

# COORDINATED VOLTAGE CONTROL IN RADIAL DISTRIBUTION SYSTEM WITH DISTRIBUTED GENERATORS USING SENSITIVITY ANALYSIS

<sup>1</sup>ANUBHAV SHRIVASTAVA, <sup>2</sup>LAKSHYA BHAT, <sup>3</sup>SHIVARUDRASWAMY

<sup>1,2,3</sup>Department of Electrical and Electronics Engineering, Manipal University, Manipal-576104, Karnataka, INDIA  
E-mail: anubhavshrivastava92@gmail.com, lakshyabhat@gmail.com, Shivarudraswamy.r@manipal.edu

**Abstract-** Distributed generation has indeed become a major area of interest in recent years. Distributed Generation can address large number of loads in a power line and hence has better efficiency over the conventional methods. However there are certain drawbacks associated with it, increase in voltage being the major one. This paper addresses the voltage control at the buses for an IEEE 30 bus system by regulating reactive power. For carrying out the analysis, the suitable location for placing distributed generators (DG) is identified through load flow analysis and seeing where the voltage profile is dipping. MATLAB programming is used to regulate the voltage at all buses within  $\pm 5\%$  of the base value even after the introduction of DG's. Three methods for regulation of voltage are discussed. A sensitivity based analysis is later carried out to determine the priority among the various methods listed in the paper.

**Keywords-** Distributed Generators, Distributed System, Reactive Power, Voltage Control, Sensitivity Analysis

## I. INTRODUCTION

There is an increase in demand to meet energy requirements daily. Adoption of distributed generators in a distribution network is one way to tackle the energy requirements effectively. A distribution network is extremely sensitive to any changes in reactive power status at the receiving end. In order to achieve optimum voltage control, it is required to control the reactive power flow in the network and this is possible by applying reactive power management at different nodes in power system. To maintain steady state operation in a power system, voltage plays a major role and hence its regulation is essential.

Various factors that govern the voltage variations are:-

- a) By connecting DGs to the system
- b) Load characteristics.
- c) Reactive power constraints
- d) Increased loading on distribution Feeders,

The introduction of DG's within the distribution system has been a good step forward. But, while it helps by injecting power in the system at different points, it can also cause the voltage at some nodes to shoot up beyond the acceptable level. This project takes up the part of controlling or containing the voltages at all the nodes within a suitable limit. With the aid of DGs (Distributed Generators), power generation facilities can be kept very close to end users. This reduces transmission losses. If the number of DGs introduced is less, the system can tolerate them. However with a large number of Distributed Generators interconnected to the system, the voltage profile shoots up and exceeds the tolerance limits. But this aggregation of DGs also creates a large area of customer friendly and optimized solutions. The

goal of this project is to control the voltage within limits by controlling the reactive power of the DG. Several methods like using capacitor banks and reactors and reduction in DG reactive power are discussed. Based on tolerance limit as dictated by statute, distribution voltage network are designed [5]. The range of voltage which must be met under a number of different standards does not exceed  $\pm 10\%$ , [3-6]. In this paper, the tolerance limit is kept as low as  $\pm 5\%$  for an even higher precision. In [6], a generic analytical expression that governs the voltage profile of the distribution with network with DG connected is stated.

There are several other advantages associated with Distributed Generation operation such as improved reliability, low transmission loss, load flow control and better efficiency [1, 4, 5]. However issues such as steady state voltage fluctuation, islanding operation, increased fault system level and degradation of power quality and stability of the radial system are the issues that need to be tackled [2]. These factors can also be affected by the kind of interface used for DG system to interconnect to the grid [3]. However, irrespective of the other demerits, the major cause of worry remains the rise in steady state voltage level of distribution system which has been addressed in this paper. Therefore, if voltage control can be achieved within desirable limits then this system with DGs connected can be favourable to conventional methods due to the vast number of advantages associated with it.

