Fast Fault Screening for Real-Time Transient Stability Assessment

Final Report 10-34
November 2010

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Fast Fault Screening for Real-Time Transient Stability Assessment

Final Report

Prepared for the
**New York State
Energy Research and
Development Authority**

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www.nyserda.org

Mark P. Razanousky
Project Manager

Prepared by:
Electric Power Research Institute (EPRI)

Dr. Stephen Lee
Project Manager

and

Dr. Liang Min
Project Manager

Subcontrator:
V&R Energy System Research, Inc.

Mrs. Marianna Vaiman
Project Manager

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Clay Burns	National Grid
Henry Chao	NYISO
Kevin DePugh	NYSEG
Jennifer Dering	NYPA
Pat Duggan	Con Ed
Bruce Fardanesh	NYPA
Mark Graham	NYPA
Rich Hackman	NYPA
Paul Haering	CHG&E
Janos Hajagos	National Grid/LIPA
Mike Hervey	National Grid/LIPA
Steve Keller	DPS
James B. Marean	NYSEG
Dejan Sobajic	NYISO
Mike Swider	NYISO
Jade Wong	Con Ed

EXECUTIVE SUMMARY

2.1 Background / Overview

Addition of new generation, uncertainty in dispatch of renewable power, increased power transfers and load growth causes a power system to be more vulnerable to transient stability violations.

Identifying weak points in the system is a very time consuming process that uses time-domain simulation approach, and can miss key problem areas.

As a deregulated system is being operated closer to the system limits, system operators require a fast screening tool that will assess the system's stability and identify the most severe fault locations in the system. Some of these locations might be already known to planners and operators while other new locations emerge as the system conditions dynamically change in a real-time operating environment.

The standard utility practice is to run a pre-selected list of faults that have been historically known as dangerous. The process involves a time consuming time-domain simulation technique.

Thus, transient stability analysis is not currently performed in operations and real-time environments. Operators rely on the planning personnel to provide them with the results of transient stability analysis. In a planning environment, this can be a time-consuming and cumbersome task.

The proposed project will allow planners and operators to assess transient (angular) stability very fast. The Fast Fault Screening (FFS) technique is a very fast approach to identify and rank the most severe three-phase and unbalanced fault locations. The smart logic to determine the most severe three-phase faults was tested in a planning environment. Testing showed that it took less than one minute to determine and rank the most severe faults using the proposed Fast Fault Screening (FFS) approach.

The current NERC Transmission Planning (TPL) standard TPL-003-0, R.1.3.1 states that "The rationale for the contingencies selected for evaluation shall be available as supporting information. An explanation of why the remaining simulations would produce less severe system results shall be available as supporting information". Fast Fault Screening (FFS) offers a faster approach to transient stability assessment that provides this "rationale" and "supporting information".

2.2 Study Results

The Fast Fault Screening (FFS) approach was used in this study to determine and rank the most severe fault locations. First, locations of the most severe faults are determined using a heuristic approach. As a result of this computation, buses with large real power flowing through them from local generators are identified.

Then, these locations were ranked using a Ranking Index that was derived using analytical computations. The Ranking Index (RI) was introduced to rank the most severe faults. RI is a very fast approximation of the fault severity that does not require running time-consuming fault analysis for each fault.

The most severe situations are those that lead to voltage collapse. The next category of severity is faults that cause a loss of generator power as a result of an outage. These two categories are followed by the situations corresponding to faults with the smallest critical clearing time. These are the most severe faults in the system. This type of situation is caused by transient stability processes in the electric system. The criterion that was used for ranking these faults is critical clearing time.

The work under this project consisted of the following two phases:

1. Extensive off-line testing of the Fast Fault Screening (FFS) capability using NY ISO planning data. The FFS approach was validated under various system conditions.
2. Extensive on-line testing of the FFS capability using NY ISO State Estimator data. Online testing included:
    - Creating a dynamic models file for the State Estimator cases;
    - Validating the FFS approach for various State Estimator cases.

Three-phase faults were analyzed during the project.

<u>Phase I. Off-line testing of the FFS</u>

The off-line testing of the FFS proceeded as follows:

1. The FFS analysis was performed on a base case provided by NYISO. The base case contains NYISO planning model. The load flow case consists of approximately 52,500 buses and 68,400 branches. A corresponding dynamic models database was also provided.

   Using the options selected during the study, the FFS identified 59 most severe potential fault locations.

   FFS computations showed that critical clearing time was relative large for many faults, which was an indicator of the robustness of the system in terms of transient stability.
2. The results of the FFS analysis for the base case were compared versus the results of time-domain simulation.

   Base case analysis showed that FFS produced consistent results that were checked using the traditional time-domain simulation approach.

   Benchmarking shows good correlation between the FFS result and computation of critical clearing time using traditional time-domain simulation.
3. Using the planning model, four transfer cases were created.

   The four additional transfer cases are:

   - 700 MW North-to-South transfer;
   - 700 MW South-to-North transfer;
   - 1000 MW West-to-East transfer;
   - 1000 MW East-to-West transfer.

4. FFS analysis was performed for each transfer case.

   The most severe fault locations were identified and ranked for each transfer case.

5. Results of the FFS analysis for each transfer cases were benchmarked versus the results of time-domain simulation.

   Critical clearing time was then computed for each fault identified by the FFS for each transfer case, and the results were benchmarked versus the FFS results. Benchmarking showed a good correlation between the FFS result and computation of critical clearing time using traditional time-domain simulation.

6. Base case and four transfer cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations.

   These cases were compared in terms of their vulnerability to transient stability limitations based on the following parameters:

   - Total Case RI;

     Total Case RI is the sum of Ranking Indices for the top five faults.

   - Total Case CCT.

     Total Case CCT is the sum of critical clearing times for the top five faults.

   The results showed that West-to-East transfer case is the most severe case since it has the largest value of the Total Case RI. Based on discussions with NYISO, this result corresponds to past NYISO experience.

   Thus, in addition to performing a very fast screening of the system for transient stability issues, FFS has been used in the project to compare various cases in terms of their vulnerability to transient stability limitations.

<u>Phase II. On-line testing of the FFS</u>

The main challenge in performing transient stability assessment using the real-time data was the absence of a key component for running these types of studies - dynamic models file. Therefore, the first step that needed to be done in order to execute either the FFS or traditional time-domain simulation was creation of this file.

The analysis during the second phase of the project proceeded as follows:

1. Creating a dynamic models file for the State-Estimator model (e.g. Energy Management System (EMS) cases);

   The major effort concentrated on converting the planning dynamic models file to be used with EMS load flow cases and creating a new dynamic models file that can be used with the EMS load flow cases.

2. Running FFS on the EMS model in order to identify potential severe fault locations and rank these locations;

   Three EMS cases, provided by NYISO, were analyzed using the FFS. The dynamic models file derived under this project was used for computations. The most severe faults were identified and ranked using the FFS for each case.

3. Running time-domain simulation on the EMS model;

   Traditional time-domain simulation was performed for each EMD case and the dynamic models file derived under this project. Critical clearing for each fault identified by the FFS for each case was computed.

4. Comparing the results of the FFS and time-domain simulation.

   Comparison of the results based on RI and CCT shows a very good correlation of the Ranking Index computed by the FFS and critical clearing time computed by time-domain simulation.

The overall study (both Phase I and Phase II) showed that the FFS is an effective practical solution for performing fast transient stability screening of a transmission system. The project demonstrated a very good correlation between the results of the FFS and conventional time-domain simulation.

2.3 Conclusions

Fast Fault Screening capability was applied and extensively tested on NYISO data. The testing was performed on both planning and State Estimator models. In order to perform testing on the State Estimator model, a dynamic models file for the model was created.

Various transfer-biased cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations during off-line testing.

During on-line testing various Energy Management System (EMS) cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations.

Then, the results of the FFS were benchmarked versus time-domain simulation. Benchmarking showed a very good correlation between the FFS and time-domain simulation.

FFS has been shown as a practical tool to perform transient stability studies required under the existing and forthcoming NERC standard TPL-001-1. FFS was also demonstrated as an effective tool for transient stability assessment in on-line and near real-time environments.

Besides the benefits mentioned above, FFS also significantly reduces the time required to perform NERC reliability standards compliance-related studies. For instance, "Innovators with EPRI Technology" published by EPRI in February 2009 reported direct benefits of using the FFS for saving power system planning and computation time. One of EPRI utility members, Entergy Services, Inc., estimated that its use of the FFS resulted in "savings of 300 man-hours and $27,000 for NERC Reliability Standards compliance-related studies". [1]

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[1] Entergy pioneers use of fast fault screening tool to identify severe contingencies for transient stability studies, EPRI Product ID 1018728, February 2009.

2.4 Future Work

Research performed under this project shows that critical locations in the transmission system vary from case to case both in real-time and in the planning environments. These are critical locations from both steady-state and transient analysis perspectives. Critical factors that affect these results include dispatch and the distribution of the online generators. With future higher penetration of wind power, the critical locations may shift widely, especially during off peak hours.

Future research direction may be identifying and analyzing the critical factors that affect transmission system performance. A tool that automatically identifies which changes in the transmission network are critical may become very useful for this type of awareness.

INDUSTRY NEED FOR FAST TRANSIENT STABILITY ANALYSIS

Two major factors contributed to the growing industry need for fast and extensive transient stability assessment:

- Stricter NERC Transmission Planning (TPL) standards.
- High planned levels of wind energy integration.

Impacts of wind energy integration on transient stability analysis include:

- Multiple wind generation scenarios need to be analyzed to ensure reliability of the transmission system due to the uncertainty in wind generation output
- Wind sites are hundreds of miles away from demand centers. Having very long transmission contributes to the increased probability of a fault occurrence.
- Reduced system inertia causes the consequences of a fault to be more severe as compared to a system with traditional synchronous machines.

Time-domain simulation at different locations based on engineering judgment is time-consuming and can miss key problem areas. Therefore, power system planners and operators need a faster way to assess grid stability and identify the most severe fault locations.

Transient stability analysis process in planning environment is described in Figure 3-1.

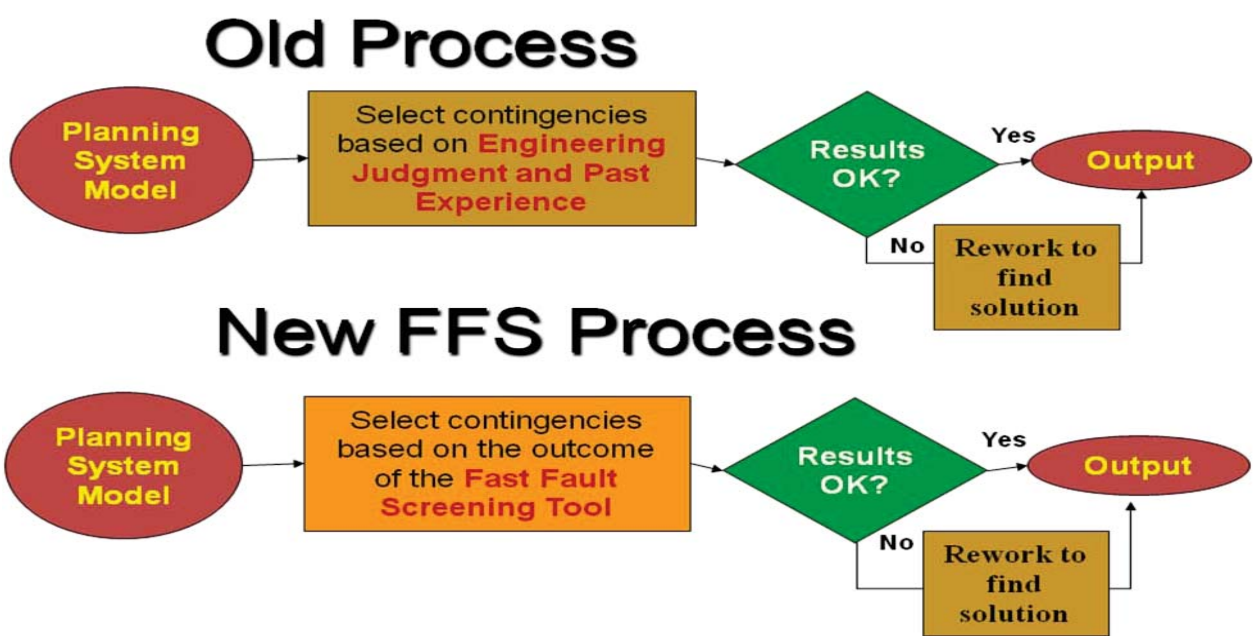


Figure 3-1. Transient Stability Assessment Process (Figure courtesy of Mr. Samrat Datta, Entergy Services)

The current TPL standard TPL-003-0, R.1.3.1 says that "The rationale for the contingencies selected for evaluation shall be available as supporting information. An explanation of why the remaining simulations would produce less severe system results shall be available as supporting information". Fast Fault Screening (FFS) offers a faster approach to transient stability assessment that provides this "rationale" and "supporting information".

The speed of the FFS calculations allows it to bring transient stability assessment to operations and near real-time environments.

METHODOLOGY OF DETERMINING AND RANKING THE MOST SEVERE THREE-PHASE FAULTS

This section describes methodology used for determining and ranking the most severe three - phase faults.

The Fast Fault Screening (FFS) approach proceeds in two steps:

1. Determine the most severe fault locations

   Locations of the most severe faults are determined using a heuristic approach. As a result of using this approach, buses with large real power flowing through them from local generators will be selected.

2. Rank the most severe faults

   Ranking index is used for ranking faults. The index is based on the phenomenon of the energy function but overcomes its limitations for a realistic dynamic model of a power system network. The index is an analytical tool with the coefficients derived using regression analysis. The criterion for ranking faults is the value of the critical clearing time.

FFS performs these two steps consecutively within the same run.

4.1 Classification of the Fault Severity

Fault severity will be classified as follows (starting with the most severe situation):

- Post-fault regime does not exist (i.e., voltage instability);
- Loss of generation;
- Situations corresponding to faults with small critical clearing time.

In addition to determining the most severe fault locations in the system, the FFS capability allows the user to determine situations that lead to voltage instability (e.g., voltage collapse) and to situations that cause significant loss of generation.

The most severe situations are those that lead to voltage collapse. This is an extremely severe situation caused by system steady-state conditions.

The next category of severity is loss of generator power as a result of an outage. Generators with large real power output are under consideration. If a generator (or generators) with large power output is connected to a line and a breaker opens this line, this may cause severe problems in the system. Thus, it is important to warn the operator about significant loss of generator power in the system. Again, this is a severe situation caused by the system steady-state conditions.

These two categories are followed by the situations corresponding to faults with the smallest critical clearing time. These are the most severe faults in the system. This type of situation is caused by transient stability processes in the electric system.

4.2 Methodology of Determining Severe Fault Locations

The methodology uses a heuristic approach for selection of fault locations. As a result, buses with large real power, flowing through them from local generators, are identified.

The Fault Selection Criterion, which consists of the following three criteria, is incorporated into this approach:

1. Bus properties
2. The difference between MW flow at a bus and generator real power in the vicinity of this bus.

   The vicinity of the bus is defined as one or two buses away to account for local generation only.
3. Power leaving a bus

The approach allowed us to identify locations of the most severe faults. These are the weakest buses in the network.

4.2.1 Criterion 1: Bus Properties

Area number for fast fault screening is selected in the **Control Area Number** field in the FFS Tab of the MAIN Pane in the POM interface.

Voltage class of buses is also specified in the FFS Tab. Voltage class of buses is specified in the **Minimum Voltage Level** field in the FFS Tab.

Buses that satisfy the above properties are candidates for fast fault screening.

To account for zero impedance lines, the user can change branch reactance limit by entering an appropriate value in the **Reactance** field in the FFS Tab. Branches with reactance exceeding the value specified in the **Reactance** field will be considered in the FFS calculations. Thus, flows on circuit breakers are not considered.

For a bus to qualify for a fault location, the bus should be connected to other buses by at least two branches, with one of them being an in-service transmission line. The number of connections is shown in the **Nlinks** column of the *ListFaultBusesCCT.csv* file (see Section 10.3).

4.2.2 Criterion 2: The Real Power Difference

The second criterion used in the approach for selecting fault locations is the difference between real flow at a bus and generator real power in the vicinity of this bus.

Power at a bus is considered as power entering a bus and power leaving a bus. Two rules are enforced for the real power difference: (a) the difference between real flow entering a bus and generator real power in the vicinity of this bus, and (b) the difference between real flow leaving a bus and generator real power in the vicinity of this bus.

Criterion 2(a) is needed to consider that only real power output from local generation flows to a bus, which is considered as a severe fault location.

This is a user-specified value, which may be changed in the **Power Difference** field in the FFS Tab.

Criterion 2(b) excludes long-distance flows through a bus, and ensures that only local generation is considered. Power entering a bus should not exceed **120%** of the real generator output in the vicinity of the bus.

The vicinity of the bus was defined as one or two buses away to account only for local generation.

4.2.3 Criterion 3: Real Power Leaving a Bus

The third criterion used in the approach accounts for the value of real power flow on the lines connected to the bus. This is the real flow that leaves the bus.

The number of fault locations would change with the change of this limit.

This is a user-specified value, which may be changed in the **Minimum Real Power** field in the FFS Tab.

4.2.4 The Fault Selection Criterion

The Fault Selection Criterion incorporates three criteria described in Sections 4.2.1 - 4.2.3.

The Fault Selection Criterion is defined by:

AREA = Control Area Number *Criterion 1/*

AND

BASKV >= Minimum Voltage Level */Criterion 1/*

AND

(| GenPower - PowOut | < Power Difference * GenPower */Criterion 2/*

OR

| GenPower1 - PowOut | < Power Difference * GenPower1 */Criterion 2/*

OR

| GenPower1 - PowOut - PowerTrans | < Power Difference * GenPower1 */Criterion 2/*

)

AND

PowIn < 1.2 * GenPower */Criterion 2/*

AND

PowOut >= Minimum Real Power. */Criterion 3/*

Where

AREA - Control area number.

BASKV - Voltage class of buses.

		AREA and BASKV are components of Criterion 1 (see Section 4.2.1). The value of AREA is selected in the **Control Area Number** field in the FFS Tab in the MAIN Pane. The value of BASKV is specified in the **Minimum Voltage Level** field in the FFS Tab.
GenPower	-	Real power output of generators located one and two buses away from a bus where a fault is applied.
GenPower1	-	Real power output of generators located one bus away from a bus where a fault is applied.
PowOut	-	Real power leaving a bus, where a fault is applied. PowOut includes only flows on transmission lines.
PowerTrans	-	Real power leaving a bus, where a fault is applied. PowerTrans includes only flows on transformers.
PowIn	-	Real power entering a bus, and flowing on lines.
Power Difference	-	The difference between real flow at a bus and generator real power in the vicinity of this bus. Power Difference is a component of Criterion 2 (see Section 4.2.2). The value of Power Difference is specified in the **Power Difference** field in the FFS Tab.
Minimum Real Power	-	The minimum value of real power, leaving a bus. Minimum Real Power includes only flows on lines. Minimum Real Power is a component of Criterion 3 (see Section 4.2.3). The value of Minimum Real Power is specified in the **Minimum Real Power** field in the FFS Tab.

4.3 Methodology of Ranking the Most Severe Faults

The approach described in Section 4.2 is used to identify locations of the most severe faults. Then, the most severe faults are ranked.

The Ranking Index (RI) is introduced to rank the most severe faults that are selected using the criteria listed in Section 4.2. RI is a very fast approximation of the fault severity that does not require running time-consuming fault analysis for each fault.

4.3.1 Using the Concept of the Energy Function as the Basis for the Ranking Index

The Fast Fault Screening ranking approach is based on one of the features of the energy function. This feature is related to the change of the shape of the potential energy surface as system becomes more stressed.

The potential energy surface of a non-stressed power system has a shape of a potential well (see Figure 4-1, left plot). As the system becomes stressed, the surface changes its shape to a trough (see Figure 4-1, right plot). The critical clearing time decreases as the surface becomes closer to the shape of the trough.

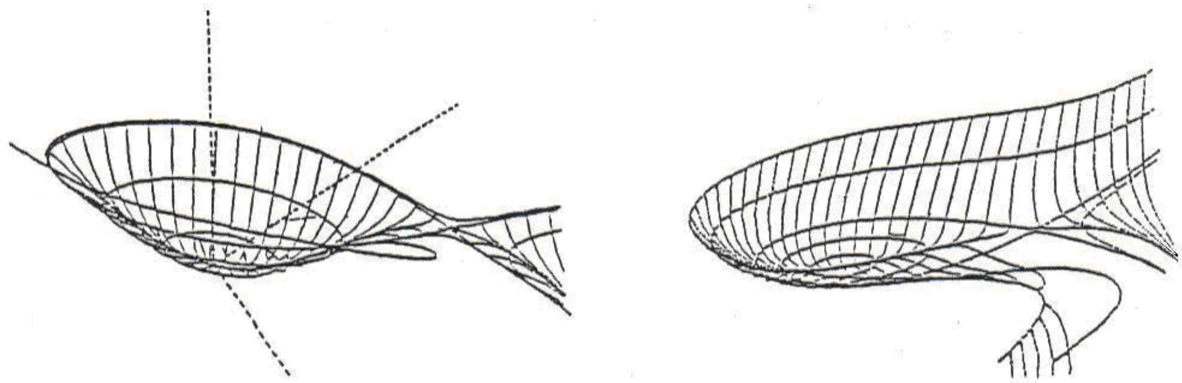


Figure 4-2. Potential Energy of a Non-Stressed System (Left) and a Stressed System (Right)

This phenomenon was discovered by V&R under the work supported by the National Science Foundation (NSF) award number III-9360318 and described in the Report submitted to NSF "Choice of Contingency Arming Schemes Actions Using Analytical Approaches".

As follows from the energy function, characteristics that have the largest impact on the transient stability of a power system are:

- Generator kinetic energy;
- Generator electrical torque;
- Generator voltage;
- Shape of the potential energy that is represented by the eigenvalue of the Jacobian matrix.

However, the energy function does not allow one to account for all dynamic models of a realistic power system, such as excitation system, governor models, etc.

The proposed approach overcomes this limitation of the energy function by introducing a Ranking Index (RI). The proposed ranking index is used perform very fast the estimation of the shape of the potential energy.

RI does not involve computation of the energy function.

4.3.2 The Components of the RI Formula

The Ranking Index (RI) is based on the power system characteristics that have the largest impact on the transient stability as described in Section 4.3.1.

These characteristics are computed using time-domain simulation over a very short time period after a fault has been cleared.

