A New Voltage Instability Detection Index based on Real-time Synchronophasor Measurements

H.K Chappa
Commonwealth Academic Fellow
Durham University
Durham,UK

T.Thakur
Department of Electrical Engineering
MANIT Bhopal
Bhopal, India 462051

B.Kazemtabrizi
School of
Engineering and Computing Sciences
Durham University
Durham,UK

***Abstract*—This paper demonstrates the performance of the Reactive Power Loss Based Voltage Instability Detection Index (QLVIDI), previously introduced in [1], under various testing conditions applied to the New England 39 bus test system using time-based simulations in the Power System Analysis Toolbox (PSAT) in MATLAB.The proposed scheme calculates an instantaneous time series of reactive power losses taking into account the direction of active power flow in every node in the system by considering the reactive power limits of the generators. This time series data is then used to evaluate a cumulative reactive power loss and the degree of deviation from the base case loss for developing QLVIDI.The effectiveness of the proposed index in early detection of imminent voltage collapse scenarios has been tested in various cases and also compared with already existing Improved voltage instability monitoring index(IVIMI).**

***Index Terms*—Voltage instability, Voltage Collapse, Reactive power losses, Phasor Measurement Unit (PMU)**

I. Introduction

Competitive power markets due to deregulation in power system, resulted in increased complexity of interconnection in transmission network, especially in developing countries. These circumstances force the grid to operate close to the steady state stability limits. Under these uncertainties, monitoring voltage stability is very important to avoid voltage collapse. Voltage collapse can result in complete or partial blackout in power system or it can split the grid. Due to growing concern for voltage instability, a number of methodologies have been proposed to study and to detect the voltage instability.It is very important that voltage instability in the network is detected in a timely manner in order to leave sufficient time for implementing any remedial actions and thus mitigating catastrophic events such as blackouts. There can be several reasons for voltage collapse in an interconnected power system. Some of them are [2] severe loading in transmission lines, deficit reactive power support, long distance bulk power transmission, HVDC links to weak AC system, reverse action of On Load Tap Changer(OLTC) under heavy reactive loading condition.

Excessive reactive power loss in the lines is the underlying reason for voltage instability. [6]. Various indices are reported in the literature to identify the weak buses and weak lines in the system. The weakest bus is defined as the one that is closest to experiencing the voltage collapse. Whereas weakest line is defined as a line that needs the reactive power the most [3]. Most of the indices for detecting the weakest line or weakest bus are static in nature and utilize the concept of singularity of Jacobian matrix in the power flow formulation. The main drawback with these static indices are, they are very slow in real time detection since Jacobian matrix will become singular near to the point of collapse. Continuation power flow(CPF) method is proposed in [4] to avoid the drawback of singularity of the Jacobian and to obtain the points on the P-V curve after the bifurcation point. CPF is used only for off line study of the network and it gives the maximum possible loading that can be made on the system.

A variety of methods for detecting voltage instability in the open literature by using synchronophasor measurements (e.g. Phasor Measurement Units - PMUs) [5], [6], [7]. The indices proposed by using PMU measurements are classified as local measurements and wide area measurements. The indices based on the loacal measurements use the concept of Thevinin equivalent at a specific bus of interest. However local measurements are cost effective but require larger data windows for accurate tracking of the Thevinin parameters and larger computation times. One of the indices based on the local measurements is voltage stability risk index(VSRI) proposed in [8]. Time series data from PMU measurements are utilized to develop the index and this index is found to be too slow in detecting the voltage instability apart from difficulty in fixing the threshold values. On the other hand global measurements give wide area picture for voltage instability but require more PMU's for the complete system observability. Synchrophasor Based Voltage Instability Monitoring Index(SVIMI) proposed in [9] considers weighted sum of voltage deviation and rate of change of voltage for early detection of impending voltage instability. This index detects voltage instability in adequate time but requires more computational effort in setting the values of maximum deviation from reference and maximum consecutive voltage deviation. Improved Synchrophasor Based Voltage Instability Monitoring Index(ISVIMI) proposed in [10] is an extension of the SVIMI, with simplified computations than SVIMI. But this index also require weights adjustment in every measurement which would still be computationally burdensome. Voltage stability index(VSI) proposed in [11] is based on the calculation of successive change in reactive power losses. Reactive power loss based voltage instability detection proposed in [1] has not considered the effect of overexcitation limiters and on load tap changing transformers(OLTC) as the operating limits of these devices influence the voltage instability. Most of the above mentioned indices are not suitable for fast early real-time detection of voltage instability and need extensive computation time for calculating the index.

