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Nuclear Maintenance Applications Center: Post-Trip Voltage Prediction at Nuclear and Other Generating Stations

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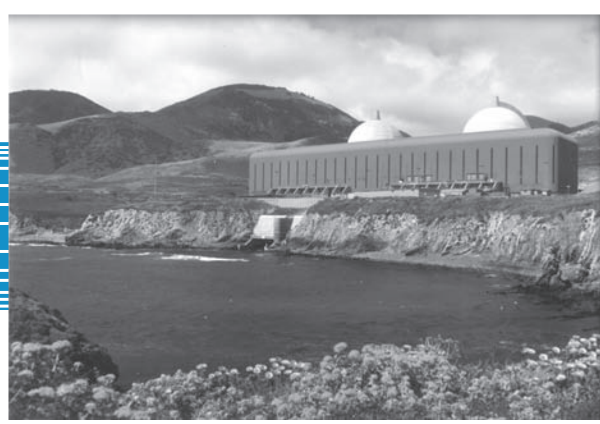

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PRODUCT DESCRIPTION

The objective of this Electric Power Research Institute (EPRI) project is to investigate the possibility of predicting the switchyard voltage in a nuclear power plant (NPP) following a trip of a nuclear unit. Two methods of post-trip voltage prediction are investigated. The first method, called the *V-Q method*, uses minimal local plant information (such as unit operating conditions—active and reactive power output and pre-trip voltage) to predict post-trip voltage based on the sensitivity of voltage to the reactive power output of the unit. This method yields excellent results if the slope of V-Q can be evaluated on-line and periodically. The second method, called the *regression tree* method, uses data mining techniques through regression trees that are developed off-line. This method requires, in addition to the local plant information, some information from the vicinity of the plant (such as the status of the nearby units and transmission facilities). The use of regression trees is proposed as a complement to the V-Q method to evaluate the post-trip voltage whenever on-line updating of the V-Q is not possible or temporarily unavailable.

Results and Findings

The accuracy and applicability of the V-Q method and the regression tree method were evaluated at two NPPs. The results of the V-Q simulation proved to be quite accurate. This method is applicable for on-line implementation at the control room of NPPs, using minimal local plant on-line measurements. The required local data are the on-line measurements of voltage, reactive power output, and V-Q slope of the unit. The regression tree method uses a database of simulated post-trip voltages (through a conventional power flow program) corresponding to a large number of scenarios, including plant output variations, contingencies of the important units, and transmission facilities in the vicinity of the NPP. The database for this method should be developed off-line; however, the developed regression trees can be used in an on-line environment to predict post-trip voltage. The accuracy of this method is not as high as that of the V-Q method, but it can complement the V-Q method whenever the slope of V-Q is not available.

Challenges and Objectives

The importance of predicting post-trip voltage at NPPs has been the focus of many Nuclear Regulatory Commission (NRC) standards and guides. The NRC Generic Letter 2006–02, "Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power," stressed the need for plant operators to know what conditions on the grid would affect plant bus voltage. That Generic Letter was the primary driver for this project. The essential auxiliaries of NPPs are sensitive to both voltage and frequency. Pumps and control valves can supply sufficient cooling circulation only if voltage and frequency are greater than predefined values. The operation of the degraded voltage relay to ensure timely bus transfer and startup of emergency diesel generators relies heavily on the voltage, including the resultant post-trip voltage. Thus, NPP operators must ensure that post-trip voltage and frequency levels are adequate to support the critical equipment.

The NRC has suggested the application of real-time contingency analysis (RTCA) software for assessment of post-trip voltages. However, RTCA is costly, and it requires extensive system data obtained from supervisory control and data acquisition as well as a system model from the state estimator. Application of RTCA for NPPs might be well beyond the need and expertise of plant staff. The methods investigated in this research project are both simple and accurate, and they require minimal effort for on-line evaluation. The objective of this research project is to investigate the possibility of predicting the switchyard voltage in an NPP following a unit trip.

Applications, Value, and Use

Plant operators can accurately predict the switchyard voltage following loss of unit by implementing the methods developed in this research project. The methods are simple, with on-line application requiring minimal local information. Implementation of these methods should assist NPPs in ensuring safe and reliable operation of the essential auxiliaries.

EPRI Perspective

Post-trip voltage after the trip of the generator of a nuclear unit is of paramount importance to NPP operators. The NRC has expressed the importance of knowing the offsite voltage level in order to ensure safe and reliable shutdown of NPPs. Also, most plants are required to ensure that they have a reliable source of offsite power in the case of a plant trip. EPRI funded this research project to evaluate methods that could possibly provide NPP operators with simple and accurate methods of predicting switchyard post-trip voltage.

This report presents recommendations that could be used for assessing post-trip voltage; however, these recommendations require review by plant operators and transmission entities to determine whether data to support the proposed assessments can be practically obtained.

Approach

The research team assessed the application and accuracy of the V-Q and decision tree methods for predicting post-trip voltage at two NPPs: San Onofre, which is part of the Western Electricity Coordinating Council (WECC) power system; and Palisades, which is part of the North American Electric Reliability Council (NERC) system.

Keywords

Decision tree method
Post-trip voltage prediction
Power flow program
Time domain program
V-Q slope method

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1
INTRODUCTION

1.1 Background

A critical aspect of safe operation of a nuclear power plant (NPP) is the reliability and security of the normal and emergency power supplies to the essential plant auxiliaries, such as circulating pumps, fans, control valves, and so on. These auxiliaries (mainly ac motors) are essential for heat removal following a plant trip so that the plant components, such as boiler tubes and furnace walls, will not be damaged due to the extremely high temperature. Unlike conventional power plants (thermal plants or hydro units), a nuclear reactor of a nuclear plant generates considerable heat from fission product decay even after the chain reaction has been completely shut down. This decay could persist for several hours; therefore, the auxiliaries require a long-term stable source of electric power supply—either from offsite (the grid) or from on-site power supplies such as emergency diesel generators) [1–3].

The loss of both offsite and on-site power supplies is referred to as a *station blackout*. Risk analyses performed for NPPs indicate that a station blackout can be a noteworthy contributor to the core damage frequency [4]. Although on-site power supplies can be used when the offsite power supply is unavailable, the loss of an offsite power supply is considered a precursor to the loss of all ac power supplies to the station, and an increase in the frequency or duration of the loss of offsite power increases the probability of core damage. Thus, the offsite power supplies are considered the preferred power supplies and must be kept at a high state of availability.

During certain operating conditions, the generators might be used to help support the voltage of the nearby high-voltage transmission system, and for this reason, the low grid voltage will not be noticed until the generator voltage support is no longer available. If the offsite transmission facilities are served from the same high-voltage system, grid contingencies and special events that would trip the nuclear generator could also cause a depression of voltage on the offsite circuits due to loss of voltage support. The essential auxiliaries of the nuclear plants are sensitive to both voltage and frequency. Pumps and control valves can supply sufficient cooling circulation only if voltage and frequency are greater than predefined values. Therefore, NPP operators must ensure that post-trip voltage and frequency levels are adequate to support the critical equipment.

The Nuclear Regulatory Commission (NRC) issued Generic Letter 2006–02, "Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power," which focused on the need for plant operators to know what the conditions are on the grid that would affect plant bus voltage [4]. That Generic Letter was the primary driver for this project. EPRI contracted with Powertech Labs Inc. to investigate and evaluate the methods that can reliably be used to predict post-trip voltage following a loss of the nuclear unit.

1.2 Objectives

The objectives of this research project were (1) to identify methodologies that can be used to predict post-trip voltage levels available to plant auxiliary equipment using a minimum set of local measurements and (2) to evaluate the accuracy of the techniques in predicting the post-trip voltage.

1.3 Literature Review

The researchers conducted a literature review of the existing methodologies regarding post-trip voltage prediction in order to determine whether an acceptable methodology exists or the development of alternative or new techniques is warranted. As part of this task, the team reviewed the paper "A Simplified Method to Predict Post-Trip Switchyard Voltage at Nuclear Generating Stations," which proposed the use of V-Q curves to predict post-trip voltage levels [5]. The paper described the safety considerations of NPPs during their upsets and indicated that offsite power supplies are the preferred power supplies [2, 5]. The availability of offsite power supplies can be affected by three main factors—tripping of the main generator, automatic bus transfers, and the addition of plant emergency loads. The paper pointed out that monitoring real-time voltage does not ensure the capability of the offsite circuits; the adequacy of post-trip voltage can be verified only through a predictive methodology [5].

The prediction of the post-trip voltage usually relies on the modeling of the transmission grid, which involves hundreds of thousands of inputs, parameters, and states, and which is beyond the jurisdiction of the NPP operators. The paper proposed a simplified method, using only a few local operating parameters, to predict post-trip switchyard voltage at NPPs. This method uses the slope of the V-Q curve (the ratio of the change of reactive power to the change of voltage) near the generator operating conditions. Because the pre-trip voltage and reactive power output of the generating plant are local variables and are easy to monitor, it is quite straightforward to calculate the post-trip voltage using the V-Q slope and the pre-trip quantities [5]. However, the paper did not verify the proposed approach by any experimental or empirical data, and the accuracy of this approach remained unknown. Because V-Q curves are sensitive to both the grid operating conditions and the plant operating conditions, this approach might not yield accurate results. As part of the literature review, the researchers also evaluated data mining techniques—especially regression trees—and their suitability to predict post-trip voltage.

2
APPROACH, STUDY CASES, AND TOOLS

2.1 Approach

In order to evaluate the accuracy of the V-Q curve methodology for predicting post-trip voltage and to generate data for the regression tree method, it was necessary to model the power system and simulate a number of scenarios and contingencies. The scenarios included (1) one or more of the nearby transmission lines out of service, (2) one or more of the nearby generators out of service, and (3) the NPP at different loading conditions. For each scenario, the pre-trip voltage, real power, and reactive power of the NPP were recorded. The slope of the V-Q curves ($\Delta Q/\Delta V$) were computed by applying a step change to the voltage amplitude of the nuclear generator (in power flow simulation, this is achieved by changing the scheduled voltage of the generator PV bus) and recording the change in its reactive power output. The post-trip voltage can be predicted by using the following equation [5]:

$$V_2 = V_1 - \frac{Q_1}{\Delta Q / \Delta V}$$

The correct (steady-state) post-trip voltage following a unit trip can also be calculated by simulating generator outage in a conventional power flow program, similar to real-time contingency analysis (RTCA). The system condition and the post-trip voltages obtained by both methods are recorded for each of the studied scenarios.

Because the V-Q method might not be sufficiently accurate to predict post-trip voltage under all possible system operating conditions, an alternative method was developed that can replace or complement the V-Q curve method. The decision tree method is based on data mining, using classification or regression trees. The decision tree method is especially suited for post-trip voltage prediction because the problem is nonlinear and the solution is constrained by the availability of a minimum set of local measurements. To develop a decision tree for post-trip voltage prediction, it is necessary to model the power system and simulate a number of scenarios and contingencies. For each simulated scenario and contingency, several attributes (generator active and reactive power, terminal voltage, auxiliaries main transformer tap setting, and so on) are recorded along with the post-trip voltage. The decision tree technique can then be used to identify key attributes that are required to accurately predict post-trip voltage. After the decision tree is developed, it is a simple task to determine post-trip voltage from the key measured attributes.

The post-trip voltage prediction by the V-Q curve and decision tree methods were evaluated through power flow simulations using the system data for two typical NPPs. The results of post-trip voltage prediction using these methods and those obtained by power flow simulations should demonstrate the application and effectiveness of the proposed approaches. The following tasks were completed in order to achieve the project objectives:

1. Obtain North American Electric Reliability Council (NERC) and Western Electricity Coordinating Council (WECC) power flow and dynamic data base cases (complete system model).
2. Identify a typical NPP in the NERC system and one in the WECC system, and perform the following tasks for each site.
3. Create several scenarios with variations in both power system and NPP operating conditions (for example, availability of any other generators and transmission facilities in the vicinity of the NPP). For each of the power system conditions, create different output conditions of the NPP (different levels of active and reactive power output, scheduled terminal voltages, and so on). For each scenario, create a new power flow base case in the NERC and WECC base cases.
4. Perform static analysis to compute the $\Delta Q/\Delta V$ at the NPP by imposing a new scheduled voltage and computing the change in the reactive power output.
5. Use the following equation to predict the post-trip voltage [5]:

   $$V_2 = V_1 - \frac{Q_1}{\Delta Q / \Delta V}$$

6. Use a power flow program to simulate NPP outage, and obtain the post-trip voltage at the NPP.
7. Use a time domain program to simulate loss of the NPP, and record the NPP voltages following the unit trip as well as at 5 seconds after the trip.
8. Store the results of voltages obtained in steps 5 and 6 in a database. In addition to the predicted voltage, record other system conditions such as total system load and generation, status of the facilities (transmission or generation) in the vicinity of the NPP. Establish a matrix of system conditions (see Table 2-1).
9. Use a decision or regression tree program to predict the post-trip voltage (the Outcome columns in Table 2-1) from the recorded quantities (the Attributes columns in Table 2-1).

Table 2-1
Post-Trip Voltage Prediction Matrix Corresponding to Different System Operating Conditions

Attributes								Outcome	
								V_{dip} from $V_2 = V_1 - \frac{Q_1}{\Delta Q / \Delta V}$	
Scenario	V_{NPP}	P_{NPP}	Q_{NPP}	Q/ V	Other Quantities . . .	V_{dip} from Time Domain Simulation (Step 7)	V_{dip} from Power flow Simulation (Step 6)	Q/ V Computed in a Power Flow Program (Step 5)	Q/ V Computed in a Time Domain Program
Generator X O/S	. . .	. . .	. . .	. .	. .	. .	. .		
	. . .	. . .	. . .	. .	. .	. .	. .		
Line AB O/S	. . .	. . .	. . .	. .	. .	. .	. .		
. . .	. . .	. . .	. . .	. .	. .	. .	. .		

Note: V_1 and Q_1 are the pre-trip reactive power and terminal voltage of the NPP generator, and Q/ V is computed by imposing a new scheduled voltage and obtaining the change in reactive power (evaluated at pre-trip condition).

2.2 Study Cases

Researchers completed the following tasks in order to create a set of power flow base cases to analyze the methodology for post-trip voltage prediction under different system operating conditions:

- Used two power flow base cases corresponding to the NERC 2007 series and the WECC 2011 approved case.
- Selected two NPPs for the study—San Onofre, in California (WECC), and Palisades, in Michigan (Reliability First).
- Created a set of power flow cases for each NPP considering several transmission system operating conditions as well as NPP status and output. For example, the team examined the availability of generators and transmission facilities in the vicinity of the NPP and different plant operating conditions (different levels of active and reactive power output, scheduled terminal voltages, and so on).

2.3 Simulation Tools

The computer simulation tools used for this project are components of Powertech's DSATools power system analysis package. The following tools were used:

- **Powerflow and Short Circuit Analysis Tool (PSAT)**. This tool is used for all tasks related to power flow analysis including the calculation of Q/ V sensitivity. In this project, PSAT plays a role similar to that of an RTCA used in energy management at the control centers of power utilities and independent system operators.
- **Voltage Security Assessment Tool (VSAT)**. This tool is used to identify the most critical and sensitive contingencies as far as its impact on the nuclear unit at the selected NPP.
- **Transient Security Assessment Tool (TSAT).** This tool is used to perform time-domain simulations for the selected cases in calculating the "exact" post-trip voltage following loss of the NPP.

3
POST-TRIP VOLTAGE PREDICTION

3.1 Post-Trip Voltage Prediction Equation

The post-trip voltage prediction following loss of NPP using the V-Q curve method relies on Equation 3-1 [5]:

$$V_{post} = V_{pre} - Q_{pre} \frac{\Delta V}{\Delta Q}\Big|_{pre} \qquad \textbf{Eq. 3-1}$$

Where:

V_{post} is the post-trip voltage following loss of NPP.

V_{pre} is the pre-trip voltage.

Q_{pre} is the reactive power delivered before the unit trip.

$\frac{\Delta V}{\Delta Q}\Big|_{pre}$ is the slope of the V-Q curve evaluated at the pre-trip operating point.

Even though the equation is simple and uses a minimum set of local quantities that are readily available at any NPP, it heavily relies on the availability of the measured change in voltage to change in the reactive power (slope). The V-Q curve analysis applied to the voltage stability assessment in power systems has been the subject of numerous technical papers and several books. The V-Q at a given bus can be calculated by assuming a fictitious and unlimited reactive power source at the bus, performing power flow simulations for different voltage levels assigned to the bus, and computing corresponding levels of reactive power (basically assigning the bus to be a PV bus with different scheduled voltages). A sample V-Q curve obtained by this method is shown in Figure 3-1. Two V-Q curves are computed, one corresponding to the base case (system intact) and one corresponding to a single-element outage. The slope of the V-Q curve changes for the two V-Q curves and different voltage levels. This confirms that success of this method depends on the availability and frequency of the measured slope of the V-Q curve, especially in weak power systems (where the available short circuit level is comparable to the nuclear unit rating).

