SOME ISSUES IN IMPLEMENTATION OF A VOLTAGE STABILITY ANALYSIS FUNCTION IN AN ENERGY MANAGEMENT SYSTEM ENVIRONMENT

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Abstract Over the last few years, the problem of voltage stability has received a lot of attraction from the power system community. This type of stability is now a major concern for utilities in both planning and operating conditions. Both static and dynamic aspects of the problem have been discussed and investigated by the researchers. The present paper concentrates on a Voltage Stability Analysis function as integrated into an Energy Management System (EMS) environment. In order to provide an optimal user interface, the function is integrated into the contingency analysis function. Key issues such as the integration approach, the voltage dependency of load characteristics, the choice of current point distance to critical point in terms of either MVAr, MW or MVA as well as a fast screening approach for finding the most potential unstable load nodes in an EMS are reviewed. The function has been implemented at the customer's NOK, Baden Switzerland-site in an on-line environment. Initial results are promising.

Key Words Voltage Stability, Voltage Collapse, Power System Stability, Energy Management System, Power System Dynamics

چکیده در طی چند سال اخیر موضوع پایداری ولتاژ از دیدگاههای استاتیکی و دینامیکی در دو بعد طراحی و بهره برداری مورد توجه محققین بسیاری قرار گرفته است. در این مقاله یک تابع بررسی پایداری ولتاژ که در سیستم مدیریت انرژی پیاده سازی شده است مورد توجه و بررسی قرار می گیرد. به منظور حداکثر استفاده مطلوب از تابع، از برنامهٔ اصلی «بررسی پیشامدها» استفاده شده است. نکات کلیدی از جمله روش مجتمع سازی با برنامه های اصلی، وابستگی مشخصه های بار به ولتاژ، انتخاب نوع فاصله تا ناپایداری ولتاژ بر حسب مگاوات، مگاوار یا مگاولت آمپر و نیز روشی ساده جهت شناسائی کلی مستعدترین گره های بار به ناپایداری در سیستم مدیریت انرژی مورد تجزیه و تحلیل قرار می گیرد.

INTRODUCTION

During the last few years, both dynamic and static aspects of voltage stability problem have received attention in the literature [1-12]. Although, system dynamics including loads may have strong influences on voltage stability phenomenon [13-15], for the vast majority of registered voltage collapses, these dynamics are slow [12]. So, for the cases in the time frame from a few minutes on, many aspects of the problem can be effectively analyzed by using static methods. This may be done by capturing snapshots of system conditions at various time intervals, typically every 5 to 15 minutes, and performing the required analysis. This type of analysis is specially attractive for an on-line environment where the speed of computation is of major concern. In this environment, a simple stability criterion, the distsances of selected load nodes from voltage collapse, in terms of MVAr, MW or MVA, is of interest. The operator is warned if specified limits are violated in order to give him enough time to take any remedial action. The present paper addresses some issues for a practical implemenation of a Voltage Stabilty Analysis (VSA) function in an EMS environment. As the main cause of almost any voltage collapse happens to be some sort of contingencies, the function described in this paper is considered to be part of contingency analysis package. The basic algorithm and the integration procedure are covered in Section 1. The choice of distance calculation type (MVAr, MW or MVA) in an on-line environment is described in Section 2. Section 3 covers how the voltage dependency of load characteristcs may affect the voltage stability analysis. A fast screening approach for finding the most potential unstable load nodes in an EMS environment is finally reviewed in Section 4.

1. ALGORITHM AND INTEGRATION PROCEDURE

1.1 Overview

The well-known pictorial representation of voltage collapse phenomenon is shown in Figure 1. The key point is to calculate how far the current operating

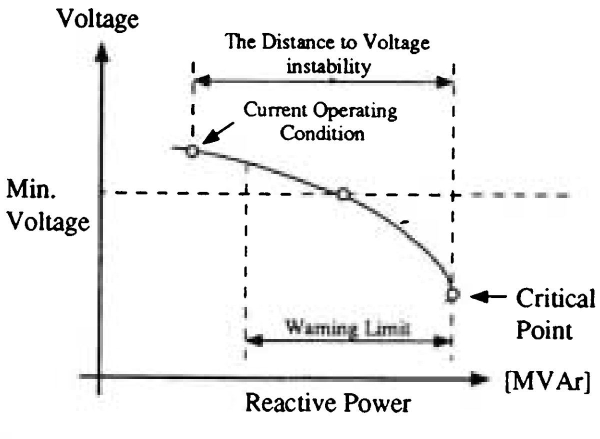

Figure1. Voltage-reactive power curve at a specific node.

point is away from the critical point. The distance is calculated in terms of MVAr, MW or MVA. Section 1.2 briefly reviews how MVAr distance is calculated. A similar approach is empolyed for the calculation of distance in terms of MW and MVA.

