Quadratic Approximation of PV Curve Path Based On Local Measurements On Presence of Voltage Dependent Loads

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Received: February 2013 Revised: May 2013 Accepted: May 2013

ABSTRACT:
Drawing PV curve path by Continuation Power Flow (CPF) runs is the commonly used method for voltage stability studies. Although time-consuming, it can carefully determine the distance between the current operating point and the collapse point. To drive the power flow equations, the bus admittance matrix and the electrical characteristics of the generators and loads are needed.

The presented method in this paper is based on this fact that, PV-curves are approximately quadratic functions and become exactly quadratic in close neighborhood of the collapse point. So, to draw the PV curve path at a load bus, the calculation of all points is not needed. Instead, using some points, the other points can be determined by the quadratic approximation of the PV curve path. The needed points can be determined using the local measurements of the voltage magnitude and the active power at the corresponding load bus. Now, having static load characteristics, the Saddle-Node Bifurcation (SNB) point can be predicted. The simulations performed on the IEEE 30-bus test system show that the voltage collapse point can be determined using only local measurements (the thing is usually claimed in model-based methods).

KEYWORDS: Voltage Stability Margin (SM), PV curve approximation, Quadratic approximation, Saddle-Node Bifurcation (SNB).

1. INTRODUCTION

Good quality and high reliability of electrical energy to supply consumer, is ideal operation of a power system. Voltage instability is one of the major concerns of power system planning and operation because the load growth without any corresponding increase in transmission capability has made the power systems to operate closer to their voltage stability boundaries [1], [2]. To prevent voltage collapse, the real time voltage instability identification is required.

In recent years, some authors have proposed the methods that use local voltage and current phasor measurements. In [3]–[7], the proximity to voltage collapse is estimated by the calculation of the Thevenin voltage and impedance equivalents seen from a bus. These parameters are calculated using bus voltage and current phasor measurements. When a load is the constant power type, the voltage collapse point coincides the maximum loadability point. In this point, the magnitude of the load impedance and the Thevenin impedance are equal. In [3], a ZIP static load model has been considered. At first, loads are separated into voltage dependent and independent parts. Then the equivalent parameters seen by the voltage independent part of load is used. In [3]–[5], some practical methods for the calculation of system equivalent parameters are presented. The main disadvantage of this method is that required parameters are not constant and must be calculated repeatedly. The work [7] estimates the ratio of the load impedance to the Thevenin impedance without the calculation of the Thevenin voltage and impedance equivalents. This is done by the derivation of the apparent power against the admittance load determined using two subsequent local measurements.

In [8], [9], Artificial Intelligence (AI) based methods are proposed. Several system conditions are simulated to generate the patterns used for training of the Neural - Fuzzy system. The trained network is used for voltage collapse prediction. This method requires offline training that has to be rerun after every topological change of the power system.

The S Different Criterion (SDC) proposed in [10]-[13] is based on the fact that in vicinity of the voltage collapse, the delivered apparent power to the receiving end of a line is maximum and with a change in the current and voltage in the receiving end, does not increase. In this condition, all of the increase in the apparent power in the sending end supplies the transmission losses. At the voltage collapse point, the SDC becomes equal to 0. The main problem is that the SDC is not a good indicator to estimate the proximity of voltage collapse if the line is loaded below its natural loading.

In [14], [15] the improved SDC index known as Bus S Different Criterion (BSDC) is proposed. The BSDC is based on the measurement of apparent power delivered to a bus instead of that of the flowing over the line. By using the BSDC, no additional check is needed whether a line is loaded under or over its natural loading. Ref. [16] uses the derivation of the load apparent power magnitude with respect to its admittance magnitude. This needs the RMS values of the voltage and current that can be obtained using scalar local measurements.

None of the above mentioned local measurement-based indices have linear characteristic. So, they cannot predict the distance to voltage collapse point. This can be done using the determination of PV curve at different buses. Continuation Power Flow (CPF) runs is the common used method for drawing PV curve paths [17], [18]. Although time-consuming, it can carefully determine the distance between the current operating point and the collapse point. To drive the power flow equations, the bus admittance matrix and the electrical characteristics of the generators and loads are needed. Some authors have estimated the upper portion of the PV curves using the first and second-order derivative of the power flow equations [19]. This also is a system model-based method.

