VOLTAGE STABILITY CONSIDERATIONS IN COMPOSITE POWER SYSTEM RELIABILITY EVALUATION

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Abstract - **This paper presents an approach which includes voltage stability considerations in the adequacy assessment of a composite power system. A fast technique for the probabilistic assessment of voltage stability is presented which can be used in conjunction with detailed contingency evaluation in a composite system adequacy assessment. Voltage stability is quantified using an indicator that can be easily included in the framework of an existing composite power system adequacy program. The effect on the adequacy indices (load point and system indices) of incorporating voltage stability constraints is illustrated by application to the IEEE-Reliability Test System.**

I. INTRODUCTION

Voltage stability has been defined by the System Dynamic Performance Subcommittee of the IEEE Power Engineering Committee as being the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and both power and voltage are controllable [1]. A voltage collapse may be caused by a variety of single or multiple contingencies such as a sudden removal of real or reactive power generation or a transmission element (a transformer or a transmission line), an increase of load without an adequate increase of reactive power. The voltage stability of a power system is greatly dependent upon the amount, location and type of reactive power sources available in the system. If the reactive power support is insufficient in quantity or physically far away then a relatively normal contingency such as a line outage or a sudden increase in load can trigger a large system voltage drop.

Voltage stability is a serious problem that power utilities usually explore in the planning stage. It is essential that techniques to protect a power system from a voltage collapse be investigated, taking into account all contingencies that cause the system to lose voltage stability. Significant progress has been made in the last decade in the development of methods to analyze and evaluate power system voltage stability [1-12]. There is no consensus on whether the voltage collapse mechanism is a steady-state [2-5] or dynamic [6-8] phenomena and therefore whether it should be analyzed by the relevant methods. This is perhaps due to the fact that voltage instability is a dynamic phenomena that possibly lends itself nicely to static analytical approaches.

Most of the computational tools developed so far are based on deterministic criteria, i.e., on the analysis of a predetermined set of severe but credible situations. Deterministic techniques usually result in effective designs, as they are based on engineering experience and on the analysts knowledge of the system. The essential weakness of such techniques is that they do not and cannot account for the probabilistic or stochastic nature of system behavior, of customer demands or of component failures. In recent years, voltage collapse has been considered recognizing the uncertainty associated with practical system operation [9-12].

Adequacy evaluation of a composite generation and transmission system in a complete sense involves the simulation and load flow analysis of each possible outage condition in the system in order to determine the inability to supply load, voltage violations, line generator overloads, violations of generator MVar, etc. and to quantitatively express the deficiencies, if any, in terms of reliability indices. Reference 13 presents an approach to calculate voltage collapse related bulk reliability indices as well as their impact on composite power system adequacy indices based on restoring system solvability by load shedding. This paper presents a fast technique to incorporate voltage stability considerations in the adequacy assessment of a composite power system. The voltage stability indicators developed in [3] are calculated for all possible system contingencies. A bisection algorithm is then used to determine the amount of load which must be shed to alleviate all voltage stability violations. The impact of considering voltage stability constraints on the adequacy indices is illustrated by application to the IEEE-RTS [14]. The proposed technique can be easily included in an existing composite power system adequacy program to monitor the effect on the adequacy indices of incorporating voltage stability constraints.

II. VOLTAGE STABILITY CONSIDERATIONS IN COMPOSITE POWER SYSTEM RELIABILITY EVALUATION

There are two fundamental approaches to composite power system adequacy evaluation: analytical enumeration and Monte Carlo simulation. There is a wide range of computer programs

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available for composite power system adequacy evaluation. These programs are briefly described in Reference 15, including a list of the calculated indices and the factors involved in the assessment. The approach presented in this paper is based on an analytical enumeration procedure for composite system evaluation. It can be also incorporated in a Monte Carlo simulation program.