## II. STEADY STATE VOLTAGE RISE

In a distribution network when we connect a distribution generator, the active power generated by the generators reduces the flow of power from the primary substation. This can result in a) Maximum

system demand and zero generation, b) Maximum generation and minimum system demand c) maximum generation and maximum system demand and maximum generation. For increase in voltage, maximum generation and minimum load withstanding capacity are usually vital for the capacity of Distributed generators [4]. However, it is also essential to analyse the effects of maximum generation and maximumload conditions for providing solution to increase in voltage [5]. The connection of distributed generator to the distribution network are illustrated in Fig.1 (a) and Fig.1 (b)[9].  $P_g$  and  $Q_g$  are the active and reactive powers of the generator respectively. The active and reactive powers of the load on the distribution system are represented as  $P_L$  and  $Q_L$  respectively. The total current flowing along the line impedance is  $I_R$ . The line impedance itself is denoted by  $Z = R + jX$  and the total power delivered to the network is denoted by  $S_R$ .  $V_s$  and  $V_g$  are the substation and connection point voltage respectively.

$$S_R = P_R + jQ_R = (P_g + jQ_g) - (P_L + jQ_L) \quad (1)$$

$$S_R = V_g I_R^*, I_R = (P_R - jQ_R) / V_g^* \quad (2)$$

$$V_g = V_s + I_R Z = V_s + I_R (R + jX) (P_R - jQ_R) / V_g^* \\ = V_s + (P_R R + X Q_R) / V_g^* + j(P_R X - Q_R R) / V_g^* \quad (3)$$

From figure 1b) the phasor diagram can be used to arrive at

$$V_g \sin \delta = (P_R X - Q_R R) / V_s \quad (4)$$

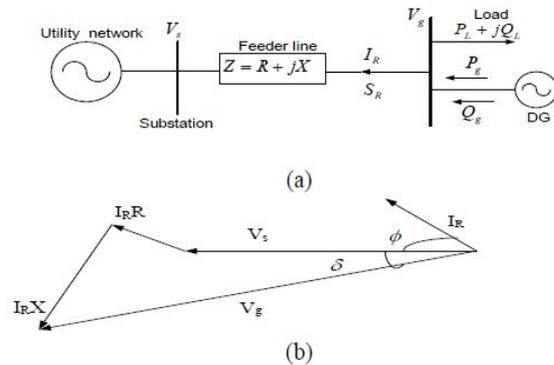


Figure 1(a) Utility network with wind DG system and Figure 1(b) Phasor Diagram

Since the Voltage angle  $\delta$  is negligible, the term  $(P_R X - Q_R R) / V_g^*$  is also negligible and can be neglected. Magnitude of voltage rise  $\Delta V$  is approximately given by [9].

$$\Delta V = (P_R R - X Q_R) / V_g^* \\ = ((P_g - P_L) R + X(Q_g - Q_L)) / V_g^* \quad (5)$$

The induction generator absorbs reactive power, whereas the synchronous generator is able to generate as well as absorb. When it produces active power, it shoots up the voltage, but the reactive power produced can have a twofold purpose: depending on the advancements in DG equipment, it can either increase or decrease voltage profile. These

factors, along with the R/X of the radial network and the distribution network characteristics or the load profile can help to assess whether the voltage profile at a particular node is increasing due to power export from DG or not.

$$\overline{V_{n+1}} = \overline{V_1} - \sum_{k=1}^n \frac{(R_k + jX_k)(P_{k+1} - jQ_{k+1})}{V_{k+1}^*} \quad (6)$$

The results of some studies that determine the voltage rise issue and the way they can be reduced are shown in [6]. There have been several methods that have been studied – switching off capacitors, switching on reactors, reduction in DG reactive power and controlling the primary substation voltage. The main aim of these methods is to keep the voltage within the tolerance limits in order to prevent system damage and overloading. The tolerance limits set by statute is  $\pm 10\%$ . However this paper has been able to keep it as tight as  $\pm 5\%$  [7]. For determining the efficiency of each method, a sensitivity analysis is carried out in the end.

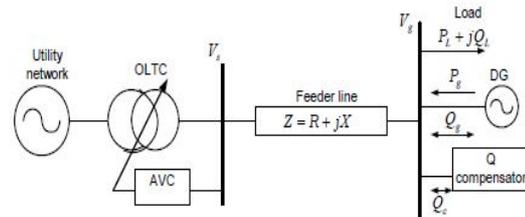


Figure 2 - A simple system illustrating the options for voltage regulation

In Figure 2, a load ( $P_L$ ,  $Q_L$ ), distributed generator, DG ( $P_g$ ,  $Q_g$ ) and reactive capacitor ( $Q_C$ ) linked to the distribution system via a distribution feeder that has impedance  $Z$  is shown. An on-load tap changer (OLTC) transformer is connected towards the utility end. A DG system which is rotating machine based is used.