These characteristics are the components of the Ranking Index:

- KE is the kinetic energy of a generator with the largest value of kinetic energy located in the vicinity of the fault
- M_{ePOSTF} is the electrical torque of the generator with the largest value of kinetic energy located in the vicinity of the fault at the moment the fault is cleared
- M_{ePREF} is the electrical torque of the generator with the largest value of kinetic energy located in the vicinity of the fault before the fault is applied
- $EigenValue_{POSTF}$ is the eigenvalue of the Jacobian matrix in the post-fault regime
- $EigenValue_{PREF}$ is the eigenvalue of the Jacobian matrix for the base case
- V_{PREF} is voltage of the generator with the largest value of kinetic energy located in the vicinity of the fault before the fault is applied
- V_{gen} is voltage of the generator with the largest value of kinetic energy located in the vicinity of the fault at the moment the fault is cleared

These components have the following effect on the RI:

- The kinetic energy, KE

  A larger value of the kinetic energy of a generator rotor injected by a fault indicates a bigger chance of loss of synchronism.

- The ratio of M_{ePOSTF} and M_{ePREF}, $\frac{M_{ePOSTF}}{M_{ePREF}}$

  The ratio depends on both the excitation system and network configuration (i.e., switching off lines) after the fault.

  The ratio of the electrical torque at the moment the fault is cleared and before the fault is applied indicates the potential energy of the post-fault condition.

  If the ratio is less than unity, its effect can significantly contribute to instability, since it causes an increase in the kinetic energy.

- Generator voltage, V_{gen}

  The difference between generator voltage prior to the fault and after fault is cleared. Voltage value. This value indicates the response of the excitation system. Low voltage corresponds to a more severe post-fault regime.

- The ratio of $EigenValue_{POSTF}$ and $EigenValue_{PREF}$, $\frac{EigenValue_{POSTF}}{EigenValue_{PREF}}$

  The shape of the potential energy function is indicated by the eigenvalue of the Jacobian matrix. When the eigenvalue of the Jacobian matrix is close to zero, the Newton method diverges.

The RI is a very fast approximation of the fault severity that does not require running time-consuming fault analysis for each fault. Simulation was performed using POM-TS for only 0.1 sec to determine KE, M_{ePOSTF}, $EigenValue_{POSTF}$, and V_{gen} for each fault.

The larger value of RI corresponds to a more severe fault.

The value of RI for each of the most severe faults was benchmarked against the critical clearing time. Critical clearing time for each fault was computed using POM-TS. The smaller the critical time is, the more severe the fault is.

Thus, the larger value of RI corresponds to a fault with a smaller critical clearing time.

It took less than one minute to identify and compute RI indices for the most severe faults in the EI planning power system model.

The participating coefficients for each characteristic are determined using regression analysis as described in Section 4.4.

4.4 The Coefficients of the RI Formula

The rank correlation coefficients of the RI formula were derived using linear regression analysis.

4.4.1 Computing Rank Correlation Coefficients Using Regression Analysis

The goal of regression analysis is to determine the values of parameters for a function that cause the function to best fit a set of data observations that you provide. Thus, regression analysis is a statistical tool for the investigation of relationships between variables.

We can calculate the correlation coefficients between *n* pairs (X,Y), where $(X_1, X_2,\ldots, X_n)$ is a permutation of the first *n* natural numbers, and $(Y_1, Y_2,\ldots, Y_n)$ is another such permutation. We may arrange the *n* pairs of any sample so that the ranks Y are in the natural order 1, 2, …, *n*. If the rank X, which corresponds to the value $Y = i$ is denoted by X_i, we have the rank correlation coefficient defined by:

$$r_s = 1 - \frac{6}{n(n^2-1)} \sum_{i-1}^{n} (x_i - i)^2 \tag{4.1}$$

The coefficient r_s is usually called Spearman's rank correlation coefficient.

M.G. Kendall showed that a method for measuring the disarray of the x ranks (i.e., the extent of their departure from the order 1, 2, …, n), is to count the number of inversions of order among them. The number of such inversions, Q, may range from 0 to $\frac{1}{2}n(n\text{-}1)$. These limits are being reached, respectively, if the x-ranking is 1, 2, …, n and n, (n-1),…,1.

The Kendall's rank correlation coefficient may be defined as:

$$t_K = 1 - \frac{4Q}{n(n-1)} \tag{4.2}$$

Both the Spearman's and Kendall's rank correlation coefficients are symmetrically distributed on the range (-1, +1).

Rank coefficients that are closer to +1 correspond to a more accurate ranking mechanism.

Computations under the contract were made using the Spearman's formula (4.1). The results were benchmarked against Kendall's formula (4.2).

An example of computing the rank correlation coefficients is shown in Table 4-1.

Table 4-1. Computing Rank Correlation Coefficients

I	x_i	$(x_i - i)^2$	Inversion
1	3	4	2
2	2	0	1
3	1	4	0
4	7	9	3
5	5	0	1
6	6	0	1
7	9	4	2
8	4	16	0
9	10	1	1
10	8	4	0
		42	11

Values of i and x_i are chosen arbitrary.

From Table 4-1 it follows that Spearman's rank correlation coefficient is:

$$r_s = 1 - \frac{6}{10(10^2 - 1)} 42 = 0.745$$

and Kendall's rank correlation coefficient is:

$$t_K = 1 - \frac{4*11}{10\,(10 \quad -1)} = 0.511$$

The value of the Spearman's rank correlation coefficient is usually larger than that of the Kendall's rank correlation coefficient for the same set of data.

4.4.2 Applying Spearman Formula to Computation of Rank Correlation Coefficients for FFS Approach

Spearman's formula was used to determine the coefficients of the ranking index (RI) formula.

We have the following formula for the RI index:

$$RI = k_1 * KE + k_2 * MAX\{(0;(1 - \frac{M_{ePOSTF}}{M_{ePREF}} \;)\} + k_3 * MIN\{(0;(1 - \frac{M_{ePOSTF}}{M_{ePREF}} \;)\} +$$

$$+ k_4 * (V_{PREF} - V_{gen}) + k_5 * (\frac{EigenValue_{POSTF}}{EigenValue_{PREF}} - 1) \quad , \tag{4.3}$$

where k_1 - k_5 are rank correlation coefficients.

Rank correlation coefficients k_1 - k_5 are determined using Spearman's formula (see Section 4.4.1).

The components of the formula are described in Section 4.3.2.

At first, a criterion for ranking faults was selected. The criterion used in this approach is the critical clearing time (CCT). Thus, a fault with the smallest critical time is the most severe fault, i.e., it has the highest ranking. Note, that the criterion also incorporates situations that lead to loss of generation and steady-state instability.

Deriving rank correlation coefficients proceeded in the following steps:

1. The most severe faults, that satisfy criteria specified in Sections 4.2.1 - 4.2.3, were identified.
2. Critical clearing time (CCT) was computed for each fault.
3. Faults were ranked using the value of the critical clearing time; situations that led to loss of generation and steady-state instability were also considered.
4. Spearman's formula was adopted to FFS methodology as follows:

$$\max r_s(k_1,...,k_5) = \max\,(1 - \frac{6}{n(n^2-1)} \sum_{i-1}^{n} (x_i(RI) - i(CCT))^2)\,, \tag{4.4}$$

where

$$k_1 + k_2 + k_3 + k_4 + k_5 = const \qquad \text{or} \qquad k_5 = 1$$

RI is the Ranking Index

CCT is the critical clearing time

n = number of critical fault locations

5. A run, corresponding to severe fault conditions, was made. These conditions were approximated by outaging 85% of the power leaving a bus (i.e., Cutoff Factor = 85%).

   Spearman's and Kendall's rank correlation coefficients were determined.

6. The coefficients were tested for a less severe fault scenario, when only 25% of the power leaving a bus was outaged (i.e., Cutoff Factor = 25%).

   Spearman's and Kendall's rank correlation coefficients were determined.

7. Computation results, obtained in items (5) and (6) above, showed that rank correlation coefficients, used for ranking index formula, were selected very effectively.

Faults were ranked using the value of the critical clearing time; situations that led to loss of generation and steady-state instability were also considered.

Spearman's rank correlation coefficient is $r_s = 0.848$ and Kendall's rank correlation coefficient is $t_k = 0.735$. The values of both coefficients are high, which means that rank correlation coefficients in the RI formula were properly selected.

TESTING OF THE FAST FAULT SCREENING CAPABILITY USING OFF-LINE PLANNING DATA

This section describes testing of the Fast Fault Screening (FFS) methodology using NY ISO planning data.

5.1 FFS Testing Process Using Off-Line Planning Data

The FFS testing proceeded as follows:

1. FFS analysis was performed on a base case provided by NYISO, see Sections 5.2.
2. Results of the FFS analysis for the base case were compared versus the results of time- domain simulation, see Section 5.4.
3. Four transfer cases were created.
4. FFS analysis was performed for each transfer case, see Section 5.5.
5. Results of the FFS analysis for each transfer cases were benchmarked versus the results of time-domain simulation.
6. Base case and four transfer cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations, see Section 5.6.

5.2 NY ISO Planning Data

The following input data was provided by NY ISO for testing of the FFS capability:

- File "CY07-ATBA-SUM12_rev4V29.raw"

  This file is the base case which contains NYISO planning model. The load flow case consists of approximately 52,500 buses and 68,400 branches. This data is referred to as "Base Case" in the following sections.

- File "2007_ATBA_29.5.DYR"

  This file specifies dynamic simulation model data associated with the planning load flow case, and referred to as "Base Case" throughout this Report.

- File "gnet-1.rsp"

  This file specifies in-service generation that is changed to negative MVA load at all type two and three buses.

- File "conl-1.rsp"

  This file lists the constant MVA loads that should be converted to a specified mixture of the constant current and constant admittance load characteristics.

5.3 FFS Options Used for the Study

The FFS capability was used to identify the most severe potential fault locations in NY ISO footprint.

The following FFS options (see Section 9.4) were selected during the analysis:

- Control Area Number: **1,2,3,4,5,6,7,8,9,10,11**
- Minimum Voltage Level, kV: **60**
- Minimum Real Power, MW: **100**
- Power Difference, %: **25**
- Cutoff Factor, %: **85**
- Reactance, p.u.: **0.0005**
- Fault Type: **LLL**

FFS options for the study are shown in Figure 5-1.

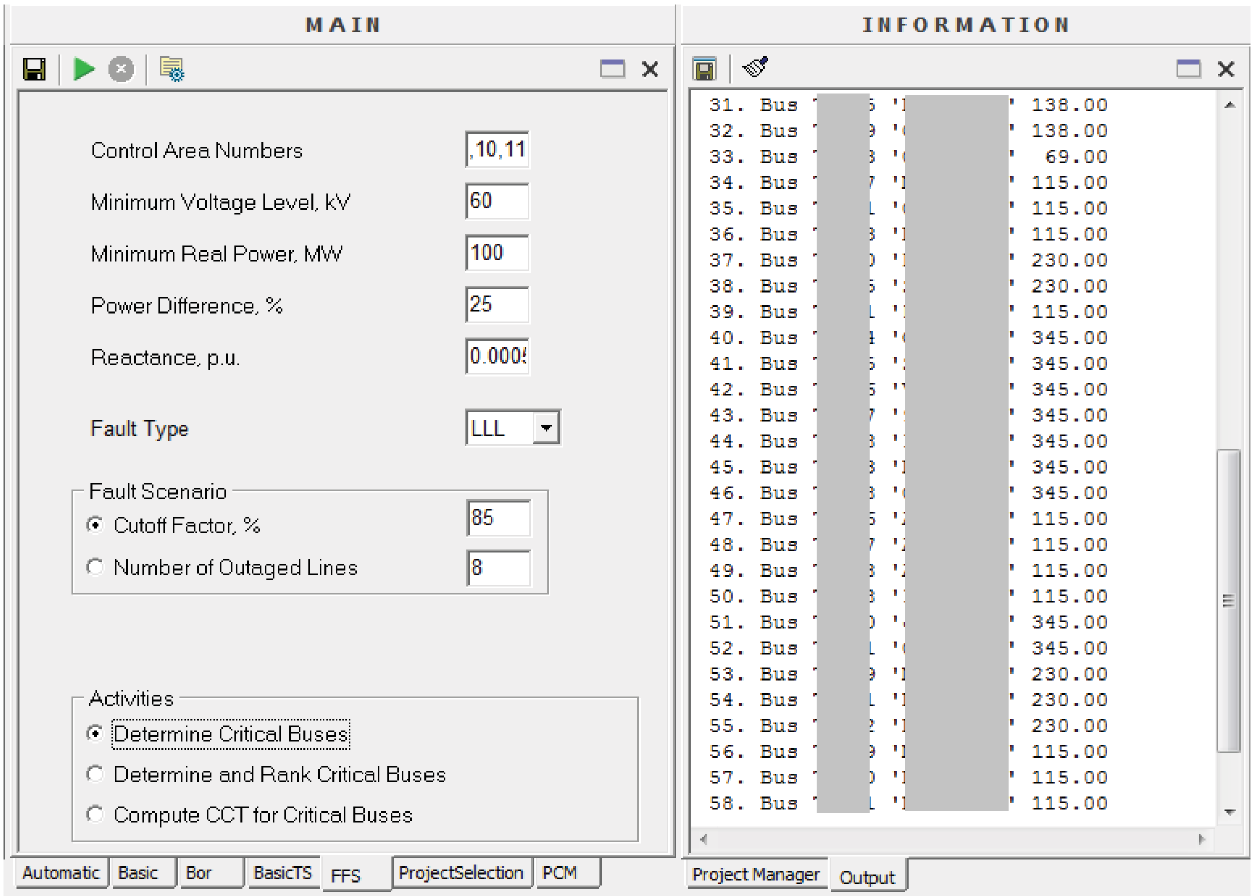


Figure 5-3. FFS Options Used for the Study

The following FFS activities were used during the study:

- Activity Determine Critical Buses

  This activity was used to determine a list of the most severe potential fault locations.

- Activity Determine and Rank Critical Buses

This activity was used to rank the most severe fault locations based on the RI .

- Activity Compute CCT for Critical Buses

  This activity was used to automatically computed critical clearing time (CCT) CCT for the most severe fault locations. The value of the CCT was used for benchmarking of the FFS approach versus time domain simulation.

5.4 Results of the Base Case Analysis

FFS identified 59 most severe potential fault locations that satisfy the options listed in Section 5.3.

FFS computations show that critical clearing time is relative large for many faults, which is an indicator of the robustness of the system in terms of transient stability.

The distribution of the Ranking Index by the critical clearing time for the Base Case is shown Figure 5-2.

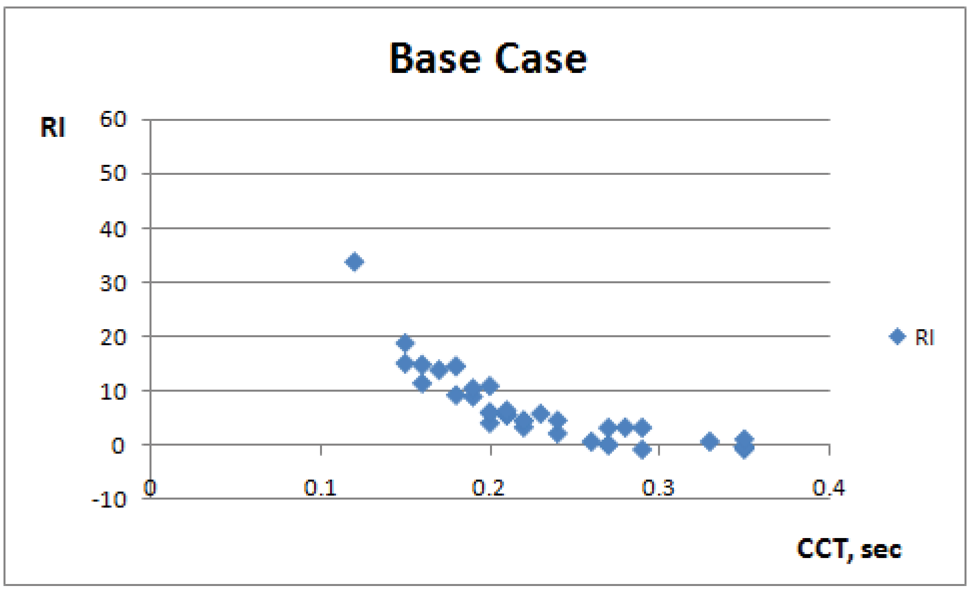


Figure 5-4. Distribution of the Ranking Index by the Critical Clearing Time for the Base Case

The FFS results show that there is one stability violation and 16 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 5-1.

Table 5-2. Weak Points in the Base Case: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Result
1			115	Stability Violation
2			345	Loss of Generation 848.8 MW
3			345	Loss of Generation 458 MW
4			138	Loss of Generation 328 MW
5			138	Loss of Generation 328 MW
6			115	Loss of Generation 325 MW
7			138	Loss of Generation 318 MW
8			138	Loss of Generation 283 MW
9			138	Loss of Generation 276 MW
10			115	Loss of Generation 270.2 MW
11			115	Loss of Generation 239.4 MW
12			138	Loss of Generation 171.6 MW
13			115	Loss of Generation 155 MW
14			138	Loss of Generation 139 MW
15			115	Loss of Generation 136.448 MW
16			138	Loss of Generation 135.3 MW
17			138	Loss of Generation 133 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 5-2.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT). Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 5-3. Ranking the Most Severe Fault Locations: Base Case

Bus Number	RI	Rank RI	CCT	Rank CCT
[illegible]	33.5666	1	0.12	1
[illegible]	15.0019	2	0.14	2
[illegible]	14.747	3	0.15	3
[illegible]	14.4956	4	0.17	6
[illegible]	13.75	5	0.16	5
[illegible]	11.4086	6	0.15	4
[illegible]	11.1935	7	0.2	9
[illegible]	9.3169	8	0.17	7
[illegible]	8.9723	9	0.19	8
[illegible]	6.7579	10	0.2	10
[illegible]	5.9803	11	0.2	11
[illegible]	4.6677	12	0.24	14
[illegible]	4.6471	13	0.22	12
[illegible]	4.5335	14	0.22	13
[illegible]	3.3661	15	0.28	17
[illegible]	3.3114	16	0.27	15
[illegible]	3.3048	17	0.29	18
[illegible]	1.2483	18	0.3	20
[illegible]	0.1304	19	0.27	16
[illegible]	-0.7012	20	0.29	19

Bus # [illegible] in on top of the list, see Table 5-2. Should a fault be applied at that bus, CCT = 0.12 sec and RI = 33.5666.

Oneline diagram for Bus # [illegible] is shown in Figure 5-3.

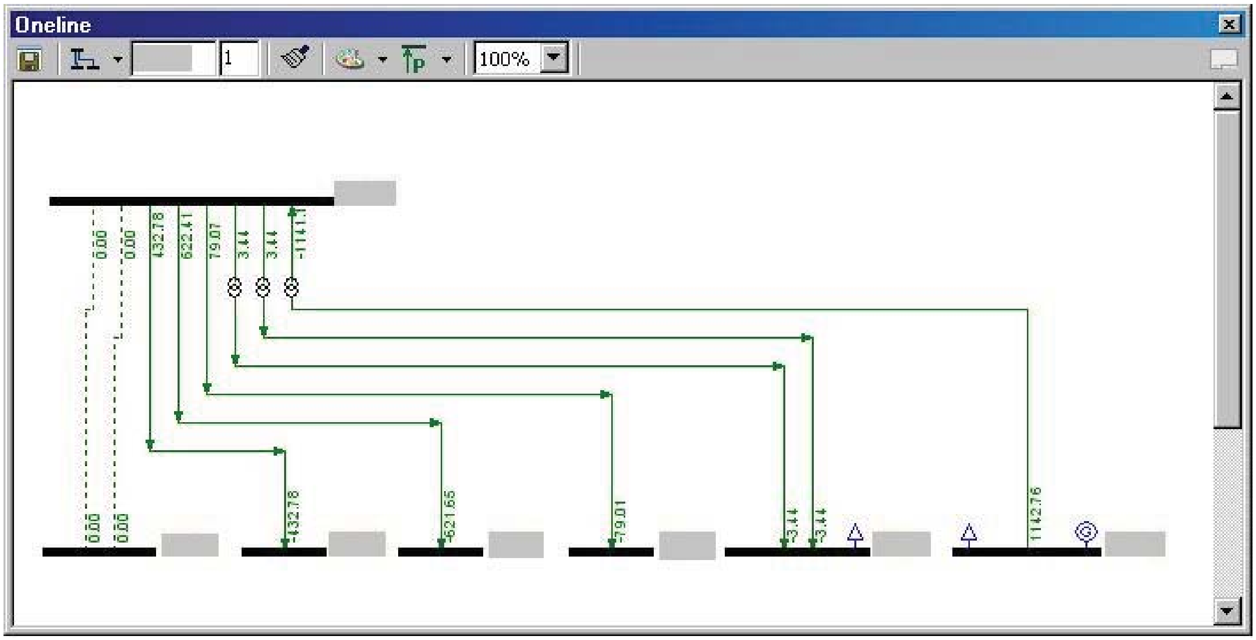


Figure 5-5. Oneline Diagram for Bus #

Time-domain simulation was then performed and three fault scenarios were applied at this bus:

- Fault clears in 0.08 sec, see Figure 5-4;
- Fault clears in 0.12 sec, see Figure 5-5;
- Fault clears in 0.13 sec, see Figure 5-6.

The following quantities were plotted for each fault scenario:

- Terminal voltage (green)
- Rotor angle (blue)
- Electrical Power (red)
- Mechanical power (black)

Figure 5-4 shows that the system remains stable if the fault clears in 0.08 sec (since it is less than the critical clearing time of 0.12 sec).

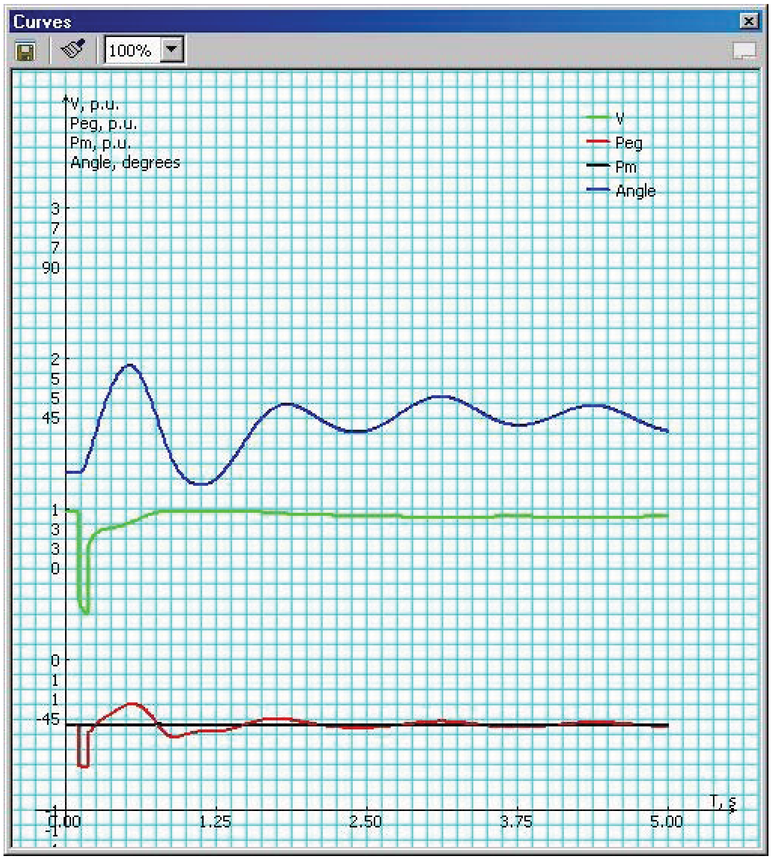


Figure 5-6. Fault at Bus # Clears in 0.08 sec

If this fault clears in 0.12 sec, the system is close to being unstable, see Figure 5-5.