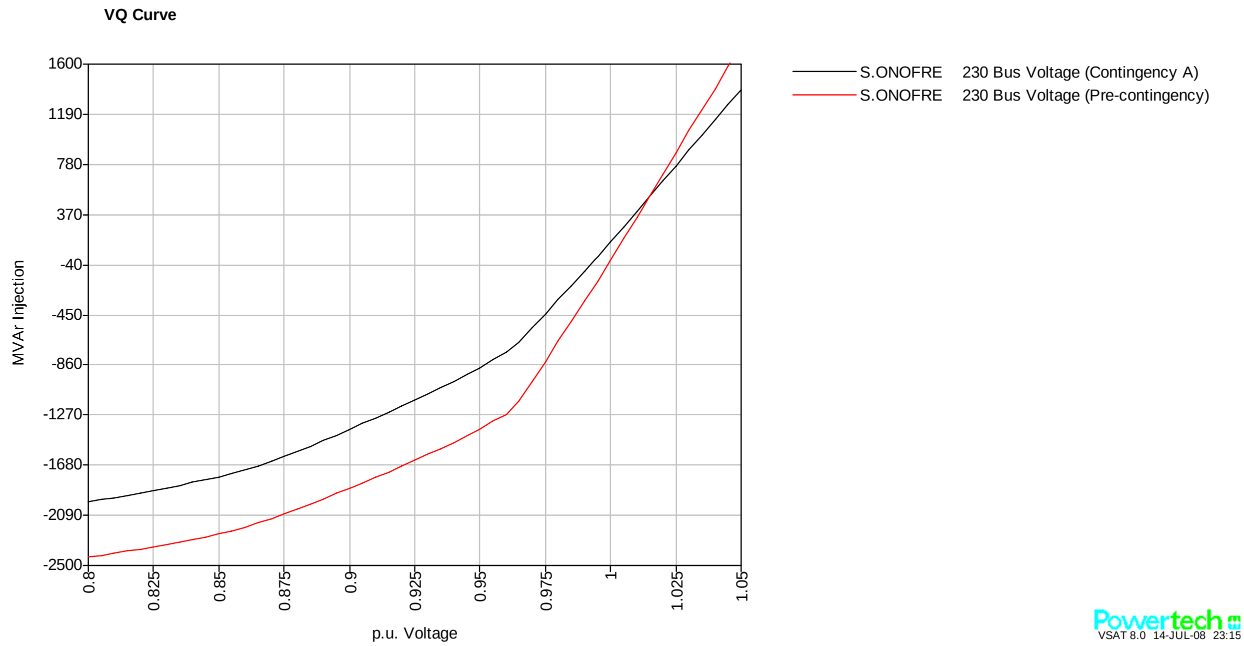


Figure 3-1
Sample V-Q Curves Corresponding to Pre- and Post-Contingency Conditions

3.2 Practical Limitations to Measuring the Slope of the V-Q Curve

A sample V-Q curve, obtained using a similar method, is shown in Figure 3-1. The local operating conditions, such as bus voltage and reactive power generated by NPP (V1 and Q1), are normally known at any power plant. The predicted post-trip voltage calculated by using Equation 3-1 is directly affected by the sensitivity of $\Delta Q/\Delta V$. Consequently, the accuracy of the predicted post-trip voltage depends directly on the availability and frequency of the measured $\Delta Q/\Delta V$. The weaker the power system (low fault level at NPP), the more frequently this sensitivity must be measured, because this value could easily change under different system conditions (such as loss of single elements in the vicinity of the NPP).

There might be practical limitations to acquiring periodic measurements of the $\Delta Q/\Delta V$ sensitivity at NPPs (to compute the slope of V-Q curve, the plant operator should change the scheduled voltage and observe the change in the reactive power output. Some of these limitations are the following:

- Security is important issue at NPPs, and operators do not want to change the scheduled voltage of the unit unless it is strictly necessary and justified.
- The operators at control centers (such as independent system operators) must authorize any changes in the scheduled voltage at the NPPs. Engineers who are responsible for the system operation do not want to change the scheduled bus voltage in a sizable and strategic plant such as an NPP.
- Because NPPs are important and strategic in the system, changing the scheduled bus voltage at these units could cause significant changes in the reactive power output of nearby generators and in the transmission bus voltages in the area.

4
POST-TRIP VOLTAGE PREDICTION AT SELECTED NUCLEAR POWER PLANTS

The post-trip voltage prediction methods—simplified V-Q curve, regression trees, power flow, and time domain simulations—were evaluated for the two NPP sites:

- San Onofre, in California (WECC), which is connected at 230 kV with an available short circuit level of approximately 12,000 MVA
- Palisades, in Michigan (NERC), which is connected at 345 kV with an available short circuit level of approximately 21,000 MVA

4.1 San Onofre

The San Onofre plant consists of two 1252 MVA, 22 kV units with an available short circuit level of approximately 12,000 MVA. Figure 4-1 is a single line diagram of this plant and its vicinity.

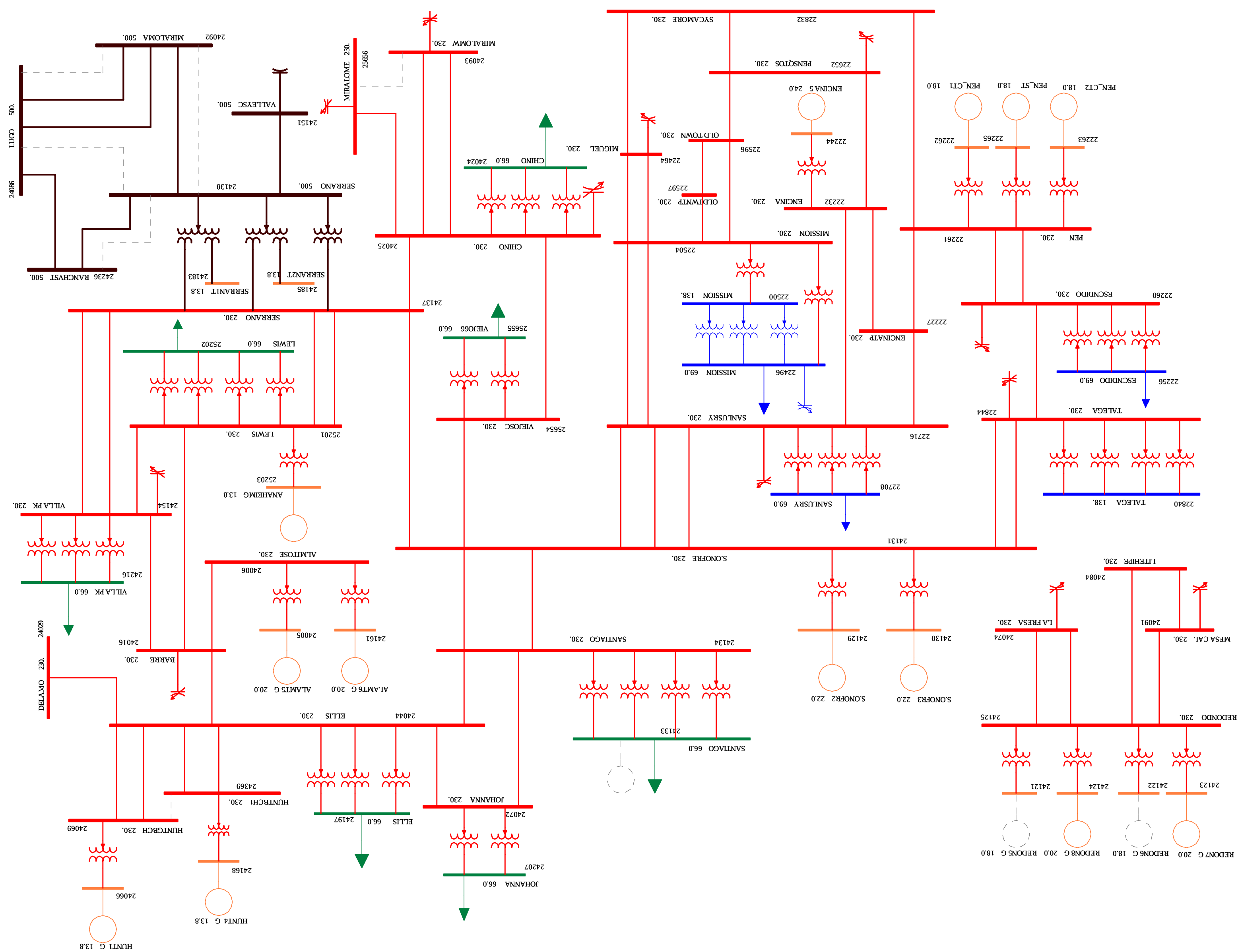


Figure 4-1
Single Line Diagram of San Onofre and Vicinity

Several power flow simulations were carried out to obtain an "exact" solution (post-trip voltage at NPP following loss of unit simulated in power flow) as well as a V-Q method solution. Table 4-1 shows the results for several power flow cases considering different active (P) and reactive (Q) power outputs of the units at San Onofre and different operating conditions of the nearby generators and transmission facilities. Table 4-1 includes the most critical system contingency conditions from the point of view of changes in the active and reactive power output. A contingency analysis was performed using VSAT software in order to identify the most severe contingencies (considering both generation and transmission facilities) that result in significant changes to the operating conditions (especially voltage changes).

Table 4-1
Post-Trip Voltage Predictions for Different System Operating Conditions at San Onofre

Scenario	Active and Reactive Power Operating Conditions in San Onofre Units	ATTRIBUTES				OUTCOME			Error (%) (1) Vs (2)	Error (%) (1) Vs (3)
		V_1	P_1	Q_1	$\Delta Q/\Delta V$	Post-trip voltage V_2 from Powerflow Simulation (1)	Post-trip voltage V_2 predicted by using formula $V_2 = V_1 - \frac{Q_1}{\Delta Q/\Delta V}$: $\Delta Q/\Delta V$ Power flow program (2)	$\Delta Q/\Delta V$ Fixed (3)		
Considering Different Internal Operating Conditions for Units at NPP San Onofre										
Base Case	Original P & Q	0.9823	1060.0	157.06	7773.58	0.9681	0.9621	0.9621	-0.61195	-0.61195
	Qmax, Pmax	1.0710	1069.9	550.00	6232.37	0.9855	0.9827	1.0002	-0.27622	1.49926
	Qmax, Phalf	1.0753	535.1	550.00	6463.53	0.9838	0.9902	1.0046	0.64921	2.10680
	Qmax, Pmin	1.0691	214.2	550.00	6500.53	0.9800	0.9845	0.9984	0.45944	1.87328
	Q275, Pmax	1.0065	1060.0	275.00	7688.04	0.9762	0.9707	0.9711	-0.56837	-0.52805
	Q275, Phalf	1.0138	535.1	274.97	7650.54	0.9769	0.9778	0.9784	0.09358	0.15182
	Q275, Pmin	1.0089	214.2	274.9810	8008.90	0.9733	0.9746	0.9735	0.13373	0.02694
	Qhalf, Pmax	0.9653	1070.0	70.0000	7536.97	0.9623	0.9560	0.9563	-0.65373	-0.62435
	Qhalf, Phalf	0.9728	535.1	70.0000	7730.93	0.9631	0.9638	0.9638	0.06660	0.07176
	Qhalf, Pmin	0.9704	214.2	70.0000	7736.70	0.9603	0.9614	0.9614	0.11572	0.12019
	Q_{-200}, Pmax	0.8956	1070.1	-200.00	6542.84	0.9335	0.9261	0.9213	-0.78762	-1.30605
	Q_{-200}, Phalf	0.9100	535.1	-200.00	6824.88	0.9379	0.9393	0.9358	0.15220	-0.22910
	Q_{-200}, Pmin	0.9057	214.2	-200.00	6822.92	0.9332	0.9350	0.9314	0.19706	-0.18708
	Qmin, Pmax	0.8139	1070.2	-409.97	3631.30	0.9235	0.9268	0.8666	0.35497	-6.15929
	Qmin, Phalf	0.8398	535.2	-410.00	4198.80	0.9245	0.9375	0.8926	1.40961	-3.44772
	Qmin, Pmin	0.8341	214.3	-410.00	4199.43	0.9195	0.9317	0.8868	1.32712	-3.55469
Considering Unit 3 at NPP San Onofre O/S										
Unit 3 O/S	Original P & Q	0.9959	1067.6	306.47	7144.19	0.9510	0.9530	0.9565	0.21405	0.57926
	Qmax, Pmax	1.0299	1070.0	550.00	7142.90	0.9510	0.9529	0.9591	0.19584	0.85274
	Qmax, Phalf	1.0314	535.0	550.00	7438.40	0.9510	0.9575	0.9607	0.68474	1.01998
	Qmax, Pmin	1.0288	214.0	550.00	7748.97	0.9510	0.9578	0.9580	0.71313	0.73676
	Q275, Pmax	0.9916	1070.0	275.00	7078.68	0.9510	0.9528	0.9562	0.18696	0.55213
	Q275, Phalf	0.9945	535.0	275.00	7211.62	0.9510	0.9564	0.9591	0.56784	0.85771
	Q275, Pmin	0.9931	214.0	275.0000	7224.85	0.9510	0.9550	0.9577	0.41954	0.70206
	Qhalf, Pmax	0.9627	1070.0	70.0000	6329.77	0.9510	0.9516	0.9537	0.06700	0.28298
	Qhalf, Phalf	0.9661	535.0	70.0000	6410.93	0.9510	0.9552	0.9571	0.44523	0.64650
	Qhalf, Pmin	0.9647	214.0	70.0000	6137.23	0.9510	0.9533	0.9557	0.24861	0.50108
	Q_{-200}, Pmax	0.9173	1070.0	-200.00	5545.22	0.9510	0.9534	0.9431	0.25279	-0.83436
	Q_{-200}, Phalf	0.9218	535.0	-200.00	5685.05	0.9510	0.9569	0.9475	0.62535	-0.36855
	Q_{-200}, Pmin	0.9189	214.1	-200.00	5494.92	0.9510	0.9553	0.9446	0.44776	-0.67411
	Qmin, Pmax	0.8740	1070.1	-410.00	4765.57	0.9510	0.9601	0.9268	0.95562	-2.54506
	Qmin, Phalf	0.8801	535.1	-410.00	4974.03	0.9510	0.9625	0.9329	1.21251	-1.90895
	Qmin, Pmin	0.8764	214.1	-410.00	4824.67	0.9510	0.9614	0.9291	1.08991	-2.29994
Considering Some Nearby Units/Plants O/S										
Gens 5 & 6 at Alamo Plant O/S (Buses 24005 & 24161)	Original P & Q	0.9872	1066.2	210.76	7859.16	0.9660	0.9604	0.9601	-0.57589	-0.60646
	Qmax, Pmax	1.0627	1070.0	549.99	6167.30	0.9781	0.9735	0.9919	-0.47295	1.41105
	Qmax, Phalf	1.0664	535.1	550.00	6425.47	0.9765	0.9808	0.9956	0.43656	1.95667
	Qmax, Pmin	1.0593	214.1	550.00	6654.17	0.9734	0.9766	0.9885	0.33060	1.55337
	Qhalf, Pmax	0.9600	1070.0	70.0000	7258.07	0.9566	0.9503	0.9510	-0.65861	-0.59176
	Qhalf, Phalf	0.9672	535.1	70.0000	7661.47	0.9569	0.9580	0.9582	0.11855	0.13232
	Qhalf, Pmin	0.9638	214.2	70.0000	7301.33	0.9529	0.9542	0.9548	0.13177	0.19289
	Q_{-200}, Pmax	0.8842	1070.1	-200.00	6315.66	0.9228	0.9158	0.9099	-0.74967	-1.39330
	Q_{-200}, Phalf	0.8989	535.2	-200.00	6677.30	0.9267	0.9288	0.9246	0.22620	-0.22960
	Q_{-200}, Pmin	0.8911	214.3	-200.00	6508.70	0.9193	0.9218	0.9168	0.27381	-0.27007
	Qmin, Pmax	0.7960	1070.2	-410.00	3374.77	0.9105	0.9175	0.8487	0.76416	-6.78607
	Qmin, Phalf	0.8233	535.1	-410.00	3999.80	0.9101	0.9258	0.8760	1.71847	-3.74921
	Qmin, Pmin	0.8143	214.4	-410.00	3846.33	0.9038	0.9209	0.8671	1.88817	-4.07000
Gens 7 - 8 at Redondo Plant O/S (Buses 24123 & 24124)	Original P & Q	0.9866	1066.0	203.74	7850.67	0.9663	0.9606	0.9604	-0.59016	-0.61679
	Pmax, Qmax	1.0636	1070.0	550.00	6186.03	0.9789	0.9747	0.9929	-0.42376	1.43121
	Phalf, Q275	1.0065	535.1	275.00	8050.30	0.9710	0.9723	0.9711	0.13087	0.00564
	Pmin, Qmin	0.8178	214.4	-410.00	3917.57	0.9067	0.9225	0.8706	1.73922	-3.98628
Gens 1 & 4 at Hunt Plant O/S (Buses 24066 & 24168)	Original P & Q	0.9852	1062.9	188.07	7810.23	0.9667	0.9611	0.9610	-0.57660	-0.58835
	Pmax, Qmax	1.0671	1070.0	550.00	6135.43	0.9803	0.9774	0.9963	-0.28770	1.63940
	Phalf, Q275	1.0087	535.1	275.00	7900.31	0.9727	0.9738	0.9733	0.12175	0.06341
	Pmin, Qmin	0.8203	214.4	-410.00	3990.03	0.9086	0.9231	0.8731	1.58896	-3.91520
Gens at PEN Plant O/S (Buses 22262, 22263 & 22265)	Original P & Q	0.9856	1063.6	192.94	7768.94	0.9651	0.9608	0.9608	-0.44898	-0.44745
	Pmax, Qmax	1.0698	1070.0	550.00	5771.10	0.9782	0.9745	0.9991	-0.37899	2.13062
	Phalf, Q275	1.0052	535.1	275.00	8105.23	0.9692	0.9713	0.9699	0.22011	0.07076
	Pmin, Qmin	0.8064	214.5	-410.00	3275.27	0.9040	0.9316	0.8592	3.04986	-4.96291
Gens at Encina Plant O/S (Buses 22236 - 22240)	Original P & Q	0.9893	1065.1	232.89	7727.41	0.9622	0.9591	0.9593	-0.32325	-0.30464
	Pmax, Qmax	1.0653	1070.0	550.00	6058.27	0.9728	0.9745	0.9945	0.16940	2.22856
	Phalf, Q275	1.0001	535.1	275.00	7969.51	0.9626	0.9656	0.9648	0.31920	0.22884
	Pmax, Q_{-200}	0.8860	1069.8	-200.00	6215.21	0.9241	0.9182	0.9117	-0.64051	-1.33861
	Pmin, Q_{-200}	0.8901	214.1	-200.00	6439.85	0.9183	0.9211	0.9158	0.30279	-0.27744
	Pmax, Qmin	0.7881	1070.1	-410.00	2660.57	0.9108	0.9422	0.8409	3.45819	-7.67107
	Pmin, Qmin	0.7996	214.3	-410.00	2911.17	0.9020	0.9404	0.8523	4.26399	-5.50286
Considering Some Nearby LT's O/S										
LT SERRANO - VALLEYSC 500 kV O/S (24138 - 24151 CKT '1 ')	Original P & Q	0.9847	1060.0	182.25	7814.54	0.9671	0.9613	0.9612	-0.59251	-0.60522
	Pmax, Qmax	1.0672	1070.0	550.00	6184.30	0.9814	0.9782	0.9964	-0.32137	1.53133
	Phalf, Q275	1.0097	535.1	275.00	7851.47	0.9737	0.9747	0.9743	0.09794	0.06190
	Pmin, Qmin	0.8263	214.3	-410.00	4128.07	0.9129	0.9256	0.8790	1.39607	-3.70631
LT SANLUSRY - S.ONOFRE 230 kV 0/S (22716 24131 '1 ')	Original P & Q	0.9838	1060.0	172.81	7730.72	0.9678	0.9614	0.9616	-0.65823	-0.64549
	Pmax, Qmax	1.0715	1070.0	550.00	6098.37	0.9851	0.9813	1.0007	-0.38525	1.58771
	Phalf, Q275	1.0136	535.1	275.00	7551.26	0.9767	0.9772	0.9782	0.05286	0.15949
	Pmin, Qmin	0.8264	214.3	-410.00	4037.43	0.9150	0.9279	0.8791	1.41420	-3.92000
LTs SANLUSRY - S.ONOFRE 230 kV and SERRANO - VALLEYSC 500 kV 0/S	Original P & Q	0.9860	1060.2	197.24	7769.47	0.9668	0.9607	0.9607	-0.63848	-0.63709
	Pmax, Qmax	1.0679	1070.0	550.00	6065.07	0.9808	0.9772	0.9971	-0.36849	1.66356
	Phalf, Q275	1.0095	535.1	275.00	7785.14	0.9734	0.9742	0.9742	0.08437	0.07898
	Pmin, Qmin	0.8182	214.3	-410.00	3962.07	0.9081	0.9217	0.8710	1.49807	-4.08911

