

LINEAR MODELING AND SIMULATION OF LOW-VOLTAGE ELECTRIC SYSTEM FOR SINGLE-POINT VULNERABILITY ASSESSMENT OF MILITARY INSTALLATION

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ABSTRACT

This paper describes the formulation and development of a linear model to support the single-point vulnerability assessment of electric distribution systems at existing and future U.S. Department of Defense (DoD) military sites. The model uses flow sensitivity factors to rank candidates for designation as “critical components” and uses triggered cascading line outages to confirm the component’s criticality. The model is written in Java and integrated in a package that employs a user-friendly graphical user interface (GUI) for convenient display of results. This paper describes the process used to formulate the model and presents a sample application.

1 INTRODUCTION

This paper reflects recent work done for the U.S. Army Corps of Engineers’ Engineer Research and Development Center (ERDC) in Champaign, Illinois, in which Argonne National Laboratory was tasked to design and develop process objects for conducting a single-point vulnerability analysis of the electrical distribution system associated with a real military installation. The task also specified how the process objects would be used to (1) perform heuristic-based vulnerability assessments on the utility network objects and (2) propagate the effects of a single-point disruption throughout the whole electrical system. The task implies the development of an electrical system model that simulates electric system operations and approximates a reaction to postulated perturbations.

The ability of a military installation to accomplish its mission depends to a large extent on the reliability of its supporting energy utility systems. One of the most vital of these systems is the electric distribution system. The system that delivers electric energy at a military installation is essential for the continued operation of the installation’s telecom command center, its fluid (water and

fuel) pumping equipment, and its heating, ventilation, and air conditioning (HVAC) system. ERDC sought to provide the capability to help identify weaknesses that might exist in military installations.

2 PROBLEM DEFINITION

2.1 Single-point Vulnerability Problem

The single-point vulnerability assessment task deals with the problem of identifying the most critical component(s) of an electric distribution system (either a node or a link) with respect to a set of mission-critical loads. An electrical system component whose outage would only affect noncritical facilities (or loads) could not be classified as a point of vulnerability under this problem definition. The component must make the delivery system inadequate for serving the user-specified critical facilities in the military installation to be considered a point of vulnerability. Critical facilities are the buildings or sets of equipment that provide crucial support to the primary mission of the military installation.

In general, a single critical vulnerable point in the system could be defined as one that, when disrupted, would either (1) cause the isolation of the critical load or (2) result in a series of cascading outages of links that would ultimately cause the system to collapse. The important considerations here are the overloading of other links as a result of the initial outage and the degradation of the system voltage, especially the voltage at the target node (i.e., a node bearing a critical facility).

2.2 Heuristics for Criticality Identification

Some well-known heuristics for determining critical components in an electrical distribution system are as follows:

1. One rule of thumb is that “the most heavily loaded link/line is usually a critical component.” If the link

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1. REPORT DATE DEC 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Linear Modeling and Simulation of Low-Voltage Electric System for Single-Point Vulnerability Assessment of Military Installation				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL, 61826				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the Proceedings of the 2008 Winter Simulation Conference, 7-10 Dec, Miami, FL					
14. ABSTRACT This paper describes the formulation and development of a linear model to support the single-point vulnerability assessment of electric distribution systems at existing and future U.S. Department of Defense (DoD) military sites. The model uses flow sensitivity factors to rank candidates for designation as ?critical components? and uses triggered cascading line outages to confirm the component?s criticality. The model is written in Java and integrated in a package that employs a user-friendly graphical user interface (GUI) for convenient display of results. This paper describes the process used to formulate the model and presents a sample application.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			
			Same as Report (SAR)	9	

is confirmed to be among the participating links, then outage of this heavily loaded link should be simulated and further explored.

2. The other rule of thumb is to “disrupt the largest supply source in the system”. The first two largest sources of power for the distribution should be immediately considered highly potential single-point vulnerabilities for the system.

The model to be developed must thus be able to (1) rank all suspect or perceived crucial nodes and links with regard to their criticality and (2) show, via simulation, the cascading impacts if those nodes or links were suddenly taken out of the system.

3 MODELING CONSIDERATIONS AND MATHEMATICAL FORMULATION

3.1 Linear versus Nonlinear

One important concern when simulating a low-voltage electric distribution system is whether to use a linear or a nonlinear model. Linear models have the advantage of speed, primarily because they have no inherent convergence problem. Linear modeling of an electric network almost always refers to the use of a direct-current (DC) load flow approach. In this approach, a simple, direct, matrix inversion is needed to obtain the solution (power flow values in links). Moreover, linear models require less data input, because the parameters needed to describe a linear system are less complicated than those needed to describe a nonlinear counterpart. The drawback of linear models is that the results are approximate, and caution is required to limit deviations that extend into intolerable regions.