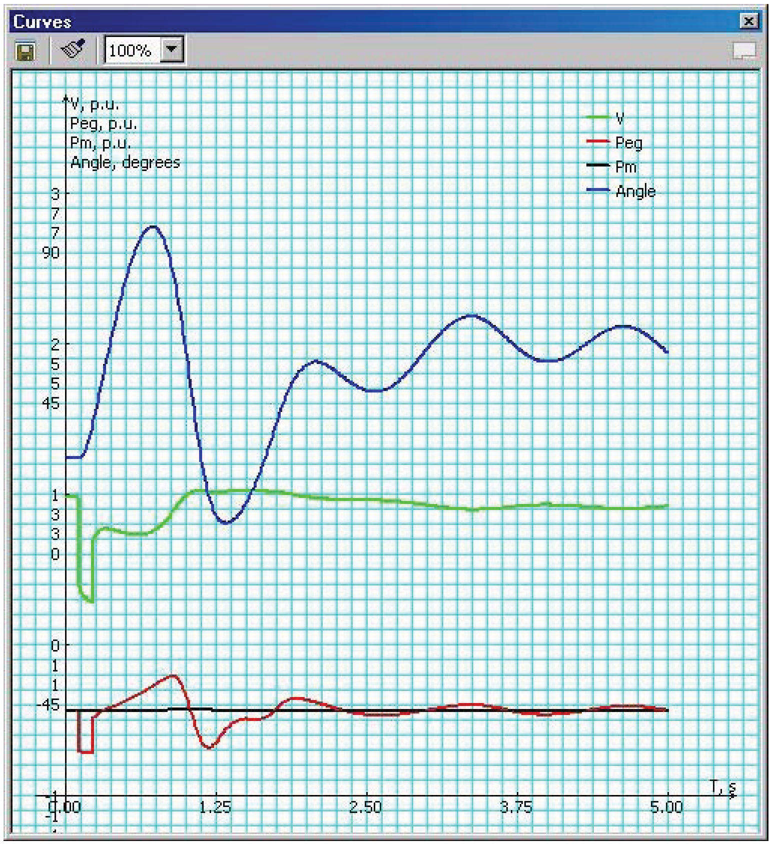


Figure 5-7. Fault at Bus # Clears in 0.12 sec

If this fault clears in 0.13 sec, the system losses synchronism, see Figure 5-6.

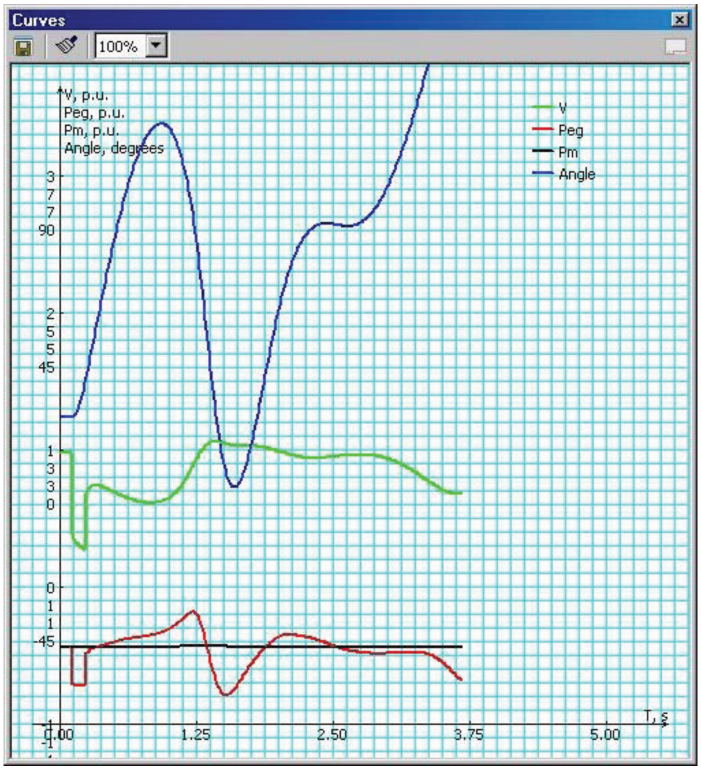


Figure 5-8. Fault at Bus # Clears in 0.13 sec

Time-domain simulation was then performed for a bus fault at Bus # , which is in the bottom of the FFS Output Table, see Table 5-2. Should a fault be applied at that bus, CCT = 0.27 sec and RI = 0.1304.

Oneline diagram for Bus # is shown in Figure 5-7.

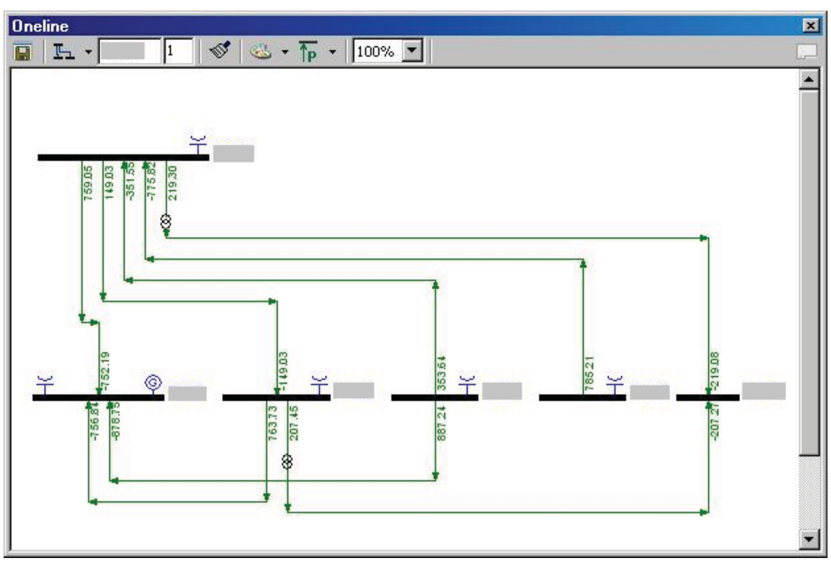


Figure 5-9. Oneline Diagram for Bus #

Time-domain simulation was then performed and three fault scenarios were applied at this bus:

- Fault clears in 0.08 sec, see Figure 5-8;
- Fault clears in 0.27 sec, see Figure 5-9;
- Fault clears in 0.28 sec, see Figure 5-10.

The following quantities were plotted for each fault scenario:

- Terminal voltage (green)
- Rotor angle (blue)
- Electrical Power (red)
- Mechanical power (black)

Figure 5-8 shows that the system remains stable if the fault clears in 0.08 sec (since it is less than the critical clearing time of 0.27 sec).

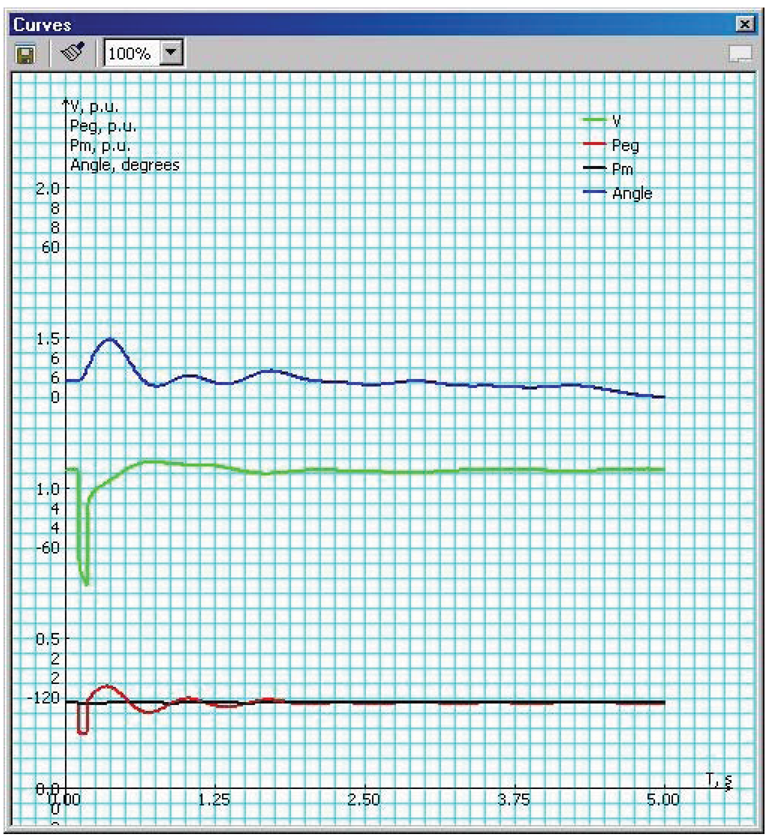


Figure 5-10. Fault at Bus # Clears in 0.08 sec

If this fault clears in 0.27 sec, the system is close to being unstable, see Figure 5-9.

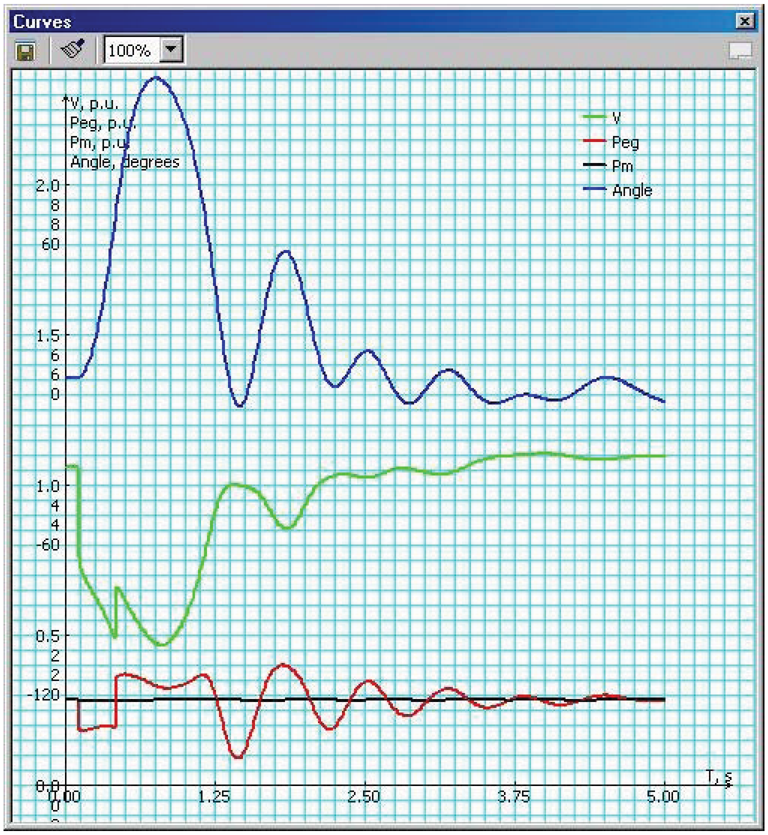


Figure 5-11. Fault at Bus # Clears in 0.27 sec

If this fault clears in 0.28 sec, the system losses synchronism, see Figure 5-10.

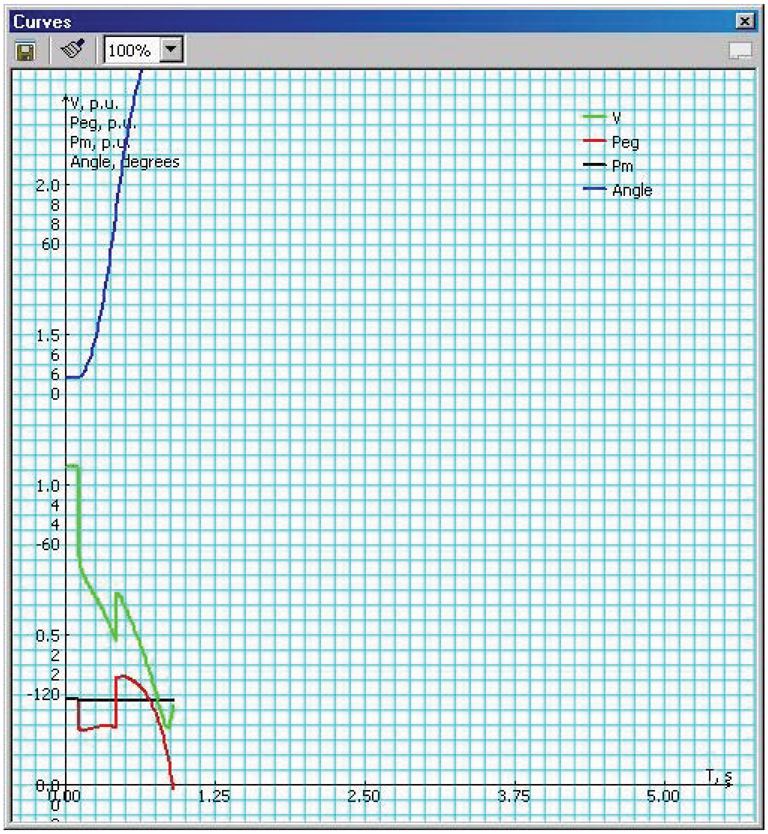


Figure 5-12. Fault at Bus # Clears in 0.28 sec

Therefore, Base Case analysis showed that FFS produced consistent results that were checked using the traditional time-domain simulation approach.

5.5 Results of the Transfer Cases Analyses

During off-line phase of the FFS testing, four transfer scenarios have been analyzed in addition to the Base Case analysis (see Section 5.4):

- 700 MW North-to-South transfer;
- 700 MW South-to-North transfer;
- 1000 MW West-to-East transfer;
- 1000 MW East-to-West transfer.

FFS analysis was performed for each transfer case.

5.5.1 Results for North-to-South Transfer Case

The FFS results for North-to-South Transfer Case show that there is one stability violation and 16 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 5-3.

Table 5-4. Weak Points in the North-South Transfer Case: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Results
1			115	Stability Violation
2			345	Loss of Generation 848.8 MW
3			345	Loss of Generation 458 MW
4			115	Loss of Generation 325 MW
5			138	Loss of Generation 318 MW
6			138	Loss of Generation 283 MW
7			138	Loss of Generation 278.456 MW
8			138	Loss of Generation 278.456 MW
9			138	Loss of Generation 276 MW
10			115	Loss of Generation 270.2 MW
11			115	Loss of Generation 239.4 MW
12			138	Loss of Generation 171.6 MW
13			115	Loss of Generation 155 MW
14			138	Loss of Generation 139 MW
15			115	Loss of Generation 136.448 MW
16			138	Loss of Generation 135.3 MW
17			138	Loss of Generation 133 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 5-4.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 5-5. Ranking the Most Severe Fault Locations: North-South Case

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			345	33.0643	0.13
2			345	14.9966	0.15
3			345	17.6576	0.15
4			345	11.5637	0.16
5			345	14.0713	0.16
6			115	14.413	0.16
7			115	8.9284	0.18
8			345	14.5521	0.18
9			115	10.1524	0.19
10			230	4.2199	0.2
11			69	5.5379	0.2
12			345	6.5591	0.2
13			115	6.5769	0.2
14			230	8.5166	0.2
15			345	5.1603	0.21
16			230	6.3328	0.21
17			138	3.1636	0.22
18			345	4.1898	0.22
19			115	4.7377	0.22
20			138	5.3357	0.23
21			138	7.5419	0.23
22			115	2.1681	0.24
23			138	3.901	0.25
24			138	0.103	0.27
25			138	0.4089	0.27
26			115	0.4561	0.27
27			138	2.402	0.28
28			138	-0.8445	0.3
29			345	1.6261	0.3
30			138	3.112	0.3
31			69	0.7594	0.33
32			138	1.9711	0.34
33			230	-0.6131	0.35
34			230	-0.611	0.35
35			138	-0.3644	0.35
36			138	-0.3216	0.35
37			138	-0.3114	0.35
38			138	-0.3025	0.35
39			69	-0.2743	0.35
40			69	-0.2738	0.35
41			69	-0.2736	0.35
42			69	-0.2719	0.35
43			345	1.1759	0.35

5.5.2 Results for South-to-North Transfer Case

The FFS results for South-to-North Transfer Case show that there is one stability violation and 16 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 5-5.

Table 5-6. Weak Points in the South-North Transfer Case: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Results
1	[redacted]	[redacted]	115	Stability Violation
2	[redacted]	[redacted]	345	Loss of Generation 848.8 MW
3	[redacted]	[redacted]	345	Loss of Generation 458 MW
4	[redacted]	[redacted]	138	Loss of Generation 400 MW
5	[redacted]	[redacted]	138	Loss of Generation 400 MW
6	[redacted]	[redacted]	115	Loss of Generation 325 MW
7	[redacted]	[redacted]	138	Loss of Generation 318 MW
8	[redacted]	[redacted]	138	Loss of Generation 283 MW
9	[redacted]	[redacted]	138	Loss of Generation 276 MW
10	[redacted]	[redacted]	115	Loss of Generation 270.2 MW
11	[redacted]	[redacted]	115	Loss of Generation 239.4 MW
12	[redacted]	[redacted]	138	Loss of Generation 171.6 MW
13	[redacted]	[redacted]	115	Loss of Generation 155 MW
14	[redacted]	[redacted]	138	Loss of Generation 139 MW
15	[redacted]	[redacted]	115	Loss of Generation 136.448 MW
16	[redacted]	[redacted]	138	Loss of Generation 135.3 MW
17	[redacted]	[redacted]	138	Loss of Generation 133 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 5-6.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 5-7. Ranking the Most Severe Fault Locations: South-North Case

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			345	33.8438	0.14
2			345	14.9686	0.15
3			345	11.3254	0.16
4			115	14.8344	0.16
5			345	13.5817	0.17
6			115	9.5235	0.18
7			138	10.0624	0.18
8			138	8.874	0.19
9			115	9.1332	0.19
10			138	10.7617	0.19
11			345	14.4373	0.19
12			230	4.1196	0.2
13			345	5.7157	0.2
14			69	6.5541	0.2
15			115	6.8995	0.2
16			230	7.3364	0.2
17			230	12.1218	0.2
18			345	1.3762	0.21
19			345	5.0139	0.21
20			230	6.2443	0.21
21			138	6.2677	0.21
22			138	3.5479	0.22
23			115	4.7363	0.22
24			138	6.4586	0.22
25			115	2.4842	0.24
26			138	1.1117	0.26
27			138	0.1577	0.27
28			115	0.3101	0.27
29			138	3.5844	0.27
30			138	-0.5135	0.28
31			138	3.5054	0.28
32			345	1.0961	0.3
33			69	0.9779	0.33
34			230	-0.6408	0.35
35			138	-0.2756	0.35
36			69	-0.2605	0.35
37			69	-0.2601	0.35
38			69	-0.2594	0.35
39			69	-0.2575	0.35
40			138	-0.24	0.35
41			138	-0.2323	0.35
42			138	-0.2152	0.35

5.5.3 Results for West-to-East Transfer Case

The FFS results for West-to-East Transfer Case show that there are two stability violations and 16 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 5-7.

Table 5-8. Weak Points in the West-East Transfer Case: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Results
1			345	Stability Violation
2			115	Stability Violation
3			345	Loss of Generation 1080.606 MW
4			345	Loss of Generation 426.657 MW
5			115	Loss of Generation 325.2 MW
6			138	Loss of Generation 323.094 MW
7			138	Loss of Generation 323.094 MW
8			138	Loss of Generation 313.244 MW
9			115	Loss of Generation 302.759 MW
10			138	Loss of Generation 278.768 MW
11			138	Loss of Generation 271.873 MW
12			115	Loss of Generation 234 MW
13			138	Loss of Generation 169.033 MW
14			138	Loss of Generation 136.921 MW
15			138	Loss of Generation 133.277 MW
16			138	Loss of Generation 131.011 MW
17			115	Loss of Generation 127.111 MW
18			115	Loss of Generation 111.925 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 5-8.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 5-9. Ranking the Most Severe Fault Locations: West-East Case

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			345	52.267	0.1
2			345	17.886	0.12
3			345	19.6999	0.12
4			345	23.8806	0.13
5			345	22.4719	0.15
6			345	15.9061	0.16
7			115	16.598	0.16
8			230	6.8669	0.19
9			115	7.755	0.19
10			115	8.8591	0.19
11			138	9.7918	0.19
12			230	15.2252	0.19
13			69	3.3946	0.2
14			230	4.2083	0.2
15			138	2.9038	0.22
16			345	3.9394	0.22
17			115	4.8302	0.22
18			345	5.0624	0.22
19			138	5.3379	0.23
20			115	2.1894	0.24
21			138	4.3839	0.24
22			138	0.3896	0.27
23			115	-0.0396	0.28
24			138	0.0063	0.28
25			138	3.0661	0.28
26			138	3.1916	0.28
27			115	-0.0506	0.29
28			138	-0.8809	0.3
29			138	3.1339	0.3
30			345	1.5575	0.33
31			69	0.6975	0.34
32			138	-0.3363	0.35
33			138	-0.2969	0.35
34			138	-0.2882	0.35
35			138	-0.2801	0.35
36			69	-0.275	0.35
37			69	-0.2743	0.35
38			69	-0.2734	0.35
39			69	-0.2726	0.35
40			345	0.9704	0.35

5.5.4 Results for East-to-West Transfer Case

The FFS results for East-to- West Transfer Case show that there are 17 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 5-9.

Table 5-10. Weak Points in the East-West Transfer Case: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Results
1			345	Loss of Generation 797.45 MW
2			345	Loss of Generation 458 MW
3			138	Loss of Generation 352.608 MW
4			138	Loss of Generation 352.608 MW
5			138	Loss of Generation 326.102 MW
6			115	Loss of Generation 325 MW
7			138	Loss of Generation 283 MW
8			138	Loss of Generation 276 MW
9			115	Loss of Generation 253.854 MW
10			115	Loss of Generation 239.4 MW
11			138	Loss of Generation 171.6 MW
12			115	Loss of Generation 155 MW
13			115	Loss of Generation 153 MW
14			138	Loss of Generation 139 MW
15			138	Loss of Generation 135.3 MW
16			138	Loss of Generation 133 MW
17			115	Loss of Generation 108 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 5-10.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 5-11. Ranking the Most Severe Fault Locations: East-West Case

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			345	19.1879	0.15
2			345	23.6512	0.15
3			345	8.2421	0.18
4			115	9.4233	0.18
5			345	10.6008	0.18
6			230	6.3301	0.19
7			345	8.7989	0.19
8			115	8.9543	0.19
9			115	9.4844	0.19
10			345	9.7432	0.19
11			138	10.5708	0.19
12			69	6.3546	0.2
13			345	5.6548	0.21
14			345	6.0471	0.21
15			138	3.4968	0.22
16			115	3.8699	0.22
17			345	4.6986	0.22
18			138	5.5615	0.22
19			230	5.9587	0.22
20			115	5.9598	0.22
21			230	4.004	0.23
22			138	5.9254	0.23
23			138	6.3448	0.23
24			115	0.8476	0.25
25			138	4.9086	0.25
26			138	0.7588	0.26
27			138	3.6576	0.26
28			138	0.1311	0.27
29			115	0.3273	0.27
30			115	1.5146	0.27
31			230	0.7703	0.28
32			138	-0.6927	0.29
33			138	3.3187	0.29
34			345	1.0762	0.3
35			115	0.4796	0.31
36			69	0.8201	0.33
37			230	-0.8274	0.35
38			138	-0.3215	0.35
39			138	-0.2854	0.35
40			138	-0.2826	0.35
41			138	-0.2806	0.35
42			69	-0.2782	0.35
43			69	-0.2779	0.35
44			69	-0.2773	0.35
45			69	-0.2772	0.35

5.6 Transfer Cases Summary

Two parameters were used in Sections 5.4 and 5.5 to rank the most severe potential fault locations: Ranking Index (RI) and critical clearing time (CCT). RI was computed using FFS and CCT was determined using traditional time-domain simulation.

