Voltage Stability Constrained Load Curtailment Procedure to Evaluate Power System Reliability Measures

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Abstract--**This paper reports a method to evaluate composite power system reliability indices incorporating the voltage stability margin criteria. To compute the load curtailment evaluation, an optimal power flow (OPF) computation algorithm, considering the steady state voltage stability margin constraint is developed. A steady state voltage stability indicator is first discussed for its applicability as a suitable indicator for representing stability margin from the collapse point. The load curtailment formulation is then evolved and described into the OPF's objective function. A criterion based on the voltage stability indicator is then incorporated as an additional constraint into the OPF. A numerical example has been used to illustrate the effect of the algorithm on the composite system reliability evaluation. The Expected Energy Not Served (EENS) and down time is computed, both analytically and by the Monte Carlo Simulation.**

Index Terms—**Down time, EENS, Load curtailment, Monte-Carlo simulation, OPF, Voltage stability**

I. INTRODUCTION

In the deregulated power systems, reliability evaluation encompassing the system security features has come into focus. Presently research is being carried to evolve methods and procedures to evaluate composite power system reliability indices which incorporate both system adequacy and security issues [1,2,3]. Economic competition, sometimes, results in paying less attention to security features of the overall system. One such security issue is the voltage stability of the system. Several voltage instability incidents have been reported, in the recent past, all over the globe. These are results of operating the system with very less voltage stability margin under normal conditions. Because of the increased demand and the competition induced due to deregulation, congestion management has become one of an important issue. In a deregulated environment, congestion alleviation would mean load curtailment in certain situations. The utilities would definitely prefer to curtail a load as lower as possible during a viability crisis situation. However, from the overall system viewpoint, any policy of load curtailment has definitely to incorporate voltage stability margin considerations. Incorporating the security constraints into the normal operation of a power system would definitely lead to a more reliable system operation. Thus, in the emerging deregulation market any control action has to incorporate security features to maintain an acceptable level of system reliability.

A power flow can have a number of operating limit violations. When such situations occur, the violations can be alleviated by appropriate or various corrective actions. The analytical process of evolving this procedure is known as Optimal Power Flow [4]. The current practice is to use the constraints based on the operating limits imposed by bus voltages, branch flows, power transfers over interfaces, etc. The operating problems in contingency analysis are violations of such constraints. Controls may include generator, real power phase shifter angle, bus load-curtailment or all the three. The objective of the corrective action algorithm is to observe all constraints while minimizing the weighted sum of the control movement. The Newton based approach to OPF was proposed in [5]. In [6] the authors have formulated the OPF extension to take into effect the contingencies that occur in power systems. The non-solvability of the Newton process due to the singularity of the Jacobian matrix is overcome by modifying the OPF through load shedding or by relaxing some inequalities [7].

Methods to understand the voltage instability phenomenon and quantify the stability indices have been reported in works [8,9,10,11,12]. In [13] a voltage stability indicator has been discussed whose value changes between zero (no load) and one (voltage collapse). The indicator incorporates the effect of all other loads in the system on the evaluation of index at individual load buses. The overall voltage stability of the system could be identified by the largest value of the index evaluated amongst all the load buses. This indicator can also be used as a normalized quantitative measure, for estimation of the voltage stability margin from the operating point. In this paper, the authors have used this capability of the indicator. Works in the direction of developing algorithms to incorporate stability issues into power system operational analysis are going on. The reported work [14] attempts to formulate the

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incorporation of the transient angle stability, into an OPF routine, as an additional constraint.

In [15] we have proposed and formulated an algorithm to include the voltage stability margin feature into the load curtailment objective function of an OPF. In this paper we apply the algorithm to investigate its effect in the evaluation of the system reliability measures.

II. VOLTAGE STABILITY MARGIN CONSTRAINTS

The transmission system can be represented using a hybrid representation, by the following set of equations

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix}$$

V_L, I_L are the voltage and current vectors at the load buses

V_G, I_G are the voltage and current vectors at the generator buses

$Z_{LL}, F_{LG}, K_{GL}, Y_{GG}$ are the sub-matrices of the hybrid matrix H.

The H matrix can be evaluated from the Y bus matrix by a partial inversion, where the voltages at the load buses are exchanged against their currents. This representation can then be used to define a voltage stability indicator at the load bus, namely L_j which is given by,

$$L_j = \left| 1 + \frac{V_{0j}}{V_j} \right| \tag{1}$$

where,

$$V_{0j} = -\sum_{i \in G} F_{ji} V_i \tag{2}$$

The term V_{0j} is representative of an equivalent generator comprising the contribution from all generators.

