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Synchrophasor-assisted detection and control of emergency voltage instability conditions

Imran Sharieff Md* and Ranjana Sodhi**

An impending voltage instability can often be avoided with a timely detection, followed by appropriate control actions. This paper proposes a complete scheme for the detection of impending voltage instability and subsequently, devising an emergency control action using synchrophasor measurements. The impending voltage instability is assessed using voltage and current phasor measurements, which can be obtained from the Phasor Measurement Units (PMUs). These measurements are exploited to find the maximum transferable power to a load bus, which, in turn, is used to deduce a Voltage Stability Monitor (Sy-VSM). The value of the proposed indicator gives the distance to voltage collapse. When the proposed Sy-VSM drops beyond a certain limit, a two-staged Load Shedding (LS) scheme is initiated as an emergency control action. Stage-1 sheds a fixed amount of load in multiple steps, taking into account the time, location and amount aspect of LS. In post-stabilization Stage-2, the amount of load curtailment is optimized using Model Predictive Control (MPC) based approach. The proposed scheme is demonstrated on the New England 39-bus system and a practical Indian Northern Regional Power Grid (NRPG) 246-bus system, and the results are found to be very encouraging.

Keywords: *Voltage stability, synchrophasor measurements, load shedding, voltage stability indicator.*

1.0 INTRODUCTION

For the stable operation of the power system, voltage profiles should be maintained within pre-specified limits. However, the system voltages may undergo a gradual or a drastic decline in voltages, following a load increase or some severe contingency. Such conditions, if not timely detected and arrested, may lead to a partial or complete voltage collapse. The real-time detection of an impending voltage instability becomes even more essential in present days when the power sectors have undergone restructuring. The restructuring has led the system operators to operator the system closer to its stability limits, thereby, making the systems more vulnerable to instabilities [1].

Power system researchers have done extensive study on voltage stability assessment algorithms, owing to the catastrophes caused by voltage instability issues. Conventional methods for voltage stability assessment like nose curves (PV and QV curves) and continuation power flow method [1] are well reported in literature. These methods, however, are time consuming as they are dependent on traditional state estimators which can take minutes to update. Thevenin based methods like [2] and [3] are quite simpler as they require only the knowledge of local measurements at the load bus. However, accurate estimation of Thevenin parameters E_{th} and Z_{th} is required in these methods which may not be possible in all cases and may end up with erroneous conclusions. Pordanjani *et al* [4] and Jian-Hong

*Research scholar, EEE Department, IIT -Ropar, Punjab-140001, imrans@iitrpr.ac.in, Mob: +91-7696740179
** Assistant professor, EEE Department, IIT -Ropar, Punjab-140001, rsodhi@iitrpr.ac.in.

et al [5] have proposed methods based on critical channel transform and modified coupled single-port circuits, respectively. These methods require transformation of the power system into a set of single-port equivalent circuits, which are simpler to analyze than the complete system. Another group of methods called supervised/unsupervised learning methods have also been proposed in literature for voltage stability assessment like Artificial Neural Networks (ANN) [6] Decision tree (DT) [7] and Regression Tree (RT) [8] based methods. In [9] relationship between Voltage Stability Margin (VSM) and other operational variables is explored. The highly ranked linear and nonlinear relationships are used for online voltage stability assessment. Recent developments in voltage stability assessment include equivalent nodal analysis [10], which is analogous to well-established modal analysis. In these methods, eigen values of reduced Jacobian matrix are used to identify critical buses and their participation factors in the power system. For large power systems calculation of Jacobian and corresponding indices for modal and nodal analysis becomes computationally intricate as the system approaches its maximum loading point. Cao *et al.* have proposed another method for voltage stability assessment by monitoring only branch active powers [11]. In this method, the authors have identified a set of critical branches before voltage collapse, where branch active powers which evolve as a function of bifurcation parameter reach maximum.

Phasor Measurement Units (PMUs) are relatively new devices in the field of power systems which measure the voltage and current phasors as fast as 1 measurement per cycle of supply frequency. As a result of their fast refresh rate and accurate measurements, synchrophasors have made the real-time monitoring and assessment of voltage stability feasible. Disturbances caused by generator and line outages in the network spread over wide geographical area and can be effectively diagnosed by PMU based Wide area monitoring systems (WAMS) [12], [13]. In [14], authors have proposed Synchrophasor based Voltage Instability Monitoring Index (SVIMI), given by the magnitude and rate of decay in synchrophasor voltage. This method utilizes only voltage measurements obtained from wide area network of PMUs making it simpler and faster. Similarly, in [15] WAMS are used to define voltage stability index which uses the properties of reduced Jacobian alike modal analysis but with lesser computational effort. When the system voltage stability deteriorates these algorithms alert the system operator, this allows the operator to initiate preventive actions like switching shunt capacitors, LTC control, Load Shedding (LS) etc., to protect the system integrity.

Generally, a voltage instability or collapse can be avoided by initiating timely preventive or corrective actions such as active power generation rescheduling, load shedding, etc. Load shedding is employed to stabilize a power system after it undergoes a major contingency or strong overload, stressing the power system to the verge of instability or collapse. Optimization of the amount of load curtailment and protection against voltage collapse forms a multi-objective optimization problem. Load shedding scheme for protection against voltage collapse have been reported in literature [16] - [18]. Adaptive centralized load shedding algorithms addressing multiple stability problems are reported in literature in [19], [20].

