Detection of Dynamic Voltage Collapse

Garng. M. Huang, *Senior Member, IEEE*, and Nirmal-Kumar C Nair, *Student Member, IEEE*

***Abstract*--This paper investigates how to detect a dynamic voltage collapse situation. The generator and governor dynamics are considered in the simulation process. An index proposed earlier has been investigated for its applicability to indicate the collapse situation. Time domain simulations, using a commercial software EUROSTAG, has been carried out in this work. The test result reflects the applicability of the index during the line loss, slow increasing loading and step loading situations. The paper also brings out the details of the simulation setup used, which would help others in carrying out further simulations and investigation.**

***Index Terms*— Voltage stability, dynamic voltage collapse, EUROSTAG, security assessment.**

I. INTRODUCTION

Power transmission capability has traditionally been limited by either angle stability or by the thermal loading capabilities of the lines. But with the developments in faster short circuit clearing times, quicker and effective excitation systems and developments in several stability control devices, the system problems associated with transient instability have been largely reduced. However, voltage instability limits are becoming more prominently significant in the context of a secure power system operation. In the deregulated power market regime, economic competition has lead to an interest in maintaining an optimum, secure and reliable power system operation. 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. Thus, lot of work is being carried out to understand voltage stability better, to detect it faster and to evolve a strategy to mitigate it once its likelihood is observed [1,2,3,4,5]. The efforts are primarily to evolve a comprehensive voltage stability assessment strategy and fast mitigation of potential problems. Thus, in the emerging deregulation market any control action has to incorporate quick system instability detection and mitigation features to maintain an acceptable level of system reliability.

Traditional methods of voltage stability investigation have relied on static analysis using the conventional power flow model. This analysis has been practically viable because of the view that the voltage collapse is a relatively slow process thus being primarily considered as a small signal phenomenon. The various analytical tools classified under steady state analysis mode have been able to address the otherwise dynamic phenomenon of voltage collapse. A variety of tools like the P-V curve, QV curve, eigenvalue, singular value, sensitivity and energy based methods have been proposed [6,7,8,9,10,11,12]. They are computationally intensive which makes it less viable for fast computation during a sequence of discontinuities like generators hitting field current or reactive limits, tap changer limits, switchable shunt capacitor's susceptance limits etc. In a dynamic voltage stability computation regime, considering all these discontinuities into the analysis are necessary. Moreover, a quick computation is necessary to take necessary corrective action in time to save the system from an impending voltage collapse.

In an earlier work the indicator L was proposed, which varies between zero and unity, based on the information of a normal power flow [13]. This indicator has been developed considering generator voltages as constant both in amplitude and phase. It has been shown to detect the tendency of the system towards a critical situation with a very fast computation speed. This indicator has also been used in another work for a viable emergency load shedding scheme [14]. However, there has been no work reported on how this indicator behaves considering the dynamics of the generators, compensators, loads and on-load-tap-changers (OLTC) following a disturbance in the system.

The authors have used this index in earlier works, effectively, to develop a voltage stability constrained optimal power flow procedure [15,16]. The main idea of the present work is to map the power system attributes at the operating state following disturbances like step load increase or loss of line into an index by which the dynamic behavior of the power system is identified. The index must be able to track the dynamic voltage collapse as it progresses. We have tried to

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Garng. M. Huang is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA(e-mail: huang@ee.tamu.edu).

Nirmal-Kumar C Nair is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: ncnair@ee.tamu.edu)

investigate how the index L could provide meaningful voltage instability information during dynamic disturbances in the system.

This paper, firstly reviews the details of the index proposed to be used for detecting the dynamic voltage collapse situation. A sample three machine, nine-bus test system is used for carrying out the simulation for the dynamic events. The details of the machines, governors and exciters are discussed. The results of the time domain simulations carried out in EUROSTAG are then presented.

II. VOLTAGE STABILITY INDICATOR

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 was demonstrated in earlier works [13,15] that when a load bus approaches a steady state voltage collapse situation, the index L approaches the numerical value 1.0. Hence for a system wide voltage stability assessment, 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.

From the derivation it is seen that for computing L index, at any load bus, one requires only the knowledge of the state variables, power information and the network topology. These measurements can be obtained very quickly in real-time. Since most of the earlier indices developed on the basis of steady state power flow model has been able to estimate the system for a dynamic phenomenon like voltage stability, the authors felt worthwhile to explore the applicability of the index L for predicting a dynamic voltage collapse situation.

