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Research paper

Load Modeling Effect on Voltage Stability in Radial Distribution Systems – A Case Study

Vericherla N Malleswari[1]*, K. Chandra Sekhar[2]

[1]Assoc. Professor, Dept of Electrical and Electronics Engineering,
Eswar College of Engineering, Narasaraopet – 522 601, Guntur District, AP, India
[2]Professor, Department of Electrical and Electronics Engineering,
RVR & JC College of Engineering, Chowdavaram – 522 019, Guntur District, AP, India
**Corresponding author E-mail: vericherla.nm@gmail.com*

Abstract

Generally, the distribution systems have served for different types of loads like commercial, industrial, residential, agriculture and municipality etc. and diverse changes in consumption pattern occur at any part of the network at any time of the day. During light loading condition, the voltage profile can increase and vice versa for peak loading condition. Under these circumstances, it is worthwhile to understand the voltage stability for planning of any Volt/VAr controls. This paper has presented the voltage stability analysis of 12-bus and 85-bus standard radial distribution systems using line stability index. Different load models have been taken and under each model, the system performance as well as its stability discussed. The focal points are suitable for planning studies like Volt/VAr controls, optimal location of Distribution Generation (DG) or load shedding etc.

Keywords: *Distribution system, backward/forward sweep load flow, voltage stability, load models*

1. Introduction

The demand for electrical energy is increasing day-by-day all over the world and forced to operate networks at unstable conditions. In history various power system blackouts including Indian power system blackouts in 2012 have been highlighted the necessity of preventive/corrective actions on long-term basis. As networks are translating towards Smart Grid (SG) [1] environment, the possibility of Demand Side Management (DSM) [2] are attracting at every place. In addition, the utilization of Electric Vehicles (EV) [2], integration of Distribution Generation (DG) [3] and upgradation of equipments towards energy efficient etc. are increasing and encouraging towards sustainability. Under these circumstances, the loading levels as well as their characteristics are changing drastically. In order to understand the effective loading on distribution system with the assumption of different types of load growth in future times, the performance analysis for current operating condition and planning studies with the estimation of system insecurity state are very important.

The performance analysis of any operating condition needs to study by using load flow technique. In power system analysis, various load flow techniques are available for transmission networks like Gauss-Seidal (GS), Newton-Raphson (NR), Decouple, Fast Decoupled and DC load flow [4]. However, these algorithms does not suite for Radial Distribution Systems (RDS) due to non-divergence characteristics with the high R/X ratio of the branches in distribution system [5]. Different techniques have been formulated in literature to overcome this problem. This paper has focused on literature survey of various load flow techniques and voltage stability analysis used for distribution system. In addition, the stability analysis of two standard test systems is presented by considering different load models.

2. Load Flow Methods for Radial Distribution System

The load flow studies can useful to identify the steady state condition of a power system at a specific generation schedule, load withdrawals and network configuration. In order to cope-up contingencies as well as to maintain security and reliability, load flow studies are essential. Load flow solution techniques like Conventional Newton-Raphson (NR), Fast Decoupled and Gauss-Seidel methods are efficient and reliable and widely used for planning, operation and control of power system, but these methods are inefficient in solving the distribution network since they are radial, high R/X ratio when compared to transmission lines, unbalancing distribution load, large number of branches and nodes, weak structure and wide ranging resistance and reactance values so this makes the network ill conditioned. The various load flow techniques is given in this literature studies.