In this work, synchrophasor measurements are used to detect and control the impending voltage instability in power system. The voltage and current measurements, obtained from the PMUs, are first pre-processed. In the pre-processing module, transients resulting from the On-Load Tap Changer (OLTC) action or the activation of Over Excitation Limiter (OEL) of generators are discarded. Voltage and current measurements, obtained after the pre-processing, are then exploited to devise a Synchrophasor-assisted Voltage Stability Monitor (Sy-VSM). Since both the measurements are readily available from PMUs, the proposed indicator is calculated very fast. In order to arrest any emanating voltage instability, a threshold value is set for the proposed Sy-VSM. The Sy-VSM is there after used to initiate an optimal load shedding strategy. Initially a fixed amount of load is shed in multiple stages to protect the system from collapse. Post-stabilization, the amount of load curtailment is optimized using Model Predictive Control (MPC) based approach. The effectiveness of the proposed strategy is demonstrated on New England 39-bus system and a practical Indian Northern Regional Power Grid (NRPG) 246-bus system.

The paper is organized into four sections. The proposed voltage instability detection and control strategy is explained in Section 2.0. The results on the two test systems are discussed in Section 3.0 and the final conclusions are drawn in Section 4.0.

2.0 PROPOSED SYNCHROPHASOR-ASSISTED VOLTAGE INSTABILITY DETECTION & CONTROL SCHEME

2.1 Voltage Instability Detection

PMUs give voltage (*V*) and current (*I*) measurements, which can be exploited to derive a condition for maximum transferable power from the network to the load. The relation between magnitude of load voltage and current phasors at any operating point Q, at a load bus-*j* can be expressed by ann^{th} order polynomial as,

$$V = g(I) = w_0 + w_1 I + w_2 I^2 + \cdots + w_n I^n = \sum_{j=0}^{n} w_j I^j \quad ...(1)$$

These measurements can further be used to calculate the magnitude of apparent power at **Q** operating point as,

$$S = V \times I = g(I) \times I = \sum_{j=0}^{n} w_j I^{j+1} \quad ...(2)$$

$$S = w_0 I + w_1 I^2 + w_2 I^3 + ... + w_n I^{n+1} \quad ...(3)$$

The condition for maximum power transfer says that $\frac{\partial S}{\partial I}$ =0 i.e,.

$$w_0 + 2w_1 I + 3w_2 I^2 + \cdots + (n+1) w_n I^n = 0 \quad ...(4)$$

Let I_{mx} be the solution of (4). I_{mx} is the value of current at which maximum power is transferred to load bus-*j*. The corresponding magnitude of apparent power (Say S_{mx}) at I_{mx} is obtained from (3) as,

$$S_{mx} = w_0 I_{mx} + w_1 I_{mx}^2 + w_2 I_{mx}^3 + \cdots + w_n I_{mx}^{n+1} \quad ..(5)$$

S_{mx} corresponds to the maximum transferable power from network to load bus-*j* i.e., the knee point (R) of the nose curve shown in Figure 1.

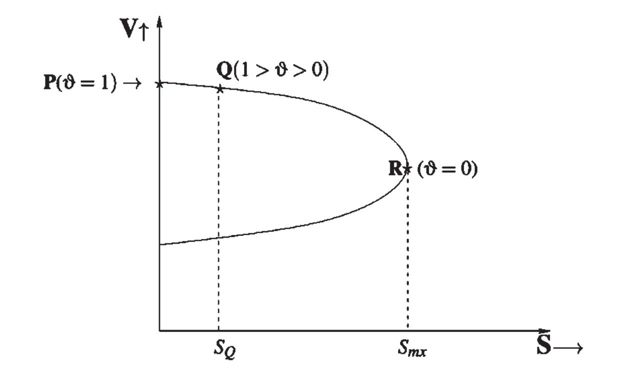

FIG. 1. MOVEMENT OF SY-VSM ALONG THE NOSE CURVE

2.1.1 Synchrophasor Assisted Voltage Stability Monitor (Sy-VSM)

From the nose curve shown in Figure 1, the distance of any operating point Q from the collapse point R can be calculated as

$$\vartheta = \frac{S_{mx} - S_Q}{S_{mx}} \quad ...(6)$$

Quantity ϑ in (6) gives an indication of the distance of a given operating point from the nose point, and thus, is defined as the Synchrophasor based Voltage Stability Monitor (Sy-VSM) as,

$$Sy - VSM\ (\vartheta) = 1 - {S_Q}/{S_{mx}} \quad ...(7)$$

Under normal conditions $\vartheta \approx 1$ (say at operating point **P** in Figure 1). When the system is stressed, the operating point **P** moves to **Q** and further upto **R**. Although the voltage collapse occurs when Sy-VSM = 0, but for practical reasons, a critical threshold ($\vartheta^{Threshold}$) should be determined by detailed system analysis, for taking necessary control actions. It can be observed from (1)-(5) that given the *V* and *I* measurements, the value of S_{mx} and thus, of the proposed indicator ϑ depends on the *w* coefficients. The estimation of *w* coefficients is discussed in next subsection.