In nonlinear modeling of a distribution network, two paradigms immediately come to mind: (1) the single-phase, full alternate-current (AC) model (using the Newton Raphson method), and (2) the three-phase load flow. Distribution systems, unlike transmission systems, have an unbalanced load, and the ratio of resistance to reactance (R/X) is usually higher than those in high-voltage transmission systems. A higher R/X ratio implies higher inaccuracies within the linear model framework.

In this work, because of the scarcity of data related to the military installation being modeled, the linear model was selected. It was also noted that R/X ratios among the various links in the distribution network were less than 10%. An R/X ratio of less than 10% implies that the disparities in results between AC and DC simulation are within tolerable limits.

Several basic electrical modeling concepts are presented next as a part of the discussion on problem formulation.

3.2 Review of DC Load Flow Formulation

The concept of DC load flow is presented here for convenience to unfamiliar readers. The DC load flow program is used to determine line flows when scheduled power injection and demand in the nodes are given. In the DC load flow formulation, the relationship between the bus real power injections and the bus voltage phase angles is shown in (1) (Wollenberg 1996).

$$[\Delta P] = [B'] [\Delta \theta] \quad (1)$$

where

$[\Delta P]$ = vector of net bus power injection, per unit

$[\Delta \theta]$ = vector of net changes in bus voltage phase angle, in radians

$[B']$ = matrix consisting of constant line susceptances (inverse of reactance), expressed per unit (Crow 2003)

The DC load flow only represents real power flows (i.e., MW) in transmission or distribution lines and transformers. It gives no indication of what happens to voltage magnitudes or megavolt-ampere-reactive (MVAR) or megavolt-ampere (MVA) flows (Stott 1974).

Given the P_s (i.e., power injections, plus for generators and minus for loads), the bus angles are determined as shown by (2).

$$[\Delta \theta] = [B']^{-1} [\Delta P] \quad (2)$$

The power flowing through each line using the DC power flow is then calculated using (3):

$$P_{ik} = (\theta_i - \theta_k) / x_{ik} \quad (3)$$

where x_{ik} is the line reactance between Nodes i and k .

The power injection in a Node i is therefore calculated as shown by (4).

$$P_i = \sum_{k=\text{buses}}^N P_k \quad (4)$$

3.3 Transmission Distribution Factor Concept

Another concept fundamental to the problem formulation is presented is the concept of transmission distribution factors (TDFs). The TDF concept shows how a certain amount of power transmitted from one node (sending node) in the system to another node (receiving node) is distributed among the various paths of lines that link the sending node to the receiving node (Christie 2000).

When the generators are taken one at a time, the TDFs of all lines in the distribution system can be calculated given the identities of the target node (i.e., the node bearing the critical facility) and the selected generator node. This calculation is accomplished by using the basic DC power flow equation with modifications in the $[\Delta P]$ vector (i.e., power injection and load vector) such that the target node is represented as a negative one (-1) while all selected generator node is represented as +1. (This is called a point-to-point power transfer analysis.) All the rest of the nodes are set to zero. Mathematically, this is written as shown in (5) for the determination of the bus angles for, say, a six-bus system:

$$[\Delta\theta] = [B']^{-1} \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad \begin{array}{l} \leftarrow \text{target "load" bus} \\ \\ \\ \\ \leftarrow \text{selected generator node} \end{array} \quad (5)$$

In the case of the equation above, the selected generator node absorbs all the incremental load changes occurring in the target node. Note that in Equation 5, the slack node (swing generator) is not included. All units of measure are specified in per unit, except for θ , which is in radians. Note also that in $[B']$, the rows and columns corresponding to the slack bus are eliminated to make the equation solvable or nonsingular. The $\Delta\theta$ for the slack node is always set to zero, by definition.

To evaluate the TDF of lines with the slack bus as the selected generator, (5) changes to (6) as shown below:

$$[\Delta\theta] = [B']^{-1} \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \leftarrow \text{target "load" bus} \quad (6)$$

Note that the $[\Delta P]$ vector in (6) has all zero elements except for the target bus, which has -1.

