Analysis of a new voltage stability pointer for line contingency ranking in a power network

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Article Info

Article history:

Received Jun 16, 2022
Revised Jul 25, 2022
Accepted Aug 10, 2022

Keywords:

FACTS devices
Reactive power
Voltage collapse
Voltage stability
Vulnerable line

ABSTRACT

Improper management of reactive power in a power network could lead to voltage instability. This paper presents a well-detailed study on voltage instability due to violation of power equilibrium in a power network and introduces a new voltage stability pointer (NVSP). The proposed NVSP is developed from a reduced 2-bus interconnected network to predict the sensistivity of voltage stability to reactive power variation. The simulation results from MATLAB were evaluated on IEEE 14-bus test system. The contingency ranking was achieved by varying the reactive power on the load buses to its maximum loading limit. The maximum reactive power point was taken at each load bus and the critical lines were ranked according to their vulnerability to voltage collapse. The results were compared with other notable voltage stability indices. The results prove that the NVSP is an essential tool in predicting voltage collapse.

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1. INTRODUCTION

The surge in reactive power demand as a result of growing industries is one of the major causes of voltage instability. This insufficient reactive power may cause voltage drop and transmission losses without compensation [1], [2]. Therefore, an appreciable amount of reactive power is needed to maintain a stable power system. A stable power system will have frequency and voltage operating close to their nominal value.

Voltage control in a power system is imperative for seamless operation of qualitative power delivery to the end users, and averting possible blackout. A voltage collapse often occurs during the perturbation when the power system feed much more load-real and reactive power- than the voltage capability [3], [4].

The reactive power requirement in power network occasionally changes with time as the load demand and generation pattern varies. The power network is designed to experience this variation because of the non-linear (dynamics) characteristics of the load. This upsurge in load demand with no adequate plan for compensation may lead to a state where power system will be overloaded. In power systems, each line in the network possesses tolerable voltage stability limit before the contingency will set in [5]. These incidents may have negative effects on the national economy.

The contingency ranking system in a power network is important in power planning to know the best location to place the compensative devices, and as such, ensures a reliable power system [6]. It will also help the power system operators to be proactive in order to keep the power system free from voltage instability that could lead to voltage collapse [4]. Therefore, voltage stability studies should be seen as a tool that needs to be integrated in power system planning, operation and control [7]. This study proposes a new method of ranking the transmission lines according to their vulnerability to voltage collapse, compare the results with the existing voltage stability indices, and analyze the results based on the accuracy and response time.

2. RELATED WORK

Voltage instability in power systems has been widely studied, especially, with a sole aim of ensuring a reliable power system that is free of unpredictable blackout. Authors in [8] and [9] presented the line voltage stability index, Lmn and fast voltage stability index, FVSI from a 2-bus interconnected system, respectively. The voltage stability indices proved to be potent at moderate power factor but not too accurate at low power factor [10].

Meanwhile *et al.* [11] presented a supervisory, control and data acquisition, SCADA-based method for identification of the critical lines in a power network. The scheme assesses the voltage stability for improvement with reactive power compensation.

Comparative analysis on reactive power compensation technique for stability improvement in power system was presented [12]. The paper considered the effect of motor and transformer which are inductive loads on voltage stability. Several methods of reactive power compensation and optimization were explored.

Delgado *et al.* [13] prepared a study on voltage stability of a power system. The Q-V and P-V curves were used to obtain the optimal reactive power compensation value to ensure voltage stability. The results from the simulation authenticate some selected techniques in the literature.

Research by Kamel *et al.* [14], a study on the effect of reactive power compensation on voltage stability in power system was introduced. The vulnerable lines in the line were evaluated with the voltage stability index. The size and optimal location of the reactive compensators were deduced from the minimum power losses analysis. The simulation was done in power simulator tool and MATLAB for the modelling and reactive power calculation, respectively. The simulation results proved that adequate supply of reactive power will improve the voltage stability.

Fan and Youbin [15] presented analysis on the impact of reactive power compensation devices in DC transmission lines. The reactive power compensation devices were varied and post-fault recovery analysis in the vulnerable HVDC transmission lines were evaluated. The results from the study concluded that suitable a reactive power converter plant will provide stability in HVDC power system.