2.1.2 Estimating w coefficients:

PMUs are high precision measurement devices and can provide time synchronized sub second phasor measurements, typically 50-60 measurements per second. To determine the *w* coefficients, first a time window is selected (in this work, it is 1 second), and V-I measurements at load bus-*j* are buffered for the assumed window length. Least squares curve fitting technique is used to obtain the polynomial that represents *g(I)* in (1) as

$$V_{n\times 1} = I_{n\times m} \times A_{m\times 1} \quad ...(8)$$

Where, **V** is a vector of measured voltage magnitudes at the *n* time-instants in the time-window, **A** the vector of *m* unknown *w* coefficients and **I** the current matrix. The matrix **A** consisting of *w* coefficients, can be calculated using Least squares curve fitting method as

$$A = (I^T\, I)^{-1} I^T\, V \quad ...(9)$$

Once the *w* coefficients are determined, the critical load S_{mx} and *Sy-VSM* are calculated using (1)-(5).

2.2 Emergency Control using Load Shedding

When the system is close to voltage instability, preventive actions are required to relieve the situation and save the power system from an imminent voltage collapse. The voltage stability Control scheme, proposed in this work, aims at achieving voltage stability through optimal load shedding. The scheme is comprised of two stages. In the first stage, stability of the system is regained through a static load shedding, which is initiated based on the value of the proposed *Sy-VSM* (ϑ). After the system is saved from a nearing voltage collapse, some of the loads are restored using Model Predictive Control (MPC) based optimal load shedding approach, as discussed in the following subsections.

2.2.1 Stage-1 Load Shedding: While going for a static load shedding in first stage, two important aspects have been addressed *viz*., the location and the amount of load shedding. Load shedding scheme is initiated based on the value of the proposed Sy-VSM as per the following rule.

$$\text{If}\,\vartheta < \vartheta^{Threshold} \text{for 1 second time} - \text{window then shed } \Delta\text{P}\; MW \quad ...(10)$$

To protect the system from collapse, initially load shedding is done at critical buses in multiple stages until Sy-VSM reaches a value greater than threshold value. In each stage of load shedding, 5% of total demand is shed. The candidate locations for the load shedding are selected on the basis of the value of ϑ. Synchrophasor based Voltage Stability Monitor (Sy-VSM) is first calculated at all the load buses. The value of Sy-VSM at any bus represents the criticality of that particular bus. So, the buses where the value of Sy-VSM is low are identified as critical buses. Since critical buses are more sensitive to load shed, distribution of load shed is done on the basis of criticality of a bus. The allocation of load shedding at each of the identified load bus would be in proportion to the value of the proposed index value (ϑ) at that bus. The distribution of load shed at j^{th} load bus (LS_j) is computed as,

$$LS_j = \frac{\vartheta_j}{\sum_{i=1}^{N_v} \vartheta_i} \times \Xi_{sh} \quad ...(11)$$

Where, N_v is the number of load buses violating the threshold on the proposed index ϑ, and the total amount of load to be shed, $\Xi_{sh} = 5\% \times Demand$. The stage-1 load shedding is carried out in multiple stages until ϑ is brought back above its set threshold, and the emanating voltage instability is arrested.

2.2.2 Stage-2: *Post-stabilization Optimal load shedding:* In emergency situations, the focus is more on to bring the system back within the acceptable operation range and not to achieve an optimal load shedding. There is a good chance that stage-1 might over-shed the load in order to bring the voltages back within pre-defined limits. Thus, after assuring the system stability via means of stage-1 load shedding, post-stabilization system conditions are analyzed using trajectory sensitivity based Model Predictive Control (MPC) [21] to carry out an optimal load shedding in stage-2 of the proposed scheme. The MPC is a discrete time optimization problem where internal dynamic model of the system is used to predict the system behaviour and control laws are accordingly decided based on the predicted trajectories. This is illustrated in Figure 2, where three steps of controls (ΔC_{k1}, ΔC_{k2}&ΔC_{k3}) are employed to stabilize the system state (X_k) from predicted instability. It is shown in [21] that this problem may further be approximated, through the use of trajectory sensitivities, as a linear (time-varying) discrete-time optimal control problem.

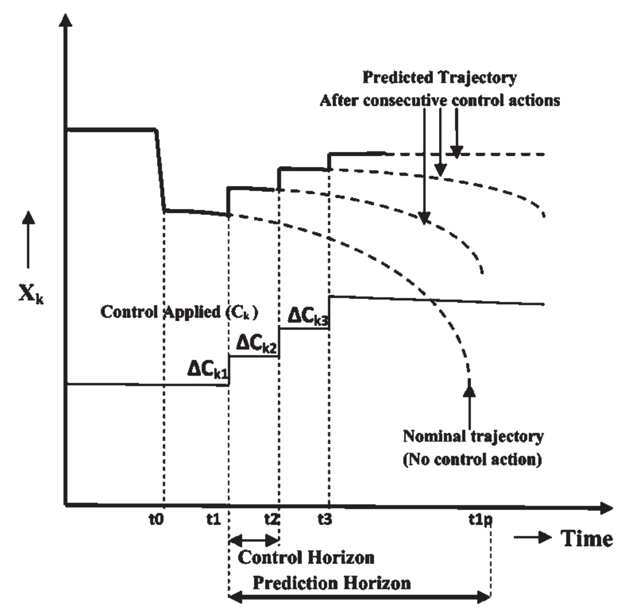

FIG. 2. MODEL PREDICTIVE CONTROL (MPC) USING TRAJECTORY SENSITIVITIES

2.2.3 VS-Control

To protect the system from collapse, initially load shedding is carried out at critical buses until the next system state (X_{k+1}) is inside the polyhedral set $X^{Ref}= [X^{min}X^{max}]$. In this work, Model Predictive Control (MPC) is used to assess the behaviour of the system post-stabilization using trajectory sensitivities and apply optimal amount of controls at present instant. The optimization problem to be solved at time t_1 can be denoted as,