III. TEST SYSTEM DETAIL

The system used for carrying out dynamic simulation is the WSCC 9 bus test system as shown in Fig.1.

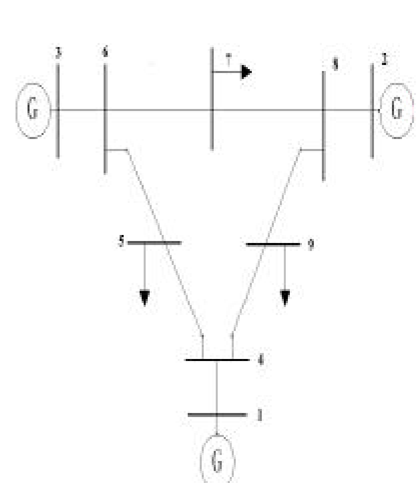

Fig.1. WSCC 9 Bus Test System

The line parameters and the thermal limits are as shown in Table I. The base loading at the bus 5 is 50 + j40 MVA, at bus 7 is 100 + j 35 MVA and at bus 9 is 125 + j 50 MVA.

TABLE I
LINE PARAMETERS AND LOADING LIMITS

Line	Resistance (p.u)	Reactance (p.u)	Susceptance (p.u)	MVA Rating
1-4	0.0000	0.0576	0.0000	250
4-5	0.0170	0.0920	0.1580	250
5-6	0.0390	0.1700	0.3580	150
3-6	0.0000	0.0586	0.0000	300
6-7	0.0119	0.1008	0.2090	150
7-8	0.0085	0.0720	0.1490	250
8-2	0.0000	0.0625	0.0000	250
8-9	0.0320	0.1610	0.3060	250
9-4	0.0100	0.0850	0.1760	250

The voltage regulator model and governor model is as shown in Fig.2 and Fig.3. The voltage regulator chain comprises of the exciter and voltage regulator while the governor chain comprises the governor, the boiler and the high and low-pressure turbines.

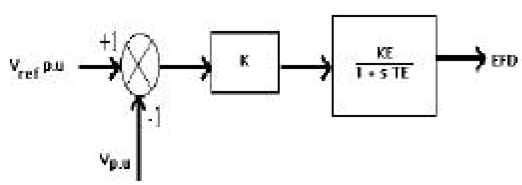

Fig.2. Block Diagram for the Voltage Regulator Model

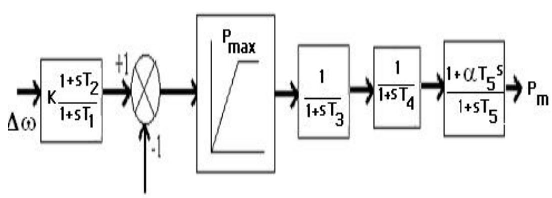

Fig.3. Block Diagram for the Governor model

The following models have been from the EUROSTAG manual. The parameters for the voltage regulators are K=30, KE=1 and TE=1. While the parameters used for the governor control loop is K=25, T1=4, T2=1, Pmax=1.05, T3=0.1, T4=0.1, T5=10 and α=0.3.

IV. SIMULATION RESULTS

EUROSTAG is a software dedicated to the dynamic simulation of electric power systems and developed by Tractebel Energy Engineering and EDF. It allows to encompass all the electrical phenomena in the range of transient, mid and long term stability.

The system as described in the previous section was modeled into EUROSTAG. The description of the generator automatic voltage regulator and the governor was also included into it dynamic test file setup. Three different simulation files were created for the test system corresponding to slow load increase, a step load increase and the loss of a transmission line supplying a load bus. Based on the time domain simulation outputs provided by EUROSTAG the index L was evaluated as per the algorithm provided in section II. The details and discussions of these three simulation results are given in the following sub-sections.

A. *Slow Change in Load*

In this simulation setup, the load at bus 5 was increased at the rate of 0.1 + j 0.08 MVA/sec. It was observed that EUROSTAG runs the time domain simulation until the steady state loadability of the system which happens to be about 235 + j 217.11 MVA, after which it stops. Note that in this simulation, we have used constant power factor increase in loading until collapse occurs. Fig.4 shows the result.

