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A Novel Method for Distributed Real Time Voltage Stability Monitoring using Synchrophasor Measurements

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Abstract

With the advent of synchrophasor technology, real time voltage stability analysis using synchrophasor data has been the focus of many researchers resulting in the development of several new algorithms. These developed algorithms have several advantages as well as limitations. This paper discusses briefly about the shortcomings of some existing synchrophasor measurement based voltage stability indicators. Most of the existing model-free algorithms are iterative in approach, thus making them computationally slow as well as making non-convergence a possibility. Some of these algorithms also have accuracy issues when the system conditions change fast by large amounts. Thus a new algorithm is necessary that is devoid of these limitations. A new algorithm for distributed real time voltage stability monitoring based on local phasor measurements has been presented in this paper. The newly developed algorithm to compute the Voltage Stability Assessment Index (VSAI) can be used for normal operation as well as for contingency cases to monitor dynamic security of a system. Results of the new algorithm tested on different IEEE test cases under different system conditions show its satisfactory performance.

Synchrophasor Based Real Time Monitoring

Power systems tend to operate very close to their stability limits with increasing loads, environmental limitations on transmission system expansion, and competitive market infrastructure. This leads to higher chances of the power system to exhibit unstable behavior that is often characterized by voltage instability, sometimes even leading to a voltage collapse and finally a blackout. Thus, monitoring the system voltage stability in real time has become necessary to efficiently operate the power grid under stressed conditions.

The event of August 14, 2003 blackout in the north eastern United States and parts of Canada that affected almost 50 million people emphasized the need for real time situational awareness. Phasor Measurement Units (PMUs) enable the wide area visualization of a power system in real time by capturing high speed time-stamped snapshots in the form of voltage and current phasors [1]. This kind of "time stamping" allows the voltage and current phasors at different geographical locations to be time-aligned or "synchronized", thus providing a precise and comprehensive view of the entire system. Hence, synchrophasor technology enables a good indication of power grid stress, like voltage instability. However, observability of the North American power grid using PMUs only is still evolving. Hence it is essential to develop distributed real time voltage stability monitoring algorithms using locally available synchrophasor measurements, so that corrective actions can be triggered locally to maintain voltage stability at the monitored weak bus.

Shortcomings of Existing Synchrophasor based Approaches for Online Voltage Stability Monitoring

Different approaches for online voltage stability monitoring have been reported in literatures [2-9].

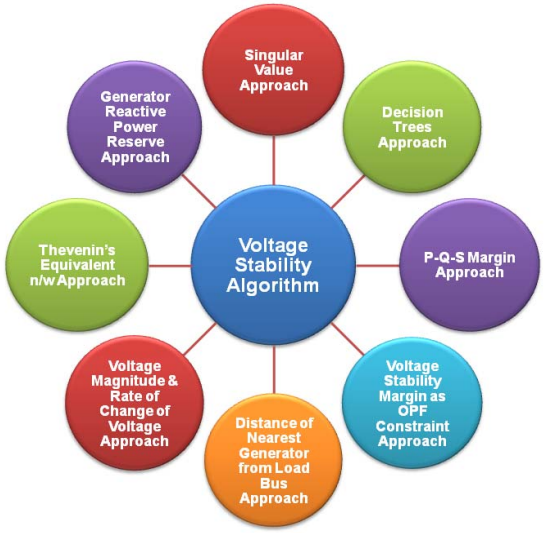

Fig. 1 Different Approaches for Real Time Voltage Stability Analysis using Synchrophasors

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Following are some of the shortcomings identified in the existing online voltage stability algorithms –

(1) The algorithms are inherently recursive in nature and thus can suffer from non-convergence issues. Moreover, for an iterative computational algorithm, the time-step cannot be guaranteed under all operating scenarios.
(2) The existing 'multiple power flow' based algorithms are computationally burdensome and relatively slow for real time applications.
(3) The existing 'Thevenin's Equivalent Network Reduction' based algorithms need a window of past data for the computation of voltage stability index at a given time instant. The basic assumption is that during this windowing period, the system conditions do not change, but the parameters of the monitored load bus changes. This can lead to the following potential problems –
    (a) During fast and large load changes in the system or during sudden contingencies, the system condition changes, leading to the change of data in the selected window for VSI computation. These can cause considerable error in determining the voltage stability limit.
    (b) If the parameters at the monitored load bus do not vary during the fast windowing period, computation of VSI cannot be possible, as this kind of computation is dependent on the rate of change of data.

