Voltage Control in Active Distribution Grids: A Review and A New Set-up Procedure for Local Control Laws

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***Abstract*—Planning, operation and control of active distribution grids by increasing the number of dispersed generators is becoming more important but also more complex. Hence, the importance of controlling the voltage is highlighted in many research papers. Traditionally, in passive distribution networks the voltage rise has been mitigated by network reinforcement. Nowadays, local voltage control, coordinated voltage control and centralized voltage control have been discussed for active networks in research papers. Although all the approaches have been proven to solve the problem of voltage rise in distribution grids, using plenty of sensors to gather huge number of measurement could cause complexity. This paper represents a literature review of different voltage control approaches in active distribution grids and proposes a new procedure to set up a local voltage control law devoted to properly manage the voltage profile (e.g. minimizing losses on MV feeders).**

Index Terms*—dispersed generation, active distribution grid, voltage control, hosting capacity.

I. Introduction

The increasing penetration of Dispersed Generation (DG) mainly based on Renewable Energy Sources (RES), as a supplement to centralized generation, has caused new challenges in modeling, operation and controlling of the Medium Voltage (MV) distribution grid. Although DGs could take some advantages from RES production such as sustainability, less maintenance and low carbon emission, since DGs power injections to the grid are not coordinated with the actual distribution grid, it can cause power quality and reliability degradation such as harmonics, voltage profile and interface protection problems and moreover it may increase system losses and operational costs [1]–[4].

The fast increasing of DG connections may affect the supply quality. In fact, voltage profile along the feeder have been influenced and over voltage at the DG's Point of Common Coupling (PCC) may occur [5], [6]. The voltage increase along the feeder leads to power flow decreasing in the HV/MV transformer which cause load compensation decreasing. Thus, new voltage regulation approaches are required which have to act not only through substation measurements [7], [8].

In the literature, several methods are proposed for voltage regulation. The first step of distribution grid's control strategies is based on local management which is already expressed by national standard, e.g. the Italian Technical Committee (TC) 316, and international standard IEC [9]. Since the possibility of reverse power flow by increasing the penetration of DGs into the grid is arising, distribution system is transforming to the active distribution network. By this transformation, Distribution System Operators (DSOs) can solve voltage problems by controlling grid's generation and consumption [10]. To do so, an active network management will be needed which, by real-time communication and control, may provide better DG integrations [11].

In fact, the voltage regulation proposals can be classified into 3 main groups: 1) Local voltage control, which is based on local PCC measurement, 2) Coordinated Voltage Control, and 3) Centralized Voltage Control, which are the evolution of local control, working with telecommunication system. It is worth mentioning that the purpose of voltage regulation is not only the elimination of voltage rises and the increasing of Hosting Capacity (HC). Voltage regulation is a resource to improve and optimize the entire electrical grid according to different objective functions, such as system losses reduction or power factor optimization. The aim of this paper is representing a literature review of the aforementioned voltage regulation methods and propose a new procedure to set up a control law to respond to the distribution challenges and needs. The structure of this paper is as follows: section II represents local voltage control, section III and IV is devoted to coordinated and centralized voltage controls. In section V the issues and needs according to these methods discussed, and finally in section VI the new procedure to set up the control law is proposed. At the end, section VII concludes this study.

II. Local Voltage Control

Local voltage control, known as decentralized method, uses local information to allow more DG to connect to the grid increasing HC. This method is used where the communication and optimization tools are limited. Thus, each DG works separately and uncoordinated with other devices, leading to less expenses [12]. The local voltage control is obtained with two contributions: the regulatory of on load tap changer in primary substation and the power factor control of DG units.

A. On Load Tap Changer (OLTC)

The automatic tap changer is controlling the voltage of MV bus-bar at Primary Substation (PS). To do so, the voltage set-point is determined (in the best case) by offline Optimal Power Flows (OPF) in order to provide a suitable voltage profile for the whole feeder [13]. In order to manage the increasing number of DGs, studies related to the operating power factor, size and location of the DGs are required [14], [15].

Usually, OLTC regulation performs considering a Line Drop Compensation (LDC), based on the resistance (R) and reactance (X) of the feeder to regulate the voltage at transformer terminal [16]. Actually, by LDC measuring the secondary current simulates the voltage drop along the feeder between transformer terminal and load [17], [18]. The fundamental operation of OLTCs with or without using LDC has been studied in [19].

