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Coordinated Voltage Control using Multiple Regulators in Distribution System with Distributed Generators

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Abstract**—**The continued interest in the use of distributed generation in recent years is leading to the growth in number of distributed generators connected to distribution networks. Steady state voltage rise resulting from the connection of these generators can be a major obstacle to their connection at lower voltage levels. The present electric distribution network is designed to keep the customer voltage within tolerance limit. This may require a reduction in connectable generation capacity, under utilization of appropriate generation sites. Thus distribution network operators need a proper voltage regulation method to allow the significant integration of distributed generation systems to existing network. In this work a voltage rise problem in a typical distribution system has been studied. A method for voltage regulation of distribution system with multiple DG system by coordinated operation distributed generator, capacitor and OLTC has been developed. A sensitivity based analysis has been carried out to determine the priority for individual generators in multiple DG environment. The effectiveness of the developed method has been evaluated under various cases through simulation results.

Keywords**—**Distributed generation, voltage control, and sensitivity factor.

I. Introduction

THE need for energy is never ending. This is certainly true for electrical energy, which is a large part of total global energy consumption. But growing in tandem with energy needs are the concerns about sustainable development and environmental issues, such as the movement to reduce greenhouse gas emissions. The result of fulfilling energy needs and meeting environmental, social concerns is the growing interest in reliable distributed energy sources. Inter connection of these generators to distribution network will offer a number of benefits such as improved reliability, power quality, efficiency, alleviation of system constraints along with the environmental benefits[1,2]. With these benefits and due to the growing momentum towards sustainable energy developments, it is expected that a large number of DG systems will be interconnected to the power system in the coming years [2, 3]. The present scenario of deregulation of the power utilities and the competition in the energy markets are further accelerating the growth in parallel operation of DG systems with the utility [2,3]. In order to achieve these benefits with large penetration of DG source in existing utility network, several technical problems are to be fronted such as degradation of system reliability, power quality problems, potentially damaging over voltages, islanding and various other safety issues[1-5]. Steady state voltage rise problem is reported as one of the main obstacles for interconnection of large amounts of distributed generation units to the existing radial networks [3, 4]. In [3], the results of some generic studies explaining the voltage rise issue and how it may be overcome are presented. Several methods like reducing primary substation voltage and constraining the generator operation are discussed. Distribution networks are designed to keep the customer voltage constant within tolerance limit as dictated by statute and has always been a top priority [5]. The range of voltage which must be met under a number of different standards does not exceed ±10%, with some standards being even tighter than this [3-6]. A simple analytical expression for the voltage profile of distribution system with DG has been presented in [6]. The conventional voltage regulation methods such as online tap changing transformer associated with automatic voltage control (AVC) relay are not going to be effective in presence of a significant number of DG systems [5]. Several methods like network reinforcement and constraining the generator operation to counter the voltage rise are discussed in [3, 4]. These methods are not effective due to many reasons. A new method for determining the introduction limit, when DG unit is introduced into distribution system of which the voltage is generally controlled by LCT (load-tap changing transformer) and LDC (line drop compensation) is presented in [7]. An attempt has been made to design an AVC relay using the artificial neural network (ANN) for voltage regulation purpose in [8]. A novel approach, using consumer load control is discussed for countering steady state voltage rise in distribution system with wind generation plant [9]. Simulation case study has been made to compare this method with the existing methods such as system reinforcement and connection point changes. The disadvantage of this method is installation and use of load control for voltage regulation alone requires a significant capital. Recent developments involving mixed voltage/power factor control have shown that by intelligently controlling the synchronous generators, voltage variations can be mitigated and reinforcement may be avoided [10]. Generators and tap-changing transformers can be used to control the level of voltage throughout a network. The transformers in the network also influence the direction and magnitude of the reactive component of power that flows to the loads [11, 12]. In this paper investigates the coordinated voltage control under various conditions in distribution system. A comprehensive