Minimize

$$\int_{t1}^{tp} F(X(t), C(t))dt \quad ...(12)$$

Subject to

$$C^{min} \le \hat{C}(t) \le C^{max}, \qquad t_1 \le t \le t_{1c}$$

$$\hat{C}(t) = C(t_{1c}), \qquad t_{1c} \le t \le t_{1p}$$

$$X^{min} \le \hat{X}(t) \le X^{max}, \qquad t_1 \le t \le t_p \quad ...(13)$$

Where, $\hat{X}$ and $\hat{C}$ are predicted states and estimated controls in the prediction horizon t_1 tot_{1p}. The control and prediction horizon at time t_1 are denoted ast_{1c}, t_{1p} respectively with $t_{1c}\le t_{1p}$. The overall cost function of the optimization problem using MPC at time t_1 is given by $\boldsymbol{F}$. Dynamic system model is given by $\boldsymbol{f}$. $[C^{min}C^{max}]$, $[X^{min}X^{max}]$ represent the lower and upper bounds of controls and states, respectively. The behavior of the system can be described by the flow,

$$X(t) = \Gamma(X_0, C_0, t) \quad ...(14)$$

With algebraic constraints

$$\phi(X(t), Y(t), C_0) = 0 \quad ...(15)$$

Where, X_0 and C_0 represent initial value of X and C, respectively. The trajectorysensitivities of selected states with respect to controls applied can approximated by expanding (14) as,

$$\Gamma(X, C_0 + \Delta C_0, t) = \Gamma(X_0, C_0, t)$$
$$+\Gamma_C(X_0, C_0, t)\,\Delta C_0 + higher\ terms \approx$$
$$\Gamma(X_0, C_0, t) + \Gamma_C(X_0, C_0, t)\Delta C_0 \quad ...(16)$$

Where, $\Gamma_C= \delta\Gamma/\delta C_0$ is called trajectory sensitivity, and can be obtained from simulation as

$$\Gamma_C\Delta C_0 = \Gamma(X, C_0 + \Delta C_0, t) - \Gamma(X_0, C_0, t)$$

Say

$$\Delta X = \Gamma(X, C_0 + \Delta C_0, t) - \Gamma(X_0, C_0, t)$$

$$\Gamma_C\Delta C_0 = \Delta X; \Gamma_C = \Delta X/\Delta C_0 \quad ...(17)$$

2.3 Boundary conditions

The upper and lower bounds of statescritical to voltage stability are defined,

- To ensure that the load bus voltages ($\boldsymbol{V_L}$) are with in prescribed limits,

$$V_L^{min} \le V_L \le V_L^{max} \quad ...(18)$$

- The field current at generator buses (I_{flG}) are maintained,to ensure that there active power capability of the generators is not completely exhausted i.e.

$$I_{flG}^{min} \leq I_{flG} \leq I_{flG}^{max} \quad ...(19)$$

- Line currents are to be maintained within pre-specified limits i.e

$$I_{line}^{min} \leq I_{line} \leq I_{line}^{max} \quad ...(20)$$

- The proposed voltage stability indicator (ϑ) is maintained above its threshold value $\vartheta^{Threshold}$.

$$\vartheta_L^{Threshold} \leq \vartheta_L \leq \vartheta_L^{max} \quad ...(21)$$

$\hat{X} = [V_L, I_{flG}, I_{line}, \vartheta_L]$ is a vector of selected states. The present operating point (X_k) should lie inside the polyhedral set $X^{Ref} = [X^{min} X^{max}]$. If X_k lies outside this region the system is prone to collapse and counter measures are taken to secure the system.

2.4 Optimization of controls

The proposed methodology aims to minimize the amount of controls $\Delta C = [\Delta P_L \;\; \Delta Q_L]^T$ in the control horizon to ensure its stability throughout prediction horizon. In this work, prediction horizon is taken as *10s* and control horizon as *1s*. The objective function for minimization of controls is formulated as,

$$Minimize \int_{t_k}^{t_{kp}} W_1 \left(F\left(\hat{X}(t), \hat{C}(t) \right) \right) dt + W_2 \Delta C \quad ...(22)$$

The time evolution of F from present time t_k till its prediction horizon t_{kp} is obtained from trajectory sensitivities Γ_{Ck} at current instant k. To ensure the boundary conditions are not violated, Hausdroff distance terms are used in objective function. The overall MPC algorithm can be defined as linear program in single step as,

Minimize

$$W_1(||X_{k+1} - X^{min} + \Gamma_{Ck}\,\Delta C_k||_1 + ||X_{k+1} - X^{max} + \Gamma_{Ck}\,\Delta C_k||_1) + W_2 \Delta C_k$$