1.2 Algorithm

System voltage stability is affected by both P and Q. However, at each operating point, the voltage stability is evaluated by considering the incremental relationship between Q and V while P is kept constant. A brief descriptin is as follows. In the well-known power flow Equation 1:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \qquad (1)$$

Let, $\Delta P = 0$, then:

$$\Delta Q = J_R \, \Delta V \qquad (2)$$

where

$$J_R = [J_{QV} - J_{Q\theta} \, J^{-1}_{P\theta} \, J_{PV}] \qquad (3)$$

is the reduced Jacobian matrix of the system. The i[th] diagonal element of J^{-1}_R is the V-Q sensitivity at node i, which is the slope of the Q-V curve at the given operating point. The loading of the node analyzed is incremented till any sign change appears in sensitivity elements of load nodes. The corresponding MVAr distance is then easily calculated. The mathematical framework is provided in [8]. The practical implementation of an improved version of the algorithm given in [8] is summarzied below.

Selection of step size for power increment is the most critical issue in the successful implementation of sensitivity method. While small steps are essential for robustness, they are undesirable from a computational viewpoint, especially in an on-line environment. The difficulty lies in the relative curvature of the solution path. In a region with little curvature, large step size may be taken, while if the curvature is high, a small step size is appropriate.

Let a scalar γ_i be defined for a point j on V-Q curve as:

$$\gamma_i = \frac{\frac{dV_i}{dQ_i}\Big|_{j-1} - \frac{dV_i}{dQ_i}\Big|_j}{STEP_{j-1}} \qquad (4)$$

where the derivatives represent the sensitivity elements at two consecutive iteration points j-1 and j and $STEP_{j-1}$ is the actual step size adopted for condition j-1. In this way, γ_j provides an approximate curvature information of the problem. The step size for condition j, then may be selected as;

$$STEP_j = \begin{cases} STEP^{max} & \text{if } \gamma_j < \text{thresh } 1 \\ STEP^{max} * r & \text{if thresh } 1 \le \gamma_j < \text{thresh } 2 \\ STEP^{max} * r^2 & \text{if thresh } 2 \le \gamma_j < \text{thresh } 3 \\ STEP^{max} * r^3 & \text{if } \gamma_j \ge \text{thresh } 3 \end{cases} \qquad (5)$$

where $STEP^{max}$ is a constant and initial step limit and r is a ratio by which the step length should be reduced (r<1.0). Thresh 1, 2 and 3 are threshold values adopted by the user.

More details are provided in Reference 16.

1.3 Integration Procedure

The voltage stability analysis function is integrated as an add-on to the contingency analysis function of a highly integrated EMS environment. The integration procedure is shown in Figure 2, where DDS denotes Dynamic Data Structure. Two flags, namely, VSA_ON_BASE (which may take the value of 0 or 1) and VSA_CAN_MODE (which may take the

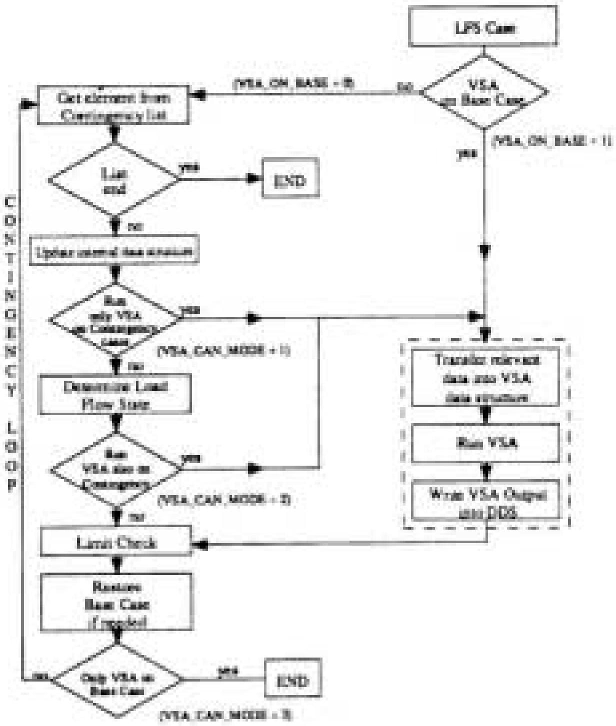

Figure 2. Voltage stabillity analysis function integration into EMS environment.

