Fast Static Contingency Screening based on Reactive Loss Compensation Index

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Abstract-- This paper presents a method of reducing the response time to system operators of static contingency screening. To achieve this objective, the reactive loss compensation index is selected as the critical system factor and an approximate power flow model is employed to solve line flow non-iteratively. The index determines the severity of transmission line contingencies. The compensation index in line outage situation is obtained, first, by evaluating the amount of reactive losses on the lines connected to the system load buses, and second, by determining the appropriate reactive compensation required to maintain their pre-contingency voltage magnitude. The compensation is simulated by applying artificial Var compensators placed at the load buses. The effectiveness of the new method in screening performance and computation time reduction is tested on the standard IEEE 30-bus system.

Index Terms-- contingency screening, ranking; reactive loss compensation; severity index; power flow.

I. INTRODUCTION

POWER system is made of interconnected components, each designed to play a critical role for the smooth operation of the system at all times. Since the operating condition of power system changes continually, definite prediction of the status of the system would be difficult, were the components to fail to play their roles. In the past, the system status prediction was possible only in off-line studies. Running a full AC load flow solution for all the possible system outages to check for limit violations is time consuming and thus out of the question for real-time application.

Power industry has developed analytical tools which can determine, in real time, the impact of losing any of these components to the security of the overall system. The main function of the tools is to assess outages and contingencies. In performing the function, the tools are focused on the minimization of the output response time of their solution with accuracy within the requirement of the contingency assessment. One common approach for response time reduction is to apply a screening technique that ranks the outages in the order of severity based on a calculated system performance index, a scalar value which measures how much a particular outage case impacts the power system. A detailed analysis can then be performed only on those highly ranked outages, saving computation time. The calculation of performance index therefore dictates the response time of the screening and contingency analysis.

The system performance index is usually derived from "critical system factors" by which system status can be uniquely determined. Two of the most widely used variables as critical system factor are bus voltage magnitude and megawatt overload on transmission lines. They are used together, or as in [1-3], each separately, in the evaluation. One problem in screening using megawatt overload alone by the deviation from the rated value on transmission lines is that voltage and reactive flow violations are not disclosed. Judged by the importance of the information on voltage and reactive power, evidenced in the major blackouts, this drawback erases any computational time savings made from the application of megawatt overload. Therefore, it is possible that a short list of the severity rankings produced by the megawatt overload screening does not include the most severe contingency determined by voltage and reactive power screening.

As a variant of megawatt overload screening, El-Abiad et. al. [4] introduced a pre-calculated distribution factor of each line as a way to check for megawatt overloads deviations and, using the distribution factor, developed a screening method which assessed the severity of every contingency quickly. The variant, however, could not overcome the inherent problem in using megawatt overload alone: exclusion of the voltage limit violations in the contingency evaluation.

Unlike the megawatt overload or voltage, reactive power has not attracted much interest as a variable for critical system factor; however, its usefulness has stimulated considerable amount of research effort. Several pioneering works [5-10] spread the use of reactive power and bus voltage magnitude deviation as critical system factors for fast performance index calculation.

Others applied non-traditional method of determining system performance index, no matter what variables are used for critical system factors, to circumvent the analytical screening process [11-15]. However, whether it be artificial neural network, expert system, or genetic algorithm of supervised or unsupervised learning, it could offer fast screening since it required a large number of training samples for accuracy.

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This paper proposes a hybrid method of reducing the response time of static screening by adopting line reactive losses and bus reactive compensation as the critical system factors and by using the power flow changes resulted from direct, one-iteration power flow model in determining the compensation. The hybrid approach produces an index, reactive loss compensation index, which decides the severity ranking of the contingencies.

The paper is organized as follows. Section II presents the line outage model with relevant mathematical processes for calculating the reactive loss compensation index. The formulation of the algorithm for the new approach is discussed in section III. Next, section IV discusses the numerical results obtained from the test of the proposed method on the standard IEEE 30-bus system. The conclusions and future works are discussed in section V.