Subject to∀

$$(C_0 + \Delta C_k) \in [C^{min} C^{max}] \quad ...(23)$$

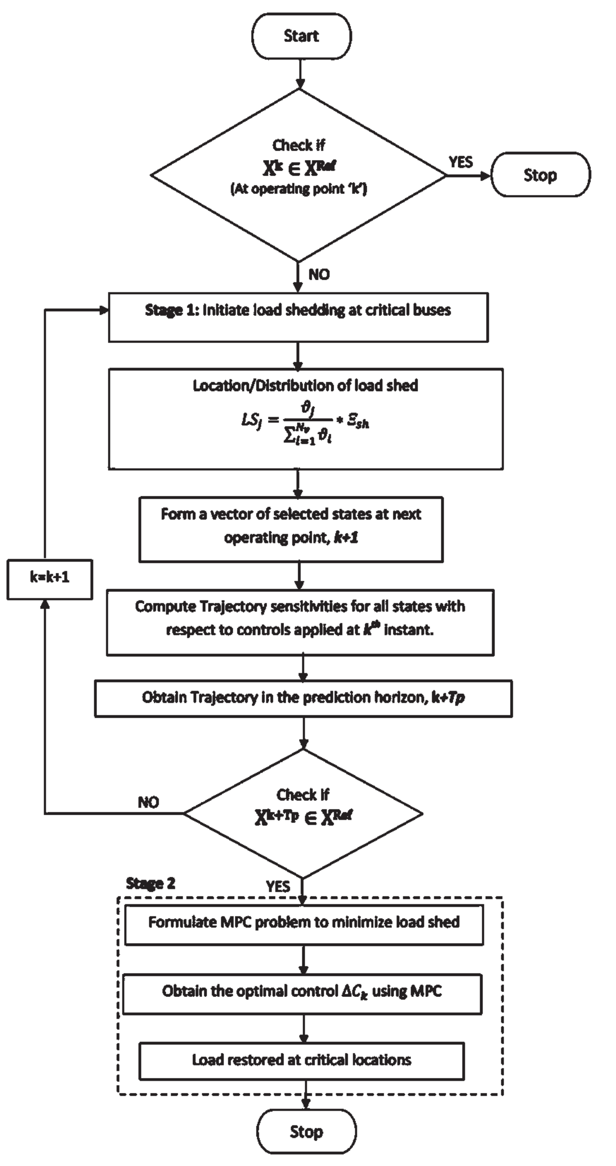

FIG. 3. FLOWCHART OF THE PROPOSED METHODOLOGY

$||\,.\,||_1$ gives the maximum distance of predicted state from its boundary conditions. W_1 and W_2 are penalty terms or weights (taken as $W_1 >> W_2$). The solution to this optimization problem ΔC_k at any instant k ensures that minimum amount of load is shed to bring the operating point inside $\boldsymbol{X^{ref}}$. The solution of this optimization problem gives the minimum amount of load to be shed/restored. The overall proposed scheme for voltage stability assessment and load shedding is depicted in the flowchart shown in Figure 3.

3.0 TEST RESULTS

The proposed scheme for voltage stability assessment and control is tested on two systems viz; New England (NE) 39-bus system and a dynamically reduced practical Northern Region Power Grid (NRPG) 246-bus system. The behaviour of the system during various stressed cases is studied. To demonstrate the efficacy of the proposed methodology, the test results of the load shedding are compared with an existing MPC based methodology [22]. Time-domain simulation of these test system is carried out to obtain the time-series data of voltage and currents. The data obtained is down-sampled at a rate of 60 and 50 measurements per second to confirm with the synchrophasor standards in the respective test systems. To address the impact of generator Q-limits on voltage stability, both the test systems are equipped with Over Excitation Limiters (OELs) and On-load Tap Changers (OLTCs).

$\vartheta^{Threshold}$ is taken as 0.5 and 0.6 for NE 39-bus system and NRPG 246-bus system, respectively. It has been observed from simulations that NRPG system has low damping. The time for recovery and oscillations observed during contingencies are taken into consideration for allocation of threshold values for these systems. The time for recovery is taken such that it coincides with the control horizon i.e. 1s. The working of the proposed scheme under various test scenarios is demonstrated as follows.

3.1 New England 39-bus system

The test system consists of 10 generators, 29 constant power type loads, 46 lines with total active power load of 609.71 MW and reactive power load of 140.94 MVAR. Total generation from base case load flow is 611.26 MW and 143.44 MVAR. The test results of the proposed scheme, for this test system, are presented for the following scenario.

Continuous load increase: In this case, load is increased slowly from t = 30 s at the rate of 0.02 p.u/s. It can be inferred from Figure 4 that after t = 60 s, three possible scenarios exist viz.,

3.2 No control When no control is applied, OLTC startsto operate to bring back the voltage level above its pre-specified level. At t = 62 s, OEL at Gen-5 connected to bus-34 hits its maximum limit, thereby withdrawing its reactive support. This leads to further deterioration of voltage profile. With every step of LTC operation, the voltage profile deteriorates, ultimately leading to a voltage collapse at t = 75 s, as shown in Figure 4. Figure 5 shows the PV curve at bus-20, it can be inferred from Figure 5 that the knee point also occurs at V=0.6 *p.u.*

3.3 Only Stage-1 control At t = 60s, the proposed Sy-VSM is below its threshold level($\vartheta \leq \vartheta^{Threshold}$) at two locations (buses 20 & 16) as shown in Figure 6.

