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The Necessity for Considering Distribution Systems in Voltage Stability Studies

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Abstract. As stated in literature, when a load is of the constant power type, the voltage stability limit point coincides with the point of maximum power transfer. But when a part of load is voltage dependent, such as polynomial load, the voltage stability limit extends beyond the maximum power point. It means that parts of the lower portion of the bus PV curve are stable. This paper shows that because of the distance between the distribution transformers equipped with LTC mechanisms and the transmission buses, the voltage instability occurs before reaching the maximum power transfer point at the transmission buses. In this condition, the voltage collapse point can't be determined using an aggregate load model seen from a transmission bus, and a detailed model of distribution system is needed.

Keywords: Voltage stability, Distribution systems, Saddle-Node Bifurcation, Load characteristics.

1 Introduction

One of the important research subjects on voltage stability studies is to calculate the voltage collapse point. For this purpose, different methods have been presented. These methods can be divided into model-based methods [1]-[3] and phasor-measurement-based ones [4]-[7]. In both of these methods, the transmission system is only considered and the distribution system is modeled as an aggregate load connected to the transmission bus. Efforts have been made to derive models for this aggregate load [8]. If the aggregate load is assumed to be constant power type, the voltage collapse point coincides with the point of maximum power transfer. But if that is voltage dependent, the voltage stability limit extends beyond the maximum power point. This is correct only if the distribution system can be modeled as an aggregate load. This paper shows that for the determination of the voltage collapse point, the explicit modeling of the distribution system is inevitable. But taking the whole distribution system into consideration increases the time computation that is not desirable for on-line voltage stability assessment. So, in some papers, methods have been presented to reduce the whole distribution system to an equivalent model [9]. In none of these papers, the importance of considering distribution system in voltage stability studies is not clearly explained. In this paper, the cause of the error in calculating the voltage collapse point and it is probably values when distribution systems are not considered is calculated. This analysis is done on a simple radial system and the IEEE 9-bus test system, which a radial distribution system is connected to buses 5, 6 and 8.

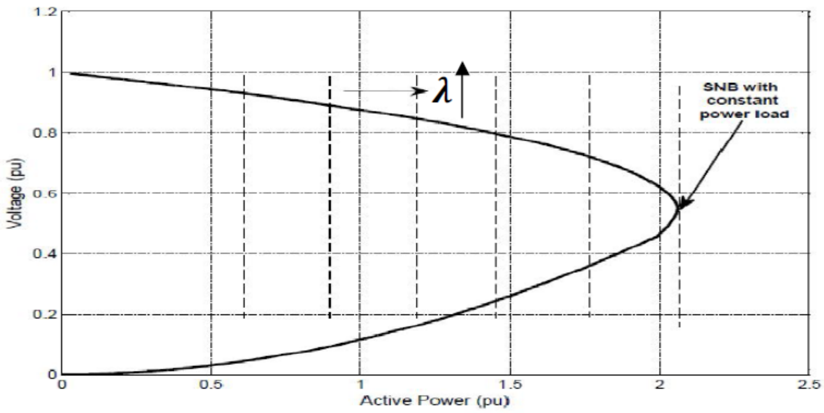
2. The Effect of Distribution System on Voltage Collapse Point

It is well known that voltage collapse point corresponds to Saddle-Node Bifurcation (SNB) [10]. Before SNB, for every load demand, there are two equilibrium points that one of them is stable and the other is unstable. At SNB point, the equilibrium points coalesce. With further increase in load demand, there will not any equilibrium point. So, for voltage instability identification, it is only enough that existence of the equilibrium point is investigated. To calculate the equilibrium points, all dynamic equations must be replaced by their equilibrium equations. This causes the steady-state load characteristics seen from the primary side of transformers having automatic tap changers to become nearly of constant power type. If this demanded power can't be transferred to the transformer locations, there is not any equilibrium point and voltage collapse occurs. In methods that have been proposed to investigate voltage stability, the transmission system is only considered and the entire distribution system is modeled as an aggregate load. The used steady-state characteristic of this load is constant power type or a mixture of constant power and voltage-dependent types that are expressed as

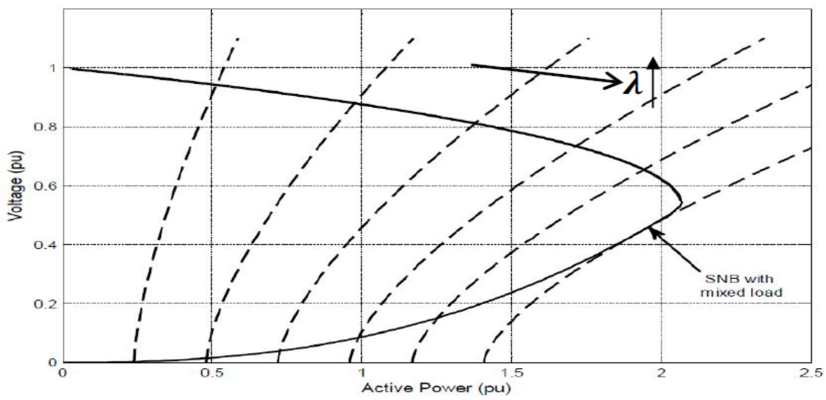
$$P = \lambda P_0 \quad \text{OR} \quad P = \lambda (P_0 + k V^{\alpha}) \qquad \textbf{(1)}$$