The TDFs for each line for each case of point-to-point power transfer is simply the delta flow calculated from the above equations. Once $[\Delta\theta]$ is calculated, the TDF for each line is calculated using (7) (Christie 2000):

$$\text{TDF}_{ij \text{ case } y} = \text{Delta flow}_{\text{case } y} = [(\Delta\theta_i - \Delta\theta_j)/x_{ij}]_{\text{case } y} \quad y = 1, 2, \dots, 5 \quad (7)$$

where

$\Delta\theta_i$ = change in node angle in node i

x_{ij} = series reactance between nodes i and j, per unit

y = case number (e.g., Case 1 when Generator 1 is selected)

TDF_{ij} = transmission distribution factor for line ij

TDF is also defined as the ratio of the delta flow in the line to changes in MW load at the test node. However, since the perturbation at the test node was assumed to be minus unity, the delta flow value (which is a fraction) is identical to the TDF for that line. The TDF is an indication of how much the line flow (for a specific line in the distribution system) would change for an incremental change in MW load at the test node.

3.4 TDFs in Multiple Generator Single Load Configurations

The previous discussion centered on how to calculate TDFs in a scheme involving point-to-point power transfers. This section discusses how to determine TDFs when it is assumed that multiple generators operate simultaneously to send power across the network to a single load. This is called the weighted TDF calculation approach.

The weighted TDF calculation approach proceeds as follows:

- (a) Calculate the sum of all generator outputs and determine the percent share contribution of each generator. Mathematically, this could be expressed as shown by (8) and (9) as follows:

$$P_{\text{sum}} = \sum P_i \quad i = 1, 2, \dots, N \quad (8)$$

$$\text{Share}_{P_i} = P_i / P_{\text{sum}} \times 100\% \quad (9)$$

where

P_i = output of generator i in MW

i = generator index

N = total number of generators or supply sources

Share_{P_i} = percent share of Generator i in total generation output

- (b) Determine the weighted TDF by first calculating the θ in all nodes in the network and then using the Share_{P_i} values calculated in Step (a). The appearance of the DC load flow for determining θ by using the Share_{P_i} values for a six-bus system (assuming Node 1 is the slack) is shown by (10):

$$[\Delta\theta] = [B']^{-1} \begin{bmatrix} 0 \\ -1 \\ 0 \\ .4 \\ .1 \end{bmatrix} \begin{array}{l} \leftarrow \text{target load bus} \\ \leftarrow \text{supply node Share_P}_5 \text{ 40\%} \\ \leftarrow \text{supply node Share_P}_6 \text{ 10\%} \end{array} \quad (10)$$

In the case of the equation above, the slack (Node 1) is assumed to have a Share_P₁ of 0.5 to make the sum equal to unity (i.e., 0.4 + 0.1 + 0.5 = 1.0). All units of measure are per unit. Note that in B', the rows and columns corresponding to the slack bus are eliminated to make the equation solvable or nonsingular. The Δθ for the slack node is always set to zero.

(c) Then the TDFs could be calculated as usual, using (11).

$$\text{TDF}_{ij \text{ case } y} = \frac{\Delta \text{flow}_{\text{case } y}}{x_{ij}} = \frac{[(\Delta\theta_i - \Delta\theta_j)/x_{ij}]}{y} \quad y = 1, 2, \dots, 5 \quad (11)$$

where

Δθ_i = change in node angle in node i
x_{ij} = series reactance between nodes i and j
y = case number
TDF_{ij} = transmission distribution factor for line ij

3.5 Flow Distribution after Generator or Line Outages

To simulate the impact of the outage of a link, a program must be developed to “eliminate” a line from the link input data matrix. If a link to be outaged does not isolate any generator, then the link can be “deleted,” and a DC load flow could be run to determine the new loading in the lines. If overloading occurs, these violations should automatically be noted by the program; however, if the link to be outaged isolates a generator, the output of that generator (which may be isolated) should be distributed in some fashion (possibly in proportion to capacity or generation level) among the surviving generators before the DC load flow is run. Again, overloading may be observed and should automatically be noted.

In the case of (10), if, for example, a link connected to Node 5 is outaged (and therefore isolates Node 5), then Node 5's pre-outage output is distributed among the remaining generators as shown in (12).

$$\text{Post-outage share of } P_6 = 0.1/(0.1 + 0.5) = 16.7\% \quad (12)$$

$$\text{Post-outage share of } P_1 \text{ (Slack)} = 0.5/(0.1 + 0.5) = 83.3\%$$

The new (post-outage) output of the surviving generators is then would be:

$$P_{6 \text{ post-outage}} = P_{6 \text{ pre-outage}} + \text{Post-outage share of } P_6 * P_{5 \text{ pre-outage}}$$

$$P_{1 \text{ post-outage}} = P_{1 \text{ pre-outage}} + \text{Post-outage share of } P_1 * P_{5 \text{ pre-outage}}$$

The system with the new dispatch and system configuration is then re-simulated by using the DC load flow, and overloaded lines are noted and observed. If a second-stage overloading occurs, it is a signal that a cascading line failure could occur. In such cases, the second-stage overloaded line (in addition to the first-stage overloaded line) must be taken out of the system, and the system is again re-simulated. If there is a third-stage overloading, the outage of the third-stage overloading must be simulated by using the DC load flow. The sequence of line trippings must be recorded to show the propagating effect of the initial disruption.