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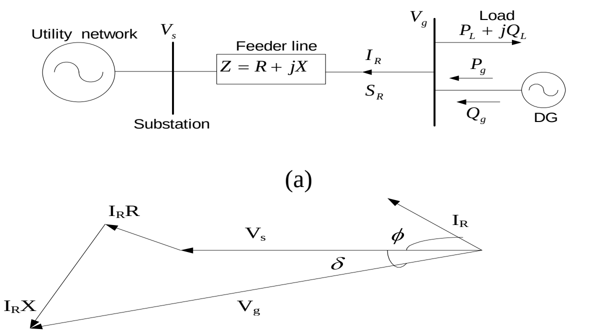
approach to voltage control in a distribution system by taking in to account of number of DG systems and capacitors under various condition has been presented. Besides offering environmental benefits, integration of modular generating units to distribution network may bring other significant benefits such as increased reliability, loss reduction, load management and also the possibility of delaying the adjustment of transmission and distribution networks [1, 4, 5]. In order to achieve these benefits with large penetration of DG source in existing utility network, several technical problems are to be fronted. Some of the technical issues must be considered for successful introduction of DG systems are steady state voltage regulation, increased system fault level, islanding operation, degradation of power quality and reliability, protection and stability of the network [2]. These issues are further complicated by the type of interface used for DG system to interconnect it to the grid [3]. One of the major concern is the rise in steady state voltage level of distribution system.

II. Steady State Voltage Rise

When the generator is connected to the radial feeder, its active power export reduces the power flow from the primary substation. This causes reduction in the voltage drop along the feeder. If the generator's power export is larger than the feeder load, power flows from the generator to the primary substation and this causes a voltage rise along the feeder. Typically, worst case scenarios are: a) no generation and maximum system demand, b) maximum generation and maximum system demand, c) maximum generation and minimum system demand. In the context of voltage rise effect, minimum load and maximum generation conditions are usually critical for the amount of generation that can be connected [4]. However, it may also be necessary to consider maximum load and maximum generation conditions for studying voltage rise problem [5].



(b)

Fig. 1 (a). Utility network with wind DG system (b) phasor diagram

Fig.1 (a) and Fig.1 (b) are illustrates the connection of distributed generator to the distribution network [9]. The active and reactive powers of the generator are P_g and Q_g respectively. P_L and Q_L represent the active and reactive power of the load connected to the distribution system. I_R is the net current through the line impedance, $Z = R + jX$ and S_R is the net power injected to network. The substation voltage and connection point voltage are V_s and V_g respectively.

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

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

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

Considering the phasor diagram in Fig. 1(b)

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

Since the voltage angle δ is very small, the term $(P_R X - Q_R R)/V_g^*$ is also very small and can be neglected. Magnitude of voltage rise ΔV is approximately given by [14]

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

The active power produced by embedded generators increase the voltage, whereas the reactive power can further increase or reduce it depending on the type of DG technology. The synchronous generator can generate or absorb reactive power, but the induction generator only consumes reactive power. These outcomes, in combination with the system's R / X ratio or distribution network characteristics and load profiles, determine whether the voltage level at the connection point is increasing by increasing the power production of DG or not. In general for a radial system the voltage level decreases along the feeder, from supply end to the end of the feeder

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

In [6], the results of some generic studies explaining the voltage rise issue and how it may be overcome are presented. Several methods like reducing primary substation voltage and constraining the generator operation are discussed. Distribution networks are designed to keep the customer voltage constant within tolerance limit as dictated by statute and has always been a top priority. The range of voltage which must be met under a number of different standards does not exceed ±10%, with some standards being even tighter than this [7].

