Semi-Centralized Control of Distributed Generation in Smart Grids

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***Abstract*—This paper proposes a semi-centralized intelligent control approach for voltage regulation in distribution grids based on sensitivity calculations. The model checks the voltage magnitudes of each end of each lateral in the system one by one, then if any of these violates the allowed voltage magnitudes, each node in a single lateral sends its reactive power capability and sensitivity information to the sensor located at the beginning node of that lateral. This information is sorted at the sensor and required voltage is computed and assigned to the bids one by one. This paper tests this approach on a modified 33 Node Distribution Test system with several renewable energy sources: photovoltaics (PVs) and wind turbines (WTs), and presents the numerical results based on a 15 minute resolution load data, PV outputs and WT outputs.**

***Index Terms*—distribution systems, voltage control, sensitivities.**

I. Introduction

With the possibility of coordinated usage of new technological devices such as intelligent sensors, inverters, power grid is becoming smarter. The trend of integrating more renewables and distributed generators into both transmission and distribution systems is increasing. EU Renewable Energy Directive states that at least 20% of the energy needs, and at least 10% of the transport fuels of the member countries should be from renewables by 2020 [1]. By 2030, the percentage amount of energy needs from renewables is aimed to be at least %27, and greenhouse gas is aimed to be at least 40 % less compared to that of 1990 [2]. US, aims to decrease the amount of power sector emissions by 32 % by 2030 compared to 2005 levels. All over the world the expectation in near future is to use more renewables in the system.

Due to the intermittent power outputs of renewables, in operation, power system may face some problems. Especially in distribution systems it is obvious that the voltage fluctuations will be more, and sometimes this may cause voltage magnitudes to be out of the safe ranges (0.95 pu-1.05 pu). Traditionally, distribution systems are "install and forget" type systems, and due to the radial structure, power flow is to single direction. However, with inclusion of more and more renewables, system needs to be controlled more, and the direction of the power flow may not be single direction any more.

To overcome these type of problems, several control devices are used in distribution systems. Traditional ones are voltage regulators and capacitors. However since their tapping mechanisms are mechanically structured, each time changing their tap positions decreases their length of life. It is specified in several previous studies that coordinated usage of these devices may help voltage fluctuation to be less and decrease system losses [3], [4], [5]. Also reactive power capabilities of DGs can be used to mitigate fluctuations.

Coordinating these devices to solve voltage deviation problems may be grouped into two. First group of methods model the problem as an optimization problem, and solves it either by using derivative [6], [7], [8], [9] or non-derivative based methods [3], [4], [10]. The second group approaches the problem as a control problem [11], [12]. Solution methodologies are different for instance [11] uses sensitivity information and solves the problem by developing an efficient algorithm. On the other hand [12] uses multi-agent systems in the solution process.

This paper proposes an intelligent control approach for voltage regulation in distribution grids. It combines the approaches used both in [12] and [11], and uses this approach to increase locality in power systems operation decisions. For this aim, it calculates the sensitivities. It checks the voltage magnitudes of the end nodes of each lateral one by one. Then, if these violate the safe voltage regions (out of the range between 0.95 pu and 1.05 pu) each node in the lateral sends their reactive capability and sensitivity information to the sensor on the beginning node of the lateral. After receiving this information, controlling sensor sorts the multiplication of reactive power capabilities with sensitivities and sorts this information. If voltage values are less then 0.95 pu, required voltage is computed and is assigned to the first sorted bid. If this bid is not enough, this process continues until the voltage magnitude of the end node is in the safe voltage range. For voltage magnitudes greater then 1.05 pu, the same process is applied in an opposite manner. This voltage control approach is then applied to the remaining laterals. Note that, our approach in this study aims to use the reactive power capabilities of the DGs, hence, we don't consider voltage regulators or bank capacitors in the simulations.

The rest of the paper is organized as follows. The next section presents the mathematical model of the voltage control approach. We briefly explain the modified 33 node test system, used in the simulations in Data Preparation section. Load data, PV data and WT data are also briefly explained in this section. Tests and Results section gives, illustrates and comments the obtained numerical simulation results. Final section concludes the paper and briefly explains the planned future work.