II. OUTAGE SIMULATION AND REACTIVE LOSS COMPENSATION

The choice of critical system factor and the process taken to evaluate it determines to a larger extent the computational efficiency of a contingency screening method. The reactive loss compensation index of our approach is derived from the voltage angle change resulted from real power flow change on a line which can be obtained using DC power flow analysis. In the power flow analysis, a simulation of line outage can be done by injecting active power at the buses where the line outage occurs. The new approach, therefore, is centered on the simulation of line outage with a non-iterative active power flow model by which the changes in bus voltage angle, $\Delta\theta$, for a given set of changes in active bus injections, ΔP , are computed to generate the compensation index. Since the evaluation of the incremental changes in bus voltage angles is an important step in the screening, we review the mathematical process leading to the evaluation. Then, we discuss the reactive loss and required compensation. Detailed description of bus injection technique and of the mathematical process for outage simulation can be found in [16, 17].

A. Line Outage Simulation and Voltage Angle Change

Under outage at a line, the incremental changes in bus voltage angles, due to the loss of active power flow in the line, determines line outage sensitivity factor. The sensitivity factor measures the ratio of the change in voltage angle in any section of the system to that of the original power flow on the faulted line. The incremental change analysis of voltage angle is done separately for transmitted and loss parts of power flow.

In the nominal π-circuit model of Fig. 1, the transmitted and the loss parts of active power flowing on line *k-m* are given, respectively, as follows:

$$P_{km}^{(tr)} = g_{km}(V_k^{\,2} - V_m^{\,2}) - 2b_{km}V_k\,V_m \sin(\theta_k - \theta_m) = -P_{mk}^{\,(tr)} \qquad (1)$$

$$P_k^{\,(loss)} = g_{km}(V_k^{\,2} + V_m^{\,2}) - 2g_{km}V_kV_m \cos(\theta_k - \theta_m) = P_m^{\,(loss)} \qquad (2)$$

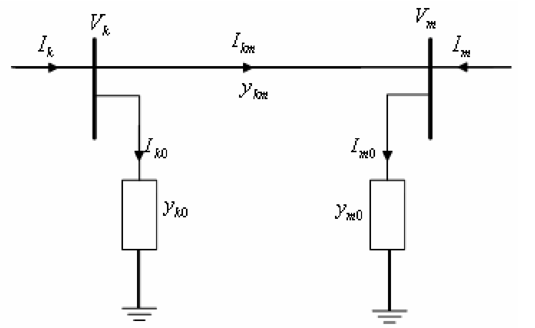

Fig. 1. Transmission Circuit Model for Line Flow Calculation

The line outage of the circuit can be simulated by applying two incremental active power injections, ΔP_k and ΔP_m , at each end of the line *k-m*. Upon the outage at the line *k-m*, these incremental injections of the transmitted and the loss parts at each end, $\Delta P_k^{\,(tr)}, \Delta P_m^{\,(tr)}$, $\Delta P_k^{\,(loss)}$ and $\Delta P_m^{\,(loss)}$, must equal the original active power flow on the line *k-m*, to effect zero power flow in the faulted line. For the incremental change analysis for the transmitted part of the line, the following equation satisfies the condition:

$$\Delta P_k^{\,(tr)} = P_{km}^{\,(tr)} + \Delta P_{km}^{\,(tr)} \qquad (3)$$

The changes in bus voltage angle influenced by the changes in bus active power injections can be obtained by the use of a DC power flow model expressed by:

$$[\Delta\,\theta\,] = [X\,][\Delta\,P\,] \qquad (4)$$

where,

$[\Delta P\,]$ is an n-by-1 vector of incremental changes of active power injection,

$[\Delta\,\theta\,]$ is an n-by-1 vector of incremental changes of bus voltage angles, and

$[X\,]$, written as $[\partial\,\theta/\partial P\,]$, is the inverse of the susceptance matrix $[B\,']$.

