9th International Conference on Probabilistic Methods Applied to Power Systems
KTH, Stockholm, Sweden – June 11-15, 2006

Contingency Simulation Using Single Phase Quadratized Power Flow

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***Abstract* -- Contingency simulation is an essential but computationally demanding procedure for power system security assessment, reliability evaluation, and real time operation. Simulation methods based on the traditional power flow (TPF) model usually suffer from lack of the realistic system model and slow convergence. To solve such problems, this paper proposes a contingency simulation methodology based on a single phase quadratized power flow (SPQPF) model that integrates the compensation method and sparsity techniques. Two major advantages of the SPQPF model exist in its ability to model realistic system component characteristics and its superior performance in achieving faster convergence, which are important to simulate contingencies realistically and efficiently. In the proposed framework, a hybrid contingency selection technique is applied first to categorize system contingencies into two classes: (1) contingencies that cause system linear changes and (2) contingencies that cause system nonlinear changes or discontinuities. The first class constitutes the majority of contingencies while the second class includes only a small portion of contingencies. For contingencies in class 1, the very first iteration of SPQPF can provide satisfactory solutions due to its faster convergence feature, compared to the several iterations generally required by TPF. To further reduce the computational effort, a sparse oriented compensation method that performs the first iteration is developed based on the SPQPF model. For the second class of contingencies, a quasi compensation iterative method is developed to analyze contingencies with high efficiency and acceptable accuracy. The proposed methodology is able to simulate the post contingency situation efficiently in a realistic manner and provide a good balance between efficiency and accuracy in the procedure of contingency simulation. Its performance is demonstrated with IEEE reliability test systems.**

***Index Terms* -- Compensation method, contingency simulation, hybrid contingency selection technique, quasi compensation iterative method, single phase quadratized power flow, sparsity technique.**

I. Introduction

CONTINGENCY simulation is an essential procedure for power system security assessment, reliability evaluation, and real time operation. It is important that simulation methods solve the post contingency situation realistically. Also, because of the large number of system contingencies, solution methods must be efficient with acceptable accuracy.

The most straightforward simulation method is to run AC power flow using the iterative algorithm for each contingency [1, 2]. Although it provides accurate power flow solutions, this procedure, which involves a huge number of AC load flow calculations, is extremely costly from the computational point of view. To reduce the computational effort required for contingency simulations, some techniques have been developed in past several decades. These techniques include mainly subnetwork solutions, contingency ranking/screening methods, compensation methods, sparsity techniques, approximate load flow algorithms, and so on.

Subnetwork solutions, such as bounding methods [3, 4], consider mainly the most stressed portion of the system instead of the whole network. A reduced local system model is solved, and a subset of state variables is obtained. The performance of such methods depends upon the proper selection of the severely impacted area and the consideration of effects from the rest of the system. In contingency ranking/screening techniques [5-7], the number of power flows to be performed is limited by selecting only the most severe contingencies. It is recognized that contingency ranking, although fast, is prone to misranking while screening, although accurate, is not efficient by wasting time in solving non-critical contingencies [8]. The compensation method [9] is based on the well-known matrix inversion lemma, by which the pre-contingency power flow solution is utilized to minimize the computational effort for the post contingency solution. Some approximate load flow algorithms, such as DC load flow [2], fast decoupled load flow [13], and linear approximate load flow [12], are also developed to solve contingencies with less computational burden.

Most of these existing techniques were developed based on the traditional power flow (TPF) model, which generally suffers from lack of the realistic system model and slow convergence. Specifically, the TPF model uses simplified generator models and load features, and the solution procedure generally takes several iterations for the TPF to meet accuracy criteria. Therefore, when solving a large number of system contingencies, these techniques result in a heavy computational burden [14].

This paper proposes a contingency simulation methodology based on the single phase quadratized power flow (SPQPF) model that integrates the compensation method and sparsity techniques. A significant advantage of the SPQPF model exists in its ability to model realistic generator and load characteristics, which makes the simulation more realistic.

This work was supported in part by the Power Systems Engineering Research Center (PSERC). Authors are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250.

Also, because the SPQPF formulation includes only linear or quadratic equations, for which Newton's method is ideally suitable to solve, it has superior performance in achieving faster convergence. In the proposed methodology, a hybrid contingency selection technique can be applied first to categorize contingencies into two classes: (1) contingencies that cause system linear changes and (2) contingencies that cause system nonlinear changes or discontinuities. The first class constitutes the majority of contingencies and the second class includes only a small portion of contingencies. For contingencies in the first class, the very first iteration of SPQPF can provide satisfactory results due to its faster convergence characteristic, compared to the several iterations generally required by TPF. To further improve the efficiency, the compensation method and sparsity techniques based on the SPQPF model are developed to reduce the computational effort in the first iteration. Therefore, in the SPQPF framework, only one iteration of the compensation method is needed for most contingencies; while considering the compensation method based on the TPF model, its effectiveness in improving the efficiency is taken away by the slow convergence of TPF. For contingencies in the second class, a quasi compensation iterative method is developed to solve SPQPF with high efficiency and acceptable accuracy. The proposed methodology is able to simulate the post contingency situation efficiently in a realistic manner and provide a good balance between efficiency and accuracy in the contingency simulation. Its performance is demonstrated with two IEEE reliability test systems.