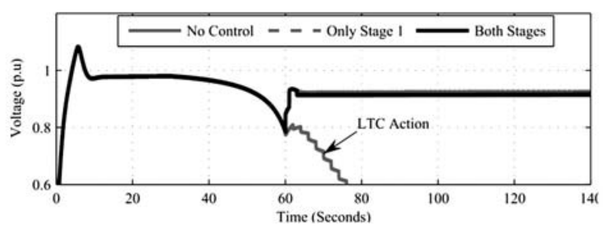

FIG. 4. CASE 1: VOLTAGE AT BUS-20

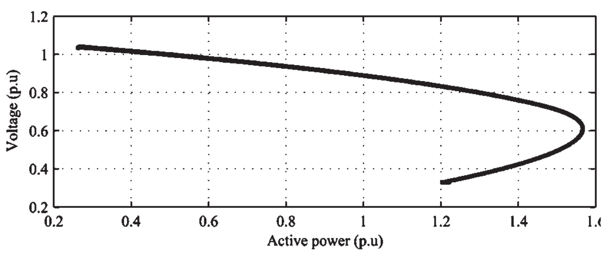

FIG. 5. CASE 1: PV CURVE

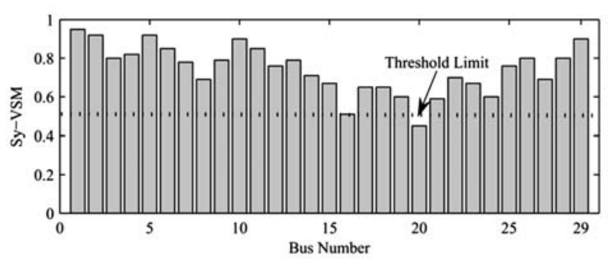

FIG. 6. CASE 1: SY-VSM(Θ) AT ALL LOAD BUSES AT T = 60S

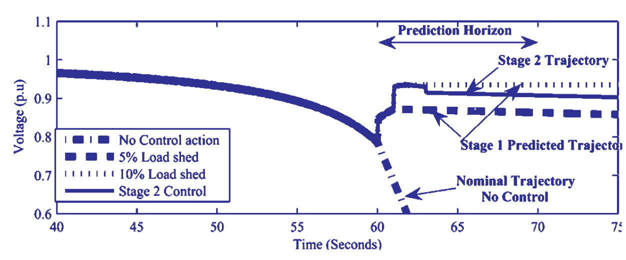

FIG. 7. CASE 1: VOLTAGE TRAJECTORIES AT BUS-20

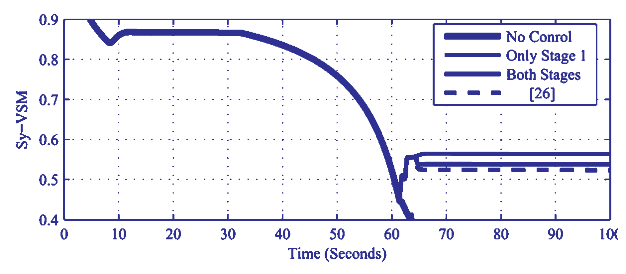

FIG. 8. CASE 1: SY-VSM (Θ) AT BUS-20

The proposed indicator gives an early warning of the possible voltage collapse by 15 seconds. At t = 60 s,. Buses 20 and 16 are, thus, marked as critical locations. Stage-1 load shedding scheme is activated to bring back the Sy-VSM above its threshold value ($\vartheta^{Threshold}$) of 0.5 at critical buses. A total of 91.4 MW and 21.1 MVAR of load is shed at critical buses. The distribution of load shed is proportional to their criticality, as discussed in Section 2. B. After load shedding, the operating point is inside X^{ref}. Figure 7 shows the evolution of voltage trajectories in all possible scenarios. It can be observed that after shedding 10% of load, voltage is restored. The system is secured, but the amount of load shed in due course is not optimal. Figure 8 also shows that after load shedding the proposed Sy-VSM is above threshold, Stage-1 acts as an emergency control action to prevent the system from collapse within a span of two seconds by shedding more load than required. The system continues to be in this over compensated state if no load restoration is employed as shown in Figures 7-8.

Stage-2 control: In this scenario, both stages of load shedding are employed. As discussed earlier, the bulk load is shed in Stage-1 to prevent the system from collapse. Post-stabilization optimal load shedding starts at t = 64 s as shown in Figures 4,7 & 8. The evolution of voltage trajectories after Stage-2 is shown in Figure 7, it can be inferred that even after load restoration, the voltage is above its limit of $0.9p.u$ in the prediction horizon. The amount of load shed in Stage-1 is optimized using Model predictive control, as discussed in Section 2.2. A total of 6.9 MW and 2.9 MVAR of load is restored at bus-20 in Stage-2 as listed in Table 1.

It can be observed from Table 1 that the proposed scheme results in somewhat conservative optimal load shedding results

TABLE 1

RESULTS FOR NE 39-BUS SYSTEM

Stage	Load Shed	Locations
1st Stage	91.4 MW& 21.1 MVAR	20 & 16
Proposed 2nd Stage	-6.9 MW & -2.9 MVAR	20
2nd Stage using [22]	-8.6 MW & -3.8 MVAR	20

as compared to that of [22]. This is mainly because the polyhedral set X^{ref}, in [22], consists of only [V_L, I_{flG}, I_{line}], and it does not put any constraint over voltage stability indicator. The proposed scheme, on the other hand, ensures that besides improving the system voltage profile, the system is completely secure from voltage stability point of view as well. This is done by enforcing a constraint on the proposed voltage stability indicator in stage-2 load shedding. Further, it is observed that the post-stabilization voltage at t = 64s, as resulted by the proposed scheme as well as by in [22], are above its set minimum value of 0.9. But since no constraint exists over $\vartheta^{Threshold}$ in [22], it is lower than the proposed methodology as shown in Figure 8, thereby, provides less voltage stability margin after optimal load shedding.