The result of post-trip voltage prediction (using Equation 3-1) under several NPP operating conditions as well as severe contingencies in the vicinity of the NPP are also summarized in Table 4-1. The “exact” steady-state post-trip voltage corresponding to the same system conditions (using PSAT software) is shown for comparison.

Based on the results shown in Table 4-1, the following comments and conclusions can be made:

- Because initial voltage and reactive power output (V1 and Q1) are readily available at any power plant, the sensitivity $\Delta Q/\Delta V$ is the most critical element in Equation 3-1. Therefore, the accuracy of the predicted post-trip voltage using this equation will be directly affected by this sensitivity.
- Reactive power output of the nuclear units is the parameter that most significantly affects the sensitivity $\Delta Q/\Delta V$. Different levels of the active power output (P) or changes in the nearby system facilities (generation or transmission) cause smaller changes in the sensitivity magnitude. In a weaker system (low short circuit or fault level), changes in the nearby system facilities could affect the sensitivity in a more significant way. Also, the error of predicted voltage increases as the real power of the unit increases (not significantly).
- Sensitivity $\Delta Q/\Delta V$ becomes smaller when a nuclear unit is close to its reactive limits, being the worst case when the unit is at its lower limit. This can be understood by considering that when the unit has reached its lower limit, this part corresponds to the bottom of the V-Q curve, and the slope of the curve is almost flat at this point. Results in Table 4-1 show that the largest errors in the predicted post-trip voltage occur when the nuclear unit is at this operating condition. Errors are >3% in some cases.
- Taking into account the estimated errors when a nuclear unit is close to its lower limit, special attention should be paid in light-load cases when units are usually absorbing important amounts of reactive power from the system and the sensitivity $\Delta Q/\Delta V$ can be higher (because fewer units are on-line). On the other hand, in these cases, the voltage is expected to rise; therefore, this operating condition is not of interest for voltage security at the plant’s safety-related electrical distribution buses. However, these cases are of interest to show that the accuracy of Equation 3-1 is lower for these cases.
- Sensitivity $\Delta Q/\Delta V$ could change in a most significant way in weak systems; therefore, especially in these cases, it is of great importance to have a more frequent measurement of this sensitivity. Table 4-1 shows the errors in the predicted post-trip voltage when the sensitivity value is not properly updated (assuming that it was not reevaluated since its last measured or simulated value) in Equation 3-1; that is, the sensitivity used is not periodically calculated. Although San Onofre is located in a strong system, significant errors (>6% in some cases) exist when the sensitivity value is not updated (see Table 4-1). It is expected that, in weaker systems, these errors will be larger.
- The V-Q method is quite accurate when measurements of pre-trip voltage, reactive power, and slope of the V-Q curve are available and frequently updated, especially in weak or stressed power systems.

A data mining program cannot use the data shown in Table 4-1 directly, because the program cannot determine whether a generator or line is out of service by reading the rows. The status of a generator or line can be indicated by a Boolean number (for example, 0 for out of service and 1 for in service). Therefore, we need to add new columns (input variables) that represent the status of generators or lines. The number of new columns depends on the number of contingencies (one generator outage or one line outage) considered. The table created for the data mining program can therefore be quite large; it is not included here due to space limitations.

To compare the accuracy of the predicted post-trip voltage using the V-Q curve and power flow methods with that of time domain simulation, loss of a nuclear unit was simulated using TSAT software. Table 4-2 shows the comparison between the post-trip voltage (PTV) results from time domain simulations and the predicted PTV obtained from the V-Q method. The scenarios included in Table 4-2 correspond to important contingencies in the vicinity of the San Onofre NPP. For time domain simulations, unit 2 at San Onofre NPP was tripped, and the post-transient steady-state voltage was registered for each scenario in Table 4-2. In three of the four scenarios included in this table, the predicted PTV is approximately 2.4% lower than the PTV computed in the time domain simulation. These differences correspond to a strong system; in weaker systems, it is expected that these differences could be higher.

Table 4-2
Comparison of Post-Trip Voltage Between Static and Dynamic Simulations at San Onofre

Scenario	ATTRIBUTES						OUTCOME			Error (%) (1) Vs (3)
	V^{NPP}	P^{NPP}	Q^{NPP}	ΔV	ΔQ	ΔQ/ΔV	PTV from Time Domain Simulation (1)	PTV from Powerflow Simulation (2)	PTV Prediction from $V_2 = V_1 - \frac{Q_1}{\Delta Q / \Delta V}$ ΔQ/ΔV Power flow program (3)	
Base Case Pmax-Qmax (Pmax=1070; Qmax=550)	1.0710	1069.9	550.00	-0.03	-186.97	6232.37	1.006604	0.9855	0.9827	-2.37164
Unit 3 at S. Onofre NPP O/S (Pmax=1070; Qmax=550)	1.0299	1070.0	550.00	-0.03	-214.29	7142.90	0.940538	0.951	0.9529	1.31015
Gens 5 & 6 at Alamo Plant O/S(Pmax=1070; Qmax=550)	1.0627	1070.0	549.99	-0.03	-185.02	6167.30	0.997728	0.9781	0.9735	-2.43121
LTs Sanlusry - S.Onofre 230 kV and Serrano - Valleysc 500 kV 0/S (Pmax=1070; Qmax=550)	1.0679	1070.0	550.00	-0.03	-181.95	6065.07	1.001838	0.9808	0.9772	-2.45861

4.2 Palisades

The Palisades plant consists of a 955 MVA, 22 kV unit with an available short circuit level of approximately 21,000 MVA. Figure 4-2 is a single line diagram of this unit and its vicinity.

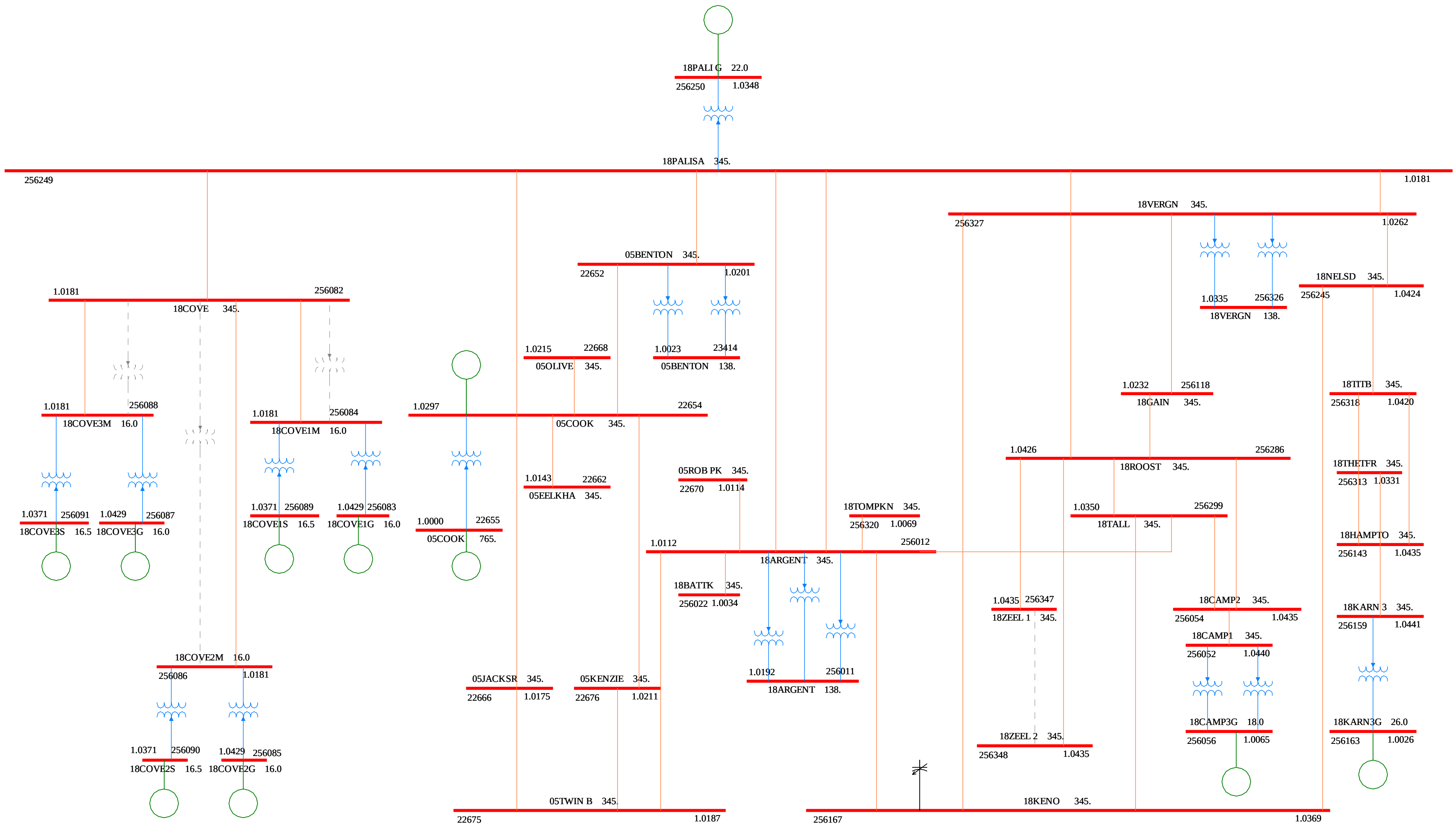


Figure 4-2
Single Line Diagram of Palisades and Vicinity

Simulations similar those performed at San Onofre were repeated for Palisades. The post-trip voltages were predicted using V-Q curve, power flow, and time domain techniques. Table 4-3 shows the results for several power flow cases considering different active and reactive power output of the unit and considering different operating conditions of the nearby generators and transmission facilities.

Only the most critical system contingency conditions from the point of view of changes in the active and reactive power output in the unit at Palisades to the changes in system conditions are considered. The contingency analysis was performed using VSAT software in order to identify the most severe contingencies (for generation and transmission facilities) that cause significant changes to the operating conditions of the nuclear generators. Table 4-3 shows comparisons of post-trip voltage prediction results from power flow and dynamic simulations as well as the simplified V-Q method.

Table 4-3
Post-Trip Voltage Predictions for Different System Operating Conditions at Palisades

Scenario	Active and Reactive Power Operating Conditions in Palisades Units	ATTRIBUTES				OUTCOME			Error (%) (1) vs (2)	Error (%) (1) vs (3)
		V_1	P_1	Q_1	$\Delta Q/\Delta V$	Post-trip voltage V_2 from Powerflow Simulation (1)	Post-trip voltage V_2 predicted by using formula $V_2 = V_1 - \frac{Q_1}{\Delta Q/\Delta V}$			
							$\Delta Q/\Delta V$ Power flow program (2)	$\Delta Q/\Delta V$ fixed (3)		
Considering Different Generator Operating Conditions										
Base Case	Original P & Q	1.0348	767.0	225.55	7026.30	1.00597	1.00270	1.00270	0.32614	0.32614
	Qmax, Pmax	1.0521	767.0	349.20	7031.63	1.00600	1.00240	1.00236	0.35927	0.36304
	Qmax, Phalf	1.0547	458.5	349.20	7100.13	1.00598	1.00550	1.00498	0.04795	0.09940
	Qmax, Pmin	1.0555	150.0	349.20	7128.47	1.00597	1.00647	1.00576	-0.05001	0.02078
	Qhalf, Pmax	1.0050	767.0	16.30	7221.27	1.00597	1.00274	1.00268	0.32177	0.32803
	Qhalf, Phalf	1.0100	458.5	33.42	7296.63	1.00598	1.00542	1.00524	0.05577	0.07331
	Qhalf, Pmin	1.0100	150.0	26.74	7293.68	1.00598	1.00633	1.00619	-0.03522	-0.02136
	Qmin, Pmax	0.9587	767.0	-312.30	6978.87	1.00597	1.00346	1.00316	0.24970	0.27989
	Qmin, Phalf	0.9618	458.5	-312.30	7057.00	1.00598	1.00605	1.00625	-0.00735	-0.02656
	Qmin, Pmin	0.9628	150.0	-312.30	7089.45	1.00597	1.00685	1.00725	-0.08754	-0.12681
Considering Some Nearby Units/Plants O/S										
Generator at Bus 22654 O/S	Original P & Q	1.0348	767.0	265.86	7441.50	1.00210	0.99907	0.99907	0.30300	0.30300
	Pmax, Qmax	1.0466	767.0	349.20	7240.50	1.00210	0.99840	0.99970	0.37046	0.23967
	Phalf, Qhalf	1.0050	458.5	25.06	7282.21	1.00210	1.00156	1.00163	0.05407	0.04671
	Pmin, Qmin	0.9588	150.0	-312.30	7064.43	1.00210	1.00301	1.00077	-0.09046	0.13316
Generator at Bus 22655 O/S	Original P & Q	1.0348	767.0	218.55	6808.68	1.00565	1.00270	1.00270	0.29403	0.29403
	Pmax, Qmax	1.0529	767.0	349.20	6956.03	1.00565	1.00266	1.00157	0.29831	0.40711
	Phalf, Qhalf	1.0098	458.5	31.82	7202.19	1.00565	1.00538	1.00513	0.02670	0.05212
	Pmin, Qmin	0.9620	150.0	-312.30	6991.40	1.00565	1.00667	1.00787	-0.10124	-0.22006
Generator at Bus 256087,91 O/S	Original P & Q	1.0348	767.0	178.70	6742.77	1.01126	1.00830	1.00830	0.29385	0.29385
	Pmax, Qmax	1.0583	767.0	349.20	7220.70	1.01126	1.00990	1.00647	0.13476	0.47580
	Phalf, Qhalf	1.0150	458.5	24.86	6709.56	1.01126	1.01130	1.01131	-0.00351	-0.00531
	Pmin, Qmin	0.9656	150.0	-312.30	6823.10	1.01126	1.01137	1.01192	-0.01097	-0.06485
Generator at Bus 256056 O/S	Original P & Q	1.0348	767.0	241.77	7220.16	1.00401	1.00131	1.00131	0.26922	0.26922
	Pmax, Qmax	1.0504	767.0	349.20	6981.37	1.00401	1.00034	1.00200	0.36676	0.20106
	Phalf, Qhalf	1.0064	458.5	19.13	7281.83	1.00401	1.00373	1.00371	0.02763	0.02987
	Pmin, Qmin	0.9608	150.0	-312.30	7067.47	1.00401	1.00502	1.00408	-0.10014	-0.00716
Generator at Bus 256083, 89 O/S	Original P & Q	1.0348	767.0	178.78	6747.11	1.01126	1.00830	1.00830	0.29335	0.29335
	Pmax, Qmax	1.0583	767.0	349.20	7223.27	1.01126	1.00991	1.00649	0.13405	0.47347
	Phalf, Qhalf	1.0143	458.5	19.94	6682.43	1.01126	1.01127	1.01129	-0.00053	-0.00336
	Pmin, Qmin	0.9656	150.0	-312.30	6821.00	1.01126	1.01137	1.01187	-0.01059	-0.06013
Generator at Bus 256085, 90 O/S	Original P & Q	1.0348	767.0	178.69	6744.38	1.01126	1.00830	1.00830	0.29308	0.29308
	Pmax, Qmax	1.0583	767.0	349.20	7223.43	1.01126	1.00992	1.00648	0.13295	0.47457
	Phalf, Qhalf	1.0133	458.5	13.74	6739.76	1.01126	1.01122	1.01122	0.00383	0.00370
	Pmin, Qmin	0.9656	150.0	-312.30	6817.93	1.01126	1.01138	1.01188	-0.01163	-0.06100
Generator at Bus 256163 O/S	Original P & Q	1.0348	767.0	240.34	7203.69	1.00447	1.00144	1.00144	0.30284	0.30284
	Pmax, Qmax	1.0505	767.0	349.20	6981.77	1.00447	1.00049	1.00203	0.39740	0.24302
	Phalf, Qhalf	1.0065	458.5	18.31	7283.12	1.00447	1.00400	1.00397	0.04715	0.04992
	Pmin, Qmin	0.9613	150.0	-312.30	7078.59	1.00447	1.00539	1.00462	-0.09150	-0.01531
Considering Some Nearby Transmission Lines O/S										
Line between buses 256249-256327 O/S	Original P & Q	1.0348	767.0	250.78	7216.00	1.00360	1.00005	1.00005	0.35537	0.35537
	Pmax, Qmax	1.0495	767.0	349.20	6845.67	1.00360	0.99847	1.00109	0.51382	0.25097
	Phalf, Qhalf	1.0048	458.5	13.90	7182.49	1.00360	1.00286	1.00287	0.07334	0.07244
	Pmin, Qmin	0.9597	150.0	-312.30	6978.30	1.00360	1.00449	1.00302	-0.08890	0.05794
Line between buses 256249-22654 O/S	Original P & Q	1.0348	767.0	257.96	7230.30	1.00294	0.99912	0.99912	0.38215	0.38215
	Pmax, Qmax	1.0485	767.0	349.20	6901.43	1.00294	0.99788	1.00018	0.50689	0.27562
	Phalf, Qhalf	1.0048	458.5	19.54	7103.51	1.00294	1.00205	1.00210	0.08891	0.08409
	Pmin, Qmin	0.9585	150.0	-312.30	6890.10	1.00294	1.00383	1.00169	-0.08825	0.12447
Line between buses 256249-256286 O/S	Original P & Q	1.0348	767.0	268.65	7239.39	1.00143	0.99769	0.99769	0.37487	0.37487
	Pmax, Qmax	1.0470	767.0	349.20	6925.47	1.00143	0.99658	0.99876	0.48693	0.26694
	Phalf, Qhalf	1.0048	458.5	30.30	7095.14	1.00143	1.00053	1.00061	0.08997	0.08145
	Pmin, Qmin	0.9568	150.0	-312.30	6858.87	1.00143	1.00233	0.99994	-0.09002	0.14911
Line between buses 22652-22654 O/S	Original P & Q	1.0348	767.0	255.94	7269.81	1.00313	0.99959	0.99959	0.35373	0.35373
	Pmax, Qmax	1.0487	767.0	349.20	6946.30	1.00313	0.99840	1.00064	0.47390	0.24927
	Phalf, Qhalf	1.0047	458.5	16.22	7127.03	1.00313	1.00239	1.00244	0.07345	0.06899
	Pmin, Qmin	0.9589	150.0	-312.30	6918.47	1.00313	1.00405	1.00186	-0.09114	0.12642
Line between buses 22652-256249 O/S	Original P & Q	1.0348	767.0	251.49	7093.67	1.00362	0.99935	0.99935	0.42755	0.42755
	Pmax, Qmax	1.0499	767.0	349.20	6642.13	1.00362	0.99733	1.00067	0.63103	0.29450
	Phalf, Qhalf	1.0059	458.5	24.07	7084.70	1.00362	1.00250	1.00251	0.11140	0.11097
	Pmin, Qmin	0.9589	150.0	-312.30	6856.03	1.00362	1.00447	1.00294	-0.08443	0.06758