Since the voltage rise may affect the Automatic Voltage Control relay (AVC) and subsequently causes regulation problems, in [16] different modern control schemes are discussed. The methods for voltage control improvement are including Enhanced Transformer Automatic Paralleling Package (TAPP), to reduces the circulating current between transformers, and super TAPP n+ relay, the enhanced TAPP scheme which has the ability to estimate the RES output current. In [20], a set-point control algorithm of AVC is proposed. State estimation-based OLTC is suggested in [21].

B. Reactive Power and Power Factor Control (PFC)

It is well known that DG injections drive a voltage rise in the MV feeders. Actually, these generators could be coupled with additional compensators to regulate the voltage in its limits [22]. Static compensators (STATCOM), D-STATCOM, static VAR compensators (SVC), fixed capacitor banks and shunt capacitor banks have been investigated in [23]–[26], although some of these devices are costly.

Generally speaking, PFC could control the system's voltage by increasing the hosting capacity of the distribution grid [11], [27], [28]. There are many studies about the combination of various methods with PFC, which allow for some advantages such as reliability, efficiency and flexibility [29], [30].

In [5], [31], 4 different local control strategies have been exploited according to European technical standards, as listed in the following: $LawA$) control of tangent of ϕ according to the PCC voltage ($\tan\phi = f(u)$); $LawB$) control of reactive power according to the PCC voltage ($q = f(u)$); $LawC$) control of tangent of ϕ according to the real power injected ($\tan\phi = f(p)$); $LawD$) control of reactive power according to the real power injected ($q = f(p)$). In Fig. 1 the aforementioned control laws are presented.

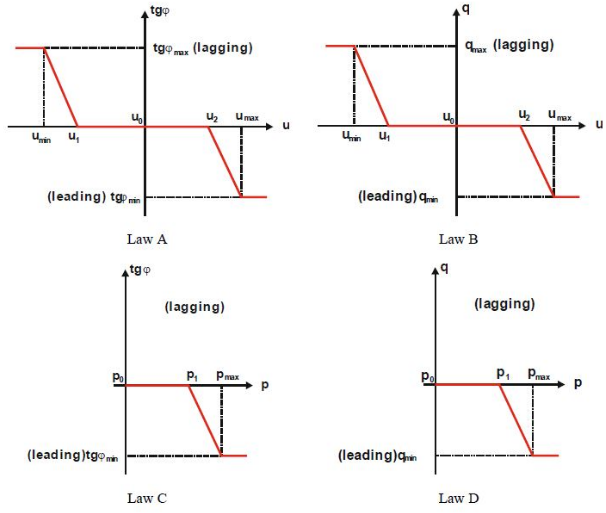

Fig. 1. Local voltage control strategy.

III. Coordinated Voltage Control (CVC)

This real time control acts according to control rules taking into account the needs of the whole distribution network. This method is suitable for simple networks with less control possibilities and optimization tools. The CVC holds the information of network topology and electrical characteristic of each feeder connected to the PS. The voltage control logic is based on two categories: 1) In case of normal operation condition no signal is sent to the CVC and the system is working according to the local voltage control strategy; 2) in case of critical condition, after receiving a warning signal CVC will elaborate the collected information to apply proper regulation actions. The goal of CVC is to improve the system operation toward an optimum.

The easiest method of CVC which is controlling substation voltage based on voltage lower and upper bound has been studied in [32]. In some proposed approaches, only reactive power compensators have been used in order to keep the voltage at the permissible level [33]. A new CVC method with reactive power managment scheme has been studied in [34]. Besides, in [35]–[38], the authors proposed a combined method of SVC by injecting reactive power and step voltage regulator by changing tap position according to the received information from sensors in the distribution line which could be able to keep the voltage lower than the maximum allowed. Moreover, in [39], [40], active power control has been implemented in order to control the voltage, while distributed methods using multiagent systems for CVC have been studied in [33], [41].