B. Northern Regional Power Grid (NRPG) 246-system

The proposed methodology is tested on a practical Northern Region Power Grid (NRPG) 246-Bus system. NRPG is the largest among the five regional power grids in India, covering approximately

30% of the area. To study the voltage stability phenomenon in practical electric power system, the actual network is reduced owing to simulation and computational constraints. Initially, coherent groups of generators are identified according to the relation factors, which represent the degree of relative coupling between the generators as suggested by Kim *et al* [23]. After the coherent groups are identified, all the machines in the group are replaced with an equivalent machine and the network is modified to make the equivalent system having same power flow conditions as the original system. The part of the original system where the study is conducted is not reduced and is kept intact called as *internal system* and the rest of the system is called *external system*. All the critical buses are located in the internal system so that the behaviour of the system under various conditions is studied. The system is reduced to 35-bus system, with most of the buses in Rajasthan region under study area and the remaining buses of different states in the external equivalent buses. The external equivalents are grouped in such a way that they form a meaningful geographical area e.g. states. The buses connecting the external equivalent buses are called boundary buses. Figure 9 shows the outline of the reduced NRPG system, consisting of 35 buses, 10 generator buses, 25 load buses and 53 branches. Based on the various test cases created in this system, the value of the $\vartheta^{Threshold}$ is kept to be 0.6 for NRPG 246-bus system.

The study area or internal system consists of 25 load buses and 6 generators, a total of 31 buses. The generation of reduced network is 685.76 MW and 211.18 MVAR. The load on the reduced system is 676.11 and 89.64 MVAR. The loads are modeled as constant power type loads. The system is simulated in PSCAD^{TM} 4.2 environment with the internal generators modeled according to the NRPG dynamic data and the external equivalent generators data accordingly to show the cumulative effect of all the generators in the coherent group.

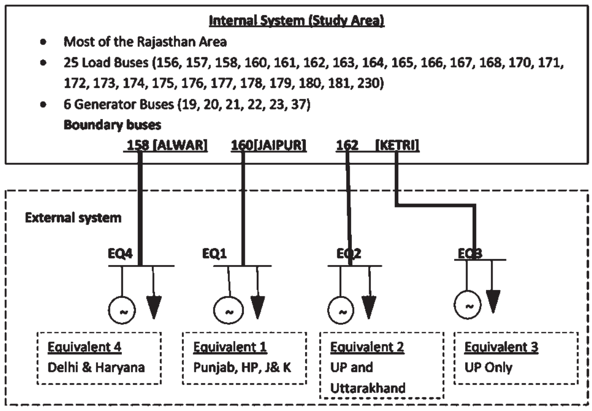

FIG. 9. OUTLINE OF REDUCED NRPG SYSTEM

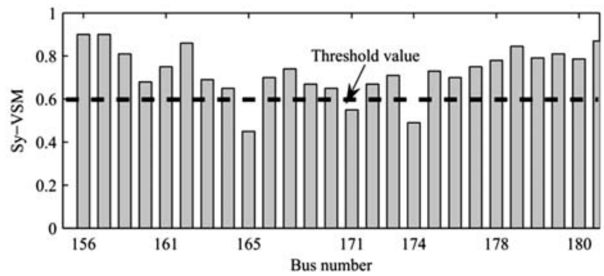

FIG. 10. NRPG CASE 1: SY-VSM (Θ) ON ALL LOAD BUSES AT T=50S.

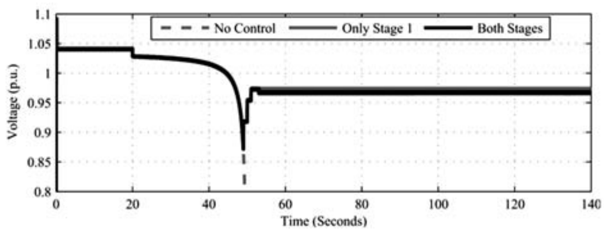

FIG. 11. NRPG CASE 1: VOLTAGE AT BUS-165

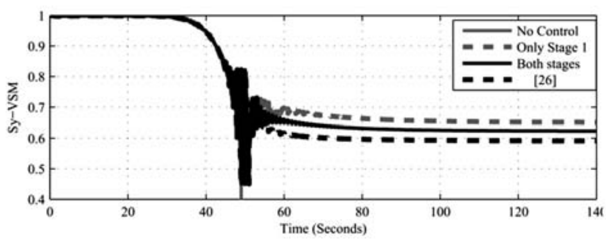

FIG. 12. NRPG CASE 1: SY-VSM (Θ) AT BUS-165

The test system is then subjected to different stressed conditions to evaluate the proposed voltage stability assessment and load shedding methodology as discussed below.

1) Generator outage: In this case, the generator at bus-37 located at Antah, Rajasthan is taken out of service at t = 20 s. This is directly connected to load bus-165, located at Bhilwara, Rajasthan. The contingency is further severed by gradual load increase at bus-165 at 0.01pu/s until t=50 s. This steers the system towards a state of voltage collapse at t = 54 s. Figure 10 shows the proposed Sy-VSM at t = 50 sat all load buses.

