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SIMULATING THE POTENTIAL IMPACTS OF A 10-KILOTON NUCLEAR EXPLOSION ON AN ELECTRIC POWER SYSTEM SERVING A MAJOR CITY

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ABSTRACT

This paper describes the methodology employed by Argonne to simulate the potential impact of a nuclear explosion on an electric system serving a large populated city. The method uses a combined deterministic and heuristics-based approach for the analysis. Initially, deterministic steady-state tools, such as load flow and *EPfast*, are used to explore the possibility of uncontrolled islanding. Heuristics are then used to estimate additional potential cascading effects, particularly during the transient period. The effects of the electromagnetic pulse are determined on the basis of findings from previous related studies, while the probable system dynamic response is estimated by using heuristics. System resilience is heuristically assessed in several aspects, including partial and full-load rejection capability of participating power plants, power swing allowance based on initial power angle values, and over-frequency relay protection sufficiency against extreme grid events such as sudden loss of a large load. Major findings are presented and discussed.

1 INTRODUCTION

High-impact man-made events such as the detonation of a nuclear device can directly damage electrical facilities over a wide area. Indirectly, the effects of the blast and the accompanying electromagnetic pulse (EMP) could “shock” the power system, potentially cause large-scale interruptions, and eventually lead to total system collapse. System collapse can be triggered by a sudden loss of a large load resulting from the simultaneous destruction of clusters of electrical demand centers. For many of the nation’s emergency response organizations, such as FEMA, it is important to estimate the impacts of a postulated nuclear blast on the electrical system to develop appropriate mitigation and recovery plans.

Facilities that could be damaged or destroyed by a blast, heat, and/or EMP generated by the explosion include generators, transmission lines, and substations on the supply system and power loads on the demand side. It is possible that the magnitude of these perturbations to the power system could precipitate a blackout that might extend well beyond the impact zone. It is necessary to estimate the geographic extent of the blackout, including consideration of multi-county, statewide, and regional or national impacts.

2 SCENARIO DESCRIPTION AND BASIC ASSUMPTIONS

2.1 Scenario Description

The scenario postulates a 10-kiloton nuclear detonation in the center of the downtown area of Any City (fictitious names are used to mask the real identity of the city and its critical electric assets) in the U.S. It is assumed that terrorists assembled a nuclear device using highly enriched uranium stolen from a nuclear facility in a foreign country. The components were smuggled into the U.S., and the device was assembled inside the country near Any City. Using a delivery van, terrorists transported the device to the downtown region of the city and detonated the device.

2.2 Basic Assumptions

The basic assumptions pertaining to location, date, time, and reach of the blast are summarized in Table 1. The assumptions also list possible measures available to local power utility and regional transmission organization (RTO) personnel to mitigate grid events. The system mitigation measures assumed for the pertinent local and regional power entities are standard for high-performance systems in the U.S. The characteristics of the blast and the size of the payload were specified by FEMA.

Table 1: Blast characteristics: basic assumptions for the scenario (DHS 2006).

Parameter	Description/Value
1. Date of Attack	January 15, 2009
2. Time of Attack	12:00 pm (noon)
3. Location of Explosion	Center of Any City
4. Detonation Altitude	Ground Level
5. Radius of Severe Damage Zone	0.5 mile
6. Radius of Moderate Damage Zone	1.0 mile
7. Radius of Light Damage Zone	3.0 miles
8. Radius of Type 1 EMP	1–3 miles
9. Radius of Type 3 EMP	1–3 miles
10. Worst Case for EMP Impacts	3-mile radius
11. Optimistic Case for EMP Impacts	1-mile radius
12. System Mitigation Measure 1	Automatic Governor Action
13. System Mitigation Measure 2	Selective Generator Tripping Scheme
14. System Mitigation Measure 3	Over-frequency Protective Relay Action

2.3 Assumed Effects of EMP on Electric Power Facilities

Included within the scope of the assumptions are the various empirical and anecdotal observations about the nature of the EMP and its potential impact on electrical equipment. Three types of EMPs (sometimes called “components”) can be generated by the nuclear blast: E1, E2 and E3. The first component, E1, is the “electromagnetic shock” that disrupts or damages electronics-based control systems, sensors, communication systems, protective systems, computers, and similar devices. The middle EMP component, E2, covers about the same geographic area as E1 and is similar to lightning in its time-dependence but is somewhat lower in amplitude. The final major EMP component, E3, is a subsequent, slower-rising, longer-duration pulse that creates disruptive currents in long electricity transmission lines, resulting in damage to connected electrical supply and distribution systems. Most references reviewed by the authors consider E1 and E3 only as most damaging to electrical equipment.