In this paper a method is proposed to predict the voltage collapse point in the presence of voltage dependent loads. This method is based on the fact that PV-curves are approximately quadratic functions and become exactly quadratic in close neighborhood of the collapse point. So, to draw the PV curve path at a load bus, the calculation of all points is not needed. Instead, using some points, the other points can be determined by the quadratic approximation of the PV curve path. The needed points can be determined using the local measurements of the voltage magnitude and the active power at the corresponding load bus. The voltage collapse point is determined by the estimated PV curve and load characteristic. The voltage collapse point is the point in which the load characteristic becomes tangent to the PV curve.

2. THEORETICAL BACKGROUND

To predict the voltage collapse point for mixed loads, the load characteristic and lower portion of the PV curve are required. In this paper, lower portion of a bus PV curve is estimated by a quadratic function. It is well known that the PV curve of a bus is affected by loading level at other buses. This concept is illustrated in Fig. 1 using IEEE 30 – bus test system. These curves are plotted at bus 19 where loading factor in other buses is changed from 0.2 to 2.

It can be seen that in contrast to the upper portion and nose point, there is not much change in the lower portion of the PV curve. This reveals that the lower portion of PV curves can more accurately be estimated.

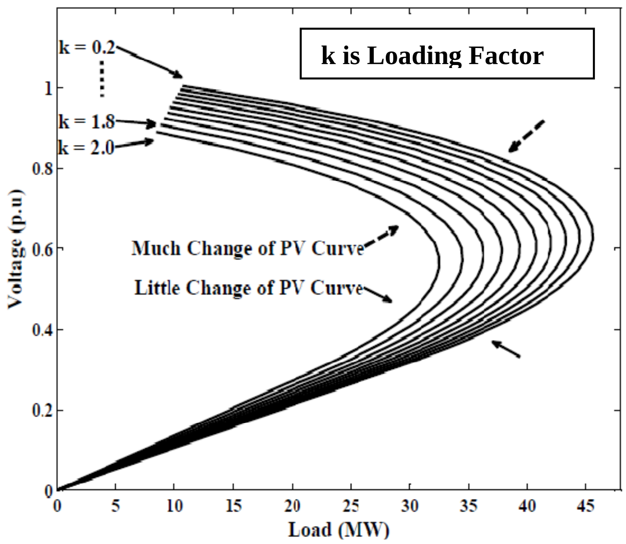

Fig. 1. The PV curves seen from bus 19 with different values of loading factor in other buses.

To present the proposed method, the following load model is considered at the bus m:

$$P_{lm}=k(P_{lom}+P_{ldm}U_m^{\alpha}) \qquad (1)$$
$$Q_{lm}=k(Q_{lom}+Q_{ldm}U_m^{\beta})$$

Where P_{lom}, Q_{lom}, P_{ldm}, Q_{ldm}, α and β are constant and the value k is an independent variable called loading factor, which is used for load increase. The load characteristic (1) intersects the PV curve at two points. The load characteristic changes by the increasing in the loading factor k. The system voltage becomes unstable where in the critical loading factor k^* the load characteristic becomes tangent to the PV curve. This is shown in Fig. 2. The load characteristics and PV curve have been drawn for bus 19. The load consists of 20% voltage independent and 80% voltage dependent types with α=2 and β=3.It can be seen that in the presence of the voltage dependent loads, the voltage stability limit extends beyond the maximum deliverable power point.

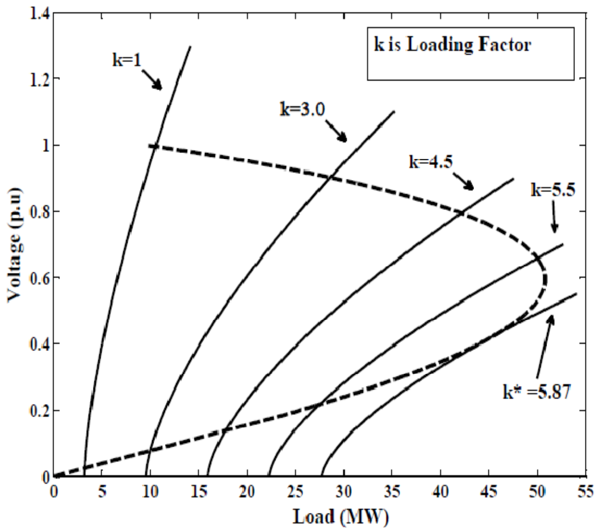

Fig. 2. The extension of the voltage stability limit beyond the maximum deliverable power point.