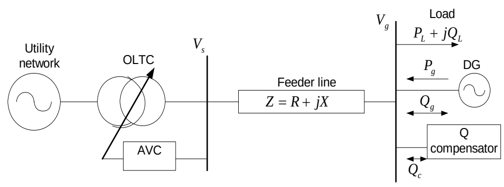


Fig. 2 A simple system illustrating the options for voltage regulation

A distributed generator, DG (P_g , Q_g) together with a local load (P_L , Q_L) and a reactive compensator (Q_C)are connected to the distribution system through a distribution feeder with impedance Z and an on-load tap changer (OLTC) transformer. In Fig. 2, the rotating machine based DG system is shown. Similarly in case of power electronic interfaced DG systems, the interfacing circuit can be used as a facility to control.

III. Voltage Sensitive Analysis

Sensitivity analysis is the measures of the impact of changes in the system parameters on system performance. In connection with power system engineering, sensitivity analysis is used to predict the changes in losses, bus voltages, and branch flows due to changes in loads and generations. There are numerous examples in power systems in which sensitivity analysis has been used. In many reactive power injection problems, real power loss sensitivity with respect to (w.r.t.) reactive power injection has been used to identify the candidate locations for the capacitor placement [15].The sensitivity analysis is one of the criteria for selecting the candidate buses for their allocation as it reduces the size of search space, thereby saving the computational time to reach an optimal solution [16]. The sensitivity method is researched in this paper to find reasonable voltage support locations. The sensitivity analysis is for the reactive power outputs of the generators to the voltages on the load buses. The analysis is on three factors, the extent, the value and the sign of the sensitivity.

The power flow equations are:

$$P_i = V_i \sum_{j=1}^{n} Vj(G_{ij} \cos\delta_{ij} + Bij \sin\delta_{ij}$$

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

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 Qg, the total derivative is: $\frac{\partial F}{\partial V_L}\frac{\partial V_L}{dQg} + \frac{\partial F}{\partial Q_G} = 0$

Thenthesensitivity dV_L / dQ_{gi} is

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

In real power flow calculations, the sensitivity can be replaced by the difference signal $\Delta V_{Li} / \Delta Q_{gi}$ the reactive power output of one generator is known, and then the voltages of load buses can be obtained by power flow calculations. 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. Coordinated Voltage Control Simulation and Results

Fig. 3 shows the 69 bus radial system considered for study. The substation voltage is 12.66 kV. The LTC for the substation transformer is assumed to adjust the secondary voltage to 1.0 pu at all time. Note that total peak load of the radial network is 2.0MW 0.970MVAR.Load data and system data are taken from [11].The bus bar voltages of this system in per unit are derived from (6).

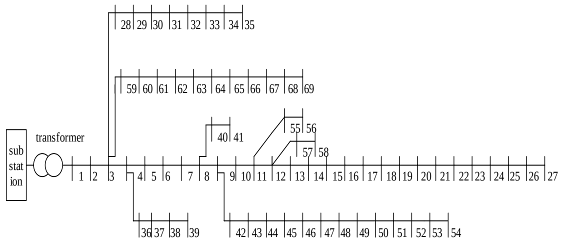


Fig. 3 Radial distribution feeder with 69 buses

A. *Voltage Profiles for 69 Bus Radial Distributed System with & Without Dg Connected& Voltage Control with Dgs, Capacitor& Oltc for Different Load Condition*

When a DG of capacity 2.0MW & 0.970 MVAR are connected at 49, 50, 61, & 64 nodes of the 69 radial feeder, voltage profiles of the system at full load can be seen in the fig.4-6. It can be seen that voltage profile at 65th bus is exceeding the upper limit 1.05.p.u.but at nodes 6 to 26 voltage profile is increased compare to voltage profiles without DGs connected at different loads considered, it can be seen in the fig.4 and it is within the voltage limits (1.05-0.95.p.u). The reactive powers of the DGs can be varied to mitigate the voltage rise.

