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***Abstract*—Increasing penetration of distributed energy sources in distribution grids also introduces certain challenges, including regulation of voltages in the distribution system, particularly voltage rise issues in cases of low load and high generation. This paper proposes a methodology to achieve cooperation between the inverters that interface the DG units to the grid, so that the voltages across all the nodes of the distribution system maintain an acceptable profile. Each node in the distribution system acts as an agent, measuring its deviation from nominal voltage. Subsequently, all the nodes engage in a multi-agent consensus algorithm, to share their measurements. The algorithm is decentralized, and each node needs to communicate exclusively wih its neighboring nodes. Utilizing the feedback of the observed total deviation of all the nodes from their desired voltage, each inverter adjusts its local reactive power injection, through a local PI controller. Control design of the local reactive power controller is also discussed in this work. Simulation results for the IEEE 123-node test feeder verify that the approach results in significantly improved voltage profile compared to the unity power factor control and it addresses the issue of voltage rise in the distribution grid by utilizing each unit's reactive power margin.**

***Index Terms*—Power Distribution, Multi-agent systems, Reactive Power Control, Voltage Control, Distributed Generation.**

I. INTRODUCTION

As an increasing capacity of customer-owned distributed generation (DG) is connected to the distribution network (DN), it is expected to operate in conditions far from the current operating norm. As an example, DG penetration is capable of causing voltage control issues in the distribution grid [1], particularly voltage rise in low load periods [2]. However, projections regarding the future grid suggest an increase in the penetration of DG [3]. In the case of microgrids, which have become a major topic of research, operation of a grid exclusively with DG units is examined [4]. Thus, it is important to address the issue of DN voltage control in the presence of DG, which is a challenging issue, given that: i) DG's are geographically dispersed and operate autonomously ii) DN voltage is strongly coupled to both active and reactive flows in the network [5].

The current industry practice for maintaining a healthy voltage profile in the distribution grid involves Load Tap Changers (LTC's), Distribution Voltage Regulators (DVR's) and switched capacitor banks [6]. These devices, although effective, are not necessarily adequate to address the severe voltage issues that can be caused by DG penetration. In order to avoid the cost of installing new voltage control devices in the DN, it is possible to control the DG inverters in order to facilitate voltage control. Given their margin for reactive power compensation and their fast control capabilities, DG inverters have the potential to alleviate the voltage control problem [7],[8].

This paper presents a methodology for voltage control, by enforcing decentralized coordination among inverters using message exchanges between neighboring nodes in the DN. In the literature, a wide variety of methods has been proposed to address the problem. A centralized methodology to coordinate voltage controlling devices using genetic algorithms is proposed in [9]. Such approaches offer reliable voltage control but require communication of all devices with a central Distribution Network Operator (DNO). In the case of DG's, the number of connected units may make this an economically unbearable approach.

Various auhors proposed decentralized control to avoid this problem. In [10] and [11] DG inverters monitor their local voltage and adjust their reactive power in cases of suppressed or high voltages. A different methodology based on adjusting each unit's power injection to avoid causing overvoltages is discussed in [12].

The decentralized voltage control approaches discussed above do not enforce cooperation between DG units, and, given that voltage phenomena can be localized, they do not achieve full utilization of the voltage control potential of DG's. Multi-agent consensus theory [13], [14] has been proposed to achieve decentralized coordination in distributed systems. In the power systems area, [16] discusses a secondary voltage control scheme using MAS theory, but focuses on transmission systems. A reactive power dispatch scheme based on a distributed solution of an optimization problem is discussed in [17]. In [18],[19] and [20] the authors introduce a methodology whereby each node in the DN can make a request of reactive power when it observes high or low voltage at its terminals. The request is shared using consensus algorithms.

