UDC 621.3 https://doi.org/10.20998/2074-272X.2022.3.09

H. Chappa, T. Thakur

A novel load shedding methodology to mitigate voltage instability in power system

Aim. *A novel technique for detecting imminent voltage instability is proposed in this paper, accompanied by a novel load shedding approach to protect the system from voltage instability.* ***Methodology***. *The proposed methodology utilizes the computation of nodal reactive power loss to voltage sensitivities with load increments in the system.* ***Originality***. *The nodal reactive power loss to voltage sensitivity is a novel computation and is explored to detect the likelihood of voltage instability in this work.* ***Results***. *If the system is experiencing an unprecedented load growth and if all the measures reach their limits, then load shedding is the last resort to safeguard the system against instability. The sudden change in nodal reactive power loss to voltage sensitivities is utilized to devise the quantity of load to be cut in the system.* ***Practical value.*** *The time-based simulations performed in New England 39 bus test system (NE-39 bus), the simulated results show that nodal reactive power loss to voltage sensitivities can be used as a trusted indicator for early diagnosing of menacing voltage instability and the timely implementation of load shedding developed from nodal reactive power loss to voltage sensitivities on the system ensures voltage stability.* References 29, tables 1, figures 9.

Key words: **voltage stability, sensitivity analysis, nodal reactive power losses, load shedding.**

Мета. *У статті пропонується новий метод виявлення навислої нестабільності напруги, що супроводжується новим підходом до скидання навантаження для захисту системи від нестабільності напруги.* ***Методологія.*** *У запропонованій методиці використовується розрахунок вузлових втрат реактивної потужності залежно від чутливості до напруги при збільшенні навантаження у системі.* ***Оригінальність***. *У цій роботі вузлові втрати реактивної потужності залежно від чутливості до напруги являють собою новий розрахунок і досліджуються визначення ймовірності нестабільності напруги.* ***Результати***. *Якщо система відчуває безпрецедентне зростання навантаження і всі заходи досягають меж своїх можливостей, скидання навантаження є останнім засобом захисту від нестабільності. Раптова зміна вузлових втрат реактивної потужності, залежно від чутливості до напруги, використовується для визначення величини навантаження, яка повинна бути відсічена в системі.* ***Практична цінність***. *Моделювання, засноване на часі, виконане в тестовій системі шини New England 39 (шина NE-39), та результати моделювання показують, що залежність вузлових втрат реактивної потужності від чутливості до напруги може використовуватися як надійний індикатор для ранньої діагностики загрозливої нестабільності напруги та своєчасного впровадження скидання навантаження, що виникає внаслідок втрати реактивної потужності у вузлах, до чутливості системи до напруги,а забезпечує стабільність напруги.* Бібл. 29, табл. 1, рис. 9.

Ключові слова: **стабільність напруги, аналіз чутливості, вузлові втрати реактивної потужності, скидання навантаження.**

Introduction. Power system voltage stability maintenance is of paramount importance in practical grid. Power system is tremendously non-linear system and is continuously subjected to several disturbances. It is very strenuous for the system operators to monitor and operate such highly non-linear system stably. Early detection of voltage instability is a pressing concern for system operators. Voltage instability may lead to complete or partial blackout in the system. After detection, the immediate concern is the prevention of system from reaching unstable state. One of the proven preventive measure is load shedding. The introduction of deregulation along with renewable penetration due to high energy demand is forcing the grid to operate in a manner in which it is not designed to operate. The operating status of the systems is continuously monitored by the system operators to find the current state of the system. All the nodes in the system have to maintain acceptable voltages. Maintaining these acceptable voltages under highly stressed conditions is a major challenge for power system operators. According to [1] voltage stability is the ability of the system to maintain acceptable voltages at all the buses under all operating conditions. Voltage stability problem, in general, occurs due to [1]:

1) severe loading in the system especially voltage dependent load;
2) line or generator contingency under highly stressed;
3) insufficient reactive power support in the system;
4) reverse action of on load tap changer.

To address the voltage instability issue in the power system, a considerable amount of research has been done so far. Many methodologies were developed based on offline study of the considered test system P-V curves and Q-V curves that are drawn based on the repetitive runs of the Newton-Raphson load flow (NR load flow) were used to analyse the system stability. However, since these methodologies were based on an offline analysis, they might not be appropriate for real-time detection. On the other hand sensitivity analysis [3] has been done to assess the voltage instability by neglecting real power variations. Such assumptions may not be valid if the system is under a highly stressed condition.

Early diagnosis of voltage instability in power system gained much attention from the past two decades, as it could trigger a complete or partial blackout in the system. Voltage instability detection in real-time can be done by utilizing synchrophasor measurements [2]. Phasor measurement units (PMU) are the main devices for synchrophasor measurements. The methodologies developed in [4, 5] utilize the concept of tracking Thevenin equivalent parameters. However, it is observed in [6], that these methodologies do not detect the accurate point of instability. Moreover, accuracy of the tracking of Thevenin parameters depends on the window size being considered. This problem has been overcome in [7]. All these methodologies come under the category of local measurements where only one bus of interest can be monitored. Even though these methodologies give sufficient picture of instability but they are not suitable to monitor many nodes at a time that are prone to voltage instability.