Developed Distributed Online Voltage Stability Monitoring Algorithm

The proposed online voltage stability algorithm is based on the Thevenin's equivalent network reduction technique. However, unlike the existing algorithms, the proposed algorithm has the following unique characteristics –

(1) This algorithm uses an iteration-free method to compute the Thevenin's Equivalent parameters. Thus, there can be two benefits –
    (a) The time step of this algorithm can be guaranteed under all operating conditions.
    (b) Convergence issues can be avoided completely.
(2) It does not need a window of past data to determine the voltage stability limit at any time instant. It can compute the Voltage Stability Assessment Index (VSAI) at a particular time instant just on the basis of the synchrophasor measurements at the monitored load bus obtained during that instant of time only. Hence, this solves the issue of inaccuracy of voltage stability limit computation during fast and large load changes or sudden contingencies.
(3) It does not assume that the system side remains constant while the load side parameters change. The proposed algorithm does not use a stochastic method that needs the rate of change of load bus parameters.

Following is a short summary of the technical details of the newly developed algorithm –

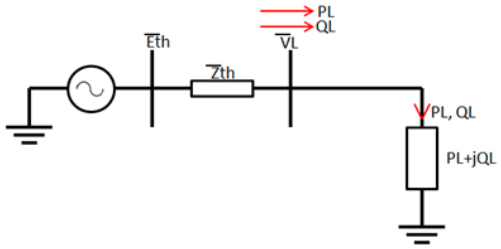

Fig. 2 Thevenin's Equivalent network as seen from a Load Bus

Where –

Eth: Thevenin's Equivalent Voltage magnitude (reference)
Zth: Thevenin's Equivalent Impedance ≈ j*Xth
V_L: Voltage magnitude of the load bus
P_L: Total Real Power consumption at the load bus
Q_L: Total Reactive Power consumption at the load bus
VSAI: Voltage Stability Analysis Index

Bus Admittance Matrix [Y] for the reduced 2-bus system is given as –

$$[Y] = \begin{bmatrix} -j*(\frac{1}{Xth}) & j*(\frac{1}{Xth}) \\ j*(\frac{1}{Xth}) & -j*(\frac{1}{Xth}) \end{bmatrix} \quad \text{---------- (1)}$$

$$\Rightarrow Y11 = -j*(\frac{1}{Xth}),$$
$$Y12 = j*(\frac{1}{Xth}),$$
$$Y21 = j*(\frac{1}{Xth}),$$
$$Y22 = -j*(\frac{1}{Xth})$$

Real Power consumed by the Load Bus is given as –

$$P_L = -|V_L| * |Eth| * |Y21| * \sin(\delta_L) \quad \text{---------- (2)}$$

Reactive Power consumed by the Load Bus is given as –

$$Q_L = |V_L| * |Eth| * |Y21| * \cos(\delta_L) - |V_L|^2 * |Y22| \quad \text{- (3)}$$

For the above network, the Thevenin's Equivalent Voltage phasor 'Eth' is computed using the equations (1), (2), and (3) in a non-iterative manner. Once 'Eth' has been computed, the following equation is used to compute the Voltage Stability Assessment Index (VSAI) for monitored load bus –

$$VSAI = |\frac{Eth - V_L}{V_L}| \quad \text{---------- (4)}$$

The proposed algorithm gives VSAI as the output, where values near "0" indicate a voltage stable load bus; whereas the values near "1" indicate that the load bus is

less voltage stable.