II. METHODOLOGY

This section describes the proposed contingency simulation methodology in detail. The implementation of the hybrid contingency selection method, the single phase quadratized power flow model, the sparse oriented compensation method, and the quasi compensation iterative method are illustrated below.

A. Hybrid Contingency Selection Technique

The hybrid contingency selection technique [15] is a computationally efficient algorithm that can be utilized to separate the entire set of system contingencies into two classes: (1) contingencies that cause system linear changes and (2) contingencies that cause system nonlinear changes or discontinuities.

This classification procedure is achieved based on the concept of the contingency stiffness index to identify nonlinear contingencies and a performance index method to identify contingencies that cause discontinuities. The contingency stiffness index represents the maximum disturbance at buses directly affected by a contingency, which is normalized by the bus equivalent admittance. Contingencies with stiffness index values higher than a pre-determined threshold are classified as contingencies that cause system nonlinear changes. In addition, discontinuities in the power systems may arise from (1) reactive power capability limits of generating units and (2) tap limits of regulating transformers. The identification of the contingencies that may cause system discontinuities is based on two performance indices defined to indicate if the reactive power generation or transformer taps at one or more buses exceeding the limits. These two types of contingencies that cause nonlinear system changes or discontinuities are categorized as the second class and all remaining contingencies fall into the first class.

Tests of the hybrid contingency selection method on large systems indicate that the first class includes the majority of contingencies, and the second class usually constitutes a small portion of the total number of contingencies. Taking advantage of this fact, the proposed contingency simulation methodology applies different techniques to solve contingencies in class 1 and 2 separately. In this way, a good balance between accuracy and efficiency can be achieved in the contingency simulation procedure.

B. Single Phase Quadratized Power Flow

In the proposed contingency simulation method, an advanced power flow model, i.e., the single phase quadratized power flow (SPQPF) model [16], is applied as a basis for performing the contingency simulation. In order to illustrate the characteristics of the SPQPF model, a comparison between the traditional power flow model and the SPQPF model is provided below.

The traditional power flow model consists of real and reactive power balance equations at each bus in the system. These equations are expressed in terms of system states in polar coordinates (bus voltage magnitudes and phase angles), and nonlinear trigonometric terms appear in the formulated equations inevitably. In addition, most system loads are induction machine loads, and their models contain relatively high-order nonlinear terms. Consequently, the conventional power flow formulation results in a set of very complex and highly nonlinear equations. When iterative methods, such as Newton-Raphson method, are used to solve such problem, the solution procedure may require many iterations and in some cases, it is hard to find the solution [14].

The single phase quadratized power flow model, however, is set up based on the application of the Kirchhoff's current law at each bus, with the intention that most of the resulting power flow equations are linear in the large-scale system. Also, system state variables (bus voltage phasors) are expressed in Cartesian coordinates (real and imaginary parts of bus voltages) that avoid trigonometric terms. As trigonometric functions are absent, power flow equations become less complex. Moreover, since Newton's method is ideal for solving quadratic equations, all power flow equations are further quadratized, i.e., the power flow model is expressed with the equations of order no greater than two. This can be achieved by the introduction of additional state variables and corresponding equations, which reduce any nonlinear terms with order higher than 2 in power flow equations. As a result, all power flow equations are linear or quadratic and can be written in the following compact format:

$$f(x) = Ax + x^T Bx + b = 0\,, \qquad (1)$$

where

- x column vector of system state variables
- A two dimensional matrix storing the coefficients of linear terms in all power flow equations
- B three dimensional matrix storing the coefficients of quadratic terms in all power flow equations
- b column vector including all known system constants,

Based on above analysis, the formulation of the quadratic power flow model is able to provide superior performance in two aspects: (a) faster convergence and (b) ability to model complex generator and load characteristics in the quadratized form. Such merits of the SPQPF model make the contingency simulation procedure more practical and cost-effective from a computational point of view.