Ghosh et.al in [6] proposed a new method with minimum data preparation for the load flow study in radial distribution system. The numbering of node and branches need not to be sequential like other methods and has the capability to manage load modeling and to compute voltage magnitude it uses the simple equations. The test case is done in 33 and 69 node radial distribution system and it uses the set of nodes of feeder, lateral(s) and sub lateral(s) nodes. Jasmon et.al in [7] by using a three fundamental equations namely real, reactive power and voltage magnitude proposed a new technique for load flow in radial distribution network by reducing the entire network to a single equivalent network. Das et al. [8] had proposed a load-flow technique using power convergence to calculate total real and reactive power fed at any node with coding at laterals and sub-lateral nodes for large radial systems with increased complexity of computation. Proposed method works only for sequential node and branch numbering schemes. Forward sweep method is used to calculate the receiving end voltages and have taken the initial zero power loss to solve radial systems. This method can solve algebraic expression and data's are stored in vector form thus saves computer memory. Haque in [9] to solve radial and meshed networks the authors presented an efficient method with more than one feeding node. Multiple-source mesh network is first converted into equivalent single-source radial system with dummy nodes later the traditional ladder network method is applied for the equivalent radial network. Shunt and load admittances effects are incorporated in this so that it can solve special transmission networks. The convergence is excellent in this radial networks. Eminoglu and Hocaoglu [10] for solving the power flow problem in radial systems the authors presented a simple and efficient method with voltage dependency of static loads, and line charging capacitance. It is based on forward and backward voltage updating for each branch using polynomial voltage equation and backward ladder equation. When compared with the improved version of the classical forward backward ladder method this algorithm has robust convergence ability that is Ratio-Flow.

Prasad et.al in [11] to compute the branch currents in Radial Distribution network proposed an efficient and simple load flow algorithm. This algorithm exploits a tree structure property of the system and implements the LFA. In each iteration of LSA, the authors has identified the exercised leaf node till the estimated voltage satisfies the convergence criterion and concluded that this leaf node identification overburdens the LFA algorithm for static and dynamic topologies. Sivanagaraju et al in [12] to analyze the weakly meshed distribution system have proposed a distinctive load flow solution. By applying the Kirchhoff's law the branch-injection to branch current matrix is formed (BIBC) for the solution of weakly meshed distribution system. Forward sweep is used to find the bus voltages. Kumar A et.al in [13] in order to obtain a reliable convergence they proposed a power flow solution in distribution systems. To obtain better convergence the equations obtained are partially converged and in node power expressions the trigonometric terms are eliminated. It is solved similar to Newton-Raphson (NR) method and it is simpler than existing system.

Augugliaro A et.al in [14] developed a method for the analysis of the radial or weakly meshed distribution system which supplies the voltage dependent loads. It's an iterative process and the loads are simulated in every single iteration as impedances and only the impedance kind of network is simulated at each iteration. For the single unknown current, the current and voltages are expressed as linear function in radial systems and independent mesh as two unknown currents in mesh systems. Since its starts from the end node and moves towards the starting node it's termed as backward method and is the most commonly used method and has the advantage of reduced computational and high precise results. D. P. Sharma et.al in [15] developed a framework for improving the load flow algorithm to meet the requirements of real time operation. They developed an efficient method to identify the leaf nodes and it gives efficient and faster results when integrated with the Load Flow Analysis (LFA).

The backward/forward sweep methods are mostly used due to their computational efficiencies and solution accuracy for radial distribution system. By specifying reference/sub-station bus voltage and considering flat voltage profile, the backward/forward sweep load flow method has the following three basic steps [8]:

i) *bus current calculations*: At iteration *k*, the bus currents ($I_i^{(k)}$) are calculated as follows:

$$I_i^{(k)} = \frac{S_i}{\left(V_i^{(k-1)}\right)^*} - Y_i V_i^{(k-1)} \quad \forall = 1, 2, ..., N_{bus} \tag{1}$$

where S_i is the complex load connected at bus *i*, Y_i is the total shunt admittance of the bus *i* and $V_i^{(k-1)}$ is the voltage of bus *i* at previous iteration.

ii) *Backward sweep*: At iteration *k*, the branch currents are calculated starting from the last layer and moving back towards reference bus using KCL.

$$I_{ij}^{(k)} = -I_j^{(k)} + \sum_l I_l^{(k)} \qquad l = N_{br}, N_{br-1}, ..., 1 \tag{2}$$

where $I_j^{(k)}$ is the current at bus *j*, $I_l^{(k)}$ is the current in branch *l* and *l* is sweep back towards reference bus.

iii) *forward sweep*: After determining branch currents, the bus voltages are calculated from reference bus to last layer bus in forward approach using KVL and is given by:

$$V_j^{(k)} = V_i^{(k)} - Z_l I_i^{(k)} \qquad l = 1, 2, ..., N_{br} \tag{3}$$

All these steps are repeated until convergence criterion satisfies. In general, the convergence criterion is the maximum of all bus voltage differences between current iteration to the previous iteration and should be zero for ideal case.