This algorithm also allows the user to set an alarm that shows up when the observed bus crosses the set limits of VSAI. This can enable the planning and execution of proper and timely control actions at that bus. In this way, if the proposed algorithm monitors all the predetermined weak buses in a given system (from voltage stability point of view), then potential voltage collapse situations can be averted.

The proposed algorithm, being computationally less intensive and simple, can be coded inside a PMU, which monitors the load bus, thus making real time distributed voltage stability algorithm practicable. Alternatively, the modern substation-level PDCs that have simple computation modules can also host the proposed algorithm so as to generate VSAI of the monitored substation as the output. Figure 3 shows a possible architecture for implementing this algorithm.

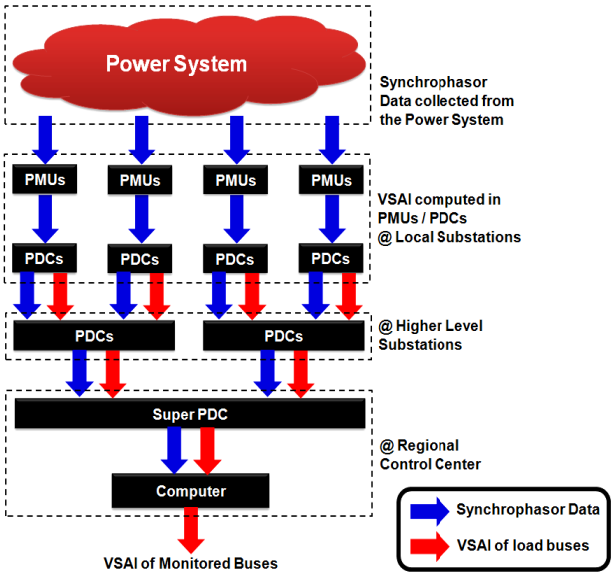

Fig. 3 Possible Architecture for Implementation of the Proposed Algorithm

Simulation Results for the Proposed Distributed Online Voltage Stability Algorithm

The developed distributed real time voltage stability algorithm has been validated on different IEEE test cases for two different scenarios that can lead to poor voltage stability scenario in a power system – a) increase in loading and b) contingencies. The results presented in this section validate the performance of the proposed algorithm as they are in lines with the theory of static analysis of voltage stability phenomenon.

Simulation Results for the IEEE-30 bus test case with gradual increase in system loading:

Figures 4 – 6 show the variation of different parameters of load bus-12 like voltage magnitude and voltage angle with real and reactive power loading at the monitored bus. These figures show the bus parameters during multiple steady state operating points in the stable zone of operation starting from the base case loading until the loading makes the operating point to shift towards the point of voltage collapse (PoC). In these simulations, the system loading has been increased in a gradual step of 1% of the Base MVA.