### III. VOLTAGE SENSITIVITY ANALYSIS

The impact of changes in system parameters on system performance can be measured by sensitive analysis. Sensitive analysis can also be used to calculate changes in branch flows, losses and bus voltages due to variations in generation and loads. In many cases that deal with reactive power injection, the variation in voltage with respect to change in reactive power injection has been used to calculate sensitivity factor. Sensitivity analysis is a major criterion for determining the priority chart for voltage control in a distribution network with DGs inserted.

The sensitivity method has been extensively researched and viable results have been tabulated. The power flow equations are:

$$P_i = V_i \sum_{j=1}^n V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij})$$

$$Q_i = V_i \sum_{j=1}^n V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$$

Let  $X = [V_L, \delta_L, \delta_G]^T$  be set as state vectors, and  $U = [P_L, Q_L, P_G, Q_G, V_O, \delta_O]^T$  be a set of control vectors, then the power flow equations can be written as  $F(X, U) = 0$ . The total derivative of the control vector is

$$\frac{dF}{dU} = \frac{\partial F}{\partial X} \frac{dX}{dU} + \frac{\partial F}{\partial U} = 0$$

For the reactive power output  $Q_g$ , the total derivative is:

$$\frac{\partial F}{\partial V_L} \frac{\partial V_L}{\partial Q_g} + \frac{\partial F}{\partial Q_G} = 0$$

Then the sensitivity  $dV_L/dQ_{gi}$  is

$$\frac{\partial V_L}{\partial Q_{gi}} \frac{dV_L}{dQ_g} = - \left[ \frac{\partial F}{\partial V_L} \right] \frac{\partial F}{\partial Q_G}$$

When the change of reactive power output occurs, the change of the voltage on the load buses can be calculated. The difference signal is the sensitivity.

#### IV. SIMULATION AND RESULTS

##### 4.1 Sensitivity Analysis of 30 Bus Systems

For carrying out sensitivity analysis, the change in peak value of the voltage waveform and change in reactive power is noted down. The ratio of these two quantities is what we call the sensitivity factor. Three methods for reduction in Voltage system for a DG connected network are studied. For analysis of sensitivity, sensitivity factor for each method is calculated and then based on the results obtained, a viable conclusion is made.

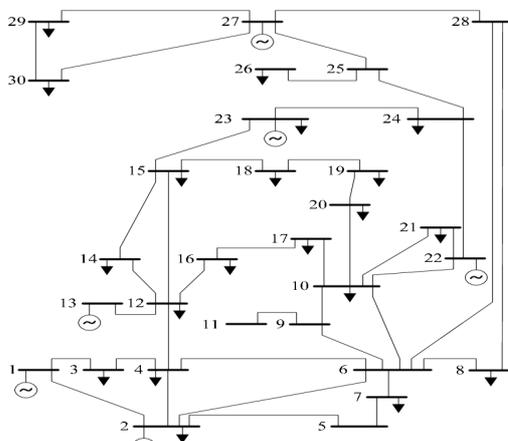


Figure 3: IEEE 30 Bus Single Line Diagram

Table 1: Capacities and Position of DGs inserted in the system

| S No. | Capacities(MVA) | Location |
|-------|-----------------|----------|
| DG1   | 150+100i        | Node 3   |
| DG2   | 70+50i          | Node 4   |
| DG3   | 100+50i         | Node 7   |
| DG4   | 80+50i          | Node 9   |
| DG5   | 100+80i         | Node 15  |
| DG6   | 200+150i        | Node 28  |