3. Voltage Stability Analysis of Radial Distribution System

Voltage stability is considered as one of the important aspects in industry as well as research sectors around the world because of the closer operation of the power systems to the limit where the expansion of network is restricted to many reasons such as investment lack or serious concerns on environmental problems [16]. Everyday distribution systems experience distinct changes in load levels. Voltage collapse occurs under critical loading conditions in distribution systems due to the variation in load. Due to the low reactance to resistance value (X/R) in Radial Distribution System (RDS) that leads to IR and IX voltage drops in systems and hence it is said to be ill-conditioned network [17]. Most of the investigations have identified the problem in high voltage transmission system than distribution network and hence the load in distribution side cannot be taken fully by these investigations and because of this the industries and researchers have paid less attention for voltage stability in distribution networks [18].When there is an increment in load at a certain bus and in order to find the radial distribution state, various steady-state voltage stability indices are introduced in ref [20, 21]. By using the method in [22] the indices can be reduced to two-bus equivalent system from actual radial system. A voltage stability index is introduced in [2] which are derived from the load flow equation in [23]. Using the load flow equation a geometrical form of criteria is presented for voltage stability analysis in radial distribution system in [24] and by using the circle diagram of synchronous generator and Jacobin matrix the feasibility and uniqueness properties of load flow (using Newton–Raphson method) is tested by reducing the system into two-bus equivalent system. To determine the distance to voltage collapse point a voltage stability margin if radial network is presented in [20]. Based on the voltage phasor an analytical approach method is presented in [25] for voltage collapse proximity determination. It is noted that from ref [26, 27] a two-bus power system can represent satisfactory load bus performance in all its situations and voltage stability problem is mainly a load stability aspects. In this work, the following stability indices have been used and compared in case studies.

In [18], the Line Stability Index (LSI) is introduced and is given by:

$$LSI_{pq} = \frac{4x_{pq}Q_q}{\left\{|V_p|\sin\left(\theta_{pq}-\delta_{pq}\right)\right\}^2} \le 1.00 \tag{4}$$

In [19], Power Stability Index (PSI) is introduced and is given by:

$$PSI_{pq} = \frac{4r_{pq}P_q}{\left\{|V_p|\cos\left(\theta_{pq}-\delta_{pq}\right)\right\}^2} \le 1.00 \tag{5}$$

In [32], Voltage Stability Index (VSI) is proposed and is given by:

$$VSI_q = \frac{4x_{pq}}{|V_p|^2}\left(\frac{P_q^2}{Q_q^2}+Q_q\right) \le 1.00 \tag{6}$$

For stable operation, the LSI and PSI should be less than 1 for all the lines. The LSI or PSI greater than 1 indicates the proximity of instability or voltage collapse. Under normal operating conditions, VSI value should be less than unity. If the value of VSI is closer to zero, then the system will be more stable. If the value of VSI is high, then the system is vulnerable to stability. The bus with high VSI value is more sensitivity and needs some corrective actions like Volt/VAr controls/DG installation/Load shed etc.

4. Time-Varying Voltage-Dependent Load Modeling

Generally, the active and reactive power demands are assumed as constant irrespective of its associated bus voltage magnitude in conventional load flow studies. But the operational characteristics of different types of loads are differ and are highly dependent on voltage and frequency variations in the network. On the other side, the nature of load characteristics and corresponding effective loading can cause for different load flow solution and convergence ability [28]. In order to consider the effects of voltage variation w.r.t. time, the voltage dependent load model is introduced in [29].

$$P_{d,i(t)} = P_{d,i(0)} \times V_{i(t)}^{\alpha} \quad \text{and} \quad Q_{d,i(t)} = Q_{d,i(0)} \times V_{i(t)}^{\beta} \tag{13}$$

where $P_{d,i(0)}$ and $Q_{d,i(0)}$ are the real and reactive power loads at bus-i respectively; $V_{i(t)}$, $P_{d,i(t)}$ and $Q_{d,i(t)}$ are the voltage, effective real and reactive loading at bus-i at time (t) respectively; α, β are the real and reactive load voltage exponents and are given in Table 1 for different types of loads [30, 31].