C. Sparse Oriented Compensation Method Based on SPQPF

The compensation method is developed based on a well-known result in matrix algebra, the Sherman Morrison formula (otherwise known as the matrix inversion lemma), to minimize the computational burden for post contingency analysis. By applying the matrix inversion lemma, the compensation method is able to utilize the pre-contingency solution as well as the outage component information to update the solution in the process of solving the post contingency situation. Results obtained by the compensation method are completely accurate, and this procedure is more efficient than the usual reformulating and re-factorizing the post contingency system Jacobian matrix as performed in other methods. The compensation method based on the traditional power flow (TPF) model, such as the fast decoupled power flow, has been explored [16]. However, due to the slow convergence of the TPF, the effectiveness of the compensation method in improving solution efficiency is taken away by the multi-iteration procedure generally required by TPF.

In this work, the compensation method based on the SPQPF model is developed. Due to the faster convergence characteristic of SPQPF, for most contingencies that cause system linear changes, only one iteration of SPQPF is capable of providing satisfactory contingency solution. Hence, it can fully take advantage the high efficiency of the compensation method. In addition, sparse techniques based on the SPQPF model can further reduce the computational effort required by the compensation method. The development of the sparse oriented compensation method based on SPQPF is described in detail next.

When Newton's method is used to solve power flow problems, in each iteration, the major computational task is to solve linearized power flow equations. For the SPQPF model, linearized power flow equations can be obtained by linearizing the SPQPF equation (1) around certain operating point x_0:

$$\begin{aligned} f(x) &\cong Ax_0 + x_0^T Bx_0 + b + \frac{df}{dx}\Big|_{x_0} \Delta x \\ &= f(x_0) + J\Delta x = 0 \end{aligned} \tag{2}$$

In (2), J is the system Jocabian matrix, where

$$J = A + x_0^T(B + B^T).$$

Consider that the pre-contingency power flow has been solved and assume x_0 is the pre-contingency power flow solution, then

$$\begin{aligned} & f(x_0) = 0 \\ & \Delta x = -J^{-1} f(x_0) = 0\,, \end{aligned} \tag{3}$$

where $f(x_0)$ is the mismatch vector.

For the pre-contingency situation, the matrix J has been computed. Assume that the triangular factorization has been used for the solution, which indicates that lower and upper triangular matrices L and U have been computed for J, where

$$J = LU\,. \tag{4}$$

Such pre-contingency solution information will be used by the matrix inversion lemma to solve post contingency situation. Consider now changes occurring to post-contingency SPQPF equations under three kinds of system component outages, including transmission line outages, transformer outages, and PV/PQ generator outages. Due to the component outage, the system post contingency Jacobian matrix is different from that of pre-contingency, and mismatch values of some SPQPF equations are not zero anymore as in the pre-contingency situation. For example, considering an outage of a transmission line terminated at buses k and m, the Jacobian matrix change ΔJ and the mismatch vector change $\Delta f(x_0)$ based on pre-contingency solutions are

$$\begin{array}{cccccccc} & V_{k,r} & V_{k,i} & & V_{m,r} & V_{m,i} & & \end{array}$$

$$\Delta J = \begin{bmatrix} 0\ \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ & -(\mathrm{g_{km}}+\mathrm{g_{skm}}) & (\mathrm{b_{km}}+\mathrm{b_{skm}}) & \cdots & g_{km} & -b_{km} & & \\ & -(\mathrm{b_{km}}+\mathrm{b_{skm}}) & -(\mathrm{g_{km}}+\mathrm{g_{skm}}) & \cdots & b_{km} & g_{km} & & \\ & 0 & 0 & & 0 & 0 & & \\ \vdots & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ & 0 & 0 & & 0 & 0 & & \\ & \mathrm{g_{km}} & -\mathrm{b_{km}} & \cdots & -(g_{km}+\mathrm{g_{smk}}) & b_{km}+\mathrm{b_{smk}} & & \\ & b_{km} & g_{km} & \cdots & -(b_{km}+b_{smk}) & -(g_{km}+g_{smk}) & & \\ & 0 & 0 & & 0 & 0 & & \\ \vdots & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0\ \cdots & 0\ \cdots & 0 & & 0 & 0 & & 0 \end{bmatrix} \tag{5}$$

and

$$\Delta f(x_0) = \begin{bmatrix} 0 & \cdots & -I_{kr}^0 & -I_{ki}^0 & 0 & \cdots & 0 & -I_{mr}^0 & -I_{mi}^0 & 0 & \cdots & 0 \end{bmatrix}^T,$$

where

$g_{km}, b_{km}, g_{skm}, b_{skm}, g_{smk}, b_{smk}$: transmission line parameters

$I_{kr}^0, I_{ki}^0, I_{mr}^0, I_{mi}^0$: real and imaginary parts of transmission line currents at buses k and m in the pre-contingency situation.

Since the transmission line model is a linear model in the SPQPF framework, the expression of ΔJ does not include the pre-contingency state variables. However, for nonlinear component outages, such as generator or transformer outages, the expression of ΔJ includes the pre-contingency state variable solution information.