In this paper performance of the proposed reactive power loss based voltage instability detection index (QLVIDI) has been demonstrated by considering the effect of overexcitation limiters i.e with generator reactive power limits. The prowess of the proposed index(QLVIDI) in being capable of early detection of voltage instability under heavy loading conditions when subject to contingencies is tested on the New England 39 bus test system with and without the presence of noise signals. Also the speed of the index has been compared with IVIMI which is one of the fastest indices in the open literature. The main reasons for choosing IVIMI for comparison purpose is this index also considers time series data from PMUs under wide area monitoring system(WAMS).

II. Proposed Methodology

The detailed description of the proposed methodology has already been given in [1] however in order to maintain consistency in this paper the method developed in [1] is explain briefly here again.Excessive reactive power loss in the lines due to excessive loading or contingencies under stressed condition is the main cause of voltage collapse in power system. Fig.1 is a two bus system with sending end voltage as V_1 and receiving end voltage as V_2. The sending end and receiving end reactive power is given as

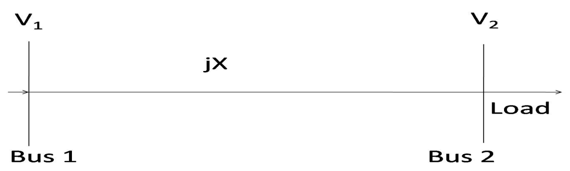


Fig. 1: Two bus system

$$Q_1 = \frac{V_1^2 - V_1 V_2 cos(\delta)}{X} \quad (1)$$

$$Q_2 = \frac{V_1 V_2 cos(\delta) - V_2^2}{X} \quad (2)$$

respectively. Sending end real power is given as

$$P_1 = \frac{V_1 V_2 sin(\delta)}{X} \quad (3)$$

where δ is the voltage phase angle difference between bus one and bus two. X is the transmission line reactance. The change in voltage from sending end to receiving end is given as

$$V_1 - V_2 = \Delta V = \frac{XQ_1}{V_1} + j\frac{XP_1}{V_1} \quad (4)$$

Receiving end voltage is majorly dependent on reactive power flow in the lines. This reactive power variable is taken in this work for detecting the voltage instability.

This proposed methodology is developed based on the fact that as loading on the transmission lines increases so do transmission losses [1]. Under the highly stressed conditions, it is observed that reactive power losses in the lines increase sharply, even with respect to small increase in loading conditions, causing voltage to decrease rapidly. Voltage magnitude monitoring alone cannot determine the voltage instability accurately as in case of over compensated systems voltage collapse can take place at high voltage profiles. On the other hand, nodal reactive power loss in system buses can be a good indicator of imminent voltage instability detection under stressed conditions.Nodal reactive power loss may be easily calculated through reactive power loss in the lines.

In this work, as an extension to the QLVIDI method in [1] time domain simulation results from PSAT can be assumed to be obtained from PMUs and Phasor Data Concentrator(PDC). Based on the direction of active power flow reactive power loss at buses are calculated according to method presented in [11]. A time series data of reactive power loss at buses are created in MATLAB using repetative runs of Newton Rapson(NR) power flow method. The initial conditions to this NR power flow were voltages and phase angles from PSAT which represent the sampled data from PMUs or any other network measurements. This time series data is used for calculating Reactive Power Loss Based Voltage Instability Detection Index (QLVIDI). For developing the index two componens are calculated namely, Cumulative Reactive Power Loss (CQL) and Change from base case Reactive Power Loss (CQLB). The details of CQL and CQLB are reported in [1].

If load on the system is increased under highly stressed condition then reactive power losses in the lines increase abruptly and the calculated reactive power losses in the buses also increase abruptly [1]. In the proposed scheme loading increases in fixed percentage per sampling time(τ) at every bus in the test system. Even though in a practical power system this fixed load increment is an unusual condition the main aim of the author in this kind of load increment is to stress the system and make the system to move from stable state to unstable state.The ratio of CQL to CQLB is called Reactive Power Loss Based Voltage Instability Detector(QLVID).The calculated time series evolution of QLVID decreases initially and then increases for any load bus with the above mentioned pattern of load increment .The instant at which QLVID starts increasing is the voltage instability detection time.

