SIMULATION ANALYSIS FOR CASCADING FAILURE OF AN ELECTRICAL POWER GRID

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ABSTRACT
In an electrical grid, destruction of generators or power transmission elements may lead to a serious power outage on an entire city or a country, not just on the region that the destroyed facilities exist. This is because of cascading failure of an electric grid. In order to prevent huge damage on a system, cascading failure needs to be analysed properly. In this study, we propose a systematic framework for examining cascading failure of an electrical grid with simulation. Procedure of cascading failure and mathematical models for simulation are introduced. In addition, demand shedding policies for reducing damage on a system are suggested. We also conduct simulation experiments as a case study which involves all the concepts that we present throughout the paper.

Keywords: electrical grid, cascading failure, simulation, demand shedding

1. INTRODUCTION
In modern countries, an electrical grid is one of the most important infrastructures to keep the societies alive. Electricity is involved in almost every part of life. It is one of basic resources for a society and used by houses, companies, schools, hospitals, and so on. In addition, other critical infrastructures including a traffic system, a finance system, and a gas/oil distribution system are highly dependent upon electricity. If there is a problem with supplying electricity to consumers, serious physical or financial damages may occur. Therefore, managing an electric grid is important for an entire society.

However, generators and transmission systems are vulnerable to many types of disasters by the nature and humans (e.g. tornado, flood, earthquake, explosion, and fire). Since the elements in a power distribution system such as power plants, transmission facilities, and consumers are tightly coupled as a form of a network, breakdown or destruction of a small part of the network can affect the whole network. The electrical failure tends to spread step by step causing blackouts and this process is called *cascading failure*.

We can find blackout cases caused by cascading failure of electrical power grids: In 2012, a typhoon called Bolaven hit South Korea and stopped distribution of electricity to approximately 2 million houses and several industrial facilities; an earthquake with magnitude 7.4 caused blackouts to 4 million houses in the year 2011 in Japan. In addition, power blackout in North America in 2003 inflicted 6 billion dollar worth of damage, and South Korea was suffered from national power outage on September in 2011. These two cases were not due to disasters, but they were enough to emphasise the strong influence of the cascading failure of a power distribution system.

Failure of a power distribution system has been studied widely. We first introduce some research on cascading failure of electrical power grids. Bienstock and Verma (2010) suggested a mixed integer programming model and a continuous nonlinear programming model to figure out whether a power grid can survive with k or fewer arcs where there are N arcs in a network. Even though this study did not consider cascading failure seriously, it gave an insight into modelling a power grid mathematically. Possible procedures of cascading failure in an electrical power grid have been presented in many articles (Carreras, Lynch, Dobson, and Newman 2002; Carreras, Lynch, Dobson, and Newman 2004; Chen, Thorp, and Dobson 2005; Dobson, Carreras, Lynch, and Newman 2007; Dobson, Carreras, and Newman 2005; Hardiman, Kumbale, and Makarov 2004; Nedic, Dobson, Kirschen, Carreras, and Lynch 2006; Pfitzner, Turitsyn, and Chertkov 2011). Most of the articles defined a series of power outage by assuming power grids to use direct current (DC) in order to simplify the problems. Since the studies deal with national-wide power distribution systems, DC approximation is enough to reflect the reality. They analysed several types of cascading failure, criticality, and so on. There are also studies of power grid failures by natural disasters. Han, Guikema, Quiring, Lee, Rosowsky, and Davidson (2009) proposed a model to predict power outages during hurricanes. On the other hand, decision making methodologies for recovery after blockouts to reduce damage have been studied as well as cascading failure itself (Guha, Moss, Naor, and Schieber 1999; Langevin, Perrier, Agard, Baptiste, Frayret, Pellerin, Riopel, and Trépanier 2009; Xu, Guikema, Davidson, Nozick, Çağnan, and Vaziri 2007). They mainly dealt with scheduling of recovery process after electric power distribution failed, especially after disasters including earthquakes and hurricanes. Lastly, Pinar, Meza, Donde, and Lesieutre (2010) suggested an optimal strategy to check the vulnerability of an electrical power grid.