Wider area measurements may be utilized for assessing voltage stability issues in the system at a time. However, it requires more number of PMUs to be installed. The index in [8] utilizes the rate of change of voltage for detecting voltage instability. The methodology in [9] developed a load shedding scheme to ensure both voltage and frequency stability. The methodology in [10] utilized the reduced set of measurements from PMU and computed the singular values of the Jacobian matrix in near real-time. The voltage distance collapse and the quantity of load to shed for ensuring voltage stability is proposed in [11]. Fast detection of voltage instability in real-time are proposed in [12, 13] by utilizing the nodal reactive power losses. Voltage instability for renewable integrated grid and the locations for reactive power support based on the dominant load type is presented in [14]. The sites that are suitable for renewable penetration are shown with the simulated results.

A methodology to shed the load based on eigen values is presented in [14]. The minimal eigen value of the power flow Jacobian matrix has adequate information to explore it as an indicator. The system has to be continually checked for this indicator before taking any preventive action. The main issue with this indicator is that the power flow Jacobian matrix is topology sensitive. Power system is dynamic system and topological changes in the network are recurrent. In such scenarios the computation of the singular eigenvalue of the power flow Jacobian matrix in real time would be a complex task. Under-voltage load shedding based on estimation of Thevenin parameters is proposed in [15]. Thevenin parameters are estimated by using recursive least square approximation techniques. Emergency load shedding based on minimum eigen values of power flow Jacobian matrix is formulated in [16]. Under-voltage relays are placed based on the values of applied L index [17] to the considered system. The amount of load to shed is decided based on the PQ limit curves. A combined load shedding method [18] is proposed by considering both frequency and voltage stability. For this, sensitivity analysis and center of inertia frequency is considered to determine the amount of load shedding at individual node. In the same token, another adaptive algorithm [19] is developed for both frequency and voltage stability. This algorithms works in three stages and the major building block is the drawing up of a lookup table and its update in near real-time. The lookup table encompasses optimal location and minimal load shedding along with consideration for the incidents that require post load shedding.

Frequency measurement and voltage stability index are used in [20] for adaptive load shedding. This algorithm considers the PMU measurements at the bus of interest and voltage stability index is computed from those measurements. The coupling between under-frequency and prolonged low voltage condition is exploited for developing the load shedding conditions. The sensitivity of dynamic voltage curves is explored in [21] to develop load shedding blueprint. The originality of this work is consideration of the dynamic conditions of the load and system to develop the minimal load shedding scheme. This dynamic load conditions study is very relevant in voltage stability investigations as the non-intersection of load characteristic and system characteristic results in voltage collapse. Furthermore, the contingencies under stressed condition abet the likelihood of voltage collapse. The contingency analysis is rigorously studied here to obtain the minimal load shedding condition.

The under frequency conjoined with voltage stability assessment is considered in [22] for minimal load shedding. It is identified that load shedding to avoid only the frequency instability may have adverse effect on voltage instability. The corrective action for under frequency protection may not be sufficient for the support of voltage stability. The supplementary arrangement is made in this work to support for voltage stability. The thermal limit of the transmission lines depend on the scale of loading of the lines. If loading is beyond the thermal limits, and the non-intersection of system curve and load curve initiates the voltage instability. To this end, the load rate of transmission is monitored in [23] to prevent the cascading failure that occurs due to voltage and frequency instability. This load shedding is based on the ranking of the outage sensitivity index and voltage magnitude. The scheme in [24] considers the under-frequency precise load shedding coupled with voltage stability criteria. The synchrophasor measurements are used to develop methodology by considering the load dynamics. This two stage load shedding is very essential for real time system monitoring. This scheme protects the system from both voltage instability and under-frequency condition. The minimal load shedding is however limited to a particular node is the main limitation of this work. An optimal load shedding based on PMU measurements for practical power system is proposed in [25].

Under impedance load shedding scheme is presented in [26] by considering the motor dynamics as they play a prominent role in driving the system to instability. By considering the load demand response and using multi-period optimal power flow, smallest singular value of the Jacobian matrix is improved in [27] by shedding the load at suitable locations. PMU measurement based methodology for load shedding is proposed in. This method considers the multiport modelling equations to estimate the Thevenin parameters and an index is obtained therefrom. This index is used in load shedding algorithm to shed minimal amount of load without compromising the stability of the system. The power flow Jacobian matrix was computed using PMU data in [28]. Following that, the power flow Jacobian matrix was subjected to V-Q sensitivity analysis. Such analysis is useful for identifying the vulnerable nodes in the system from a voltage stability point of view. At the weak nodes a fixed amount of load i.e. 5 % load shedding is employed and checked for the stability condition. In this method the load shedding is done only at weak nodes corresponding to voltage instability.

The detailed literature review shown above disclose that, most of the methodologies use singularity condition of power flow Jacobian matrix or sensitivity analysis of Jacobian matrix for detecting instability. In the sensitivity analysis of the power flow Jacobian matrix, decoupling of active power variations with respect to voltage is considered. This assumption is not a valid assumption especially when the system is under stress condition. However, reactive power loss to voltage sensitivity may provide accurate and early detection of voltage collapse in power system.

Goal. In this work nodal reactive power loss to voltage sensitivity has been used as a litmus test for detecting the voltage instability and a load shedding scheme is also derived therefrom. The main reason for considering nodal reactive power loss to voltage sensitivity is that it can be obtained in real-time. Moreover, the sensitivity analysis obtained from the reduced Jacobian matrix seems to be inaccurate especially when the system is under the stressed condition. This assumption for decoupling of active power variations and voltage is overcome by considering Nodal Reactive Power loss to Voltage Sensitivity (NRPVS). The following sections go into sensitivity analysis and bus reactive power losses calculations in greater depth.