Based on the results shown Table 4-3, the following comments can be made:

- Reactive power output of the nuclear unit is the parameter that affects the sensitivity ΔQ/ΔV most significantly. Different levels of the active power output (P) or changes in the nearby system facilities (generation or transmission) cause smaller changes in the sensitivity magnitude.
- The error in the post-trip voltage prediction is rather small because the plant is located in a strong system, and the V-Q curve near the operating point is quite linear even under different plant status and system operating conditions. Nonetheless, the errors are larger if the sensitivity values are not updated. It is expected that these errors would be greater in weaker systems.

Again, to compare the accuracy of the predicted post-trip voltage using the V-Q curve and power flow methods with that of time domain simulation, loss of the nuclear unit was simulated using TSAT software. Table 4-4 shows the comparison between the PTV results from time domain simulations and the predicted PTV value obtained from the V-Q method. The scenarios considered only important system elements outages in the vicinity of the Palisades NPP. For time domain simulations, the unit was tripped, and the post-transient steady state voltage was registered for each scenario in Table 4-4. In all four scenarios, the predicted PTV is slightly lower (<1%) than the PTV computed in the time domain simulation. These differences correspond to a strong system, and it is expected that these differences would be greater in weaker systems.

Table 4-4
Comparison of Post-Trip Voltage Between Static and Dynamic Simulations at Palisades

Scenario	ATTRIBUTES						OUTCOME			Error (%) (1) Vs (3)
	V^{NPP}	P^{NPP}	Q^{NPP}	ΔV	ΔQ	ΔQ/ΔV	PTV from Time Domain Simulation (1)	PTV from Powerflow Simulation (2)	PTV Prediction from $V_2 = V_1 - \frac{Q_1}{\Delta Q / \Delta V}$ ΔQ/ΔV Power flow program (3)	
Original Case (P=767; Q225.35)	1.0348	767	225.546	-0.03	-210.79	7026.3000	1.008487	1.00597	1.0027	-0.57385
Pmax-Qmax (P=767; Q349.18)	1.05206	767	349.2	-0.03	-210.949	7031.6333	1.010221	1.00597	1.0024	-0.77431
Pmax-Qmax with Gen22654_OS (P=767; Q349.18)	1.04663	767	349.2	-0.03	-217.215	7240.5000	1.003839	1.0021	0.9984	-0.54169
Pmax-Qmax with LT 256249-256327_OS (P=767; Q349.18)	1.04948	767	349.2	-0.03	-205.37	6845.6667	1.007345	1.0036	0.9985	-0.88107

4.3 Dynamic Simulation Results for Post-Trip Voltage Prediction

4.3.1 San Onofre

This section examines the results of time domain simulation for loss of a nuclear unit under a few severe contingencies. The prediction of post-trip voltage is mainly of concern in the timeframe for the operation of the degraded voltage relay. Normally, the relay starts the emergency diesel if a low-voltage condition persists for a few (~5) seconds.

The time domain simulation was carried out for 10 seconds, and loss of NPP occurred at time = 0.5 second. Table 4-5 shows the dynamic results of simulations of tripping San Onofre Unit 2. The table shows the value of the post-trip voltage at several times. The initial voltage (before the loss of unit), the voltage after 5 seconds, and the steady-state voltage (voltage at 10 seconds, which is assumed to represent steady-state or final value), and the post-trip voltage obtained from a power flow simulation are reported. The time domain simulations were carried out for a few severe contingencies.

Table 4-5
Dynamic Simulation Results of Post-Trip Voltage at San Onofre

Case		V_{ini}	V_{min}	V_{5sec}	V_{fin} (Dynamic)	V_{pf} (Power Flow)
Base Case Pmax and Qmax (Pmax=1070; Qmax=550)	—	1.07098	0.985076	1.006248	1.006604	0.9855
Unit 3 at San Onofre NPP O/S (Pmax=1070; Qmax=550)	—	1.029875	0.919678	0.940588	0.940538	0.951
Generators 5 and 6 at Alamo Plant O/S (Pmax=1070; Qmax=550)	—	1.062674	0.975488	0.997402	0.997728	0.9781
LTs Sanlusry—San Onofre 230 kV and Serrano Valleysc 500 kV lines O/S (Pmax=1070; Qmax=550)	—	1.067665	0.979637	1.001453	1.001838	0.9808

Figure 4-3 shows the time trajectories (plots) of the post-trip voltages for the dynamic simulation scenarios described in Table 4-5.

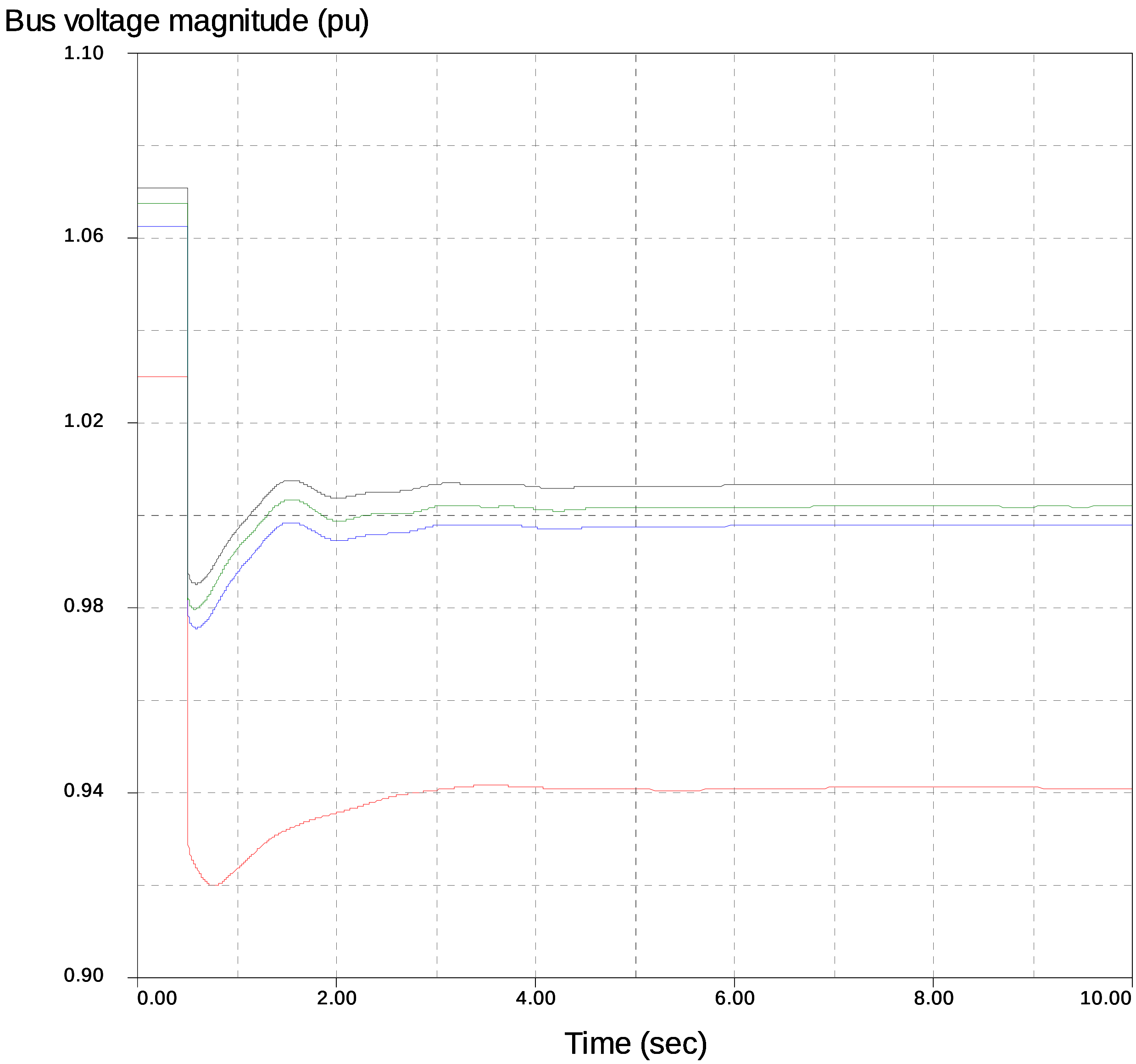


Figure 4-3
Dynamic Simulation Results Following Loss of Unit 2 at San Onofre

4.3.2 Palisades

The time domain simulation was carried out for 10 seconds, and loss of NPP occurred at time = 0.5 second. Table 4-6 shows the results of dynamic simulations of tripping the Palisades nuclear unit. The table shows the post-trip voltage at several times. The initial voltage (before the loss of unit), the voltage after 5 seconds, and the steady-state voltage (voltage at 10 seconds, which is assumed to represent steady-state or final value), and the post-trip voltage obtained from a power flow simulation are reported. The time domain simulations were carried out for a few severe contingencies. Figure 4-4 shows the time trajectories (plots) of the post-trip voltages for the dynamic simulation scenarios described in Table 4-6.

Table 4-6 shows that the final voltage magnitude (V_{fin}) from dynamic simulation is close to the post-trip voltage from the power flow program (V_{pf}). The Palisades NPP is located where the available fault level is high as compared to the fault contribution of the Palisades unit.

Table 4-6
Dynamic Simulation Results of Post-Trip Voltage at Palisades

Case		V_{ini}	V_{min}	V_{5sec}	V_{fin} (Dynamic)	V_{pf} (Power Flow)
Palisade_NPP_Orig (P=767; Q=225.35)	—	1.034805	1.002601	1.008573	1.008487	1.00597
Palisade_NPP_Pmax&Qmax (P=767; Q=349.18)	—	1.052072	1.001789	1.010321	1.010221	1.00597
Palisade_NPP_Gen22654_OS (P=767; Q=349.18)	—	1.046638	0.995364	1.003716	1.003839	1.0021
Palisade_NPP_LT256249–256327_OS (P=767; Q=349.18)	—	1.049472	0.998453	1.007475	1.007345	1.0036

Figure 4-4 shows the time trajectories (plots) of the post-trip voltages for the dynamic simulation scenarios described in Table 4-6.

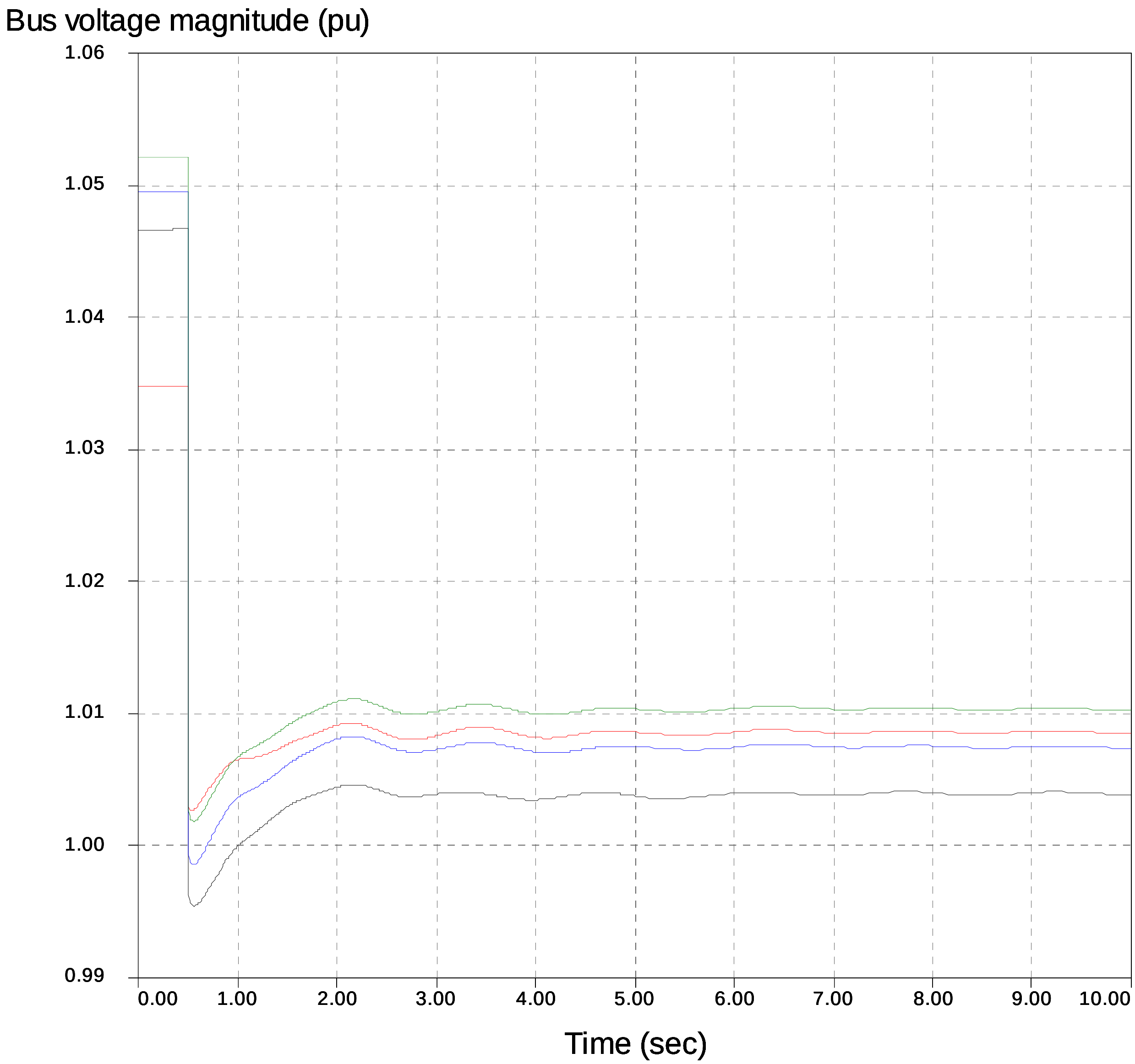


Figure 4-4
Dynamic Simulation Results Following Loss of Palisades Nuclear Unit

5

POST-TRIP VOLTAGE PREDICTION USING DECISION OR REGRESSION TREES

Data mining is a step in the knowledge discovery process. It is the extraction of implicit and interesting knowledge (rules, regulations, patterns, models, and constraints) from data in large databases. Most of the methods commonly used for data mining can be classified into the following groups: statistical methods, decision or regression trees, neural networks, rule induction, case-based reasoning, genetic algorithms or evolutionary programming, and fuzzy reasoning. In this project, data mining techniques were used to examine the models for post-trip voltage prediction. Based on the literature survey, the regression tree, one of the most widely recognized data mining methods, was selected as the core data mining method.