In South Korea, there is a national research to design models for integrative disasters which may cause catastrophic damage to the critical social infrastructures including an electrical grid, a traffic system, a healthcare system, etc. As a part of the research, a cascading failure model needs to be developed taking the structure of the South Korean electrical system into consideration. As a first step, in this paper, we suggest a simulation framework for cascading failure which can be a basic reference for future studies. In addition, we introduce demand shedding policies for controlling balance of demand and supply, and minimising the loss of the total demand. Details of each subject are explained in the following sections.

The manuscript is organised as follows. In Section 2, we introduce a procedure of cascading failure of an electrical grid. In Section 3, internal mathematical models for finding stable flow of the electricity is presented. In Section 4, we suggest applying efficient demand shedding policies to reduce damage on the whole network.

2. A PROCEDURE OF CASCADING FAILURE

At first, we shortly introduce how the power outage spreads in an electrical grid. Figure 1 illustrates a flow chart for cascading failure of an electrical grid. As mentioned before, an electrical grid tries to be stable with balanced electrical flow. Stable flow is unique under assumption of DC approximation. We discuss how the stable flow can be obtained in Section 3. If an object in a grid is destroyed or harmed by a certain event, the structure of the network changes and the stability may also be broken. Then the grid tries to get balanced with new flow according to the physical property of the electricity. However, the new flow may not satisfy the pre-determined capacity of nodes or links because it ensures the safety of the network only in terms of the structure of the network, and does not consider detailed information of the elements in the network. In Figure 1, $f_{ij} < u_{ij}$ is the condition that the new flow does not violate the capacities of the elements, where f_{ij} is the balanced flow of the electricity from node i to node j, and u_{ij} is the capacity of the link from node i to node j. We do not consider the capacity of each node in a network in this paper. If the condition is violated for some elements, those elements are no longer functional in the network. In other words, the elements are considered to be destroyed and removed from the original network. This is why the cascading failure occurs. After the additional breakdown, the network repeats the same procedure until there is no breakdown.

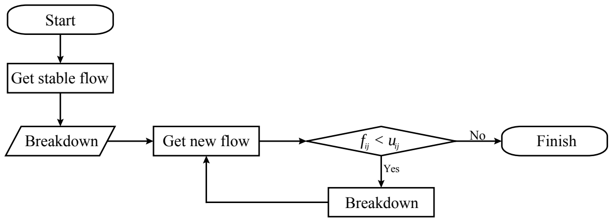

Figure 1: A flow chart for cascading failure

According to the procedure of cascading failure, one can expect huge failure of the entire network, even though an initial event destroys a single element. If the capacity of links are not enough to stand increasing burden, the extent of damage would be more serious.

3. A MATHEMATICAL MODEL FOR AN ELECTICAL GRID

As shown in Figure 1 and explained in the previous section, an electrical grid tends to remain stable due to its physical property. Therefore, modelling the balancing behaviour of the electricity in a network is one of the important jobs to be done. In this section, we explain the mathematical structure of DC-approximated networks and two alternative methodologies for obtaining stable flow of the networks. Some fundamental mathematical structure of the model has been borrowed in the previous study (Bienstock and Verma 1996).

3.1. A Mathematical Model

A network for an electrical power grid has three types of nodes: Generator, customer, and intermediate nodes. Generator nodes are responsible for generating the electricity and include various types of power plants. Though generator nodes may use the electricity themselves, we consider them as the nodes without consumption, and use the net value of the electricity as the amount of generation. Customer nodes are nodes that consume the electricity without generation. Intermediate nodes are nodes with net value of 0, which means the nodes are the medium connecting generators and customers. We model the supply/demand of the nodes in a vector $\begin{bmatrix} b_1 & b_2 & \cdots & b_m \end{bmatrix}^T$, where m is the number of nodes in a network, and b_i is the amount of supply/demand of the node i. If b_i is positive/negative/zero, node i is considered as a generator/customer/intermediate node.

The structure of a network is modelled in matrix $N = \left[N_{ij} \right]$ $(i = 1, \ldots, m, j = 1, \ldots, n)$. $N_{ij} = 1$ if node i is a source of arc j, $N_{ij} = -1$ if node i is a target of arc j, and $N_{ij} = 0$ otherwise.

