Reactive Power Control for Voltage Regulation in the Presence of Massive Pervasion of Distributed Generators

Haleema Qamar, Hafsa Qamar, Alfredo Vaccaro
Department of Engineering
University of Sannio
Benevento, Italy
halimaqamar@gmail.com, hafsaqamar02@gmail.com,
vaccaro@unisannio.it

Nisar Ahmed
Faculty of Electrical Engineering
GIK Institute of Engineering Sciences and Technology
Topi, Pakistan
nisarahmed@giki.edu.pk

Abstract—**The high penetration of distributed generators in the conventional grid causes voltage rise in the network. In this paper, reactive power control with various control topologies has been used for voltage regulation in gird-connected photovoltaic system. Reactive power control using PV inverters is effective only if inverter's apparent power ratings are taken into account. This paper demonstrates that during peak hours, real power generation is maximum and so is the voltage rise at point of common coupling but the ability of inverters to provide the required reactive power is diminished due to apparent power capability of inverter. So some other source of reactive power along with PV inverters should be used during peak times to bring the voltage back into the statuary limits. This solution turns out to be cost effective as well as very simple to implement.**

Keywords— Grid-connected PV System; reactive power control; Distributed Generators (DGs); Fuzzy Logic Control (FLC); peak hours; inverter rating.

I. INTRODUCTION

Most of the electric power networks are radial in nature that are designed for passive loads. But due to the profound penetration of Distributed Generators (DGs), the traditional passivity hypothesis does not remain valid anymore as there are active elements in the form of distributed generators connected to the grid now [1]. This causes sudden voltage rise at the point of common coupling (PCC). During critical grid conditions, voltage rise can be drastic and may exceed the statuary limits that are typically ±5% of the nominal voltage (or between 0.95pu to 1.05pu) [2]. When peak generation hours of PV coincide with low load conditions, voltage at PCC increases drastically. This is the most critical time for voltage rise and very careful control is required to bring the voltage back to the nominal value for proper operation of the network [3, 4]. Sensitivity of PCC voltage depends on network impedance seen by PV system [5]. PCC voltage is very sensitive to the active and reactive power of the distributed generators because for low voltage network the typical values of transmission line resistance-to-reactance, R/X, ratios are greater than one [6, 7]. For a simple 2-bus radial network (as shown in Fig. 1) with voltages U_1 and U_2 at bus 1 and 2 respectively, line resistance R, line reactance X, active power P_1 and reactive power Q_1 flow from bus 1 to 2, voltage drop ΔU is given as follows [8].

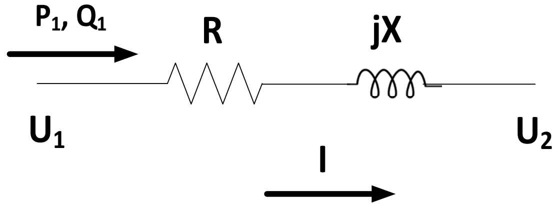

Fig. 1 Model of two bus radial network

$$U_1 - U_2 \cong \frac{RP_1 + XQ_1}{U_1} \quad (1)$$

But due to active power injection by the DGs, it is quite possible that the sign of U_1-U_2 is reversed and now there is voltage rise, instead of voltage drop [9]. Due to bidirectional power flow, more sophisticated strategies are required for voltage regulation in the distribution network [10, 11]. Integration of DGs effects the voltage profile, power losses and stability of the power network [12-14]. This calls for some control mechanism that is able to sense the voltage and apply the remedial measures to bring voltage as close to the nominal voltage as possible. Some ancillary services can be obtained from PV system by controlling the inverters. Voltage regulation is one of the most predominant ancillary services required from PV inverters[15, 16]. Various researchers have worked on this aspect [17-21]. The traditional methods of voltage regulation include the use of On Load Tap changer (OLTC), Switched capacitors (SC) and Step Voltage Regulator (SVR) as suggested in detail in [22]. But voltage variation of renewable power source is so rapid that traditional devices are not able to take the correction action at that pace. The very nature of renewable power sources i.e. their uncertainty limits the use of traditional devices for voltage regulation. Some of the advanced techniques for voltage regulation have been demonstrated in [9, 18, 22-25]. In [26], it has been shown that voltage rise is dependent on voltage unbalance in the network. Compensating the voltage unbalance by suppression of negative sequence currents helps in reducing