The aforementioned approaches are useful in simple and small networks, however by increasing the number of objectives, the control rules could become complicated. Hence, optimization algorithms have been used in many research papers. Genetic Algorithm (GA) has been used in [42]–[44]. In addition, Particle Swarm Optimization (PSO) algorithm has been investigated in [45]. Two new CVC algorithms, focused on time domain simulation and statistical distribution network planning, have been discussed in [46]. The combination of local-learning algorithm and nonlinear programming for computational time reduction was implemented in [42], [47]. In [48], a new two-stage voltage control scheme for controlling OLTC, capacitor banks and DGs using micro genetic algorithm and recursive genetic algorithm has been used. This method is based on finding the optimal reactive injection looking for the minimization of the power losses. Structural changes to minimize the operational conflicts by giving the priority in action to the resources close, based on the electrical distance, has been proposed in [49]. Finally, the importance of reliable communication infrastructure and the quality of service in CVC was discussed in [50].

IV. Centralized Voltage Control

This last-step-regulation procedure needs a complete and continuous communication between PS and the sensors widespread on the distribution network. It is based on continuous OPF calculations of the network model which is obtained by the state estimator. In each cycle, the obtained voltage set-points are delivered to the local DG. Actually, the centralized voltage control is an advanced control based on OPF, it has to generate a new voltage set-point by comparing the optimum value created by OPF and the measured value in order to adopt the optimum according to the current network status.

There are many intelligent techniques which are used for centralized control to formulate different type of objective functions [51]–[53]. The advantage of using these methods is to provide optimized solution compared to the conventional methods and, as they have flexibility in defining constraints, to effectivelly handle the nonlinear programming. GA, PSO, Evolutionary PSO, Discrete PSO, sensitivity theory, tabu search, Artificial Neural Network, fuzzy logic and multi agent are extensively report in literature review [54]–[56]. In these studies, by solving a constraint optimization problem for minimizing the system losses, control actions are scheduled to reactive power suppliers.

An improved centralized voltage control of OLTC and Static Voltage Regulator based on standard communication lines and automation server has been studied in [57]. The voltage fluctuations are forecasted using JIT modeling. Similarly, in [58], day-ahead load forecasts using GA are exploited in order to define the optimal dispatch schedule of OLTC and shunt capacitor. The PSCAD/EMTDC network model with different load profiles and dynamic loads is validated by the OPF developed in [59].

V. Needs and Issues

As discussed in the previous sections, voltage control methodologies and approaches are investigated and discussed in the literature as a means of enhancing the distribution grid HC. Table I, shows the different approaches comparison [60]; for some approaches to regulate the voltage along the system and hold it in the allowable limits, an accurate knowledge about each node's voltage is required. However, due to lack of (or limited number of) complete Supervisory Control And Data Acquisition (SCADA) in distribution networks, real time measurements are rarely available through feeders and only are available at PS. To compensate this shortage, state estimation of measurements has to be done by sensors and communication assets to evaluate voltage profiles and to dispatch the DG units and the other resources available in the network accordingly. However, state estimation procedures based on a very limited number of measures typically are affected by uncertainty and errors which may cause wrong decisions. On the other hand, aligning sensors for each node of the distribution system is very costly and unaffordable. Hence, a cost effective approach to set up the voltage law has to be proposed to cope with all of these problems.

TABLE I
Decentralized, coordination and centralized voltage control comparison.

Decentralized methods	**Coordinated and Centralized methods**
local control	vast control
needs no communication	needs vast communication
with no coordination	with vast coordination
Affordable	costly

VI. Proposed Method

The strategy proposed in this paper has been developed according to the DSO needs and European technical standards. DSO are in charge to set the local voltage control on DG power plants according to Fig. 1. Thus, generation units could be considered in order to develop new algorithms for the reactive resources management in the MV distribution networks. This can be done by corrective adjustments of the reactive production of a single generator. In particular, each generating unit has to give reactive support in those situations in which its production would lead to voltage violation, according to the standard EN 50160. However, no literature could be found for this purpose. The procedure has been proposed in this paper is based on the optimal reactive power flow (ORPF), a non linear problem with continue and discrete variables. In the proposed strategy, the ORPF operates off-line on the basis of a historical network behavior. The goal of the procedure is to statistically set up the parameters of the local voltage control law. With respect to the proposed approach, each reactive resource operates locally and the parameters of the local characteristic are adjusted according to the output of an optimum computation. With respect to such an approach, no communication infrastructure is necessary since still is a local voltage control.