In order to obtain flow of each link, say $f = \left[f_j \right]^T$ $(j = 1, \ldots, n)$, we need two additional matrices, X and θ. X is $n \times n$ diagonal matrix such that i th diagonal element indicates the reactance of node i . θ is $m \times 1$ column vector that represents the phase of each node.

In a DC-approximated electrical grid, we can eliminate a node assuming the phase θ of the node to be zero. This is because the phase of nodes in a network should be synchronised and a single node is able to be considered as the synchronisation node. Therefore, we can reduce the dimension of N , b , and θ into $\overline{N}$, $\overline{b}$, and $\overline{\theta}$, respectively, by removing the corresponding row of the matrices or vectors. Then, the phase and the flow of a network are uniquely determined with the following equations:

$$\overline{\theta} = (\overline{N}X^{-1}\overline{N}^T)^{-1}\overline{b} \text{, and} \quad (1)$$

$$f = X^{-1}\overline{N}^T\overline{\theta} \text{.} \quad (2)$$

3.2. Obtaining Balanced Flow: Matrix Operation

The first method to get flow of a network is calculating the phase vector $\overline{\theta}$ and f using conventional matrix operation. This method is simple but involves a lot of matrix inversion and multiplication operations which require long computation time and large memory. In addition, those operations need to be repeated in every round of cascading, so there is no advantage on statistical analysis either. In small scale problems, however, it is still worth using the matrix operations since they can be easily implemented and solved in reasonable computation time.

3.3. Obtaining Balanced Flow: Linear Programming

Even though the balanced flow is unique, linear programming approach guarantees much faster computation time in many cases. This is because linear programming solvers such as CPLEX and Gurobi do not perform full matrix operations by reducing the original matrices, and tend to get a solution in the initialisation phase according to the properties of algorithms for linear programming (e.g. simplex method) (International Business Machines Corporation 2012, Gurobi Optimization 2013).

In addition, a linear programming model which has been built once is reused with the dual simplex method. As mentioned before, the flow vector is calculated from the first in every cascading round with pure matrix operations. However, minor changes of constraints and decision variables can be adopted without remodelling if the dual simplex method is used for the linear programming model. Hence, after a linear programming model is set, the single model can be used in all cascading round, and even in multiple replication of experiments. This approach should save huge amount of time. Since it is known that there is only one solution, setting the objective function is trivial. We set an arbitrary objective function that maximises the sum of flow. The linear programming model is written as follows:

$$\max \quad \sum_{i=1}^{n} f_i$$

subject to

$$\overline{N}f = \overline{b} \quad (3)$$

$$Xf = \overline{N}^T\overline{\theta} \quad (4)$$

Constraints (3) and (4) are equivalent to (1) and (2). Equation (3) describes the flow has to satisfy every supply/demand of the nodes, and (4) presents the relationships among the flow, the reactance, and the phase.

In experiments that we conducted and explained in next section, the linear programming based procedure showed much higher computational performance. For networks with 1,000 nodes, the linear programming approach finished simulation in average of 5 seconds, while matrix operation took more than 10 minutes in most cases. Therefore, it is wise to use linear programming model for national-wide networks which have numerous nodes and links.

4. SIMULATION CONSIDERING DEMAND SHEDDING

The cascading failure model that we presented in Section 2 with Figure 1 assumes that the total amount of supply and that of demand is the same. This assumption is quite intuitive in terms of the fact that the power grid cannot have surplus electricity and the demand is satisfied in a stable network. However, the balance of the supply and demand breaks when one or more elements of a network fail. In order to meet the balance of the supply and demand, generators reduce the amount of generation when the sum of the supply is greater than the sum of the demand, and demand nodes forcibly reduce the amount of demand by causing partial outage when the sum of the demand exceeds that of the supply. This procedure is called demand shedding.