The distribution of the Ranking Index by the critical clearing time for the four transfer cases is shown Figure 5-11.

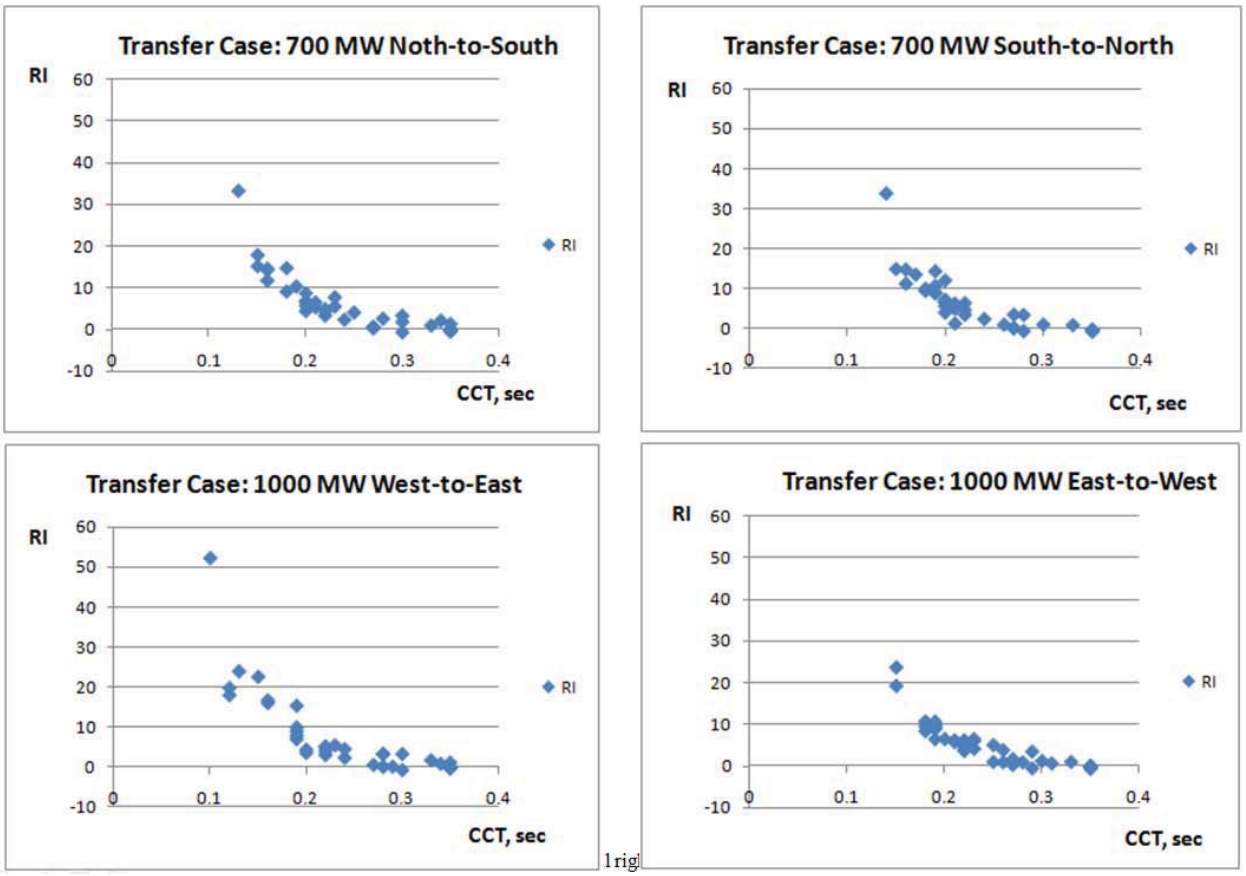


Figure 5-13. Distribution of the Ranking Index by the Critical Clearing Time for Transfer Cases

Base Case (see Section 5.4) and four transfer cases (see Section 5.5) were compared in terms of their vulnerability to transient stability limitations based on the following parameters:

- Total Case RI;

  Total Case RI is the sum of Ranking Indices for the top five faults.

- Total Case CCT.

  Total Case CCT is the sum of critical clearing times for the top five faults.

The Total Case RI and CCT for the base case and transfer cases are summarized in Table 5-11.

Table 5-12. Summary of Total Case RI and CCT for the Base Case and Transfer Cases

No.	Case	Total Case RI: Top 5 Faults	Total Case CCT, sec: Top 5 Faults
1	Base Case	94.10	0.74
2	North-South Transfer Case	91.35	0.75
3	South-North Transfer Case	88.55	0.78
4	West-East Transfer Case	136.21	0.62
5	East-West Transfer Case	71.11	0.84

The Total Case RI is shown in Figure 5-12. From Figure 5-12 it follows that West-to-East transfer case is the most severe case since it has the largest value of the Total Case RI. Based on discussions with NYISO, this result corresponds to past NYISO experience.

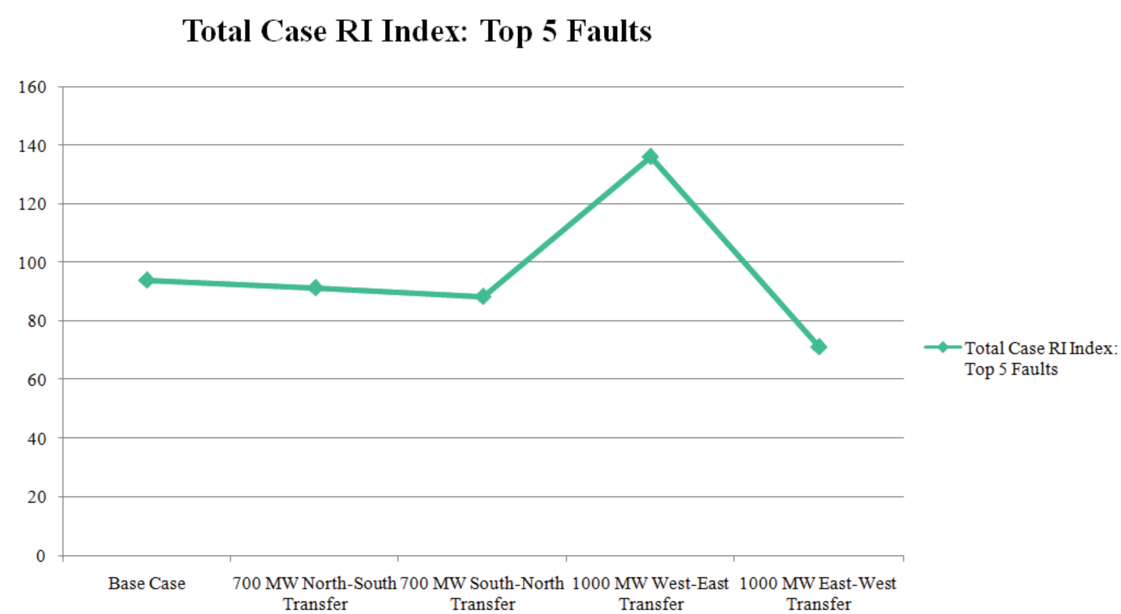


Figure 5-14. Total Case RI for the Base Case and Transfer Cases

From Figure 5-13 it follows that West-to-East transfer case is the most severe case since it has the smallest value of the Total Case CCT. This corresponds to the results shown in Figure 5-12. Thus, there is a good correlation between the results of the FFS (Figure 5-12) and time-domain simulation (Figure 5-13).

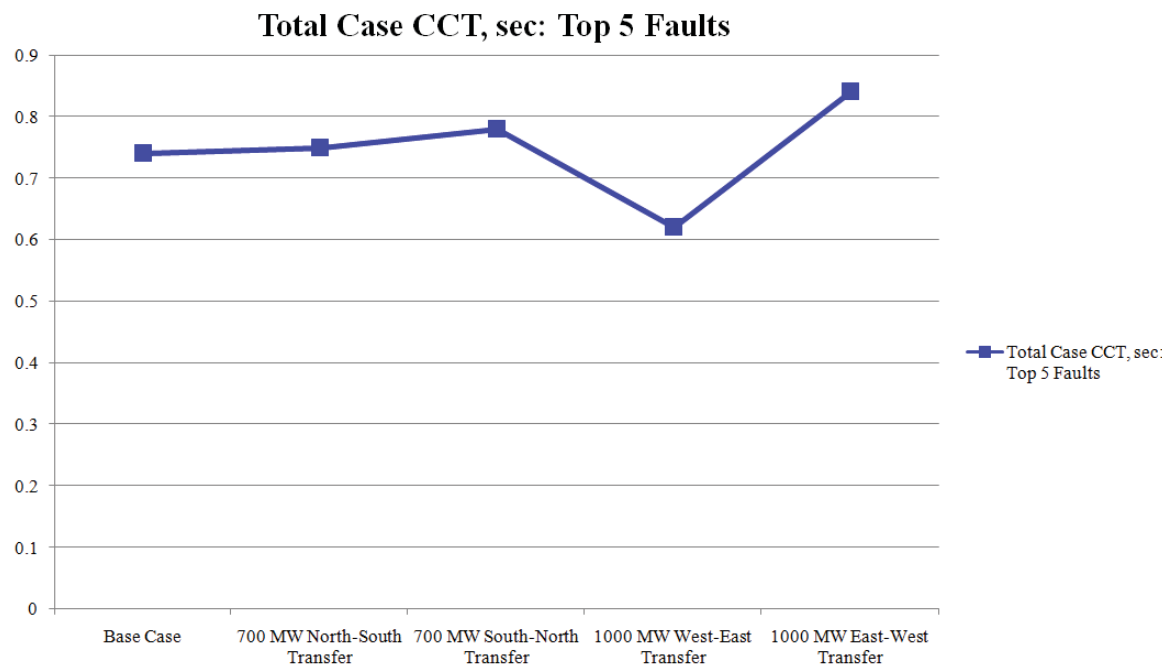


Figure 5-15. Total Case CCT for the Base Case and Transfer Cases

In addition to performing a very fast screening of the system for transient stability issues, FFS has been used in the project to compare various cases in terms of their vulnerability to transient stability limitations.

5.7 Conclusions: Testing FFS Using NYISO Planning Data

The off-line testing for the FFS was performed using NYISO planning model.

The testing shows that:

- There is a good correlation of the results between the FFS and time-domain simulation;
- NYISO model is robust in terms of transient stability (e.g., critical clearing times are generally high);
- Transfer analysis has been performed and the effect of the power transfers on transient stability of NYISO model was analyzed using the FFS and time-domain simulation.

TESTING OF THE FAST FAULT SCREENING CAPABILITY USING REAL-TIME STATE ESTIMATOR DATA

The main challenge in performing transient stability assessment using the real-time data is the absence of a key component for running these types of studies - dynamic models file. Transient stability analysis cannot be performed without this data.

Therefore, the first step that needed to be done in order to execute either the FFS or traditional time-domain simulation is creation of this file.

The analysis during the second phase of the project proceeded as follows:

- Creating a dynamic models file for the State-Estimator model (e.g. EMS cases);
- Running FFS on the EMS model in order to identify potential severe fault locations and rank these locations;
- Running time-domain simulation on the EMS model;
- Comparing the results of the FFS and time-domain simulation.

6.1 State-Estimator Model Provided by NYISO

NYISO provided a set of four EMS cases which were in PSS/E rev. 27.

These cases are summarized in Table 6-1. The cases represent various system conditions described by the following three characteristics:

- System load;
- Roseton generation;
- Maintenance schedules.

Table 6-13. Description of EMS Case

No.	File	Date	Load Level	Maintenance	Generation
1	PSSE-FILE1.RAW	Jul 30, 16:00	MW		MW
2	PSSE-FILE2.RAW	Aug 4, 16:00	MW		MW
3	PSSE-FILE3.RAW	Aug 5, 14:00	MW		MW
4	PSSE-FILE4.RAW	Aug 7, 4:00,	MW		MW

POM Suite was used to generate EMS case summary which is shown in Table 6-2.

Table 6-14. EMS Case Summary

	EMS Cases				Planning Case
	PSSE-FILE1.RAW	PSSE-FILE2.RAW	PSSE-FILE3.RAW	PSSE-FILE4.RAW	
Buses	3230	3217	3219	3209	52541
Loads	2501	2497	2498	2498	31171
Generators	**1302**	**1289**	**1294**	**1271**	**7772**
Lines	6193	6192	6191	6191	49341
Transformers	1127	1121	1121	1112	19079
Dynamic Models	1043*	1043*	1043*	1044*	17054

Table 6-2 also shows the number of corresponding elements in the planning case (the last column in Table 6-2)..

* Note that Dynamic Models (the last row in Table 6-2) were generated in the course of the study and were not provided by NYISO.

6.2 Creating a Dynamic Models File for the State-Estimator Model

A real-time dynamic models file was crated based on the planning model described in Section 5.2.

The major effort concentrated on converting the planning dynamic models file to be used with EMS load flow cases and creating a new dynamic models file that can be used with the EMS load flow cases. The file was called EMSDynModels.txt.

Creation of the dynamic models file proceed in five steps.

6.2.1 Step 1: Creating a Correspondence Table between Buses in Planning and State-Estimator Models

This is a manual process since bus names are different in planning and state estimator models.

Correspondence between the buses in planning and EMS cases was created based on the following considerations:

- Bus names and nominal voltages are identical for some of the buses in two data sets;
- Bus names and nominal voltages are similar for some of the buses in two data sets;
- Electrical connections (positions of the buses in the one-line) for buses having the same voltage class match in both data sets;
- Additional information provided by NYISO.

  NYISO provided a list of hydro units in NYISO state estimator model.

Several examples of deriving a correspondence between a list of hydro units provided by NYISO and units in the state-estimator models is shown in Table 6-3 and Table 6-4.

Table 6-3 shows a list of units as given in the hydro unit list (left column) and real-time model (right column). As seen from Table 6-3, there are 14 units in the hydro unit list and 15 units in the EMS case.

Table 6-15. Example 1: Units

No.	List of Hydro Units in NYISO State Estimator Model		No.	Generating Unit Specification in the EMS Load Flow Case "PSSE-FILE1.RAW"
	Generating Unit Name	Maximum Operating MW		
1		254	1	,' ', 13.000, 2
2		254	2	,' ', 13.000, 2
3		190	3	,' ', 13.000, 2
4		190	4	,' ', 13.000, 2
5		190	5	,' ', 13.000, 2
6		190	6	,' ', 13.000, 2
7		190	7	,' ', 13.000, 2
8		190	8	,' ', 13.000, 2
9		191	9	,' ', 13.000, 2
10		191	10	,' ', 13.000, 2
11		191	11	,' ', 13.000, 2
12		254	12	,' ', 13.000, 2
13		190	13	,' ', 13.000, 2
14		2987	14	,' ', 13.000, 2
			15	,' ', 13.000, 2

Table 6-4 shows a list of units as given in the hydro unit list (left column) and real-time model (right column). As seen from Table 6-4, there are 12 units in the hydro unit list and 4 units in the EMS case.

Table 6-16. Example 2: Units

No.	List of Hydro Units in NYISO State Estimator Model		No.	Generating Unit Specification in the EMS Load Flow Case "PSSE-FILE1.RAW"
	Generating Unit Name	Maximum Operating MW		
1		28	1	,'', 115.000, 2
2		28	2	,'', 115.000, 2
3		28	3	,'', 138.000, 2
4		28	4	,'', 500.000, 2
5		28		
6		28		
7		28		
8		28		
9		28		
10		28		
11		28		
12		28		

Matching of the planning and real-time data that was performed by V&R Energy under this project is valid for demonstration and proof-of-concept analysis.

<u>V&R Energy's recommendation:</u>

Valid matching of the planning and EMS load flow models may be performed only with active involvement of the utility/ISO. As a result of this process, the data may be implemented in the real-time environment of the utility/ISO

6.2.2 Step 2: Creating a Generator List for the Real-Time Data

Based on the results of Step 1 (see Section 6.2.1), create a generator list for the EMS case such that it matches generators in the planning load flow case "CY07-ATBA-SUM12_rev4V29.RAW". Matching of generating units is performed using the load flow data.

6.2.3 Step 3: Creating a "Dynamic" Generator List for the Real-Time Data

A "dynamic" generator list for the EMS case is created such that it matches generators in the planning dynamics file, 2007_ATBA_29.5.DYR.

During this step, the type of dynamic model is also taken into account.

6.2.4 Step 4: Checking the Correspondence between the Generators Maximum Power Output

The correspondence between the maximum power output of generators in planning load flow and dynamics data is checked for those generators that are present in the EMS case.

This step is needed because generators are equivalenced differently in planning and EMS cases. This allows us to answer the following question: "If there is an equivalent generator in the EMS case, how is it related to generator(s) in the planning model?"

It is important to check equivalent generators inside as well as outside of NYISO's footprint.

6.2.5 Step 5: Creating a Real-Time Dynamic Models File

Equivalent dynamic models are created for the generators in the EMS case. Then, an EMS dynamic models file, "EMSDynModels.txt", is generated.

An example of creating an EMS dynamic model file is shown in Figure 6-1.

Step 2	Step 3		Step 5
Planning Load Flow Case →	Planning Dynamics Model →	EMS Load Flow Case →	EMS Dynamics Model
,' . 1 ', 13.8, 2,	'GENSAE' 1	,'1 ', 214.33,	'GENSAE' 1
,' . 2 ', 13.8, 2,	'GENSAL' 2	,'1 ', 214.73,	'GENSAL' 1
,' . 3 ', 13.8, 2,	'GENSAL' 3	,'1 ', 215.16,	'GENSAE' 1
,' . 4 ', 13.8, 2,	'GENSAE' 4	,'1 ', 189.50,	'GENSAL' 1

Figure 6-16. Example of Creating an EMS Dynamic Models File

The following rules were used to create equivalent generator models:

Rule 1. Generators of the same type are equivalenced:

- Steam units
- Hydro units
- Generators, described by the classical model

Rule 2. Current and maximum power output of the equivalent generator is equal to the sum of the current and maximum power outputs, respectively, of generators being equivalenced.

Rule 3. Inertia of the equivalent generator is equal to the sum of inertia of all generators being equivalenced.

Rule 4. Base power of the equivalent generator is equal to the sum of the base powers of all generators being equivalenced.

Rule 5. Turbine governors are equivalenced as follows:

- For the group of generators being equivalenced, the model associated with the generator with the largest power output is used.

Rule 6. Excitation system models are equivalenced as follows:

- For the group of generators being equivalenced, the model associated with the generator with the largest power output is used.

Rule 7. If there is a stabilizer associat ed with a generator being equivalenced, then this stabilizer model is used for the equivalent generator.

Rule 8. Parameters of the equivalent generators, turbine governors and exciters that are in p.u. are recomputed based on the total MBASE.

Rule 9. When equivalencing generators that are connected to different buses, transmission losses are accounted by use of additional loads.

Two fragments of the real-time dynamic models file are listed below.

Fragment 1 of dynamic models file for the EMS data is for hydro unit
[redacted],'[redacted] ', 13.000:

- [redacted] 'GENSAE' 1 - Salient pole generator model
- [redacted] 'ESST1A' 1 - 1992 IEEE type ST1A excitation system model
- [redacted] 'USRMDL' 1 'HYGOV4' - Hydro turbine-governor model

These are the models that are used for this generator in the planning dynamic models file.

Fragment 2 of dynamic models file for the EMS data is for hydro unit
[redacted],'[redacted] ', 24.000:

- [redacted] 'GENROU' 1 - Round rotor generator model
- [redacted] 'IEEET1' 1 - 1968 IEEE type 1 excitation system model
- [redacted] 'IEESGO' 1 1973 IEEE standard turbine-governor model

These are the models that are used for this generator in the planning dynamic models file.

6.3 FFS Options during Real-Time Analysis

The FFS capability was used to identify the most severe potential fault locations in NY ISO footprint using the real-time State-Estimator data.

The following FFS options (see Section 9.4) were selected during the analysis:

- Control Area Number: **1 - 23**
- Minimum Voltage Level, kV: **60**
- Minimum Real Power, MW: **100**
- Power Difference, %: **25**
- Number of Outaged Lines **2**

  This corresponds to loss of two elements during fault scenario.

- Reactance, p.u.: **0.0005**
- Fault Type: **LLL**

6.4 Results for the EMS Case "PSSE-FILE1.RAW"

FFS identified 35 most severe potential fault locations that satisfy the options listed in Section 6.3.

FFS computations show that critical clearing time is relative large for many faults, which is an indicator of the robustness of the system in terms of transient stability. The distribution of the Ranking Index by the critical clearing time for case "PSSE-FILE1.RAW" is shown in Figure 6-2.

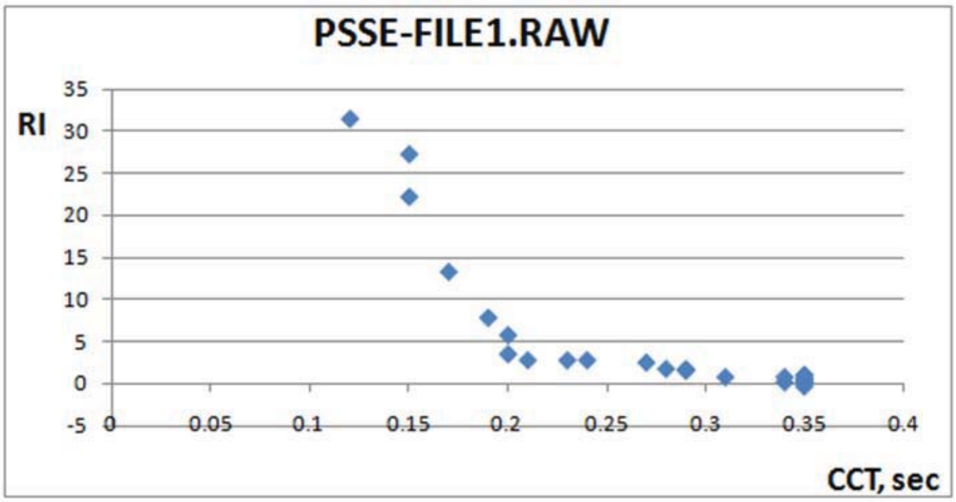


Figure 6-17. Distribution of the Ranking Index by the Critical Clearing Time for Case "PSSE-FILE1.RAW"

The FFS results show that there is one stability violation and 11 instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 6-5.