TABLE 1. Modes of Operation

MODE	VSA_ON_BASE	VSA_CAN_MODE
A:Run only Contingency Analysis	0	0
B:Run VSA on Contingency Cases	0	1
C:Run VSA and Contingency on Contingency Cases	0	2
D:Run VSA only on Base Case	X (DO NOT CARE)	3
E:The same as A, but also VSA on Base Case	1	0
F:The same as B, but also VSA on Base Case	1	1
G: The same as C, but also VSA on Base Case	1	2

value of 0, 1, 2 or 3) may be used to set appropriate options. All foreseen contingency and voltage stability analyses can, thus, be performed as shown in Table 1.

For instance, only contingency analysis may be run for Mode A. The user may select Mode B where VSA is run following the selected contingencies. Note that no contingency analysis is performed here. The user may select Mode C where in fact both options A and B are run together.

In either of the above cases, Modes E, F and G may be selected to run the VSA function on the base case as well. For voltage stability analysis only on base case, Mode D is available.

Special care has been taken to provide a user interface for specifying the points to be analyzed (MODES, limits, etc.) as well as to present the results in a form which is readable and understandable by the operator. In effect, the proximities of some load nodes, selected by the user, to voltage instability are calculated. Similar to other limit violations, the operator is warned if either of the following limit violations has occurred:

- Warning limit violation
- Alarm limit violation

These two types of limits are bus dependent. Alarm limit violation represents a more severe case in comparison with the warning limit violation. There is no golden rule for specifying the limit values. In practice, they are defined according to the utility experiences. An appropriate choice is to set them as a percentage of peak demand on the specific bus of concern.

2. CHOICE OF DISTANCE CALCULATION TYPE

The distance to voltage instability point may be calculated in terms of MVAr, MW or MVA. Each of them may be considered as a suitable candidate in planning phase. In an on-line environment, however, the choice may not be so clear-cut, as the computational time is of major concern. To analyze the problem, an 18 node ABB internal test system, shown in Figure 3, is used. Using the algorithm described in Reference 16, the voltage stability analysis results for the base case are shown in Table 2. Five load nodes are selected. The results in terms of MVAr, MW and MVA are presented. They show, generally, the same pattern, for all nodes, with node 4 as the weakest and, node 17, as the strongest. The distances in terms of MW are, however, appreciably higher than the case where either MVAr, or MVA is selected. It implies that if the distance to critical point is to be found, more calculation steps should be performed whenever MW is considered. To analyze the actual effect, Table 3 summarizes the CPU time on a VAX 3100 machine when either MVAr, MW or

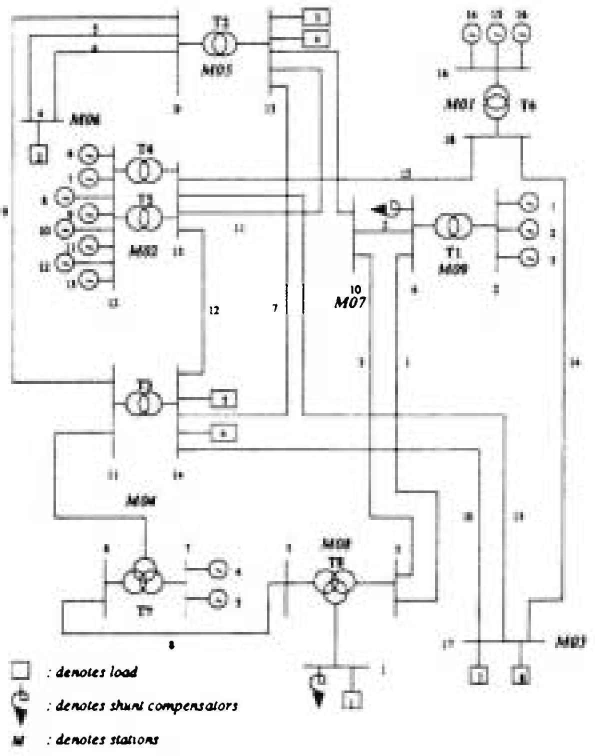

Figure 3. System under study.