This paper proposes a different MAS methodology for voltage control in a DN. Each node observes the deviation of its local voltage from the nominal value and initializes its voltage deviation state. Then, all nodes engage in a consensus iterative message passing algorithm, that converges to the Average Voltage Deviation (AVD) in the DN. Subsequently,

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the average deviation estimate is locally used by each DG inverter to adjust its total reactive power injection, using a local PI controller that has been appropriately tuned. Hence, all inverters jointly participate in voltage control of the DN. The proposed approach only requires distributed communications between neighboring nodes, and it assumes no centralized DNO. This paper also discusses tuning of the local reactive power controllers. The approach is verified using numerical experiments in a standard IEEE test feeder.

The remaining of the paper is organized as follows. Section II discusses the iterative consensus algorithm that allows each node to converge to the total voltage deviation in the DN. Section III presents the local control architecture that allows each DG inverter to provide voltage control to the DN using the total voltage deviation calculated by the consensus algorithm. Section IV briefly discusses design of the local PI controller for voltage support. Section V presents results from numerical experiments in the IEEE 123-node test feeder and Section VI offers concluding remarks and directions of future research.

II. Decentralized Consensus on Total Voltage Deviation

The voltage control approach introduced in this paper proposes that all the inverters jointly control the average voltage deviation from the nominal value across all nodes in the network. However, that information is not locally available at each inverter. At each node in the DN only the local voltage can be measured. We propose that all the nodes in the DN engage in an iterative consensus algorithm, by exchanging message exchanges exclusively with neighbors, in order to converge to the Average Voltage Deviation. Suppose a DN with N nodes and K DG's interfaced with inverters synchronized with Phase Lock Loop (PLL). Not all nodes necessarily have DG's connected to them, but all nodes participate in the consensus algorithm. Let $\mathcal{V}$ denote all the nodes in the DN. Initially, each node measures its local voltage magnitude and calculates the local deviation from nominal value and initializes its δV state:

$$\delta V_i[0] = V_i - V_i^N \tag{1}$$

Subsequently, each node transmits its δV state to its neighbors, receives their own states and updates its state at the next step. If $\mathcal{N}_i$ denotes the set of neighbors of i, i.e. the set of distribution nodes that can exchange data with i, this update is:

$$\delta V_i[k+1] = a_{ii}\delta V_i[k] + \sum_{j\in\mathcal{N}_i} a_{ij}\delta V_j[k] \tag{2}$$

Constants a_{ij} in (2) are chosen as positive and summing up to 1. It is common in the literature [13], [18] to choose them as:

$$a_{ij} = \begin{cases} \frac{1}{1+D_i} & if\, j \in \mathcal{N}_i \\ 0 & otherwise \end{cases} \tag{3}$$

In this work, a_{ij} is chosen as in (3). Under the assumption that the communications graph of the DN is connected (i.e. there exists a communications path between any two nodes in the network) under the iteration in (2) the state of each node converges to the average of the initial states of all the nodes in the network [13]. Hence, given the initialization in (1), the states of each node i in the DN converges as:

$$\lim_{k\to\infty} \delta V_i[k] = \frac{\sum\limits_{i\in\mathcal{V}} \delta V_i[0]}{N} = \frac{\sum\limits_{i\in\mathcal{V}} V_i - V_i^N}{N} \tag{4}$$

As indicated by (4), the state of all nodes converges to the AVD from its nominal value across the entire network. This paper proposes controlling this quantity, instead of the terminal voltage of each converter, via the inverter's reactive power injection.

Because this consensus protocol will be coupled with the local controllers of the DG inverters, the time constant T_c of the convergence of the consensus control needs to be specified. According to [13], the asymptotic consensus is reached with speed that is faster or equal to the second largest eigenvalue of A, denoted as $\lambda_2(A)$. A is the matrix with elements a_{ij}. Hence, the time constant T_c is given as:

$$T_c = \frac{\Delta T}{\lambda_2(A)} \tag{5}$$

Where ΔT is the time delay between two iterations of the form of 2, i.e. the time needed in order for each node to receive data, update its state and transmit data.