As monitoring QLVID is difficult, so QLVIDI is calculated from QLVID and the sign of the QLVIDI becomes positive [1] It then shows there is an increased likelyhood of voltage instability in the corresponding buses. This index detects the voltage instability so quickly leaving suffcient time for control actions like activiation of FACTS controllors, OLTC controllers, generator's AVR adjustment etc.The steps involved in calculating QLVIDI are given is Fig.2.

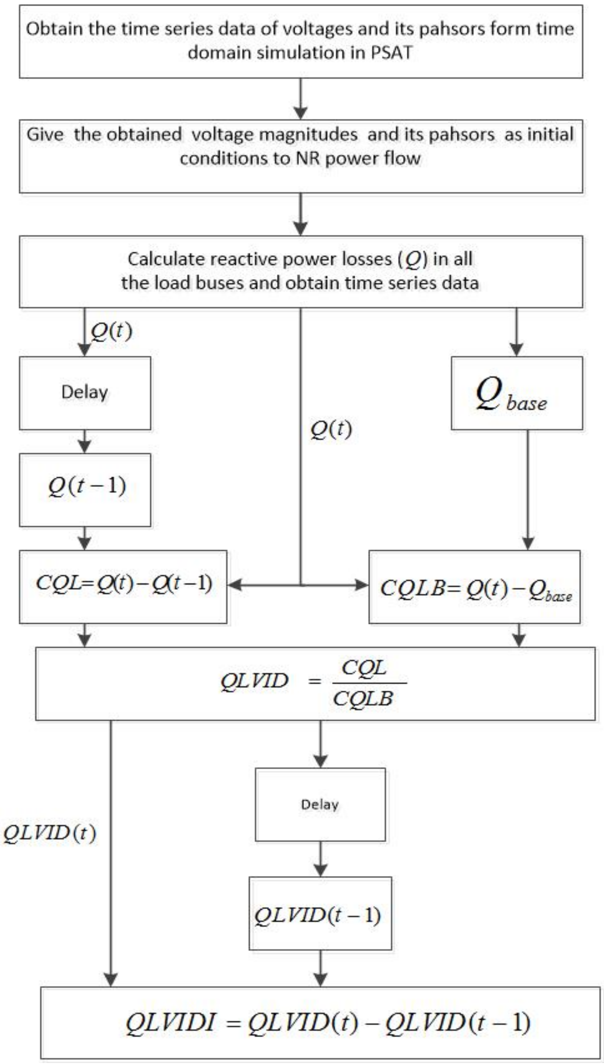


Fig. 2: Flow chart of QLVIDI calculation [1]

III. Simulation Results

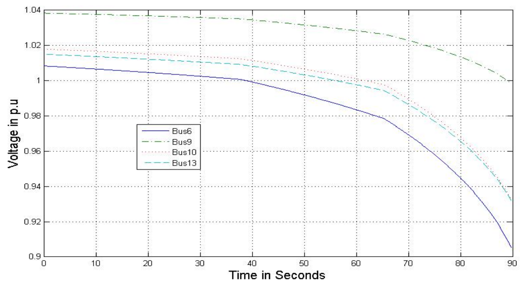
In this work New England 39 bus test system [12] is taken to validate the performance of QLVIDI in detecting long term voltage instability. In the considered test system continuous load increment of 0.1% per sampling time(τ) in all the buses simultaneously is considered. The test system is initially run in PSAT [13] by considering the generator's fourth order model and IEEE type I DC excitation system to obtain the time series data of voltages and phase angles. These obtained time series voltages and phase angles are given as initial condtions to Newton Rapson load flow method developed in MATLAB environment to calculate the nodal reactive power losses and QLVIDI. The test system results are demonstrated in two cases. Firstly considering only load increments without any contingencies and load increments followed by line outages. Continuation power flow method(CPF) has also been applied on the test system to find the value of loading parameter at the time of voltage instability detection.