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the overvoltage at PCC. In [27], voltage unbalance is reduced by using controllable Energy Storage Unit (ESU). In both these techniques, the control becomes quite intricate and some other control technique has to be coupled with them for achieving promising results. In [5], active power curtailment has been suggested for voltage rise mitigation. But this approach is irrational as it suggests cutting off the renewable power source temporarily. [28] suggests the use of storage device which absorbs the power when PCC voltage rises and vice versa. This technique is not suitable because of the maintenance required by the energy storage devices (batteries). Inverter based technologies belong to an emerging class of user-end reactive power control. These technologies although not widely deployed at the moment, but show enough promise to be used in the near future. Reactive power control is based on injection/absorption of reactive power by the PV inverters based on voltage rise/fall at PCC [29]. Reactive power control is feasible to use for voltage regulation because of its scalability, efficiency, flexibility and reliability [21]. Reactive power control can be adapted as per the requirements of accuracy and the available budget. For example, local, global and decentralized control are three basic topologies of reactive power control. Local control is very simple to implement because it does not demand complex communication system but does not give accurate results as decision is only based on the local data, ignoring the state of the system [30]. Global control gives precise results but it is very demanding when it comes to cost and computing efforts required. It requires extensive communication network that transfers data to fusion center where all decisions are made [31]. A good compromise between these two above stated topologies is the decentralized control. Decentralized control assesses the global variables with only limited communication. Its performance is far better than the local control and it approaches the performance of global control [32]. Based on these observations, we have used reactive power control for voltage regulation in this study. We have obtained simulation results for all three above stated topologies.

II. PROBLEM FORMULATION

Since we are using reactive power control for voltage regulation in grid connected photovoltaic system, the analysis of apparent power capability of inverter is necessary as inverter provides the required reactive power at point of common coupling (PCC) between grid and photovoltaic source. A traditional Fuzzy Logic Control (FLC) [33] is deployed in our system for voltage regulation. The FLC operates in such a way that when voltage at PCC is high, inverter injects large amount of reactive power to mitigate voltage rise and when voltage is low, inverter absorbs reactive power to bring back PCC voltage to nominal value. Thus in FLC, the amount of reactive power produced by the inverter is decided by the voltage at PCC. But in actual case, inverter cannot produce as much reactive power as proposed by the FLC because it is limited by the apparent power capability of the inverter [21]. The limit on apparent power of the inverter impediments the effective voltage regulation at PCC. This limit on apparent power of the inverter is given by [34-35]

$$|q^{(g)}| \leq \sqrt{s^2 - (p^{(g)})^2} \qquad (2)$$

$$-\sqrt{s^2 - (p^{(g)})^2} \leq q^{(g)} \leq \sqrt{s^2 - (p^{(g)})^2} \qquad (3)$$

where $q^{(g)}$ is the reactive power generated by the inverter, $p^{(g)}$ is the output of PV source and s is the apparent power of the inverter. From the above equations, it is clear that reactive power generated by the inverter is limited by the apparent power of the inverter and active power of PV source.

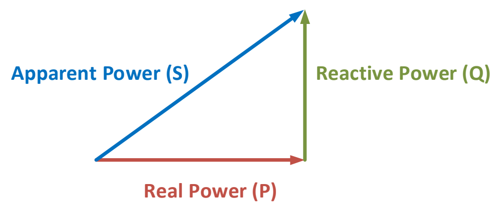

Fig. 2 Power Triangle

Fig. 2 is the representation of the equation

$$S = P + jQ \qquad (4)$$

where S is the apparent power, P is the real power and Q is the reactive power generated by the inverter. The apparent power S of the inverter is a fixed quantity that depends on the rating of inverter. The real power P depends on the solar irradiance i.e. high solar irradiance tends to increase P and vice versa. The reactive power Q is limited by S and P in such a way that when P increases, Q has to decrease to keep S constant. Thus, when solar irradiance is high, photovoltaic produces more power due to which voltage at PCC increases but inverter cannot provide enough Q to effectively mitigate voltage rise at PCC. From the above discussion it is evident that at times of maximum PV penetration and minimum load demand, inverter cannot produce enough reactive power for effective voltage regulation due to its dependence on other factors. This calls for a system that contains some additional source of reactive power generation when PV penetration is maximum or load is minimum. In the following section, we will show the reactive power produced by the inverter in grid connected PV system for various control techniques and then propose a system which can effectively regulate voltage at PCC even at maximum PV pervasion.