The following list is a summary of major impacts of EMP components, particularly E1 (Items 1 and 6 below) and E3 (Items 2 - 5 below), on electric power systems within the estimated 3-mile radius of a 10-kiloton nuclear explosion.

1. Electronic circuits and programmable logic controllers embedded in most electronic control and telemetry equipment are destroyed.
2. High-amplitude surge currents, similar to those caused by geomagnetically induced currents from solar storms of equivalent intensity, are induced in transmission lines.
3. The substation equipment located at the terminals of EMP-affected transmission lines is put at risk of permanent damage because of high current and voltage surges.
4. Excessive currents are induced in transformer cores, resulting in overheating and fires.
5. Transformer saturation and direct-current offsets tend to add inductive load to the system and cause voltage collapse, as available volt-ampere reactive (VAR) compensators are stretched beyond their capability.
6. Relays and control equipment malfunction and trigger unintended or undesirable system actions or switching.

2.4 Brief Description of the Electric System

The backbone electrical system that supports Any City consists of a robust network of 345- and 138-kilovolt (kV) transmission lines. The total load within the 3-mile radius of the postulated nuclear blast is estimated to be between 2,500 and 3,000 megawatts (MW) during winter and could reach about 3,800 MW during summer. A multi-circuit, 345-kV ring encircles Any City (see Figure 1). Major substations within the 1-mile radius of the postulated blast are linked primarily by a 138-kV underground transmission system with support of a 345-kV transmission system. However, switchyards for most of these substations are located aboveground and are vulnerable to direct impact by the blast.

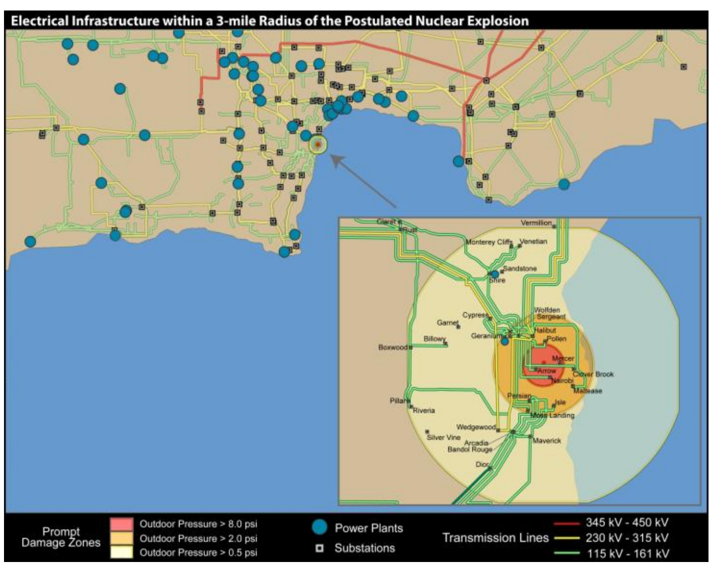

Figure 1: Electric infrastructure serving Any City and 3-mile radius of the postulated nuclear-explosion damage zone.

The two major utility-owned power plants nearest to the downtown area are located about 1.8 to 5.5 miles from the location of the postulated blast. A cluster of other large (more than 1,000 MW each in capacity) fossil-fired power plants (located about 30–50 miles northwest of the city's centroid) supply power to the downtown area. It was noted that gas plants are normally not dispatched during winter because of the relatively high seasonal cost of natural gas.

2.5 Pre-Event Conditions

Table 2 lists the condition of the electric power system prior to the attack. The 15 power plants serving the downtown area of Any City have participation factors (i.e., percent share of Any City load) ranging from 8 to 26%, involving 10–86% of their generator rating. It was observed that power plants nearer to the downtown area tend to exhibit higher participation factors.