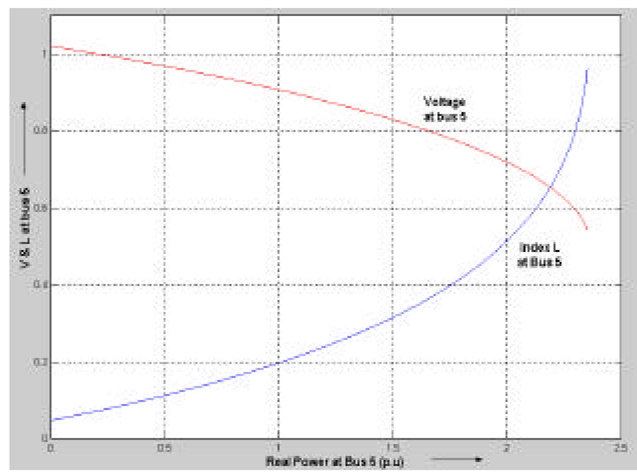

Fig.4. Collapse by slow increase in Bus 5 loading

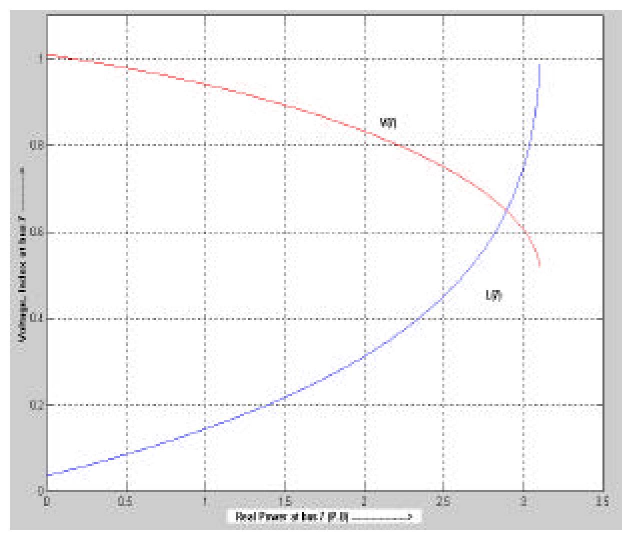

Fig.5. Collapse by slow increase in Bus 7 loading

Fig.5 shows the result for increasing load at bus 7 when the load at bus 5 is 90 + j30 MVA and at bus 9 is 125 + j50 MVA. The collapse occurs when load reaches 310.5 + j 286.86 MVA.

Therefore from both the results it can be observed that for slow changes in the loading, the index L gives a pretty accurate picture of the system from viewpoint of voltage stability and it approaches unity towards collapse loading. A practical strategy, to make quick corrective actions, could be realizable if the value of index reaches a set emergency threshold.

B. Step Change in Load

In this simulation setup, the load at Bus 5 is increased in a step from its base value loading of 50 + j 40 MVA at time t=10 seconds. The index, at the first largest dip in the voltage and at the final settled value of voltage, is computed. The voltages and indices profile, when there occurs a step change at bus 5 from the base load of 50 + j 40 to 229.6 + j183.68 at time 10 seconds, as evaluated using EUROSTAG simulation is as shown in Fig.6.

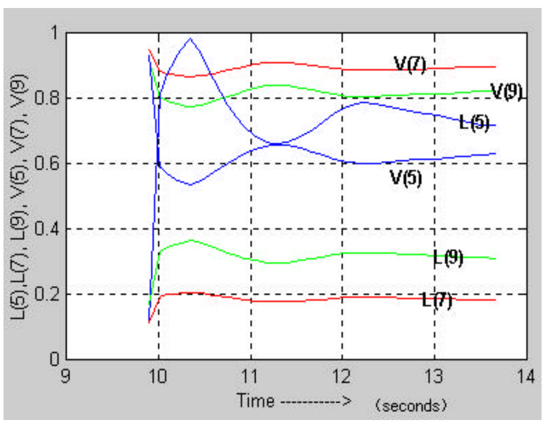

Fig.6. Voltage and Index for Step Change in Bus 5 load

Table II gives the summarized results for various step changes. From Table II results it can be seen that the system collapses dynamically when there is a step change from base loading of Bus 5 to about 2.29 + j 1.83 p.u., which is less than the steady state loadability. The index L(5) evaluated at the instant when the first largest dip in voltage occurs is nearing one during the collapse step loading. In other words, the index L is able to predict the dynamic voltage collapse of the system if one were able to evaluate it during these large load changes.

TABLE II
INDEX EVALUATED DURING STEP LOAD CHANGES AT BUS 5 FROM ITS BASE LOADING VALUE

Final Load at Bus 5 (MVA)	Index at first Voltage dip for Bus 5	Index at Bus 5 after disturbance
50 + j 40	-	0.1135
200 + j 160	0.5224	0.4961
210 + j 168	0.5941	0.5548
220 + j 176	0.7002	0.6322
225 + j 180	0.7844	0.6818
229.6 + j 183.68	0.982	0.7396
229.67 + j 183.736	1.0037	0.7396

EUROSTAG fails to run the simulation if the step change in load is to 229.692 + 183.7536 MVA. The waveform for bus voltage at 5 when this simulation is run is as shown in Fig.7 .