ORPF objective function could be losses minimization, generator reactive power minimization and voltage deviation of each node from the related value minimization. ORPF constraints can be defined as: voltage limits of buses, reactive power capability limits of generators and power factor limits at the substation. With respect to the proposed approach, several grid working conditions have to be evaluated (e.g. evaluating the power injections over a solar year) solving for each one the ORPF problem, then interpolation of the ORPF outputs by a defined mathematical law, as those presented in Section II, has to be done. The final goal is to properly define the local voltage regulation setting. In order to validate the model, the network losses, maximum, minimum and average voltage of generator PCC and standard deviation of the voltage at PCC should be compared with ORPF outputs. If the indexes meet the requirements, it can be adopted for the real case. In the following the mathematical overview of ORPF and its equality and inequality constraints are detailed.

$$P_{g,k} - P_{d,k} - V_k \sum_{m=1}^{N} V_m Y_{km} \cos(\delta_k - \delta_m - \theta_{km}) = 0. \quad (1)$$

$$Q_{g,k} - Q_{d,k} - V_k \sum_{m=1}^{N} V_m Y_{km} \sin(\delta_k - \delta_m - \theta_{km}) = 0. \quad (2)$$

$$V_{min} < V_i < V_{max}. \quad (3)$$

$$I_{ij} < I_{max}. \quad (4)$$

$$\overline{P_i} - P_{calc,i}(V, \delta) = 0. \quad (5)$$

$$\overline{Q_i} - Q_{calc,i}(V, \delta) = 0. \quad (6)$$

$$Q_{min,i} \leqslant Q_{i(V,\delta)} \leqslant Q_{max,i}. \quad (7)$$

where $P_{g,k}$, $Q_{g,k}$, $P_{d,k}$ and $Q_{d,k}$ demonstrates active and reactive power of the generators and demand absorption of bus k respectively. V and δ are voltage magnitude and voltage phase respectively. N is the total number, whereas Y and θ are magnitude and the phase of the bus admittance.

In the following, the local voltage control law by interpolation of ORPF results for a 15 kV radial MV distribution network is discussed. The objective function is losses minimization and the constraints are voltage limits of each node and reactive power capability limits of generators. The time period is one year with the step of one hour (8760 steps). Since in passive condition the voltage along the feeder is decreeing [61] for each feeder three different locations are considered for DG connection, the first ($GEN-01$), the last ($GEN-03$) and the middle ($GEN-02$) node of the feeder under evaluation, which are defined according to the electrical characteristic of the feeder itself, Fig. 2 represents the defined nodes. The setting procedure for $lawB$ is carried out considering two rated power of generators, the first (4 MW) correspond to an injection not causing voltage violation in the grid, the second (sized at 6 MW) represent a big generator that in some samples causes nodal overvoltages.

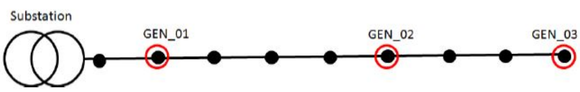

Fig. 2. DG units location.

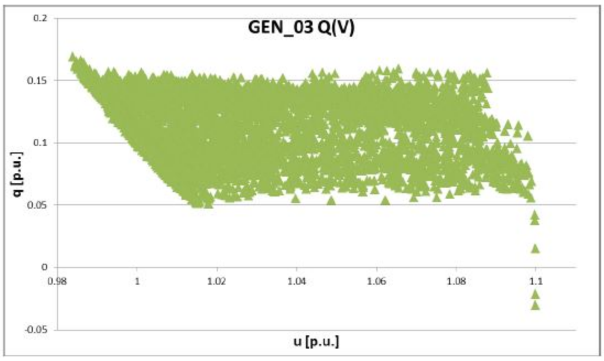

Fig. 3. ORPF outputs at 4 MW for GEN-03.