1. Calculation of voltage stability indicators

For a given system contingency, voltage stability indicators can be calculated using the AC load flow results as follows:

The hybrid representation of a transmission system is given by the following equation:

$$\begin{bmatrix} \mathbf{V^L} \\ \mathbf{I^G} \end{bmatrix} = \begin{bmatrix} \mathbf{Z^{LL}} & \mathbf{F^{LG}} \\ \mathbf{K^{GL}} & \mathbf{Y^{GG}} \end{bmatrix} \begin{bmatrix} \mathbf{I^L} \\ \mathbf{V^G} \end{bmatrix} \tag{1}$$

where $\mathbf{V^L}$, $\mathbf{I^L}$ are the vectors of voltage and currents at customer nodes,
$\mathbf{V^G}$, $\mathbf{I^G}$ are the vectors of voltage and currents at generator nodes,
$\mathbf{Z^{LL}}$, $\mathbf{F^{LG}}$, $\mathbf{K^{GL}}$, $\mathbf{Y^{GG}}$ are sub matrices of the hybrid matrix.

Reference 3 defines the indicator L_{Kj} to assess the voltage stability of load bus K under a given outage condition j as follows:

$$L_{Kj} = \left| 1 - \frac{\sum_{i \in \alpha_G} F^{\oplus}_{Ki} V^{\oplus}_{i}}{V^{\oplus}_{K}} \right| \tag{2}$$

The indicator at each bus varies between zero (no load) and one (voltage collapse). The superscript ($\oplus$) for any of the sub matrices' elements and the bus voltages represents the adjusted value after modifying the hybrid matrix and the bus voltages due to outage j.

2. Incorporating voltage stability considerations in composite power system adequacy evaluation

There is no consensus among power utilities regarding uniform failure criteria and therefore all utilities do not use the same fundamental network solution technique to calculate the system adequacy. The basic justification for these differences lies in the intent behind the adequacy studies. This paper deals with the problem of incorporating voltage stability considerations in composite power system reliability evaluation. The utilization of AC load flow is therefore an integral part of the solution process.

It should be noted that the occurrence of a system problem may be itself recorded as a failure event. In many cases, however, it is possible to eliminate a system problem by taking appropriate corrective action. It is, therefore, of interest to determine whether it is possible to eliminate a system problem by employing proper corrective actions such as generation rescheduling, correction of MVar limit violations, alleviation of line overloads, the solution of ill-conditioned network situations and/or load curtailment.

The basic structure of the contingency enumeration approach after incorporating voltage stability considerations is shown in Figure 1. In this figure, load is curtailed, if necessary, for some contingency due to violating the operational constraints (capacity deficiency in the system, bus isolation, network islanding and line/transformer overloads) or due to violating the voltage stability constraints. Load curtailments due to violating operational constraints are discussed in detail in many composite power system reliability publication and are not repeated in this paper. If the voltage stability constraints are violated, load is curtailed to ensure that the voltage stability indicators at all system load buses are less than or equal an acceptable threshold value.

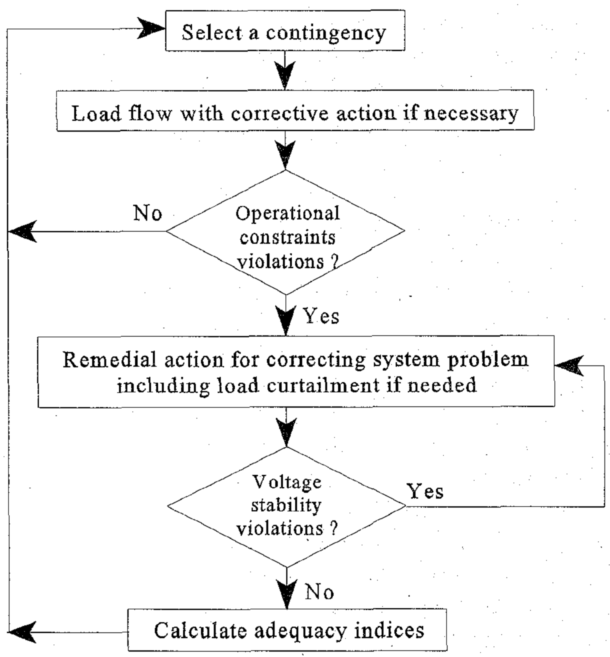

Figure 1: Basic structure of the contingency enumeration approach.