Nodal reactive power loss calculation. The reactive power loss in the power system has correlation with the bus voltage. Usually, the reactive power loss is attributed as line reactive power loss. However, it has been identified in the literature that bus reactive power loss is proposed and that bus reactive power loss trend in the system has significant link with the voltage trend in time domain simulations. The computation of nodal reactive power loss is as follows. Figure 1 presents the bus B-1 with its interconnections and a PMU.

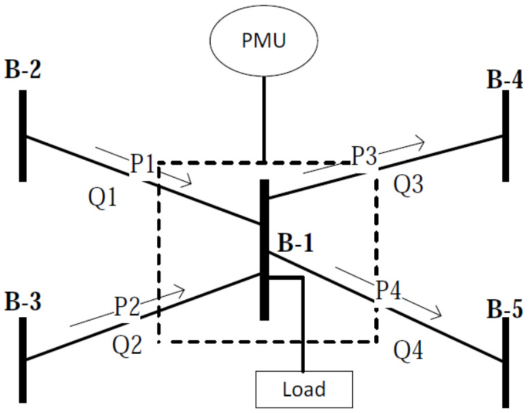

Fig. 1. Power network showing direction of real power flow and line losses [11]

This bus B-1 is the monitored bus. The direction of arrows indicates the active power flow direction in the lines. The load flow equation at any given node j is represented as:

$$S_{bus}^{j} = V_j \sum_{i=1}^{n} I_i^{*} . \tag{1}$$

where S_{bus}^{j} is the apparent power at bus j; V_j is the voltage at bus j; I_i is the current at bus i.

PMU measurements are utilized in bus B-1 to compute all the line losses and direction of active power flows. The bus reactive power losses are evaluated at any bus j by using the following equation:

$$Q_{loss}^{j} = \sum_{i=1,\ i\neq j}^{n} I_{ij}^{2} \cdot X_{ij} , \tag{2}$$

where I_{ij} is the current from any bus i to j; X_{ij} is the reactance of the line placed between buses i and j.

In brief, the nodal reactive power losses are the summation of line reactive power losses feeding the bus of interest.

There are several methodologies proposed to detect the incipient voltage instability by considering the decoupling of power flow Jacobian matrix. As the name suggests, Jacobian matrix represents the sensitivities of the bus voltages and reactive power losses. The decoupling of the Jacobian matrix essentially means considering the real power load and voltage are weakly coupled and subsequently the terms belong to them will be dropped. In the same line the terms related to reactive power and frequency are also dropped. The details of the sensitivity analysis are as follows:

Sensitivity analysis. The power balance equations under steady state by assuming bus numbers i = 1, 2 ... n for a n-bus system are given as

$$P_{Gi} - P_{Di}(V_i) - \sum_{j=1}^{n} V_i V_j Y_{ij} \cos\left(\theta_i - \theta_j - \alpha_{ij}\right) = 0 ; \tag{3}$$

$$Q_{Di}(V_i) - \sum_{j=1}^{n} V_i V_j Y_{ij} \sin\left(\theta_i - \theta_j - \alpha_{ij}\right) = 0 . \tag{4}$$

where P_{Gi} is the real power generated at bus i; $P_{Di}(V_i)$ is the load demand at bus i and this load demand is function of voltage; V_i, V_j ,θ_i, θ_j are the voltages and the corresponding angles at buses i and j respectively; Y_{ij} is the admittance between buses i and j; α_{ij} is the angle corresponding to Y_{ij}.

By applying NR load flow method to (3), (4) yields [1]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\Theta} & J_{PV} \\ J_{Q\Theta} & J_{Q\Theta} \end{bmatrix} \begin{bmatrix} \Delta\Theta \\ \Delta V \end{bmatrix} ; \tag{5}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta\Theta \\ \Delta V \end{bmatrix} , \tag{6}$$

where J is the Jacobian matrix and

$$J_{P\Theta} = \frac{\partial P}{\partial \Theta},\ J_{PV} = \frac{\partial P}{\partial V},\ J_{Q\Theta} = \frac{\partial Q}{\partial \Theta},\ J_{QV} = \frac{\partial Q}{\partial V} , \tag{7}$$

and ΔP, ΔQ, $\Delta\Theta$ and ΔV are the incremental changes in real power, reactive power, bus voltage angle and bus voltage magnitude respectively.

If real power variations are assumed to be zero then (5) can be simplified as

$$\Delta\Theta = -\left[J_{P\theta}\right]^{-1} J_{PV}\, \Delta V ; \tag{8}$$

$$\Delta Q = \left[J_{QV} - \left[J_{P\theta}\right]^{-1} J_{PV}\, J_{Q\theta}\right] \Delta V ; \tag{9}$$

$$\Delta Q = J_R\, \Delta V ; \tag{10}$$

$$\Delta V = J_R^{-1}\, \Delta Q , \tag{11}$$

where J_R is the diminished Jacobian matrix.

The diagonal elements of J_R represent the Q-V sensitivities at any node.

Sensitivity analysis is obtained from the assumption that active power variations are decoupled from voltage variations. This is not a valid assumption if the system is under high stress. By applying Schur decomposition to the Jacobian matrix in (6), the gravity of the active power dissimilarity under stressed conditions can be deduced.

Suggested methodology. The development in synchrophasor measurements leads to the accurate measurement of voltage magnitudes, branch currents, and phasor angles. These measurements are used to compute nodal reactive power losses. It has been observed that nodal reactive power loss along with voltage magnitudes at any node has suitable information to detect imminent voltage instability. In addition to that, the critical aspect of Q-V sensitivity analysis may be overcome by considering nodal reactive power to voltage sensitivity analysis. When a system is subjected to continuous load increments, then reactive power loss in the branches also increases continuously. If the system is stressed with excessive loading, then line losses will increase, especially the reactive power losses. This has effect on voltage magnitude at the buses.