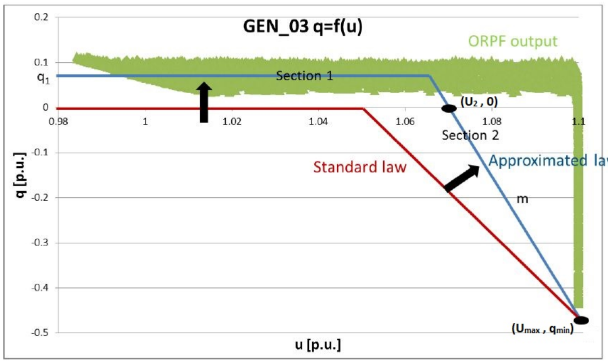

Fig. 4. Interpolation of GEN-03 ORPF output to the local control $LawB$ at 6 MW.

For each time sample, one of the mentioned generators is connected to the defined nodes and for each condition the ORPF has been solved. For brevity only results of the most critical node, i.e. the one depicting more violations ($GEN-03$) have been showed here. The ORPF outputs of the $GEN-03$ for both injected values are shown in Fig. 3 and Fig. 4. The ORPF results depict that generators have to inject reactive power in order to support the voltage profile and reduce the network losses until the voltage is within the constraints. The mathematical law considered in the interpolation procedure is a linear piecewise law. Therefore, a linear function with only two piecewises (named Section 1 and Section 2) is considered in Fig. 4. Section 1 is represented by a constant line equal to the average between 5^{th} and 95^{th} percentile of reactive power value q_1 of all the operation points with voltage lower than U_2. Beside, section 2 of the piecewise function is represented by a line with a fixed negative slope. In order to guarantee a continuous function, Section 2 starts at a reactive power value equal to q_1 and it links the points (U_2,0) and (U_{max},q_{min}).

In order to check the settings, standard local voltage control is tested in the same network considering the same generation scenario. A comparison between the network losses calculated by the adopted new settings of the local curve $LawB$ $approximate$ (App.), the losses obtained with the standard settings of the $LawB$ $standard$ (St.) and losses optimized thanks to ORPF is reported in Fig. 5. The losses are computed with respect to the losses obtained in the passive network scenario, hence the relative network losses are equal to:

$$p_{Loss} = \frac{P_{Loss} - P_{Loss-passive}}{P_{Loss-passive}}. \qquad (8)$$

The results show that the proposed approach drives to a local voltage control setting effective in improving the network losses (the more HC, the more amount of losses [62] which is the proof of positive amount of losses here). The ORPF keeps the voltage profile higher than the standard control law in order to limit the network losses driving to better performances. It's worthwhile to underline how in the under investigation case (6 MW injection from DG unit) in the standard local control scenario, voltage violations are detected. The proposed set-up procedure allows both to an improvement in the grid losses and in a minimization of the voltage violations. The proposed approach proved to be a sound improvement with respect to the standard voltage control approach, resulting to be adequate for the short-medium term scenario, i.e. for those grids where the on-line ORPF approach is complex, or costly, to be implemented.

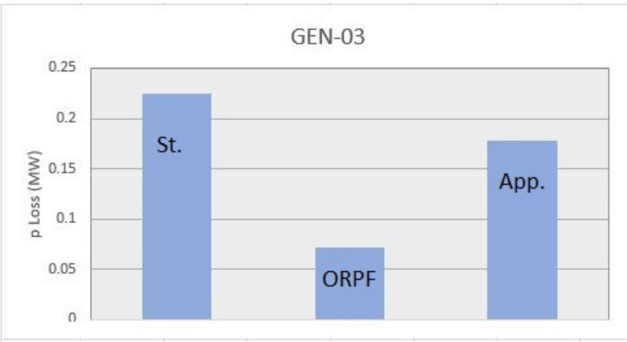

Fig. 5. Comparison between network losses of ORPF, standard local control and approximate local control at 6 MW.

VII. Conclusion

In this paper, different voltage control laws for distributed generation in the active distribution networks have been discussed. The control methods are classified into three main groups: local voltage control, coordinated voltage control and centralized voltage control. For each category, different research papers with various approaches are overviewed. Since plenty of sensors in smart architectures needed to be deployed, this can result unfeasible with respect to both the economic and the technical viability of the approach. Therefore, a new approach to set up the local control law was proposed. The results of the proposed method showed that the local operation based on a proper set-up could drive to good improvement in the management of the distribution grid voltage profile.

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