Samaan *et al.* [16] considered the behavior of a dynamic reactive power reserve on steady-state and transient conditions for power stability. The results from the simulation show that adequate reactive power reserve will ensure voltage stability during severe perturbations and contingencies.

Angadi *et al.* [17] developed a modified Newton Raphson power flow controller for contingency ranking in power transmission lines. Each of the lines was subjected to contingency condition and were classified with WEKA software and MATLAB. The results show that voltage stability analysis with line contingence is imperative to ensuring power stability.

Gita and Kumar [18] discussed the importance of line contingency ranking with the aim of securing the power system. The severity of each line to voltage collapse and the effect of reactive compensation devices to voltage stability were analyzed. The simulation results from MATLAB show that voltage profile and active power quality evaluation can be achieved through identification of the weak lines and buses for adequate controlling mechanism.

Research by Angadi *et al.* [19], an analytical method of predicting the vulnerability of transmission line to voltage collapse was presented. The order of ranking according to their susceptibility to voltage collapse was evaluated through voltage stability index and subjected to machine learning process for intelligence compliance. The approach seems suitable for the prediction of critical transmission lines based on the results from the simulation.

A voltage stability index for black out prediction in power system [20]. The index is used to determine the most critical lines and is indexed in their order of vulnerability. The results from the simulation suggest that the strategy is potent in averting voltage collapse and total blackout in power system.

Tao *et al.* [21] presented a new technique for the assessment of voltage stability margin with the aim of providing assistance to the system operator in ensuring a secured and safe power system. Several reactive compensation methods were explored on the power network. The stability of the system proved to be improved when the FACTS devices were placed close to the generating station from the results obtained from the simulation. Hence, the stability and safety of the system are greatly improved.

Ziegler and Wolter *et al.* [22] presented a technique that measures the sensitivity merit in descending order with the aim to ensuring improved voltage stability. The reactive power devices were employed and their optimal value calculation was evaluated. The simulation results show that the method is sufficient to estimate the optimal and placement of reactive power devices which in turn improve the voltage stability.

Optimum positioning of the reactive power devices in a specific electrical system for improved voltage stability [23]. The stability of the system is tied to polarity of the Eigen-values-positive value implies stability and negative implies instability. The study concluded that identifying the weakest buses in a network with the aim of adequate reactive power compensation will prevent the power system from instability.

Al Mamari *et al.* [24] proposed an algorithm that optimizes the reactive power compensation devices for voltage stability improvement. The results from the simulation were compared with the conventional Newton-Raphson method. The new algorithm was able to improve the voltage stability by controlling different variable power components and in turn reduced the active power loss.

Research by Mundra *et al.* [25], an optimization technique for the reactive power compensation in some hybrid power generation settings was presented. Voltage stability violation as a result of power losses-active and reactive-were investigated. The results from the simulation were validated by differential evolution algorithm.

Mahela *et al.* [26] proposed a solution to address the problems associated with over voltages in transmission line through adequate planning of FACTS devices. An interconnected network of different voltage levels was investigated and the voltage stability of the system was analyzed through reactive power compensation by capacitor and reactor.

Eladl *et al.* [27] proposed a genetic algorithm, GA-based technique for minimization of the power losses and voltage stability improvement through reactive power compensation. The simulation result was tested on IEEE 30-bus test system. The results validate the new technique as the best tool for voltage stability assessment when compared with other similar techniques.

A machine learning technique using adaptive neuro-fuzzy controller for dynamic reactive power compensation in a power grid [28]. Pre-fault, fault, and post-fault conditions were analysed to evaluate the performance of the new technique. The results from the simulation were compared with the traditional control technique-proportional integral controller and fuzzy logic controller. The study concluded that the new technique is efficient.

Similarly, a new optimization technique using the behavior of the coronavirus for optimum reactive power integration and reserve [29]. The results from the simulation proved to be efficient when compared with other methods.