At the stroke of voltage instability branch reactive power losses increase abruptly and voltage magnitudes rapidly reduce to unacceptably low values. The power system perceives this condition as non-intersection of system characteristic with load characteristic. The type load and the magnitude of load are essentially accountable for this condition. The voltage instability condition can be identified using the reactive power losses and voltage magnitudes from the PMU measurements. It has been identified that nodal reactive power loss trajectory can detect the voltage instability accurately as opposed to voltage magnitude. In the case of overcompensated systems voltage collapse takes place at voltage magnitudes close to nominal values. So voltage magnitude alone is not a suitable criterion for voltage instability detection.

As the bus reactive power losses are obtained from line reactive powers losses, the trend of these losses along with voltage magnitudes at any node gives reliable information to detect voltage instability. It has also been discerned that the bus power losses shoots up at high load conditions but much before loadings corresponding to voltage collapse. This property of the trend of nodal power losses (reactive) has been exploited here to detect the voltage instability.

Under normal operating conditions with nominal loadings on the system NRPVS trend is smooth but if the system is sufficiently stressed then its trend varies abruptly and will progress in the direction of sharp change. At the collapse point, a large sudden change in NRPVS occurs. The point where the first sharp change in NRPVS occurs is the detection point and the time at which it occurs is known as instability detection time.

After early detection of voltage instability from NRPVS, its values are used to determine the quantity of load to cut in each bus to ensure both voltage stability and acceptable voltage magnitudes.

Load shedding at any load busy J can be computed as

$$Loadshed_j = \frac{NRPVS_j}{\sum_{J\in nl} NRPVS_j}, \qquad (12)$$

where $J\in nl$ means the bus j corresponds only to the load buses; $Loadshed_j$ is the load shedding at load bus j and $NRPVS_j$ is the nodal reactive power loss to voltage sensitivity at bus j.

The flowchart of the algorithm is given Fig. 2.

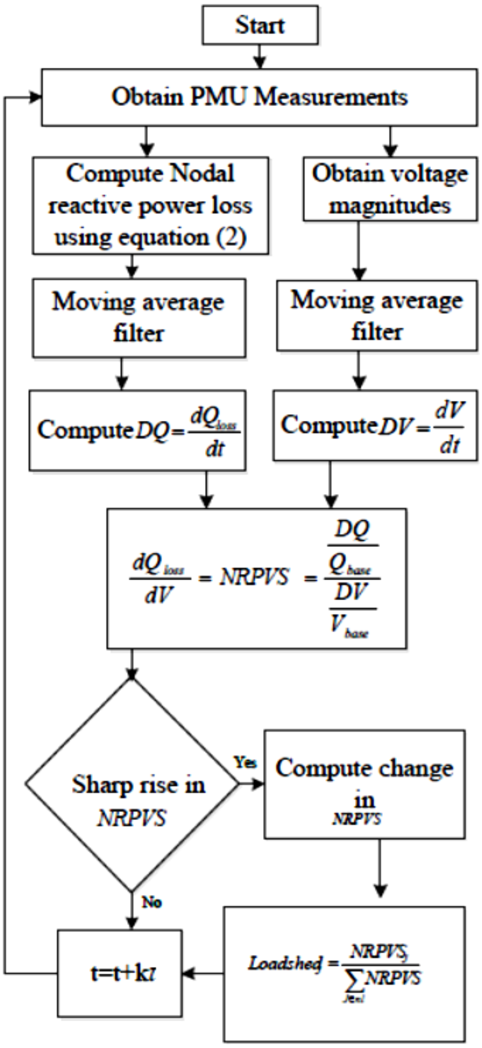

Fig. 2. Proposed methodology

They steps of the algorithm to implement in real time are as follows:

1) Obtain the PMU measurements at all the load buses.

2) With these measurements compute the bus reactive power losses by considering the direction of active power flows and branch reactive power losses.

3) As PMU data may contain noise signals, these are filtered by using moving average filter.

Moving average filter. It contains a sliding window of suitable size of our choice. The output of this filter at any time k is given as:

$$Y_k = \frac{1}{M} \sum_{j=k-M+1}^{k} Y_i , \qquad (13)$$

where M is the window size.

4) Evaluate rate change in bus 1 reactive power losses and rate change in voltage magnitudes in all the load buses.

5) Then normalize the computed rate change in bus reactive power losses and rate change in voltage magnitudes with its base values. Base values are the values obtained under base load condition of the system. This normalization is done only for computational simplicity.

6) Divide normalized rate change of bus reactive losses with normalized rate change of voltage magnitude and name it as NRPVS.

7) Monitor NRPVS under real time and find any sudden change.

8) Compute the value of NRPVS at the instant of sudden change.

9) Compute load shedding in each node by using the values in previous step.

