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Voltage regulation in active networks by distributed and cooperative meta-heuristic optimizers

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ABSTRACT

The availability of intelligence at substation level, combined with the adoption of pervasive communication networks, offers technologies and opportunities to decentralize voltage regulation in active power distribution systems.

Armed with such a vision, this paper proposes the employment of meta-heuristic optimizer agents aimed at addressing voltage regulation in a distributed scenario. In particular, it is demonstrated that the cost functions describing the voltage regulation objectives can be obtained by solving distributed consensus problems over a network of cooperative and dynamic agents. In addition, all the basic operations required to solve the voltage regulation problem can be computed by the distributed meta-heuristic optimizer agents according to a totally decentralized/non-hierarchical paradigm.

Definitively, in a very simple way, based on the global grid conditions each voltage controller may decide if and when a reactive power flow injection into the network is most useful.

1. Introduction

The massive diffusion of distributed generation (DG) into electricity distribution networks is one of the expected features of the next-generation smart grids. However, the integration of DG into running distribution systems perturbs the power flow and voltage conditions of customer and utility equipment by inducing several side effects. Thus, the increased penetration of DG into smart grids by proper coordination of their operation and restriction of their negative impact on grid operations and control is a crucial issue. In this context, voltage regulation is one of the main issues to address [1,2].

Voltage regulation is normally achieved by the optimal coordination of a large set of regulating devices, all used with the aim of supporting the load buses' voltages and improving the power quality at the distribution level. This is obtained by minimizing a cost function given by the combination of control objectives (voltage profile flattening, power losses, reactive power cost, etc.) in the presence of several constraints (reliability indexes, voltage stability limits, etc.).

To solve this problem, a large number of iterative numerical algorithms have been proposed in the literature relating to power systems. They include nonlinear programming algorithms [3] and more recently, meta-heuristic based and bio-inspired methodologies [4,5].

Although these solution strategies offer considerable insight into the important role played by modern optimization techniques in voltage regulation, their application requires the implementation of a data fusion center acquiring and processing all the power system measurements.

However, the large-scale deployment of this voltage regulation paradigm may not be affordable when addressing the increasing grid complexity and the massive pervasion of DG characterizing the future smart grids [6]. Unaffordable complexity, communication network bandwidth and redundancy of hardware facilities represent the main barriers that could be imposed by technology and costs [7,8].

Thus, much research effort in voltage regulation has been oriented toward designing advanced architecture that moves away from the older centralized paradigm to a system distributed in the field with an increasing pervasion of intelligent and cooperative entities [9].

In addressing these needs, the conceptualization of control paradigms, aimed at distributing the intelligence at substation level, and the deployment of pervasive communication networks, aimed at allowing substations to communicate with other substations and with all the systems at substation level, represent the most promising enabling technologies [10].

Therefore, the deployment of distributed optimization techniques in the context of multi-agent systems, subject to limited communication connectivity, could play a strategic role. This is

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mainly due to the successful application of distributed computing paradigms in coordinating networks of cooperative agents, aimed at enhancing operational effectiveness in complex systems [11,12].

Armed with such a vision, voltage regulation architecture based on cooperative multi-agent paradigms, aimed at improving the performance of secondary voltage control actions under different system operating states, has been proposed [7,8,13–16].

In particular, in paper [14] a real-time simulation of multi-agent systems for a decentralized secondary voltage control method in a distribution network is proposed. In this framework, the multi-agent paradigm aims at sharing the voltage regulation efforts and performing the effective coordination of the distributed generators.

Paper [15] outlines the important role of multi-agent systems in addressing autonomous voltage regulation in active distribution networks. It shows that the autonomous voltage control within each feeder can be deployed by a combination of active and reactive power supports of DG, according to decentralized regulation architecture.

In paper [16] the problem of reactive power dispatch of DG, aimed at providing voltage support in active distribution networks, is formalized by a nonlinear programming problem and solved by a scheme based on a multi-agent system. In addressing this issue, the control net protocol for a multi-agent system has been adopted. It allows the multi-agent system to deploy a model-free voltage regulation procedure.

According to these trends, in paper [17] the authors proposed fully decentralized voltage regulation architecture based on cooperative dynamic agents. As with self-organizing biological populations, the network voltage regulation is achieved by the cooperation of the single dynamic agents (i.e., controlling DG operating in a voltage support mode) that communicate with a reduced number of surrounding elements by short-range communication links. This computing paradigm allows each agent to assess the evolution of the objective function describing the voltage regulation objectives and, thanks to the adoption of local gradient descent optimizers, to identify proper actions aimed at minimizing the objective function.