One steady-state stability violation occurs after the following N-2 contingency:

[redacted] 345 - [redacted] 345 ,"1 "

[redacted] 345 - [redacted] 345 ,"1 "

Table 6-17. Weak Points in Case "PSSE-FILE1.RAW": Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Result
1			345	Stability Violation
2			345	Loss of Generation 1042.65 MW
3			345	Loss of Generation 839.74 MW
4			345	Loss of Generation 732.1 MW
5			345	Loss of Generation 636.53 MW
6			345	Loss of Generation 602.25 MW
7			345	Loss of Generation 421.2 MW
8			138	Loss of Generation 390.08 MW
9			115	Loss of Generation 229.25 MW
10			138	Loss of Generation 213.19 MW
11			138	Loss of Generation 144.73 MW
12			115	Loss of Generation 138.11 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 6-6.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of the critical clearing time.

Table 6-18. Ranking the Most Severe Fault Locations: Case "PSSE-FILE1.RAW"

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			115	31.3979	0.12
2			115	27.2127	0.15
3			345	22.1454	0.15
4			230	13.2443	0.17
5			230	7.8108	0.19
6			115	5.7328	0.2
7			138	3.4894	0.2
8			345	2.7756	0.21
9			115	2.7582	0.23
10			230	2.7672	0.24
11			138	2.4808	0.27
12			230	1.7347	0.28
13			230	1.712	0.29
14			138	1.508	0.29
15			345	0.7509	0.31
16			138	0.1383	0.34
17			138	0.7585	0.34
18			115	1.0241	0.35
19			115	0.9664	0.35
20			230	0.6072	0.35
21			69	0.3245	0.35
22			115	0.1631	0.35
23			115	-0.3542	0.35

Comparison of the results based on RI and CCT is given in Table 6-7. Table 6-7 shows a very good correlation of the FFS (RI) and time-domain simulation (CCT).

Table 6-19. Comparison of RI and CCT: Case "PSSE-FILE1.RAW"

Bus Number	Bus Name	Bus Base kV	RI	Rank RI	CCT	Rank CCT
		115	31.3979	1	0.12	1
		115	27.2127	2	0.15	2
		345	22.1454	3	0.15	3
		230	13.2443	4	0.17	4
		230	7.8108	5	0.19	5
		115	5.7328	6	0.2	6
		138	3.4894	7	0.2	7
		345	2.7756	8	0.21	8
		115	2.7582	9	0.23	9
		230	2.7672	10	0.24	10
		138	2.4808	11	0.27	11
		230	1.7347	12	0.28	12
		230	1.712	13	0.29	13
		138	1.508	14	0.29	14
		345	0.7509	18	0.31	15
		138	0.1383	22	0.34	16
		138	0.7585	17	0.34	17
		115	1.0241	15	0.35	18
		115	0.9664	16	0.35	19
		230	0.6072	19	0.35	20
		69	0.3245	20	0.35	21
		115	0.1631	21	0.35	22
		115	-0.3542	23	0.35	23

Bus # 115 kV is the first bus in the FFS list, see Table 6-7. Should a fault be applied at that bus, CCT = 0.12 sec and RI = 31.3979.

Oneline diagram for Bus # is shown in Figure 6-3.

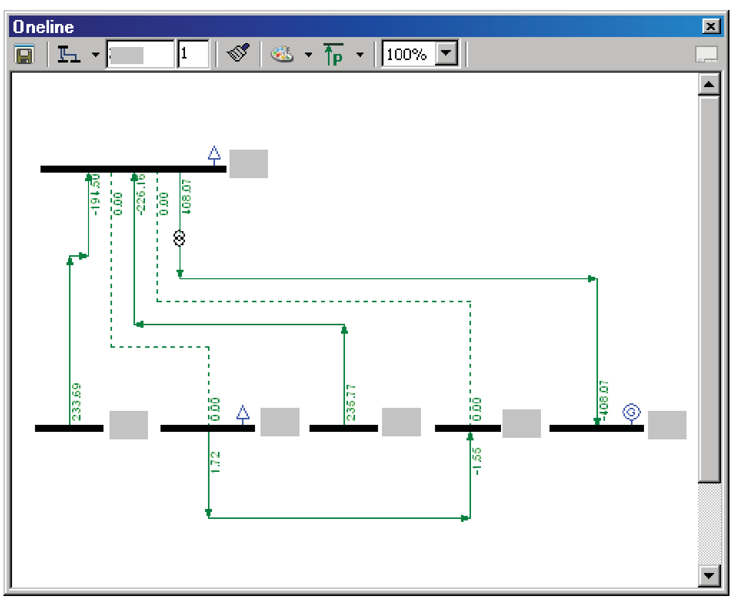
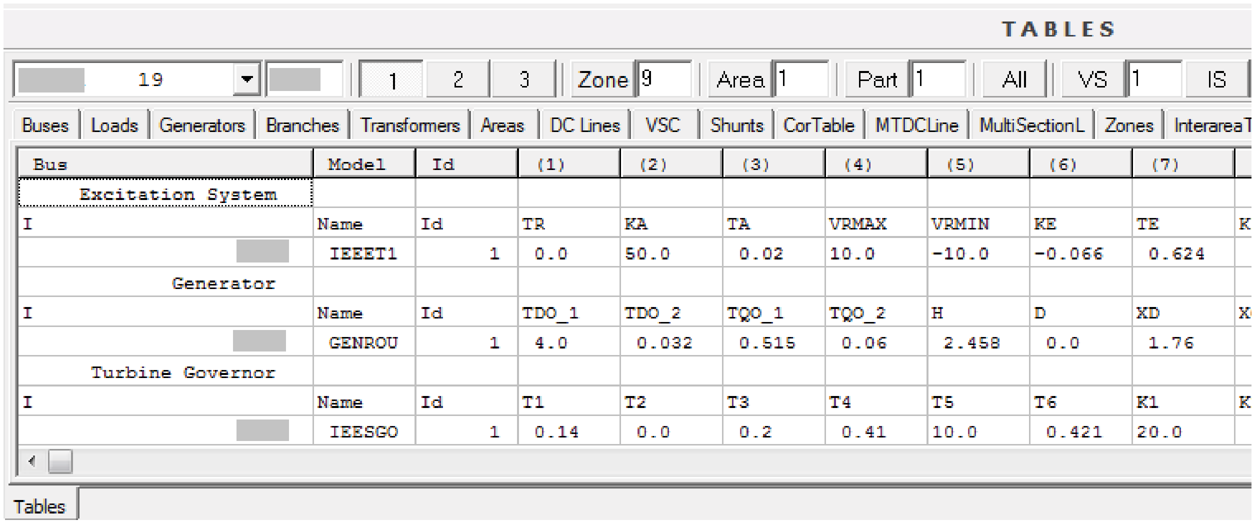


Figure 6-18. Oneline Diagram for Bus # 115.0

Generator connected to this bus is [redacted] 19 kV.

Dynamic models developed for generator [redacted] 19 kV are listed in POM Data Tables, shown in Figure 6-4.



TABLES

[redacted] 19 [redacted] | 1 | 2 | 3 | Zone 9 | Area 1 | Part 1 | All | VS 1 | IS

Buses | Loads | Generators | Branches | Transformers | Areas | DC Lines | VSC | Shunts | CorTable | MTDCLine | MultiSectionL | Zones | InterareaT

Bus	Model	Id	(1)	(2)	(3)	(4)	(5)	(6)	(7)	
Excitation System										
I	Name	Id	TR	KA	TA	VRMAX	VRMIN	KE	TE	K
[redacted]	IEEET1	1	0.0	50.0	0.02	10.0	-10.0	-0.066	0.624	
Generator										
I	Name	Id	TDO_1	TDO_2	TQO_1	TQO_2	H	D	XD	X
[redacted]	GENROU	1	4.0	0.032	0.515	0.06	2.458	0.0	1.76	
Turbine Governor										
I	Name	Id	T1	T2	T3	T4	T5	T6	K1	K
[redacted]	IEESGO	1	0.14	0.0	0.2	0.41	10.0	0.421	20.0	

Tables

Figure 6-19. Dynamic Models for Generator [redacted] 19.0

Time-domain simulation was then performed and three-phase fault scenarios were applied at this bus:

- Fault clears in 0.08 sec, see Figure 6-5;
- Fault clears in 0.12 sec, see Figure 6-6;
- Fault clears in 0.13 sec, see Figure 6-7.

The following quantities were plotted for each fault scenario:

- Terminal voltage (green)
- Rotor angle (blue)

Figure 6-5 shows that the system remains stable if the fault clears in 0.08 sec (since it is less than the critical clearing time of 0.12 sec).

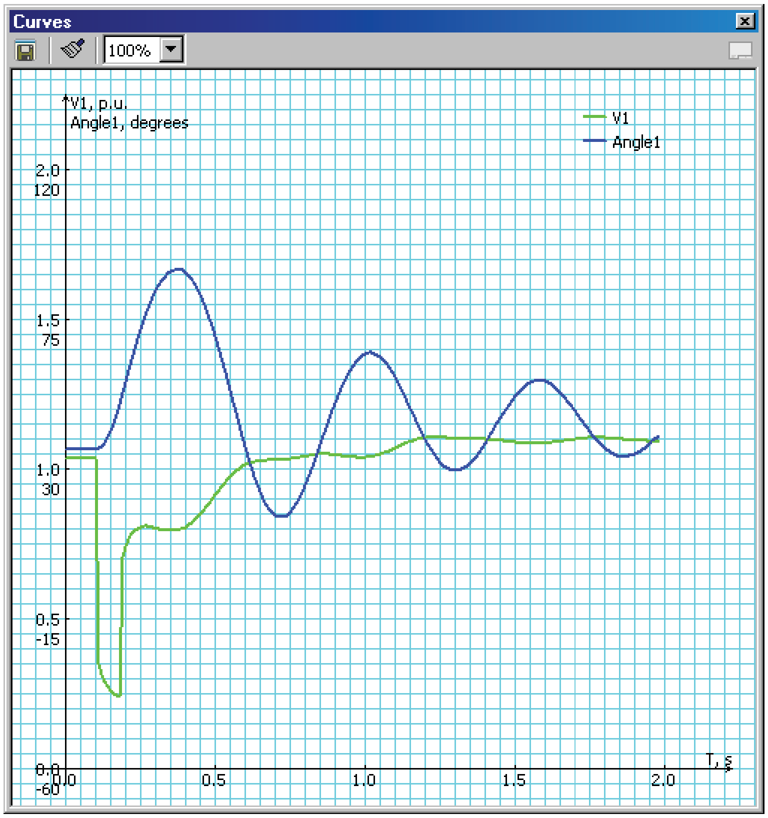


Figure 6-20. Fault at Bus # 115.0 Clears in 0.08 sec

If this fault clears in 0.12 sec, the system is close to being unstable, see Figure 6-6.

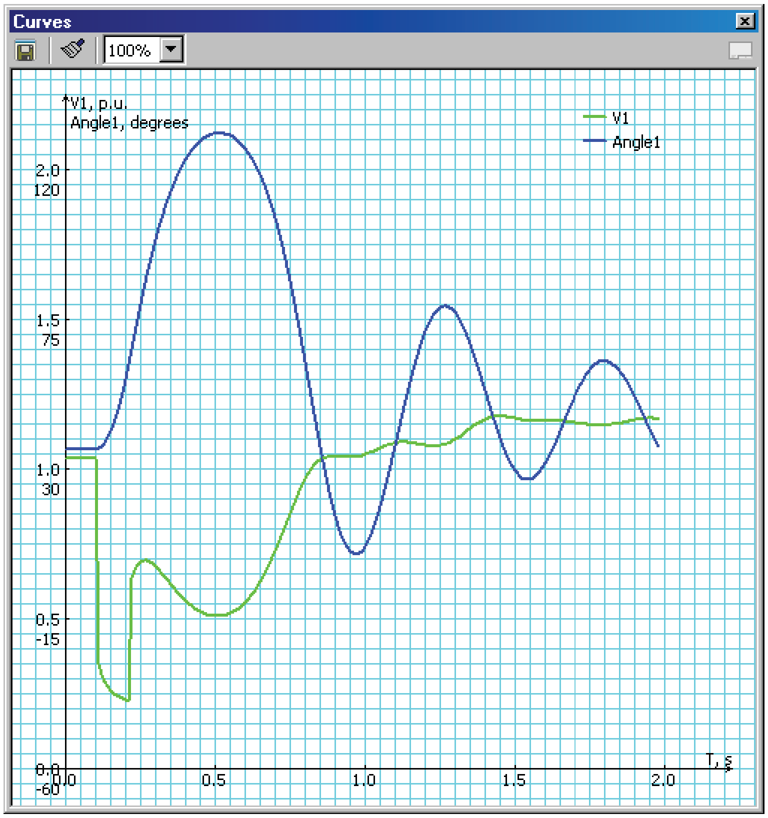


Figure 6-21. Fault at Bus # 115.0 Clears in 0.12 sec

If this fault clears in 0.13 sec, the system losses synchronism, see Figure 6-7.

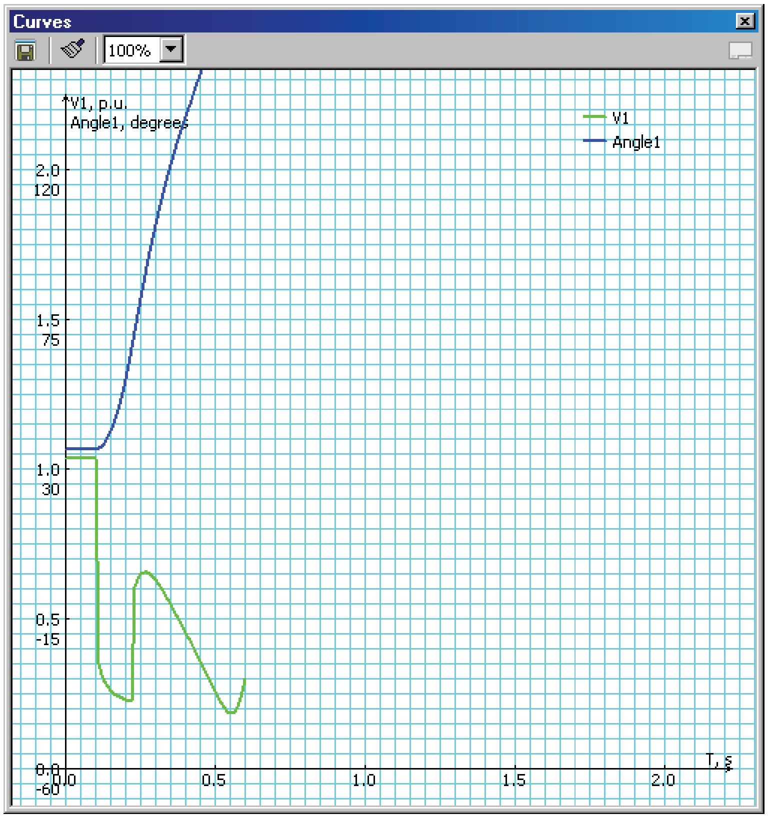


Figure 6-22. Fault at Bus #[redacted] 115.0 Clears in 0.13 sec

Benchmarking with the results of the FFS for planning model (see Section 5.4) shows that Bus #[redacted] is the first bus in the FFS list in both planning and EMS models, see Table 6-8.

Table 6-20. Comparing the FFS Results for the Planning Base Case and EMS Case "PSSE-FILE1.RAW"

Case	Bus Number	Bus Name	Bus Base kV	RI	CCT, sec
EMS Case	[redacted]	[redacted]	115	31.3979	0.12
Planning Case	[redacted]	[redacted]	115	33.5666	0.12

Time-domain simulation was then performed for a bus fault at Bus #[redacted] 138 kV, which is in the middle of the FFS Output Table, see Table 6-6. Should a fault be applied at that bus, CCT = 0.2 sec and RI = 3.4894.

Oneline diagram for Bus #[redacted] is shown in Figure 6-8.

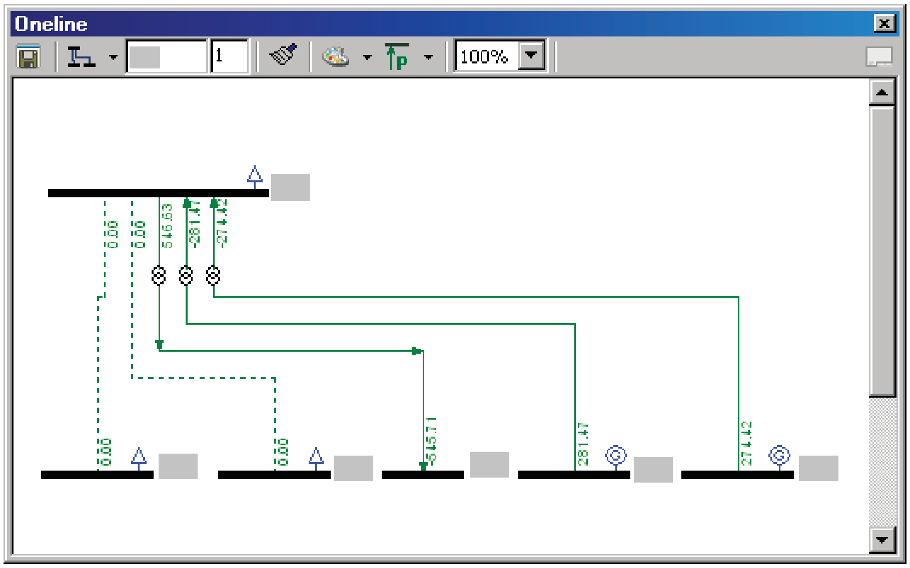
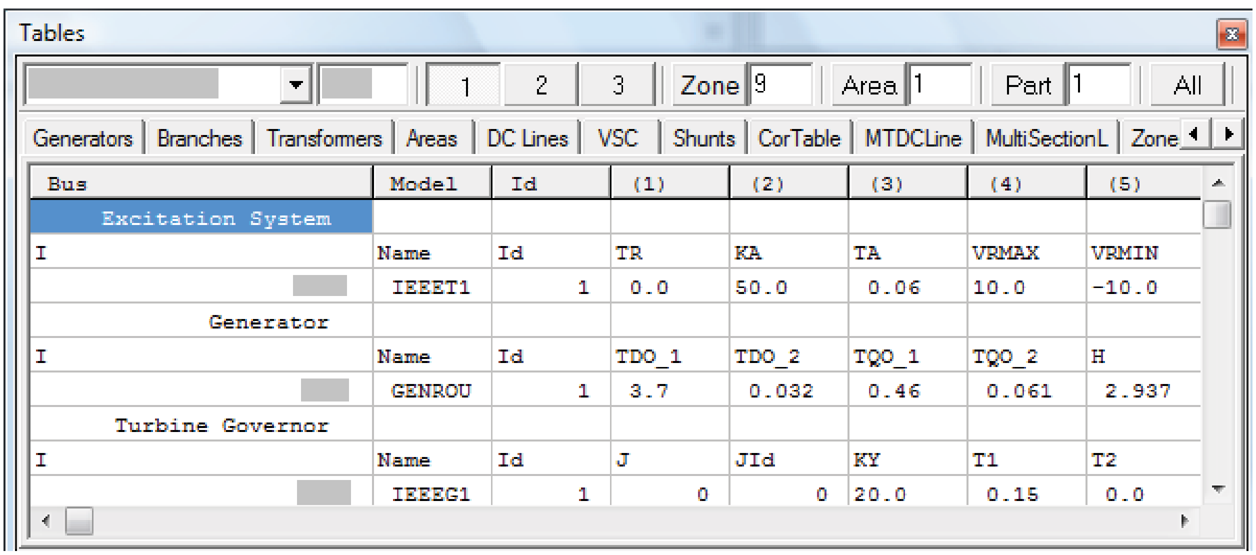


Figure 6-23. Oneline Diagram for Bus # 138.0

Generator connected to this bus is 13 kV.

Dynamic models developed for generator 13 are listed in POM Data Tables, shown in Figure 6-9.



Bus	Model	Id	(1)	(2)	(3)	(4)	(5)
Excitation System							
I	Name	Id	TR	KA	TA	VRMAX	VRMIN
	IEEET1	1	0.0	50.0	0.06	10.0	-10.0
Generator							
I	Name	Id	TDO_1	TDO_2	TQO_1	TQO_2	H
	GENROU	1	3.7	0.032	0.46	0.061	2.937
Turbine Governor							
I	Name	Id	J	JId	KY	T1	T2
	IEEEG1	1	0	0	20.0	0.15	0.0

Figure 6-24. Dynamic Models for Generator 13.0

Time-domain simulation was then performed and three fault scenarios were applied at this bus:

- Fault clears in 0.08 sec, see Figure 6-10;
- Fault clears in 0.20 sec, see Figure 6-11;
- Fault clears in 0.21 sec, see Figure 6-12.

The following quantities were plotted for each fault scenario:

- Terminal voltage (green)
- Rotor angle (blue)

Figure 6-10 shows that the system remains stable if the fault clears in 0.08 sec (since it is less than the critical clearing time of 0.20 sec).

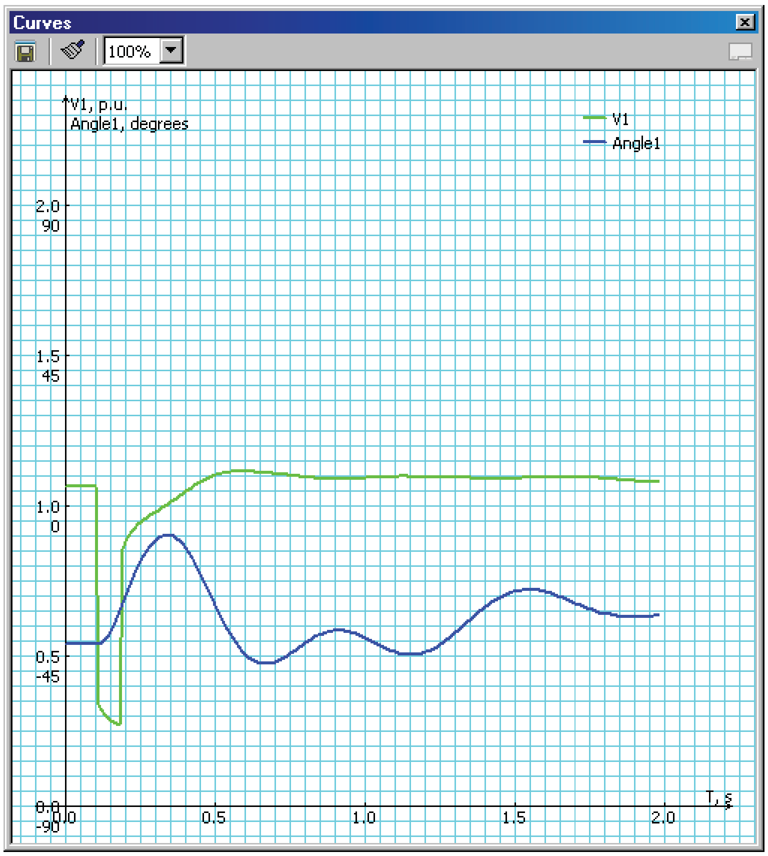


Figure 6-25. Fault at Bus # 138.0 Clears in 0.08 sec

If this fault clears in 0.20 sec, the system is close to being unstable, see Figure 6-11.