If the voltage stability constraints are violated, the load bus which has the highest voltage stability indicator is selected to carry out load shedding using a bisection algorithm as shown in Figure 2. Load shedding at this bus is an efficient way to reduce the voltage stability indicators. In this case, the system is initially operating at point 1 which has a voltage stability indicator of L_1. A bisection algorithm [16] can be used to determine the minimum amount of load to be shed (ΔP) to reduce the value of the voltage stability indicator at the selected bus from L_1 to L_2, where L_2 is the minimum acceptable voltage stability indicator "threshold value". Initial load limits $[P_1, P_2]$ are defined for the selected bus load where P_1 equals zero and P_2 equals the original load at the selected load bus (P_o). Voltage stability violation is then checked at the mid point of these limits, P_m. If it is found that the voltage stability constraints are satisfied, then the lower load limit of the interval is replaced by the mid point value, P_m. Otherwise, the upper value is replaced by the mid-point value, P_m. The procedure is repeated until the required minimum load ($\Delta P = P_o - P_m$) which must be shed at the selected bus to reduce the value of the voltage stability indicator at this bus from L_1 to L_2 is determined. The voltage stability indicators are then recalculated for all the system load buses, using the procedure described in [3], and the bisection process is repeated in the case of another voltage violation until all buses do not are violate the voltage stability constraints.

The threshold value of the voltage stability indicator is less than one and should be selected for a given system in such a way that the power system is far from a voltage instability point. It is worthwhile noting that the threshold values are nearly the same for every power system. Such a value can be obtained in the state where the voltage profile is higher than or equal to the minimum acceptable voltage and at the same time all the generators are operating within their reactive power limits [5]. The load power factor is assumed to be constant at each load bus after shedding a portion of the load.

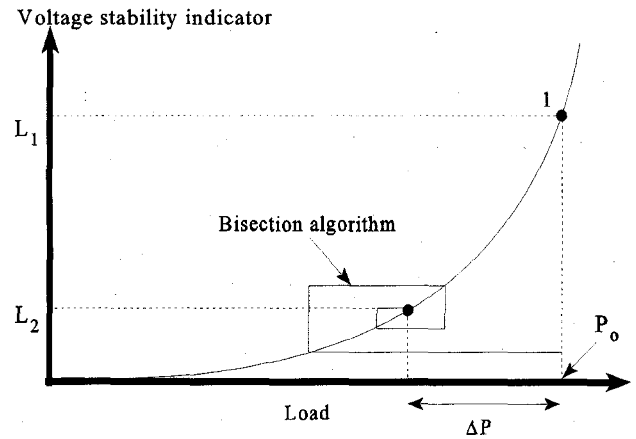

Figure 2: Functional description of the load-shedding calculation process using the bisection algorithm.

III. ADEQUACY INDICES FOR THE IEEE-RTS CONSIDERING VOLTAGE STABILITY CONSTRAINTS

The single line diagram of the 24-bus IEEE-RTS is shown in Figure 3 [14]. The system has 10 generator (PV) buses, 10 load (PQ) buses, 33 transmission lines and 5 transformers. The total number of generating units is 32 with a minimum and maximum rating of 12 MW and 400 MW respectively. The system can be divided into two subsystems on the bases of voltage levels. The north subsystem is at 230 KV and the south subsystem is at 138 KV. The northern region has a surplus in power while the southern region is a power deficient area. The north subsystem load is 1518 MW while that of the south subsystem is 1332 MW. The installed capacity in the north region is 2721 MW and that of the south is 684 MW. In the analysis conducted in this section, independent overlapping outages up to the fourth level for generating units and up to the third level for transmission lines and/or generating units are considered.