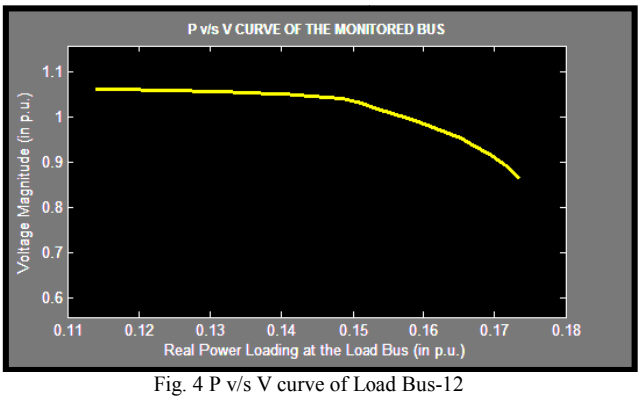

Fig. 4 P v/s V curve of Load Bus-12

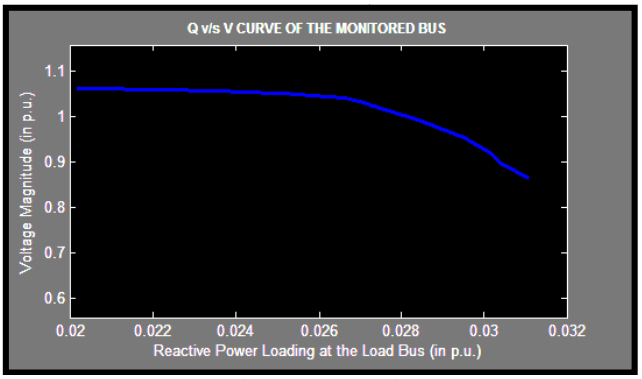

Fig. 5 Q v/s V curve of Load Bus-12

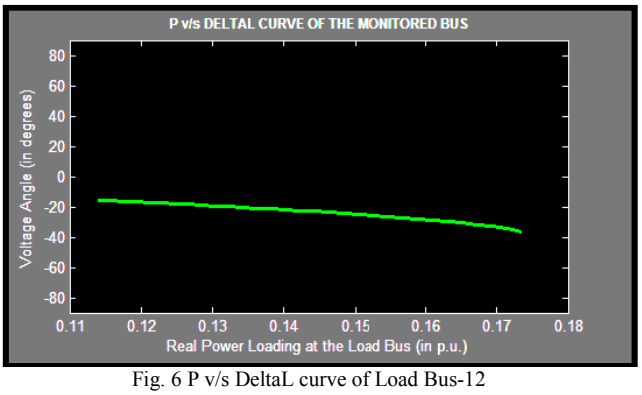

Fig. 6 P v/s DeltaL curve of Load Bus-12

It can be seen in figures 4 and 5 and table 1 that, with the gradual increase in real and reactive power loading at bus-12, the bus voltage magnitude drops, leading to the gradual shifting of the point of operation towards the PoC. The amount of reactive power available at the bus is insufficient in maintaining a desired level of voltage required for certain amount of real power consumption. Thus, this leads to the weakening of the bus from voltage stability point of view, which gets reflected clearly in the VSAI of this bus, as shown in figure 7.

From figure 7 and table 1 it can be seen that, when the system (and also the bus-12) is at the base case loading, the VSAI of the concerned bus is near "0", signifying a highly voltage stable condition, whereas when the system loading (and thus also for bus-12) is increased such that the bus point of operation moves towards the PoC, the VSAI is near "1", thus signifying that the monitored bus has become very weak from voltage stability standpoint.

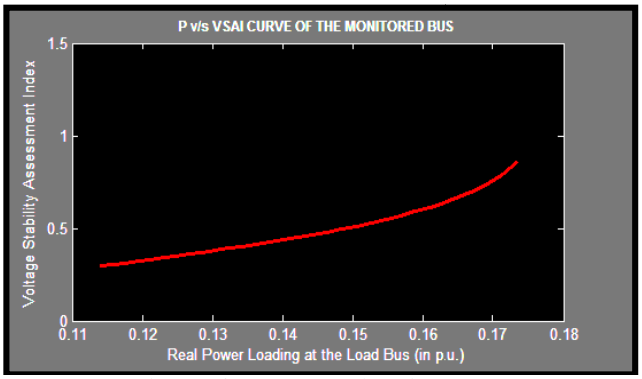

Fig. 7 P v/s VSAI curve of Load Bus-12

TABLE-1: Bus parameters during different cases of loading

Bus-12	VL in (pu)	DeltaL (degrees)	PL (pu)	QL (pu)	VSAI
Base Loading	1.0618	-15.4491	0.1139	0.0202	0.2951
Heavy Loading	0.8628	-36.40	0.1736	0.0311	0.8629

Simulation Results for the IEEE-57 bus test case with gradual increase in system loading:

Figures 8 – 10 show the variation of different parameters of load bus-57 like voltage magnitude and voltage angle with real and reactive power loading at the monitored bus. These figures show the bus parameters during each steady state operating point in the stable zone of operation starting from the base case loading until the loading makes the operating point to shift towards the point of voltage collapse (PoC). In these simulations, the system loading has been increased in a gradual step of 1% of the Base MVA.

