Abstract—This paper presents the application of an Improved system-wide Synchrophasor based Voltage Instability Monitoring Index (ISVIMI) to effectively detect the onset of static voltage instability. To detect the voltage instability, the method requires only load bus voltage phasors. These can be obtained from Phasor Measurement Units (PMUs), which are being increasingly deployed in the power transmission networks. The effectiveness of the proposed method, for real time detection of the voltage instability has been established on Northern Region Power Grid (NRPG) 246-bus Indian system.

Keywords- Voltage stability, Synchrophasor, Phasor measurement unit, Early detection.

I. INTRODUCTION

POWER system is possibly one of the most complex man-made dynamical systems. Its stability and control have always been challenging tasks. Instability in a power system may be analyzed in different ways depending upon the system configuration, operating conditions and disturbances. With the development of improved control and protective devices like static VAR compensators, generator fast speed governing systems and voltage regulators, transient stability limits of power systems have increased considerably. The improvement in the transient stability limits allow more real power transfer over longer distances. Also due to economical, geographical and environmental reasons, the transmission and generation networks of the power system are being operated close to their maximum loadability limit. These factors have resulted in the increased reactive power demand in the system, leading to the difficulty of voltage control. This has contributed to the increasing number of voltage instability incidents worldwide that had led to the system voltage collapse [1].

Voltage stability can be defined as the ability of a power system to maintain steady acceptable voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition [2]. The problem of voltage collapse may be caused by the inability of power system to supply the reactive power or by an excessive absorption of reactive power in the system. The nature of loads also plays an important role in deciding the final state of the system. Other factors that strongly influence voltage instability and collapse include transformer On-Load Tap Changer (OLTC) dynamics and generator exciter current limits. To prevent the system from going into the state of voltage instability, it is required to know the closeness of a particular operating point to the point of voltage instability or stability boundary. In most of the incidences of voltage instability, which occurred worldwide, voltage collapse occurred after several minutes of initiation of the disturbance. Hence, most of the studies have considered the voltage stability as a static phenomenon.

A number of methods for voltage stability and voltage collapse prediction have been proposed in the literature. In [3], [4], voltage stability analysis using PV and QV curves was proposed and in [4], [5], voltage stability margin prediction using continuation power flow method is discussed. In the above two methods, a particular direction of change in load was assumed. But in practice, the change in load may not follow the assumed linear direction and the actual results may be different from those expected. Further, it is difficult to consider all possible load change directions. Voltage collapse indices based on load flow solution and system Y-bus were discussed in [6], [7], and those based on sensitivity of the load flow Jacobian were discussed in [8], [9]. The methods proposed in [6-9] need load flow solution for every load change and also need topology data to update Y-bus to incorporate the changes in the network configuration. It is difficult to implement the above methods online as they take significant time to execute.

With the use of the synchronized phasor measurements using Phasor Measurement Units (PMUs), it has become possible to build Wide Area Monitoring Systems (WAMS) and Wide Area Control Systems (WACS). The phasor measurement based voltage instability monitoring methods can be classified broadly into two categories, a) Local phasor measurement based methods and b) Global phasor measurements based methods.
The local phasor measurements based methods mainly use the Thevenin equivalent concept in the prediction of voltage instability [10], [11], [12], [13]. The methods track the Thevenin equivalent of the system based on local phasors. The parameter tracking is normally carried out over a measurement window in which the unknowns (Thevenin voltage and impedance) remain constant. These methods do not give the clear idea on the effects of various generator controls. Whereas, the global phasor measurements based methods give the wide area picture of the voltage stability [14]. These methods require system wide measurements to implement the algorithms. Some authors have proposed the optimal placement of the measuring devices to make the system completely observable [15], [16].

In this paper, an Improved Voltage Instability Monitoring Index (IVIMI) using synchronized phasor measurements is proposed. The IVIMI proposed belongs to the global phasor measurements based method. The improved algorithm is able to detect the impending voltage instability at an early stage, which will facilitate the system operator to initiate some emergency control action for retaining the system stability. In this paper, Section-II presents the algorithm to find the IVIMI, and Section-III discusses the simulation results, followed by conclusions in Section-IV.