To predict the voltage stability limit at the bus m, using the Least Square (LS) method, the lower portion of PV curve is estimated by a quadratic function, as:

$$P_m=a_{0m}+a_{1m}U_m+a_{2m}U_m^2 \quad (2)$$

Here at least, three successive measurements of the voltage magnitude and active power are needed. The occurrence of a disturbance causes a sudden change in the stability status. In this condition, the quadratic function must quickly be updated. Therefore, the number of the used measurements must be limited in a sliding window that in this paper the last five points are used. In the critical loading factor k^*, P_{lm} and P_m are equal, so:

$$k^*(P_{lom}+P_{ldm}U_m^{\alpha})=a_{0m}+a_{1m}U_m+a_{2m}U_m^2 \quad (3)$$

Also the slope of two curves is equal, thus:

$$(dP_{lm}/dU)=(dP_m/dU) \quad (4)$$

$$k^*\alpha P_{ldm}U_m^{\alpha-1}=a_{1m}+2a_{2m}U_m \quad (5)$$

The values of k^* and U_m are determined by solving equations (3) and (5). In this paper the gauss – seidal method is used to solve the above equations. The determination of the voltage stability limit for bus m can be summarized in the following steps:

Step 1) Successive measurements of the voltage magnitude and active power and verifying whether the maximum power point is reached or not (this is done by checking the direction of the voltage magnitude and active power load variations).

Step 2) If operating point is beyond the maximum loadability point, the lower portion of the PV curve is estimated by a quadratic function.

Step 3) The voltage collapse point is predicted by comparison of the PV curve and load characteristic.

Step 4) The prediction is updated repeatedly to include any change in the power system.

3. SIMULATION RESULTS

The presented method is tested on IEEE 30-bus test system. In each test, the load is increased at all buses by constant step 1% until the power flow program fails to converge. The total demand of the base case is 291.2 MW and 129 MVAr, approximately. The active power generation is distributed according to the rated capacity of the generators. In the first scenario, it is assumed that the applied load to each bus consists of 50% voltage independent and 50% voltage dependent with α=2 and β=3. By continuation power flow method, the voltage collapse point occurs at a load level of 486MW i.e. k^*=2.70. Fig. 3 shows the PV curve at critical bus 29. The maximum deliverable power point of the critical bus 29 occurs at k=1.9 (Fig. 3). The predicted value of k^* (k^*_p) at this bus versus current loading factor is plotted in Fig. 4. For example, at the current loading factor k=2.2, the predicted value of critical loading factor is k^*_p = 2.72.

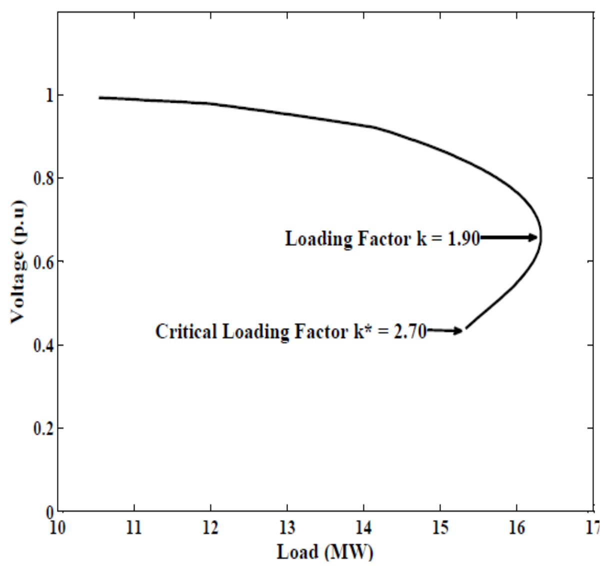

Fig. 3. PV curve at the critical bus 29 with 50% voltage independent and 50% voltage dependent loads.