2. *Effect on the load point indices of incorporating voltage stability considerations*

Table 1 lists the probability and frequency of failure for the different buses in the IEEE-RTS. Two cases are presented: Case I is the traditional adequacy evaluation (without voltage stability considerations, i.e., only operational constraints violations are considered) and Case II presents the indices after considering voltage stability constraints. It can be seen from this table that an increase in the failure probability and frequency occurs when voltage stability constraints are considered. The highest percentage increase in the indices when considering voltage stability constraints are for buses 3-6, 8-10, which are located in the 138 KV portion of the network and has inadequate MVar generation. On the other hand buses 19 and 20 which have the lowest percentage increase in the indices are located in the 230 KV side of the network which has 80% of the total system generation. It should be noted that the inclusion of voltage stability considerations do not affect the indices of buses 1, 2, 7 and 15-18 since these buses are voltage controlled buses.

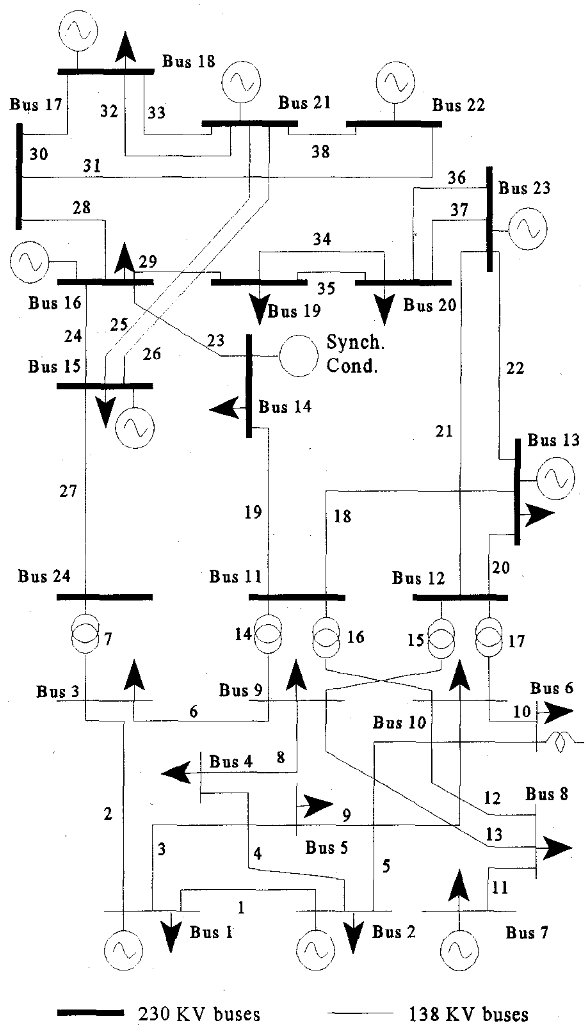

Figure 3: Single line diagram of the IEEE-RTS.

Table 1: Effect on the basic load point reliability indices for the IEEE-RTS of voltage stability considerations.

	Failure probability			Failure frequency, occ./year		
Bus	Case I	Case II	% Increase	Case I	Case II	% Increase
1	0.022121	0.022121	0	16.1163	16.1163	0
2	0.040691	0.040691	0	29.3499	29.3499	0
3	0.035973	0.039858	10.8	24.0812	26.6098	10.5
4	0.030453	0.032402	6.4	21.3727	22.7406	6.4
5	0.030713	0.032648	6.3	21.6890	22.8385	5.3
6	0.028481	0.032354	13.6	20.1240	22.8206	13.4
7	0.016587	0.016587	0	12.1405	12.1405	0
8	0.024958	0.025931	3.9	17.3626	17.9008	3.1
9	0.020945	0.021908	4.6	13.0602	13.6087	4.2
10	0.021914	0.022878	4.4	13.7758	14.3544	4.2
13	0.069587	0.069587	0	44.3912	44.3912	0
14	0.009168	0.009562	4.3	6.5388	6.7938	3.9
15	0.057700	0.057700	0	36.0577	36.0577	0
16	0.025452	0.025452	0	17.8907	17.8907	0
18	0.084624	0.084624	0	52.2797	52.2797	0
19	0.038315	0.038698	1.0	23.1251	23.2407	0.5
20	0.047868	0.048299	0.9	31.1860	31.3419	0.5