II. PROPOSED VOLTAGE INSTABILITY MONITORING INDEX

The deficiency of the reactive power at the load bus results locally in a decline in the voltage. Therefore, the voltage magnitude variation has been considered as an important factor in deciding the voltage stability. But, for voltage stability monitoring, only the bus voltage magnitude is not a very reliable indicator as the instability may occur near nominal voltage in over compensated networks. The other factor, which can be used in detecting voltage instability, is the rate of change of voltage, which reflects the dynamic condition prevailing in the system. Considering the above two measurements (voltage magnitude and rate of voltage change), a synchronphasor based Voltage Instability Monitoring Index (VIMI) was proposed in [17]. The basic definition of the proposed IVIMI, an improved version of the VIMI proposed in [17] is as follows,

\[
IVIMI_1 = w_1(i) \times \frac{VDR_1}{VDR_{max}} + w_2(i) \times \frac{CVD_1}{CVD_{max}}
\]

where, \(VDR_i\) is the voltage deviation from its reference value at \(i\)th measuring instant, \(VDR_{max}\) is the maximum voltage deviation from its reference value, \(CVD_i\) is the consecutive voltage deviation at the \(i\)th measuring instant, \(CVD_{max}\) is the maximum consecutive voltage deviation, \(W_1(i)\) is the weight of the voltage deviation criterion at \(i\)th measuring instant, \(W_2(i)\) is the weight of the rate of voltage change criterion at the \(i\)-th measuring instant.

In (1), one important factor is to find the values of \(VDR_{max}\) and \(CVD_{max}\). In [17], the procedure used to find the threshold values of \(VDR_{max}\) and \(CVD_{max}\) is based on the results obtained by simulating various power system events. The method used in [17] is time consuming. Sometimes, events causing voltage instability in the system may not be in the list of simulations carried out to determine the two threshold values (\(VDR_{max}\) and \(CVD_{max}\)). This type of situations may lead to false alarms to the system operator. By considering the above difficulties, an improved method is proposed to obtain the IVIMI using the definition (1) and is described in the following.

A. Calculation of \(VDR_i\) and \(VDR_{max}\)

At each measuring instant \(i\), the voltage deviation from the reference or the nominal value is calculated as,

\[
VDR_i = V_{ref} - V_i
\]

In (2), \(V_{ref}\) is the reference value of voltage magnitude, which is the nominal voltage level or the base case value and \(V_i\) is the voltage magnitude at \(i\)th measuring instant. The maximum voltage deviation from its reference can be calculated as,

\[
VDR_{max} = \min \{V_n - V_{min}\}
\]

In (3), \(V_n\) is the set of nominal voltages of all the buses and \(V_{min}\) is the minimum voltage magnitude allowed in the system before initiating some control action like load shedding etc.

B. Calculation of \(CVD_i\) and \(CVD_{max}\).

The difference between the voltages at two consecutive time instants indicates the rate of voltage decay/riser for a constant sampling time. Hence, the deviation in consecutive voltages at \(i\)th measuring instant can be written as,

\[
CVD_i = V_{i-1} - V_i
\]

As the system voltages move from stable state to unstable state, voltages at most of the buses will decay and therefore, the CVD value difference rises. Maximum consecutive voltage deviations (\(CVD_{max}\)) of the system can be obtained simply by tracking the maximum of the CVD until any of the bus voltages falls below the \(V_{min}\), i.e. the \(CVD_{max}\) is dynamic until any of the bus voltages reaches \(V_{min}\). Once any of the bus voltages falls below the \(V_{min}\), the \(CVD_{max}\) is held at its value obtained just before going below the \(V_{min}\).

The weights \(w_1\) and \(w_2\) can be calculated using the algorithm proposed in [17].

IVIMI calculated at each load bus-\(p\) has been used to define Improved System-wide Voltage Instability Monitoring Index (ISVIMI) at \(i\)th measuring instant, as shown below.

\[
ISVIMI = \max (IVIMI_p); \quad p \in \text{load buses set}
\]

In the index defined in (1), numerator and denominator signify the measured deviation from its nominal state/base case and tolerable deviation of the system, respectively. As the measured deviation approaches the tolerable deviations of the system, the ISVIMI reaches numerical value 1.0 and gives an indication to the system operator to initiate some emergency control action like voltage control through generator’s excitation system, shunt FACTS controllers or power flow control through series FACTS controllers and/or possibly as a last resort, load curtailment, to retain the system stability.
III. CASE STUDY