III. Local Reactive Power Control in a DG unit

The decentralized consensus algorithm discussed in Section II allows all nodes in the DN to continuously update their estimate regarding the AVD from the nominal (or desired) value. If DG units are connected to a certain node, they can use this estimate to adjust their reactive power injection in order to regulate the AVD to zero. Even though regulation of that quantity to zero does not in itself guarantee a good voltage profile of the network, with proper tuning of the controllers the proposed methodology perfoms excellent control of voltages in the DN.

Fig. 1 shows a typical distribution connected DC/AC converter used to interface a DG to the distribution grid. Three phase inverters are discussed in this work, but this approach can be extended to single phase inverters of lower power ratings. The inverter uses a Phase Lock Loop (PLL) [21] to estimate the frequency of the distribution grid voltage and to orient its rotating dq reference frame to the distribution voltage rotating vector.

The proposed approach is to make the inverter responsive to voltage deviations in the network by making it regulate the AVD through an integral controller by adjusting it reactive power reference q^*. Subsequently, the inverter controls its reactive power injection to match q^* using the dq voltage and current quantities. As is common practice in voltage oriented control, the PLL adjusts the angle of the reference frame so that v_q is zero, which is why the instantaneous reactive power is given by:

$$q = \frac{3}{2} V_d I_q \tag{6}$$

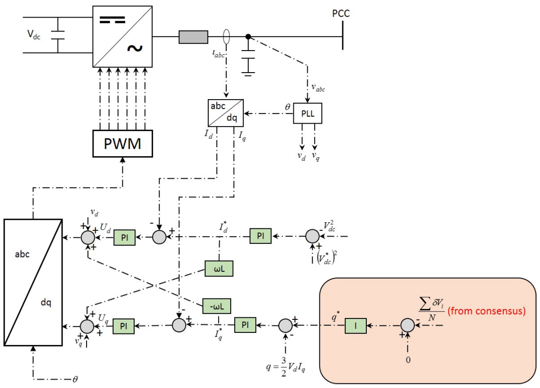

Fig. 1. PLL synchronized inverter with an additional control of average voltage deviation

The control hierarchy and design of the DC/AC converter is otherwise left unchanged, as shown in Fig. 1. The choice of an integral controller has been made because this work is not focused on making the inverters responsive to fast transient voltage phenomena in the DN. Rather, this approach is aimed at improving the daily voltage profile of the DN in heavily loaded feeders or feeders with high DG penetration. This is going to be reflected in the control design. If response to transient undervoltages of a fast time scale is needed, then more sophisticated control structures should be examined.

IV. Control Design

As mentioned above, the local I controllers in each DG inverter must be designed in order to get the required performance of the voltage control for the entire distribution grid. All that is required is to tune the individual I controllers for each inverter so that the DN voltage control has the desired time constant T_v. This time must be i) adequately slower than the time constant of the convergence of the consensus protocol outlined in Section II ii) slower than the time constant of the local reactive power controller shown in Fig. 1. The first specification requires that the voltage controller updates the reactive power reference of each inverter slower than the time needed for convergence of the consensus algorithm to the AVD. This ensures that the reactive power controllers will largely ignore the transient response of the consensus algorithm and operate based on the correct AVD value. The second specification ensures that the converter will not update the reactive power reference faster than the reactive power control capabilities of the inverter. This time scale separation is standard practice in cascaded control design for power electronics converters.

The time constant for the consensus algorithm is given by (5). The time constant for reactive power control is typically 0.01 0.1 s and is typically much faster than the time needed for convergence of the consensus algorithm for a relatively large network. Hence, the design will be based on making T_V sufficiently slower than T_c. In this paper we choose:

$$T_v = a * T_c \tag{7}$$

where a = 5-10.