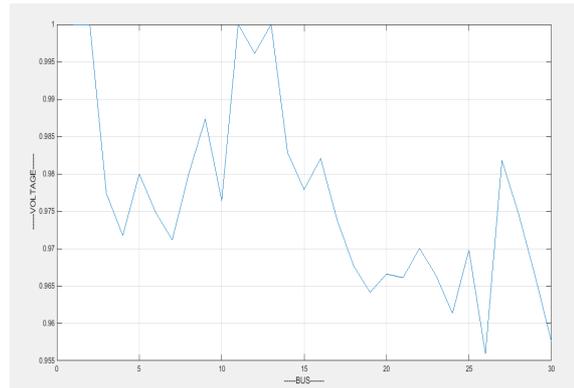


Figure 4: Voltage Profile without DGs

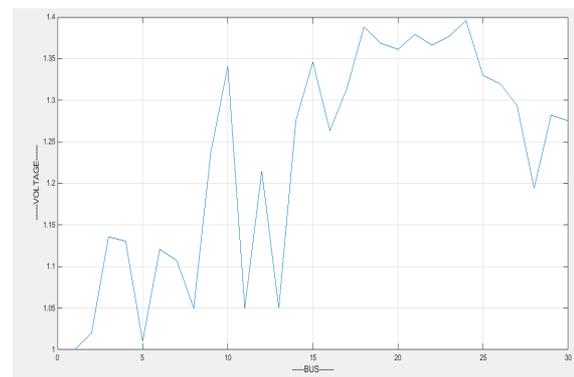


Figure 5: Voltage profile with DG

Fig 4 shows the voltage profile of the system w/o DGs connected. It can be seen that  $V_{max} = 1.00$  p.u and  $V_{min} = 0.95$  p.u. After connecting all 6 DGs to the distribution system the voltage profile of the system can be seen from the Fig 5, which shows  $V_{max} = 1.396$  p.u and  $V_{min} = 1.0$  p.u and % of increase in peak voltage as 39.6%. Table 1 shows the DG's size and location in the system. It can be seen that voltage level exceeds the voltage limit (upper limit is 1.05 p.u, lower voltage limit is 0.95 p.u).

##### 4.2 Methods For Reduction In Voltage Profile And Carrying Out Sensitivity Analysis

###### A) Switch off capacitors

In this method, we are going to switch off all capacitors. We will note its effect on the voltage waveform and note down the peak value of voltage after switching off each capacitor. There will be a considerable drop in the peak value, however it will

still violate the limits set and hence we will go for further methods of reduction.

Table No. 2: Capacity of Capacitors and their respective location in the distribution network

| S.no        | Capacities (MVAR) | Location | Vmax after switching off (pu) |
|-------------|-------------------|----------|-------------------------------|
| Capacitor 1 | 100i              | Node 10  | 1.344                         |
| Capacitor 2 | 50i               | Node 18  | 1.323                         |
| Capacitor 3 | 100i              | Node 21  | 1.254                         |
| Capacitor 4 | 70i               | Node 24  | 1.196                         |

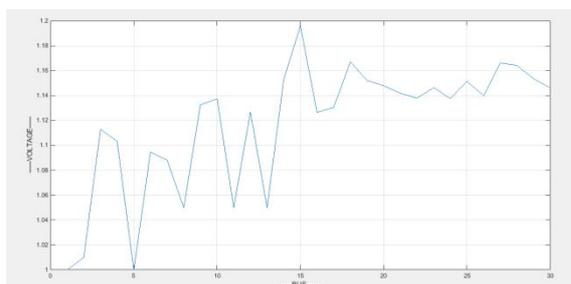


Figure 6: Sensitivity Analysis by switching off capacitors

Net  $\Delta Q$  after switching off capacitors=  
 $100+50+100+70= 320$  MVAR  
 $\Delta V$  max=  $1.396 - 1.196= 0.2$  pu  
 Sensitivity Factor  $\mu= \Delta V/\Delta Q = 6.25 \times 10^{-4}$

Table no 2 shows the capacitors used along with their location and also the Vmax after switching off each capacitor respectively. Fig.6 shows the voltage profile of the system after switching off all the capacitors. It can be seen that the peak voltage of the system is still crossing the upper voltage limit (1.05 p.u), Vmax is 1.196 p.u and sensitivity factor  $\mu=6.25 \times 10^{-4}$

**B) Switching on reactors**

In this method we introduce reactors to the system at different nodes and analyze the voltage waveforms and evaluate the change in reactive power and  $\Delta V$  max to calculate the sensitivity factor.

Table No. 3: Capacity of Reactors and their respective location in the distribution network

| S.no      | Capacities (MVAR) | Location | V max after switching on (pu) |
|-----------|-------------------|----------|-------------------------------|
| Reactor 1 | 67.5i             | Node 15  | 1.161                         |
| Reactor 2 | 33i               | Node 27  | 1.152                         |
| Reactor 3 | 48i               | Node 28  | 1.135                         |