Using (4) we can express the changes in the voltage angle on the transmission line between bus *k* and bus *m* in terms of the active power injection at bus *k*:

$$\Delta\theta_{km}^{\,(tr)} = (X_{kk} - X_{km} - X_{mk} + X_{mm})\Delta P_k^{\,(tr)} \qquad (5)$$

The combination of (1), (3) and (5) results in an expression for the transmitted part of the incremental bus injection in terms of the original power flow on the faulted line *k - m*:

$$\Delta P_k^{(tr)} = P_{km}^{(tr)} \big/ \{1 + a(X_{kk} - X_{km} - X_{mk} - X_{mm})\} \qquad (6)$$

where $a = 2b_{km}V_kV_m \cos\theta_{km}$, and b_{km} is the susceptance of the line *k - m*.

Then the sensitivity factor at the bus *n* in any section of the system is obtained by:

$$\alpha_{n,km} = \Delta\theta_n^{(tr)} \big/ P_{km}^{(tr)} \tag{7}$$

Further, from (4), the change in the voltage angle at bus *n* for the transmitted part of active power injection, $\Delta\theta_n^{(tr)}$, can be written as:

$$\Delta\theta_n^{(tr)} = (X_{nk} - X_{nm})\Delta P_k^{(tr)} \tag{8}$$

Finally, by combining equations (7) and (8) along with (6), we produce the DC power flow model equation for sensitivity factor of transmitted part of outage injection:

$$\alpha_{n.km} = (X_{nk} - X_{nm}) / \{1 + a(X_{kk} - X_{km} - X_{mk} - X_{mm})\} \tag{9}$$

Similarly, the sensitivity factor of the loss part for the active power injection is obtained as:

$$\beta_{n.km} = (X_{nk} - X_{nm}) / \{1 - b(X_{kk} + X_{km} - X_{mk} - X_{mm})\} \tag{10}$$

where $b = 2g_{km}V_kV_m \sin\theta_{km}$ and g_{km} is the conductance of the line *k* - *m*.

Then the total change in voltage angle at bus *n* due to the transmitted and loss parts of the outage injections is obtained as:

$$\Delta\theta_{n.km} = \alpha_{n.km}\Delta P_{km}^{(tr)} + \beta_{n.km}\Delta P_k^{(loss)} \tag{11}$$

B. Evaluation of Reactive Loss Compensation Index

The loss amount in a bus under outage can be interpreted as the amount of compensation to the bus to keep constant voltage magnitude at the bus. In other words, the amount of Var compensation required by the system under a line outage must be the same as the total sum of reactive losses over all the lines connected to the load buses. It's because the change in voltage magnitude at the PQ buses for a line outage is caused by changes in reactive power losses on the transmission line connecting the load buses.

Used with the values obtained from equation (11), the reactive losses on the lines are obtained in terms of the active power flow. With the same nominal π-circuit transmission line model, the reactive flows on the line *k*-*m*, measured at each end of the buses are expressed by:

$$Q_{km} = V_k^2(b_{km} + b^{sh}) + V_kV_m g_{km} \sin\theta_{km} - V_kV_m b_{km}\cos\theta_{km} \tag{12}$$

$$Q_{mk} = V_m^2(b_{km} + b^{sh}) - V_kV_m g_{km} \sin\theta_{km} - V_kV_m b_{km}\cos\theta_{km} \tag{13}$$

Then the reactive power loss in line *k*-*m* is the algebraic sum of (12) and (13):

$$\begin{aligned} Q_{km}^{(loss)} &= Q_{km} + Q_{mk} \\ &= (V_k^2 + V_m^2)(b_{km} + b^{sh}) - 2V_kV_m b_{km}\cos\theta_{km} \end{aligned} \tag{14}$$

where b^{sh} is shunt susceptane.