The launching of the DC load flow is triggered automatically. If the simulation does not result in a second-stage overloading, the link is disregarded as being critical. Otherwise, the second-stage overloaded lines should be identified and the system should be re-simulated, assuming again that these lines (in addition to the first-stage outaged line) are removed.

4 ALGORITHM FOR SINGLE-POINT VULNERABILITY DETERMINATION

4.1 Steps in Vulnerability Assessment

The three concepts described above were used to adopt a deterministic approach to identify the single-point vulnerability of the distribution system. The steps for assessing single-point vulnerability of the links follow here. Steps for assessments involving nodes follow a similar logic. A requisite of these steps, is for the military manager of the site to identify and tag the critical facilities within the site or installation.

Step 1. *Identify all links that are involved in delivering power to the facility.*

This undertaking traces the flow of power from the source(es) to the facility under consideration and, in the process, identifies all links supporting the flow. (These links are sometimes called “participating links” in this document.) A TDF-based approach is employed to identify which lines are sensitive to the load when certain sources of power are assumed. The link with the largest sensitivity to the facility is the most promising candidate for single-

point vulnerability and is the line most crucial to the facility (i.e., it is the line carrying the greatest amount of power to the facility).

The amount of interrupted power caused by a disrupted line at the critical facility is roughly equal to its TDF (sensitivity factor) multiplied by the magnitude of the load in MW. So, if a link has a TDF of 1.0, cutting off the link would completely isolate the critical facility. (This would be expected of the service line linking the facility to the distribution grid.)

If the facility is served by several feeders (e.g., three) or from several sections of the network, the facility is said to have high electric service reliability. This is so because it would take three single point disruptions (in our example) to isolate the facility. However, a systems analysis is needed to determine if the remaining links would have enough capacity to absorb the power shifted to them by the disrupted line.

In carrying out the TDF calculation, the process first assumes a point-to-point transfer of power. That is, the generators are examined one at time, first to determine which links are involved in delivering power from that specific generator to the target load and second to determine which among those identified links has the highest TDF or sensitivity factor. The link with the highest sensitivity factor is a candidate (maybe secondary) for single-vulnerability assessment. The entire process takes into account only the first five largest generators in order to minimize the computation time and search effort. However, the five-candidate list would be enough to capture some of the most critical links. The combined effect of having all generators operating simultaneously could be determined by adopting the point-to-point approach and then applying the principle of superposition. Alternatively, the weighted TDF approach could be employed.

Step 2. Rank the links according to their TDFs.

A disrupted link with a TDF of 1.0 isolates the facility and cuts off power completely. If the link involved is near the facility, the outage would not be as widespread as if the link was nearer to the source. (This demonstrates that the concept of “proximity of supply” to the target node is a factor in determining critical single vulnerable points.) This link and the nodes at its ends are automatically identified as “single-point vulnerabilities.”

If a link has a TDF of less than 1.0, it is possible for other links to support the facility, subject to their individual design capacities. A systems analysis should then be conducted to determine if the outage of the primary link causes a cascade of overloading events among the surviving links. A link that has a high TDF but does not

cause the overloading of other links is not a single-point vulnerability candidate. If, however, the link with a high TDF causes another link to be overloaded, that second overloaded link should also be taken out to determine if further overloading occurs. If it does occur, the link is a single-point vulnerability link. Simulation should stop after the outage of the second overloaded line is completed. After this, it would be fair to conclude that the disturbance would propagate throughout the system and that the system would not adequately serve the critical facility.

Since the simulation would consider both nodes and links, it is appropriate that an outright DC load flow simulation be performed to determine the second-stage overloading events.

Step 3. Simulate extent of cascading effects.