5.1 Overview of Decision and Regression Tree Technique

Researchers have extensively studied decision trees in the context of various power system security assessment problems. The decision tree approaches appear to be of two categories: (1) the *single-contingency* approach, which builds a decision tree for each possible contingency, and (2) the *multi-contingency* or *global* approach, which considers several or all contingencies together and uses a single tree to handle all the contingencies.

Most decision tree applications use a *classification tree* (also called a *crisp decision tree*). However, two other categories of decision trees—*regression trees* and *fuzzy trees*—have been applied in the area of power security assessment. The tree induction algorithms are similar for the three kinds of decision trees. The major differences among the decision trees are the following:

- *Regression trees* infer information about a numeric output variable (such as *security index*), whereas *classification trees* infer a categorical or symbolic output variable (such as *stable* or *unstable*) representing different classes.
- *Fuzzy trees* use fuzzy logic to represent output information smoothly, whereas the *classification trees* use standard logic (a crisp threshold) to propagate states in the tree induction.

In Wehenkel's research, regression trees have been applied successfully to the estimation of contingency severity for voltage security of the Electricité de France system [6].

5.2 Feature and Attribute Selection and Extraction

The first step in the application of decision or regression trees is the creation of an appropriate training data set. A common approach in power systems is to simulate the system in response to various contingencies and operating conditions and then collect a set of predisturbance system features (bus voltages, line flows, interface flows, generators output, and so on) along with the corresponding system outcome (the security status or an index such as the critical clearing time and the system energy margin).

One of the most important aspects of achieving good performance of a neural network or decision tree has proven to be the proper selection of training features. Selection of attributes or features is the process of identifying those features that contribute the most to the discrimination ability of the decision tree or neural network. Only those features are then used to train the decision tree or neural network, and the rest of the features are discarded.

Except for those features that are selected on the basis of the engineering understanding of the problem, the most commonly used feature selection method is the *correlation analysis approach.* In the correlation analysis approach, highly correlated features are identified based on calculations of the correlation coefficients between every pair of features. Those highly correlated features are regrouped together, and only one feature is selected to represent each group.

Decision tree induction can also be used for feature selection. When a decision tree is constructed from the given data, the attributes or features that do not appear in the tree are assumed to be irrelevant to the target information. The set of features appearing on the tree form the selected subset of the features. From decision tree induction, we can get the features' importance rankings, which reflect the contribution that each feature makes in classifying or predicting the target information. Wehenkel applied decision trees to identify the attributes or features in strong correlation with the security class [7–9]. Those attributes or features were used as input variables to a multilayer perception model, and a normalized security margin was used as output information.

5.3 Decision or Regression Tree Method

Decision trees are hierarchical, sequential tree structures that recursively partition the set of observed examples (data). It is a way to represent rules underlying the data. A decision tree can be used in classification, prediction, and regression. There are many advantages to using decision trees. The first is their interpretability. A tree structure shows how an output is derived. A second important asset is their ability to identify among the candidate attributes the most relevant parameters for each problem. A third characteristic is their excellent computation efficiency.

The weather and play problem (see Table 5-1) is a tiny dataset that illustrates the decision tree method. Entirely fictitious, it supposedly concerns the weather conditions that are suitable for playing some unspecified game. In general, records or examples in a data set are characterized by the values of attributes or variables, which measure different aspects of the record or example. In this case, there are four attributes or features—*outlook, temperature, humidity,* and *windy;* the outcome is *play* for whether to play.

Table 5-1
Weather Data with Play Decisions

Outlook	Temperature	Humidity	Windy	Play
Sunny	85	85	False	No
Sunny	80	90	True	No
Overcast	83	86	False	Yes
Rainy	70	96	False	Yes
Rainy	68	80	False	Yes
Rainy	65	70	True	No
Overcast	64	65	True	Yes
Sunny	72	95	False	No
Sunny	69	70	False	Yes
Rainy	75	80	False	Yes
Sunny	75	70	True	Yes
Overcast	72	90	True	Yes
Overcast	81	75	False	Yes
Rainy	71	91	True	No

Figure 5-1 shows a decision tree for the data set of the weather data with play decisions. From this decision tree, we can simply look up the appropriate conditions to decide whether to play; for example, *if outlook = sunny and humidity ≤ 75, then play = yes.* In this flowchart-like tree structure, the following conditions exist:

- An *internal node* (also called a *decision node*) denotes a test on an attribute or variable such as outlook, humidity, or windy.
- A *branch* represents an outcome of the test, and all records or examples in branch have the same value or same range of values for the tested attribute.
- A *leaf node* (also called a *terminal node*) represents an outcome or decision such as play (yes or no).

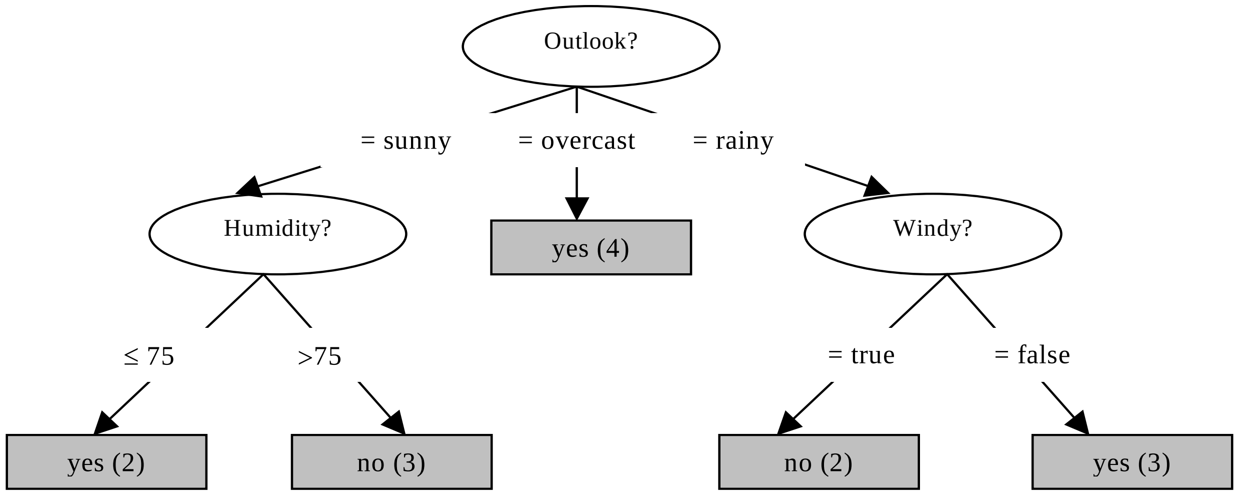


Figure 5-1
Decision Tree for the Weather Data with Play Decisions

Generally, decision tree algorithms can handle two types of attributes or variables: (1) c*ontinuous attributes*, which measure numbers—either real value or integer values, also called *numerical* or *quantitative* attributes, such as *temperature* and *humidity* in Table 5-1, and (2) c*ategorical attributes*, which take on values in specified, finite sets of possibilities. If the values are discrete numerical values (integers) representing level of measurement, they are called *ordinal* attributes. If the values are in the form of symbols, they are called *nominal* or *symbolic* attributes, such as *outlook, windy,* and *play* in Table 5-1.

In the data set used for decision trees, one attribute is named the *target attribute* or *goal attribute* (such as *play* in Table 5-1) representing decisions for classification, regression, or prediction, and the others are *candidate attributes* (such as *temperature, humidity, outlook,* and *windy* in Table 5-1) describing predecision conditions. The target attribute and candidate attribute are also called the *response variable* and *predictor variable*, respectively. There are two types of decision trees: *classification trees* and *regression trees*. In a classification tree, the tree is built for classifying data samples in terms of the categorical target attribute (response variable), whereas regression trees have a continuous target attribute (response variable). Two major issues should be considered in decision tree algorithms: (1) model construction and (2) model selection.

5.3.1 Model Construction

A decision tree model is built starting with a root node. A training data set is partitioned to the child nodes using a splitting rule. A splitting rule can be of the following form, where A is the selected attribute (variable), c is a constant, s is the data sample, L is the left branch of the node, and R is the right branch of the node:

If A < c, then s belongs to L; otherwise, to R.

In this case, splitting is done using one attribute (variable), and a node has two branches and thus two children. A node can also have more branches, and the splitting can be done based on several attributes (variables). The best splitting for each node is searched based on a purity function calculated from the data. For example, in a classification tree, the data are considered pure when the data set contains data samples from only one class. The most frequently used purity functions are entropy, the Gini index, and towing rules. The data portion that falls into each child node is partitioned again, in an effort to maximize the purity function. The tree is constructed until the purity of the data in each leaf node is at a predefined level or until the leaf nodes contain a predefined minimum number of data samples. In a classification tree, each leaf node is then labeled with a class. Usually the class of the node is determined based on majority rule—the node is labeled to the class to which the majority of the training data belong.

5.3.2 Model Selection

The model selection problem includes choosing the correct size for the tree. Construction of the tree can be stopped early, using some condition to the purity function, or a fully constructed tree can be pruned afterward. Pruned subtrees can then be evaluated with cross-validation or with a pruning data set, which can be different from the training data. Usually, the size of the tree is decided based on different pruning methods, and a tree with a predetermined number of nodes is constructed using all the training data. This tree can then be tested with a testing data set that has not been used in the model construction and selection. Many different methods of inducing decision trees have been used, but most of the work on decision trees is an offshoot of the following methods:

- **Classification and regression trees.** In the mid-1980s, four statisticians published the book *Classification and Regression Trees*. This method is a complete binary tree algorithm (exactly two branches from each internal node). Pruning is used to determine the size of the tree. The target attribute (response variable) and the candidate attributes (predictor variables) can be nominal, ordinal, or continuous [10].
- **The ID3, C4.5, and M5 algorithms—the Waikato environment for knowledge analysis (Weka) methodology.** During the 1970s and early 1980s, J. Ross Quinlan developed a system (ID3 and its extension, C4.5) for inferring classification trees from data samples. The number of branches equals the number of categories of candidate attributes (predictor variables). Pruning is used to determine the size of the tree. Both categorical and continuous candidate attributes (predictor variables) are supported in the C4.5 algorithm, although a target attribute (response variable) is allowed to be categorical only in the ID3 algorithm. The M5 is a regression tree algorithm that Quinlan proposed for continuous target attribute (response variable) [11–13].

- **Automatic interaction detection (AID).** Morgan and Sonquist proposed the AID tree algorithm for detecting complex statistical relationships [14]. In an AID tree, the number of branches varies from two to the number of categories of predictor variables. A statistical significance test (with multiplicity adjustments in the later versions) is used as stopping rule during tree growing in order to control the size of the tree. The AID algorithm was designed for categorical predictor variables and continuous (quantitative) response variables. In 1980, Kass proposed a modification to AID called *chi-squared automatic interaction detection* (CHAID) for nominal categorical response variables [15]. More recently, SPSS Inc. extended CHAID to handle ordinal categorical and continuous response variables.

5.4 Post-Trip Voltage Prediction at Palisades Using Regression Trees

The post-trip voltage prediction using the regression tree technique was evaluated using the results of scenarios analyzed with the V-Q and power flow methods. The software used, the Waikato Environment for Knowledge Analysis (Weka), was developed at the University of Waikato, New Zealand (http://www.cs.waikato.ac.nz/ml/weka/). To be able to use the regression tree software, first we must decide on attributes that might affect the outcome (the post-trip voltage). Then we must create a large number of scenarios (perform simulations) that span the space of attributes. For the post-trip voltage prediction application, we selected unit operating conditions such voltage, active and reactive power output, slope of V-Q curve in the pre-trip state, and the status of the important elements (lines or generators in the vicinity of the NPP) as attributes. The predicted post-trip voltage obtained from power flow simulation (corresponding to the studied scenarios) constituted the outcome or target of the regression tree. A matrix of conditions similar to those shown in Table 4-1 and Table 4-3 was used in the Weka software to produce the regression trees.

For San Onofre, 48 scenarios were simulated. The distribution of the unit operating conditions—voltage, active power, reactive power output, and slope of the V-Q curve—for these scenarios are shown in Figures 5-2 through 5-5. These figures show that the distributions of the unit operating conditions seem reasonable because they span a good portion of the normal operating space.