Table 2: Pre-event conditions: basic assumptions for the scenario.

Parameter	Description/Value
1. January 15 Winter Load	16,000 MW
2. Summer Peak Load	22,000 MW
3. Number of Customers	4 million
4. Load of Any City Downtown	2,500–3,000 MW
5. Load of Downtown Area as Percentage of Total Load of Local Utility	~12–15 %
6. Resiliency	Robust 345-kV Ring Encircles Any City
7. Diversity of Supply	Coal, Gas, Nuclear
8. Average System Power Factor	0.958
9. Average Line Loading Level	~40%
10. Steady-state Stability Margin	~70%
11. Major Gateways (Substations) at Outskirts of Downtown Any City	Indigo, Green, Purple, White (4)
12. Large Power Plants Serving the Downtown Area	Crystal, Kiwi, Mountain, Shire, Indigo, Velvet, Shimmer, Canton, Tree Fern, Bubble, Sabal, Aegean, Tropical, Scotland, Amazon (15)

The portion of the generator output that directly supports the load of Any City (that portion being expressed as a percentage of individual generator ratings) provides important indicators of the potential output reduction that these power plants may need to perform to quickly restore supply-demand balance in case of a sudden loss of the entire Any City load. Quick output reduction of generators is sometimes referred to as "load rejection" and is initiated by autonomous governor actions of individual generators.

With regard to power system stability allowance, the average voltage angular difference between sending and receiving ends of all transmission lines within local power utility territory is less than ten electrical degrees, which indicates an unstressed system operating well below its steady-state stability limit (typically capped by a threshold angular voltage difference of 45–50 degrees).

3 METHODOLOGY AND DATA SOURCES

3.1 Overall Methodology

The overall methodology for impact assessment of electrical infrastructure is based on the following procedure, which is described further in Sections 3.3-3.5:

1. Run a base case load flow to establish pre-event conditions.

2. Identify electrical facilities at risk of damage by the blast and EMP; estimate the potential amount of load (megawatts) to be lost as a result of the blast and EMP.
3. Run *EPfast* (*EPfast* is Argonne's model for simulating system collapse) assuming all at-risk facilities are offline, to explore tendency to splinter into smaller pieces of isolated networks triggered usually by possible cascading line overloads.
4. If no islanding occurs, proceed to Step 5. Otherwise, assess the extent and depth of outages by quantifying the megawatts lost for each of the formed island grids (island grids are small networks that are separated from the original grid due to a major disturbance). Apply heuristics to estimate additional impacts due to transient effects. Generate reports. Stop.
5. Apply heuristics to estimate impacts of transients on system stability.
6. Estimate the depth and extent of power outages. Generate reports. Stop.
7. Perform a restoration-time assessment.

3.2 Data Sources

The primary sources of data for this analysis include the following:

1. Information provided by FEMA pertaining to basic scenario assumptions;
2. Load flow data on the U.S. System from the Federal Energy Regulatory Commission;
3. Platts *PowerMap* (Platts PowerMap 2011);
4. Information provided by pertinent RTO and local power utility pertaining to system protection and resiliency;
5. Information provided to Argonne by a private engineering company; and
6. Information verbally provided to Argonne personnel by local power plant operators pertaining to operational characteristics of coal plants and settings of protective over-frequency relays.

3.3 Deterministic Approach for Assessing Blast and EMP Effects

The deterministic component of the methodology has two aspects. The first involves the identification of the electric facilities directly affected by the blast (e.g., fire, heat, and air pressure) and those directly and indirectly affected by the EMP. The second aspect involves the use of a steady-state electric simulation model, *EPfast,* to explore the possibility of the grid's splintering into island grids as a result of the simultaneous disruption of a cluster of transmission lines, substations, and power generating facilities. Theoretically, the simultaneous loss of a large number of electric assets would cause inadvertent power flows (i.e., re-routing of power) that could potentially result in line overloads and cascading failures leading to system collapse.