Although, different researches have been conducted on voltage stability, there is still need for improvement in terms of the accuracy and computational time. This research introduces a new technique of predicting voltage collapse from a voltage-band violation in a power network. This is with the aim of reducing power outages as a result of voltage instability and it will also help the system operators to predict possible outage in a real time, such that, a corrective measure could be introduced before the incident.

3. METHOD

The major objective of the proposed NVSP is to monitor the proximity of power network to voltage collapse. Monitoring and assessment of power flow in electric power system is imperative for sustaining a reliable power network [30]. The proposed methodology is derived from a reduced one-line diagram of a 2-bus power system as shown in Figure 1.

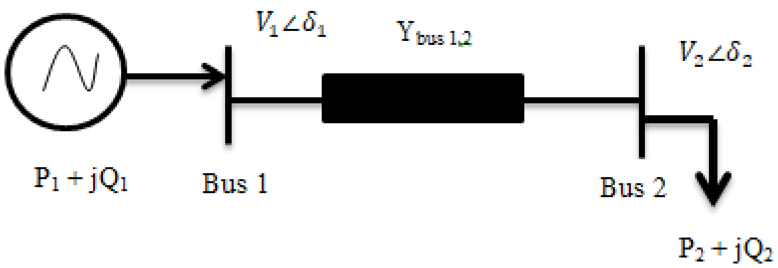

Figure 1. A 2-bus power system

where V_1, V_2 is sending and receiving voltages at system buses; δ_1, δ_2 is sending and receiving voltage angles at system buses; P_1, P_2 is sending and receiving real power at buses; Q_1, Q_2 is sending and receiving reactive power at buses; Y_{bus} is (G + jB) line admittance

The line current I from the generator bus is expressed as:

$$I = (V_1 - V_2).Y_{bus} \tag{1}$$

Meanwhile, the current, I from the load bus can also be determined by:

$$I = \left(\frac{S_2}{V_2}\right) = \frac{P_{2-}jQ_2}{V_2\angle-\delta_2} \tag{2}$$

Equating (1) and (2), will give:

$$P_2 - jQ_2 = (V_1 - V_2).Y_{bus}\,.V_2\angle-\delta_2 \tag{3}$$

Rearranging (3):

$$P_2 - jQ_2 = |V_1V_2Y_{bus}|\angle(\theta - \delta_2) - |V_2|^2.|Y_{bus}|\angle\theta \tag{4}$$

Divide (4) by $|Y_{bus}|\angle\theta$:

$$\frac{P_{2-}jQ_2}{|Y_{bus}|\angle\theta} = |V_1V_2|\angle-\delta_2 - |V_2|^2 \tag{5}$$

Expressing (5):

$$|V_2|^2 - |V_1V_2|\angle-\delta_2 + \frac{P_{2-}jQ_2}{|Y_{bus}|\angle\theta} = 0 \tag{6}$$

From (6):

$$a = 1; b = |V_1|\angle-\delta_2 \ and \ c = \frac{P_{2-}jQ_2}{|Y_{bus}|\angle\theta}$$

$$V_2 = |V_1|\angle-\delta_2 \pm \frac{\sqrt{|V_1|\angle-\delta_2\,|^2 - 4\frac{P_{2-}jQ_2}{|Y_{bus}|\angle\theta}}}{2} \tag{7}$$

If ($\Delta = b^2 - 4ac$) is discriminated to 0, (7) will give 1 real root/ 2 equal roots of V_2. The real roots of V_2 can be expressed as:

$$|V_1|\angle-\delta_2\,|^2 - 4\frac{P_{2-}jQ_2}{|Y_{bus}|\angle\theta} \leq 0$$

$$\frac{4(P_{2-}jQ_2)}{|Y_{bus}|\angle\theta.|V_1|\angle-\delta_2\,|^2} \leq 1 \tag{8}$$

Separate (8) to form real and imaginary parts:

$$\frac{4(P_{2-}jQ_2)}{|G-jB|\angle\theta.|V_1|\angle-\delta_2\,|^2} \leq 1$$

$$\text{Real } \frac{4P_2}{G\,cos\theta\,.\,|V_1|^2\,cos^2\,(-\delta_2\,)} \leq 1 \tag{9}$$