The risk indices presented in Table 1 are based on the theoretical foundation that the point of collapse is reached when the voltage stability indicator equals or is greater than 1.0. Experiments show that a voltage instability indicator of 0.2 to 0.3 is a good criterion for safe operation [5]. When the 0.3 threshold is exceeded, the indicator increases rapidly with a small increase in loading or a change in the network topology. Table 2 shows the effect of on the probability and frequency of failure for different load buses (Case III) using a voltage stability indicator threshold value of 0.3. Table 2 shows that the risk indices for a given load bus increase as the threshold value of the indicator decreases. It can be seen from this table that the southern region of the IEEE-RTS is more sensitive to the change in the voltage stability threshold value. This is due to a deficiency in MVar generation in this region. The northern subsystem which contains 80% of the total system generation is less likely to experience voltage instability problems.

Table 3 lists the average load and energy curtailment indices for different load buses of the IEEE-RTS. Two cases are compared: Case I (without considering voltage stability constraints) and Case III (Considering a practical voltage stability indicator threshold value of 0.3). It can be seen from this table that the incorporation of voltage stability constraints increases the average load and energy curtailment indices. It can also be seen that the southern subsystem which contains 20% of the total system generation and 47% of the total system load violates the voltage stability constraints more often than the northern subsystem.

The adequacy indices calculated for Cases I, II and III do not consider uncertainty in the forecast load. It was assumed that loads in the IEEE-RTS are normally distributed with a standard deviation of 4%. The normal distribution can be approximated by a discrete seven interval model. Table 4 lists the voltage stability indices for different IEEE-RTS load buses. Two cases are presented: without including load forecast uncertainty (Case III) and when load forecast uncertainty is included (Case IV). It can be seen from Table 4 that the risk indices increase when load forecast uncertainty is considered. This is due to the fact that the voltage stability indicators sometimes increase rapidly even with only a small increase in the system load. The maximum increases are for buses 3-6, 8-10 which are located in the 138 KV portion of the network. Buses 14, 19, 20 are located in the 230 KV side of the network which has 80% of the total system generation and therefore are less affected by the load forecast uncertainty.

Table 2: Effect on the basic load point indices for the IEEE-RTS of using a practical voltage stability criterion.

	Failure probability			Failure frequency, occ./year		
Bus	Case I	Case III	% Increase	Case I	Case III	% Increase
3	0.035973	0.040974	13.9	24.0812	27.2212	13.0
4	0.030453	0.033455	9.9	21.3727	23.4437	9.7
5	0.030713	0.033714	9.8	21.6890	23.6688	9.1
6	0.028481	0.033489	17.6	20.1240	23.4731	16.6
8	0.024958	0.026963	8.0	17.3626	18.7481	8.0
9	0.020945	0.022947	9.6	13.0602	14.2977	9.5
10	0.021914	0.023923	9.2	13.7758	14.9163	8.3
14	0.009168	0.009671	5.5	6.5388	6.8351	4.5
19	0.038315	0.038821	1.3	23.1251	23.2998	0.8
20	0.047868	0.048375	1.1	31.1860	31.4667	0.9

Table 3: Effect on the average load and energy curtailment indices for the IEEE-RTS of voltage stability considerations.