The EMP effects would be assessed by superimposing the electric-facilities geographic layer on the damage-intensity footprint of the blast. Facilities that are within the 3-mile radius of the blast are assumed to be either extensively damaged or significantly affected by EMPs. Electric facilities in this group are called Category 1 facilities. Substations that are connected to the terminals of the affected Category 1 assets would also be considered disrupted because these serve as sinks to the large currents induced within the Category 1 transmission lines. Facilities affected in this fashion are called Category 2 facilities. Substations within the Category 2 facilities could be damaged or disrupted and would further cause all the transmission lines connecting with them to likewise de-energize. The transmission lines affected by the outage of Category 2 substations are likewise considered as Category 2 facilities. Together, the Category 1 and 2 facilities represent all facilities that would be assumed to simultaneously cease operation at the moment of the blast. The impacts of the simultaneous failure of these facilities are examined using Argonne's *EPfast* model (Portante et al. 2011).

3.4 Heuristics-based Methodology for Assessing Effects of Transients

Heuristics are increasingly the tool of choice in conducting quick impact assessments, especially when a full-blown transient stability simulation using sophisticated software is not available. Heuristics are "rules of thumb" derived via empirical observations of actual system behaviors or responses to extreme events. They can provide insights into the potential impacts of a disturbance. Specifically, they bound the extent of the impacts by relating the system size and characteristics to the intensity or magnitude of the disturbance or events. They can provide reasonable data with regard to the potential of an outage for spreading beyond the source region of the nuclear blast.

During extreme events, such as a sudden loss of large load or generation, the power system is subjected to a transient stress characterized by abrupt changes in frequency and voltage. Because the power system operates in electrical synchronism (i.e., always maintains a frequency of 60 cycles per second or hertz [Hz]), this normally steady and harmonious operation is "jolted" by these extreme events, causing the synchronized operation mode to move suddenly into a chaotic state (Wollenberg and Wood 1996). The jolt can cause generators to "swing out of step" and disengage from the grid and cause the network to separate, forming into "island grids." In the process of island grid formation, many loads could be lost, resulting in widespread blackouts.

Power systems maintain a frequency of 60 Hz, varying very slightly between 59.05 and 60.05 Hz during normal changes in loads. During loss of a large load, the supply-demand balance is disrupted; the supply suddenly becomes much greater than the demand, which causes the generators to accelerate. As a consequence, frequency could rise in a few seconds. The size of the disturbance determines, in part, the extent of frequency excursions during transients (i.e., first 10 seconds after the event). The ability of the system to regulate frequency changes also affects the magnitude of frequency perturbation. Figure 2 shows the typical frequency response of the system for a sudden loss of load equivalent to 10% of its system load. The percent regulation normally refers to the droop settings of frequency-sensitive governors of generating units within the system.

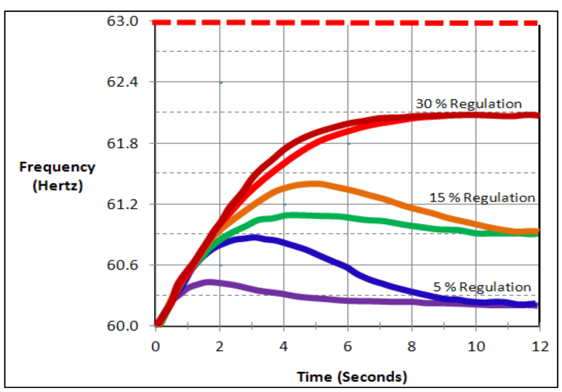

Figure 2: Frequency response to a sudden 10% loss of load.

3.4.1 Over-frequency Protection Schemes

To maintain system stability and supply-demand balance, power systems are fitted with protection schemes for both under- and over-frequency events. A sustained over-frequency condition is not desirable because it can damage both loads and generators. A total of three generator-related schemes can be implemented to mitigate extreme over-frequency tendencies in power systems:

1. Automatic governor action;
2. Selective generator tripping; and

3. Over-frequency relay action.

For large, abrupt changes in loads, governor action is the first line of defense for maintaining the supply-demand balance. Governor response to frequency perturbation is quick and usually occurs within the first 12 seconds of a disturbance.