Simulation results. The proposed methodology has been tested in New England 39 bus test system with all the dynamic components responsible for voltage stability issues. All the synchronous generators are considered with two-axis flux decay model with enforced excitation limits. The equations governing the model are as follows:

$$\dot{\delta}_i = \Omega_b \cdot (\omega_i - 1); \tag{14}$$

$$\dot{\omega}_i = \frac{P_{mi} - P_{ei} - D_i \cdot (\omega_i - 1)}{M_i}; \tag{15}$$

$$\dot{e}'_{qi} = \frac{-f_{si}(e'_{qi}) - (x_{di} - x'_{di}) \cdot i_{di} + v^{*}_{fi}}{T'_{d0i}}; \tag{16}$$

$$\dot{e}'_{di} = \frac{-e'_{di} + (x_{qi} - x'_{qi}) \cdot i_{qi}}{T'_{q0i}}; \tag{17}$$

$$p_{ei} = (v_{qi} + r_{ai} \cdot i_{qi}) \cdot i_{qi} + (v_{di} + r_{ai} \cdot i_{di}) \cdot i_{di}; \tag{18}$$

$$v_{qi} + r_{ai} \cdot i_{qi} - e'_{qi} + (x'_{di} - x_{li}) \cdot i_{di} = 0; \tag{19}$$

$$v_{di} + r_{ai} \cdot i_{di} - e'_{di} + (x'_{qi} - x_{li}) \cdot i_{qi} = 0; \tag{20}$$

$$\dot{V}_{mi} = \frac{V_i - v_{mi}}{T_{ri}}; \tag{21}$$

$$\dot{V}_{ri} = \frac{K_{ai} \cdot \left(v_{refi} - v_{mi} - v_{r2i} - \frac{k_{fi}}{T_{fi}} \cdot v_{fi} \right) - v_{r1i}}{T_{ai}}; \tag{22}$$

$$v_r = \begin{cases} v_{r1i} & \text{if } v_{r\min i} \le v_{r1i} \le v_{r\max i}; \\ v_{r\max i} & \text{if } v_{r1i} > v_{r\max i}; \\ v_{r\min i} & \text{if } v_{r1i} < v_{r\min i}; \end{cases}; \tag{23}$$

$$v_{ri} = \frac{-\left(\frac{k_{fi}}{T_{fi}}\right) \cdot v_{fi} + v_{r2i}}{T_{fi}}; \tag{24}$$

$$\dot{v}_{fi} = \frac{-v_{fi} \cdot (1 + s_e(v_{fi})) - v_{ri}}{T_{ei}}, \tag{25}$$

where all parameters are described in Table 1.

The load is considered as the composite ZIP load with 20 % constant impedance load, 20 % constant current load, and 60 % constant power load. The ZIP load model mimics the practical load and therefore such model is being considered. The simulations are performed in PSAT [29] toolbox in MATLAB environment. The data obtained from PSAT simulations were treated as the data from PMU measurements. All of the load buses are loaded with (0.001+j0.001) pu/s. This load increment is applied simultaneously to all the load nodes. Such load increment is known as stress in the system. The authors believe that any index should detect the unforeseen event with accuracy for the concomitant load variations in the system. This work proposed for long term voltage stability and therefore such a pattern of load increment is chosen for simulations. This pattern of load increment plunge the system from a stable operating state to an unstable state.

Table 1

Description of parameters

No.	Parameters	Description
1	δ	Rotor angle
2	Ω_b	Base speed
3	ω	Rotor speed in p.u.
4	P_{mi}	Mechanical power input
5	P_{ei}	Electrical power input
6	D	Damping coefficient
7	M	Mechanical starting time
8	e_{qi}	q-axis transient voltage
9	e'_{di}	d-axis transient voltage
10	x_{qi}	Synchronous reactance in q-axis
11	x'_{qi}	Transient reactance in q-axis
12	x_{di}	Synchronous reactance in d-axis
13	x'_{di}	Transient reactance in d-axis
14	i_q	Quadrature axis current
15	i_d	Direct axis current
16	T_{d0}'	Open circuit transient time constant in d-axis
17	T_{q0}'	Open circuit transient time constant in q-axis
18	v_{qi}	q-axis voltage
19	v_{di}	d-axis voltage
20	r_a	Armature resistance
21	x_{li}	Leakage reactance
22	v_f	Field voltage
23	v_{mi}	Transducer
24	T_r	Transducer time constant
25	K_f	Stabilizer gain
26	T_f	Stabilizer time constant
27	K_a	Amplifier gain
28	v_r	Regulator voltage
29	v_{ref}	Reference voltage
30	$v_{r\max i}$	Regulator maximum voltage
31	$v_{r\min i}$	Regulator minimum voltage
32	v_{r1}	Saturation voltage point 1
33	v_{r2}	Saturation voltage point 2
34	$s_e(v_f)$	Saturation function
35	T_{ei}	Field circuit time constant
36	V	Terminal voltage

The proposed methodology detects the early occurrence of voltage instability. The voltage magnitude plot is shown in Fig. 3 delineate that voltage magnitude drops as load increases. This is due to the fact that the transmission line acting drain to reactive power. This causes insufficient reactive power support at load buses. The insufficient reactive power support is reflected as drop in voltage magnitude. The incessant drop in voltage against time is regarded as voltage instability problem. The voltage plot depicts that voltage instability occurred at 182 s.

The plot of nodal reactive losses at the cogitated buses is shown in Fig. 4. This figure depicts reactive losses in the nodes with time-based load increments. As mentioned earlier and from the reactive power loss equations the nodal reactive power losses trend has something noteworthy. If the load variations are less and continual, the nodal reactive power loss trend shows a small variation. The line reactive power loss seems to be linear till a particular load increment and any load increment beyond that limit causes the reactive power loss to shoot up. As the nodal reactive power loss is the summation of all the incoming line reactive power losses and therefore nodal reactive power losses also increase abruptly. The point at which such abrupt change occurs has some information to report the stability status of the system. However, if the stress on the system is continuous and reaches the point instability, the nodal reactive power losses increase abruptly. It has been observed that voltage magnitude and nodal reactive power loss has a direct relationship and this is explored in this work.