Table 1: Exponents for different load models

Load type	α	β	% (Assumed)
Constant power	0.00	0.00	20
Constant current	1.00	1.00	10
Constant impedance	2.00	2.00	10
Batery charge	2.59	4.06	10
Flurocent lamps	2.07	3.21	5
Fluorecent lighting	1.00	3.00	5
Air conditioner	0.50	2.50	10
Pumps, fans other motors	0.08	1.60	10
Incandancent lamps	1.54	0.00	5
Small industrial motors	0.10	0.60	10
Large industrial motors	0.05	0.50	5

5. Results and Discussions

The standard 12-node and 85-node test systems have been taken for simulation studies. At each node, the static load is modeled as composite load considering all types of loads as assumed in percent given in Table 1. With the 100% constant power model, the base case simulations are performed at first. The system has 435 kW real and 405 kVAr reactive loads at base. The corresponding node voltages and voltage stability indices are given in Table 2. As highlighted, bus-9 is most critical bus for voltage instability due to high value of VSI [32]. The results are comparable with the other indices given in [18, 19]. The network has 20.7117 kW real and 8.0393 kVAr reactive power losses.

Table 2: 12-node results for 100% constant power load

Node	Vol (p.u)	Ang (Deg)	LSI	PSI	VSI
1	1.0000	0.0000	0.0000	0.0000	0.0000
2	0.9943	0.1162	0.0061	0.0025	0.0018
3	0.9890	0.2234	0.0033	0.0019	0.0014
4	0.9806	0.4022	0.0108	0.0046	0.0032
5	0.9698	0.6287	0.0091	0.0039	0.0027
6	0.9665	0.6979	0.0016	0.0009	0.0007
7	0.9637	0.7584	0.0055	0.0023	0.0016
8	0.9553	1.0114	0.0266	0.0076	0.0039
9	0.9473	1.2422	**0.0303**	**0.0089**	**0.0046**
10	0.9445	1.3180	0.0121	0.0040	0.0021
11	0.9436	1.3417	0.0064	0.0024	0.0013
12	0.9434	1.3488	0.0026	0.0007	0.0004

The voltage profile of the base case is taken as the bus voltages at a specific time and the time-varying voltage-dependent equivalent composite load is calculated at each load using specified load type and its corresponding exponentials. By having this net effective modulated load at each bus, the load flow is performed. Due to voltage-dependent nature, the effective loading on the system has been changed to 422.683 kW and 385.3623 kVAr. For this new effective loading, it has 18.658 kW real and 7.2546 kVAr reactive power losses. The results of composite case are given in Table 3. From the results, we can see an improvement in voltage profile, stability and decrement in losses due to decrement in effective loading.

Table 3: 12-node results for composite load model

Node	Vol (p.u)	Ang (Deg)	LSI	PSI	VSI
1	1.0000	0.0000	0.0000	0.0000	0.0000
2	0.9945	0.1087	0.0060	0.0025	0.0018
3	0.9895	0.2078	0.0033	0.0018	0.0014
4	0.9814	0.3724	0.0105	0.0045	0.0032
5	0.9711	0.5786	0.0087	0.0038	0.0027
6	0.9680	0.6413	0.0015	0.0009	0.0006
7	0.9654	0.6959	0.0052	0.0022	0.0016
8	0.9574	0.9256	0.0249	0.0073	0.0037
9	0.9498	1.1335	0.0280	0.0084	0.0044
10	0.9471	1.2015	0.0111	0.0038	0.0020
11	0.9463	1.2227	0.0059	0.0023	0.0013
12	0.9461	1.2291	0.0024	0.0007	0.0004

The similar approach is carried for 85-node system. The base case system has a total of 2.5703 MW real and 2.6222 MVAr reactive loads. By performing load flow, we have 316.0698 kW real and 198.5720 kVAr reactive losses. For the composite load model, the system has a total of 2.3822 MW real and 2.2989 MVAr reactive loads and corresponding losses are 240.7581 kW and 151.5675 kVAr. The voltage profile is given in Fig. 1.