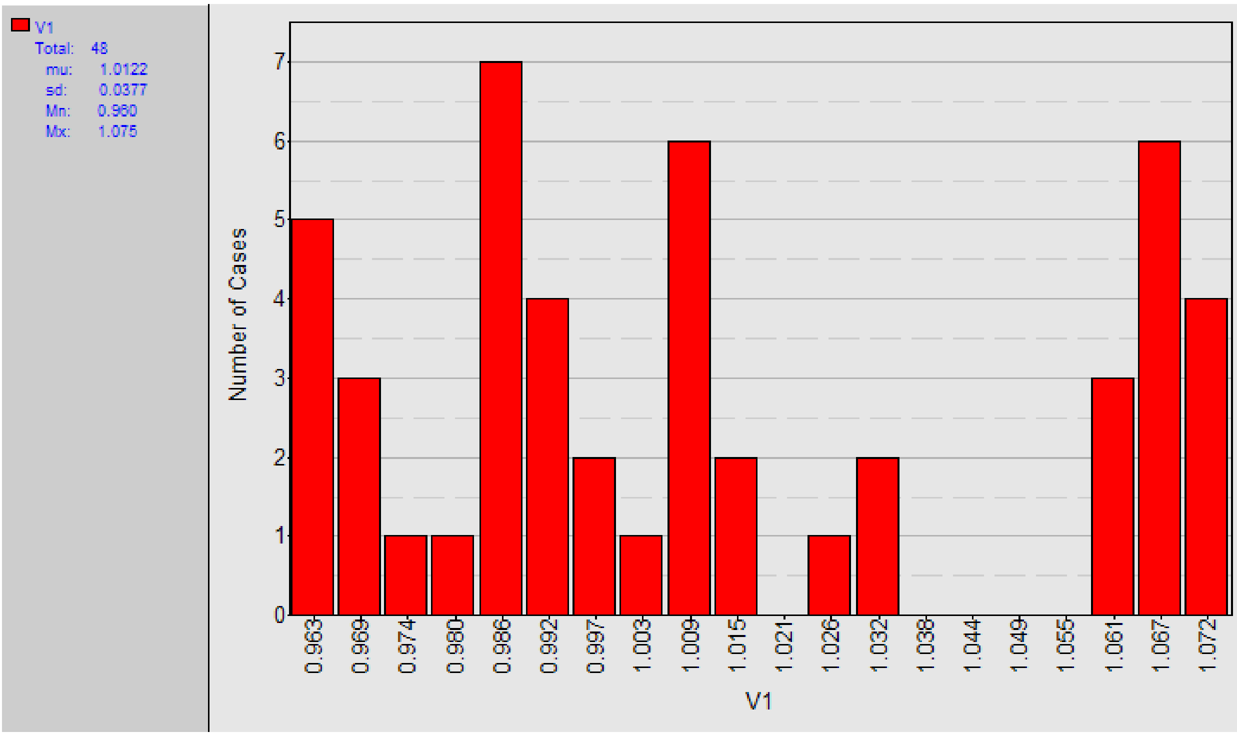


Figure 5-2
Distribution of Pre-Trip Voltage at San Onofre

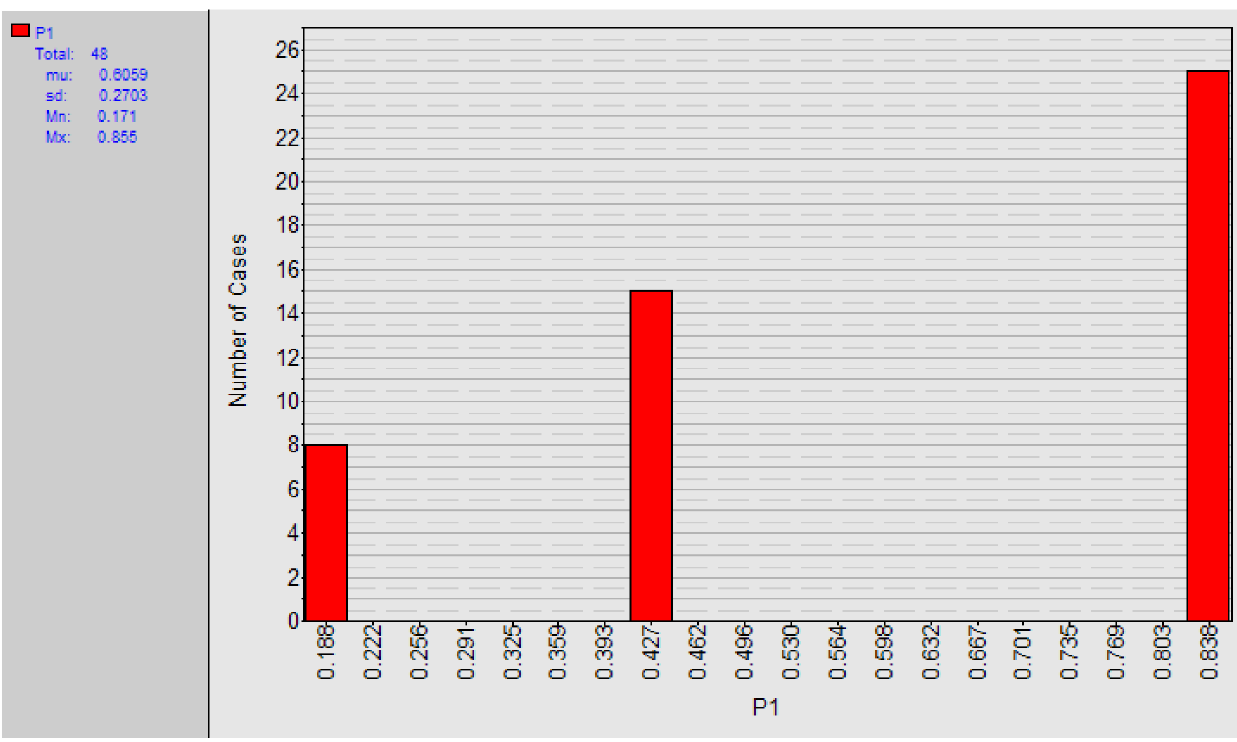


Figure 5-3
Distribution of Pre-Trip Active Power at San Onofre

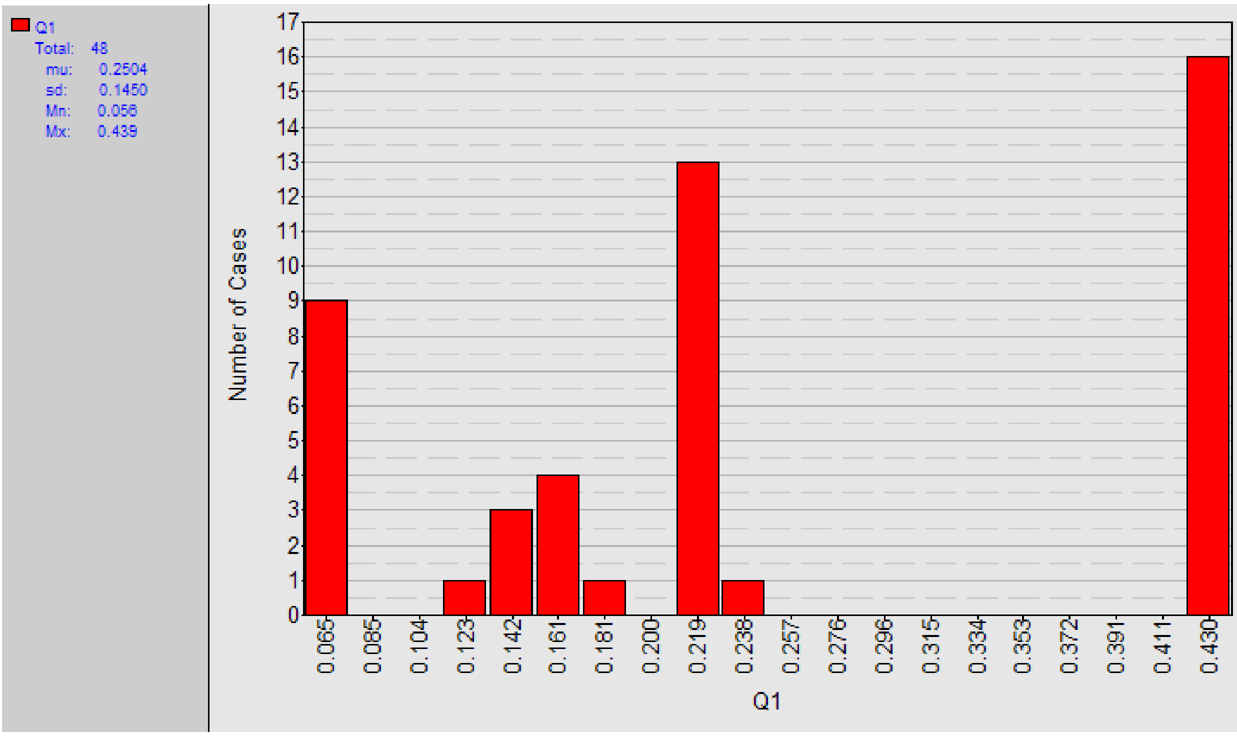


Figure 5-4
Distribution of Pre-Trip Reactive Power at San Onofre

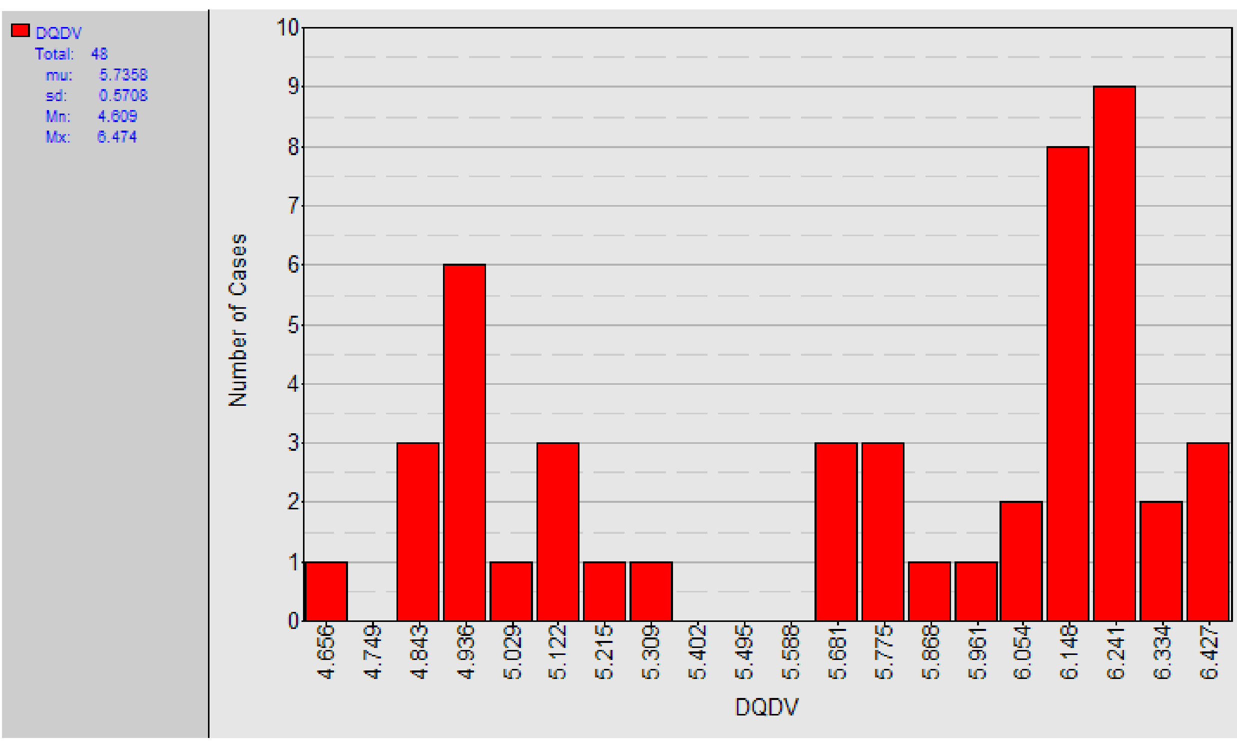
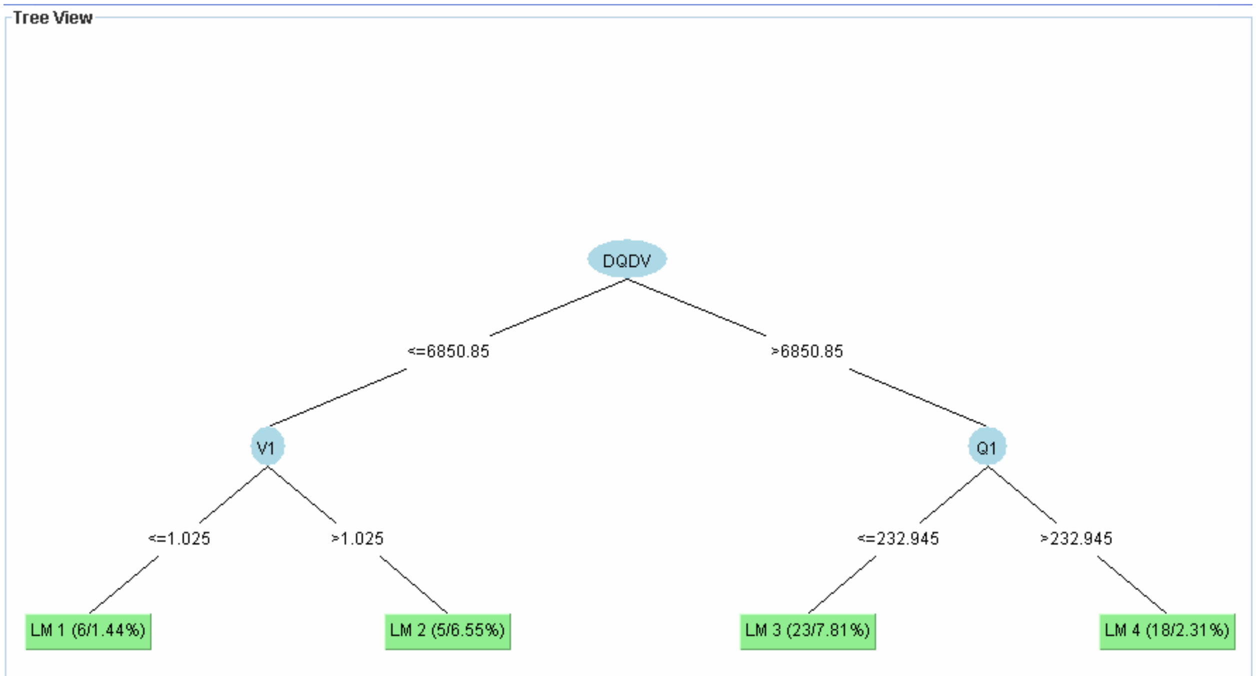


Figure 5-5
Distribution of Pre-Trip Slope of V-Q Curve at San Onofre

The regression tree corresponding to the predicted post-trip voltage developed by the Weka software for the studied scenarios is shown in Figure 5-6. The lower part of the figure shows the relationship that Weka has developed for post-trip voltage prediction at each node of the tree.



LM1: V2 = 0.431 + 0.563V1 - 2e-7P1 - 8.51e-5Q1 + 1.54e-6DQDV

LM2: V2 = 0.509 + 0.487V1 - 2e-7P1 - 8.51e-5Q1 + 1.54e-6DQDV

LM3: V2 = 0.0448 + 0.947V1 - 3.06e-7P1 - 1.35e-4Q1 + 1.29e-6DQDV

LM4: V2 = -0.0378 + 1.01V1 - 9.45e-8P1 - 1.43e-4Q1 + 3.89e-6DQDV

V1, pre-trip voltage; V2, post-trip voltage; P1, pre-trip active power; Q1, pre-trip reactive power; DQDV, slope of the V-Q curve calculated at the pre-trip conditions

Figure 5-6
Regression Tree Developed for Post-Trip Voltage Prediction at San Onofre

The regression tree has found a stronger effect of reactive power than active power on the post-trip voltage (the coefficient of P1 and Q1 show that the effect of active power is much smaller than the reactive power output of the unit on the post-trip voltage). Another interesting finding of the regression tree is the selection of the top node—that is, the slope of the V-Q curve. This has been the main point in the application of simplified methods based on the V-Q curve.

The application of a regression tree for predicting post-trip voltage after the loss of a nuclear unit appears promising and deserves further investigation. The regression tree is less accurate than the V-Q curve method in predicting post-trip voltage; however, the regression tree method is perceived to be a complement to the V-Q method when the measurement of the slope of V-Q curve is not available.

6 CONCLUSIONS

This research project investigated methods of predicting post-trip voltage at NPPs following a unit loss. The main objective of evaluating the adequacy of the V-Q curve method was achieved through a comprehensive power system simulation study. An alternative technique using a regression tree was also proposed, and its validity was assessed. Literature surveys in the areas of the post-trip voltage prediction and data mining technique using decision or regression trees were carried out as well. Finally, a survey was designed in order to identify the need for prediction of post-trip voltage at NPPs as well as to determine the tools that are currently used at NPPs. The results of this project can be summarized as follows:

- The simplified V-Q curve method yields accurate results [5]. For a weak or heavily stressed power system, however, it requires frequent on-line measurement of the slope of the V-Q curve. The accuracy of the V-Q curve method was evaluated through a large number of power flow simulations of the post-trip voltage prediction for two NPPs with different available fault levels in the WECC and NERC systems.
- The power flow or RTCA is the most accurate steady-state analysis for predicting post-trip voltage; however, it depends on the reliability and availability of a state estimator and is not easily accessible to most NPP operators because it is expensive and its use requires expertise.
- Regression trees are less accurate than the V-Q method, and they can be trained off-line. A regression tree can be developed through the results of extensive offline simulations. The developed trees can then be used on-line. This method can be considered a complement to the V-Q curve method, especially when a V-Q slope measurement is not available.

7
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A

SURVEY ON POST-TRIP VOLTAGE PREDICTION METHODS AND DEGRADED VOLTAGE RELAY SETTINGS AT NUCLEAR POWER PLANTS

A.1 Background Information

In the event of a postulated tripping of a nuclear power plant (NPP), it is preferred that the safety equipment be fed from the offsite power systems *[IEEE std. 765–1995, NUREG-0800].* A subsequent voltage depression will appear at the offsite circuits as a result of reduced voltage support from the NPP. The essential auxiliaries (e.g., pumps, fans, control valves, etc.) are sensitive to both voltage and frequency of their supplies. If the post-trip voltage levels are inadequate to support the critical plant equipment, the degraded voltage relay scheme will initiate the onsite emergency generation units, violating the federal regulation on "preferred source of power" (offsite).

Salem Nuclear Generating Station's tripping on July 29, 2003 (similar event at Callaway plant in INPO on August 11, 1999) illuminates an undesirable risk factor associated with an unexpected loss of offsite power circuits. It is being realized that real-time voltage monitoring may deem insufficient in ensuring the availability of the offsite circuits. Thus, there exists a need for developing a more effective methodology using predictive approach [*H.C. Leake, APS*]. Use of real time contingency analysis (RTCA) is one solution to this problem [*NRC GL 2006–02*], however no NPPs currently have this tool and neither do all transmission system operators with NPPs in their operating area. If validated, the approach that uses the sensitivity of voltage to reactive power (V-Q curve) in predicting the post-trip voltage levels as outlined in [*H.C. Leake, APS*] could fill this gap in the ability of the NPP to meet NRC expectations.

EPRI has contracted Powertech Labs Inc to investigate the applicability of the V-Q curve method for predicting post-trip voltage levels, and possible improvements to this approach. The proposed alternative method uses a minimum set of local measurements, whereas RTCA schemes require more measurements and are more expensive. However, the accuracy and reliability of this method needs to be established. The alternative method will include use of data mining and decision trees to identify the key quantities/attributes that contribute to the post-trip voltage prediction. While static analysis (power flow) will be carried out to determine the post-trip voltages, time domain analysis software package will also be utilized to simulate the postulated events. In order to demonstrate the reliability and accuracy of the proposed scheme in predicting post-trip voltages, two typical NPPs will be studied.

In the subsequent section, your feedback on existing industry practices and desire for alternative voltage prediction solutions is sought.

IEEE Std. 765–1995, IEEE Standard for Preferred Power Supply (PPS) for Nuclear Power Generating Stations.

NUREG-0800; US NRC, Standard Review Plan, Section: 8.2 Offsite Power System.

H.C. Leake, A Simplified Method to Predict Post-Trip Switchyard Voltage at Nuclear Generating Stations, Arizona Public Service.

NRC GL 2006–02. Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power.

A.2 Survey

Power Plant Name	
Contact Name and Email (Optional)	

1. Does your plant utilize any post-trip voltage prediction method?

☐ Yes
☐ No

2. If your answer to question 1 is **'yes,'** please indicate which approach do you follow presently?

☐ Informal communication with transmission system operators (TSO) to monitor real-time operability
☐ Use of in-house RTCA solutions to monitor real-time operability
☐ Grid reliability evaluations as part of maintenance risk assessment
☐ Use of long-term periodic studies, operating experience and training
☐ Other methods. Please provide brief description below:

____

3. If your answer to question 1 is **'no,'** please indicate if your NPP is

☐ Planning to work with transmission system operators (TSO) to utilize RTCA solutions
☐ Planning to use in-house RTCA solutions
☐ Not using any RTCA tool

4. Please indicate what method does your NPP follow in selecting the degraded voltage relay set points (voltage levels, time delays etc.)

*[*Please provide one example of your NPP's relay settings: *voltage__________ time delay________]*

☐ Based on systematic comprehensive study
☐ Based on experience
☐ Based on existing standards
☐ Others (please explain) ____

5. Is your NPP interested in the post-trip voltage prediction method outlined in the preceding section (third paragraph of Part I)?

☐ Yes
☐ No

6. Please indicate if your NPP would be interested in participating in an EPRI/Powertech sponsored workshop (June 2008) to discuss the result of this research work for post-trip voltage prediction?

☐ Yes
☐ No

Please provide additional comments in light of the discussions and questionnaire presented so far.

Thank you.

B
TRANSLATED TABLE OF CONTENTS

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Powertech Labs Inc.

核電廠維護應用中心：核電廠和其他發電站的跳機後電壓預測

1018535

2009 年 6 月總結報告

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文獻引用

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本報告描述由電力科學研究院 (EPRI) 贊助的研究。

本報告為合編文件，在文獻中引用時應遵循以下方式：

*核電廠維護應用中心：核電廠和其他發電站的跳機後電壓預測。*EPRI, Palo Alto, CA: 2009. 1018535.