If governor response is not sufficient, a selective generating-unit tripping option would most likely be initiated to restore supply-demand balance. Selective generator tripping is usually done prior to automatic activation of over-frequency relays (i.e., frequency perturbation still rising but below threshold value of 63 Hz).

As a final mitigation measure, automatic over-frequency relays may come into play to protect generators from damage. The tripping action by over-frequency relays could aid in restoring supply-demand balance to the system. Under this scheme, the relays at generator stations are generally set at a threshold of 63.0 Hz, at which point the generators are tripped and islanded. In a two-step scheme, 10 percent of total system generation is typically shed at each step. Typical set points are 63.0 Hz, with minimal time delay, and 63.0 Hz with a short time delay.

3.4.2 Heuristics for Assessing Transient Effects

The heuristics-based assessment method looks at empirical curves or data on power system behaviors vis-à-vis certain disturbances that are akin to the scenario being postulated. The approach examines the pre-event steady-state stability indicators and stress levels to estimate allowance to absorb large disturbances. An important element of heuristics is the expert opinions of the utility operators who are particularly knowledgeable of the system under consideration. Along this line, it is important to consider the experience-based opinions of the pertinent local power utility, independent system operator, and RTO.

3.5 Determining the Outage Area

The extent and depth of the power outage would be based on the combined effects of both steady-state and transient perturbations in the power system resulting from the blast. The steady-state impacts would be deterministic in nature and would be indicated in part by the number of island grids formed because of cascading overloads and quantity of load lost in the process of island formation. Assessment in this respect could be aided by use of the *EPfast* model. The steady-state aspect would also include the extent of physical destruction directly caused by the blast and the electrical disruption directly or indirectly caused by the EMP. Assessment in this respect could be aided by superimposing the footprint of EMP impact zone on the electric infrastructure spatial layer and then manually projecting the cascading influence of the EMP onto the physical network.

Effects of transient impacts include (1) perceived impacts of power swings on various generators, (2) effects of estimated frequency perturbations on over-frequency relays, and (3) influence of EMP-induced VAR equipment failure on the probable occurrence of voltage collapse. Determining the spatial dimensions of transient effects is difficult and would rely heavily on heuristics or known “rules of thumb.”

4 RESULTS AND RELATED DISCUSSIONS

4.1 Immediate Impacts and Outage Area Due to Nuclear Blast

The damage to equipment due to the direct impact of the blast is estimated to extend up to a radius of 3 miles from ground zero (it traverses the high-, medium-, and light-damage zones), as shown in Figure 1. This 3-mile-radius zone may also be termed the “source region.” Significant levels of EMP effects are known to extend up to the periphery of the source region. The indirect effects of EMP also impact equipment located outside of the 3-mile radius, because it is attached to the terminals of transmission lines within the zone that are impacted by EMP-induced current surges. Equipment beyond the 3-mile-radius could further impact more distant transmission and feeder lines linked to it, so the potential for equipment damage outside of the 3-mile-radius zone is high.

As explained in Section 3.3, the impacted elements within the 3-mile radius are designated as Category 1, while impacts extending beyond the 3-mile radius due to the cascading effects of EMP are designated Category 2. Figure 3 shows the electrical facilities belonging to Categories 1 and 2. A more enhanced depiction of Category 2 transmission facilities is shown in Figure 4. The estimated outage area due to the combined effects of Category 1 and 2 impacts is shown in Figure 5.

The results of *EPfast* simulations indicate that there would most likely be no occurrence of any island grid due to cascading overloads. This result appears consistent with the theory that, overall, the loss of a large but radially situated load would most likely result in the underloading of the network lines rather than their overloading.

With the likelihood of no major islanding event occurring, the extent of the power outage in the region could be estimated on the basis of the physical spatial expanse of Category 2 facilities (Figure 5). The farthest Category 2 element is about eleven miles from the center of the blast.