Although this architecture exhibits several advantages over traditional voltage regulation paradigms (i.e., less network bandwidth, less computation time, easy to extend and reconfigure), its deployment reveals some shortcomings principally arising from the suboptimal solutions identified by the local optimizers. This is mainly due to the adoption of a gradient descent based algorithm, which leads the dynamic agents to converge to local minima.

The purpose of this paper is to fill this gap by proposing a more effective algorithm aimed at solving the voltage regulation problem in a decentralized/non-hierarchical scenario.

In addressing this issue, the authors propose the deployment of a network of meta-heuristic optimizer agents. The insight is to allow the agents network to assess, in a completely decentralized way, the many important variables characterizing the power system operation (i.e., mean grid voltage magnitude, power losses, regulation costs) by solving distributed consensus problems [18–20]. This is obtained without the need for a central fusion center acquiring and processing all the power systems measurements. These global variables are then amalgamated with local measurements and processed by each meta-heuristic optimizer in order to improve the grid voltage profile, by regulating the reactive power flows injected by the DG into the electrical grid. This is realized by adopting a decentralized search minimization technique based on simulated annealing (SA) [21]. This technique emulates the behavior of a set of atoms in metal annealing. It models the cooling process evolving from a high temperature to a freezing point, where the energy of the system has acquired the globally minimal value. This physical annealing process is analogous to the determination of near-global or global optimum solutions for nonlinear optimization problems.

The integration of SA in the decentralized regulation framework was expected to make it possible to overcome the intrinsic limitations of algorithms based on distributed gradient descent, in identifying effective solutions to the voltage regulation problem.

In order to assess the proposed methodology, this paper presents and discusses some simulation results obtained by applying the proposed methodology in the task of voltage regulation on the 30 bus IEEE test network. A comparative analysis with a rigorous centralized solution algorithm and a distributed framework based on distributed gradient descent optimizers, demonstrates the effectiveness of the proposed methodology.

The outline of the paper is as follows: the voltage regulation problem is formulated in Section 2. Section 3 proposes a distributed/non-hierarchical computing paradigm for voltage regulation. Section 4 contains the description of the simulations and a discussion of the results. Conclusions and future works are summarized in Section 5.

2. Problem statement

Voltage regulation in power distribution systems aims to identify, for each network state Γ, the asset of the voltage regulating devices y that minimizes an objective function J subject to a number of equality and inequality constraints $g(\Gamma,y)$. From a mathematical point of view, the overall problem can be formalized by the following constrained nonlinear programming problem:

$$\begin{cases} \min\limits_{y\in\Omega} J(y,\Gamma) \\ g(\Gamma,y)\le 0 \end{cases} \tag{1}$$

The voltage regulation devices asset includes the reactive power injected by the DG operating in a voltage supporting mode, the reactive power injected by the capacitor banks and the tap positions of under-load tap-changing (ULTC) transformers.

As far as the problem constraints are concerned, they include the allowed voltage range for each bus (i.e. $V_{\min,i}\le V_i\le V_{\max,i}\quad i=1:n$), the maximum allowable currents for the n_l power lines (i.e., $I_l\le I_{\max,l}\ l=1:n_l$) and the minimum and maximum allowable limits for each voltage regulation device. In addition, the regulation devices asset y should satisfy the power flow equations, which represent equality constraints for problem (1).

The objective function J could integrate both technical and economic criteria. Traditionally, this is expressed by a weighted sum of O normalized design objectives:

$$J(y,\Gamma)=\alpha_{F_1}\frac{F_1(y,\Gamma)}{\bar{F}_1}+\alpha_{F_2}\frac{F_2(y,\Gamma)}{\bar{F}_2}+\cdots+\alpha_{F_O}\frac{F_O(y,\Gamma)}{\bar{F}_O} \tag{2}$$

where $F_i(y,\Gamma)$ denotes the ith design objective and α_{F_i} and $\bar{F}_i$ represent the corresponding weighting factor and normalization threshold, respectively.

The design objectives include the following figures of merit that should be minimized:

- the active power losses:

$$F_1=P_g-P_l\ge 0 \tag{3}$$

where P_g and P_l represent the total active power generated and absorbed on the power system;

- the average voltage deviation:

$$F_2=\frac{\sum_{i=1}^{n}\left|V_i-V^*\right|}{n} \tag{4}$$

where V_i and V_i^* denote the current and the desired voltage at bus i, respectively and n is the number of buses;