The index L_j can also be derived and expressed in terms of the power terms as the following.

$$L_j = \left| \frac{\overset{*}{S}_{j+}}{Y_{jj+} V_j^{2}} \right| \tag{3}$$

where,

$$S_{j+} = S_j + S_{jcorr} \tag{4}$$

* indicates the complex conjugate of the vector

$$S_{jcorr} = \Big(\sum_{\substack{i \in Loads \\ i \neq j}} \frac{\overset{*}{Z}_{ji}}{\overset{*}{Z}_{jj}} \frac{S_i}{V_i} \Big) V_j \tag{5}$$

$$Y_{jj+} = \frac{1}{Z_{jj}} \tag{6}$$

The complex power term component S_{jcorr} represents the contributions of the other loads in the system to the index evaluated at the node j.

It can be seen that when a load bus approaches a steady state voltage collapse situation, the index L approaches the numerical value 1.0. Hence for an overall system voltage stability condition, the index evaluated at any of the buses must be less than unity. Thus the index value L gives an indication of how far the system is from voltage collapse. This feature of this indicator has been exploited in our proposed algorithm to evolve a voltage collapse margin incorporated OPF routine.

In the conventional optimal power flow approach, the objective is to minimize the total amount of load curtailment considering the load flow system constraints like line flow, voltage magnitude, the maximum active and reactive power generation etc. The control variables for the OPF evaluation are the real and reactive power generation of each generation bus and the real and reactive load at each load bus.

III. LOAD CURTAILMENT FORMULATION INCORPORATING VOLTAGE STABILITY MARGIN

The OPF problem formulation which we have used is presented herewith. In order to keep the load power factor as a constant, we assume that when a certain amount of real load has been shed at one bus, the corresponding reactive load will also be shed in the same proportions.

Objective: $min \sum_{i=1}^{n} load\_curtail_i$

S.T.:

$$P_{gi} - P_{li} - \sum_{j=1}^{n} |V_i||V_j|(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}) = 0 \tag{7}$$

$$Q_{gi} - Q_{li} - \sum_{j=1}^{n} |V_i||V_j|(G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}) = 0 \tag{8}$$

$$P_{li} / P_{lireq} = Q_{li} / Q_{lireq} \tag{9}$$

$$0 \le P_{li} \le P_{lireq} \tag{10}$$

$$0 \le Q_{li} \le Q_{lireq} \tag{11}$$

$$|V_i|_{min} \le |V_i| \le |V_i|_{max} \tag{12}$$

$$P_{gi\,min} \le P_{gi} \le P_{gi\,max} \tag{13}$$

$$Q_{gi\,\min} \le Q_{gi} \le Q_{gi\,\max} \tag{14}$$

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$$P_{ij}^2 + Q_{ij}^2 \leq S_{ij\max}^2 \qquad (15)$$

$$L_i \leq L_{crit} \qquad (16)$$

Here,

$$load\_curtail_i = P_{lireq} - P_{li}$$

where,

P_{lireq} : real load demand at bus i

P_{li} : actual real load supply at bus i

n : total number of load flow buses in the system

P_{gi} : real power generation at bus i

Q_{gi} : reactive power generation at bus i

Q_{lireq} : reactive load demand at bus i

Q_{li} : actual reactive load supply at bus i

$|V_i|$: voltage magnitude at bus i

$|V_j|$: voltage magnitude at bus j

G_{ij}, B_{ij} : real/reactive part of the ij[th] element of the bus admittance matrix

δ_{ij} : angle difference between the voltage phasor at bus i and bus j

$P_{gi\min}, P_{gi\max}$: minimum/maximum real power generation at generation bus i

$Q_{gi\min}, Q_{gi\max}$: minimum/maximum reactive power generation at generation bus i

$|V_i|_{min}, |V_i|_{max}$: minimum/maximum voltage magnitude at bus i

P_{ij}, Q_{ij} : real /reactive power flow through transmission line ij

$S_{ij\max}$: maximum apparent power flow allowable through the ij[th] line

L_i is the index L evaluated at the i th bus other than the generation buses

L_{crit} is the threshold value of the index acceptable for the system

It can be observed in the OPF formulation that it includes the power balance equations (7,8) generation limits (13,14), line loading limits (15), voltage magnitude limits (12). For the load curtailment policy which we have adopted, i.e constant power factor, an additional constraint (9) has been added. To incorporate the feature of voltage stability margin into the OPFs description the constraint (16) has been included.

IV. THE EFFECT OF INCORPORATING VOLTAGE STABILITY MARGIN ON COMPOSITE POWER SYSTEM RELIABILITY MEASURES

A three-bus test system (Fig 1) is used for evaluating the reliability measures, EENS and down times, based on the proposed algorithm. A simple system has been chosen for convenience while evaluating the reliability indices using the involved analytical methods. We have applied the analytical methods of evaluating the indices to this sample system. This section gives the details and outcome of the analysis carried out. The results using the Monte Carlo simulation method have also been evaluated to illustrate the procedure when applying for larger systems.