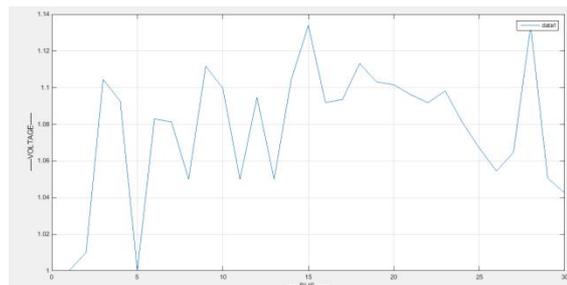


Figure 7: Sensitivity Analysis by Switching on reactors

Net  $\Delta Q= 67.5+33+48=148.5$  MVAR  
 $\Delta V$  max=  $1.196-1.135= 0.061$  pu  
 Sensitivity Factor  $\mu= \Delta V/\Delta Q =4.107 \times 10^{-4}$   
 Fig 7 shows the voltage profile of the system after switching on all the reactors. It can be seen that the voltage level at all nodes are still not within the limits. V max=1.135 p.u and Sensitivity Factor  $\mu= \Delta V/\Delta Q =4.107 \times 10^{-4}$  and V min= 1.0 p.u. Thus voltage profile of the system is still not within the tolerance limit set ( $\pm 5\%$ ).

**C) Reduction in DG reactive powers**

In this method we reduce the reactive power from every node that contains a distributed generator. The amount of reactive power reduced to get feasible results can be obtained from experimental analysis such that the voltage profile ultimately falls within tolerance limits.

Table 4: Reduction in DG capacities

| S.no | Capacity (MVA) | Amount of reactive power reduced $\Delta Q$ (MVAR) |
|------|----------------|--|
| DG1  | 150+100i       | 40i  |
| DG2  | 70+50i         | 30i  |
| DG3  | 100+50i        | 20i  |
| DG4  | 80+50i         | 20i  |
| DG5  | 100+80i        | 50i  |
| DG6  | 200+150i       | 100i   |

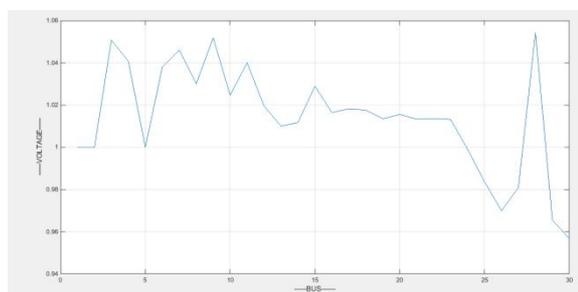


Figure 8: Sensitivity analysis by reduction in DG reactive capacities

Net  $\Delta Q= 40+30+20+20+50+100=260$  MVAR  
 $\Delta V$  max=  $1.135-1.054= 0.081$  pu  
 Sensitivity Factor  $\mu= \Delta V/\Delta Q =3.115 \times 10^{-4}$   
 Figure 8 shows the voltage profile of the system after reducing the capacities of all the DGs to required value. It can be seen that V max= 1.054 pu and V

min= 0.957 pu. Now the voltage profile falls within the tolerance limit ( $\pm 5\%$ ). Sensitivity factor using this method  $\mu = \Delta V / \Delta Q = 3.115 \times 10^{-4}$ .

Table 5: Sensitivity Analysis Chart

| S.no | Method                         | Sensitivity factor     |
|------|--------------------------------|------------------------|
| 1)   | Switching Off capacitor        | $6.25 \times 10^{-4}$  |
| 2)   | Switching on reactors          | $4.107 \times 10^{-4}$ |
| 3)   | Reduction in DG Reactive power | $3.115 \times 10^{-4}$ |

From table no 5, we can validate that for reducing the voltage of the system, the first priority should be to switch off the capacitors (sensitivity factor highest) and the least priority should be reduction in Reactive capacities of DGs (sensitivity factor lowest). These results hold true for the 30 bus system when DG capacities, reactors and capacitors of set values as mentioned before are introduced in the system.

## CONCLUSION

In this paper Voltage control for a 30 bus distribution system with DGs connected has been studied. A comprehensive approach for controlling voltage is taken into account by presenting three different methods: Reducing reactive power, introducing reactors and switching off capacitors. The coordinated voltage control based on sensitivity analysis has been done here.

It has been observed that sensitivity factor is highest in case of switching off of capacitors and lowest in case of reduction in DG reactive powers. Thus a priority based chart for reactive power control has been established from which it can be easily inferred that in case of a sudden increase in voltage while operation with DGs, the first and foremost priority should be switching off the capacitors.

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