Design of the local voltage deviation controllers to get the desired time constant of voltage deviation control for the entire DN is not an easy task, because the dependence between voltage magnitude and reactive power injection in a power grid is nonlinear, due to the nonlinearity of the power flow equations. A feasible design approach is to linearize the power flow equations around a certain operating point, obtain a linear expression between voltage and reactive power based on sensitivity matrices, and design the controllers based on that linear system. This will not guarantee the desired performance in all operating points, but it is a sufficiently good initial approach, as verified in the results section. Let the power flow equations in a distribution network be given by:

$$P_G - P_L = f_P(V, \theta) \tag{8a}$$

$$Q_G - Q_L = f_Q(V, \theta) \tag{8b}$$

Linearizing around an operating point and assuming only reactive power generation varies:

$$\begin{bmatrix} 0 \\ \Delta Q_G \end{bmatrix} = \begin{bmatrix} \left.\frac{\partial f_P}{\partial V}\right|_{x_0} & \left.\frac{\partial f_P}{\partial \theta}\right|_{x_0} \\ \left.\frac{\partial f_Q}{\partial V}\right|_{x_0} & \left.\frac{\partial f_q}{\partial \theta}\right|_{x_0} \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} \tag{9}$$

By eliminating active power equations, the following linearized reactive power voltage equation is obtained:

$$\Delta V = (C - DB^{-1}A)^{-1} \Delta Q_G = S \Delta Q_G \tag{10}$$

This equation holds close to the operating point we linearized around. Given that $Q_{G,i}$ tracks q_i^* infinitely fast enough and that the consensus protocol converges much faster than the local I controller acts, the linearized expression that links the AVD in the DN with the local I control actions is:

$$\frac{d\frac{(\Delta v)}{N}}{dt} = -\frac{1}{N} \sum_{i=0}^{K} \sum_{j=0}^{N} s_{ij} K_{Ii} (\frac{\Delta V}{N}) \tag{11}$$

where K_{Ii} is the integral controller gain for the voltage deviation controller of inverter i. The time constant for this system is:

$$\tau_v = \frac{N}{\sum_{i=0}^{K} \sum_{j=0}^{N} s_{ij} K_{Ii}} \tag{12}$$

By equating the time constant with the desired time constant in (7) that results from the system specifications we obtain:

$$\sum_{i=0}^{K} \sum_{j=0}^{N} s_{ij} K_{Ii} = \frac{N}{a \times T_c} \tag{13}$$

This does not uniquely specify the KIi gain for each inverter. However, a reasonable choice would be to choose the ratio between the kIi of two different inverters to be equal to the ratio of their rated powers as:

$$\frac{K_{Ii}}{K_{Ij}} = \frac{S_i^r}{S_j^r} \tag{14}$$

The system of equations (13) and (14) uniquely specify the integral controller gains for the K inverters. As an example, if all inverters in the DN have the same power rating, the inverter gain obtained through this control design is:

$$K_I = \frac{1}{\sum_{i=0}^{K}\sum_{j=0}^{N} s_{ij}} \frac{N}{a \times T_c} \tag{15}$$

V. RESULTS

The proposed distributed voltage control approach has been tested in a standard IEEE 123-node distribution feeder [22] to verify its applicability. The test feeder does not include DG data, and thus PV units of various capacities have been added in several nodes of the feeder. Operation of the feeder is simulated during an entire day, in order to showcase various voltage control issues that manifest due to changes in the balance between power supply from the PV units and power consumption by the loads. In order to achieve that, a typical solar irradiation curve [23] and a daily load curve [24] have been used. The loading and the solar power generation in the feeder are assumed particularly high, in order to showcase the proposed method's capability to address severe voltage regulation problems. A solar penetration of $5.2MW$ and a peak load of $6MW$ is assumed.