Where V is the voltage magnitude at the load bus, P_0 and α are constant, and λ is a parameter called loading factor, which is used to increase the load demand. There are the similar equations for the reactive power demand. These load characteristics for different loading factors with the load bus PV curve are shown in Fig .1. It can be seen that with constant power loads, the SNB point corresponds to the PV curve nose point. When the load is of mixed type with α more than zero, the SNB point occurs in the lower portion of the PV curve.

Fig .2 shows a distribution system connected to a transmission system replaced by its two-bus Thevenin equivalent circuit. It is assumed that the loads connected to buses 4 and 5 are of constant power type. The line impedances and the active and reactive load power are as shown in Appendix.



(a)



(b)

Fig. 1: The load characteristics for different loading factors and the load bus PV curve (a) Constant power load (b) Mixed load

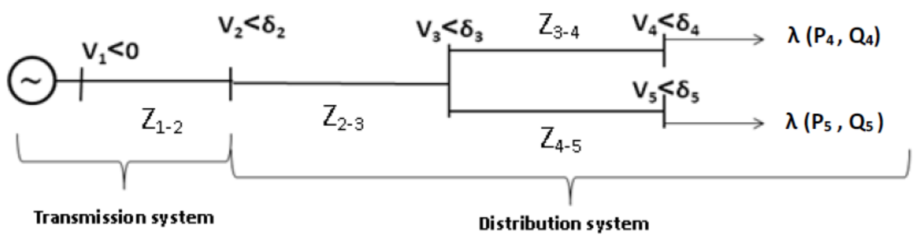


Fig. 2: Distribution system connected to a transmission bus

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For each λ value, the load characteristic seen from bus 2 can be determined by voltage changing and computing the active and reactive power delivered to bus 2. These characteristics for the different λ values as well as the PV curves at bus 2 are shown in Fig. 3.

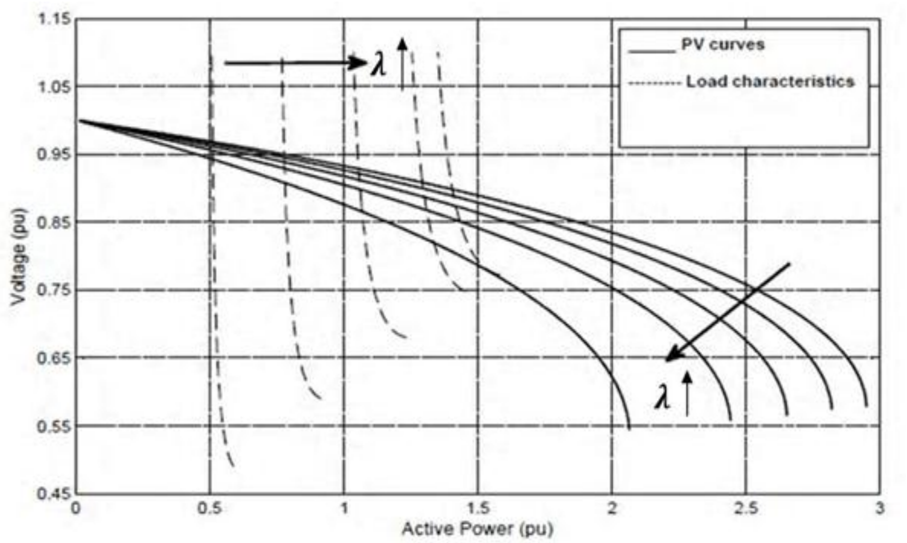

Fig. 3: The load characteristics and PV curves at bus 2 in Fig. 2

The reason for being the different PV curves is to vary the power factor at bus 2 when λ changes. It can be seen that the SNB point occurs before reaching the maximum deliverable power point. The important point in Figure 3 is that the load characteristics considerably changes when the consumed load power at bus 2 increases. In other word, with having the load characteristic in lightly loaded level, the one in highly loaded level can't be obtained as shown in Fig. 4.