As each link with high TDFs is assumed to be outaged, overloading in certain lines will occur. It is assumed that overloaded lines will subsequently trip, thereby creating a second-tier outage condition. The second-tier outage situation, when simulated, could lead to a third-tier outage situation and then to a fourth and so on, until the system splinters into island grids. Island grids must maintain a supply-demand balance. Because the generation sources are dispersed throughout the installation and come in various sizes, an island grid may contain no generation sources at all. This implies total blackout for the island grids having no generation. From the perspective of the installation, this is seen as a further loss of loads (i.e., unserved demand). Other island grids with generation and loads greater than supply, will require load shedding. Overall, as the system collapses and island grids form, there would be a general net loss of load within the installation. The sequence of line trippings is recorded to show the propagating effect of the initial disruption. Figure 1 illustrates the concepts of system collapse and island grid formation after the vulnerability assessment steps outlined above characterize the response from a critical link outage. A sequence of island grid formation after the loss of a critical generator is shown in Figure 2.

4.2 Codes and Flowchart

The flowchart for algorithm execution is shown in Figure 3. The flowchart highlights the process of identifying critical links or nodes..

The code was written in Java and integrated in a package with a user-friendly GUI. The GUI is highly sophisticated, addresses a broad range of user requirements, and deserves a separate paper for a detailed description.

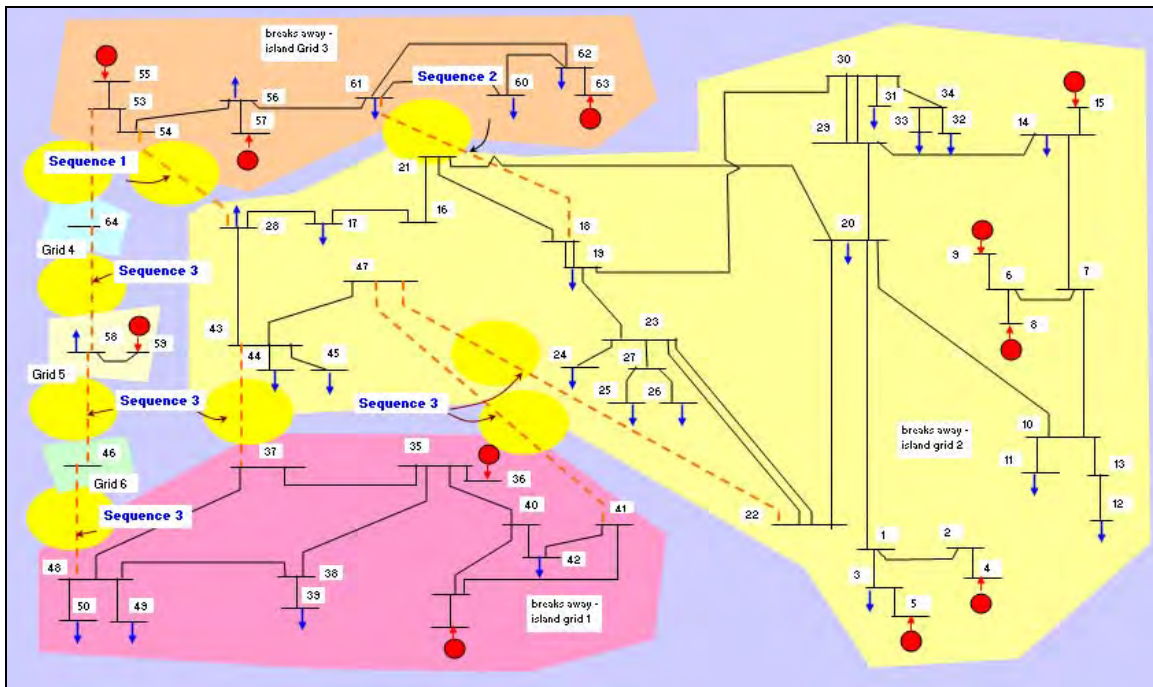


Figure 1: A 64-node network splinters into six island grids after a critical link indicated in “Sequence 1” tripped and triggered cascading line outages. Each colored area represents a splintered island grid. Location of line outage is indicated by the yellow circle.

