alpha f_{km}^{r} + (1-\alpha) f_{km}^{r-1} \tag{26}$$

The effective flow $\hat{f}_{km}^{r}$ indicates that a temporary overloading on a transmission line does not make a failure. The transmission line will fail when it is overloaded continuously.

5.2. Simulation Result

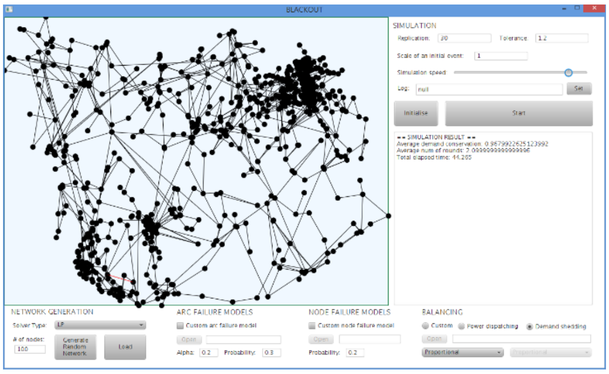

Figure 5: Simulation Result from cascading simulator with AC flow

The simulator shows a cascading procedure, and it helps to find which components are critically influenced by other components when failure is occurred. Result of the simulator contains electricity demand conservation ratio after the initial failure occurrence, and average number of cascading failure phase right before stabilizing of the power grid infrastructure.

As shown in Figure 5, the total elapsed time is 44.265 seconds for 30 times replication. It indicates that it takes about 1.5 second per one cascading procedure to calculate. Moreover, the demand conservation is about 96.80, and it shows that there are only 3.2% loss of demand during cascading procedure.

6. CONCLUSION

This study set out to determine an AC flow model using network modeling to simulate and analyze the cascading procedure when a power grid infrastructure breaks down. Moreover, the AC flow model can deal with the demand as bounded-range data, and provides solutions in the certain range of interval. This approach indicates that the model is flexible to solve a problem and reflects real cases properly.

Furthermore, we proposed a way to calculate a complex AC flow. This calculation may be able to applicable on other AC flow models, in order to derive the AC flow and phase of the components.

For further study, we need to modify the AC flow model. It has quadratic constraints, and it should be solved by quadratic constraints programming. The quadratic constraints programming takes more time than linear programming. Therefore, if the quadratic constraints are expressed in terms of linear constraints, then the total elapsed time might be diminished greatly. In addition, developing failure models and demand shedding strategies might provide a more realistic simulation results.

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REFERENCES

Chulhan Kim, Kiwook Bae, Soojeong Bae, and Tae-Eog Lee, 2013. Simulation analysis for cascading failure of an electrical power grid. *Proceedings of the 12th International Conference on Modeling and Applied Simulation*. September 25-27, Athens (Greece)

Bienstock, D. and Verma, A., 2010. The $N-k$ problem in power grids: New models, formulations, and numerical experiments. *SIAM Journal of Optimization*, 20 (5), 2352–2380.

Carreras, B., Lynch, V., Dobson, I., and Newman, D.E., 2002. Critical points and transitions in an electric power transmission model for cascading failure blackouts. *Chaos*, 12 (4), 985–994.

Carreras, B., Lynch, V., Dobson, I., and Newman, D.E., 2004. Complex dynamics of blackouts in power transmission systems. *Chaos*, 14 (3), 643–652.

Andersson, G., 2008. Modelling and analysis of electric power systems. *Power Flow Analysis-Fault Analysis Power Systems Dynamics and Stability*. Available from:http://educationdisha.com/upload/modelling_hs08_script_02.pdf[accessed 13 May 2014].

Dobson, I., Carreras, B., Lynch, V., Newman, D.E., 2007. Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization. *Chaos*, 17 (2), 026103.

Dobson, I., Carreras, B., Newman, D.E., 2005. A loading-dependent model of probabilistic cascading failure. *Probability in the Engineering and Informational Sciences*, 19 (1), 15-32.

Kirschen, D.S., Jayaweera, D., Nedic, D.P., Allan, R.N. 2004. A Probabilistic Indicator of System Stress. *IEEE Transaction on power system*, 19 (3) 1650-1657

Chen, J., Thorp, J.S., and Dobson, I., 2005. Cascading dynamics and mitigation assessment in power system disturbances via a hidden failure model. *International Journal of Electrical power & Energy Systems*, 27 (4), 318-326.

Bernstein, A., Bienstock, D., Hay, D., Uzunoglu, M., and Zussman, G., 2011. *Power Grid Vulnerability ot Geographically Correlated Filures – Numerical Evaluation*. Available from: http://www.ee.columbia.edu/~zussman/pub_files/CUEE-2011-05-06-power-cascades.pdf[accessed 13 May 2014].

Bienstock, D., 2011. Optimal Control of Cascading Power Grid Filures. Preceedings of the 50th IEEE Conference on Decision and Control and European Control Conference, December 12-15, Orlando (USA).

International Business Machines Corporation, 2012. *IBM ILOG CPLEX optimization studio: Getting started with CPLEX*. Version 12 Release 5. USA: International Business Machines Corporation.

Gurobi Optimization, 2013. *Gurobi optimizer reference manual*. Gurobi Optimization. Available from: http://www.gurobi.com/documentation/5.1/reference-manual[accessed 13 May 2014].

Nedic, D.P., Dobson, I., Kirschen, D.S., Carreras, B.A., and Lynch, V.E., 2006. Criticality in a cascading failure blackout model. *International journal of Electrical Power & Energy Systems*, 28 (9), 627-633.

Pfitzner, R., Turitsyn, K., and Chertkov, M., 2011. Statistical classification of cascading failures in power grids. *Proceedings of the 2011 IEEE Power & Energy Society General Meeting*, pp. 1-8. July 24-29, Detroit (MI, USA).

Pinar, a., Meza, J. Donde, V., and Lesieutre, B., 2010. Optimization strategies for the vulnerability analysis of the electric power grid. *SIAM Journal on Optimization*, 20 (4), 1786-1810.

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