III. SIMULATIONS

We have implemented a nine bus grid connected PV system with fuzzy logic reactive power control for voltage regulation at PCC. We have executed various control paradigms (local, global and decentralized) in FLC to observe the reactive power injected by the inverters and voltages at PCC. The block diagram of Simulink model of the implemented system is given as follows:

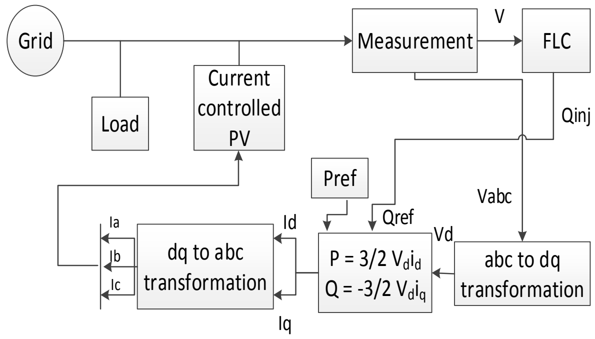

Fig. 3 Block diagram of Simulink Model

The above figure shows the block diagram of grid connected PV system for one bus only for the sake of understanding. In our nine bus system, the same hierarchy is repeated on all nine buses. The system under consideration has PV pervasion as well as dynamic loads on all nine buses. Three phase voltage source with line to line voltage of 380V rms is used as grid. The interconnection of grid, load and PV source at one point makes the point of common coupling (PCC). Three phase current controlled current sources are used to model PV sources and inverters collectively. The measurement block measures the three phase voltage V_{abc} at PCC and supplies to FLC as well as abc to dq transformation block where V_{abc} is converted to V_d and V_q. The output of FLC is the reactive power Q_{inj} which is set as the reference reactive power Q_{ref}. A pre-defined generation profile is set as reference active power P_{ref}. Following equations are then implemented to obtain i_d and i_q.

$$P = \frac{3}{2} V_d i_d \quad (4)$$

$$Q = -\frac{3}{2} V_d i_q \quad (5)$$

i_d and i_q are fed to dq to abc transformation block to produce i_a, i_b and i_c. These currents are fed to current controlled PV sources. To demonstrate the effect of maximum PV pervasion and minimum load demand on reactive power injection, we have assigned specific generation and load profiles. The entire load and generation profiles throughout a day are spread in 60 seconds in our system as shown below.

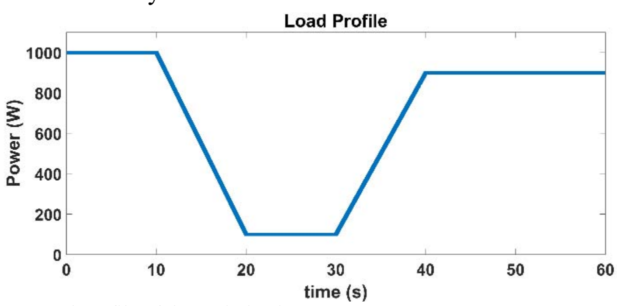

Fig. 4 Load profile of dynamic loads

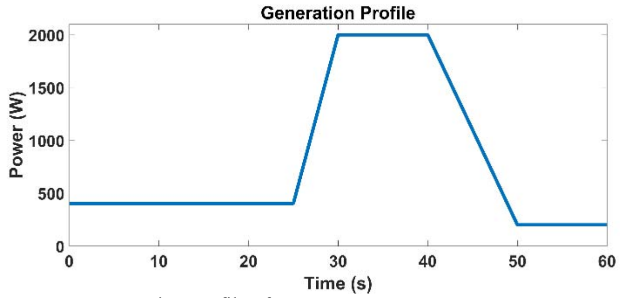

Fig. 5 Power generation profile of PV sources

The above stated system is simulated for various reactive power control techniques based on local, global and decentralized fuzzy logic. The results of reactive power injected by PV inverters for all three cases are obtained as follows. The reactive power injected by PV inverters at all nine buses for local, global and decentralized reactive power control are shown in Fig. 6,7 and 8 respectively.