A. Continuous load increment

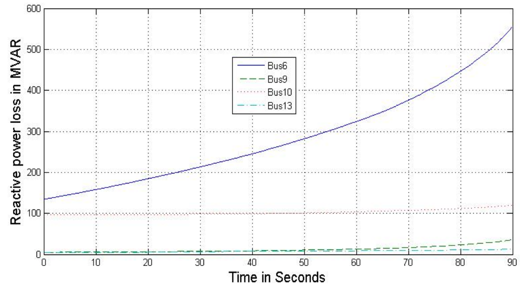
The test system is considered with generaors reactive power limitations. As load on the system increses continuously, voltage tries to maintain allowable value until exciter hits its limits. As and when the exciter hits the limits, field current will not be increased further causing insufficient reactive power to the system and system will experience the unrecoverable voltages in some or all the buses causing voltage instability. By performing the contingency analysis [14] bus numbers 6,9,10 and 13 are identified as weak buses and the plots for only these buses are shown.Fig.3(a) shows the time series evolution of voltages with continual load increment. From the Fig.3(a) it is evident that voltage collapse has ocurred in 90 sec at a total loading of 6975.17 MVA. The calculated CPF load parameter(λ) corresponding to this load is 2.09. Calculated reactive power losses in the considered buses are shown in Fig.3(b),which clearly depicts as load increases, nodal reactive power losses also increase. From Fig.3(b) it is observed that nodal reactive power losses initially increases slowly with time but as time progresses with load, stress on the system increases so the nodal reactve power losses shoots up. QLVIDI has been calculated based on the nodal reactive power losses and to obtain the trend of the time series values of the QLVIDI filtering technique has been used. Many filtering techniques are available in the literature, however in this work rloess filter has been considered.Fig 3.(c) depicts the trend of QLVIDI and it has become positive at a time equal to 65.39 sec when the system total load is 6818.22 MVA and CPF load parameter(λ) equal to 2.06. Actual CPF analysis is done on the system (Fig.3(d)) and the bifurcation point occurs at a λ equal to 2.12. The proposed method can detect the voltage instability at a λ equal to 2.06.

B. Continuous load increment with contingency

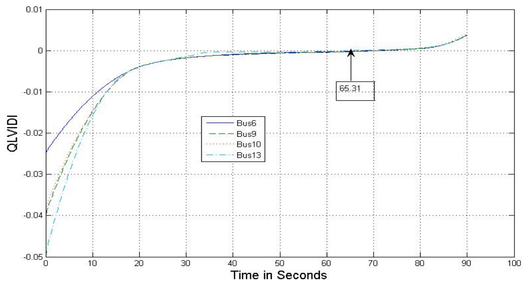
In this work contingencies are introduced in the test system following an N-1 criterion.There can be few multiple contingencies that can occur in the system with least probability of occurrance. So single credible contingency has been studied in this work. Branch connecting between the buses 8 and 9 is set to open at time t =10 seconds along with the continuous load increment of 0.1% per sampling time(τ)in all the buses.Fig.4(a) shows the plot of considered bus voltages, voltage collapse has occurred in 56 seconds at a loading of 6743.33 MVA.Fig. 4(b) shows the nodal reactive power losses and at time t=10 seconds there is a sudden rise in the reactive power losses due to branch contingency. However this sudden sharp rise in reactive power losses will not force the index to issue a false alarm because the smoothener or filter will average out such transcients. QLVIDI in Fig.4(c) shows voltage instability has been detected in 42.88 seconds at a total system loading of 6674.46 MVA. The proposed index has also been tested under the presence of noise signal in the actual time series data. A gaussian noise with signal to noise ratio (SNR) 80 db has been added to the already obtained time series nodal reactive power losses. With the same load scenario as in section III.(a), gaussian noise is added in all the reactive power losses. The rloess filter used in the proposed index not only act as a smoothener to obtain the trend of QLVIDI but also it acts as a low pass filter which eliminates the unwanted spurious signals. A plot of QLVIDI in the presence of noise is shown in Fig.5(a) which detects the impending voltage instability in 69.31 seconds. This confirms that this proposed index detects the voltage instability in quicker time along with handling the noise signals.