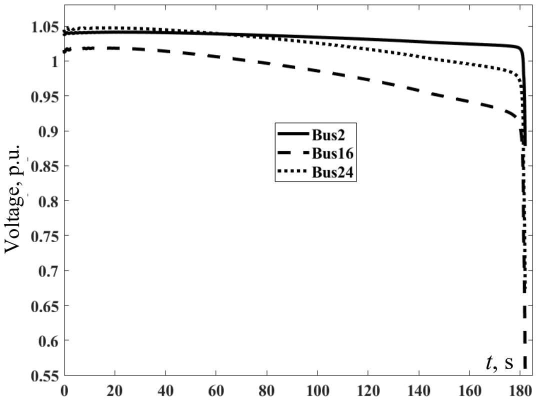

Fig. 3. Plot of voltages in p.u.

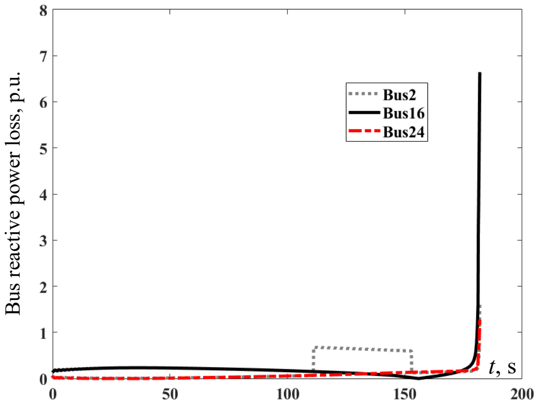

Fig. 4. Bus reactive power losses in p.u.

The reactive power loss to voltage sensitivity plot is evinced in Fig. 5. It has been noticed from Fig. 5 that, sudden change in reactive power loss to voltage occurs at 147 s. At this instant NRPVS is computed at all the nodes and the values are shown in Fig. 6. From this figure, it is observed that buses 2, 16 and 24 have the maximum change and therefore the plots of these buses are shown in this paper.

The quantity of load to cut at the load buses are computed using the above computed NRPVS. The plot in Fig. 7 shows the quantity of load to cut in the load buses to safeguard the system from the occurrence of voltage instability. The above-computed amount of load for load shedding has been applied on all the load buses at 148 s and it is observed that voltage magnitudes of all the nodes improved and the system is stable. The improved voltages after application of load shedding strategy are shown in Fig. 8. The comparison of voltages before and after the application of load shedding strategy is shown in Fig. 9. For this plot only 16 bus has been considered. However, it is obvious that at other nodes also voltage magnitudes will improve and system reaches stable state.