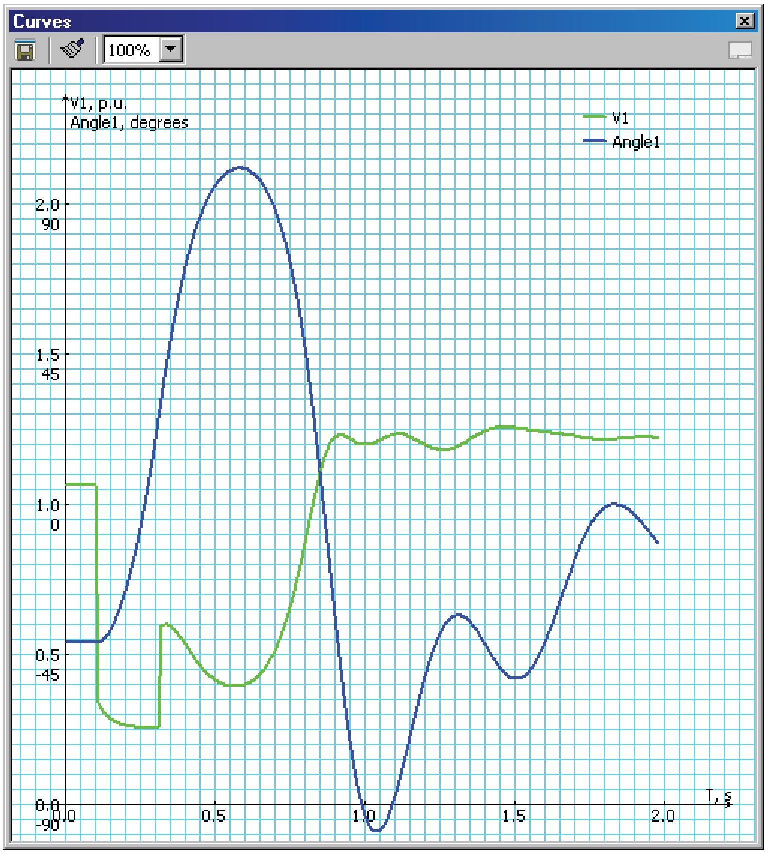


Figure 6-26. Fault at Bus # 138.0 Clears in 0.20 sec

If this fault clears in 0.21 sec, the system losses synchronism, see Figure 6-12.

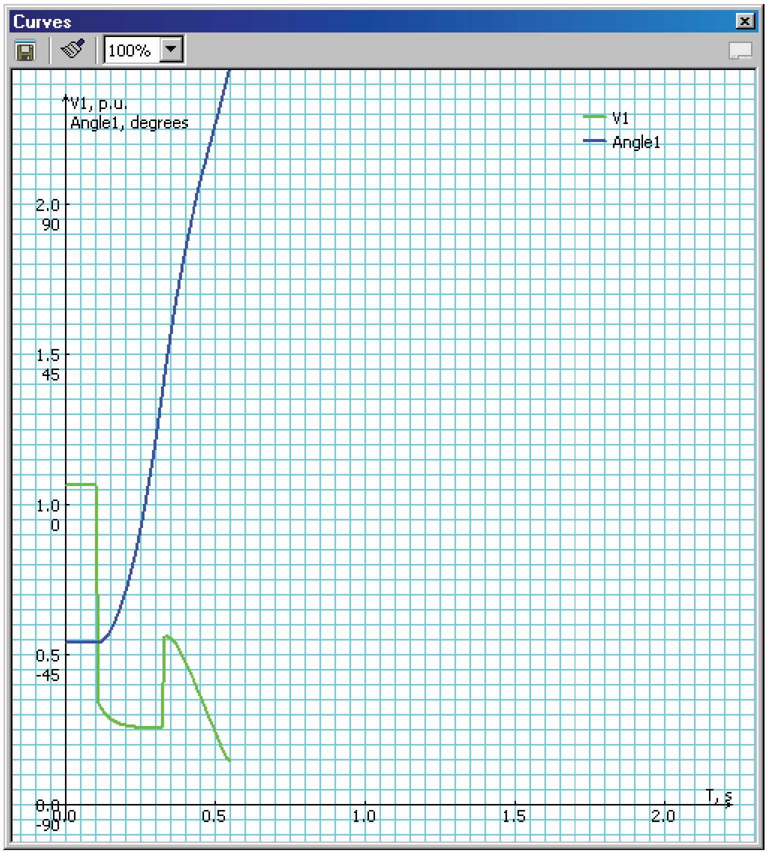


Figure 6-27. Fault at Bus #[redacted] [redacted] 138.0 Clears in 0.21 sec

Therefore, analysis of case "PSSE-FILE1.RAW" showed that FFS produced consistent results that were checked using the traditional time-domain simulation approach.

6.5 Results for the EMS Case "PSSE-FILE2.RAW"

FFS identified 30 most severe potential fault locations that satisfy the options listed in Section 6.3.

FFS computations show that critical clearing time is relative large for many faults, which is an indicator of the robustness of the system in terms of transient stability. The distribution of the Ranking Index by the critical clearing time for case "PSSE-FILE2.RAW" is shown in Figure 6-13.

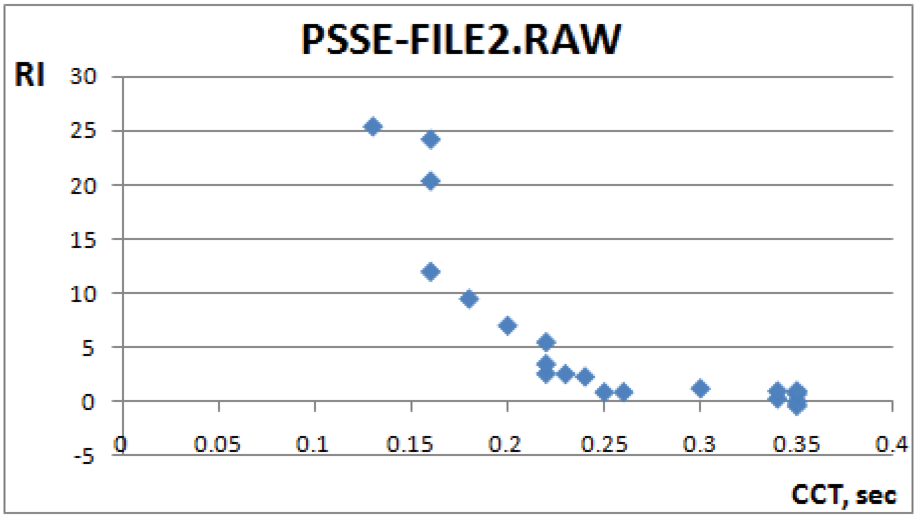


Figure 6-28. Distribution of the Ranking Index by the Critical Clearing Time for Case "PSSE-FILE2.RAW"

The FFS results show that there is one stability violation and nine instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 6-9.

One steady-state stability violation occurs after the following N-2 contingency:

345 - 345 ,"1 "

345 - 345 ,"1 "

Table 6-21. Weak Points in Case "PSSE-FILE2.RAW": Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Result
1			345	Stability Violation
2			345	Loss of Generation 1048.49 MW
3			345	Loss of Generation 839.48 MW
4			345	Loss of Generation 730.4 MW
5			345	Loss of Generation 702.28 MW
6			345	Loss of Generation 614.83 MW
7			345	Loss of Generation 600.1 MW
8			138	Loss of Generation 389.25 MW
9			115	Loss of Generation 241.31 MW
10			138	Loss of Generation 144.96 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 6-10.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of the critical clearing time.

Table 6-22. Ranking the Most Severe Fault Locations: Case "PSSE-FILE2.RAW"

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			345	25.4495	0.13
2			115	24.2723	0.16
3			345	20.421	0.16
4			345	12.0363	0.16
5			138	9.533	0.18
6			230	7.0578	0.2
7			115	5.52	0.22
8			230	3.498	0.22
9			115	2.62	0.22
10			345	2.5811	0.23
11			115	2.3314	0.24
12			138	0.8949	0.25
13			345	0.9147	0.26
14			138	1.2468	0.3
15			115	1.0042	0.34
16			138	0.3029	0.34
17			115	1.0364	0.35
18			115	0.7545	0.35
19			115	0.0336	0.35
20			115	-0.3605	0.35

Comparison of the results based on RI and CCT is given in Table 6-11.

Table 6-23. Comparison of RI and CCT: Case “PSSE-FILE2.RAW”

Bus Number	Bus Name	Bus Base kV	RI	Rank RI	CCT	Rank CCT
		345	25.4495	1	0.13	1
		115	24.2723	2	0.16	2
		345	20.421	3	0.16	3
		345	12.0363	4	0.16	4
		138	9.533	5	0.18	5
		230	7.0578	6	0.2	6
		115	5.52	7	0.22	7
		230	3.498	8	0.22	8
		115	2.62	9	0.22	9
		345	2.5811	10	0.23	10
		115	2.3314	11	0.24	11
		138	0.8949	16	0.25	12
		345	0.9147	15	0.26	13
		138	1.2468	12	0.3	14
		115	1.0042	14	0.34	15
		138	0.3029	18	0.34	16
		115	1.0364	13	0.35	17
		115	0.7545	17	0.35	18
		115	0.0336	19	0.35	19
		115	-0.3605	20	0.35	20

Table 6-11 shows a very good correlation of the FFS (RI) and time-domain simulation (CCT).

6.6 Results for the EMS Case “PSSE-FILE4.RAW”

FFS identified 27 most severe potential fault locations that satisfy the options listed in Section 6.3.

Testing shows that there are several faults with very small critical clearing time. The distribution of the Ranking Index by the critical clearing time for case “PSSE-FILE4.RAW” is shown in Figure 6-14.

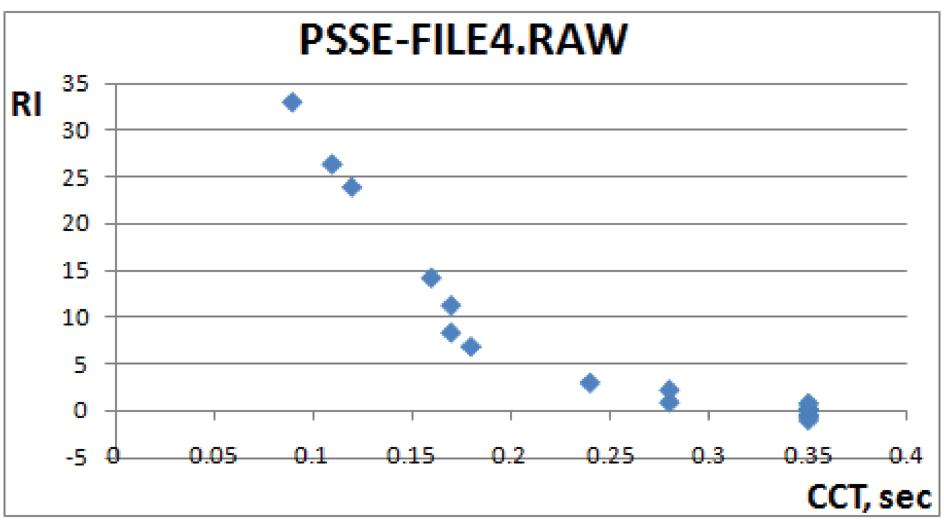


Figure 6-29. Distribution of the Ranking Index by the Critical Clearing Time for Case “PSSE-FILE4.RAW”

The FFS results show that there is one stability violation and eight instances of loss of generator real power above 100 MW. Potential weak points in the system that occur due to steady-state problems are summarized in Table 6-12.

One steady-state stability violation occurs after the following N-2 contingency:

[redacted] 345 - [redacted] 345 ,"1 “

[redacted] 345 - [redacted] 345 ,"1 "

Table 6-24. Weak Points in Case “PSSE-FILE4.RAW”: Steady-State Issues

N	Bus Number	Bus Name	Bus Base kV	Result
1	[redacted]	[redacted]	345	Stability Violation
2	[redacted]	[redacted]	345	Loss of Generation 1045.71 MW
3	[redacted]	[redacted]	345	Loss of Generation 841.82 MW
4	[redacted]	[redacted]	345	Loss of Generation 692.29 MW
5	[redacted]	[redacted]	345	Loss of Generation 604.39 MW
6	[redacted]	[redacted]	345	Loss of Generation 567.42 MW
7	[redacted]	[redacted]	345	Loss of Generation 390.07 MW
8	[redacted]	[redacted]	138	Loss of Generation 253.91 MW
9	[redacted]	[redacted]	138	Loss of Generation 104.66 MW

Then, the most severe fault locations (e.g., weak points) from transient stability perspective were identified and ranked by FFS.

Ranking was done using the Ranking Index (RI) and conventional time-domain simulation, see Table 6-13.

Column **Rank RI** shows FFS-based ranking. Column "**Rank CCT"** shows ranking based on the value of the critical clearing time (CCT).Benchmarking shows good correlation between the FFS result and computation of critical clearing time.

Table 6-25. Ranking the Most Severe Fault Locations: Case "PSSE-FILE4.RAW"

N	Bus Number	Bus Name	Bus Base kV	RI	CCT
1			115	33.0518	0.09
2			345	26.4162	0.11
3			345	23.9657	0.12
4			138	14.2638	0.16
5			230	11.3193	0.17
6			345	8.4025	0.17
7			115	6.9146	0.18
8			115	3.0473	0.24
9			115	2.2843	0.28
10			115	0.9626	0.28
11			345	0.8449	0.35
12			138	0.2633	0.35
13			230	0.2243	0.35
14			230	0.1327	0.35
15			230	0.13	0.35
16			138	-0.3663	0.35
17			138	-0.5597	0.35
18			138	-0.9391	0.35

Comparison of the results based on RI and CCT is given in Table 6-14.

Table 6-26. Comparison of RI and CCT: Case "PSSE-FILE4.RAW"

Bus Number	Bus Name	Bus Base kV	RI	Rank RI	CCT	Rank CCT
		115	33.0518	1	0.09	1
		345	26.4162	2	0.11	2
		345	23.9657	3	0.12	3
		138	14.2638	4	0.16	4
		230	11.3193	5	0.17	5
		345	8.4025	6	0.17	6
		115	6.9146	7	0.18	7
		115	3.0473	8	0.24	8
		115	2.2843	9	0.28	9
		115	0.9626	10	0.28	10
		345	0.8449	11	0.35	11
		138	0.2633	12	0.35	12
		230	0.2243	13	0.35	13
		230	0.1327	14	0.35	14
		230	0.13	15	0.35	15
		138	-0.3663	16	0.35	16
		138	-0.5597	17	0.35	17
		138	-0.9391	18	0.35	18

Table 6-14 shows a very good correlation of the FFS (RI) and time-domain simulation (CCT).

6.7 State-Estimator Case Summary

Two parameters were used in Sections 6.4 - 6.6 to rank the most severe potential fault locations: Ranking Index (RI) and critical clearing time (CCT). RI was computed using FFS and CCT was determined using traditional time-domain simulation.

Three transfer cases “PSSE-FILE1.RAW”, “PSSE-FILE2.RAW”, and “PSSE-FILE4.RAW" (see Sections 6.4 - 6.6) were compared in terms of their vulnerability to transient stability limitations based on the following parameters:

- Total Case RI;

  Total Case RI is the sum of Ranking Indices for the top five faults.

- Total Case CCT.

  Total Case CCT is the sum of critical clearing times for the top five faults.

The Total Case RI and CCT for three EMS cases are summarized in Table 6-15.

Table 6-27. Summary of Total Case RI and CCT for EMS Cases

Case	Total Case RI	Total Case CCT	Smallest CCT, sec
PSSE-FILE1.RAW	101.8111	0.78	0.12
PSSE-FILE2.RAW	91.7121	0.79	0.13
PSSE-FILE4.RAW	109.0168	0.65	0.09

Thus, comparison of the State-Estimator cases shows that case “PSSE-FILE4.RAW” is the most severe case since it has:

- The largest value of the case Ranking Index (RI);
- The smallest value of the critical clearing time (CCT) at the most severe fault location;
- The smallest value of the case CCT.

Comparison of the EMS cases based on the Total Case RI is shown in Figure 6-15. From Figure 6-15 it follows that case “PSSE-FILE4.RAW" is the most severe case since it has the largest value of the Total Case RI.

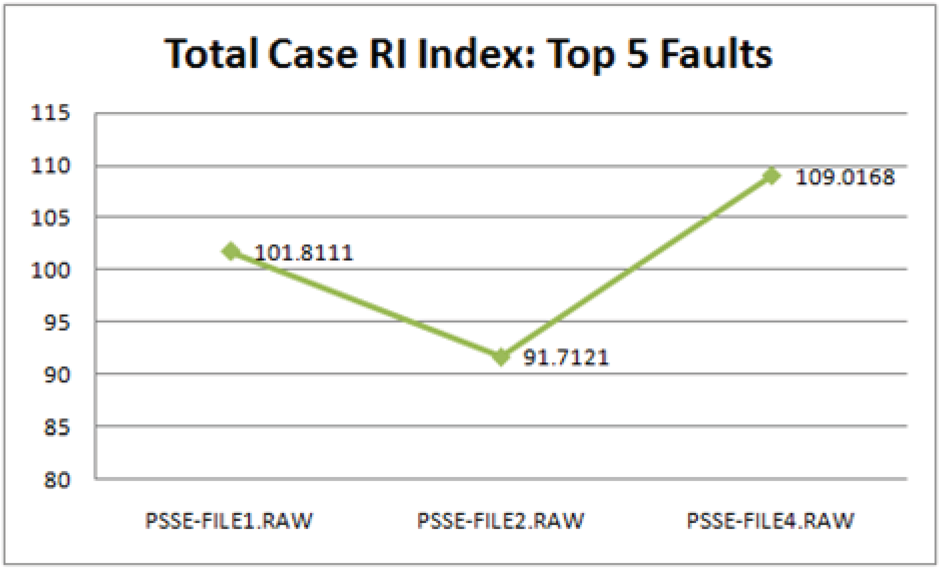


Figure 6-30. Total Case RI for EMS Cases

From Figure 6-16 it follows that case “PSSE-FILE4.RAW" is the most severe case since it has the smallest value of the Total Case CCT. This corresponds to the results shown in Figure 6-15. Thus, there is a good correlation between the results of the FFS (Figure 6-15) and time-domain simulation (Figure 6-16).

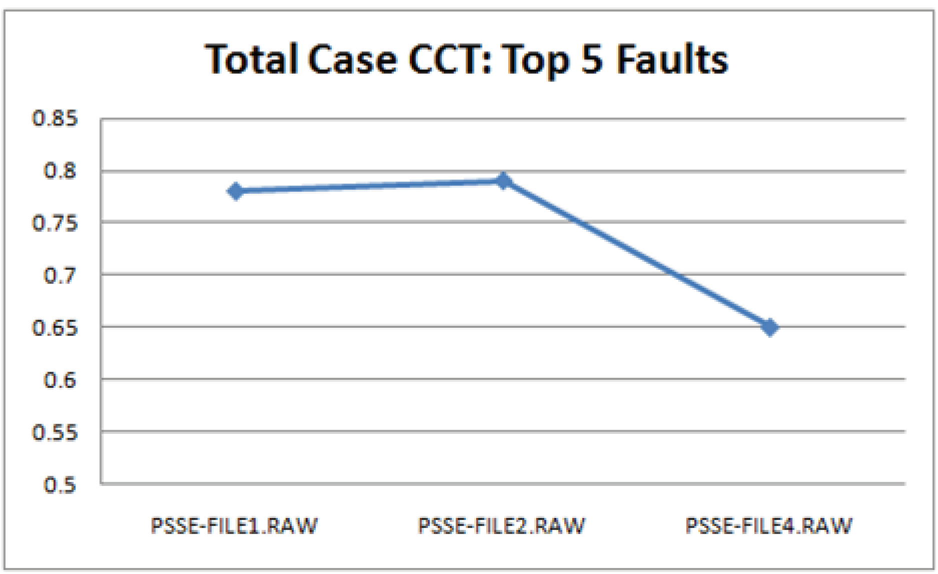


Figure 6-31. Total Case CCT for EMS Cases

In addition to performing a very fast screening of the system for transient stability issues, FFS has been used in the project to compare various EMS cases in terms of their vulnerability to transient stability limitations.

6.8 Conclusions: Testing FFS Using NYISO State-Estimator Data

A process for creating a dynamic models file for the State Estimator model (EMS cases) was developed. A dynamic models file for the EMS cases was created and used for transient stability analysis under the project.

The FFS analysis was performed for the NYISO State Estimator model and the results of the FFS were benchmarked versus time-domain simulation. The testing shows that there is a good correlation of the results between the FFS and time-domain simulation.

EMS cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations

CONCLUSION

Fast Fault Screening (FFS) is a very fast approach for transient stability assessment that allowed us to perform the following analyses:

- Apply a screening methodology and determine the locations of the most severe three-phase faults that may lead to transient instability.
- Rank the most severe fault locations in order to identify the weakest locations in the power system network.

In addition to performing a very fast screening of the system for transient stability issues, FFS has been used in the project to compare various cases in terms of their vulnerability to transient stability limitations.

Three-phase faults were analyzed during this project.

The work under this project consisted of the following two phases:

1. Extensive off-line testing of the Fast Fault Screening (FFS) capability using NY ISO planning data.

   The FFS approach was validated under various system conditions.

2. Extensive on-line testing of the FFS capability using NY ISO State Estimator data.

   Online testing included:

   - Creating a dynamic models file for the State Estimator cases;
   - Validating the FFS approach for various State Estimator cases.

Four transfer-biased cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations during off-line testing.

During on-line testing, three Energy Management System (EMS) cases were compared based on the FFS results in terms of their vulnerability to transient stability limitations.

Then, the results of the FFS were benchmarked versus time-domain simulation. Benchmarking showed a very good correlation between the FFS and time-domain simulation.

FFS has been shown as a practical tool to perform transient stability studies required under the existing and forthcoming NERC standard TPL-001-1. FFS was also demonstrated as an effective tool for transient stability assessment in on-line and near real-time environments.