The failure of EUROSTAG to run indicates that a voltage collapse has occured at bus 5 and in an actual system a local load voltage collapse spreads to the rest of the system causing potential blackout threats.

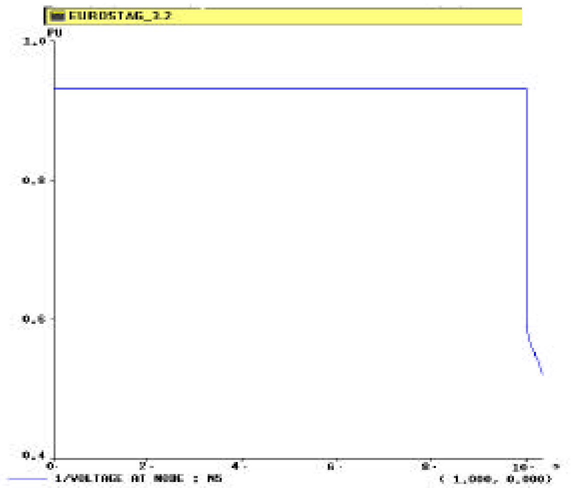

Fig.7. Dynamic Voltage Collapse due to Step Change in Load

C. Loss of Line

To investigate into the dynamic voltage profile during loss of a transmission line, the loss of line 4-5 supplying to the load bus 5 at time t=10 seconds was simulated. The time domain simulations were run for different loading at load bus 5. The voltage profile when the initial loading was 90 + j72 MVA is as shown in Fig.8.

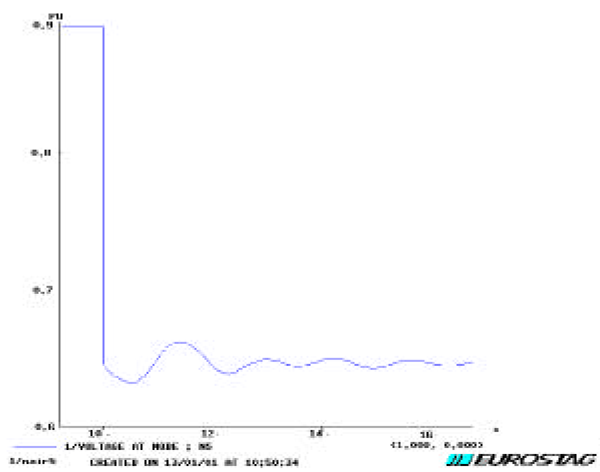

Fig.8. Voltage Profile at Bus 5 following Line 4-5 outage

The voltage profile indicates that the system is still voltage stable. However, it was observed that EUROSTAG was not able to run simulation when the initial load at BUS 5 was 94 + j 75.2 MVA, which indicates the dynamic collapse loading for the test system. For the above line contingency, the steady state voltage stability limit works out to be 96.4 + j 89.06 MVA which is higher than the dynamic limit. The indices evaluated for the line 4-5 outage during different loading condition at Bus 5 is as given in Table III.

TABLE III
INDEX EVALUATED DURING LOSS OF LINE 4-5 FOR DIFFERENT INITIAL LOADING AT BUS 5

Initial Load at Bus 5	Index at bus 5 before line outage	Index at bus 5 at first voltage dip	Index at bus 5 after disturbance
50 + j 40	0.1135	0.2312	0.2300
70 + j56	0.1437	0.3706	0.3666
80 + j 64	0.1602	0.4801	0.4722
90 + j 72	0.1771	0.6787	0.6502
93 + j 74.4	0.1802	0.8093	0.7508
93.97 + j 75.176	0.1823	0.8951	0.7980

It is observed from Table III that the index evaluated at the first voltage dip is able to track closely to unity when the disturbance was nearing the dynamic voltage collapse. Thus, the index L is able to indicate in numerical terms the severity from view-point of dynamic voltage collapse for the line contingency disturbance.

Fig.9. depicts the variations of index, for various Bus 5 loading, as evaluated in Table III. The top curve shows index evaluated at the first largest voltage dip instant while the bottom curve depicts the index value at instant when the disturbance has died out. The index evaluated at largest dip in voltage is seen to approach approximately unity at collapse loading for Bus 5. Thus as the initial loading on bus 5 increases, during the line outage situation the index computed at the first largest dip in voltage is able to give information as regards to the closeness from a voltage collapse point.