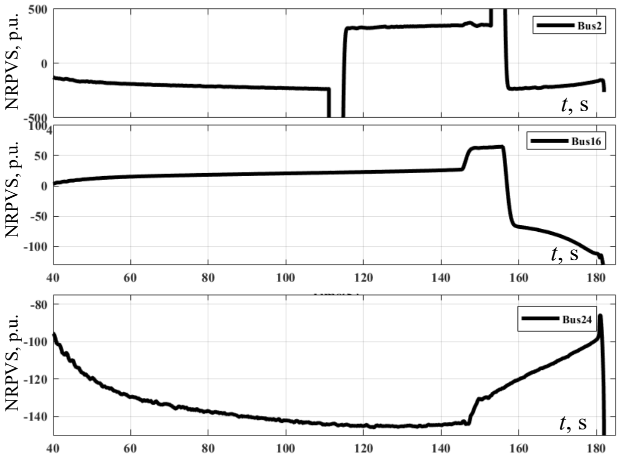

Fig. 5. Curves of NRPVS for buses 2, 16 and 24

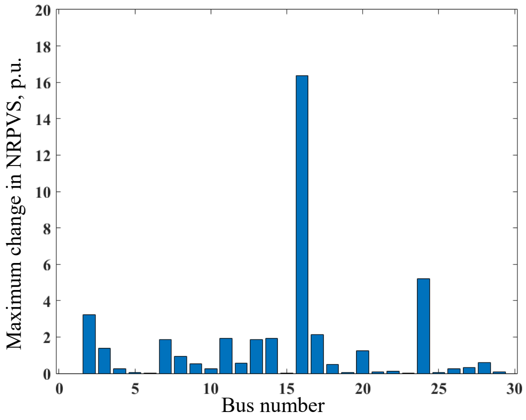

Fig. 6. NRPVS of load buses at 146 s

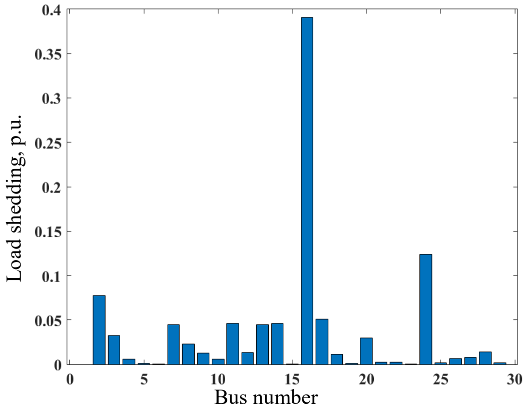

Fig. 7. Load to be shed in all nodes

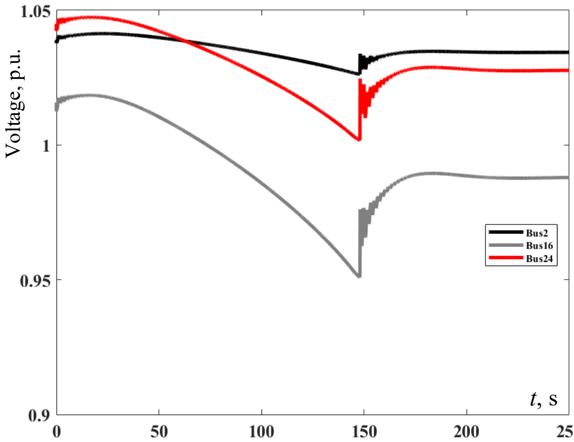

Fig. 8. Voltages plot after load shedding

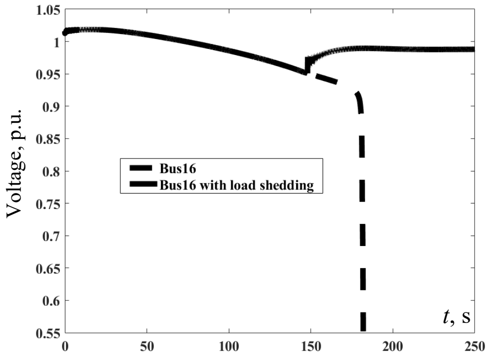

Fig. 9. Comparison of voltages with and without load shedding

Conclusions.

In this work, a novel methodology for voltage instability detection and its prevention through load shedding has been proposed. Nodal reactive power loss to voltage sensitivity has been developed and the trend of it is used for voltage instability detection. The value of the sudden change in nodal reactive power loss to voltage sensitivity is used to devise the load shedding scheme. The nodes at which this sudden change occurs are considered here to show the simulation results. This methodology while applied to New England 39 bus test system, detected voltage instability at time close to 150 s where the actual voltage instability occurred at 182 s. This is leaving a margin of 32 s for the system operator to respond. Load shedding, which is a means for preserving the voltage instability, when applied at 150 s, the system reached to stable state. The simulated results show that this methodology could detect the voltage instability in good time and the load shedding can bring back the voltages to acceptable values.

Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Kundur P. *Power System Stability and Control*. New York, McGraw Hill Publ., 1994. 1200 p. Available at: http://powerunit-ju.com/wp-content/uploads/2018/01/Power-System-Stability-and-Control-by-Prabha-Kundur.pdf (Accessed 12 May 2021).

2. Chappa H., Thakur T. Voltage instability detection using synchrophasor measurements: A review. *International Transactions on Electrical Energy Systems*, 2020, vol. 30, no. 6, art. no. e12343. doi: https://doi.org/10.1002/2050-7038.12343.

3. Gao B., Morison G.K., Kundur P. Voltage stability evaluation using modal analysis. *IEEE Transactions on Power Systems*, 1992, vol. 7, no. 4, pp. 1529-1542. doi: https://doi.org/10.1109/59.207377.

4. Wang Y., Li W., Lu J. A new node voltage stability index based on local voltage phasors. *Electric Power Systems Research*, 2009, vol. 79, no. 1, pp. 265-271. doi: https://doi.org/10.1016/j.epsr.2008.06.010.

5. Vournas C.D., Van Cutsem T. Local Identification of Voltage Emergency Situations. *IEEE Transactions on Power Systems*, 2008, vol. 23, no. 3, pp. 1239-1248. doi: https://doi.org/10.1109/TPWRS.2008.926425.

6. Wang Y., Pordanjani I.R., Li W., Xu W., Chen T., Vaahedi E., Gurney J. Voltage Stability Monitoring Based on the Concept of Coupled Single-Port Circuit. *IEEE Transactions on Power Systems*, 2011, vol. 26, no. 4, pp. 2154-2163. doi: https://doi.org/10.1109/TPWRS.2011.2154366.

7. Cui B., Wang Z. Voltage stability assessment based on improved coupled single-port method. *IET Generation, Transmission & Distribution*, 2017, vol. 11, no. 10, pp. 2703-2711. doi: https://doi.org/10.1049/iet-gtd.2016.2067.

8. Sodhi R., Srivastava S.C., Singh S.N. A Simple Scheme for Wide Area Detection of Impending Voltage Instability. *IEEE Transactions on Smart Grid*, 2012, vol. 3, no. 2, pp. 818-827. doi: https://doi.org/10.1109/TSG.2011.2180936.

9. Seethalekshmi K., Singh S.N., Srivastava S.C. A Synchrophasor Assisted Frequency and Voltage Stability Based Load Shedding Scheme for Self-Healing of Power System. *IEEE Transactions on Smart Grid*, 2011, vol. 2, no. 2, pp. 221-230. doi: https://doi.org/10.1109/TSG.2011.2113361.

10. Lim J.M., DeMarco C.L. SVD-Based Voltage Stability Assessment From Phasor Measurement Unit Data. *IEEE Transactions on Power Systems*, 2016, vol. 31, no. 4, pp. 2557-2565. doi: https://doi.org/10.1109/TPWRS.2015.2487996.

11. Kamel M., Karrar A.A., Eltom A.H. Development and Application of a New Voltage Stability Index for On-Line Monitoring and Shedding. *IEEE Transactions on Power Systems*, 2018, vol. 33, no. 2, pp. 1231-1241. doi: https://doi.org/10.1109/TPWRS.2017.2722984.

12. Chappa H.K., Thakur T., Srivastava S.C. Reactive power loss based voltage instability detection using synchrophasor technology. *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2015, pp. 1-5. doi: https://doi.org/10.1109/APPEEC.2015.7381029.

13. Chappa H., Thakur T. A Fast Online Voltage Instability Detection in Power Transmission System Using Wide-Area Measurements. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, 2019, vol. 43, no. S1, pp. 427-438. doi: https://doi.org/10.1007/s40998-018-0120-2.