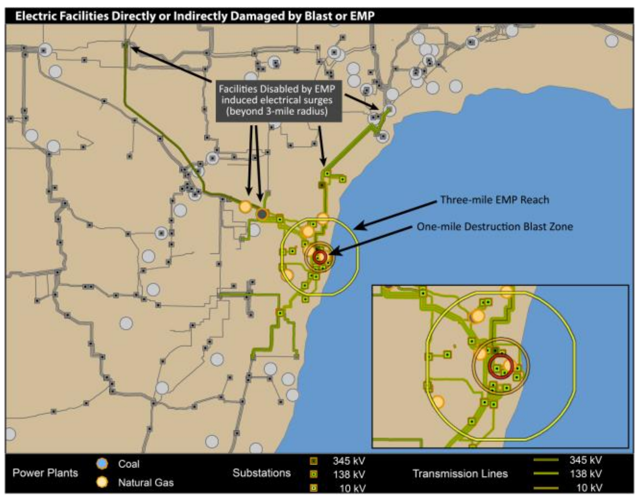

Figure 3: Electric facilities (Categories 1 and 2) instantly affected by the blast and EMP.

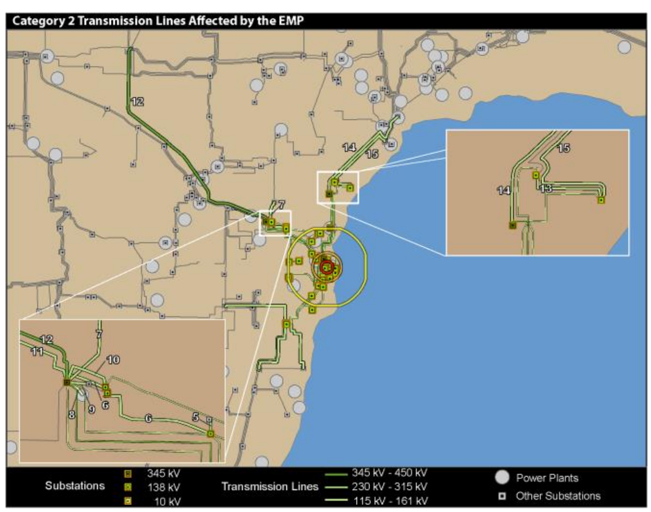

Figure 4: Category 2 transmission lines affected by the EMP.

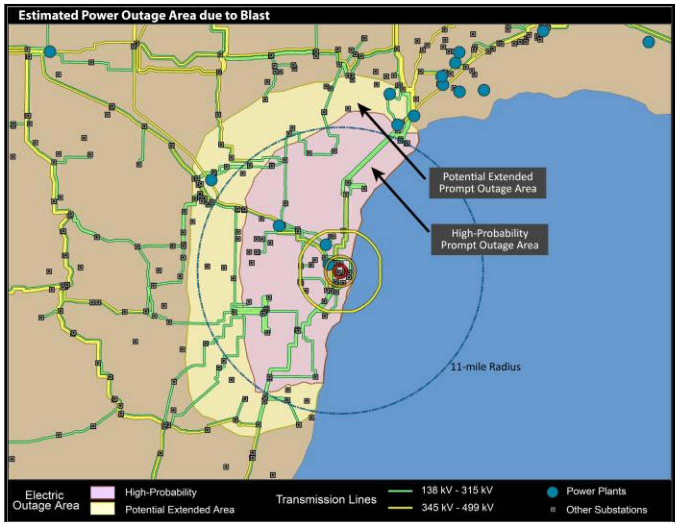

Figure 5: Estimated power outage area due to the blast.

The immediate impacts of the nuclear explosion may be summarized as follows:

- Grid Operations
  - A sudden loss of about 2,500–3,000 MW of clustered load would occur within Any City and the surrounding metropolitan area.
  - The local power utility system would most likely experience a partial network collapse. The resulting power outage area would probably extend beyond the 3-mile radius to as far as 11 miles out, but within the 345-kV transmission ring encircling Any City. The 345-kV transmission ring has an average radius of about 25 miles from ground zero. These estimates were determined by tracing the cascading effects of EMP on the network and by evaluating the impacts of ensuing line trippings.
  - Service would be disrupted to an estimated 3 million people in the metropolitan Any City area.
  - *EPfast* simulation results indicate that, most likely, no islanding would occur as triggered by steady-state cascading line overloads.
- Substations
  - Destruction of, extensive damage to, or disruption of a large number of high-voltage substations would occur, consequently affecting a large number of power plants and transmission lines in the counties containing Any City and the surrounding metropolitan areas.
- Generating Plants
  - Significant damage to the 600-MW, 700-MW, and 10 other smaller non-utility-owned generating units (fossil-fired units totaling about 100 MW) would occur within a 1-mile radius of the blast. These impacts were estimated based on previous studies involving a similarly sized nuclear explosion (DHS 2006)
  - Partial output reduction (load rejection) would likely occur in several large coal-fired power plants serving Any City.
  - Possible selective tripping would be performed on one large power plant, Canton Power Plant (coal-fired), as a mitigation measure.