產品描述

本專案由電力科學研究院 (EPRI)
主持開發，主要研究目的是在核電機組跳機後，對核電廠 (NPP)
開關場的電壓進行預測。目前已研究出兩種方法可進行跳機後電壓的預測。第一種方法稱之為 *V-Q（向量量化）法*，即在最低限度地使用當地核電廠資訊（如機組運轉情況—
有功和無功功率輸出和跳機前電壓）的情況下，根據電壓對機組無功功率輸出的靈敏度，預測跳機後電壓。如能對 V-Q
斜率進行線上和週期性評估，則此法得出的預測結果將非常準確。第二種方法稱之為*迴歸樹*法，透過離線繪製迴歸樹來充分利用資料挖掘技術。除利用當地電廠資訊外，此法還要求使用鄰近電廠的一些資訊（如鄰近機組和傳輸設備的狀態資訊）。當 V-Q
法線上更新失敗或暫時無法使用時，可另行採用迴歸樹法來評估跳機後電壓。

結果和發現

我們在兩家核電廠對 V-Q 法和迴歸樹法的準確性和適用性進行了評估。結果證明，通過 V-Q
模擬得出的預測結果相當準確。此法適用於在核電廠控制室線上實施，實施過程中無需大量使用當地電廠的線上測量數據。所需的當地資料為電壓的線上測量數據、無功功率輸出以及機組的 V-Q
斜率。迴歸樹法使用模擬跳機後電壓資料庫（透過常規潮流程式），與模擬的大量情境相對應，包括電廠輸出變化、重要機組的突發事件以及核電廠附近的傳輸設備。適用於此法的資料庫應離線開發；但所繪製的迴歸樹可於線上環境中預測跳機後電壓。與 V-Q
法相比，此法的準確性稍低。但在 V-Q 斜率無法使用時，此法即可派上用場。

挑戰和目的

核能管理委員會 (NRC)
制定的許多標準和指南中一直將預測核電廠跳機後電壓的重要性視為重點。NRC 在 2006

年 2
月發佈之「電力網絡可靠度及其對電廠風險和異地電力系統的運轉能力帶來的影響」(Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power)
一般函告（Generic Letter 2006–
02）中，強調電廠經營者必需瞭解電力網絡在何種條件下會對電廠的匯流排電壓產生影響。本函告是促成此研究專案的主要推動力。核電廠的重要輔機對電壓和頻率都非常靈敏。只有當電壓和頻率大於預定值時，幫浦和控制閥才能夠充分進行冷卻迴圈。運轉確保及時匯流排傳輸和啟動緊急柴油發電機組的低電壓繼電器需要完全依賴於電壓，包括必然產生的跳機後電壓。因此，核電廠經營者必須確保跳機後電壓和頻率水準能夠足以支援關鍵設備的運作。NRC 建議採用突發事件即時分析 (RTCA)
軟體來評估跳機後電壓。但是，RTCA
的成本高昂，且需要從監控和資料擷取過程以及從狀態估計器獲得的系統模型中獲取大量系統資料。RTCA
在核電廠的應用可能會遠遠超出電廠員工的需求及所掌握的知識範圍。此專案研究的方法既簡單又準確，且不必在線上評估方面付出很大努力。此研究專案的主要研究目的是在機組跳機後，對核電廠 (NPP) 開關場的電壓進行預測。

應用、數值和使用

藉由實施本研究專案所開發的方法，電廠經營者能夠在損失機組後準確預測開關場電壓。使用這些方法非常簡便，只需少量當地資訊便可線上應用。這些方法的實施宗旨在於協助核電廠確保關鍵輔機安全可靠的運轉。

EPRI 遠景

對核電廠經營者來說，核機組發電機跳機後的跳機後電壓至關重要。NRC
已明確表示為確保核電廠安全可靠地關閉，必須瞭解異地電壓水準。同時，要求大多數電廠確保在電廠跳機後具有可靠的異地電源。EPRI
為此研究專案提供評估這些方法的經費支援，而核電廠經營者可採用這些既簡單又準確的方法來預測開關場跳機後電壓。

本報告中提出能夠用於評估跳機後電壓的多項建議；但是，這些建議必須經由核電廠經營者和輸電單位進行審核，以確定是否能夠實際取得支援擬議評估的資料。

方法

為在兩家核電廠預測跳機後電壓，研究團隊對 V-Q
法和決策樹法的應用和準確性進行了評估：聖奧羅菲屬於西部電力協調委員會 (WECC) 電力系統；帕利塞德則屬於北美電力可靠性委員會 (NERC) 系統。

關鍵字

決策樹法

跳機後電壓預測

電力潮流程式

時域程式

V-Q 斜率法

鳴謝

電力科學研究院 (EPRI) 衷心感謝亞利桑那電力公共事業公司 (APS) 的 Harvey Leake 先生為本專案提供的寶貴建議和不懈支持。

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核电厂维护应用中心：核电厂和其他发电站的跳机后电压预测

1018535

总结报告 2009 年 6 月

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本报告所描述研究由电力科学研究院 (EPRI) 赞助进行。

本报告为集体编撰的文件，在文献中引用时应遵循以下方式：

*核电厂维护应用中心：核电厂和其他发电站的跳机后电压预测。*EPRI, Palo Alto, CA: 2009. 1018535.

产品描述

本项目由电力科学研究院 (EPRI)
主持开发，主要研究目的是在核电机组跳机后，对核电厂 (NPP)
开关站的电压进行预测。目前已研制出两种方法可进行跳机后电压的预测。第一种方法称之为 *V-Q（矢量量化）法*，即在最低限度地使用当地核电厂信息（如机组运行条件 — 有功和无功功率输出和跳机前电压）的情况下，基于电压对机组无功功率输出的灵敏度，预测跳机后电压。如能对 V-Q
斜率进行在线和周期性评估，则此法得出的预测结果将非常准确。第二种方法称之为 *回归树*法，通过离线绘制回归树来充分利用数据挖掘技术。除利用当地电厂信息外，此法还要求使用邻近电厂的一些信息（如邻近机组和传输设备的状态信息）。当 V-Q
法在线更新失败或暂时不可用时，回归树法拟作为对 V-Q
法评估跳机后电压的补充方式。

结果和发现

我们在两家核电厂对 V-Q 法和回归树法的准确性和适用性进行了评估。结果证明，通过
V-Q
模拟得出的预测结果相当准确。此法适用于在核电厂控制室在线实施，实施过程中无需大量使用当地电厂的在线测量结果。其中必需的当地数据为电压的在线测量结果、无功功率输出以及机组的 V-Q
斜率。回归树法使用模拟的跳机后电压数据库（通过常规潮流程序），与模拟的大量情境相对应，包括电厂输出变化、重要机组的突发事件以及核电厂附近的传输设备。适用于此法的数据库应离线开发；但所绘制的回归树可于在线环境中用来预测跳机后电压。与 V-Q 法相比，此法的准确性稍低。但在 V-Q 斜率无法使用时，此法能够作为很好的补充。

挑战和目的

核管理委员会 (NRC) 制定的许多标准和指南中一直将预测核电厂跳机后电压的重要性作为重中之重。NRC 于 2006 年 2 月发布的“ 电力网可靠度及电力网对电厂风险和厂外电力系统的可运行性带来的影响”(Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power) 一般函告（Generic Letter 2006–02）中，强调电厂经营者必需了解电力网在何种条件下会对电厂的总线电压产生影响。本函告是促成此研究项目的主要推动力。核电厂的重要辅机对电压和频率都非常灵敏。只有当电压和频率大于预定值时，泵和控制阀才能够充分进行冷却循环。运行确保及时总线传输和启动紧急柴油发电机组的低电压继电器需要完全依赖于电压，包括必然产生的跳机后电压。因此，核电厂经营者必须确保跳机后电压和频率水平能够足以支持关键设备的运行。NRC 建议采用突发事件实时分析 (RTCA) 软件来评估跳机后电压。但是，RTCA 的成本高昂，且需要从监控和数据采集过程以及从状态估计器获得的系统模型中获取大量系统数据。RTCA 在核电厂的应用可能会远远超出电厂员工的需求及所掌握的知识范围。此研究项目中研制的方法既简单又准确，且不必在在线评估方面付出很大努力。此研究项目的主要研究目的是在机组跳机后，对核电厂 (NPP) 开关站的电压进行预测。

应用、数值和使用

通过实施此研究项目中研制的方法，电厂经营者能够在损失机组后准确预测开关站电压。在使用这些方法时非常简便，只需少量当地信息便可在线应用。这些方法的实施宗旨在于协助核电厂确保关键辅机安全可靠的运行。

EPRI 远景

对核电厂经营者来说，核机组发电机跳机后的跳机后电压至关重要。NRC 已明确表示为确保核电厂安全可靠地关闭，必须了解厂外电压水平。同时，要求大多数电厂确保在电厂跳机后具有可靠的厂外电力源。EPRI 为此研究项目提供评估这些方法的资金支持，而核电厂经营者可采用这些既简单又准确的方法来预测开关站跳机后电压。

本报告中提出能够用于评估跳机后电压的多项建议；但是，这些建议要求由核电厂经营者和输电单位进行审核，以确定是否能够实际获得支持拟议评估的数据。

方法

为在两家核电厂预测跳机后电压，研究团队对 V-Q
法和决策树法的应用和准确性进行了评估：圣奥罗菲属于西部电力协调委员会 (WECC) 电力系统；帕利塞德属于北美电力可靠性委员会 (NERC) 系统。

关键词

决策树法

跳机后电压预测

潮流程序

时域程序

V-Q 斜率法

致谢书

电力科学研究院 (EPRI) 衷心感谢亚利桑那电力公共事业公司 (APS) 的 Harvey Leake 先生为此项目提供的宝贵建议和不懈支持。

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Centre d’applications de maintenance nucléaire : Prévisions de tension après déclenchement aux centrales nucléaires et autres

1018535

Rapport final, juin 2009

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RÉFÉRENCES

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Ce rapport décrit une recherche effectuée sous l'égide de l'Electric Power Research Institute (EPRI).

Le rapport est un document d'entreprise qui doit être cité dans la bibliographie de la façon suivante :

Centre d'applications de maintenance nucléaire: Prévisions de tension après déclenchement aux centrales nucléaires et autres. EPRI, Palo Alto, Californie, États-Unis : 2009. 1018535.

DESCRIPTION DU PRODUIT

Ce projet de l'Electric Power Research Institute (EPRI) a pour objet de rechercher la possibilité de prédire la tension à un poste extérieur d'interconnexion dans une centrale nucléaire à la suite du déclenchement d'une unité nucléaire. Deux méthodes de prévision de tension après déclenchement font l'objet de cette recherche. La première méthode nommée *Méthode V-Q* utilise une information minimale de la centrale locale (comme les conditions de fonctionnement de l'unité—puissance de sortie active et réactive et tension avant déclenchement) pour prévoir la tension après déclenchement en se basant sur la sensibilité de la tension par rapport à la puissance de sortie réactive de l'unité. Cette méthode fournit d'excellents résultats si la pente de V-Q peut être évaluée en ligne et de façon périodique. La deuxième méthode, appelée méthode par *arbre de régression*, utilise des techniques d'exploration de données par le biais d'arbres de régression mis au point en différé. Cette méthode exige, en plus de l'information de la centrale locale, certains renseignements du voisinage de la centrale (comme l'état des unités voisines et des installations de transmission). L'utilisation d'arbres de régression comme complément à la méthode V-Q a été proposée pour évaluer la tension après déclenchement lorsque la mise à jour en direct de V-Q n'est pas possible ou disponible temporairement.

Résultats et conclusions

L'exactitude et l'applicabilité de la méthode V-Q et de la méthode par arbre de régression ont été évaluées dans deux centrales nucléaires. Les résultats de la simulation V-Q ont prouvé qu'elle était très exacte. Cette méthode est applicable à la mise en œuvre en ligne dans la salle de commande des centrales nucléaires en utilisant des mesures minimales en direct de la central locale. Les données locales nécessaires sont les suivantes : mesures de tension en ligne, puissance de sortie réactive et pente V-Q de l'unité. La méthode par arbre de régression utilise une base de données de tensions simulées après déclenchement (par le biais d'un programme de débit conventionnel de puissance) correspondant à un nombre important de scénarios, notamment les variations de puissance de sortie de la centrale, les impondérables des unités importantes et les installations de transmission au voisinage de la centrale nucléaire. La base de données de cette méthode devrait être mise au point en différé ; cependant, les arbres de régression mis au point peuvent être utilisés en direct pour prévoir la tension après déclenchement. L'exactitude de cette méthode n'est pas aussi élevée que celle de la méthode V-Q, mais elle peut la complémenter à chaque fois que la pente de V-Q n'est pas disponible.

Défis et objectifs

L'importance de la prévision de la tension après déclenchement dans les centrales nucléaires a fait l'objet de nombreuses normes et directives de la part de la Nuclear Regulatory Commission (Commission de réglementation de l'énergie nucléaire) (NRC). La lettre générique 2006-02 de la NRC, "Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power" (Fiabilité des réseaux, répercussions sur les risques aux centrales et opérabilité de la puissance hors site), insistait sur la nécessité pour les exploitants de centrale de connaître les conditions du réseau qui pourraient influer sur la tension de bus à la centrale. Cette lettre générique a été l'impulsion principale de ce projet. Les matériels auxiliaires essentiels des centrales nucléaires sont sensibles tant à la tension qu'à la fréquence. Les pompes et les vannes de commande peuvent offrir une circulation de refroidissement suffisante uniquement si la tension et la fréquence sont plus élevées que les valeurs prédéfinies. Le fonctionnement du relais de tension dégradée en vue d'assurer en temps opportun un transfert de bus et le démarrage des génératrices Diesel de secours, table énormément sur la tension, notamment la tension après déclenchement qui en résulte. Par conséquent, les exploitants de centrales nucléaires doivent s'assurer que les niveaux de tension après déclenchement et des fréquences sont suffisants pour prendre en charge l'équipement critique. La NRC a suggéré l'application du logiciel d'analyse des impondérables en temps réel pour l'évaluation des tensions après déclenchement. Toutefois, cette analyse est dispendieuse et exige des données système à grande échelle provenant de l'acquisition des données de supervision et de contrôle ainsi qu'un modèle du système provenant de l'estimateur d'état. L'application de l'analyse des impondérables en temps réel dans les centrales nucléaires peut dépasser les besoins et les compétences du personnel des centrales. Les méthodes qui ont été étudiées dans ce projet de recherche sont à la fois simples et exactes, et exigent peu d'effort pour une évaluation en direct. Ce projet de recherche a pour objet d'étudier la possibilité de prédire la tension à un poste extérieur d'interconnexion dans une centrale nucléaire, à la suite du déclenchement d'une unité.

Applications, valeur et utilisation

Les exploitants de centrales peuvent prédire avec exactitude la tension d'un poste extérieur d'interconnexion à la suite de la perte d'une unité en mettant en œuvre les méthodes mises au point dans ce projet de recherche. Les méthodes sont simples et l'application en direct exige des informations locales minimales. La mise en application de ces méthodes devrait aider les centrales nucléaires à assurer une exploitation sûre et fiable des composants auxiliaires essentiels.

Point de vue de l'EPRI

La tension après déclenchement suivant le démarrage de la génératrice d'une unité nucléaire est très importante pour les exploitants de centrales nucléaires. La Nuclear Regulatory Commission a insisté sur l'importance de connaître le niveau de tension hors site de manière à assurer une interruption sûre et fiable des opérations aux centrales nucléaires. La plupart des centrales doivent également s'assurer qu'elles possèdent une source fiable d'alimentation en cas de déclenchement d'une centrale. L'EPRI a financé ce projet de recherche pour évaluer les méthodes qui pourraient offrir aux exploitants de centrales nucléaires des méthodes simples et exactes de prédiction de tension après déclenchement dans les postes extérieurs d'interconnexion.

Ce rapport présente des recommandations qui peuvent être utilisées pour évaluer la tension après déclenchement ; toutefois, ces recommandations doivent être étudiées par les exploitants de centrales et les services de transmission pour déterminer si les données visant à appuyer les évaluations proposées peuvent être obtenues de façon pratique.

Approche

L'équipe de recherche a évalué l'application et l'exactitude des méthodes V-Q et d'arbre de décision pour prédire la tension après déclenchement dans deux centrales nucléaires. San Onofre fait partie du réseau électrique Western Electricity Coordinating Council (WECC) et Palisades, du réseau North American Electric Reliability Council (NERC).

Mots-clés
Méthode par arbre décisionnel
Prévisions de tension après déclenchement
Programme de débit de puissance
Programme de domaine temporel
Méthode par pente V-Q

REMERCIEMENTS

L'Electric Power Research Institute (EPRI) souhaite remercier Harvey Leake de l'Arizona Public Service pour ses remarques précieuses et son soutien constant au cours de ce projet.

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原子力保全アプリケーションセンター：原子力発電所およびその他の発電所におけるトリップ後の電圧の予測

1018535

2009年6月最終レポート

保証と責任の制限に関する免責事項

本書は、ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI)のスポンサーまたは共同スポンサーによる作業の一環として以下の組織によって作成されたものである。EPRI、EPRIのメンバー、共同スポンサー、下記の組織、またはこれらを代表するどの人物も、

（A）明示あるいは黙示を問わず、（I）特定目的に対する市場性および適格性を含み、本書で開示される情報、装置、方式、プロセス、または類似の事項を使用すること、あるいは（II）その使用が、いずれかの当事者の知的財産権を含む私有の権利を侵害または干渉しないこと、あるいは（III）本書が特定のユーザーの状況に適していることを保証または代表するものではなく、また

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本書を作成した組織

Powertech Labs Inc.