14. Chappa H.K., Thakur T., Suresh Kumar L.V., Kumar Y.V.P., Pradeep D.J., Reddy C.P., Ariwa E. Real Time Voltage Instability Detection in DFIG Based Wind Integrated Grid with Dynamic Components. *International Journal of Computing and Digital Systems*, 2021, vol. 10, no. 1, pp. 795-804. doi: https://doi.org/10.12785/ijcds/100173.

15. Tsai S.-J. S., Wong K.-H. Adaptive undervoltage load shedding relay design using Thevenin equivalent estimation. *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1-8. doi: https://doi.org/10.1109/PES.2008.4596370.

16. Arya L., Pande V., Kothari D. A technique for load-shedding based on voltage stability consideration. *International Journal of Electrical Power & Energy Systems*, 2005, vol. 27, no. 7, pp. 506-517. doi: https://doi.org/10.1016/j.ijepes.2005.05.001.

17. Kessel P., Glavitsch H. Estimating the Voltage Stability of a Power System. *IEEE Transactions on Power Delivery*, 1986, vol. 1, no. 3, pp. 346-354. doi: https://doi.org/10.1109/TPWRD.1986.4308013.

18. Jianjun Z., Dongyu S., Dong Z., Yang G. Load Shedding Control Strategy for Power System Based on the System Frequency and Voltage Stability. *2018 China International Conference on Electricity Distribution (CICED)*, 2018, pp. 1352-1355. doi: https://doi.org/10.1109/CICED.2018.8592262.

19. Shekari T., Gholami A., Aminifar F., Sanaye-Pasand M. An Adaptive Wide-Area Load Shedding Scheme Incorporating Power System Real-Time Limitations. *IEEE Systems Journal*, 2018, vol. 12, no. 1, pp. 759-767. doi: https://doi.org/10.1109/JSYST.2016.2535170.

20. Saffarian A., Sanaye-Pasand M. Enhancement of Power System Stability Using Adaptive Combinational Load Shedding Methods. *IEEE Transactions on Power Systems*, 2011, vol. 26, no. 3, pp. 1010-1020. doi: https://doi.org/10.1109/TPWRS.2010.2078525.

21. Arief A., Nappu M.B., Dong Z.Y. Dynamic under-voltage load shedding scheme considering composite load modeling. *Electric Power Systems Research*, 2022, vol. 202, p. 107598. doi: https://doi.org/10.1016/j.epsr.2021.107598.

22. Horri R., Mahdinia Roudsari H. Adaptive Under-Frequency Load-Shedding Considering Load Dynamics and Post Corrective Actions to Prevent Voltage Instability. *Electric Power Systems Research*, 2020, vol. 185, p. 106366. doi: https://doi.org/10.1016/j.epsr.2020.106366.

23. Hoseinzadeh B., Leth Bak C. Centralized coordination of load shedding and protection system of transmission lines. *International Transactions on Electrical Energy Systems*, 2019, vol. 29, no. 1, p. e2674. doi: https://doi.org/10.1002/etep.2674.

24. Yao M., Molzahn D.K., Mathieu J.L. An Optimal Power-Flow Approach to Improve Power System Voltage Stability Using Demand Response. IEEE Transactions on Control of Network Systems, 2019, vol. 6, no. 3, pp. 1015-1025. doi: https://doi.org/10.1109/TCNS.2019.2910455.

25. Mahari A., Seyedi H. A wide area synchrophasor-based load shedding scheme to prevent voltage collapse. *International Journal of Electrical Power & Energy Systems*, 2016, vol. 78, pp. 248-257. doi: https://doi.org/10.1016/j.ijepes.2015.11.070.

26. Modarresi J., Gholipour E., Khodabakhshian A New adaptive and centralised under-voltage load shedding to prevent short-term voltage instability. *IET Generation, Transmission & Distribution*, 2018, vol. 12, no. 11, pp. 2530-2538. doi: https://doi.org/10.1049/iet-gtd.2017.0783.

27. Gadiraju K.V.R., Kolwalkar A., Gurrala G. *Systems and methods for predicting power system instability*. US Patent no. 20130154614, Jun. 2013. Available at: http://www.freepatentsonline.com/y2013/0154614.html (Accessed 12 May 2021).

28. Jamroen C., Piriyanont B., Dechanupaprittha S. Load shedding scheme based on voltage instability index using synchrophasor data. *2017 International Electrical Engineering Congress (IEECON)*, 2017, pp. 1-4. doi: https://doi.org/10.1109/IEECON.2017.8075776.

29. Milano F. An Open Source Power System Analysis Toolbox. *IEEE Transactions on Power Systems*, 2005, vol. 20, no. 3, pp. 1199-1206. doi: https://doi.org/10.1109/TPWRS.2005.851911.

Received 10.02.2022
Accepted 26.03.2022
Published 01.06.2022

Hemanthakumar Chappa[1]*, PhD, Assistant Professor,*
Tripta Thakur[2]*, PhD, Director General,*
[1] Department of Electrical & Electronics Engineering,
GMR Institute of Technology,
Rajam-532 127, Srikakulam Dist., Andhra Pradesh, India,
e-mail: hemanthkumar.ch@gmrit.edu.in (Corresponding author);
[2] National Power Training Institute,
NPTI Complex, Sector-33, Faridabad, 121003, Haryana, India,
e-mail: tripta_thakur@yahoo.co.in

How to cite this article:
Chappa H., Thakur T. A novel load shedding methodology to mitigate voltage instability in power system. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 63-70. doi: https://doi.org/10.20998/2074-272X.2022.3.09