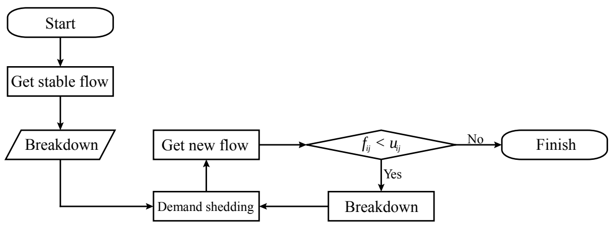

Figure 2: A flowchart for cascading failure considering demand shedding

The notable issue here is that the method to carry out demand shedding is not physically determined and there is room for humans to be involved as decision makers. That is, the damage caused by cascading failure can be lessened according to which demand shedding policy is used. Figure 2 shows the updated cascading failure flow chart applying a demand shedding policy. Most of the previous studies that we reviewed in Section 1 did not consider demand shedding seriously.

In this section, we review typical demand shedding policies that can be used in the real industry.

When power outage occurs, a decision maker needs to balance supply and demand manually. This shedding can be adjusting the amount of generation of a power plant or leading some demand nodes to be gone out. Since a power grid deals with the electricity and the tolerance of the network for standing unstable state may not be too long, the decision has to be made quickly to avoid severe damage on the network. If the decision making process is automated, the automated procedure should save a lot of time for shedding and eventually reduce damage on the network.

The demand shedding can be mathematically optimised to minimise the total damage on the network, it may need long computation time for a large network and not be able to meet a desired time limit for decision making. Therefore, we suggest to use pre-defined shedding rules based on empirical knowledge from the real system. We present four demand shedding policies on behalf of various possible policies.

4.1. Proportional Shedding Policy

This policy does not prioritise the nodes in a network. If some nodes fail, so the total amount of the demand exceeds the total supply, the policy decrease demand of all customer nodes based on the proportion of the demand of each node to the total amount of original demand. For example, let two customer nodes, say A and B, have demand of 100 and 200, respectively. If there is failure on some generator nodes and 60 should be reduced, A and B have 80 and 160 after the proportional shedding, respectively. This is because A has 1/3 of the total demand, B has 2/3 of the total demand, and the proportional shedding policy does not break the ratio of the demand of nodes to the demand of other nodes. The procedure is the same on the situation that the total supply is greater than total demand.

4.2. Largest-demand-first Shedding Policy

This policy gives priority to nodes according to the amount of their demand (supply). If imbalance occurs, the policy reduces the amount of demand (supply) in order of the priority. For instance, if there are two nodes A (100) and B (200), and 220 should be reduced, the nodes remain with demand of 80 and 0 after the shedding, respectively. Since the demand of node B is larger than the demand of A, B has higher priority. Therefore, the demand of B has been reduced to 0, and the demand of A has been reduced by the remaining 20.

4.3. Fewest-connection-first Shedding Policy

Fewest-connection-first policy is the same with the Largest-demand-first shedding policy in terms of prioritising the nodes in a network. The difference is that this policy gives higher priority to nodes with the fewer number of outgoing links. The electrical grid is modelled by a network with directed links (directed graph). This policy has come from the idea that avoiding demand shedding on hub nodes which are connected to many other nodes may preserve the original demand well.

4.4. Fewest-outgoing-first Shedding Policy

Fewest-connection-first policy introduced in Section 4.1.3 gives priorities to nodes considering the number of connected other nodes. Fewest-outgoing-first policy is similar with the Fewest-connection-first policy except that this policy only counts the number of outgoing links. Shedding a node with many outgoing links may affect a lot of other nodes, and this policy is intended to minimise damage by preserve those nodes as long as possible.

5. SIMULATION

We implemented the concepts explained in the previous sections into Java based software platform which can process existing network data or generate random network, and simulate cascading failure after an initial failure event (see Figure 3).

Figure 3: Cascading simulator

In the simulator, a user can customise the following conditions as input for cascading simulation.

- Input network: A user can put pre-defined input files describing a network or make the simulator generate an arbitrary network.
- Alpha (α): Exponential smoothing parameter for links (see Section 4.2.1).
- Tolerance (T): Tolerance of links in a network. Each link sets to have capacity of the initial stable flow multiplied by tolerance ($f_{ij}^{0} \times T$).
- Disaster scale (D): The scale of initial failure event. The simulator let D arbitrary elements in a network fail at first.
- Simulation speed.
- The number of replication.
- Demand shedding policy.