	Average load curtailed, MW			Average energy curtailed, MWh		
Bus	Case I	Case III	% Increase	Case I	Case III	% Increase
3	20.8120	22.3120	7.2	292.413	311.609	6.6
4	8.7120	9.2120	5.7	112.307	118.705	5.7
5	8.2350	8.4850	3.0	106.639	109.532	2.7
6	15.4260	16.9260	9.7	199.177	218.107	9.5
8	21.1270	21.6270	2.4	273.289	277.26	1.5
9	20.9380	21.4380	2.4	291.456	297.537	2.1
10	23.9470	24.4470	2.1	335.466	339.772	1.3
14	18.9800	19.2300	1.3	226.232	228.034	0.8
19	22.9900	23.2400	1.1	340.921	342.579	0.5
20	17.0320	17.2820	1.5	236.665	238.586	0.8

Figure 4 shows the effect on the basic load point risk indices (probability and frequency of failure) at buses 3 and 16 of changing the threshold value of the voltage stability indicator. It can be seen from this figure that, for a given load point, the risk indices increase as the threshold value decreases. The load point risk indices for buses 3 and 19 respectively, when a threshold value for the voltage stability indicator of 0.3 is used, are approximately 13% and 1% higher than the values obtained

Table 4: Effect on the basic load point indices for the IEEE-RTS of using a practical voltage stability criterion.

	Failure probability			Failure frequency, occ./year		
Bus	Case III	Case IV	% Increase	Case III	Case IV	% Increase
3	0.040974	0.04265	4.1	27.2212	28.2637	3.8
4	0.033455	0.03443	2.9	23.4437	24.1145	2.9
5	0.033714	0.03469	2.9	23.6688	24.3033	2.7
6	0.033489	0.03523	5.2	23.4731	24.6199	4.9
8	0.026963	0.0276	2.4	18.7481	19.1898	2.4
9	0.022947	0.0236	2.8	14.2977	14.6985	2.8
10	0.023923	0.02457	2.7	14.9163	15.2806	2.4
14	0.009671	0.0098	1.6	6.8351	6.9258	1.3
19	0.038821	0.03897	0.4	23.2998	23.3548	0.2
20	0.048375	0.04854	0.3	31.4667	31.5502	0.3

for the load points without including any voltage stability constraints. Figure 4 also shows that bus 3 which is located in the southern subsystem is more sensitive to voltage stability constraints than bus 19 which is located near the major generating stations.

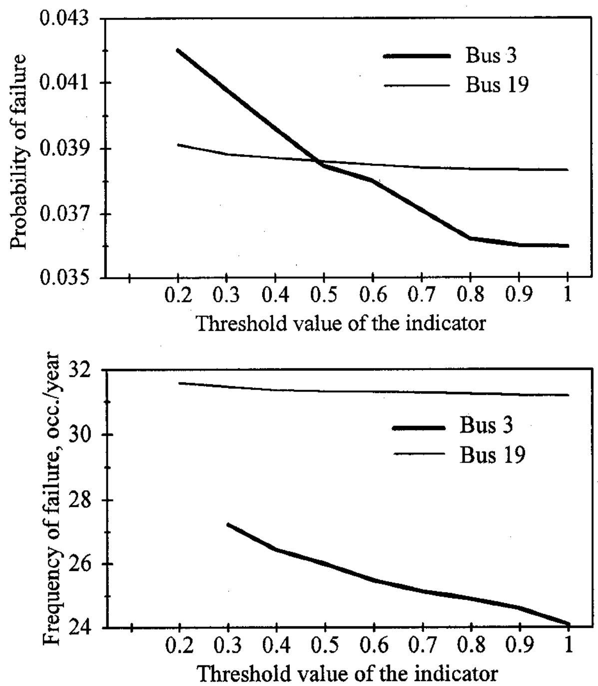

Figure 4: Effect on the probability and frequency of failure of changing the threshold value of the voltage stability indicator.

2. *Effect on the system indices of incorporating voltage stability considerations*

The load point indices are very useful in system design and in comparing alternative system configurations. The overall system indices indicate the adequacy of the composite generation and transmission system to meet its total load demand and energy requirements. It is important to appreciate that the two sets of load point and system indices do not replace each other but are complementary. Table 5 shows the effect on the overall system indices of the IEEE-RTS of incorporating voltage stability considerations. Table 5 shows that there is an increase of more than 3% in the overall system indices by incorporating voltage stability considerations in the analysis (Case III). It can be seen from this table that the maximum percentage increases in the system indices due to incorporating voltage stability considerations are lower than those obtained for the load points. This is due to the fact that the voltage stability constraints do not impact some of the PV controlled load points (1, 2, 7 and 15-18).