Besides the benefits mentioned above, FFS also significantly reduces the time required to perform NERC reliability standards compliance-related studies. For instance, "Innovators with EPRI Technology" published by EPRI in February 2009 reported direct benefits of using the FFS for saving power system planning and computation time. One of EPRI utility members, Entergy Services, Inc., estimated that its use of the FFS resulted in "savings of 300 man-hours and $27,000 for NERC Reliability Standards compliance-related studies".[2]

[2] Entergy pioneers use of fast fault screening tool to identify severe contingencies for transient stability studies, EPRI Product ID 1018728, February 2009.

APPENDIX A

USING POM SUITE OF APPLICATIONS FOR FAST FAULT SCREENING

This section describes the use of Physical and Operational Margins (POM) suite of applications, version 4 for the FFS analysis.

8.1 POM Interface with FFS Capability

Physical and Operational Margins suite of applications, version 4 was used as the basis for computations under the current project.

Physical and Operational Margins (POM) and POM - Transient Stability (POM-TS) applications were used during the study.

FFS Tab is a part of POM-TS, see Figure 8-1.

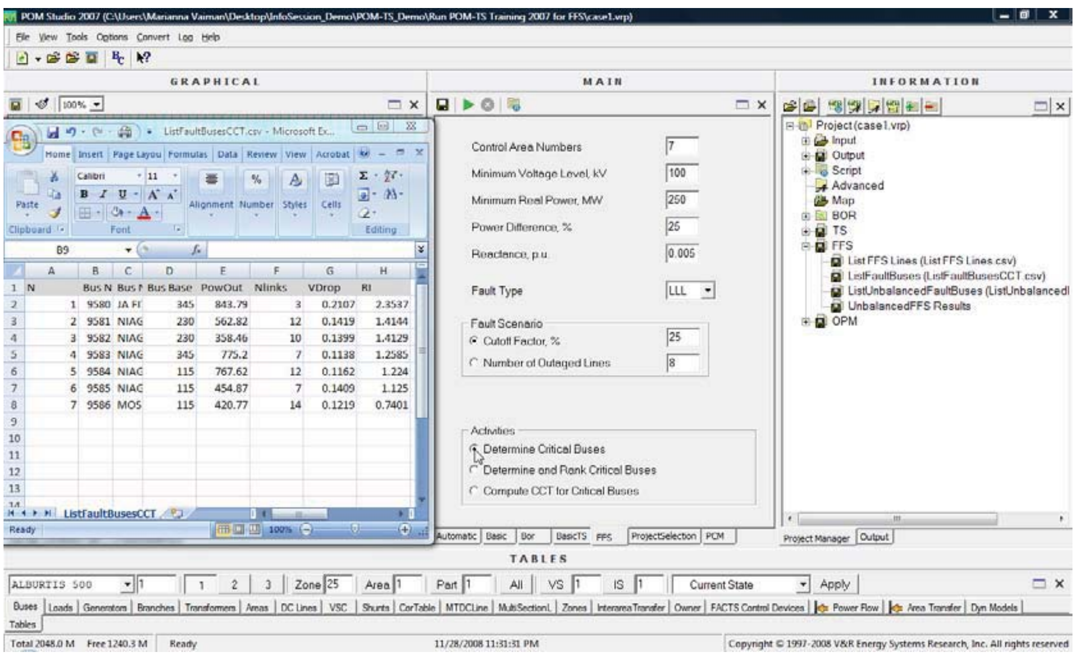


Figure 8-1. POM Suite ver. 4 Interface with FFS Tab

8.2 Using POM -Transient Stability (POM-TS) as the Basis for the FFS

The program "Physical and Operational Margins-Transient Stability" (POM-TS) of the POM Suite was used as the basis for all computations under this project.

POM-Transient Stability (POM-TS) is a fast, user-friendly and comprehensive dynamic simulation tool. Fully integrated into the POM Suite, POM-TS is designed to determine transient stability limits after any disturbance is applied to a power system network of any practical dimensions. Its execution time for a one second simulation is approximately six seconds for a 50000 bus case and 17000 dynamic models.

All the functions of POM-TS are directly accessible from the POM application. The user has an ability to switch between the dynamic and steady-state functions without any restrictions. Both dynamic and steady-state parameters are listed in POM Tables in the interface. POM-TS supports the library of dynamic models in Siemens PTI's PSS/E and GE's PSLF formats. It allows for an easy inclusion of the user-defined models using POM scripting without the need for external compilers.

POM Script is based on Microsoft® VBScript. The same scripting language is used for load flow and transient stability analysis. All the pre-built and user-defined scripting functions are directly accessible from the POM interface (see Figure 8-2).

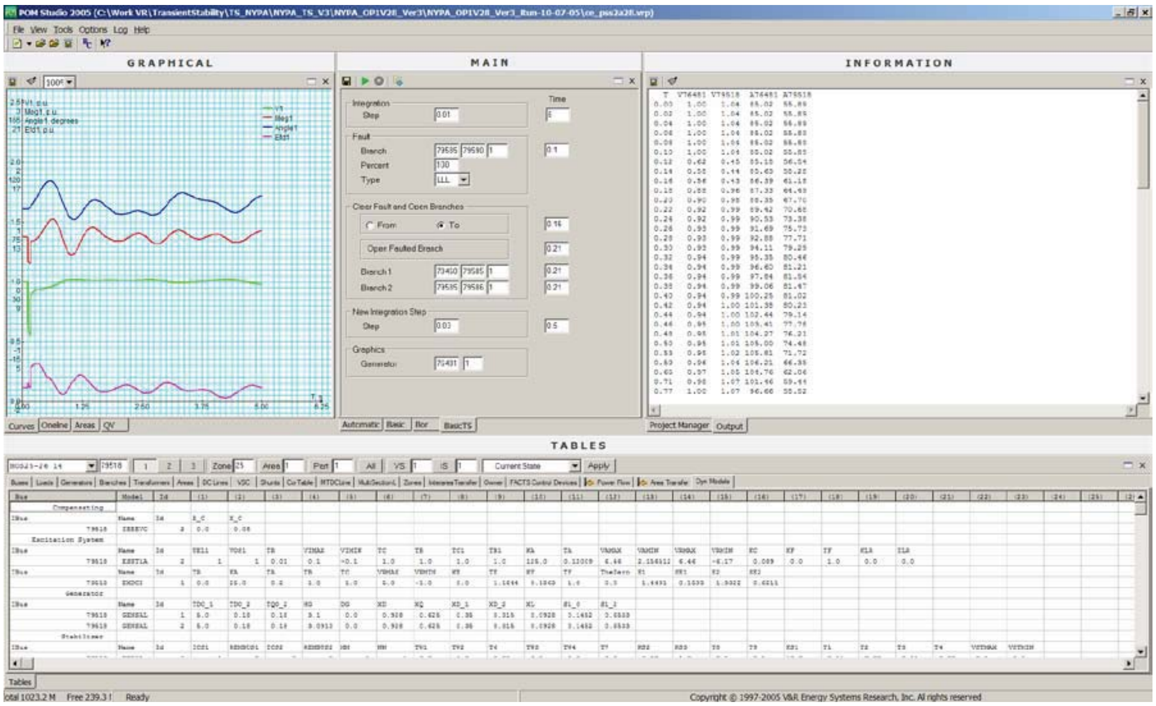


Figure 8-2. POM-TS Interface

A library of standard scripts is provided with POM-TS.

POM-TS allows the user to perform massive fault analysis using conventional time-domain simulation. From hundreds to hundreds of thousands of faults may be applied within one run while performance criteria are monitored.

POM-TS has the capability to simultaneously monitor multiple criteria during massive fault analysis:

- Rotor angle
- Damping
- Voltage dip
- Frequency

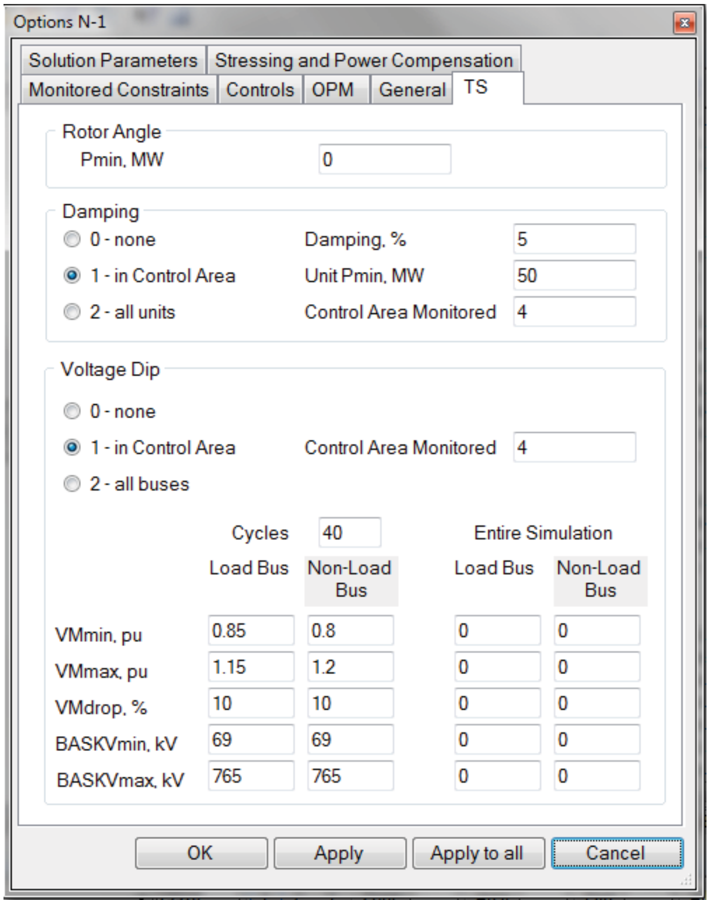


Figure 8-3. Performance Criteria

Three sets of options may be specified in POM-TS for various types of faults in order to meet NERC compliance requirements:

- Faults that do not result in the loss of components;
- Faults resulting in the loss of a single component;
- Faults resulting in the loss of two or more components.

POM-TS offers the capability to simulate balanced and unbalanced faults:

- Three-phase, double line-to-ground, line-to-ground, line-to-line faults may be simulated.
- Critical clearing time is easily determined.
- Simultaneous events at multiple buses or points along a transmission line may be simulated.
- Any sequence of switching events may be specified within the same simulation run.
- Any system quantities may be selected as an output and can be displayed graphically.
- Database output - reporting of "critical" faults that cause criteria violations.

POM-TS works in four modes:

- BasicTS
- Script
- AutomaticTS
- Fast Fault Screening

For each fault applied in BasicTS, a corresponding script is generated and displayed. Scripts can be further modified and re-used.

NYPA and LIPA engineers applied several faults and obtained results using Siemens PTI's PSS/E. The same faults were applied by V&R engineers using POM-TS. The results were then benchmarked.

Comparison showed that POM-TS and PSS/E results were close. Nevertheless, the execution time for POM-TS was several times faster. Figure 8-4 shows angle (left screen) and terminal voltage (right screen) comparison, where:

- Left screen: black plot is drawn by PSS/E and blue plot is drawn by POM-TS.
- Right screen: black plot is drawn by PSS/E and green plot is drawn by POM-TS.

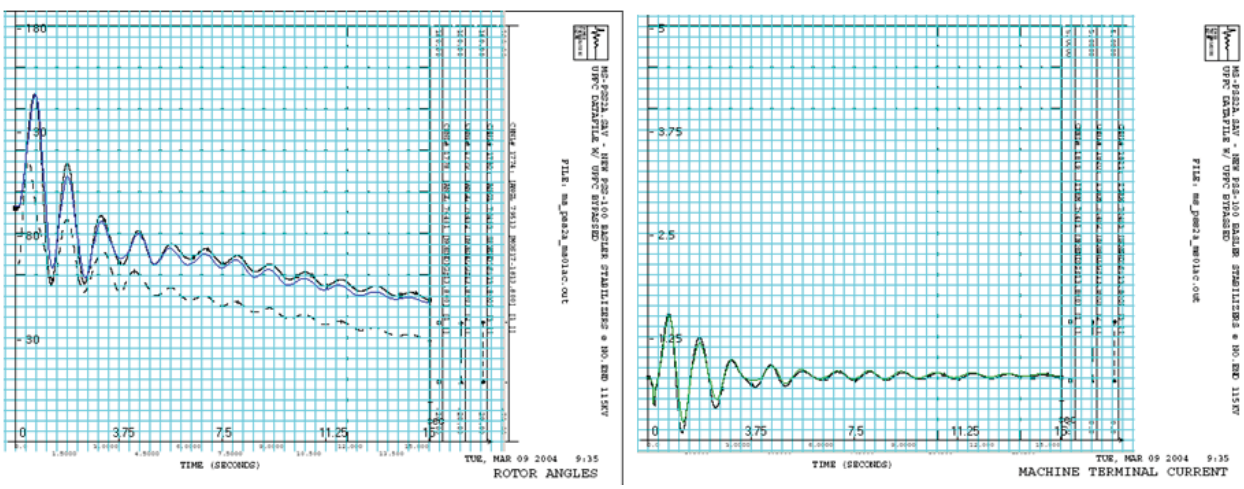


Figure 8-4. POM-TS and PSS/E Results

POM-TS version 4 was used during the present project as the basis for Fast Fault Screening functionality.

APPENDIX B

EXECUTING THE FFS

This section describes how to run the FFS capability from POM Suite of Applications.

9.1 FFS Input Files

All input/output data for a single body of work is organized as a Project in POM.

Files can be located anywhere on the hard drive but organized as one project in POM Project Manager. POM Project Manager is accessible through the Project Manager Tab in the INFORMATION Pane.

Both POM and POM-TS input files are required when working with FFS.

POM input files are accessible through the Input folder of the Project Manager.

POM-TS input files are accessible through the TS folder of the Project Manager.

POM and POM-TS input files should be bound to the corresponding Items of the Input and TS folders, respectively.

POM and POM-TS input files may be viewed within the POM interface. Files are opened in the MAIN Pane using a built-in file editor.

Changes to the files can be made and saved in the POM MAIN Pane. The project must be reloaded for the changes to take effect.

9.2 FFS Tab

To open Fast Fault Screening capability, click FFS Tab in the MAIN Pain or select FastFaultScreening item from the View Menu. FFS Tab is shown in Figure 9-1.

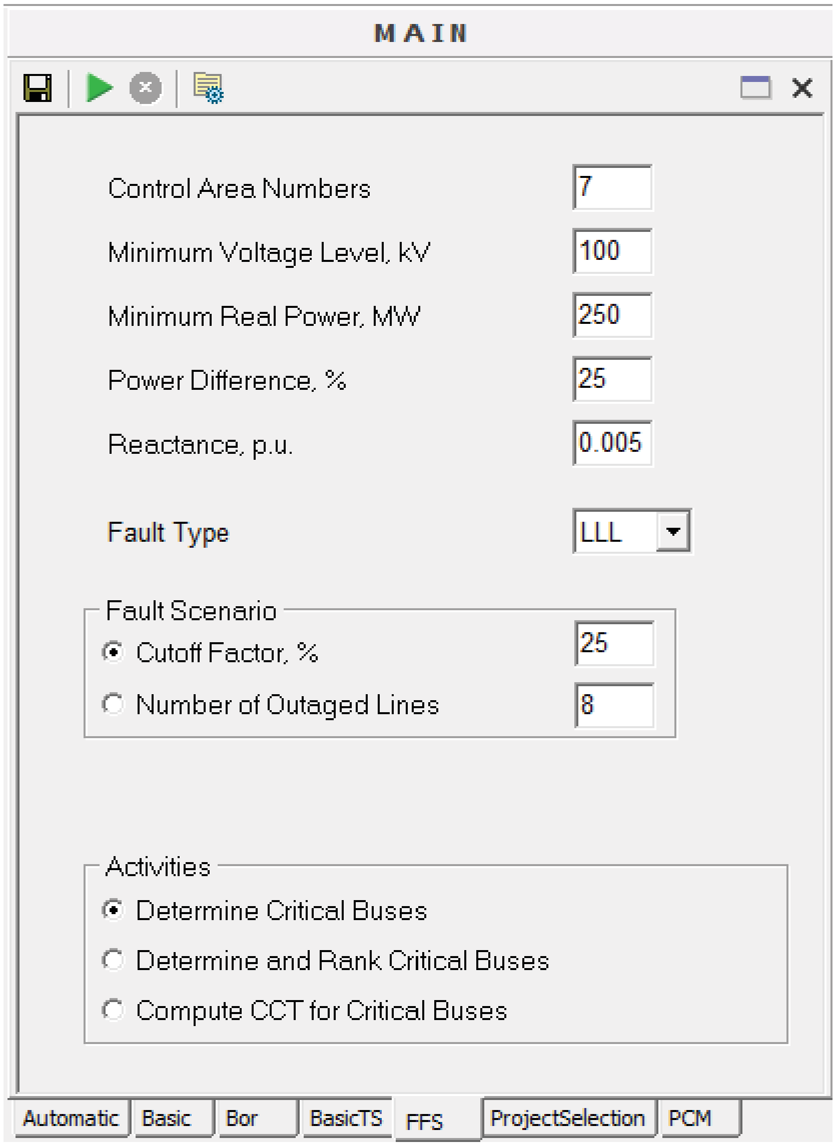


Figure 9-5. FFS Tab

FFS Tab consists of FFS Tab toolbar, FFS options, and Activities. The options offer the control over the FFS analysis.

9.3 FFS Tab Toolbar

FFS Tab toolbar is shown in Figure 9-2.

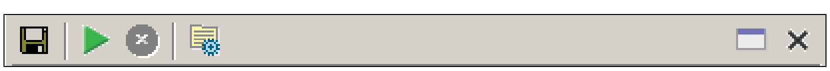
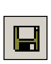


Figure 9-6. FFS Tab Toolbar

The options available from the toolbar are:

 Save Settings button

Click on the button to save values entered in the FFS Tab to a settings file (*.ini).

Execute button

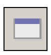
Click on the button to execute FFS capability.

Stop button

Click on the button to interrupt FFS computations.

Show Script button

Click on the button to enable the “echo” function and view the script that is used to execute the FFS capability. The user can copy this script, modify it and reuse it.



View as Window button

Click on the button to make the Tab “floating” above the rest of the interface.

Close button

Click on the button to close the Tab.

9.4 FFS Options

Options needed to perform FFS analyses are specified in the FFS Tab (see Figure 9-1).

There are seven FFS options, as shown in Figure 9-3.

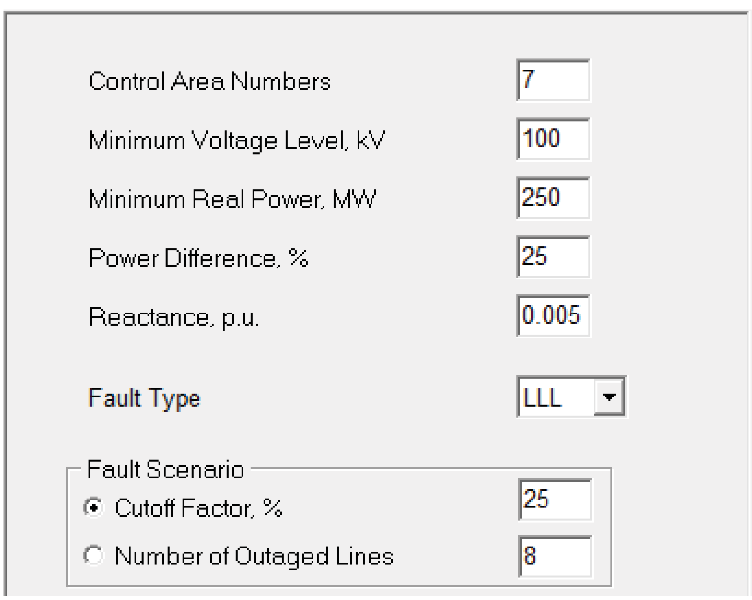


Figure 9-7. FFS Options

The FFS options are:

- Control Area Number

  Control area number, in which fast fault screening is performed.

- Minimum Voltage Level, kV

  Voltage class of buses that are considered in FFS analysis.

- Minimum Real Power, MW

  The value of the real power flow on the lines connected to a bus. Only flows on transmission lines are accounted for; flows on transformers are not considered.

  This is the real power flow that flows from the bus (i.e., leaves the bus).

- Power Difference, %

  The difference between real (MW) flow at a bus (i.e., entering a bus) and generator real power in the vicinity of this bus.

- Reactance, p.u.

  Branch reactance limit. Only branches with the value of reactance equal or greater than the value entered in this field are considered when using Fault Selection Criterion (see Section 4.2.4). Branches with the value of reactance less than the value entered in this field are not considered. The value is used to account for circuit breakers.

- Fault Type

  Specifies fault type:

  LLL - three-phase fault

  LG - - line-to-ground fault

  LL - line-to-line fault

  LLG - double line-to-ground fault

- Fault Scenario

  The option is used to account for substation configuration and fault scenario.

  - Fault Scenario: Cutoff Factor, %

    A fraction of the power leaving a bus, which is being outaged during a fault simulation.

  - Fault Scenario: Number of Outaged Lines

    The number of lines that are being outaged during a fault simulation.

9.5 FFS Activities

Three activities are available within the FFS analyses. The FFS activities are shown in Figure 9-4.

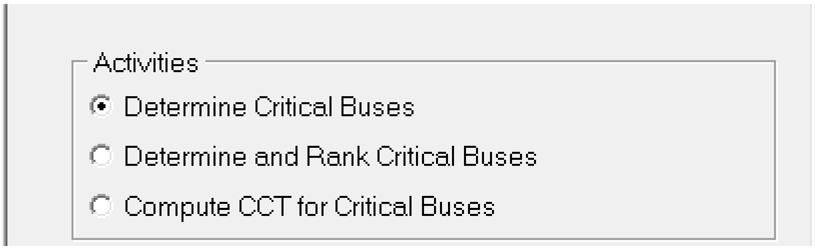


Figure 9-8. FFS Activities

The activities are:

- Determine Critical Buses
- Determine and Rank Critical Buses
- Compute CCT for Critical Buses

9.5.1 Activity "Determine Critical Buses"

Activity "Determine Critical Buses" determines the most severe fault locations based on the fault selection criterion listed in Section 4.2.4. The output of this activity is the list of the most severe LLL faults. These are the most severe fault locations. The activity creates a file *List FFS Lines.csv*. A sample file *List FFS Lines.csv* is shown in Figure 9-5.

N	Bus Number	Outaged Lines	Power Flow on Outaged Lines (MW)
1	9580	RemoveBranch 7845	783.36
2	9581	RemoveBranch 7958	590.7
3	9582	RemoveBranch 7541	226.93
4	9583	RemoveBranch 7666	191.98
5	9584	RemoveBranch 7959	91.33
		RemoveBranch 7959	91.33
6	9585	RemoveBranch 7671	180.17
		RemoveBranch 7671	163.87
7	9586	RemoveBranch 7671	160.28

Figure 9-9. File "*List FFS Lines.csv*"

The file shows the buses that are the most severe LLL fault locations, as well as the branches that are being outaged as a part of the fault scenario.