II. Mathematical Model

This section explains the mathematical model of the model. We use voltage sensitivities of each node according to reactive powers in the system in each time step. Voltage sensitivity matrix can be defined as follows:

$$\textbf{Sensitivity Matrix} = \begin{bmatrix} S_{2,1} & S_{2,2} & \cdots & S_{2,n} \\ S_{3,1} & S_{3,2} & \cdots & S_{3,n} \\ \vdots & \vdots & \cdots & \vdots \\ S_{n,1} & S_{n,2} & \cdots & S_{n,n} \end{bmatrix}$$

where, n represents the number of nodes in the distribution system, and each entry of which can be calculated numerically as follows:

$$\textbf{Sensitivity Matrix}_{xi} = \frac{X\left(Q_{\textbf{node}_x} + \Delta Q_i\right) - X\left(Q_{\textbf{node}_x}\right)}{\Delta Q_i} \quad (1)$$

Here X represents the numerical simulation of power flow, $Q_{\textbf{node}_x}$ represents the reactive power output of node x, and ΔQ_i represents a very small change in reactive power.

In other words, at each time step, difference of the node voltage magnitudes of the initial state and the node voltage magnitudes when reactive power injection of each node is slightly changed are calculated. Then the results are divided to those slight changes in reactive power injections.

The model is similar to the approach given in [12]. Our approach takes locality into consideration, assuming that each lateral in the system is able to retrieve sensitivity and reactive power capability information at each time step. The model checks the voltage magnitudes of the end nodes of each lateral for a given simulation time t. This is done after a load flow calculation is performed at time t. For this case, there are three possible values for an end node lateral voltage magnitude:

- *it may be in between 0.95 pu and 1.05 pu.* If this is the case no further computation is needed for that specific lateral.
- *it may be less then 0.95 pu.* If this is the case, then, the sensor on the lateral receives the reactive power capability and sensitivity information of of each node in the lateral. Note that, the reactive power capability of each DG is calculated by using well known $S^2 = P^2 + Q^2$ equation. We assume that the apparent power is constant for renewable energy sources, and reactive power capability will then obviously become as $Q_{\text{capability}} = \pm\sqrt{P_{\text{output}}{}^2 - S_{\text{apparent power}}{}^2}$. After receiving this information controlling sensor sorts the multiplication of reactive power capabilities with sensitivities. Required voltage is computed and is assigned to the first sorted bid. If this bid is not enough, this process continues until the voltage magnitude of the end node is in the safe voltage range.
- *it may be greater than 1.05 pu.* This is opposite to the previous case. Again the reactive power capability information and sensitivity information of each node in the lateral is sent to the sensor in the lateral. Required voltage drop is computed and is assigned to the first sorted bid. If this bid is not enough, this process continues until the voltage magnitude of the end node is in the safe voltage range. Note that, this study doesn't consider over-voltage cases, since the radial structure of the system causes voltage drops.

The flowchart of the model is given in Fig. (1).

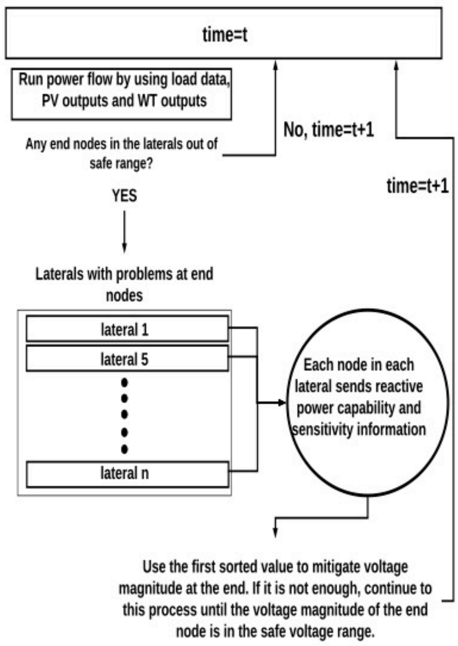

Fig. 1: Flowchart of the proposed approach.

III. Data Preparation

We used a 12.66 kV, 33 node distribution system [13]. Since, the aim is to see the impacts of renewable energy sources and to take remedial actions, we assumed that all nodes except the 1^{st}, 18^{th}, 22^{nd} and 33^{th} nodes are installed with either PVs, or WTs as shown in Fig (2). In the figure, the laterals are shown with dotted lines. There are four laterals in this test system. The laterals are specified in the figure to signify that each lateral has as a semi-independent voltage improving mechanism based on the information kept in their sensors. Base case load data of the system can be found in [13] where the loads for the base configuration is 5084.26 kW and 2547.32 kvar.