注記

EPRIの詳細については、EPRIお客さまサポートセンター（電話: 米国 800.313.3774、電子メール: askepri@epri.com）までお問い合わせください。

引用

このレポートの作成者は以下の通りである。

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このレポートでは、Electric Power Research Institute(EPRI)がスポンサーとなった研究について述べている。

このレポートは企業文書であるため、文献に引用される場合、引用情報は次のとおり記載する必要がある。

*原子力保全アプリケーションセンター：原子力発電所およびその他の発電所におけるトリップ後の電圧の予測。*EPRI, Palo Alto, CA: 2009. 1018535.

成果品説明

このElectric Power Research Institute (EPRI)プロジェクトの目的は、原子力発電所(NPP)において原子炉がトリップした後の開閉所電圧を予測する可能性を調査するものである。トリップ後の電圧予測について2種類の方法を検討した。第1の方法は、*V-Q法*と呼ばれ、最低限のローカルの発電所情報(有効および無効電力出力およびトリップ前の電圧などの運転条件)を使い、発電機の無効電力出力に対する電圧感度に基づき、トリップ後の電圧を予測する。この方法は、V-Q勾配を運転中および定期的に評価することができる場合に優れた結果をもたらす。第2の方法は、*回帰木*法と呼ばれ、停止中で作成された回帰木によるデータマイニング技術を用いる。この方法は、ローカルの発電所情報に加え、周辺の発電所情報(周辺の発電機や送電設備の状況など)も必要とする。回帰木の使用は、運転中によるV-Qの更新ができなかったり、一時的に利用不可能な場合にトリップ後の電圧を評価するためのV-Q法を補完するものとして提案されている。

結果と発見

V-Q法および回帰木法の精度および適用性が2箇所の原子力発電所で評価された。V-Qシミュレーション結果は非常に精度が高いことが証明された。ローカルの発電所における最低限の運転中の測定値を使うこの方法は、原子力発電所の制御室における運転中での実施に適用できる。必要なローカルデータは、電圧、無効電力出力および装置のV-Q勾配などの運転中の測定値である。回帰木法は、発電機出力の変動、重要補機の偶発事象、原子力発電所周辺の送電設備を含む多くのシナリオに対応した、(従来の電力フロープログラムにより)シミュレーションしたトリップ後電圧のデータベースを使用する。この方法で使われるデータベースは、停止中に作成されるべきですが、開発された回帰木は運転中の環境でトリップ後の電圧を予測するために使用することができる。こ

の方法の精度は、V-Q法ほど高くないが、V-Qの勾配が得られないときにV-Q法を補完するものとして使用できる。

課題および目的

原子力発電所におけるトリップ後電圧を予測する重要性は、原子力規制委員会(NRC)による多くの基準およびガイドの焦点となっていた。NRCのジェネリックレター2006–02「送電網の信頼性ならびに発電所リスクおよび外部電源の運転性への影響」では、どの送電網の状況が発電所のブス電圧へ影響を及ぼすか発電所の運転員が知っておくことの必要性を強調している。このジェネリックレターが本プロジェクトの主な動機になっている。原子力発電所の重要補機は、電圧および周波数の両方に敏感である。ポンプおよび制御弁は、電圧と周波数が一定の値を超えている場合のみ十分な冷却循環を提供することができる。迅速なブス切換および非常用ディーゼル発電機の起動を確実に行うための低電圧リレー動作は、「トリップ後電圧」等の「電圧」に大きく依存する。したがって、原子力発電所の運転員はトリップ後の電圧および周波数レベルが重要な機器をサポートするのに適しているか確認する必要がある。原子力規制委員会(NRC)は、トリップ後の電圧評価に、リアルタイム安定度解析(RTCA)ソフトウェアを適用することを推奨している。しかし、リアルタイム安定度解析（RTCA）は高価であり、また監視制御· 情報取得システムから得られる広範な系統データや状態評価から得られた系統モデルが必要になる。原子力発電所に対するリアルタイム安定度解析(RTCA)の適用は、発電所の技術者のニーズを遙かに超え、その専門知識が及ばない可能性がある。本研究プロジェクトで検討した方法は、簡素かつ精度が高く、最低限の取り組みで運転中の評価が可能になる。本研究プロジェクトの目的は、発電所のトリップ後における開閉所電圧の予測の可能性を検討するものである。

適用、価値、および使用

発電所の運転員は、本研究プロジェクトで開発された方法を実施することで、発電機が停止された後の開閉所の電圧を正確に予測することができる。この方法は簡単で、最低限のローカルの発電所の情報しか必要とせず運転中に適用できる。これらの方法の実施は、原子力発電所における重要補機の安全で信頼性のある運転を確保することを援助することができる。

EPRIの展望

原子力発電所の発電機がトリップした後の電圧は、原子力発電所の運転員にとって非常に重要である。原子力規制委員会(NRC)は、原子力発電所の安全性と信頼性を確実にするために、外部電源の電圧レベルを知ることの重要性を表明している。また、ほとんどの発電所では、発電所のトリップに備え、信頼性の高い外部電源の用意が要求されている。EPRIは、開閉所におけるトリップ後の電圧を、簡単かつ正確に予測し、原子力発電所の運転員に提供できる方法を評価するため、本研究プロジェクトに資金提供を行った。

本レポートでは、トリップ後の電圧の評価に使用できる推奨事項を提供しているが、発電所の運転員および送電会社はこの推奨をレビューし、提案された評価をサポートするデータが実際に取得できるかどうか判断する必要がある。

アプローチ

研究チームは、トリップ後の電圧を予測するためのV-Q法および決定木法の適用および正確性を2箇所の原子力発電所で評価した。1箇所は、Western Electricity Coordinating Council (WECC)の発電系統の一部であるSan Onofre発電所、もう1箇所は、North American Electric Reliability Council (NERC)系統の一部であるPalisades発電所である。

キーワード

決定木法
トリップ後の電圧予測
電力フローダイアグラム
時間領域プログラム
V-Q勾配法

謝辞

Electric Power Research Institute
(EPRI)は、このプロジェクトに貴重なご意見および継続的なご支援を頂いたことに対し、Arizona Public ServiceのHarvey Leake氏に深く感謝する。

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Centro de Aplicaciones de Mantenimiento para Centrales Nucleares: predicción de la tensión tras disparos en centrales nucleares y otras instalaciones de generación eléctrica

1018535

Informe definitivo, junio de 2009

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NOTA

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MENCIONES

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En este informe se describen investigaciones financiadas por el *Electric Power Research Institute* (Instituto de Investigación de Energía Eléctrica o EPRI).

Este informe es un documento corporativo que debe referenciarse en la literatura con el siguiente formato:

Centro de Aplicaciones de Mantenimiento para Centrales Nucleares: predicción de la tensión tras disparos en centrales nucleares y otras instalaciones de generación eléctrica (Nuclear Maintenance Applications Center: Post-Trip Voltage Prediction at Nuclear and Other Generating Stations). EPRI, Palo Alto, CA: 2009. 1018535.

DESCRIPCIÓN DEL PRODUCTO

Este proyecto del *Electric Power Research Institute* (Instituto de Investigación de Energía Eléctrica o EPRI) tiene como fin investigar la posibilidad de predecir la tensión del parque eléctrico de una central nuclear tras el disparo de una de sus unidades. Se han investigado dos métodos para predecir dicha tensión tras un disparo, el primero de los cuales se conoce como *método V-Q*. Este método utiliza la información básica local de la central (por ejemplo, las condiciones de operación de la unidad, la salida de potencia activa y reactiva, y la tensión anterior al disparo) para predecir la tensión tras un disparo a partir de la sensibilidad de la tensión en la salida de potencia reactiva de la unidad. Este método proporciona excelentes resultados si la pendiente de V-Q puede evaluarse en línea y de forma periódica. El segundo método se conoce como el método de *jerarquías de regresión* y se vale de técnicas de recogida de datos mediante jerarquías de regresión desarrolladas fuera de línea. Este método requiere, además de los datos locales de la central, cierta información de la zona circundante (como el estado de las unidades colindantes y las instalaciones de transmisión). La utilización de las jerarquías de regresión se propone como complemento del método V-Q para evaluar la tensión tras un disparo cuando resulte imposible actualizar la V-Q en línea o cuando no se disponga de ella temporalmente.

Resultados y hallazgos

La precisión y la capacidad de aplicación de los métodos V-Q y de jerarquías de regresión se evaluaron en dos centrales nucleares. Se observó que los resultados de la simulación V-Q fueron bastante precisos. Este método es adecuado para su implantación en línea en las salas de control de las centrales utilizando mediciones básicas locales de la central. Los datos locales necesarios son las mediciones en línea de la tensión, la salida de potencia reactiva y la pendiente de V-Q de la unidad. El método de jerarquías de regresión utiliza una base de datos de simulación de la tensión posterior al disparo (a través de un programa convencional de flujo de potencia) para predecir un gran número de situaciones. Entre ellas se encuentran las variaciones en la salida eléctrica de la central, las contingencias de las unidades importantes y las instalaciones de transmisión en la zona circundante a la central. La base de datos para este método debe elaborarse fuera de línea. Sin embargo, las jerarquías de regresión desarrolladas pueden utilizarse en un entorno en línea para predecir la tensión tras un disparo. La precisión de este método no es tan alta como la del método V-Q, pero puede servir de complemento para éste último cuando la pendiente de V-Q no esté disponible.

Retos y objetivos

La importancia de la predicción de la tensión tras un disparo en centrales nucleares ha sido un tema fundamental de muchos estándares y directrices de la Comisión Reguladora del Sector Nuclear de los EE. UU (NRC). En la Carta Genérica 2006–02 de la NRC, Fiabilidad de las redes e impacto sobre los riesgos para la central y la operabilidad de las instalaciones externas (*Grid*

Reliability and the Impact on Plant Risk and the Operability of Offsite Power) se puso de manifiesto la necesidad de que los operadores de las centrales conocieran las condiciones de las redes que pudieran afectar a la tensión de las barras de la central. La Carta Genérica es el principal factor de impulso de este proyecto. Los sistemas auxiliares esenciales de las centrales nucleares son sensibles tanto a la tensión como a la frecuencia. Las bombas y las válvulas de control únicamente pueden suministrar suficiente refrigeración por circuito cerrado cuando la tensión y la frecuencia son mayores que los valores predefinidos. La operación del relé de tensión degradada para garantizar una transferencia de las barras adecuada y el arranque de los generadores diésel de emergencia depende en gran medida de la tensión, incluida la tensión tras un disparo. Por esta razón los operadores de las centrales nucleares deben asegurarse de que los niveles de tensión y frecuencia posteriores al disparo son adecuados para el abastecimiento de los equipos esenciales. La NRC recomienda la utilización de programas de análisis de contingencias en tiempo real (RTCA, por sus siglas en inglés) para evaluar las tensiones posteriores a los disparos. Sin embargo, el coste de los programas de RTCA es alto y requieren una gran cantidad de datos del sistema que deben obtenerse mediante actividades de adquisición de datos y control de vigilancia, además de un modelo de sistema de cálculo de estado. La utilización de programas RTCA en las centrales nucleares podría encontrarse fuera del alcance de sus plantillas, ya sea en términos de necesidad o de capacidad de aplicación. Los métodos investigados en este proyecto son simples y precisos y requieren un esfuerzo mínimo para realizar su evaluación en línea. Este proyecto de investigación tiene como fin investigar la posibilidad de predecir la tensión del parque eléctrico de una central tras el disparo de una unidad.

Aplicaciones, valor y utilización

Al implantar los métodos desarrollados en este proyecto de investigación, los operadores de las centrales podrán predecir con precisión la tensión del parque eléctrico tras la pérdida de una unidad. Los métodos son sencillos y su aplicación en línea requiere poca información local. La utilización de estos métodos debe ayudar a las centrales nucleares a garantizar una operación segura y fiable de sus sistemas auxiliares esenciales.

La perspectiva de EPRI

La tensión posterior a un disparo del generador de una unidad nuclear es de importancia vital para los operadores de las centrales nucleares. La NRC ha puesto de manifiesto la importancia de conocer el nivel de tensión externa para asegurar paradas seguras y fiables en las centrales nucleares. Además, la mayoría de las centrales están obligadas a contar con una fuente fiable de energía externa para situaciones en las que se produzcan disparos. EPRI ha financiado este proyecto de investigación para evaluar métodos que ofrecieran a los operadores de las centrales nucleares la posibilidad de contar con formas sencillas y precisas de predecir la tensión del parque eléctrico tras un disparo.

En este informe se ofrecen recomendaciones que pueden emplearse para evaluar la tensión tras un disparo. Sin embargo, es necesario que los operadores y las entidades divulgadoras examinen dichas recomendaciones para determinar si los datos para realizar dichas valoraciones pueden obtenerse de forma práctica.

Enfoque

El equipo de investigación examinó la utilización y la precisión de los métodos V-Q y de jerarquías de decisión para predecir la tensión posterior a los disparos en dos centrales nucleares: la central de San Onofre, que pertenece al Consejo Coordinador de Electricidad del Oeste de los

EE.UU. (WECC), y la de Palisades, que forma parte del Consejo de Fiabilidad Eléctrica Norteamericano (NERC).

Palabras clave
Método jerárquico de toma de decisiones
Predicción de la tensión tras un disparo
Programa de flujo de potencia
Programa de dominio del tiempo
Método de pendiente de V-Q

AGRADECIMIENTOS

El *Electric Power Research Institute* (Instituto de Investigación de Energía Eléctrica o EPRI) desea agradecer a Harvey Leake, del Arizona Public Service, sus valiosos comentarios y su apoyo incondicional durante este proyecto.

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1018535

최종 보고서, 2009년 6월

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결과 및 발견

V-Q 방법 및 회귀 트리 방법의 정확성과 적용 가능성을 두 곳의 NPP에서 평가했습니다. V-Q 시뮬레이션의 결과는 상당히 정확한 것으로 판명되었습니다. 이 방법은 최소한의 지역 발전소 온라인 측정을 사용하여 NPP 제어실에서 온라인 구현에 적용할 수 있습니다. 필요한 지역 정보는 전압의 온라인 측정, 무효 전력 출력, 장치의 V-Q 곡선 등입니다. 회귀 트리 방법은 발전소 출력 변수, 중요 장치의 비상 계획, NPP 주변의 전송 시설 등을 포함하여 다양한 시나리오에 대해 시뮬레이션한 트립 후 전압(기존의 전력 흐름 프로그램 사용)의 데이터베이스를 사용합니다. 이 방법에 대한 데이터베이스는 오프라인으로 구축해야 하지만 마련된 회귀 트리는 트립 후 전압 예측을 위해 온라인 환경에서 사용할 수 있습니다. 이 방법의 정확성은 V-Q 방법만큼 높지 않지만 V-Q 곡선을 그릴 수 없을 경우 V-Q 방법을 보완할 수 있습니다.

문제점 및 목표

NPP에서 트립 후 전압 예측의 중요성은 원자력 규제 위원회(NRC)의 다양한 표준 및 지침에서 강조되어 왔습니다. NRC 일반 서한(Generic Letter) 2006-02, "그리드 신뢰성과 발전소 위험과 및 오프사이트 전력 가동성에 미치는 영향(Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power)"은 발전소 운전원이 발전소 버스 전압에 영향을 주는 그리드 상태를 알아야 하는 필요성을 강조했습니다. 이 일반 서한은 이 프로젝트의 주요 지침이었습니다. NPP의 필수적인 보조 장치는 전압과 주파수에 모두 민감합니다. 펌프와 컨트롤 밸브는 전압과 주파수가 미리 정해진 값보다 클 경우에만 충분한 냉각 순환을 공급할 수 있습니다. 비상 디젤 발전기가 제 때에 버스 전송과 시동을 하도록 하기 위한 저전압 계전기의 작동은 트립 후 결과 전압을 포함한 전압에 크게 의존하고 있습니다. 따라서 NPP 운전원은 트립 후 전압과 주파수 레벨이 주요 장비를 지원하기에 적절한지 확인해야 합니다. NRC는 트립 후 전압 평가를 위해 실시간 비상계획 분석(RTCA) 소프트웨어의 사용을 제안했습니다. 하지만 RTCA는 비용이 많이 들고, 감독 제어 및 데이터 습득으로 얻은 확장적인 시스템 정보와 상태 추정기의 시스템 모델을 필요로 합니다. NPP에서 RTCA를 채택하려면 수요와 발전소 직원의 전문지식이 훨씬 많이 갖추어져야 할 것입니다. 이 연구 프로젝트에서 조사한 방법은 간단하고 정확하며 온라인 평가를 위한 최소한의 노력만 있으면 됩니다. 본 연구 프로젝트의 목적은 장치 트립 후 원자력 발전소(NPP) 스위치야드 전압에 대한 예측 가능성을 조사하는 것입니다.

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EPRI 관점

원자력 발전소의 발전기가 트립한 후의 전압은 NPP 운전원에게 가장 중요합니다. NRC는 NPP의 안전하고 신뢰성 있는 가동 중지를 위해 오프사이트 전압 레벨을 아는 것이 중요한 이유를 강조했습니다. 또한 대부분의 발전소에서는 발전소 트립에 대비하여 신뢰성 있는 오프사이트 전력 소스를 갖추도록 해야 합니다. EPRI는 NPP

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접근 방법

연구 팀은 두 곳의 NPP, 즉 WESS(Western Electricity Coordinating Council) 전력 시스템의 일부인 San Onofre와 NERC(North American Electric Reliability Council) 시스템의 일부인 Palisades에서 트립 후 전압 예측을 위해 V-Q 방법 및 의사결정 트리 방법의 적용과 정확성을 평가했습니다.

키워드

의사결정 트리 방법(Decision tree method)
트립 후 전압 예측(Post-trip voltage prediction)
전력 흐름 프로그램(Power flow program)
시간 도메인 프로그램(Time domain program)
V-Q 곡선 방법(V-Q slope method)

감사의 말씀

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