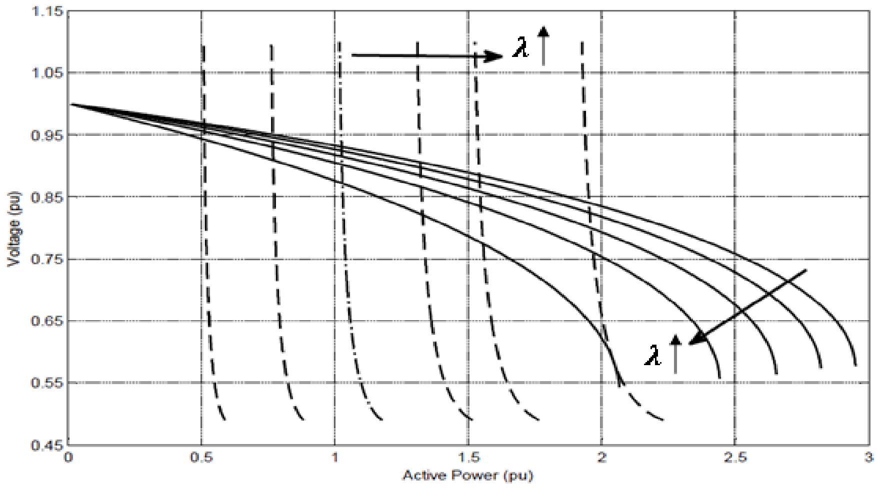

Fig. 4: The change in load characteristics with loading factor

In each voltage magnitude, the load power demand has been increased using some scaling factors such as λ in equation 1. In this case, the active load demand in the SNB point is equal to P_L = 2.05 p.u. that shows a considerable error in calculating the SNB point as compared with the correct value in Figure 3(P_L = 1.55 p.u.). So, in voltage stability studies, the distribution system can't replace by an aggregate load and the whole distribution system must be modeled. In next section, the effect of distribution system is simulated with more details.

3. Simulation on the IEEE 9-bus test system

In this section, the IEEE 9-bus test system in which a radial distribution system is connected to buses 5, 6 and 8 is used for simulation (Fig. 5).Two cascaded levels of LTC transformers are chosen. It is assumed that the speed of tap operation in the upstream LTCs is double that of the downstream ones. The time delay for upstream and downstream taps is 10 and 20 second, respectively. The tap values can be changed between 0.88 to 1.12pu for the upstream LTCs and between 0.85 to 1.15pu for downstream ones. The size of tap step is 1% for all LTCs. The line and transformer impedances of the distribution systems are shown in Appendix. The loads are of constant impedance types with a loading factor using to increase the power demand.

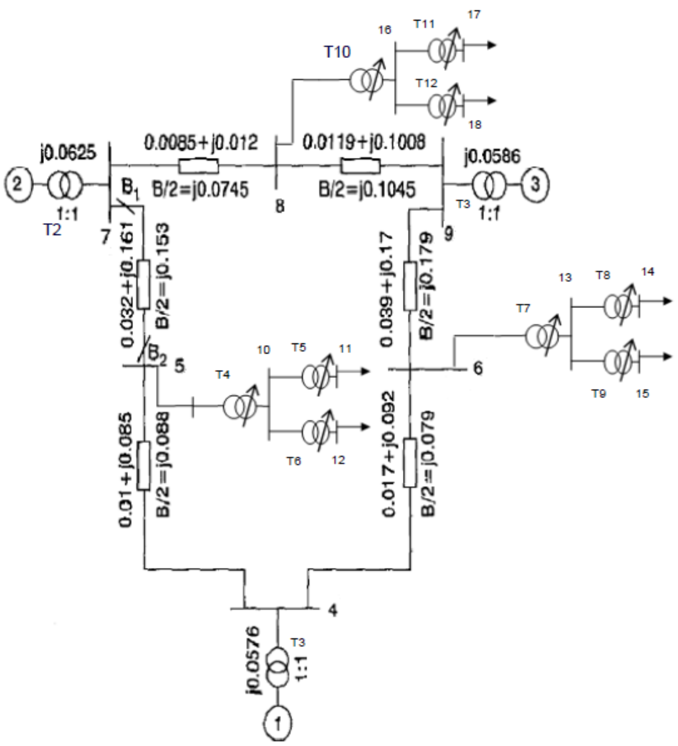

Fig. 5: The modified IEEE 9-bus test system with distribution systems connected to buses 5, 6 and 8

Table I shows the power values delivered to buses 5, 6 and 8 at the SNB point. In the case that the distribution systems replaced by an aggregate load, the SNB point is the same as the maximum transfer power point (assuming that the aggregate load is of the constant power type). It can be seen that when the distribution system is completely modeled, the SNB occurs very before reaching the maximum transfer power point.

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Table1. Simulation results on the IEEE 9-bus test system

	Active power at maximum power transfer point		
	Bus 5	Bus 6	Bus 8
A detail model for the distribution system	1.906	0.767	1.439
The distribution system replaced by an aggregate load model	2.515	1.012	1.901

Figure 6 shows the voltage response at bus 11. The SNB has occurred at 1320 second, at this instant the delivered active power to bus 5 is 1.906 pu.