9.5.2 Activity “Determine and Rank Critical Buses”

Activity “Determine and Rank Critical Buses” determines the most severe fault locations based on the fault selection criterion listed in Section 4.2.4 and ranks them based on the RI given in the Section 4.4.2.

The output of this activity consists of the files:

- File *List FFS Lines.csv* (see Section 9.5.1)

  The file shows locations of the most severe LLL faults.

- File *ListFaultBusesCCT.csv*

  The file shows the ranking of the most severe faults based on the Ranking Index, RI (see Section 4.2.4).

A sample file *ListFaultBusesCCT.csv* is shown in Figure 9-6.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
N	Bus Nun	us Nan	us Base	PowOu	PowIn	GenPowe	GenPower	Nlink	igenValu	KE	MDrop	VDrop	RI
1	9580	JA FIT	345	843.8	0	875	875	3	1.0612	0.5682	0.0251	0.2107	**2.3537**
2	9581	NIAG	230	562.8	129.5	2115	715	12	0.9997	0.5687	-0.174	0.1419	**1.4144**
3	9582	NIAG	230	358.5	0	755	755	10	1.0031	0.5763	-0.169	0.1399	**1.4129**
4	9583	NIAG	345	775.2	0	755	0	7	1.0624	0.374	-0.042	0.1138	**1.2585**
5	9584	NIAG	115	767.6	0	1495	780	12	1.0066	0.7893	-0.292	0.1162	**1.224**
6	9585	NIAG	115	454.9	0	645	645	7	1.0018	0.785	-0.524	0.1409	**1.125**
7	9586	MOS	115	420.8	0	456	0	14	0.8376	0.6668	-0.499	0.1219	**0.7401**

Figure 9-10. File *ListFaultBusesCCT.csv*: “Activity Determine and Rank Critical Buses”

The faults are sorted by their severity, with the most severe fault listed at the top of the file. A higher value of the RI corresponds to a more severe fault.

9.5.3 Activity “Compute CCT for Critical Buses”

Activity “Compute CCT for Critical Buses” automatically computes the critical clearing time (CCT) for critical buses that were identified by activity “Determine Critical Buses” (see Section 9.5.1). This activity also ranks the most severe fault locations based on the RI (see Section 4.2.4). The output of this activity consists of the files:

- File *List FFS Lines.csv* (see Section 9.5.1)

  The file shows locations of the most severe LLL faults.

- File *ListFaultBusesCCT.csv*

  The file shows the ranking of the most severe faults based on the Ranking Index, RI (see Section 4.2.4 and the critical clearing time for each fault.

A sample file *ListFaultBusesCCT.csv* is shown in Figure 9-7.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
N	Bus Nun	us Nan	us Base	PowOut	PowIn	3enPowe	enPowe	Nlink:	EigenValu	KE	MDrop	VDrop	RI	CCT
1	9580	JA FIT	345	843.79	0	875	875	3	1.0612	0.5682	0.0251	0.2107	2.3537	0.09
2	9581	NIAG.	230	562.82	129.54	2115	715	12	0.9997	0.5687	-0.1736	0.1419	1.4144	0.16
3	9582	NIAG.	230	358.46	0	755	755	10	1.0031	0.5763	-0.1689	0.1399	1.4129	0.17
4	9583	NIAG	345	775.2	0	755	0	7	1.0624	0.374	-0.0415	0.1138	1.2585	0.19
5	9584	NIAG:	115	767.62	0	1495	780	12	1.0066	0.7893	-0.2923	0.1162	1.224	0.19
6	9585	NIAG:	115	454.87	0	645	645	7	1.0018	0.785	-0.5236	0.1409	1.125	0.19
7	9586	MOS :	115	420.77	0	456	0	14	0.8375	0.6668	-0.4991	0.1219	0.74	0.2

Figure 9-11. File *ListFaultBusesCCT.csv*: Activity "Compute CCT for Critical Buses"

The faults are sorted by their severity, with the most severe fault listed at the top of the file. A higher value of the RI corresponds to a more severe fault, e.g., a fault with the smaller critical clearing time.

9.6 Executing the FFS Capability

To execute the FFS capability in POM Suite ver. 4, enter the desired values in the FFS Tab fields (see Section 9.2), and click on the  button on the FFS Tab toolbar.

The list of buses, identified by FFS as locations of the most severe faults, is displayed in the Output Tab of the INFORMATION Pane (see Figure 9-8).

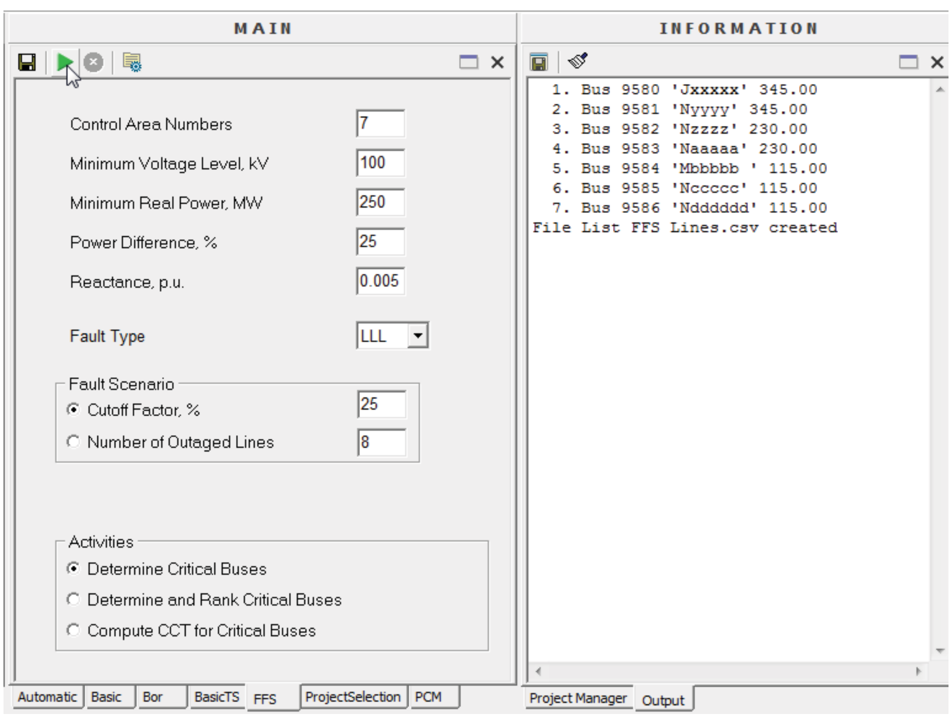


Figure 9-12. Executing FFS

Detailed information about each bus and fault ranking using the RI (see Section 4.3) is written to the output files (see Section 10.3).

9.7 FFS Item of the Project Manager

FFS Item of the Project Manager contains FFS output files.

FFS outputs the following files:

- File *List FFS Lines.csv* upon execution of activities "Determine Critical Buses" (see Section 9.5.1), "Determine and Rank Critical Buses (see Section 9.5.2), and "Compute CCT for Critical Buses" (see Section 9.5.3).
- File *ListFaultBusesCCT.csv* upon execution of activities "Determine "Determine and Rank Critical Buses (see Section 9.5.2), and "Compute CCT for Critical Buses" (see

  Section 9.5.3).

The files are saved in the same directory that the power flow case resides.

Once execution of the FFS capability is repeated, POM replaces the existing output file with new data. It is the user's responsibility to ensure that files that are needed for future reference or computations are not overwritten.

You can access the output files through the FFS folder of the Project Manager (see Figure 9-9).

The output files are described in Section 10.2 of this Specification.

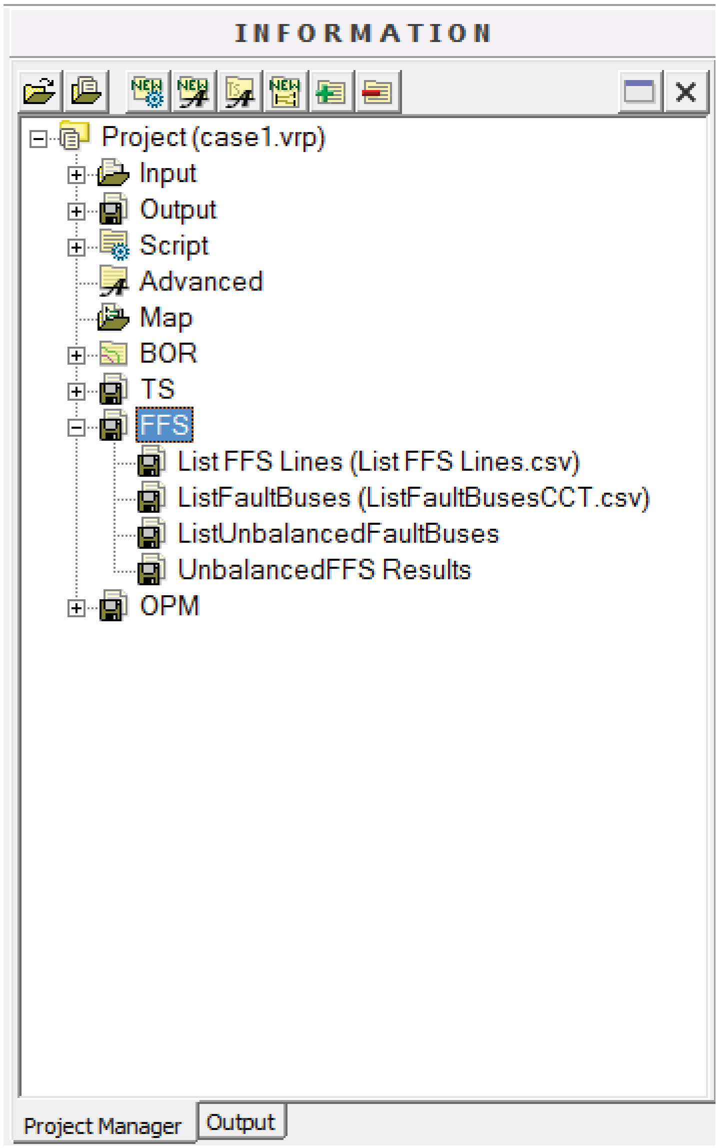


Figure 9-13. FFS Folder of the POM Project Manager

APPNEDIX C

FFS OUTPUT

This section describes results of determining and ranking the most severe faults.

Progress of the FFS computations and a list of the most severe fault locations are displayed in the Output Tab of the INFORMATION Pane.

Upon completing computations, the FFS generates output files. Output files are saved in the same directory that the power flow case resides.

10.1 Output Tab of the INFORMATION Pane

The Output Tab of the INFORMATION Pane shows the progress of reading POM and POM-TS input files, as well as the progress of FFS computations and a list of the most severe fault locations.

10.1.1 Output Tab Toolbar

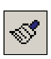
The Output Tab toolbar is shown in Figure 10-1.

Figure 10-1. Output Tab Toolbar

The options available from the toolbar are:

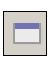
Save Output button

Click on the button to save the contents of the Output Tab to a file.



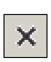
Clear button

Click on the button to clear the contents of the Output Tab.



View as Window button

Click on the button to make the Tab “floating” above the rest of the interface.



Close button

Click on the button to close the Tab.

10.1.2 Displaying Results in the Output Tab during Execution of the Activity “Determine Critical Buses”

When activity “Determine Critical Buses” is executed, the Output Tab shows results of identifying the most severe fault locations. Locations of the most severe faults are determined using the Fault Selection Criterion as described in Section 4.2.4.

The following information is displayed in the Output Tab during FFS analysis (see Figure 10-2).

- Consecutive number of a severe fault location.
- Number of a bus identified by FFS as a severe fault location as given in the power flow case.
- Name of a bus identified by FFS as a severe fault location as given in the power flow case.
- Base voltage of a bus identified by FFS as a severe fault location as given in the power flow case.

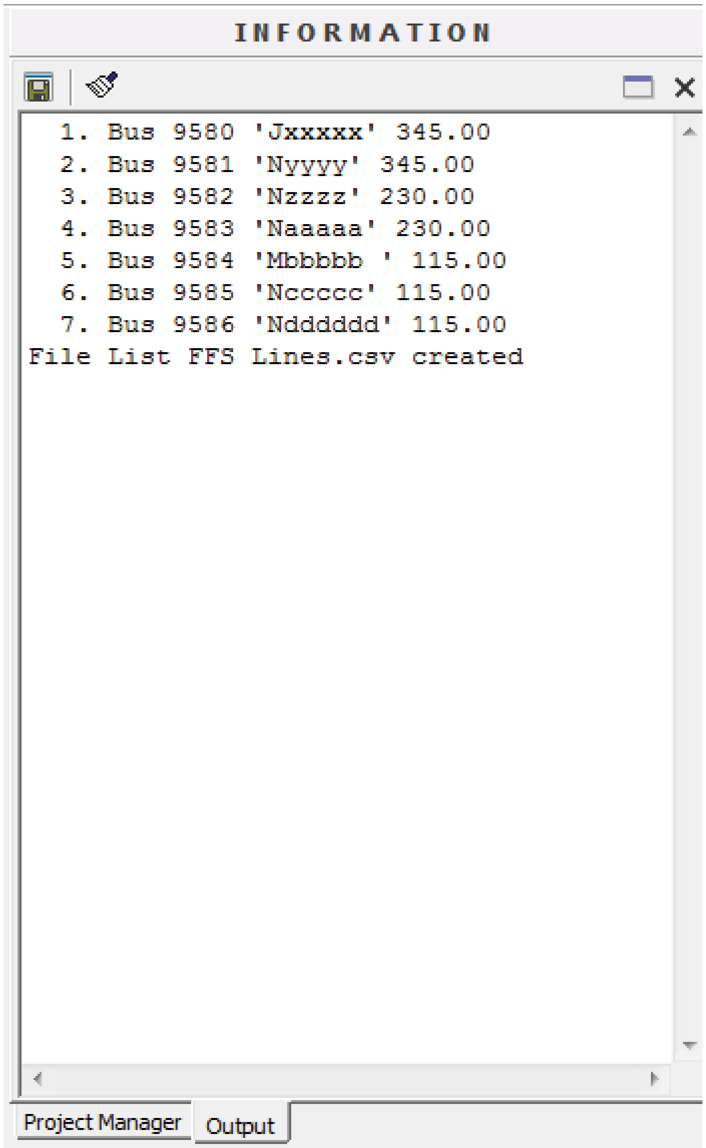


Figure 10-2. Output Tab during Execution of Activity "Determine Critical Buses"

A message stating that the file *List FFS Lines.csv* has been created follows the list of critical buses.

10.1.3 Displaying Results in the Output Tab during Execution of the Activity "Determine and Rank Critical Buses"

When activity "Determine and Rank Critical Buses" is executed, the Output Tab shows results of identifying the most severe fault locations. Locations of the most severe faults are determined using the Fault Selection Criterion as described in Section 4.2.4.

The same information as described in Section 10.1.2 is shown during the execution of activity "Determine and Rank Critical Buses".

Messages stating that the files *List FFS Lines.csv* and *ListFaultBusesCCT.csv* have been created follow the list of critical buses (see Figure 10-3).

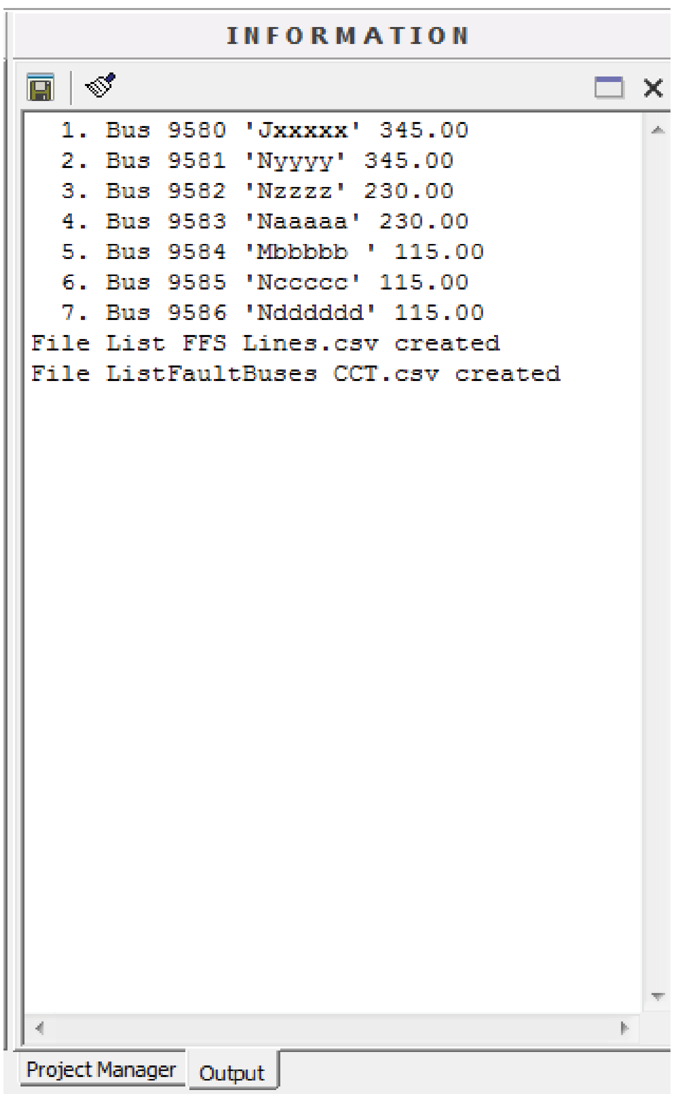


Figure 10-3. Output Tab during Execution of Activity "Determine and Rank Critical Buses"

10.1.4 Displaying Results in the Output Tab during Execution of the Activity "Compute CCT for Critical Buses"

When activity "Compute CCT for Critical Buses" is executed, the Output Tab shows results of identifying the most severe fault locations. Locations of the most severe faults are determined using the Fault Selection Criterion as described in Section 4.2.4.

The same information as described in Section 10.1.3 is shown during the execution of activity "Determine and Rank Critical Buses".

Messages stating that the files *List FFS Lines.csv* and *ListFaultBusesCCT.csv* have been created follow the list of critical buses. Critical clearing time for each critical bus is displayed following these messages.

10.1.5 Saving the Contents of the Output Tab

The contents of the Output Tab may be saved to a file by clicking on the Save Output button on the Output Tab toolbar (see Figure 10-4).

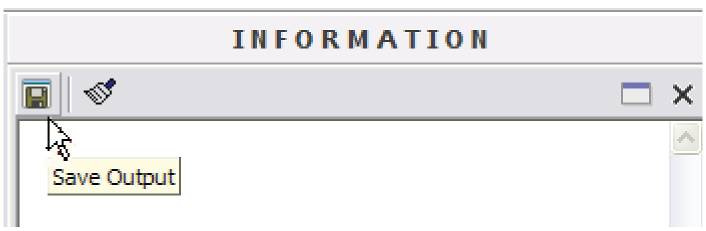


Figure 10-4. Saving Contents of the Output Tab

Clicking on the Save Output button in the Output Tab toolbar displays the **Save As** dialog box. Select a drive or folder in the **Save in** drop-down box where the contents of the Output Tab will be saved. Enter the file name in the **File name** drop-down box and click on the **Save** button.

The saved file can be exported to a ***Fixed width*** MS Excel file. To do this, open MS Excel, select *File>Open* from the Main Menu and follow Text Import Wizard for ***Fixed width*** file type.

The output file will be displayed as an MS Excel spreadsheet.

10.2 The *List FFS Lines.csv* File

The *List FFS Lines.csv* file is saved in the same directory that the power flow case resides.

The *List FFS Lines.csv* file contains information on the branches that are being outaged as a part of the fault scenario. The file *List FFS Lines.csv* is shown in Figure 9-5.

The following information is written to the *List FFS Lines.csv* file for each severe fault location:

- N

  Consecutive number of a bus identified by FFS as a severe fault location.

- Bus Number

  Number of a bus identified by FFS as a severe fault location as given in the power flow case.

- Outaged Lines

  Branches that that are being outaged as a part of the fault scenario

- Power Flow on Outaged Lines (MW)

  Real power flowing on the outaged lines.

10.3 The ***ListFaultBusesCCT.csv*** File

The *ListFaultBusesCCT.csv* file is saved in the same directory that the power flow case resides.

The *ListFaultBusesCCT.csv* file contains information on ranking the most severe faults using the RI index (see Section 4.3).

Thus, detailed information about each bus identified by FFS capability as a severe fault location, and its ranking using the RI is written to the *ListFaultBusesCCT.csv* file. The file is shown in Figure 9-6 and Figure 9-7.

The *ListFaultBusesCCT.csv* file is automatically bound to the *ListFaultBuses* Item of the FFS folder of the Project Manager (see Section 9.7).

The entries in the file are sorted by the value of RI. The entries are sorted in descending order. Thus, fault locations are shown in the order of severity with the most severe fault shown at the top of the file.

The following information is written to the *ListFaultBusesCCT.csv* file for each severe fault location:

- N

  Consecutive number of a bus identified by FFS as a severe fault location.

- Bus Number

  Number of a bus identified by FFS as a severe fault location as given in the power flow case.

- PowOut

  Real power leaving a bus, where fault is applied (see Section 4.2.4).

  PowOut includes only flows on transmission lines.

- PowIn

  Real power entering a bus, and flowing on lines (see Section 4.2.4).

- GenPower

  Real power output of generators located one and two buses away from a bus where fault is applied, (see Section 4.2.4).

- GenPower1

  Real power output of generators located one bus away from a bus where fault is applied, (see Section 4.2.4).

- Nlinks

  The number of connections (see Section 4.2.1).

- Eigenvalue

  The ratio of $EigenValue_{POSTF}$ and $EigenValue_{PREF}$, $\frac{EigenValue_{POSTF}}{EigenValue_{PREF}}$, as given in Section 4.3.2.

- KE

  The kinetic energy of a generator with the largest value of kinetic energy located in the vicinity of the fault, as given in Section 4.3.2.

- MDrop

  The ratio of M_{ePOSTF} and M_{ePREF}, $\frac{M_{ePOSTF}}{M_{ePREF}}$, as given in Section 4.3.2.

- VBus

  The difference between V_{PREF} and V_{gen}, $(V_{PREF} - V_{gen})$, as given in Section 4.3.2.

- RI

  The Ranking Index. The ranking Index is discussed in Sections 4.3 and 4.4.

- CCT

  The critical clearing time.

  The critical clearing time is computed when the activity " Compute CCT for Critical Buses" is executed.

The values entered in the columns **PowOut**, **PowIn**, **GenPower**, **GenPower1**, and **Nlinks** are used to select the most severe fault locations using the Fault Location Criterion (see Section 4.2.4).
The values entered in the columns **Eigenvalue**, **KE**, **MDrop**, and **VBus** are used to rank the most severe fault locations (see Section 4.3.2).

The value entered in the column **RI** is the value of the Ranking Index (see Section 4.3).

For information on other
NYSERDA reports, contact:

New York State Energy Research
and Development Authority
17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
www.nyserda.org

Fast Fault Screening for Real-Time Transient Stability Assessment

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