The Jacobian matrix and the mismatch vector for the post-contingency situation can be obtained as follows:

$$J' = J + \Delta J$$
$$f(x_0)' = f(x_0) + \Delta f(x_0) = \Delta f(x_0),$$

where
J': post contingency system Jacobian matrix
J : pre-contingency system Jacobian matrix
$f(x_0)'$: mismatch vector due to component outage

Based on (2), linearized SPQPF equations for post-contingency situation is modified using J' and $f(x_0)'$:

$$f(x_0)' + J'\Delta x = 0 \tag{6}$$

The solution of the first iteration can be updated by following equations:

$$\Delta x = -J'^{-1} f(x_0)' = -(J + \Delta J)^{-1} \Delta f(x_0) \tag{7}$$
$$x^{post} = x_0 + \Delta x \cdot$$

Note in (7), $f(x_0)'$ is the vector containing negative current values of the outage component in the pre-contingency situation, and it is available from the pre-contingency solution; ΔJ is a sparse matrix with nonzero entries representing changes in the Jacobian matrix caused by the outage component. ΔJ can be expressed as the multiplication of two matrices, i.e.,

$$\Delta J = CD^T,$$

where
C n by m matrix
D^T m by n matrix, all nonzero entries are 1s.
n dimension of the Jacobian matrix
m number of outage component state variables

Consider, for example, that a transmission line outage occurs, matrices C and D^T can be derived from equation (5) easily:

$$C_{n,4} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -(g_{km} + g_{skm}) & (b_{km} + b_{skm}) & g_{km} & -b_{km} \\ -(b_{km} + b_{skm}) & -(g_{km} + g_{skm}) & b_{km} & g_{km} \\ 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 \\ g_{km} & -b_{km} & -(g_{km} + g_{smk}) & (b_{km} + b_{smk}) \\ b_{km} & g_{km} & -(b_{km} + b_{smk}) & -(g_{km} + g_{smk}) \\ 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 \;\cdots & 0 & 0 & 0 \end{bmatrix}$$

$$D_{4,n}^T = \begin{array}{c} \\ \end{array}\begin{matrix} & V_{k,r} & V_{k,i} & & V_{m,r} & V_{m,i} & \\ \end{matrix}$$
$$D_{4,n}^T = \begin{bmatrix} 0 \cdots & 1 & 0 \cdots & 0 & 0 \cdots & 0 \\ 0 \cdots & 0 & 1 \cdots & 0 & 0 \cdots & 0 \\ 0 \cdots & 0 & 0 \cdots & 1 & 0 \cdots & 0 \\ 0 \cdots & 0 & 0 \cdots & 0 & 1 \cdots & 0 \end{bmatrix}$$

In the compensation method, the matrix inversion lemma is applied to obtain the inversion of the updated Jacobian matrix J'^{-1}:

$$J'^{-1} = (J + CD^T)^{-1} = J^{-1} - J^{-1}C[I_m + D^T J^{-1} C]^{-1} D^T J^{-1}$$

where
I_m : m by m identity matrix.

Substitute the expression of J'^{-1} in (7), the updated solution is obtained as

$$\Delta x = -J'^{-1} f(x_0)' = -\{J^{-1} f(x_0)' - J^{-1}C[I_m + D^T J^{-1} C]^{-1} D^T J^{-1} f(x_0)'\} \cdot \tag{8}$$

In order to calculate Δx based on (8), following substitutions are performed step by step. The expression $J^{-1}C$ is a n by m matrix, and $J^{-1} f(x_0)'$ is a n by 1 vector. Define matrix $\phi_{n,m}$ and vector $\gamma_{n,1}$ such that

$$\phi_{n,m} = J^{-1}C$$
$$\gamma_{n,1} = J^{-1} f(x_0)' \cdot$$

Substitute $\phi_{n,m}$ and $\gamma_{n,1}$ in (8):

$$\Delta x = -\{\gamma - \phi[I_m + D^T \phi]^{-1} D^T \gamma\} \cdot \tag{9}$$

In (9), the expression $D^T\gamma$ is a m by 1 vector, and $I_m + D^T\phi$ is a m by m matrix. Define vector $\alpha_{m,1}$ and matrix $\beta_{m,m}$ such that

$$\alpha_{m,1} = D^T \gamma$$
$$\beta_{m,m} = I_m + D^T \phi \cdot$$

Substitute α and β in equation (9)

$$\Delta x = -\{\gamma - \phi\beta^{-1}\alpha\}. \qquad (10)$$

In (10), the expression $\beta^{-1}\alpha$ is a m by 1 vector. Define vector $\delta_{m,1}$ such that

$$\delta_{m,1} = \beta^{-1}\alpha \;.$$

Substitute δ in equation (10):

$$\Delta x = \phi\delta - \gamma \;. \qquad (11)$$

In summary, the computation of the solution Δx includes following steps:

Step 1. Compute $\phi_{n,m} = J^{-1}C$
Step 2. Compute $\gamma_{n,1} = J^{-1}f(x_0)'$
Step 3. Compute $\beta_{m,m} = I_m + D^T\phi$
Step 4. Compute $\alpha_{m,1} = D^T\gamma$
Step 5. Compute $\delta_{m,1} = \beta^{-1}\alpha$
Step 6. Substitute ϕ, γ, and δ in (11)

In the procedure of solving steps 1 and 2, the sparsity technique based on the SPQPF model is used to improve computational efficiency. Recall that the Jacobian matrix J has been decomposed into the product of a lower triangular matrix (L) and an upper triangular matrix (U) in the procedure of obtaining the pre-contingency solution, as shown in (4). The solution of $\phi_{n,m}$ and $\gamma_{n,1}$ can be obtained with a series of forward and back substitutions. In addition, the optimal ordering scheme based on SPQPF is developed to maximize sparsity benefits [16]. This procedure takes advantage of the sparsity properties of matrix J .

The computational effort and solution time required in the proposed sparse oriented compensation method is analyzed next. Recall that the Jacobian matrix J is already factorized and matrix C is a n by m matrix, step 1 requires m forward and back substitutions for n by n Jacobian matrix. Similarly, since $f(x_0)'$ is a n by 1 vector, step 2 requires one forward and back substitution for the Jacobian matrix. In large scale system, since m is far less than n, the computational effort in steps 3, 4, 5, and 6 are negligible compared to that of steps 1 and 2. As a result, in the proposed compensation method, the solution time to obtain Δx is approximately the execution time for performing $(m+1)$ forward and back substitutions for the n by n Jacobian matrix in general. The number m, which is the number of outage component state variables, varies for different components in the SPQPF framework. For the transmission line or the PV/PQ generator outage, the number m is 4; for the transformer outage, the number m is 6. Therefore, the sparse oriented compensation method requires the solution time of approximately performing 5 or 7 forward and back substitutions for the Jacobian matrix to obtain Δx under transmission line/generator outages or transformer outages, respectively.

A power flow solution speed study is provided in [16], in which the fast decoupled load flow technology is used to solve power flow for a 981 bus, 1862 branch electric power network. The study indicates that the normalized execution time for the formulation and factorization of the matrix B' or B'' is nearly 10 times as much as the execution time for one forward and back substitution for B' or B''. Considering also the one forward and back substitution required to obtain the solution, the fast decoupled power flow algorithm needs the solution time of approximately performing 11 forward and back substitutions for the Jacobian matrix for the specified power system. Moreover, with the system size increasing, the solution time in terms of forward and back substitution increases exponentially, which is far less efficient compared to the sparse oriented compensation method that requires the solution time of performing only 5 or 7 forward or back substations. In addition, the compensation method based on SPQPF requires only one iteration to provide the post contingency solution for most of contingencies, while traditional power flow requires several iterations. Hence, for a large-scale system, the sparse oriented compensation method based on SPQPF can reduce computational effort significantly, and is a highly efficient method for contingency analysis compared to other methods based on the traditional power flow model that requires the reformation and re-factorization of the post contingency Jacobian matrix.

D. Quasi Compensation Iterative Method

For the small group of contingencies that cause system nonlinear changes or discontinuities, more iteration of SPQPF is necessary to guarantee the accuracy of solutions. To improve the solution efficiency, a quasi compensation iterative method is developed to solve the SPQPF. In this method, the Jacobian matrix obtained from the pre-contingency solution is not updated during iterations; only matrix C and related matrices/vectors from steps 1 to 6 are updated in each iteration. In this way, although multi-iterations are performed, the post contingency situation can still be solved with high efficiency as well as acceptable accuracy. For certain contingencies that may require many iterations due to their highly nonlinear or discontinuity influence on the system, they can be solved using the general SPQPF algorithm which updates the Jacobian matrix in each iteration.

III. Case Study

The proposed contingency simulation methodology is demonstrated with IEEE reliability test systems (RTS-79 and RTS-96) [17, 18]. First level independent contingencies of both systems are solved, and solutions illustrate the expected performance. The IEEE 24-bus RTS-79 is shown in Figure 1. For this system, the hybrid contingency selection technique is first used to categorize the first level contingencies into two classes, i.e., (1) contingencies that cause system linear changes and (2) contingencies that cause nonlinear system changes or discontinuities. Contingencies in the first class are solved using the sparse oriented compensation method based on the SPQPF model. Post contingency solutions obtained from the proposed method are verified by the first iteration results of the SPQPF. Compared with the final solutions of SPQPF, the proposed simulation method is able to provide solutions with high accuracy. To illustrate the performance of the compensation method, an example contingency with an outage of the transmission line between buses 10 and 50 is solved by both the proposed method and the SPQPF iterative algorithm. Table 1 provides system bus voltage magnitudes and phase angles obtained from the proposed method, the first iteration of SPQPF, and the final iteration of SPQPF. This example shows that the results of the sparse oriented compensation method based on the SPQPF model are exactly the same as those of the first iteration results of SPQPF, which verifies the correctness of the proposed compensation method. In addition, compared with final solutions of SPQPF, the one iteration results of the proposed method can provide solutions with satisfactory accuracy. The highest bus voltage magnitude and phase angle errors are 0.1584% and 0.0412 degree, respectively.