5.1. Simulation

In this subsection, we discuss details of the behaviour of the simulator.

5.1.1. Simulation Model

Figure 4 shows a simplified diagram representing the structure (objects) of a simulation model. A network object has node objects and link objects, and can be converted into a matrix introduced in Section 3.1. A Node object holds information of the location and the amount of power supply or demand, while a Link object has capacity, reactance, and its source and target objects (Nodes). A simulation model refers to a Setting object that contains input customization data mentioned at first in this section.

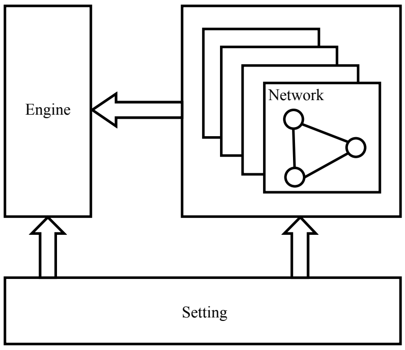

Figure 4: The structure of a simulation model and a simulation engine

As shown in Figure 4, we defined a simulation engine to be separated from a simulation model, so that the engine can manage simulation of general models (networks). The Engine object also uses a Setting to get configuration of simulation experiments.

5.1.2. Failure Model

In the real power grid, a link can stand during certain amount time even if the flow goes beyond the capacity. In other words, each link actually behaves based on the *effective capacity* or the *effective flow* which is the calibrated nominal capacity or flow. There can be many methods for determining whether a link fails or not such as moving average and exponential smoothing.

Moving average and exponential smoothing methods are to obtain the effective flow that can give links some extra sustainability on overflow by smoothing a certain degree of change. The moving average method gets the effective flow by calculating

$$\hat{f}_{ij}^{r} = \frac{1}{r+1} \sum_{k=0}^{r} f_{ij}^{k} \tag{5}$$

where f_{ij}^{k} is the flow from node i to node j at k th round. Exponential smoothing method also uses the effective flow obtained by

$$\hat{f}_{ij}^{r} = \alpha f_{ij}^{r} + (1-\alpha) f_{ij}^{r-1} . \tag{6}$$

On the other hand, we can give extra endurance to the links and use the effective capacity by multiplying extra endurance, say $\overline{T}$, to the capacity u_{ij} . That is,

$$\hat{u}_{ij} = \overline{T} \times u_{ij} = \overline{T} \times T \times f_{ij}^{0} \tag{7}$$

In the simulator, we applied exponential smoothing method to reflect all historical flow data into the effective flow of links.

5.1.3. Network Separation

During a simulation experiment, a network can be divided into several sub-networks after nodes or links are broken. The simulator that we designed considers such network separation as introducing new small networks working independently. That is, if a network is divided into two sub-networks, the simulator then deals with two individual networks. After splitting-up, each network set a new synchronisation node ($\theta_i = 0$) to sync the phase of nodes, and the simulator calculates the stable flow and demand shedding operations in parallel with the other networks.

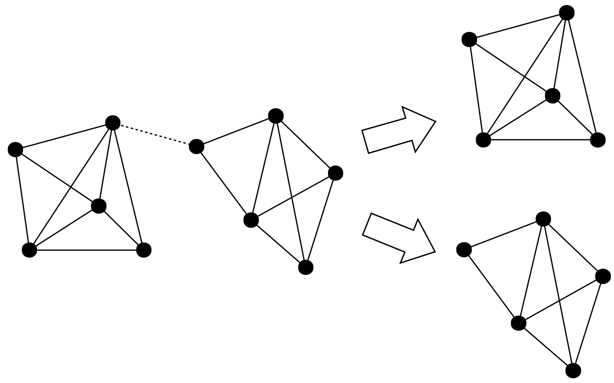

Figure 5: An example of network separation

Figure 5 illustrates an example of network separation into two networks. If a dotted link of the left network fails, the network is divided to two right side networks and each of them behaves independently upon the other network.

5.1.4. Node Failure

A node in a network fails due to the following reasons.