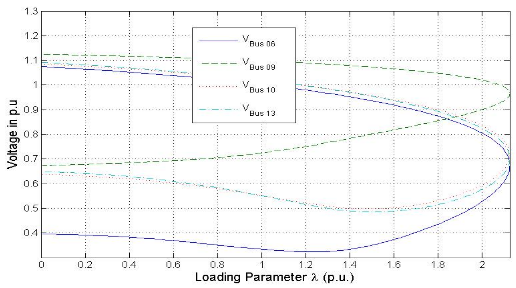
(a)



(b)

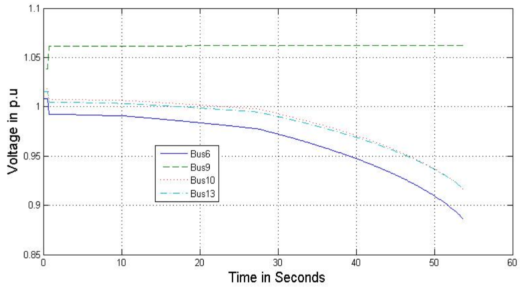


(c)

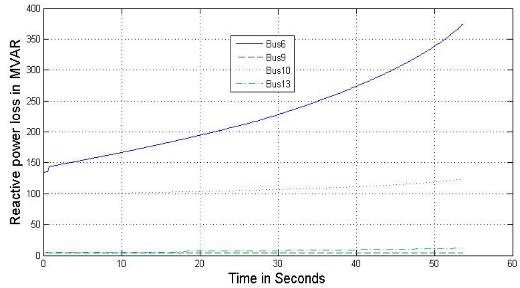


(d)

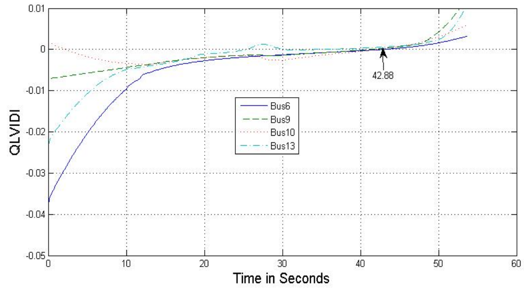
Fig. 3: (a)Voltages for continuous load increment (b) Reactive power losses in buses (c)QLVIDI in buses (d)CPF Voltages



(a)

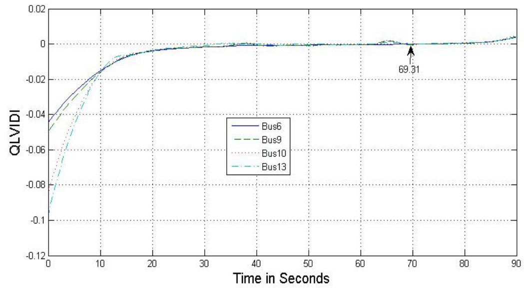


(b)



(c)

Fig. 4: Various plots under contingency (a)Voltages for continuous load increment (b) Reactive power losses in buses (c)QLVIDI in buses

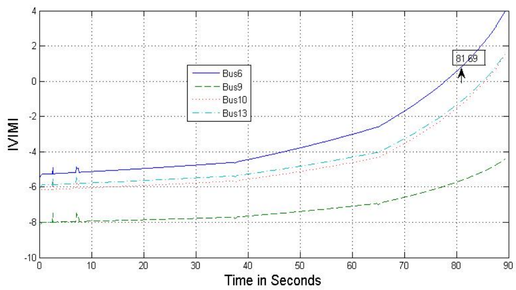


(a)

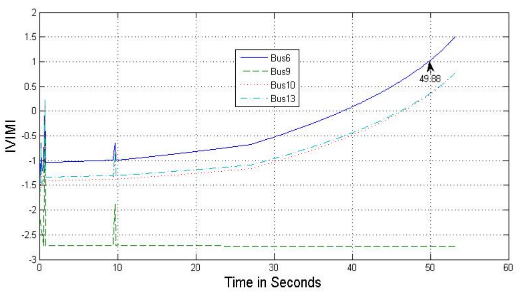
Fig. 5: QLVIDI in the presence of noise

C. Comparision with the existing index

The performance of the QLVIDI has been compared with the already existing IVIMI [10]. Fig 6.(a) shows the IVIMI under continuous load increment in all the buses without



(a)



(b)

Fig. 6: IVIMI plots (a)IVIMI without contingency (b) IVIMI with contingency

any contingency. If the value of IVIMI becomes unity is an indication of voltage instability. It can be observed that IVIMI becomes unity in 81.69 seconds with a system loading of 6923.12 MVA. Fig 6.(b) shows the IVIMI plot under contingency condition mentioned in section III.(b). IVIMI becomes unity in 49.88 seconds at a total loading of 6719.31 MVA. The comparison of various parameters of the indices are given in table I and II.