We can then express the derivative of the reactive power losses on line *k*-*m*, $\Delta q_{km}^{(loss)}$, with respect to the change in voltage angle difference between bus *k* and bus *m*, $\Delta\theta_{km}$:

$$\Delta q_{km}^{(loss)} = 2V_kV_m b_{km} \sin\theta_{km}\Delta\theta_{km} \tag{15}$$

Equation (15) represents the incremental change in the reactive power loss on line *k*-*m* due to change in the line active flow. Then, the reactive losses on all the affected lines can be calculated using (11). The total sum of reactive losses is equivalent to the amount of Var compensation required by the system under a line outage to maintain the original bus voltage magnitude. The compensation amount, made by the artificial Var compensators placed at the system load buses, is called reactive loss compensation index (RLCI):

$$RLCI = \sum_{n \in \{loadbus\}} Q_{i,k}^{(loss)} \tag{16}$$

where $Q_{i,k}^{(loss)} = \sum_{j \in L} \Delta q_{ij,k}^{(loss)}$ is the incremental reactive losses summed up at bus *i* over the set of connecting lines *j* for an outage on line *k*.

The main part of the new approach in the contingency screening is centered on the calculation and interpretation of RLCI for severity of the outage. The important observation of the RLCI contingency screening is that, under a power system where the PQ buses are modeled as constant voltage buses and the reactive power limits at the remaining PV buses are not violated, only the load buses are the places where the reactive losses are compensated. This means that the contingency screening can be done on the reduced network, the inherent advantage of time saving in calculation.

III. CONTINGENCY SCREENING WITH REACTIVE LOSS COMPENSATION INDEX

A. RLCI Contingency Screening and Ranking Process

The RLCI contingency screening process as illustrated in Fig.2 is composed of the following steps:

Step 1: The result of base case power flow solution is obtained as input to the screening process.

Step 2: Developed, from the line data of the power system, thee susceptance matrix $[B']$ and its inverse matrix $[X]$ in the form of $[\partial\theta/\partial P]$.

Step 3: The number of line outage cases to be screened, *s*, is specified as a condition for terminating the loop process.

Step 4: Select an outage case, for example, line *k-m,* and set the initial value of the loop variable k = 1.

Step 5: Calculate the sensitivity factors due to the transmitted and loss parts of the injections at the buses k and m.

Step 6: Compute the changes in bus voltage angles for the transmitted and loss parts of the injections.

Step 7: Calculate RLCI.

Step 8: Increase the loop variable k by 1(i.e. k = k+1). Stop if k =s, otherwise, go to Step 4.

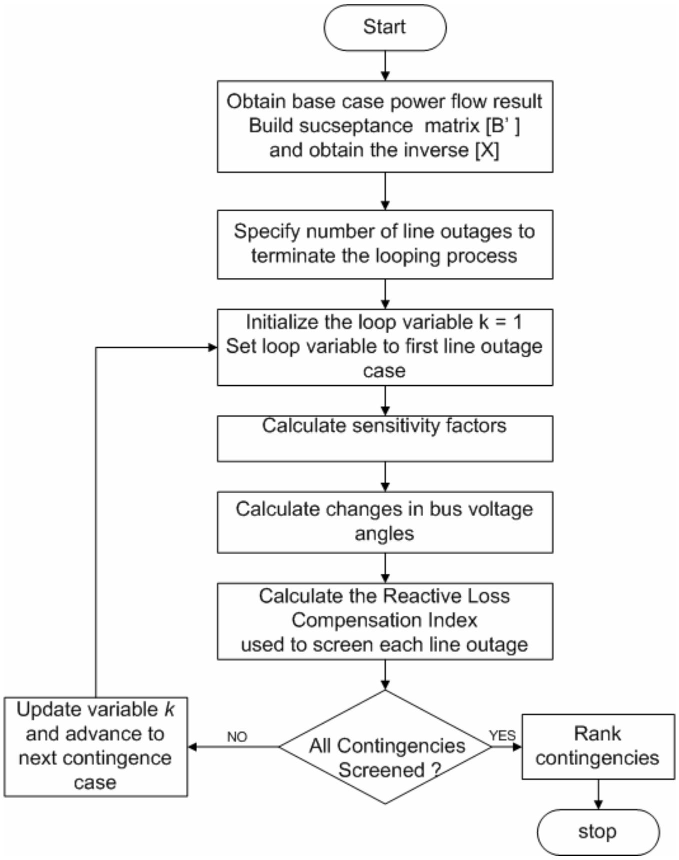

Fig.2. Flow chart of the RLCI screening algorithm.