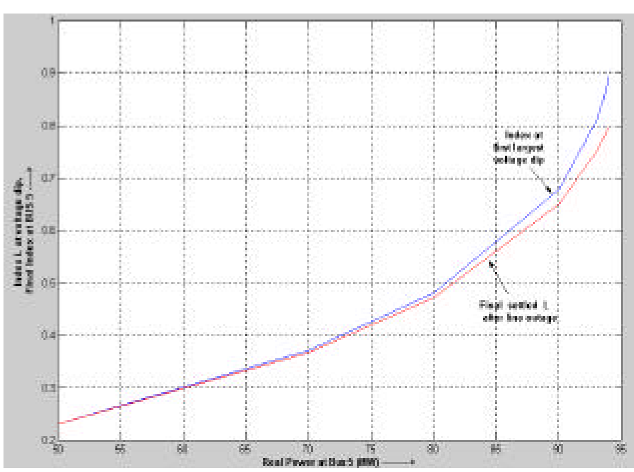

Fig.9. Profile of Index variations for result in Table III

V. CONCLUSIONS

This paper reviews the L index used as a steady state voltage stability indicator, which have been used by the authors in an earlier work to formulate a voltage stability constrained optimal power flow algorithm. The detailed modeling for the generator and governor dynamics was included for a test case and time domain simulations were run on it, for a variety of dynamic disturbance scenarios using EUROSTAG.

For slow changing load conditions it was observed that the index is able to track the voltage stability condition of the load buses and hence the system effectively. It has been brought about from the results of the simulations that the index approaches very near to unity during a collapse situation. It was also observed that this collapse point coincided with the steady state loadability limit.

For a sudden step load change scenario, the index computed at the first largest dip in the voltage following the change is able to indicate whether a dynamic voltage collapse is to occur. From the results of the simulations it was also observed that the dynamic voltage collapse loading was less than the steady state loadability point.

For the loss of line disturbance, the index approximately approached unity when critical initial loading existed. The dynamic loadability, for the contingency considered, was also less than its steady state capability.

Thus the investigation on a test system for prediction of dynamic voltage collapse, based on the L indicator, has given encouraging results. Further detailed modeling of load dynamics, tap-changing dynamics, over-excitation limiters for generators can be incorporated into the EUROSTAG model and the indicator's performance has to be evaluated for various disturbance scenarios.

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VII. BIOGRAPHIES

Dr. Garng Huang received his B.S. and MS. in E.E. from National Chiao Tung University, Hsinchu, Taiwan, R.O.C. in 1975, 1977 respectively. He received his doctorate degree in Systems Science and Mathematics from

Washington University, St. Louis in 1980. He had been teaching there since then until 1984. He joined Texas A&M University, Department of Electrical Engineering in 1984. He is currently a professor and the director of graduate studies there. He has been working on many funded research projects, such as Emergency Control of Large Interconnected Power System, HVDC Systems, Restoration of Large Scale Power Systems, On-line Detection of System Instabilities and On-line Stabilization of Large Power Systems, Fast Parallel/Distributed Textured Algorithms, Fast Parallel Textured Algorithms for Large Power Systems, Hierarchical Aggregation and Decomposition Algorithm for Data Network Routing Problem, etc. His current interest is the large scale systems theory, large scale parallel/distributed computing and control and their applications.

Dr. Huang is a senior Member of IEEE, and a Registered Professional Engineer of Texas. He has served as the Technical Committee Chairman of Energy System Control Committee and an associated editor in the IEEE Automatic Control Society; he has also been serving in a number of committees and subcommittees of IEEE PAS Society. Dr. Huang has published more than a hundred papers and reports in the areas of nonlinear, distributed control systems, parallel/distributed computing and their applications to power systems, data networks and flexible structures.

Nirmal-Kumar C Nair received his B.E in E.E. from M.S. University, Baroda, India in 1990. Thereafter, he received his M.E in E.E with specialization in High Voltage Engineering from Indian Institute of Science, Bangalore, India in 1998. He has around a decade of teaching and research experience in the field of electrical engineering. In 2000, he joined Texas A&M University to pursue his Ph.D under the guidance of Dr. Huang in the area of stability, security, reliability and energy market issues in power systems with focus on the deregulated environment. Mr. Nair is a student member of IEEE.