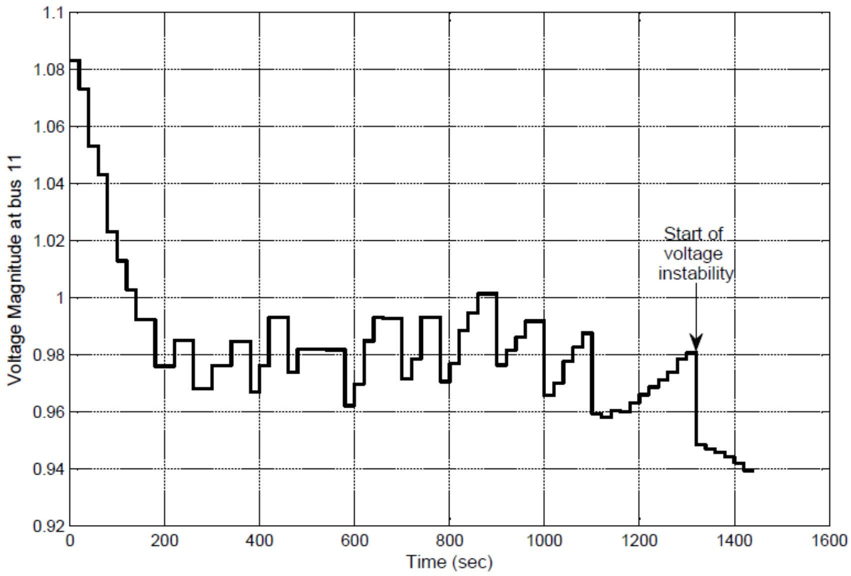

Fig.6: The response of voltage magnitude at bus 11

4. Conclusions

In this paper shown that the voltage instability in power systems occurs before reaching the maximum power transfer point at the transmission buses and the voltage collapse point can't be determined using an aggregate load model seen from a transmission bus. Results of Simulations on the IEEE 9-bus test system and a simple system show that if the distribution systems are not considered in voltage stability studies, a considerable error makes in determining the voltage collapse point. An appropriate model of distribution system is needed to determine when voltage collapse occurs.

Appendix

Table 2. The line data of simple system

Bus number	Bus number	R (pu)	X (pu)
1	2	0.01	0.1
2	1	0.01	0.1
2	3	0.02	0.1
3	2	0.02	0.1
3	4	0.025	0.075
3	5	0.022	0.055
4	3	0.025	0.075
5	3	0.022	0.055

Table 3. The bus data of simple system

Bus number	Active power (pu)	Reactive power (pu)
4	0.2	0.1
5	0.3	0.2

Table 4. The shunt capacitor admittances and LTC reactances of the modified IEEE 9-bus test system

Bus number	LTC: X (pu)	Y_c (pu)
10	T_4: 0.05	0
11	T_5: 0.06	0.3
12	T_6: 0.06	0.25
13	T_7: 0.05	0
14	T_8: 0.06	0.1
15	T_9: 0.06	0.08
16	T_{10}: 0.05	0
17	T_{11}: 0.06	0.2
18	T_{12}: 0.06	0.15

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Table 4. The line data of modified IEEE 9-bus test system

Bus number	Bus number	R (pu)	X (pu)	$B_c/2$ (pu)
1	4	0	0.0576	0
2	7	0	0.0625	0
3	9	0	0.0586	0
4	1	0	0.0576	0
4	5	0.01	0.085	0.088
4	6	0.017	0.092	0.079
5	4	0.01	0.085	0.088
5	7	0.032	0.161	0.153
5	10	0.02	0.05	0
6	4	0.017	0.092	0.079
6	9	0.039	0.17	0.179
6	13	0.022	0.06	0
7	2	0	0.0625	0
7	5	0.032	0.161	0.153
7	8	0.0085	0.012	0.0745
8	7	0.0085	0.012	0.0745
8	9	0.0119	0.1008	0.1045
8	16	0.018	0.04	0
9	3	0	0.0586	0
9	6	0.039	0.17	0.179
9	8	0.0119	0.1008	0.1045
10	5	0.02	0.05	0
10	11	0.025	0.06	0
10	12	0.03	0.08	0
11	10	0.025	0.06	0
12	10	0.03	0.08	0
13	6	0.022	0.06	0
13	14	0.027	0.07	0
13	15	0.032	0.09	0
14	13	0.027	0.07	0
15	13	0.032	0.09	0
16	8	0.018	0.04	0
16	17	0.022	0.05	0
16	18	0.028	0.07	0
17	16	0.022	0.05	0
18	16	0.028	0.07	0

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