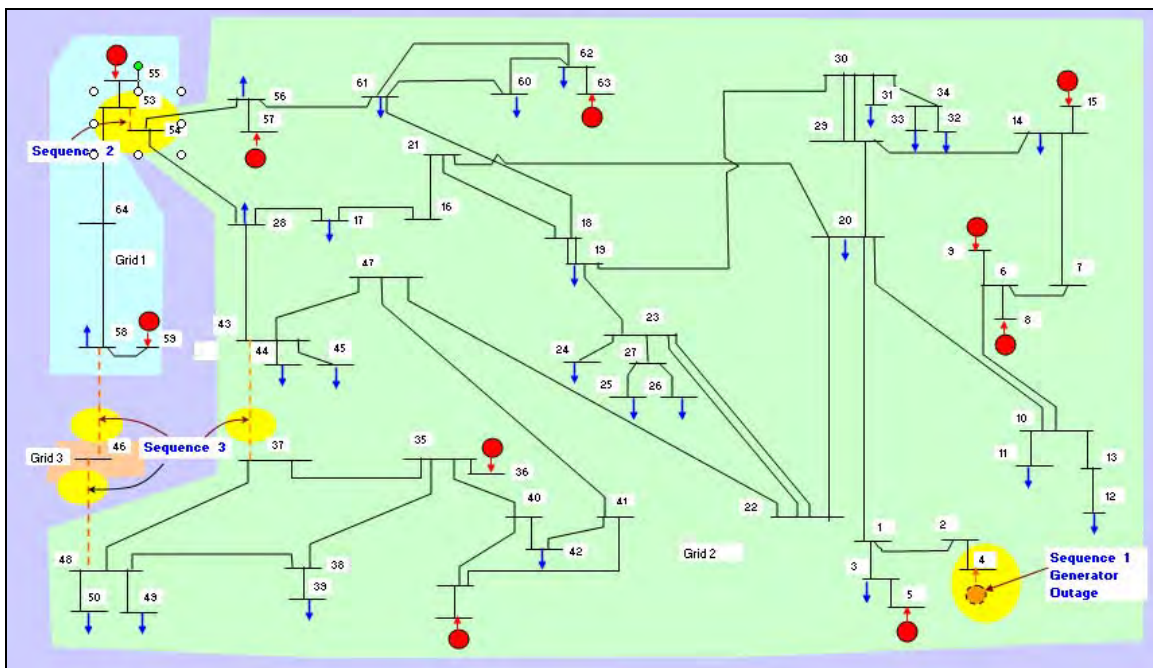


Figure 2: Three island grids formed as a result of the outage of a critical generator in “Sequence 1.” Line outage is indicated by the yellow circle. The other events that ensued are labeled as “Sequence 2” and “Sequence 3.”

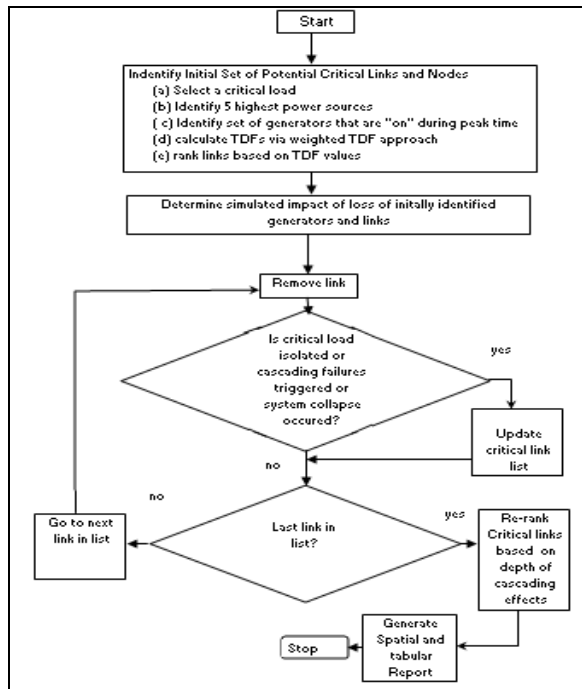


Figure 3: Simplified flowchart for single-point vulnerability assessment code.

5 IMPLEMENTING THE SCHEME AND SIMULATION RESULTS

5.1 Important Assumptions

Time-of-day assumptions represents a particular modeling concern. Time of day relates directly to the system loading condition (i.e., considering both generator dispatch and load distribution) and contributes to the definition of the component's criticality. A component may not be critical during low-load or average-day conditions but be critical during peak-day conditions when reserve margins are at their lowest.

Another important assumption is that in most military installations, there are no sophisticated automatic load-shedding schemes in case there is a supply-demand imbalance. This assumption implies that the system demand remains fairly constant as the cascading event progresses. During final settlements into various island grids, the generation sources in each island grid are allowed to re-dispatch to match demand and thus maintain the supply-demand balance.

There were no impedance data for a number of lines at the installation. Argonne developed an impedance reconstruction module to generate approximate impedance values for data-deficient lines. In the process, certain assumptions were made about the construction

materials (e.g., copper or aluminum) and distances between wires on the basis of their voltage levels.