Using the proposed voltage instability monitoring index, studies have been carried out on the Indian North Regional Power Grid (NRPG) system. The reduced NRPG (400kV and 220kV buses only) network consists of 246 buses, 376 lines/transformers, 42 generating units and 40 shunt reactors [18]. Two cases have been considered to study the effectiveness of the proposed algorithm. The loads in the test system are replaced with ZIP load models [4],

\[
P = [a(V/V_o)^2 + b(V/V_o) + c]P_o \tag{6}
\]

\[
Q = [d(V/V_o)^2 + e(V/V_o) + f]Q_o \tag{7}
\]

where, \((a + b + c = 1)\) and \((d + e + f = 1)\). Coefficients \(a, b, c\) are the proportions of ZIP components in the active power load, and coefficients \(d, e, f\) are the proportions of ZIP components in the reactive power load. \(P_o\) and \(Q_o\) are the real and reactive power demands at the nominal voltage \(V_o\). Time series data for the two scenarios were generated using PSAT software [19] by considering two-axis flux decay dynamic model of generators with IEEE type DC-1 excitation system and over excitation limiters [4]. The results obtained using the proposed algorithm has been compared with Voltage Instability Monitoring Index proposed in [17] and Voltage Stability Risk Index (VSRI) proposed in [20].

A. Case-I: Load Increase

In this case, real and reactive power loading at all the load buses are increased progressively at a rate of \((0.006+j0.006)\) pu MVA per sec. The loading was started at time \(t=10s\). With the said time-domain simulation, voltage collapse is observed at around 258s. Voltage critical buses identified based on ISVIMI from the simulation are 156, 158, 173 and 174. Voltage variations at some of the critical buses are shown in Fig.1.

B. Case-II : Line Outage

In this case, a line outage between buses 133 (Delhi) and 182 ( Sahibabad in UP) is simulated at time \(t=5sec\) and simultaneously real and reactive power loadings are increased in Rajasthan at a rate of \((0.003+j0.003)\) pu MVA per sec. Voltage critical buses, identified for this scenario, are 156, 158, and 174. Voltage variations at critical buses are shown in Fig. 5. The results obtained using the proposed IVIMI and the indices proposed in [17] and [20] are shown in Figs. 6-8, respectively. In this scenario, voltage collapse is observed at around 266s. The proposed SVIMI reaches unity in around 170s, whereas as VIMI proposed in [17] reaches unity in around 240s.

Hence, in both the cases, the proposed ISVIMI reaches numerical value of unity much earlier than the VIMI proposed in [17] and, thereby, will provide more time to the system operator to initiate appropriate actions to retain the stability. Similarly, comparing the proposed IVIMI results with the results of the VSRI [20], it is found that the proposed IVIMI increases gradually depending on the condition of the system and reaches unity, whereas VSRI value is constant almost up to the collapse point and changes its value abruptly near the collapse. VSRI type indices fail to give proper alarm signal to the system operator or, sometimes, the system operator may not find time to take emergency control action after receiving the alarm.
IV. CONCLUSIONS

In this paper, a system-wide Improved Voltage Instability Monitoring Index (ISVIMI) is described to detect the impending long-term voltage stability. The method requires only voltage phasors at all the load buses. In this scheme, the voltage magnitude and its rate of change at load buses are used to develop the index. The ISVIMI approaches unity much earlier than the SVIMI proposed in [17], and performs much better as compared to the VSRI in [20]. The method described is simple and requires less computational efforts, which makes it suitable for online applications. The proposed method is satisfactorily tested on the NRPG 246 bus test system under various disturbance scenarios leading to voltage collapse. The validation of the proposed methodology is also being further carried out using real time data generator through Real Time Digital Simulator (RTDS) at IIT Kanpur.

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Ch. V. V. S. Bhashkara Reddy (S’11) received the M. Tech. degree from Regional Engineering College, Warangal, India in 2000. Presently, he is pursuing the Ph.D. degree in Electrical Engineering at the Indian Institute of Technology Kanpur, India. His research interests include wide area monitoring and control and power system operation and control.

S. C. Srivistava (SM’91) received the Ph.D. degree in Electrical Engineering from the Indian Institute of Technology Delhi, New Delhi, India. He is presently working as Professor in the Department of Electrical Engineering at Indian Institute of Technology Kanpur, India. His research interests include power system security, stability analysis and control, Wide Area Monitoring and Control (WAMS), and power system restructuring. He is a Fellow of the Indian National Academy of Engineering (INAE), the Institution of Engineers (India), and IEETE (India).

Saikat Chakrabarti (S’06-M’07-SM’11) received the Ph.D. degree from Memorial university of Newfoundland, St. John’s, NF, Canada. Currently, he is Assistant Professor in the Department of Electrical Engineering, Indian Institute of Technology Kanpur, India. His research interests include power system dynamics and stability, state estimation, reliability, and synchrophasor applications to power systems.