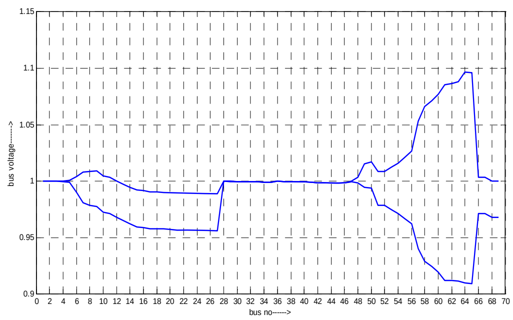


Fig.4 voltage profile for full load with &without DGs connected.

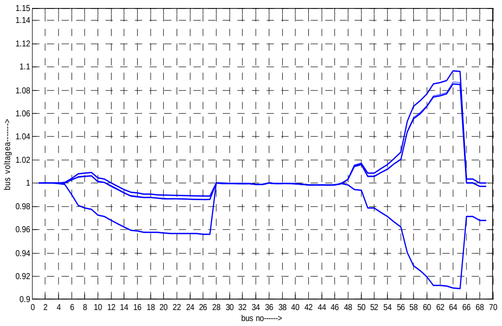


Fig.5 voltage profile for full load with &without DGs connected &voltage control by DGs & Capacitor.

The figures 4-9 showed that the voltage rise in the 65th node at different loading conditions, when 4 DGS are connected. The voltage sensitivity analysis has been done to give the priority among 4 DGs. The analysis helps us to identify which DGs reactive power can be varied to mitigate the voltage rise. The DG when connected provides a highest sensitivity index that DG can be select to control its reactive power.

From the voltage sensitivity factor analysis the highest in 61 bus generator compare to 49, 50 & 64th bus generator, therefore we should select the 61 bus generator first to decrease its reactive power to control rise in voltage from Q_{max} to Q_{min}. It is more effective in achieving the voltage control compared to other bus generators.

Fig.4-9 shows the voltage profiles for 69 bus test feeder without & with voltage control by varying DGs reactive powers from Q_{max} to $Q_{min.}$ The voltage sensitivity analysis showed that the generator connected at 61 bus is having highest sensitivity index, So the reactive power of the 61 bus generator was varied to Q_{min} .With this reactive power change only small reduction in peak voltage can be seen. So, the next generator in the sorted list based on sensitivity index was selected which is the 49, 50, &64 bus generators and again the reactive power was varied from Q_{max} to Q_{min}. It was seen that voltage rise is mitigated in small amount, but still the voltage profile is above the voltage limit at all loads as shown in the figs.

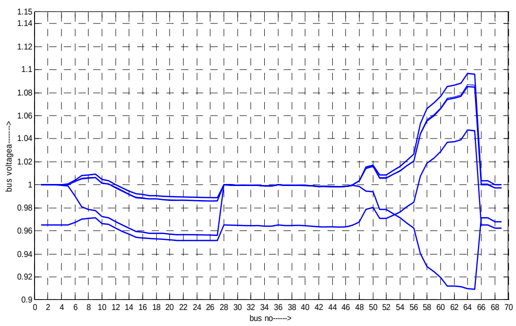


Fig.6 voltage profile for full load with &without DGs connected & voltage control by DGs, Capacitor, and Oltc

Figs.4-6 has shown the voltage profile of the 69 bus system for full load after decreasing the reactive powers of the 4 DGs to Q_{min} connected at 61, 49, 50&64 buses respectively. Still voltage peak is crossing the upper voltage limit of the system, now capacitor which is connected at 59 th bus of capacity 1000kVAR is switched off, even though the peak voltage is still crossing the voltage limit as shown in the fig from 4 to 9.Then controlling OLTC tap setting at the substation we can mitigate the rise in voltage that can be seen in the figs shown above. After OLTC tap setting variation voltage profiles of the system at all loads come down and they are within limits. We should note that OLTC tap setting limits should not cross ± 10%.Fig 7-9 has shown that voltage profile of the 69 bus system for 90% load, it can be seen that after connected 4 DGs to the 49,50,61 & 64th bus voltage profile at 65th bus has crossed the voltage limit.