Lastly, the primary supply substations that feed power to Site X from the local grid are represented as generators in the model.

5.2 Features and Characteristics of the Subject Military Installation

For security reasons, the name of the actual military installation whose electric system was subjected to vulnerability assessment is not disclosed here; instead, it is called Site X. This site encompasses a large area and is divided into several partitions. In the initial testing phase of the vulnerability assessment model, the application was directed to Partition 1 of Site X. The layout of facilities in Partition 1 is shown in Figure 4. The general characteristics of the distribution system in that partition are summarized in Table 1.

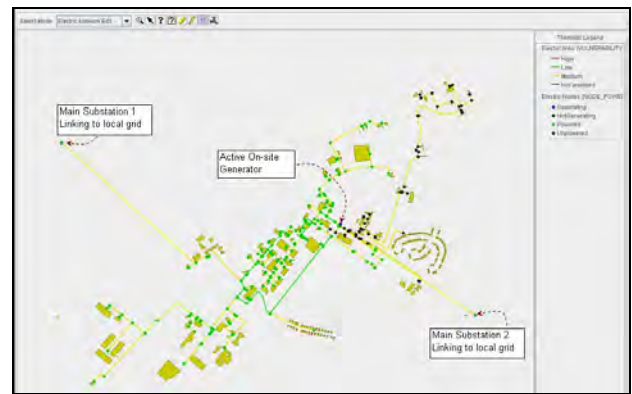


Figure 4: Layout of electric distribution system showing various nodes and links as depicted in the model's GUI. Yellow and green indicate normal flow.

Table 1: Salient Features of Electric System for Site X. (The abbreviation SS stands for "substation.")

Parameter	Description
1. Total demand	8.3 MW
2. Total no. of lines	294
3. Total no. of buses	288
4. Voltage levels	12.5 kV, 480 V
5. No. of supply SSs	2
6. Voltage ratio of SS	230/12.5 kV
7. Wiring methods	Under - and aboveground
8. No. of on-site generators	Numerous; one active
9. System configuration	Looped/radial

Note that the integrative environment within which the model operates includes other infrastructures, such as the water network, natural gas system, buildings, and

roads These are interdependent within the installation, discussed in greater detail in one of the listed references (see Bozada 2006). Including other infrastructures enables the model to extend its analysis to consider interdependency implications among the various coupled infrastructures. (e.g., how disruptions in an electric system affect the water system and natural gas network).

5.3 Simulation Results

An application requiring the vulnerability assessment model to identify and rank the most critical lines in Partition 1 of Site X was undertaken by the authors. The manner by which the simulation was triggered via the GUI is shown in Figure 5. The resulting ranked links in Site X are listed in an output table shown in Figure 6. The results indicate that Line Node 7-1-6892 to Node 7-1-622 is the most critical line. The outage of this line would lead to system collapse, de-energizing 288 nodes and 290 lines. The location of this most critical link is shown in Figure 7.

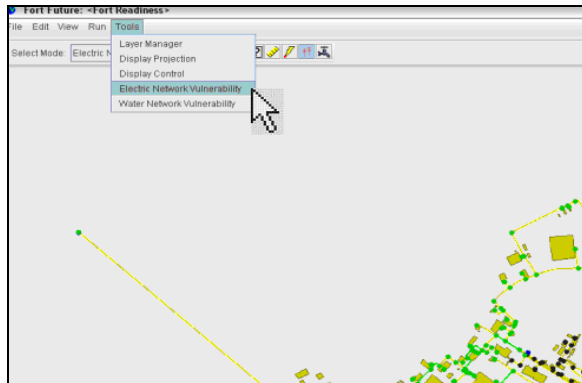


Figure 5: Model's GUI showing user action to start a ranking of critical links in Site X.