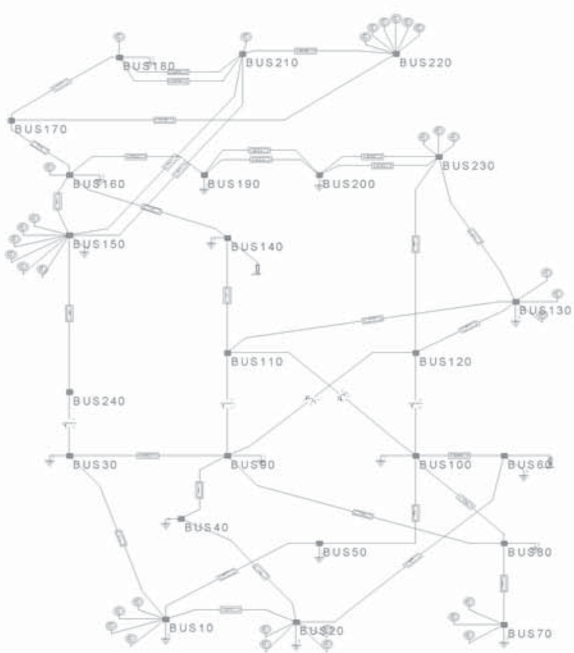

Figure 1. IEEE 24-Bus RTS-79

Table 2 shows that the iteration number increases with the decrease in tolerance. While tolerance is greater than 0.0001, most contingencies in the second class require less than 10 iterations. Certain threshold for the iteration number can be pre-defined and for any contingencies with the iteration number exceeding the threshold, general SPQPF should be applied to solve such contingencies. For example, if the threshold for the iteration number in the quasi compensation iterative method is selected as 10, when the contingency with the outage of the cable between buses 60 and 100 occurs, the iteration number exceeds 10 as the tolerance is less than 0.001, then the general SPQPF algorithm can be applied to solve this contingency.

For the second class of contingencies, the quasi compensation iterative method is applied. Iteration numbers are determined by the pre-defined SPQPF mismatch tolerance. Table 2 shows iteration numbers and corresponding normalized tolerances for contingencies that cause system nonlinear change or discontinuity in the second class.

TABLE 1
SOLUTIONS OF PROPOSED COMPENSATION METHOD, FIRST ITERATION, AND FINAL ITERATION OF SPQPF FOR THE EXAMPLE CONTINGENCY (WITH OUTAGE OF TRANSMISSION LINE BETWEEN BUSES 10 AND 50)

Bus	Proposed Method (KV/Degree)	1st Iteration of SPQPF(KV/Degree)	Final Solution of SPQPF(KV/Degree)
170	137.912009/16.7088	137.912009/ 16.7088	137.910661 / 16.7016
180	139.431602 / 18.0657	139.431602 / 18.0657	139.430090 / 18.0584
210	139.431724 / 18.8879	139.431724 / 18.8879	139.430090 / 18.8805
220	139.431623 / 24.5392	139.431623 / 24.5392	139.430090 / 24.5318
160	135.049086 / 12.2340	135.049086 / 12.2340	135.048001 / 12.2271
190	135.870002 / 10.2886	135.870002 / 10.2886	135.869337 / 10.2828
200	137.906376 / 10.5535	137.906376 / 10.5535	137.905991 / 10.5488
230	139.430296 / 11.4114	139.430296 / 11.4114	139.430090 / 11.4072
150	134.651491 / 13.3290	134.651491 / 13.3290	134.649630 / 13.3213
140	130.134854 / 0.8548	130.134854 / 0.8548	130.134751 / 0.8482
240	130.197909 / 6.9747	130.197909 / 6.9747	130.166774 / 6.9645
30	78.285222 / -3.8631	78.285222 / -3.8631	78.241595 / -3.8854
90	79.415759 / -6.9687	79.415759 / -6.9687	79.387982 / -6.9863
10	82.593568 / -3.9611	82.593568 / -3.9611	82.462939 / -4.0023
20	82.566926 / -4.4136	82.566926 / -4.4136	82.462939 / -4.4530
40	79.330629 / -8.0905	79.330629 / -8.0905	79.268941 / -8.1207
50	78.469324 / -13.8575	78.469324 / -13.8575	78.423324 / -13.8545
100	80.828558 / -10.4099	80.828558 / -10.4099	80.796520 / -10.4219
80	78.755044 / -11.4295	78.755044 / -11.4295	78.740988 / -11.4504
60	79.697942 / -12.4605	79.697942 / -12.4605	79.647350 / -12.4847
110	131.206876 / -2.7103	131.206876 / -2.7103	131.188517 / -2.7164
130	135.446373 / 0.0000	135.446373 / 0.0000	135.446373 / 0.0000
70	81.667613 / -7.7444	81.667613 / -7.7444	81.666196 / -7.7681
120	132.572529 / -1.4548	132.572529 / -1.4548	132.549395 / -1.4601