TABLE I: Comparision of Various Indices

Continuous load increment		
	QLVIDI	IVIMI
Collapse time(S)	90	90
Detection time(S)	65.31	81.69
Critical load(MVA)	6975.17	6975.17
Load Margin(MVA)	156.95	52.05

TABLE II: Comparision of Various Indices under contingency

Continuous load increment along with branch outage		
	QLVIDI	IVIMI
Collapse time(S)	56	56
Detection time(S)	42.88	49.88
Critical load(MVA)	6743.33	6743.33
Load Margin(MVA)	68.87	24.02

IV. Conclusion

This paper explored long term voltage instability index QLVIDI, calculated from reactive power losses in the lines and direction of active power flow. This index is very effective, computationally very simple and has good capability to detect slowly developing long term voltage instability. The capability of the index in early detection of imminent voltage instability could potentially help the system operator to make proper remedial actions in sufficient time so as to minimise the risk of comprimising system operational security.

References

[1] H. K. Chappa,T. Thakur and S. C. Srivastava "Reactive power loss based voltage instability detection using synchrophasor technology", *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)* pp.1-5,Brisbane,QLD, Nov. 2015

[2] Byung Ha Lee and Kwang Y. Lee, "A study on voltage collapse mechanism in electric power systems", *IEEE Trans. Power Syst.,* vol. 6, no. 3, pp. 966-973, Aug. 1991.

[3] A. Sode-Yome,N. Mithulananthan and Kwang Y. Lee "A Comprehensive Comparison of FACTS Devices for Enhancing Static Voltage Stability", *IEEE Proc. Power Engineering Society General Meeting* pp.1-8,Tampa,FL, June 2007.

[4] V. Ajjarapu and C. Christy, "The continuation power flow:a tool for steady state voltage stability analysis ", *IEEE Trans. Power Syst.,* vol. 7, no. 1, pp. 416-423, Feb. 1992.

[5] Prabha Kundur, *Power System Stability and Control*, Mc.Graw-Hill,New York, 1994

[6] Carson W. Taylor, *Power System voltage Stability*, Mc.Graw-Hill, Singapore,1994

[7] V.Balamourougan, T.S. Sidhu, M.S. Sachdev, "Technique for online prediction of voltage collapse", *IEE Proc. Gener. Transm. Distrib.,* vol.151, no. 4, pp. 454-460, July 2004.

[8] Kim, "System and method for calculating voltage stability risk-index in power system using time series data", US7236898 B2, Jun. , 2007. [Online]. Available: http://www.freepatentsonline.com/y2005/0256922.html.

[9] Ranjana Sodhe, S.C Srivastava and S.N Singh, , "A simple scheme for wide area detection of impending voltage instability", *IEEE Trans. Smart Grid.,*vol. 3, no.2, pp. 818-827, Jun. 2012.

[10] Ch.V.V.S. Bhaskara Reddy , "Early detection and control of voltage stability and fast assessment of ATC using synchrophasor measurements", Ph.D. dissertation, Dept. Elect. Eng., Indian Institute of Technology, Kanpur, July 2014.

[11] Kasi Viswanadha Raju Gadiraju, Amol Kolwalkar, Gurunath Gurrala, "Systems and methods for predicting power system instability", U.S 0154614 A1, Jun. 2013 [Online]. Available: http://www.freepatentsonline.com/y2013/0154614.html

[12] Power System Test Case Archive, http://www.ee.washington.edu/research/ pstca/

[13] F.Milano, "An open source power system analysis tool box", *IEEE Trans. Power Syst.,* vol. 20, no. 3, pp. 1199-1206, 2005.

[14] S.D Naik, M.K Khedkar and S.S Bhat, "Effect of line contingency on static voltage stability and maximum loadability in large multi bus power system", *Int. J. Elect. Power and Energy Syst.,*vol.67, pp. 448-452, 2015.