Where: G = $\frac{1}{R}$

$$\frac{4P_2R}{G\,cos\theta\,.\,|V_1|^2\,cos^2\,(-\delta_2\,)} \leq 1 \tag{10}$$

$$cos\theta = \frac{R}{|Z|} \tag{11}$$

Substitute (11) into (10):

$$\frac{4P_2|Z|}{|V_1|^2\,cos^2\,(\delta_2\,)} \leq 1 \tag{12}$$

If voltage angle, δ_2 is very small, then:

$$\approx \frac{4P_2|Z|}{|V_1|^2} \leq 1 \quad (13)$$

Imaginary part:

$$\frac{4Q_2}{B \sin\theta \,.\, |V_1|^2 \sin^2(-\delta_2)} \leq 1 \quad (14)$$

Recall that

$$B = \frac{1}{X} \quad (15)$$

Substituting (15) into (14):

$$\frac{4Q_2X}{\sin\theta \,.\, |V_1|^2 \sin^2(-\delta_2)} \leq 1 \quad (16)$$

Substitute $\sin\theta = \frac{X}{Z}$, (16) will become:

$$\frac{4Q_2Z}{|V_1|^2 \sin^2(-\delta_2)} \leq 1 \quad (17)$$

Assuming voltage angle, δ_2 is negligible, then (17) will become:

$$NVSP \approx \frac{4Q_2|Z|}{|V_1|^2} \leq 1 \quad (18)$$

4. RESULTS AND DISCUSSION

The newly developed NVSP is tested with the IEEE 14 bus and line test data from the line diagram of IEEE 14 bus as shown in Figure 2 in MATLAB environment. The results of the NVSP using IEEE 14-bus system base case are presented in Table 1. The IEEE 14-bus voltage in per unit using NVSP for base case is presented in Figure 3. It was observed from the graph that the system is stable at base case.

Table 1. Analysis of NVSP on IEEE 14-bus test system

Bus no	From bus	To bus	NVSP
1	1	2	0.0282
2	1	5	0.0131
3	3	2	0.1013
4	2	4	-0.0265
5	2	5	0.0107
6	4	3	0.1357
7	4	5	0.0027
8	4	7	0.0488
9	4	9	0.3590
10	6	5	0.0155
11	6	11	0.0153
12	6	12	0.0175
13	6	13	0.0326
14	7	8	0.0000
15	7	9	0.0691
16	9	10	0.0207
17	9	14	0.0590
18	10	11	0.0150
19	12	13	0.0685
20	13	14	0.0776

4.1. Determination of vulnerable lines and maximum reactive power limit

The maximum reactive power limit and vulnerability analysis were carried out on the data and the simulation result is presented in Table 2. The reactive power, Q_2 on the load buses were increased at a constant step size and the NVSP were well observed. The contingency ranking is presented in Table 3.

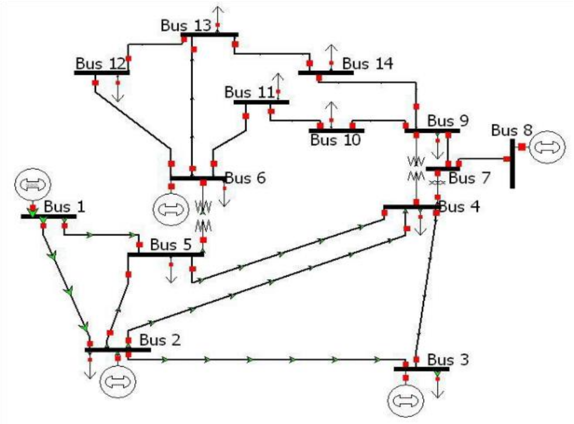

Figure 2. 14-Bus IEEE line diagram

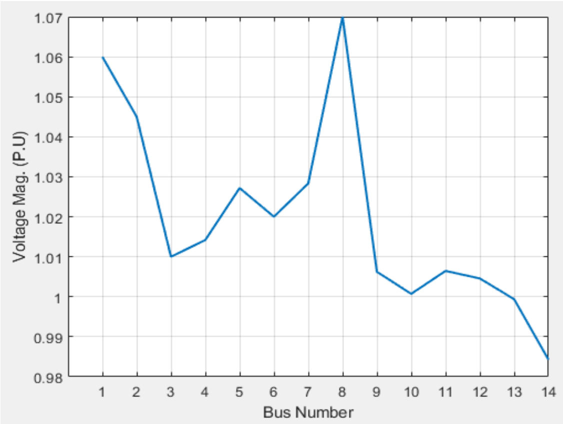

Figure 3. The IEEE 14-bus voltage (in p.u) using NVSP (base case)