It can be observed that Sy-VSM at buses 165, 174 & 171 is below its threshold value 0.6. These load buses are identified as critical buses. The evolution of voltage at load bus-165 is shown in Figure 11. It can be observed from Figure 11 that if no corrective measure is taken in time, the system voltages collapse at t = 54 s. The variation of the proposed indicator, ϑ, is shown in Figure 12. The proposed indicator crosses its set threshold i.e. $\vartheta^{Threshold}$= 0.6 at t = 50 s, giving an early indication of the impending voltage instability by 4s.

To arrest the deteriorating condition, Stage-1 load shedding is initiated as per the proposed load shedding strategy at t=51 s. As an emergency control action, a total of 131.5 MW & 18.2 MVAR load is shed on critical buses 165, 174 and 171 in three phases. The system stabilizes at t=56 s and continues to operate in stable condition. Afterwards, Stage-2 post-stabilization optimal load shedding is initiated at t = 57 s. The Stage-2 control restores a total of 12.3 MW and 1.4 MVAR load. In response to the applied controls in Stage-1 and Stage-2, the time evolution of Sy-VSM at load bus-165 is shown in Figure 12.

TABLE 2

RESULTS FOR NRPG 246-BUS SYSTEM

Stage	LS (Case-1) (MVA)	LS (Case-2) (MVA)
1st Stage	(131.5+j18.2)	(160.1+j25.7)
Proposed 2nd Stage	(-12.3-j1.4)	(-4.8-j0.5)
2nd Stage using [22]	(-15.2-j1.9)	(-4.8-j0.5)

The load shedding results of the proposed scheme as well as of [22] are listed in Table 2. It can be observed from Table 2 that the total load restored by the proposed scheme is (12.3+j1.4) MVA, whereas that of [22] is (15.2+j1.9) MVA at load buses 165 and 174. The difference is owing to the fact that the proposed scheme incorporates the real-time voltage stability indicator (ϑ) into the control process of MPC. As a result of this, the proposed scheme ensures that a minimum of 0.4 units of voltage stability margins are maintained even after restoring the loads shed in stage-1 while the same cannot be said about the results of [22]. It can be confirmed from Figure 12 that[22] is violating the Sy-VSM threshold after t=75s, whereas all other states are still within bounds. Due to this lower stability margin, the system controlled using conventional MPC is still prone to collapse when subjected with any strained condition.

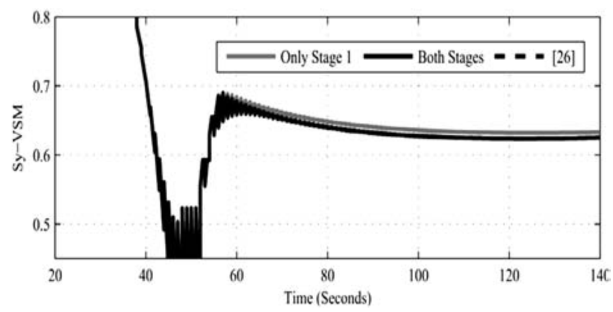

FIG. 13. NRPG CASE 2: SY-VSM (Θ) AT BUS-174

2) Line outage: In this case, the line connecting bus-165 located at Bhilwara and bus-174 located at Jodhpur is taken out. Further, the load at bus-174 is gradually increased at 0.01 pu/s. Due to this strained conditions, the system voltage deteriorates and collapses at t = 51 s. To protect the system from this imminent collapse, Stage-1 load shedding is activated at t = 42 s, giving an early warning of 10 seconds. After shedding 160.1 MW and 25.7 MVAR of load in multiple stages, the system stabilizes at t=55 s. Stage-2 restores 4.8 MW and 0.5 MVAR of load at load bus-174 which coincides with the load restored by [22] as listed in Table 2. The reason for the same outcome of the two methods is because both the methods attain the same Sy-VSM after stage-2 optimal load shedding, as can be observed from Figure 13.

4.0 CONCLUSIONS

This paper presents a simple technique for utilizing voltage and current synchrophasor measurements to detect and control an impending voltage instability. A new voltage stability monitor viz., Sy-VSM is proposed for this purpose and a threshold value is set for Sy-VSM in order to initiate a control action. The proposed control strategy is comprised of two stages. In stage-1, the system is brought back to a stable condition by shedding load in multiple steps. Once the system is stable, the amount of load curtailment is optimized using Model Predictive Control (MPC) based approach in stage-2. The following key results have been established with the various test cases shown on NE 39-bus and Indian Northern Regional Power Grid (NRPG) 246-bus system:

- The proposed indicator timely prevents the system from voltage collapse by giving an early warning. In case of continuous load increase in NE 39-bus system, the indicator gives an early warning of an impending instability by 15 seconds. Similarly, in Northern Regional Power Grid 246-bus system, an early warning by 4 seconds alarms for an emergency load shedding.
- The proposed voltage stability indicator is fairly simple and requires less time for its computation. For NE 39-bus system, Sy-VSM is calculated in 0.011 seconds in case of line outage and in case of NRPG 246-bus system, 0.024 seconds were taken to compute the Sy-VSM. Less computational time taken by Sy-VSM makes it suitable for real-time applications.
- The two-stage control strategy is simple and effectively reduces the total amount of load shedding while maintaining a good voltage stability margin. As an example, in NRPG 246- bus system, the un-optimized load shedding amount in case of generator outage followed by load increase was 131.5 MW & 18.2 MVAR and after the application of the proposed MPC in stage-2, the load shedding amount is reduced to 119.2 MW & 16.8 MVAR.
- As synchrophasor measurements inherently involve system dynamics, the proposed stability indicator is model-free and is deduced from the local measurements only.

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