Electric Network Vulnerability Analysis									
Analysis	Component	Vulnerability	Unpowered Critical	Powered Critical	Unpowered Non-critical	Powered Non-critical	Used generators	Unused generators	Links w/ No Flow
Select	Link [7-1-6892 - 7-1-622]	Medium	0	0	288	0	0	0	290
Run	Link [7-1-6522 - 7-1-4514]	Medium	0	0	288	0	0	0	290
Results	Link [7-1-1065 - 7-1-1059]	Medium	0	0	284	4	1	2	286
	Link [7-1-1063 - 7-1-1053]	Medium	0	0	284	4	1	2	286
	Link [7-1-1065 - 7-1-1053]	Medium	0	0	284	4	1	2	286
Component	Link [7-1-1059 - 7-1-1040]	Medium	0	0	280	0	1	2	282
Highlight	Link [7-1-4540 - 7-1-4522]	Medium	0	0	70	218	3	0	95
Zoom To	Link [7-1-4522 - 7-1-4514]	Medium	0	0	66	222	3	0	95
	Link [7-1-4514 - 7-1-4494]	Medium	0	0	66	222	3	0	95
Outages	Link [7-1-4504 - 7-1-4492]	Medium	0	0	60	228	3	0	96
	Link [7-1-4493 - 7-1-4502]	Medium	0	0	91	237	3	0	95
	Link [7-1-4513 - 7-1-4502]	Medium	0	0	91	237	3	0	95
	Link [7-1-1016 - 7-1-1025]	Medium	0	0	44	244	3	0	43
	Link [7-1-4550 - 7-1-4540]	Medium	0	0	41	247	3	0	40
	Link [7-1-4513 - 7-1-4508]	Medium	0	0	41	247	3	0	40
	Link [7-1-4551 - 7-1-4550]	Medium	0	0	39	249	3	0	38
	Link [7-1-4552 - 7-1-4550]	Medium	0	0	39	249	3	0	38
	Link [7-1-4544 - 7-1-4551]	Medium	0	0	39	249	3	0	38
	Link [7-1-4508 - 7-1-4494]	Medium	0	0	39	249	3	0	38
	Link [7-1-4498 - 7-1-4492]	Medium	0	0	36	252	3	0	36

Figure 6: Tabular output pane showing results from action initiated in Figure 5. Table shows list of critical lines ranked from the most to the least critical.

Highlighting a specific link in the tabular output pane and clicking it simulates the outage of that specific link. In Figure 8, Link 7-1-4540 to 7-1-4522 is selected as the outaged line (i.e., its corresponding record is highlighted and pointed to by the cursor in the tabular output pane).



Figure 7: Location of the most critical link identified in the table shown in Figure 6.

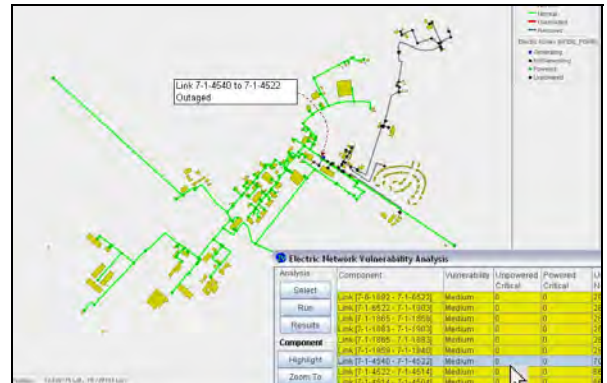


Figure 8: Exploration of segments affected by the tripping of a specific link of interest.

The corresponding sections isolated or affected by this action is indicated by segments of the electric network that are in black. The green lines indicate unaffected segments.

6 SUMMARY AND CONCLUSIONS

This work illustrates how linear modeling concepts in power system simulation are used in vulnerability assessment studies. Although the linear models are approximate, they are sufficient for assessing the relative criticality of components in the distribution system of a military installation. The model has been used by DoD provide improved and deliberate security measures to protect its military installations.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of the following organizations: Argonne's Infrastructure Assurance Center and Modeling, Simulation, and Visualization Group for providing technical and logistical support and the U.S. Army Corps of Engineers' ERDC for providing the data and funds for the project.

REFERENCES

- Bozada, T. A., Perkins, T. K., North, M. J., Simunich, K. L., Tatara, E. 2006. *An Applied Approach to Representing Human Behavior in Military Logistics Operations*, Simulation Interoperability Standards Organization (SISO), 2006 Fall Simulation Interoperability Workshop, September 10-15, 2006; available at http://ms.ie.org/SIW_LOG/06F/06FSIW-102.pdf.
- Christie, R., F. Wollenberg, and I. Wangensteen. 2000. Transmission Management in the Deregulated Environment, in *Proceedings of IEEE*, 88(2): 170-195.
- Crow, M.. 2003. *Computational Methods for Electric Power Systems*, CRC Press LLC.
- Stott, B., and O. Alsac. 1974. Fast Decoupled Load Flow, *IEEE Transactions on Power Apparatus and Systems*, Vol-PAS 93: 859-869, May/June.
- Wollenberg, B., and A. Wood. 1996. *Power Generation Operation and Control*, Second Edition, John Wiley and Sons, Inc., Canada.

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