Table 2. Maximum reactive power limit and vulnerable lines identification using NVSP

Bus No	From	To	NVSP	Max, Q_2 MVar
4	4	3	0.1631	133
	2	4	0.9587	
	4	7	0.0586	
	4	5	0.0033	
	4	9	0.4314	
5	1	5	0.8456	103. 5
	6	5	1.0028	
	2	5	0.7210	
	4	5	0.1943	
7	7	8	0.0000	115.5
	4	7	1.0018	
	7	9	0.0878	
9	4	9	1.0075	46
	7	9	0.1997	
	9	14	0.0636	
	9	10	0.0223	
10	10	11	0.0231	99.8
	9	10	0.4542	
11	6	11	0.8118	96.8
	10	11	0.9665	
12	12	13	0.0961	90.6
	6	12	0.9886	
13	6	13	0.3134	55.8
	12	13	0.6940	
	13	14	0.0856	
14	13	14	0.9080	55
	9	14	0.7133	

Table 3. Contingency ranking using NVSP on IEEE 14 bus test data

Ranking	NVSP	From	To	Bus no	Q2 (Max) MVar	Voltage Mag (p.u)
1	1.0075	4	9	9	46	0.969
2	0.9080	13	14	14	55	0.853
3	0.6940	12	13	13	55.8	0.952
4	0.9886	6	12	12	90.6	0.848
5	0.9665	10	11	11	96.8	0.849
6	0.4542	9	10	10	99.8	0.825
7	1.0028	6	5	5	103.5	0.970
8	1.0018	4	7	7	115	0.913
9	0.9587	2	4	4	133	0.926

4.2. Discussion

The stability limit was determined by NVSP as it approaches unity. The system is more stable when the index is far less than unity (that is, NVSP< 1) and become unstable as the value approaches one (NVSP≈ 1) without adequate compensation from the FACTS devices.

The maximum reactive power that causes the NVSP to reach unity is noted and described as the maximum loading point. Any increase beyond this maximum reactive load may lead to voltage collapse. The Figure 4 shows comparison between the results obtained in NVSP with the authors in [8], [9] using IEEE-14 bus data. The results revealed a close prediction value between NVSP and [9] with an improved computation time.

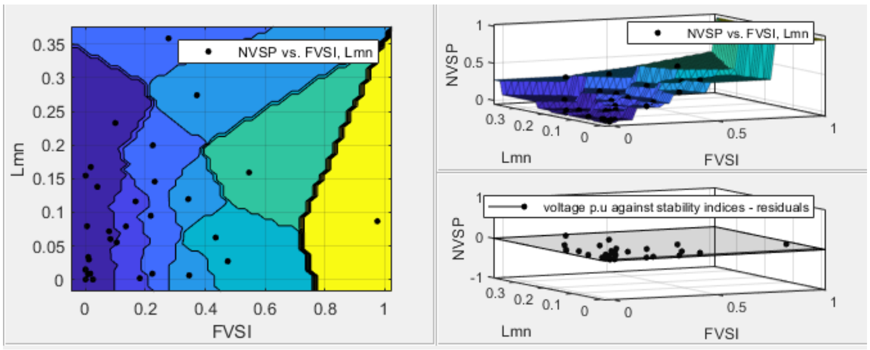

Figure 4. Comparison between NVSP

4 CONCLUSION

This paper has presented a new voltage index for predicting voltage collapse in power systems. The index was compared with other indices. The proposed NVSP is capable of identifying vulnerable lines and buses in power network. The results from the analysis show that NVSP is an essential tool for voltage stability assessment. The study concluded that evaluation of line vulnerability and placement of reactive power compensation devices will improve voltage stability and profile.

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