We used load data, PV data, and WT data provided by University of Glasgow (Grid 2025 Challenge) [14], and used in the simulations. Data provided is a 15 minute resolution, yearly data, hence we chose a random day and used in the

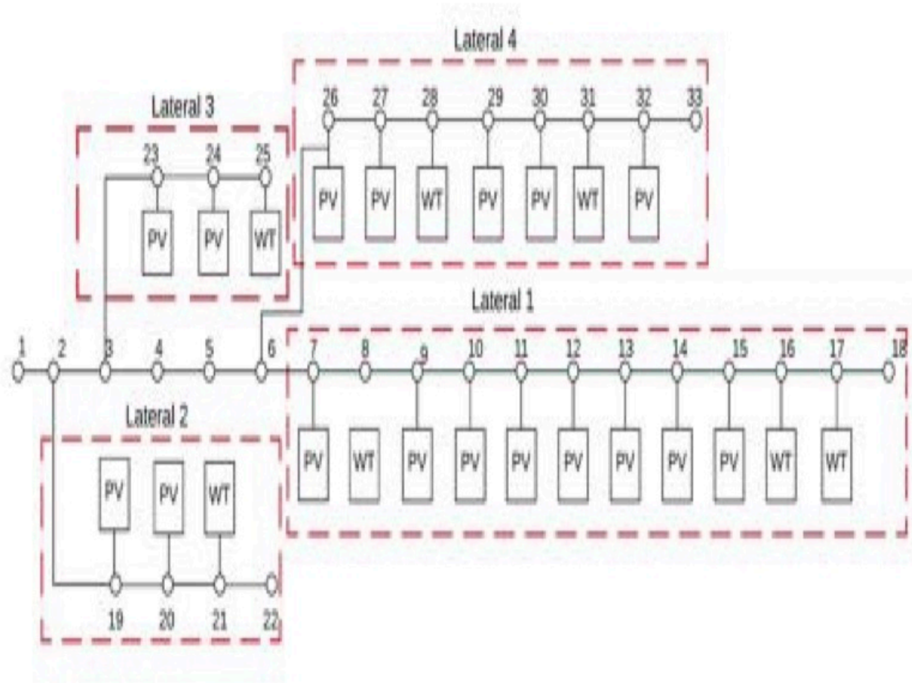

Fig. 2: Modified 33 Bus Test System.

simulations. Scaled load data, PV output data, and WT data are illustrated in Fig. (3). Note that, in the simulations we assumed that same scaling is applied on the base case load data for all nodes. This is the case for PVs, and WTs as well however they have slightly different apparent powers (each of them ranging from 3 to 5 kVA). We selected a random day for the simulations: April 25, 2025.

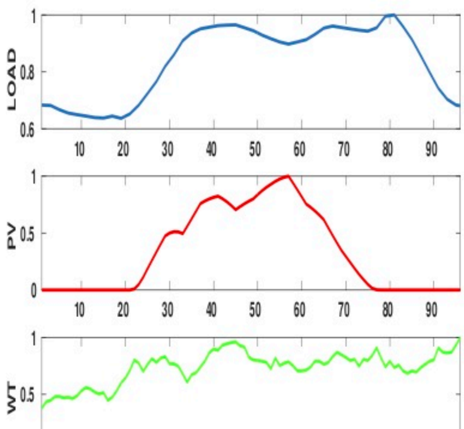

Fig. 3: 15 minute load, PV output and WT output profiles

IV. Tests and Results

We performed all numerical simulations by using Matlab and open source power systems package Matpower [15]. We run all simulations on a laptop that had a 2.20 GHz Core Duo CPU, and 2.00 GB Memory. Modifications specified above for 33 node system were employed on Matpower's 33 node file. There are totally 17 PV stations, each of them with 10 PVs, and 7 WT stations each of them again with 10 WTs. We initially performed base case power flows to see the initial state of the system when we apply no control. For this aim, we assume that PVs and WTs don't exist and we performed power flow on 33 node system by using Matpower for each 96 time steps that represent a full daily simulation. Illustration of the numerical results for all 96 different time steps are shown in Fig. 4. In the figure, all separate lines represent voltage magnitudes for that specific time interval. Note that the vertical line represents the under-voltage limit: 0.95 pu. It is obvious from the figure that the system has an under-voltage problem.

Next, we consider the case assuming PVs and WTs have their actual power outputs, with no control approach is applied. The voltage magnitudes for all simulated time steps are illustrated in Fig. (5) for this case. There is a slight improvement in voltage magnitudes compared to the previous case because of the PVs and WTs, however the under-voltage problem still exists.