A certain connected communications graph structure for message exchanges between inverters must be assumed, in order to apply the proposed consensus algorithm for calculation of total voltage deviation. Here we assume that any two nodes that are electrically connected can also exchanges messages. In order to accelerate convergence of the algorithm, additional communications lines are also assumed. After calculating the convergence rate of the consensus algorithm and using the methodlogies of Section IV a time constant of 20s is used for the AVD. This choice defines the control design for the local controllers of each DG that was added to the system, as in (13),(14).

The daily operation of the feeder was simulated in MATLAB. In order to speed up the procedure, this demonstation assumes balanced three phase system, thus solving an equivalent single phase power flow. However, this assumption has been known to not hold for distribution systems. For this purpose, the study included in this paper is preliminary, and a detailed unbalanced load flow study is deferred to a longer version of this work which will be presented as a journal paper. Fig. 2 illustrates the effect of the proposed voltage control approach in the feeder voltages. Specifically, it shows that maximum and minimum voltage magnitude among all the nodes in the feeder at each time in the day. For this particularly stressed case, unity power factor control leads to voltage rise when the solar generation is at its maximum and undervoltage when the load is at the peak and the solar generation is suppressed in the afternoon. The problem is addressed by applying the proposed coordinated control of the inverters, as the distributed inverters adjust their generation during the day to solve both the undervoltage and the overvoltage problem. Note that the inverters have been slightly oversized in this case, and can provide some reactive power, even when active power generation is at its peak. The proposed method maintains all voltages within the acceptable limits.

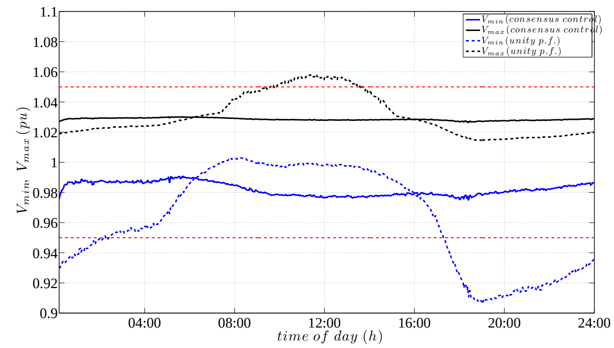

Fig. 2. Profile of minimum and maximum voltage in the feeder during the day, with the proposed control versus unity power factor control

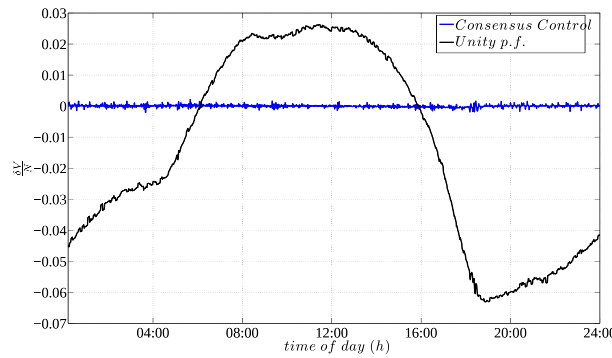

Fig. 3. Total Voltage Deviation with consensus coordination and with unity power factor control

Fig. 3 shows the controlled quantity, which is the total voltage deviation $\frac{\delta V}{N}$ for the feeder. The proposed methodology manages to regulate the quantity to zero, while unity power factor control allows this quantity to deviate. In our case, we allow utilization of the converters for reactive power support even when no active power is generated. In certain cases, the grid regulations impose power factor constraints on these devices, which would make this operation impossible. However, this study demonstrates that it would be beneficial to operate DG inverters in this manner for voltage support of the grid in high load and low irradiation periods.