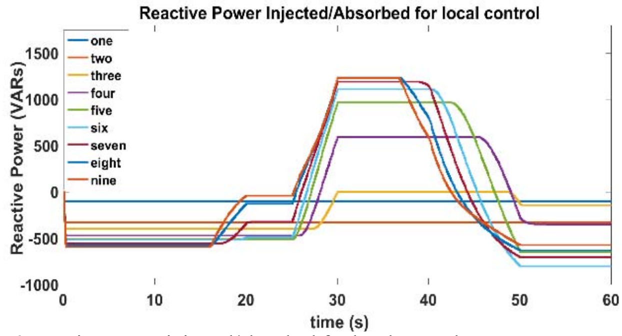

Fig. 6 Reactive power injected/absorbed for local control

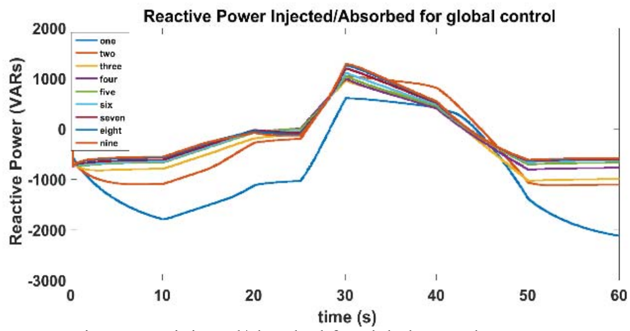

Fig. 7 Reactive power injected/absorbed for global control

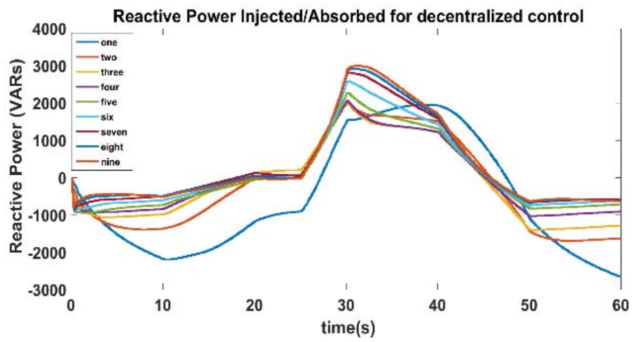

Fig. 8 Reactive power injected/absorbed for decentralized control

The above figures show that the amount of reactive power injected by the PV inverters for all control techniques reaches the peak values from 25 to 40 seconds. The load and generation profiles (Figs. 4 and 5 respectively) show that this time duration signifies maximum PV pervasion and minimum load demand. Voltage at PCC rises when PV penetration is highest and load demand is lowest due to which massive amount of reactive power is injected by PV inverters to mitigate this voltage rise. This massive reactive power injection during the time of highest PV penetration and lowest load demand is shown in the above figures but in actual case scenario, this is not possible. The amount of reactive power injected by PV inverter is limited by apparent power capability of inverter. This limit on the reactive power produced by the inverter causes hindrance in effective voltage regulation. Thus, some other source of reactive power like Static Var Compensator (SVC), capacitor banks, FACTS should be included in the system to provide reactive power specifically at time of maximum PV pervasion and minimum load demand.

IV. RESULTS

We have obtained average voltages of the network for all three control strategies shown in Fig. 9. It clearly shows that during peak time of 25 to 40 seconds when PV generation is maximum and load is minimum, average voltages are quite high, especially for local control. Fig. 10 depicts that during this peak time, maximum reactive power is injected to mitigate the voltage rise. But in actual case scenario, this is the time when apparent power rating of the inverter limits the amount of reactive power injected. During this peak time, real power generation P is maximum which limits the reactive power injection Q according to the equation (4). Hence proved that some other source of reactive power along with inverters is required during peak time only for effective voltage regulation. This work can be extended by simulating a system that comprises of another reactive power source along with PV inverters which operates only during peak hours to mitigate the voltage rise at PCC. The simulations should be capable of showing that the additional reactive power source (capacitor banks) is triggered only during the peak hours in order to provide supplementary reactive power.

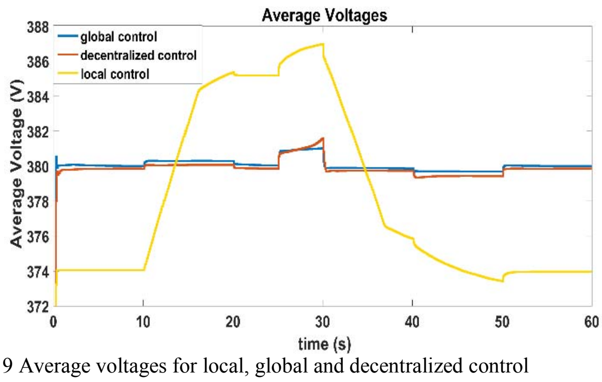

Fig. 9 Average voltages for local, global and decentralized control

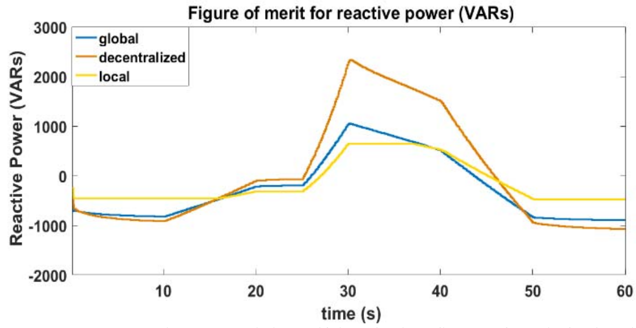

Fig. 10 Average reactive power injected/absorbed as figure of merit for local, global and decentralized control

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