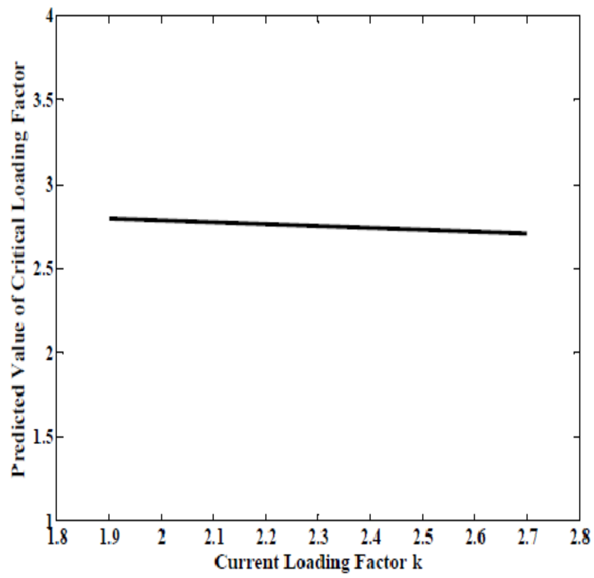

Fig. 4. The predicted value of critical loading factor k^*_p at the critical bus 29 with 50% voltage independent and 50% voltage dependent loads.

It can be seen that the voltage collapse point is acceptably predicted even where the current loading factor is far from the voltage stability limit. In Fig. 5 the predicted values at all buses are plotted. Since the load is increased at all buses simultaneously, the values of k^* are the same for different buses. Fig. 5 shows that the predicted values of critical loading factor at different buses are close to the actual point k^*=2.70.

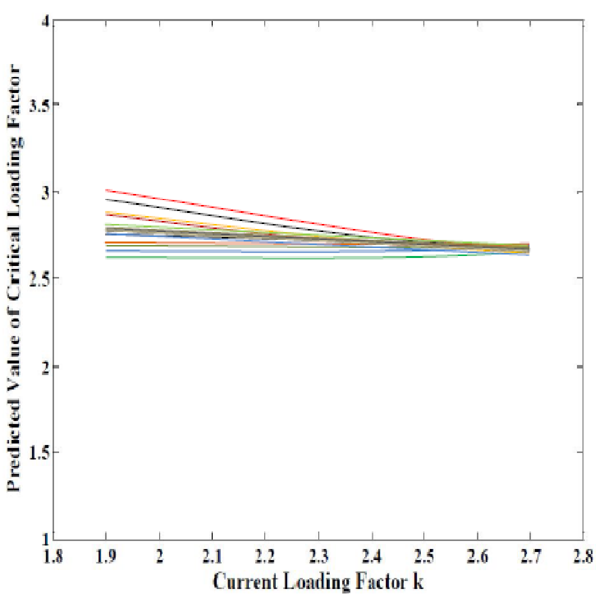

Fig. 5. The predicted value of critical loading factor k^*_p at all buses with 50% voltage independent and 50% voltage dependent loads.

In Table 1 the values of k^*_p where k=2.2 are presented. The values are close to the actual value k^*=2.70.

Table 1. The predicted values of critical loading factor at operating point k=2.2, with 50% voltage independent and 50% voltage dependent loads.

Bus No.	Predicted Values of Critical Loading Factor k^*_p
3	2.66
4	2.71
7	2.72
10	2.80
12	2.78
14	2.71
15	2.70
16	2.64
17	2.70
18	2.69
19	2.71
20	2.70
21	2.66
23	2.69
24	2.63
26	2.62
29	2.72
30	2.60

In other test, the loading pattern is changed. In this case the applied load to each bus consist of 60% voltage independent and 40% voltage dependent types with α=1 and β=2. If the load at all buses is increased, the voltage collapse will occur at k*=2.38. But if after k=1.8, the loading factor at buses 1 to 14 is kept constant and only at buses 15 to 30 is increased, the new critical loading factor becomes k*=2.95. For the critical bus 30 the PV curves and the values of k^*_p are shown in Figs. 6 and 7, respectively.