Fig. 4 shows the reactive power injection of the DG connected in node 4. That particular node is close to the distribution transformer, and its voltage profile is strongly coupled to the transmission voltage. Thus, its voltage profile is acceptable even with unity power factor control, as shown in Fig. 5. However, due to the proposed coordination scheme, the reactive power controller of the DG in node 4 observes the total voltage deviation, not the local voltage alone. Hence, node 4 becomes responsive to the voltage imbalance in its feeder and generates or consumes reactive power according to what is needed. Hence, the proposed methodology encourages cooperation between the DG units and even units whose voltage is within limits participate in the feeder voltage control. Note that in this particular study, the voltage at the secondary of the distribution transformer is considered constant at 1.04

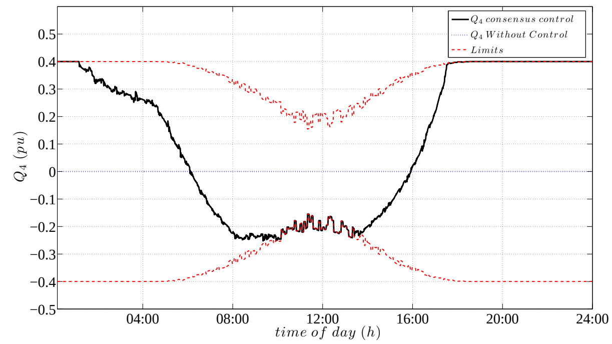

Fig. 4. Reactive power injection and reactive power limits of the DG inverter at node 4

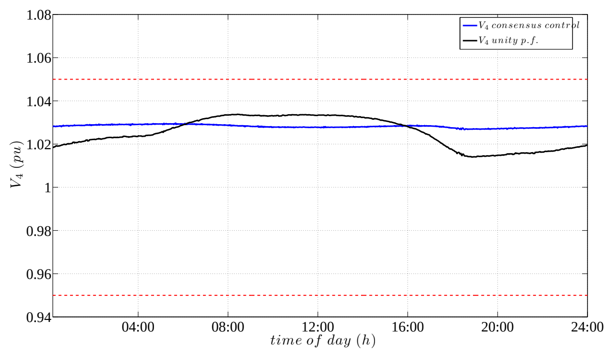

Fig. 5. Voltage at node 4, with and without the proposed consensus control

pu.

Fig. 6 shows the capability of the distributed algorithm to calculate the total voltage deviation in each node. In this particular example, the total average deviation is -0.036 pu.In this example Node 4 and node 55 are initialized at the voltage deviation they observe locally, which is obviously different for each node. In fact Node 4 observes voltage above nominal and 55 observes voltage below nominal. However, they gradually converge to the average deviation for the entire feeder.

VI. Conclusions

This paper presented a novel scheme for regulation of voltages in a distribution grid with high DG penetration, based

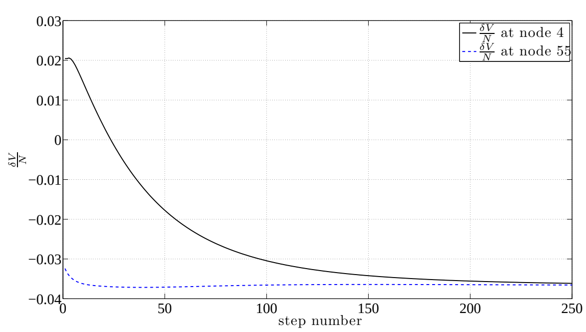

Fig. 6. Step by step evolution of distributed calculation of total voltage deviation

an multi-agent consensus methodologies. It was shown that it is feasible to control voltages in the Distribution Network using a feedback of the Average Voltage Deviation in the DN. The feedback is obtained in each inverter by performing linear iterative updates exclusively with neighbors. The methodology was shown to be effective in maintaining a good voltage profile across the entire DN, and successfully addressed both undervoltage and overvoltage problems. The control design of the local reactive power controllers was also adressed. There is significant potential in: i) investigating more sophisticated methodologies for control of reactive power, especially if fast response to voltage transients is desired ii) inverstigating how this methodology will interact with existing distribution voltage control schemes iii) Examine this approach using three phase modelling and simulation iv) Examine the effects of loss of communications/messages or unexpected delays in message transmission.

Appendix A
Parameters used in test case

Appendix one text goes here.

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