The RLCI value we would obtain from the screening process, in signed number, represents the amount of Var compensation to account for line reactive loss. A large RLCI of an outage indicates higher Var compensation; a smaller RLCI indicates negligible compensation. By arranging the outage cases with the corresponding RLCI values in the decreasing order, we can place the most severe outage case (largest RLCI value) at the top, and the least severe one (smallest RLCI) at the bottom of the contingency list.

B. Computational Efficiency of the Screening Method

One factor that reduces the response time in the screening algorithm is the choice of RLCI as the critical system factor. The evaluation of RLCI in terms of real power flow on transmission lines allows us to use only the active power model to obtain the information on reactive losses without having to run a complete 1P1Q load flow solution, and thereby to avoid the computation burden of the traditional screening method.

Another time saving comes from the reduced set of load buses used for the calculation of RLCI in the proposed method; only a fraction of the entire network is used to perform contingency analysis. The use of reduced network to perform contingency analysis is a practical approach of using the power flow results for selected sub-system rather than the entire power system to evaluate the impact of contingencies.

IV. NUMERICAL RESULTS OF EVALUATION

The fast method of RLCI contingency screening, coded in Matlab programming environment, is tested on the IEEE 30-bus system (see Fig. 3) in a PC Windows XP platform. The test bus system and the data used for this study are from the American Electric Power Service Corporation network [19].

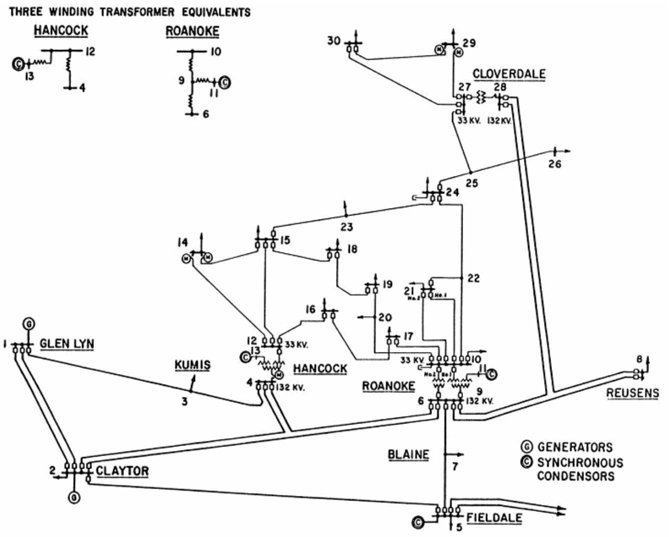

Fig. 3. IEEE 30-Bus Test System

A total of 41 line outages were simulated and, for each outage case, the RLCI was calculated to rank the contingencies in the order of severity. We also performed the screening time comparison for single line outage contingencies between the RLCI screening and the 1P1Q method.

A. Ranking Performance Evaluation

The RLCI generated ranking is evaluated by comparing it with a benchmark, generator Var limiting index, which gives a measure of reactive power limit violations on constant voltage buses. The benchmark is generated by using a contingency screening open source code of Power System Analysis Tool (PSAT) software [18], for each outage case, and by running fast decoupled power flow algorithm in Matlab.

Table I summarizes the comparison for the first ten most severe line outages, sorted by the benchmark index. The first column shows the single outages with each line indicated by the two connecting bus numbers; the second and fourth columns are the screenings ranks determined by Var limiting index and RLC, respectively. The third and fifth columns give the generator VAR limiting index value and the RLCI value, respectively, for each of the outages.