TABLE 2
ITERATION NUMBERS AND CORRESPONDING TOLERANCES FOR CONTINGENCIES IN THE SECOND CLASS

		Iteration # for Various Tolerances		
No.	Contingency	0.01	0.001	0.0001
1	G210	4	6	8
2	G180	4	6	7
3	C140 – 160	4	5	7
4	C130 – 230	3	4	5
5	C110 – 140	3	4	6
6	C210 – 220	3	4	6
7	C160 – 170	3	4	6
8,9	G70 -1,2	2	4	5
10	T30 – 240	3	4	6
11	C150 – 240	3	4	6
12	C160 – 190	3	4	5
13	C120 – 230	2	3	5

The effectiveness of SPQPF based sparsity techniques in improving solution efficiency is tested on IEEE RTS-79 and RTS-96. The normalized average contingency solution time is provided in Table 3. For RTS-79 as shown in Figure 1, since the system is small, the improvement is not obvious. The solution time is reduced by 10% when using sparsity techniques. For the RTS-96, which is three times as large as the RTS-79 in terms of system size, the solution speed is improved 40% by using sparsity techniques. This trend shows that with an increase in system scale, the improvement in solution speed by the SPQPF based sparsity techniques will be more significant. In the future work, more sparsity techniques [10, 11] will be developed based on the SPQPF model, and their effectiveness will be tested on large-scale systems.

TABLE 3
SOLUTION SPEED TEST WITH AND WITHOUT SPQPF BASED SPARSITY TECHNIQUES FOR RTS-79 AND RTS-96

RTS System	Normalized Average Contingency Solution Speed	
	w/o Sparsity Technique	With Sparsity Technique
RTS-79	1	0.9
RTS-96	1	0.6

IV. Methodology Implementation

The proposed methodology, implemented in a Visual C++ environment using object-oriented techniques, is created as an expansion of existing power system analysis software, developed by the power system laboratory in the Georgia Institute of Technology. A separate class that contains the proposed method was created.

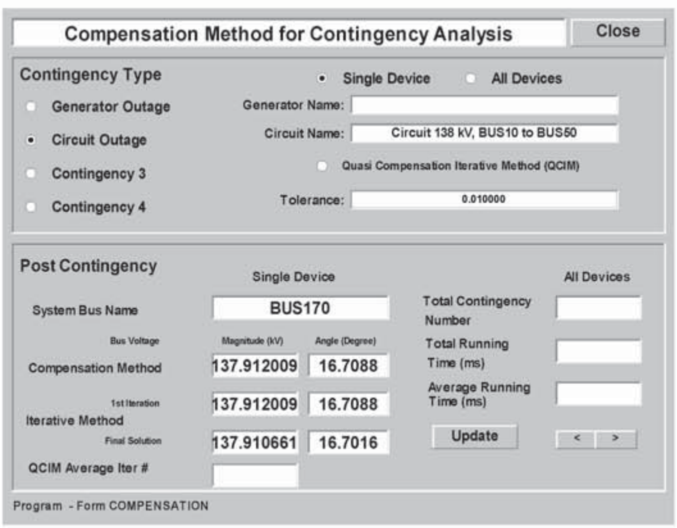

Figure 2. User interface of the proposed methodology for contingency simulation

A user interface is developed to facilitate the input of data, as shown in Figure 2. Users can select among three options: (1) "Single Device", (2) "Quasi Compensation Iterative Method (QCIM)", or (3) "All Devices". For the first two options, users also need to specify the type of contingencies (generator or circuit outage) and the outage device name. If the "Single Device" is selected, after the user presses the update button, the system bus name and corresponding bus voltage magnitudes and phase angles obtained from the compensation method, the first iteration solutions of SPQPF, and the final solutions of SPQPF will be displayed in the user interface. Users can use forward and backward buttons to watch different bus voltage phasors in the system. If the "QCIM" option is selected, users need to specify the tolerance value. The iterative number corresponding to the pre-defined tolerance will be provided in the user interface. If the "All Devices" is selected, all possible system first level independent contingencies will be solved and the total contingency number, total execution time, as well as the average execution time will be provided. The selection of the analyzed power system and the utilization of the SPQPF based sparsity techniques or not are done in the general user interface of the software.