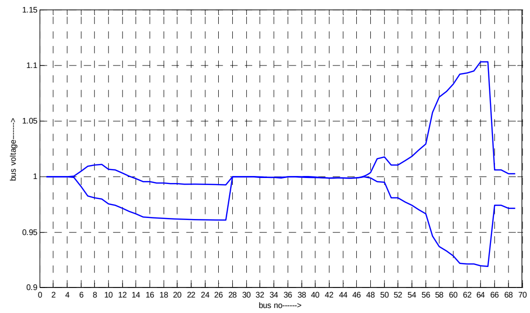


Fig.7 voltage profile for 90% load with &without DGs connected.

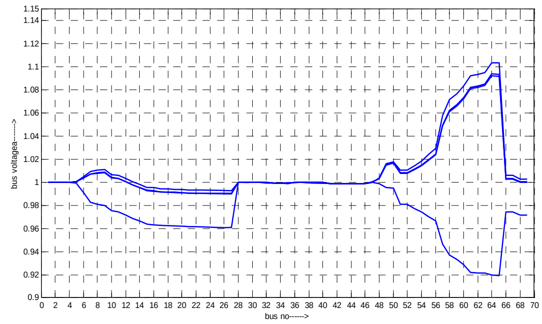


Fig.8: voltage profile for 90% load with &without DGs connected, &voltage control by DGs& Capacitor.

Even after reducing the reactive powers of all 4 generators to Qmin voltage profile still crossing the limit & even after switching off the capacitor connected at 59th bus, it can be seen in the fig.8.

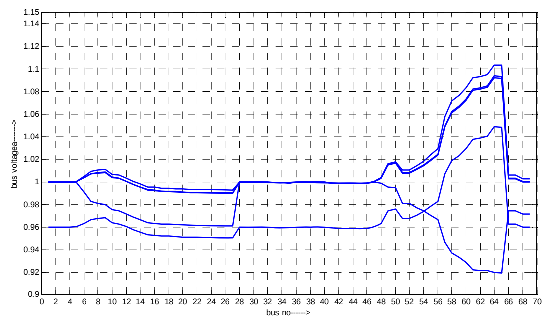


Fig.. 9 voltage profile for 90% load with &without DGs connected & voltage control by DGs, Capacitor, and Oltc

Figure 9 shows that the voltage profile of the 69 bus system without & with voltage control using reactive power of the DGs, switching off the capacitor & by oltc tap changing. it can be seen that voltage profile is within the limit after oltc has changed its tap position to 0.960.

The coordinated voltage control is done based on the voltage sensitivity analysis with two DGs. DG's improve the voltage profile and support the voltage regulation. Distribution generation affects the voltage level of the system through the connection point due to their power injection. With reduced DG reactive power, switching off the capacitor and OLTC tap settings, voltage profile of the feeder can be improved without disturbing the consumer.

V.CONCLUSION

Coordinated voltage control analysis of distribution network with the integration of distributed generation is presented in this paper. This paper presented a coordinated voltage control at different load conditions in distribution system with DG. A comprehensive approach to voltage control in a distribution system by taking in to account a number of DG systems and OLTC at different load has been presented.

The coordinated voltage and reactive power control based on voltage sensitivity analysis in the presence of Distributed Generation has been done here. It has been seen that the presence of DG affects the rise of under voltage/over voltage and also the DGs presence will not interfere with the effectiveness of the OLTC operation. The coordinated voltage control has been done by controlling reactive power of the DGs & OLTC tap setting operation to mitigate the risk of under voltage/over voltage & to maintain the distributed feeder voltage within the permissible limits base on voltage sensitivity analysis to give priority in reactive power control among four generators. Further, by involving DGs active power control also, we can control the rise in voltage in the system effectively for reduced load.

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