Table 5: Effect on the system indices for the IEEE-RTS of voltage stability considerations.

Index	Case I	Case III	% Increase
Basic Values			
Bulk Power Interruption Index (MW/MW-Yr)	3.52198	3.65289	3.7
Bulk Power Energy Curtailment Index (MH/MW-Yr)	49.2961	50.8648	3.2
Bulk Power Supply Average MW Curtailment Index (MW/Dist.)	160.521	165.775	3.3
Severity Index (System Minutes)	2957.77	3050.89	3.2
Modified Bulk Power Energy Curtailment Index	0.005637	0.005807	3.0
Average Values			
Load Curtailment/Load Point/Year	590.450	612.397	3.7
Energy Curtailment/Load Point/Year	8264.34	8527.35	3.2

Figure 5 shows the effect on the severity index (system minutes) of changing the threshold value of the voltage stability indicator when load forecast uncertainty is not included (Case III) and when the load forecast uncertainty is included (Case IV). It can be seen from this figure that the severity index increases as the threshold value decreases. The severity index, when a threshold value for the voltage stability indicator of 0.3 is used, is 3% higher than the one obtained for the system without including any voltage stability constraints (only operational constraints are included) and 5% higher when load forecast uncertainty is included. Similar curves can be drawn for other system indices.

Voltage stability is a serious problem that must be considered in the system planning stage. It is essential that techniques to protect a power system from a voltage collapse, which take into account all the contingencies that can cause the system to lose voltage stability, be investigated. This can be achieved by including acceptable voltage stability constraints in the evaluation of composite power system adequacy indices. The studies presented in this paper show that the inclusion of voltage stability considerations in composite generation and transmission adequacy assessment can result in a significant increase in both the load point and system adequacy indices. This increase is further amplified by considering load forecast uncertainty in the analysis.

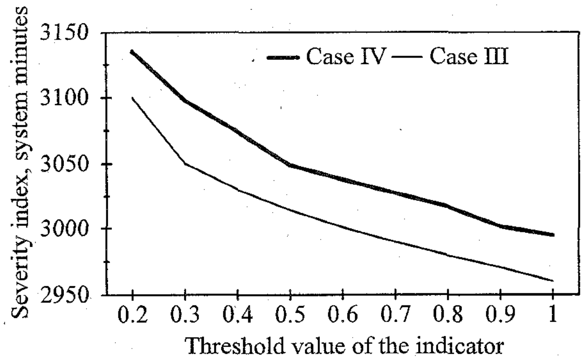

Figure 5: Effect of changing the threshold value of the voltage stability indicator on the severity index.

IV. CONCLUSIONS

This paper presents an effective and fast technique to incorporate voltage stability considerations in composite generation and transmission system adequacy evaluation. In this technique, load shedding is performed in two stages. In the first stage, load is curtailed, if necessary, to eliminate any operational constraint violations and in the second stage load is curtailed, also if necessary, to restore the system to a voltage-stable operating point using a simple voltage stability indicator derived from the AC load flow results. A fast bisection algorithm is used to calculate the amount of load to be shed in the case of voltage stability violations. The proposed technique can be easily incorporated in an existing composite power system adequacy program. The numerical results show that the proposed technique suitably reflects the effects of voltage stability constraints on the composite generation and transmission system adequacy indices.

V. REFERENCES

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VI. BIOGRAPHIES

Roy Billinton (F'78) came to Canada from England in 1952. Obtained B.Sc. and M.Sc. Degrees from the University of Manitoba and Ph.D. and D.Sc. Degrees from the University of Saskatchewan. Worked for Manitoba Hydro in the System Planning and Production Divisions. Joined the University of Saskatchewan in 1964. Formerly Head of the Electrical Engineering Department. Presently C.J. Mackenzie Professor of Engineering and Associate Dean, Graduate Studies, Research and Extension of the College of Engineering.

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