The result shows that, even though the severity order of ranking produced by the RLCI method is not exactly the same as that by the Var limiting index, RLCI screening captures all ten worst contingencies. The biggest error of RLCI screening is the case for line 2-4 outage: RLCI method ranks it as the 4th most severe outage while its correct ranking by VAR index screening is 10th. Other outages are similarly ranked in the both sides of the method. We can conclude that, with capturing all 10 worst case contingencies, the proposed RLCI screening method has the acceptable level of accuracy.

TABLE I

RANKING COMPARISON FOR TEN MOST SEVERE OUTAGE CASES

Line Outage Case	Rank by Var index	VAr Index	Rank by RLCI	RLCI
9 - 10	1	0.9999	1	0.1360
28 - 27	2	0.9989	2	0.0770
2 - 6	3	0.9982	3	0.0531
4 - 12	4	0.9958	5	0.0259
3 – 4	5	0.9918	6	0.0225
2 – 5	6	0.9908	10	0.0088
4 – 6	7	0.9853	7	0.0198
6 – 10	8	0.9835	8	0.0164
6 – 9	9	0.9828	9	0.0158
2 – 4	10	0.8938	4	0.0298

The ten least severe line outages are compared and summarized in Table II. Again, the RLCI method captures all 10 least ranked contingencies. The only minor discrepancies between RLCI and the Var limiting index are: lines 15-23, 22-24, 8-28, and 5-7 are ranked 35th, 36th, 39th and 41st, respectively, by the RLCI method, while they are ranked as 36th, 35th, 40th and 39th, respectively, in the conventional method.

TABLE II

RANKING COMPARISON FOR TEN LEAST SEVERE OUTAGE CASES

Line Outage Case	Rank by VAR index	VAr Index	Rank by RLCI	RLCI
9 - 11	32	0.8384	32	0
12 -13	33	0.8373	33	0
10 – 22	34	0.8345	34	-0.000924
22 - 24	35	0.8339	36	-0.000241
15 – 23	36	0.8336	35	-0.000122
10 – 21	37	0.8333	37	-0.000297
25 – 26	38	0.8292	38	-0.000317
5 – 7	39	0.8287	41	-0.00422
8 – 28	40	0.8279	39	-0.000741
6 – 8	41	0.8277	40	-0.00404

B. Screening Time Evaluation

The screening times are evaluated with the CPU average times taken for all the single line outages by RLCI and the conventional 1P1Q method at the major steps of the contingency screening. For both RLCI and 1P1Q methods, the CPU time measurement for a screening step is done by adding a line of syntax *tic* ("start time") and a syntax *toc* ("end time") between the code segment of the step. At the end of the execution, the CPU time of the step is displayed on the Matlab command window.

Table III presents the screening time comparison between RLCI and 1P1Q screening methods. The result shows that the proposed RLCI screening method reduces the computation time in average by 60%.

TABLE III

SCREENING TIME COMPARISON FOR SINGLE LINE OUTAGES

Process Description	RLCI Method	1P-1Q Method
Inversion of B' matrix	0.02s	0.02s
Iterative/Non-iterative solution for calculating $\Delta P - \Delta\theta$	0.0245s	0.0567s
LRCI calculation / Q – V iteration	0.002s	0.014s
Approximate Screening Time	0.0465s	0.0767s

V. CONCLUSIONS

A new method of reducing response time to operators of static contingency screening was discussed. The screening method based on load reactive loss compensation index showed a reduction in execution time over the 1P1Q method of n-1 contingency screening algorithm. Compared with the conventional Var limiting index benchmark, the accuracy of RLCI screening was acceptable in that the new method captured all ten most severe and ten least severe contingencies of the 41 outage cases of the IEEE 30-bus test system. In addition, the RLCI approach reduced the computation time in every step of the screening process. Overall, the RLCI approach, with 60% faster response time and acceptable accuracy, demonstrated its promise as a real-time contingency screening tool.

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VII. BIOGRAPHIES

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