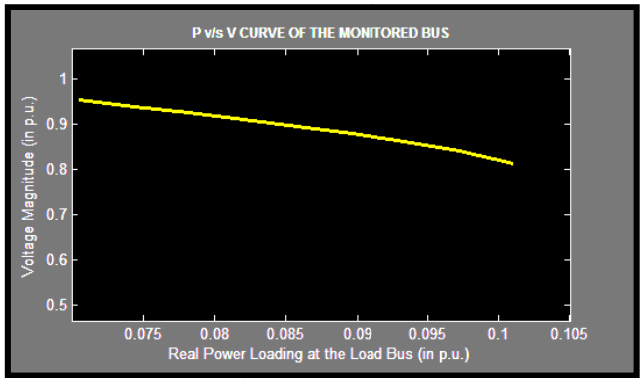

Fig. 8 P v/s V curve of Load Bus-57

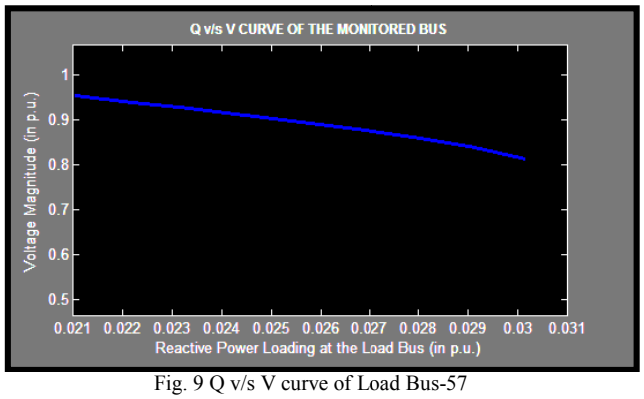

Fig. 9 Q v/s V curve of Load Bus-57

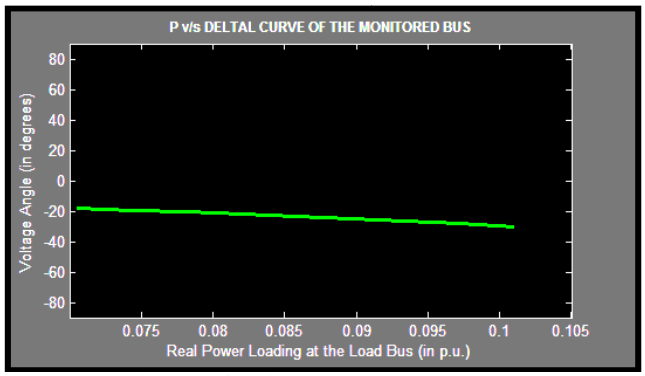

Fig. 10 P v/s DeltaL curve of Load Bus-57

It can be seen in figures 8 and 9 and table 2 that, with the gradual increase in real and reactive power loading at bus-57, the bus voltage magnitude drops, leading to the gradual shifting of the point of operation towards the PoC. Thus, this leads to the weakening of the bus from voltage stability point of view, which gets reflected clearly in the VSAI of this bus, as shown in figure 10.

From figure 11 and table 2 it can be seen that, when the system (and also the bus-57) is at base case loading, the VSAI of the concerned bus is near "0", signifying a highly voltage stable condition, whereas when the system loading (and thus also for bus-57) is increased such that the bus point of operation moves towards the PoC, the VSAI is near "1", thus signifying that the monitored bus

has become very weak from voltage stability point of view.