V. Conclusions

This paper proposes a systematic contingency simulation methodology using single phase quadratized power flow, which can take advantage of the superior performance of the SPQPF model to simulate contingencies in a realistic manner efficiently. In addition, the compensation method and sparsity techniques based on the SPQPF model are developed to further reduce the computational effort. In the proposed framework, the hybrid contingency selection method is applied first to categorize system contingencies into two classes. Contingencies in the first class that cause linear system changes are solved using the sparse oriented compensation method, in which one iteration of the sparse oriented compensation method is able to provide satisfactory solutions. Contingencies in the second class that cause system nonlinear changes or discontinuities are solved using the quasi compensation iterative method. Using the two different methods for the different types of contingencies provides the solution procedure a good balance between efficiency and accuracy.

The contingency simulation results for IEEE RTS-79 and RTS-96 demonstrate the expected performance of the proposed methodology, and this methodology will be further tested in large-scale power systems in future work.

VI. References

[1] J. Carpentier, "Static Security Assessment and Control: A Short Survey," *Athens Power Tech Proceedings*, vol. 1, pp. 1-9, Sept. 1993.

[2] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*, John Wiley & Sons, Inc. 1996.

[3] V. Brandwajn, "Efficient Bounding Method for Linear Contingency Analysis," *IEEE Trans. on Power Systems,* vol. PWRS-3, No. 1, pp. 38-43, Feb. 1988.

[4] J. L. Carpentier, P. J. D. Bono, and P. J. Tournebise, "Improved Efficient Bounding Method for DC Contingency Analysis Using Reciprocity Properties," *IEEE Trans. on Power Systems,* vol. 9, No. 1, pp. 76-84, Feb. 1994.

[5] G. Irisarri, A. M. Sasson, and D. Levner, "Automatic Contingency Selection for On-Line Security Analysis – Real Time Tests," *IEEE Trans. on Power Apparatus and Systems,* vol. PAS-98, No. 5, pp. 1552-1559, Sep. / Oct. 1979.

[6] A. Mohamed and G. B. Jasmon, "Voltage Contingency Selection Technique for Security Assessment," *IEE Proceedings*, vol. 136, No. 1, Jan. 1989.

[7] I. Musirin and T. K. A. Rahman, "Fast Automatic Contingency Analysis and Ranking Technique for Power System Security Assessment," *Proceedings of Conference on Research and Development*, 2003.

[8] PSERC Project Report, "Comprehensive Power System Reliability Assessment," 2003.

[9] O. Alsac, B. Stott, and W. F. Tinney, "Sparsity Oriented Compensation Methods for Modified Network Solutions," *IEEE Trans. on Power Apparatus and Systems,* vol. PAS-102, No. 5, pp. 1050-1060, May 1983.

[10] R. Bacher, G. C. Ejebe, and W. F. Tinney, "Approximate Sparse Vector Techniques for Power Network Solutions," *IEEE Trans. on Power Systems,* vol. 6, No. 1, Feb. 1991.

[11] W. F. Tinney, V. Brandwajn, and S. M. Chen, "Sparse Vector Methods," *IEEE Trans. on Power Apparatus and Systems,* vol. PAS-104, pp. 295-301, Feb. 1985.

[12] P. W. Sauer, K. E. Reinhard, and T. J. Overbye, "Extended Factors for Linear Contingency Analysis." *Proceedings of the 34th Hawaii International Conference on System Sciences*, 2001.

[13] R. A. M. Van Amerongen, "A General Purpose Version of the Fast Decoupled Load Flow," *IEEE Trans. on Power Systems,* vol. 4, No. 2, pp. 760-770, May 1989.

[14] S. W. Kang, "A New Approach for Power Transaction Evaluation and Transfer Capability Analysis," Ph.D. Dissertation, Georgia Institute of Technology, 2001.

[15] A. P. S. Meliopoulos and C. Cheng, "A Hybrid Contingency Selection Method," *Proceedings of the 10th Power System Computation Conference*, pp. 605-612, Aug. 1994.

[16] A. P. S. Meliopoulos, *Power System Modeling, Analysis, and Control*, Georgia Institute of Technology, 2002.

[17] IEEE Committee Report, "IEEE Reliability Test System," *IEEE Trans. on Power Apparatus and Systems,* vol. PAS-98, No. 6, pp. 2047-2054, Nov. / Dec. 1979.

[18] Reliability Test System Task Force, "The IEEE Reliability Test System-1996," *IEEE Trans. on Power Systems,* vol. 14, No. 3, Aug. 1999.