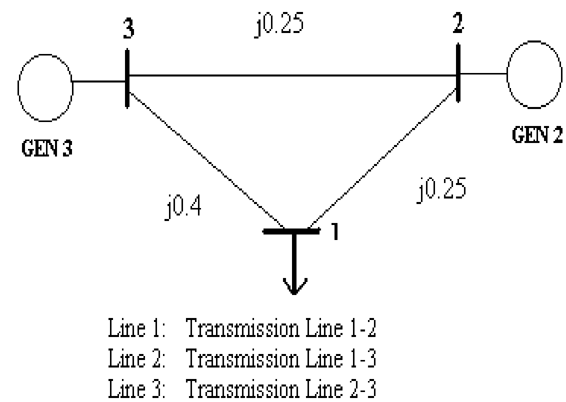

Fig. 1. Three-bus test system

In the above case we chose MVA limit of Line 1and 2 as 2.5 p.u while the limit of Line 3 was kept at 1.5 p.u. The load demand at Bus 3 was taken to be 1.4 + j 0.5 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u. The maximum and minimum acceptable voltage magnitude at the load bus 3 is taken to be 1.1 and 0.8 p.u. The L_{crit} limit is taken to be 0.3. By changing the value of L_{crit} we can change the voltage stability margin. A larger value indicates lower stability margin.

The state space of all the contingencies, resulting in a load curtailment, for the test system is enlisted in Table 1. For the remaining possible contingencies there happens to be a total loss of the load demand i.e 1.4 p.u. The curtailment value evaluated with and without the voltage stability margin criteria, in the OPF load curtailment formulation as discussed in this paper, are both shown in Table 1. It is to be noted that the curtailment value shown in the table represents the amount of real power curtailment. The load curtailment policy described in our algorithm sheds the same proportion of the reactive load and the active load.

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TABLE I
LOAD CURTAILMENT VALUES FOR CONTINGENCIES

Contingency (Outage Components)	Curtailment without L constraint(p.u)	Curtailment with L<=0.3 constraint(p.u)
No outage	0.0000	0.0000
Line 3	0.0000	0.0000
Gen 2	0.1675	0.1675
Gen 3	0.0403	0.0505
Line 2	0.2407	0.5252
Line 1	0.5954	0.8532
Gen 2, Line 2	0.7563	0.7592
Gen 3, Line 2	0.2407	0.5252
Gen 3, Line 3	0.2407	0.2407
Lines 2 & 3	0.2407	0.5252
Lines 1 & 3	0.5954	0.8532
Gen 2, Line 1	0.5954	0.8532
Gen 2, Line 3	0.5954	0.5954
Gen 3, Line 1	0.9049	0.9489
Gen 3, Lines 2 & 3	0.2407	0.5232

Since there are a total of five independent components in the test system there are 32 possible system states. To get the down times and EENS index analytically we reduce the complete state space into an equivalent three-state model as shown in Fig. 2. This three-state model has been formulated based on whether the states have load curtailment or not. It can be seen from Table 1, that there are only 2 states when curtailment does not occur i.e. when all components are UP or when Line 3 is DOWN. For all other states there is load curtailment. The equivalent transition rates for this three-stage model is evaluated using the frequency balance approach.

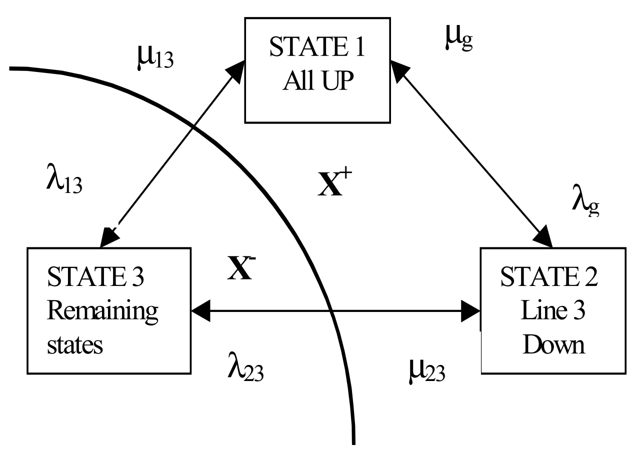

Fig. 2. Reduced equivalent three-state model for the system states

Here, λ denotes the failure rate and μ denotes the repair rate of the components. Here suffix (l) denotes the lines and suffix (g) denotes the generators. Failure of one component at a time is only considered for analysis.