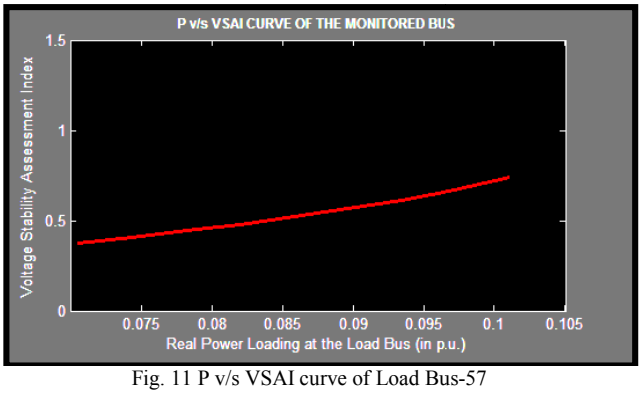

Fig. 11 P v/s VSAI curve of Load Bus-57

TABLE-2: Bus parameters during different cases of loading

Bus-57	VL in (pu)	DeltaL (degrees)	PL (pu)	QL (pu)	VSAI
Base Loading	0.9526	-17.9291	0.0705	0.0210	0.3738
Heavy Loading	0.8135	-30.3711	0.1011	0.0302	0.7413

Simulation Results for the IEEE-14 bus test case with multiple contingencies:

Contingencies like tripping of transmission lines tend to make the system weaker from voltage stability aspect. More reactive power needs to be then transferred as per the load demand though lesser number of transmission lines, thus generally stressing the lines more than the pre-contingency scenarios.

In this simulation, a scenario for multiple contingencies has been created. Initially, the system operates at base loading, and then at t=4 seconds, one of the lines connecting to load bus-9 is tripped due to a fault. This is followed by tripping of another line connected to the same bus at t = 10 seconds.

In figure 12 and table 3 it can be seen that, initially during the pre-contingency steady state situation, the monitored load bus-9 is at nominal voltage condition, and the VSAI is 0.357 (i.e. near "0"). However, when the line 9-10 connected to that bus is tripped after the occurrence of a fault, the voltage magnitude drops and the voltage angle at that bus separates further from its adjacent bus. It is worth mentioning that the loading i.e. the real and reactive power demand at the bus still remains the same. Thus, this leads to a weaker voltage stability situation, which is indicated by a higher VSAI at that bus, i.e. 0.4902 during the post-contingency steady state condition. Due to the loss of one line, when the load demand has not reduced, the other lines connected to that bus become overloaded, and the relay monitoring the line 9-14 connected to bus-9 trips that line as per the predefined settings. This leads to the deterioration of both, voltage magnitude as well as voltage angle as can be seen in table 3. The result is an even weaker voltage stability situation, which is clearly indicated by a higher VSAI at bus-9, i.e. 0.5107 during the post-multiple contingency steady state condition.

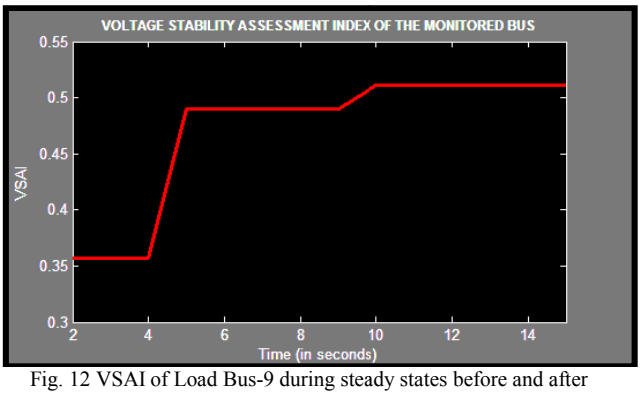

Fig. 12 VSAI of Load Bus-9 during steady states before and after multiple contingencies

TABLE-3: Bus parameters before and after multiple contingencies

Bus-9	VL in (pu)	DeltaL (degrees)	VSAI
Before Contingency	1.0332	-14.8304	0.3570
After 1st Contingency	0.9664	-19.0046	0.4902
After 2nd Contingency	0.9493	-19.5935	0.5107

Simulation Results for the IEEE-118 bus test case with single contingency:

In this simulation, a scenario for a single contingency has been created. Initially, the system operates at base loading, and then suddenly at t=8 seconds, one of the lines connecting to load bus-9 is tripped due to a fault.