Then the proposed approach is applied each time step. Voltage magnitudes obtained after the control approach applied is shown in 6. It is obvious from the figure that the

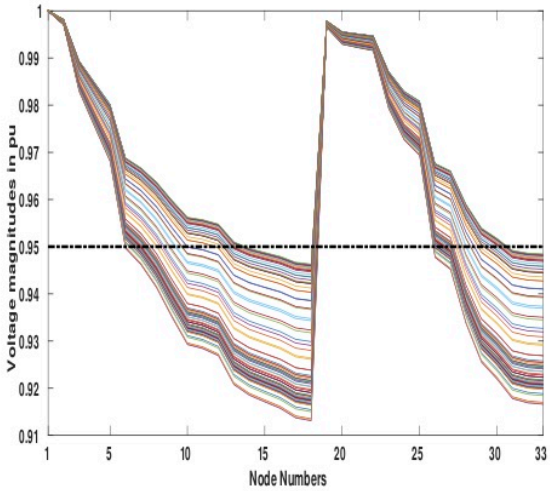

Fig. 4: Initial state voltage magnitudes, before control approach is applied

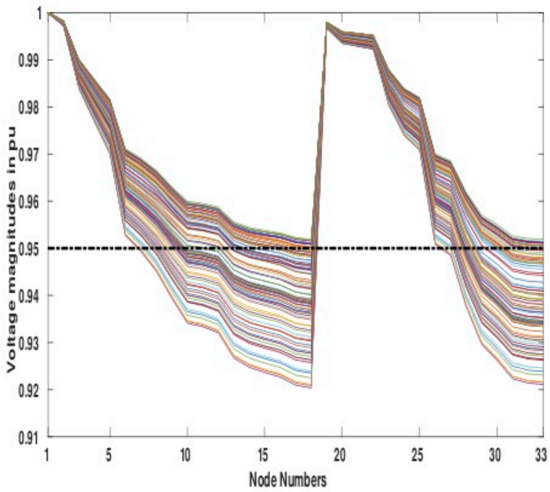

Fig. 5: Initial state voltage magnitudes with PVs and WTs before control approach is applied

voltage magnitudes improved this case, and all the voltages are in between 0.95 and 1.05 pu.

For instance at time step 66 (equivalent to 4.30 pm) the voltage magnitude at the end node of the first lateral, node 18 is: 0.9336 pu for the case with PVs and WTs before control approach is applied. Hence, the requested voltage magnitude will be the difference between 0.95 and 0.9336. This lateral has nodes 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 as the candidate nodes. After calculating their reactive power capabilities, they are multiplied with corresponding sensitivities, and sorted. Then the highest value's node number information, and its reactive power information is stored. If these values are not sufficient this process is repeated. If there are not enough PVs or WTs in the laterals, cases where reactive power capability may not be enough may be encountered. However, future's electricity grid is expected to have enough renewables installed. In those cases, communication with other areas -laterals- and getting reactive power from them may be a solution.

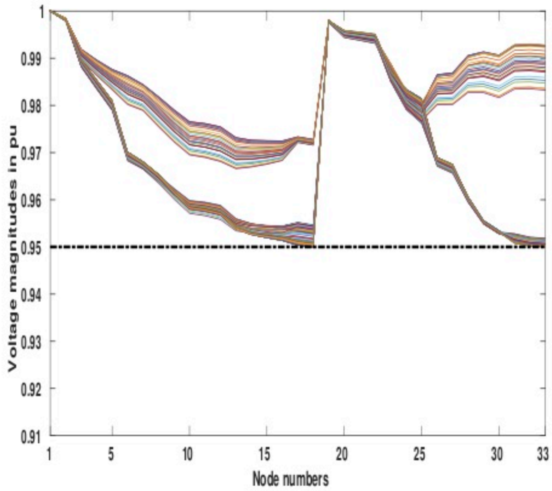

Fig. 6: Voltage magnitudes, after control approach is applied

Mean voltage magnitudes, and their standard deviations for the case when there are no PVs and WTs exist in the system and no control is applied, are found as 0.9572, and 0.0260 respectively. With PVs and WTs mean voltage magnitudes improve to 0.9633 and 0.0219 respectively. After control approach is applied these values are better: 0.9741, and 0.0163.

V. Conclusion and Future Work

This paper proposed an intelligent voltage control method based on sensitivity information of lateral nodes. The approach is tested on a modified 33 node test system, with PVs, and WTs, and it is found that the voltage magnitudes are improved. The approach uses sensitivity information of the node voltages according to reactive power changes. This is due to using local information and energy exchange in the laterals with under-voltage problems. Since, the lateral based energy exchange is only used, these type of methods may be used in future's smart grids.

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