MVA is selected as the VSA distance calculation type. Also shown, are the results for four other systems, namely a 5 node, a 14 node, a 30 node and a 118 node IEEE systems. Although the execution time depends on the system and the number of load nodes to be analyzed, the results shown generally demonstrate a faster execution time for MVAr and MVA in comparison with MW cases. Due to strong coupling between reactive power and voltage, in terms of physical considerations, it may be more meaningful to select MVAr as the distance calculation type.

Generally it should be mentioned that in practice, active and reactive powers of a node can not be, independently, varied. However, in terms of distance to voltage collapse, they show more or less the same pattern as shown in Figure 1. In effect, whether MVAr, MW or MVA is used, the operator is warned of the most vulnerable nodes to voltage instability. He should then take remedial actions to prevent any unwanted situation.

3. EFFECT OF LOAD CHARACTERISTICS

Since voltage characteristics of loads have an important influence on the calculation of the distances, they have to be considered. The characteristics empolyed are:

$$P_i(V) = P_i^0 \, (a_p V_i^2 + b_p V_i + c_p) \qquad (6)$$

$$Q_i(V) = Q_i^0 \, (a_q V_i^2 + b_q V_i + c_q) \qquad (7)$$

where a_p (a_q), b_p (b_q) and c_p (c_q) represent constant impedances, constant current and constant power coefficients for active (reactive) demand, respectively.

Table 4 summarizes the distance results whenever all eight major loads connected to five load nodes are considered to be voltage dependent as defined by

TABLE 2. VSA Distances, Voltage Independent Load Characteristics Considered.

Option \ NODE NO.	1	4	13	14	17
MVAr Analysis [MVAr]	196	32	221	233	261
MW Analysis [MW]	390	73	601	598	669
MVA Analysis [MVA]	154	22	177	181	203

TABLE 3. CPU Time for Different Systems.

Option \ System	18	5	14	30	118
MVAr Analysis [sec.]	0.57	0.32	0.47	2.17	46.30
MW Analysis [sec.]	0.79	0.36	0.54	2.47	56.26
MVA Analysis [sec.]	0.48	0.29	0.42	1.93	38.07

TABLE 4. VSA Distances, Voltage Dependent Load Characteristics for all Loads Considered (See Equations 8 and 9).

Option \ NODE NO.	1	4	13	14	17
MVAr Analysis [MVAr]	284	87	531	592	657
MW Analysis [MW]	531	170	1149	1165	1298
MVA Analysis [MVA]	219	63	416	445	493

Equations 6 and 7 with:

$$a_p = 0.1,\ b_p = 0.2,\ c_p = 0.7 \quad (8)$$

$$a_q = 0.1,\ b_q = 0.2,\ c_q = 0.7 \quad (9)$$

The results clearly demonstrate that the distances have been , considerably increased (compare with Table 2). It is suggested [8] that if the security of the network is evaluated by keeping a minimum margin to voltage instability, a constant power representation of loads, will give the safest operational state of the network. The differences between the results of Tables 2 and 4 are, however, quite significant and if the loads are truly voltage dependent (which often happens to be the case), with constant power representation, the operator may be unnecessarily warned of limit violations. He then should think of remedial actions, which upon not available sufficient resources, he would find himself under large pressure. Therefore, appropriate and proper modelling of voltage dependency of load characteristics have beneficial effects, especially, in an on-line environment.

Although a number of good papers have been published in the field of load modelling [ex. 17, 18], the difficulty lies in the fact that evaluating the required data is not straight-forward. So, from a practical point of view, constant load representation is considered to be more attractive. In effect, for analysis of voltage stability, the least number of loads should be properly modelled so that the required accuracy is not sacrified. Section 3.1 explains the case.

3.1 Case Study

To alalyze the effect of load characteristics on voltage stability, the system shown in Figure 3 is studied in more details. The MVAr-analysis results are shown in Table 5. Voltage dependent load characteristics is considered only for one node, at a time. If more than one load is connected to the node of concern, all are treated to be voltage dependent. Each main column shows the results for the corresponding node. The errors in comparison to the values of Table 4 (where all loads considered to be voltage dependent) are also demonstrated. The relative errors for the case, where Node 4 loads are condidered to be voltage dependent, are quite small (maximun error=22%) where in other cases, the errors may be up to about

TABLE 5. VSA Distances; Voltage Dependent Load Characteristics Considered only for one Node at a Time, MVAr-analysis (MVAr).