Fig. 7 shows, if the loading pattern does not change, the critical value k* is acceptably predicted. Where the loading pattern changes at k=1.8, the new stability margin is quickly estimated.

In Fig. 8, the predicted values of k* versus current loading factor at buses 15 to 30 are plotted. The error in prediction at the critical buses is less than the other buses. Therefore, with and without change in the loading pattern, the predicted values of the critical loading factor k* is acceptable.

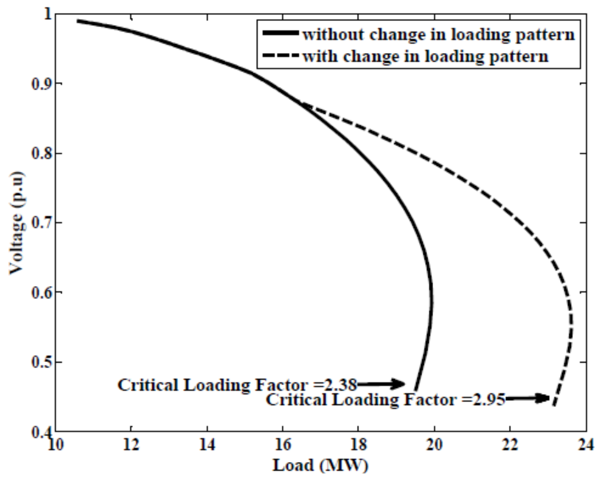

Fig. 6. PV curves at the critical bus 30 with 60% voltage independent and 40% voltage dependent loads.

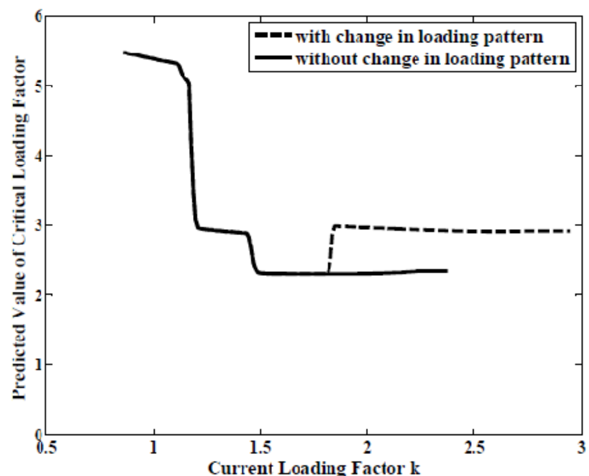

Fig. 7. The predicted value of critical loading factor k^*_p at the critical bus 30 with 60% voltage independent and 40% voltage dependent loads.

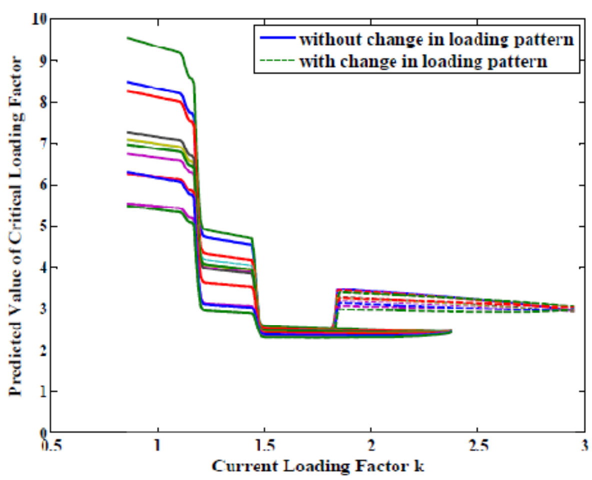

Fig. 8. The predicted value of critical loading factor k^*_p at buses 15 to 30 with 60% voltage independent and 40% voltage dependent loads.

4. CONCLUSION

The low portion of the PV curves has been estimated to predict voltage collapse point in the presence of voltage dependent loads. This is done by a quadratic function using the Least Square method. Contrary to the other methods based on the local measurements, the proposed method can acceptably predict the voltage stability limit. The voltage collapse point at a bus depends on the power demand at the other buses. But if the voltage collapse point lies on the lower portion of the PV curve, this dependency decreases. The error in prediction of the voltage collapse point at critical buses is less compared to the other buses.

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