- Self-failure: During changing the amount of generation or demand, a node can fail with some internal errors. This kind of failure generally happens to generator nodes.
- Isolation: If all of connected links from/to the node fail, the node gets isolated and cannot do anything for the whole network, even though the node itself is still functional.
- Exhaustion: A node fails if the amount of demand or supply after converges to zero after shedding.

The simulator does not deal with self-failure of the node and assumes that all nodes can stand any types of demand/supply changes. In case of isolation, the simulator considers isolated nodes as failed nodes and removes from the network. Finally, generator and customer nodes that no longer have demand/supply (nodes that are exhausted) are treated as failed nodes.

The nodes may be able to function as intermediate nodes, but the simulator removes the nodes for consistency.

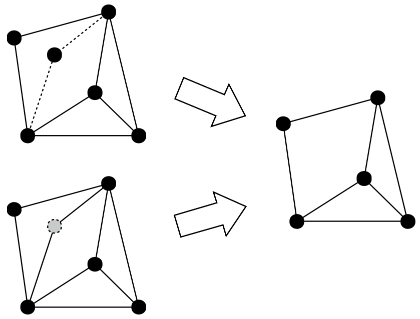

Figure 6: Examples of node failure

Figure 6 shows examples of node failure. The network on the top of left column describes isolation of a node. The node is removed after all of its connected links. The bottom network in the same column shows the case of self-failure and exhaustion. After the node is determined not to be functional, the node and its connected links are all removed.

5.2. Experiment: Comparing Demand Shedding Policies

We conducted simulation experiments with the simulator that is explained in the previous section to compare demand shedding policies introduced in Section 4. We simulated many types of networks as part of an effort to analyse the Korea electrical grid and present two virtual networks that are noteworthy.

The first sample network is tree-like and contains 102 nodes. The network has 4 generator nodes out of the 102 nodes and they are located in the root of tree. The second network is a much complex network that consists of 217 nodes and 285 links. In this network, each node is entangled by the other nodes more tightly.

We set the initial capacity of the nodes as 1.3 of the initial stable flow, which means that T is 1.3. In order to observe the dramatic effect of small failure, the scale of initial failure T was set to be 1. In addition, the value α was 0.5 to give the same proportion of historical data and the newly determined data. The simulation experiments were replicated 1,000 times for each network and demand shedding policy.

The simulation result is shown in Table 1. Proportional, LDF, FCF, and FOF in the first column of the table means the proportional shedding, the largest-demand-first policy, the fewest-connection-first, and the fewest-outgoing-first, respectively. The results for both the first and the second networks imply that the proportional shedding policy guarantees better performance compared to the other policies. In addition, LDF, FCF, and FOF policies do not show critical difference in terms of both the number of survived nodes and the percentage of preserved demand. Of course, these results do not cover all types of networks, but they are still valuable as the reference for the future studies. Besides, since the fundamental ideas (algorithms) and the simulator can deal with general networks provided in the pre-defined format, this study makes the future study much easier to achieve additional valuable results.

Table 1: Simulation Result

Network 1		
	% of survived nodes	% of preserved demand
Proportional	87.3	87.0
LDF	77.3	78.1
FCF	76.8	77.4
FOF	76.3	76.6
Network 2		
	# of survived nodes	% of preserved demand
Proportional	71.7	74.6
LDF	64.6	67.7
FCF	63.6	66.7
FOF	64.4	67.4

6. CONCLUSION

In this paper, we proposed a framework to conduct a simulation experiments for cascading failure of an electrical power grid. The cascading procedure, internal mathematical models and operations were introduced, and the simulator utilising the concepts had been implemented. In addition, we emphasised the importance of demand shedding policies and showed that cascading failure with different shedding policies end up differently in terms of the amount of preserved demand and the number of nodes.

Since this study deals with network models with capacity, the concepts that were introduced throughout the paper may be applicable to other reference systems such as the gas/oil system and the traffic systems like public transportation.

For further study, the simulation needs to consider self-failure of nodes which can cause serious problems and is decided with complex mechanism in real industry. Applying self-failure may include giving probability to fail to vulnerable nodes in the network and determine whether each node fails or not in every round of cascading. Besides, networks that have node capacity as well as link capacity should be considered for more realistic analysis.

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