* Node No.	NODE 1		NODE 4		NODE 13		NODE 14		NODE 17	
	value	% error	value	% error	value	%error	value	% error	value	% error
1	239	16%	226	20%	197	31%	199	30%	199	30%
4	32	63%	86	1%	33	62%	33	62%	33	62%
13	221	58%	435	18%	256	52%	228	57%	228	57%
14	244	59%	465	21%	248	58%	284	52%	255	57%
17	271	59%	510	22%	275	58%	283	57%	319	51%

* Voltage dependent load characteristics is considered only for the load(s) connected to this node.

60% high.

Tables 6 and 7 show the results for MW-analysis and MVA-analysis, respectively. The same general conclusion applies to these cases, too. The results demonstrate the fact that if results with sufficient accuracy are to be obtained, the detailed load characteristics have to be considered only for Node 4. This is the weakest node as all earlier results demonstrate. Section 4 reviews how the problem can be investigated in a large scale power system.

4. A FAST SCREENING APPROACH FOR FINDING MOST POTENTIAL UNSTABLE LOAD NODES

From two viewpoints, a screening approach for finding the most potential unstable nodes is desirable. First, in a large scale power system, the number of load nodes are quite high and if all of them are selected for voltage stability analysis, the computational requirements are too high. Moreover, not all load

TABLE 6. VSA Distances; Voltage Dependent Load Characteristics Considered only for one Node at a Time, MW-analysis (MW).

* Node No.	NODE 1		NODE 4		NODE 13		NODE 14		NODE17	
	value	% error	value	% error	value	%error	value	% error	value	% error
1	446	16%	450	15%	392	26%	395	25%	395	25%
4	73	57%	167	2%	73	57%	73	57%	73	57%
13	599	48%	941	18%	679	41%	618	46%	619	46%
14	600	48%	946	19%	610	48%	695	40%	623	47%
17	671	48%	1042	20%	677	48%	695	46%	723	44%

* Voltage dependent load characteristics is considered only for the load(s) connected to this node.

TABLE 7. VSA Distances; Voltage Dependent Load Characteristics Considered only for one Node at a Time, MVA-analysis (MVA).

* Node No.	NODE 1		NODE 4		NODE 13		NODE 14		NODE 17	
	value	% error	value	% error	value	%error	value	% error	value	% error
1	182	17%	176	20%	155	29%	155	29%	156	28%
4	22	65%	62	2%	22	65%	22	65%	22	65%
13	176	58%	330	21%	200	52%	182	56%	182	56%
14	180	60%	350	21%	183	59%	209	53%	187	58%
17	202	59%	383	22%	206	58%	210	57%	236	52%

* Voltage dependent load characteristics is considered only for the load(s) connected to this node.

nodes are under the same risk and the distance analysis of a strong node is unnecessary. Second, as shown in Section 3.1, for an acceptable results to be achieved, the load characteristics should be considered for the weakest node(s) in the system.

Both these reasons suggest that the most potential unstable load nodes should be found in a reliable manner. Although some approaches such as minimum singular value decomposition or modal analysis [9] may be applied, the computational time may be high in an on-line environment. Based on the recommendation by Reference [5], a low cost voltage stability index for weak spot detection is the sum of the MVAr or MW losses, provided a sufficient part of the generation is included in the monitored part of the system. This idea may be effectively empolyed in an on-line mode. A large scale power system may be composed of several areas. As the Database (DB) is updated continuously, the resulting dynamic data is available to all application functions, including contingency analysis and voltage stability functions. The area with the highest MVAr or MW loss and the nodes connected to that specific area are readily identified on-line. The authors have implemented the approach and are under the process of investigating it for large scale networks.

CONCLUSION

Although the theoretical aspects have, so far, received attention in literature, the practical issues of voltage stability function have not. The paper addressed some issues on the practical implementation of a voltage stability analysis function in an on-line environment. The integration procedure in an EMS environment, choice of distance calculation type and voltage dependency of load characteristics were investigated.

As already mentioned, the function has been implemented at NOK, Switzerland. It is under FAT (Factory Test). As soon as final checks are made, full results will be reported.

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