Moreover, X^+ = { States with no load curtailment} X^- = { States with load curtailment} and the equivalent transition rates are given by equations (17,18).

$$\mu_{13} = \frac{P_1(\lambda_g + \lambda_g + \lambda_l + \lambda_l)}{1 - P_1 - P_2} = \frac{P_1(2\lambda_g + 2\lambda_l)}{1 - P_1 - P_2} \tag{17}$$

$$\mu_{23} = \frac{P_2(\lambda_g + \lambda_g + \lambda_l + \lambda_l)}{1 - P_1 - P_2} = \frac{P_2(2\lambda_g + 2\lambda_l)}{1 - P_1 - P_2} \tag{18}$$

where,

$$P_1 = \frac{\mu_l^3 \mu_g^2}{(\lambda_l + \mu_l)^3 (\lambda_g + \mu_g)^3} \tag{19}$$

$$P_2 = \frac{\lambda_l \mu_l^2 \mu_g^2}{(\lambda_l + \mu_l)^3 (\lambda_g + \mu_g)^3} \tag{20}$$

Here P_1 and P_2 the probabilities of the State 1 and State 2 of X^+

The Expected Energy Not Served and Down Time is defined by the following expressions.

$$EENS = 8760 * \left[\sum_{i=1}^{32} P_i * Curtailed \quad load\,(i) \right] hours \tag{21}$$

$$Down \;\; Time \begin{cases} = P(X^-) * 8760 \quad hours \\ = [1 - (P_1 - P_2)] * 8760 \quad hours \end{cases} \tag{22}$$

The probabilities of all the states required for evaluating the EENS, is obtained in the same way as P_1 and P_2. The results of the reliability index for two sets of failure and repair rates are given in Table 2 and Table 3.

Case I: $\lambda_l = 1$ /year $\mu_l = 1095$ /year
$\lambda_g = 1$ /year $\mu_g = 365$ /year
Case II: $\lambda_l = 10$ /year $\mu_l = 1095$ /year
$\lambda_g = 36.5$ /year $\mu_g = 365$ /year

TABLE II
RELIABILITY INDEX EVALUATED FOR CASE I

Reliability Index	Analytically	Monte-Carlo
EENS Without L Constraint (MW-hrs)	11.760899	11.7763
EENS With L<=0.3 Constraint (MW-hrs)	16.28370	16.6572
Down Time per Year (Hours)	63.6919	63.6161

TABLE III
RELIABILITY INDEX EVALUATED FOR CASE II

Reliability Index	Analytically	Monte-Carlo
EENS Without L Constraint (MW-hrs)	324.734	328.604
EENS With L<=0.3 Constraint (MW-hrs)	370.615	374.043
Down Time per Year (Hours)	1650.77	1664.80

For case 1, the EENS without the voltage stability margin constraint incorporation yields 11.761 MW-hrs while it is 16.283 MW-hrs when a constraint of L_{crit} of 0.3 is introduced into the load curtailment evaluation procedure. It was further observed in our computations that by reducing the L_{crit} the EENS became still larger. This brings out the fact that a more reliable operation from the point of view of voltage stability margin would be at the cost of a larger non-served energy. The same trend was observed when a larger failure rates of component, as in Case 2 scenario, is present.

The down times evaluated analytically were identical when computed with and without voltage stability margin criteria. This is because of the fact that for the test case example, the states when curtailment occurred were identical when evaluated both with and without the L index criteria. The only difference was the amount of load curtailment. However, the authors feel that for larger and practical systems this situation might not be true thus resulting in different down times.

The Monte-Carlo simulation based on the next event approach is then applied to the same test system. The EENS and the down time evaluated for the two cases and both situations of with and without voltage stability index L, agree quite closely with the analytical results. This is quite evident from the simulation results as shown in Table 2 and Table 3. A coefficient of variation of 0.03 was chosen as the stopping criteria for Monte-Carlo simulation runs.

V. CONCLUSIONS

The load curtailment evaluation is effected by the proposed incorporation of the voltage stability margin index into the OPF algorithm. The amount of curtailment evaluated is observed to increase if more voltage stability margin, from a possible collapse, is required in a system. The EENS increases when we tend to operate the system with a larger voltage stability margin. The down time evaluated, for the simple test case used for illustration in this paper, shows no change by incorporating the voltage stability margin. However, the authors feel that for a more bigger and practical system the down times would be larger if the operation demands a higher voltage stable operative margin. The Monte-Carlo simulation results match closely with the analytically computed reliability indices. Thus the proposed algorithm can be implemented, on larger systems, more time efficiently by using the numerical simulation methods.

This paper is thus able to formulate an effective method, which could be used in evaluating composite system reliability incorporating voltage stability.

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VII. BIOGRAPHIES

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