4.2 Extent and Depth of Power Outage

The application of heuristics to assess the transient effects of the disturbance on the outage area resulted in the following findings:

- Cascading electrical network disruptions would likely extend slightly beyond the 11-mile radius from ground zero but may be confined to areas within the 345-kV transmission ring. The 11-mile power outage reach reflects the distance of the farthest Category 2 facility relative to ground zero.
- Frequency perturbations would most likely be unable to reach the relay tripping threshold of 63.0 Hz, and, thus, would not cause automatic generator tripping.
- By means of autonomous governor responses, participating fossil-fuel-fired power plants would most likely be able to handle partial load rejections without tripping from the grid (Kundur 1981).
- If governor response is not sufficient, a selective generating-unit tripping option would most likely be initiated to restore supply-demand balance.
- The local power utility and RTO systems appear resilient against an abrupt 10 percent load loss based on a generic system frequency response curve.
- Power swings resulting from the disturbance would likely be unable to force any generator to step out of synchronism because of a large allowance for power swings. The average initial power angle value of less than 10 degrees is well below the maximum safety steady-state stability limit of 45 degrees, thus providing space for inherent electromechanical restorative forces to return the system to stable operating conditions.

Overall, a number of participating generators would most likely trip primarily because of load rejection. The RTO supports the above findings as indicated by statements provided by RTO personnel during an interview. As an overall result, the prompt instantaneous outage area is estimated to be as shown in Figure 5.

4.3 Potential for Wider Power Outage Area

The possibility of an extended outage area beyond the 345-kV transmission ring cannot be dismissed. The response of the power system during actual events often differs significantly from its simulated behavior. An extended outage area may be possible for several reasons:

- The electric power grid is so complex that it is difficult to completely account for all the synergistic interactions that would occur during a major grid event, such as the one under this scenario.
- The impact of EMP on VAR compensating equipment and subsequent voltage perturbations are not sufficiently accounted for in this analysis.
- Protective schemes and equipment may fail to operate as intended or designed.
- VAR compensators may prematurely trip, leading to widespread voltage collapse.
- The exact effects of EMP on the operation of solid-state electronics that constitute most of the modern control systems of the grid are not fully understood.

4.4 Emergency Response Benefits

Such an incident would cause substantial damage to Any City and the surrounding metropolitan area, requiring a robust emergency response. The capability to model the effects on the area electrical grid enables more precise, better integrated emergency plans to be developed for reducing the adverse impacts on people and property. The benefits are twofold. First, the information resulting from this effort can be used to estimate not only the direct impacts of the event on the grid, but also its cascading impacts on other critical infrastructure and key resources, such as ascertaining which area drinking water providers may be without electricity to drive pumps even though their facilities are undamaged by the blast itself. Second, the response to an event like the one depicted will require large logistical operations to be staged from nearby areas that have sufficient electrical and other critical assets. Detailed understanding of the likely electrical outage characteristics facilitates advance identification and preparation of candidate sites that are capable of hosting these massive efforts. Thus, this and other similar modeling efforts can contribute significantly to more effective emergency response.

5 CONCLUSIONS

The study shows that extreme grid events, such as a sudden loss of large load due to a nuclear detonation, have significant steady-state and transient effects on the power system. Although the steady-state effects are substantial (primarily manifesting in the amount of instantaneous megawatt power loss and cascading line overloads), the transient perturbation in both frequency and voltage could have a much more profound impact on system stability. The use of tools such as load flow and *EPfast* for steady-state analysis, coupled with heuristics to represent transient assessments, could be sufficient to bound the extent of impacts of large disruptions and support better emergency planning coordination.

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