The node-83 is the most voltage instable node with highest values of all stability indices for base case and node-69 is as per LSI and PSI and node-8 is as per VSI are became most instable under composite load model. Similarly, the stability index by [18], [19] and [32] are given in Fig. 2, Fig. 3 and Fig. 4 respectively.

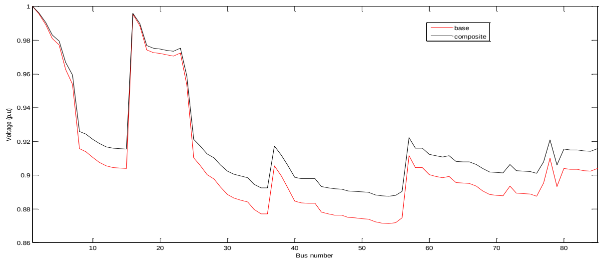

Fig. 1: Voltage profile of 85-node system

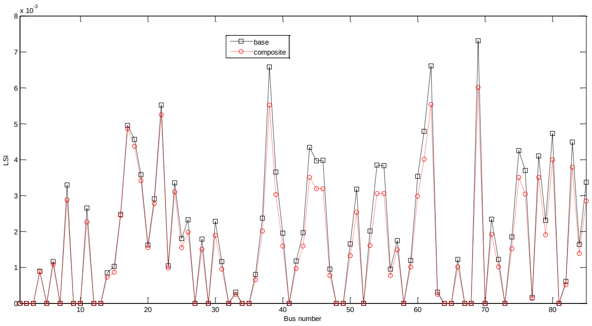

Fig. 2: Stability index of 85-node system [18]

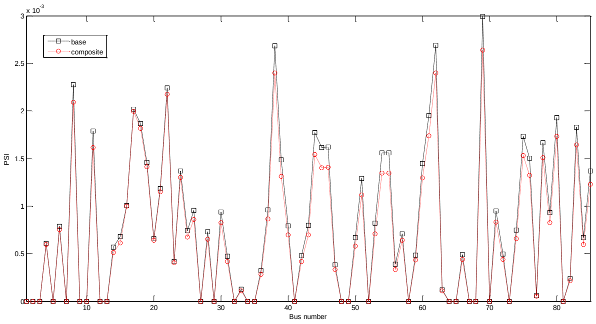

Fig. 3: Stability index of 85-node system [19]

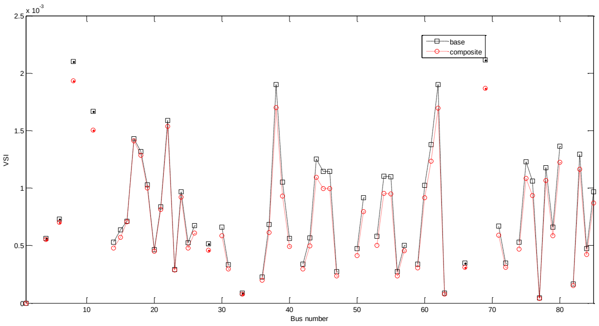

Fig. 4: Stability index of 85-node system [32]

6. Results and Discussions

This paper has explored the various load flow techniques and stability indices and load models are used for radial distribution system. Among various methods, the backward/forward sweep load flow method [8] is simulated on 12-node and 85-node test systems. The results have shown the changes in performance due to type of load which have dependent on voltage magnitudes of their associated buses. The stability indices proposed in [18], [19] and [32] are computed and a comparative study is presented. The simulations are performed for nominal constant power load model and composite load model. Under different loading characteristics, the node stability may also change as seen in node-85 test system. In addition, there is a change in voltage profile, angle, real and reactive power loss due to change in effective loading on the feeder under composite load model. The stability indices indicates most sensitive location for instable and can be used to implement any short of remedial action like Volt/VAr control, DG installation or load shed under inevitable case.

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