In figure 13 and table 4 it can be seen that, initially during the pre-contingency steady state situation, the monitored load bus-20 is at a nominal voltage condition, and the VSAI is 0.2112 (i.e. near "0"). However, when the line 19-20 connected to that bus is tripped after the occurrence of a fault, the voltage magnitude drops and the voltage angle at that bus separates further from its adjacent bus. It is worth mentioning that despite the occurrence of the fault in the line, the loading i.e. the real and reactive power demand at the bus still remains the same as the pre-contingency steady state situation. Thus, this leads to a weaker voltage stability condition, which is indicated by a higher VSAI at that bus, i.e. 0.2612 during the post-contingency steady state condition. Thus from this result, it can be seen that the proposed real time distributed voltage stability algorithm is sensitive enough to capture the effect of single contingency events on voltage stability, where the voltage magnitude and voltage angle

just deviate (or worsen) by a relatively small amount from the values during the pre-contingency case.

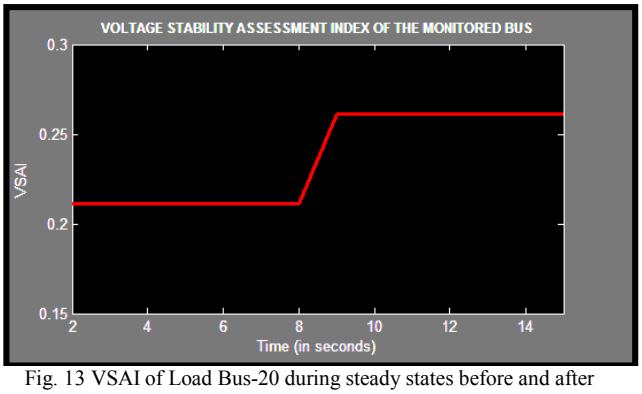

Fig. 13 VSAI of Load Bus-20 during steady states before and after single contingency

TABLE-4: Bus parameters before and after single contingency

Bus-20	VL in (pu)	DeltaL (degrees)	VSAI
Before Contingency	0.9581	12.1782	0.2112
After Contingency	0.9471	15.0651	0.2612

Conclusion

In this paper, the need of developing a new voltage stability algorithm has been discussed. Then a novel distributed real time voltage stability monitoring algorithm has been presented. The developed algorithm utilizes local synchrophasor measurements to compute the Thevenin's equivalent parameters in a non-iterative manner. This algorithm can prove to be beneficial to the present day power system industry as it is very fast and fairly accurate, and does not need a window of past measurement data to compute the voltage stability index at any time instant. The proposed algorithm has been tested on different IEEE test cases like the IEEE-14 bus system, IEEE-30 bus system, IEEE-57 bus system, and IEEE-118 bus system. Simulation results that have been presented in this paper validate the accuracy of the newly developed algorithm in identifying two types of voltage stability conditions of a system – small disturbance voltage stability (mainly caused by gradual load increase), and large disturbance voltage stability (mainly caused by contingencies in the system).

Acknowledgement

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Biographies

Saugata S. Biswas received his B.E. degree in Electrical Engineering from Nagpur University, Maharashtra, India, in 2007. He is the recipient of several Gold Medal awards from Nagpur University for his academic achievements during 2003-2007. He worked in the Design and Development Department of a Switchgear industry in India from 2007 to 2009. From 2009 to 2010, he was in the Mississippi State University as a PhD student. From 2011, he is continuing as a PhD student at Washington State University. He is the recipient of the '2013 EECS Outstanding PhD Student in Electrical Engineering' award from Washington State University, Pullman. His research interests include synchrophasor device testing, real time voltage stability monitoring and control using synchrophasor technology, and substation automation technology for component level diagnostics and prognostics of substation health monitoring.

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