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Multi-agent systems for reactive power control in smart grids

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ABSTRACT

Power system monitoring is the most fundamental prerequisite for making reasonable decisions in a control center. In recent years, with the advent of smart grids, monitoring and control of reactive power in power systems has entered a new era. This issue have highlighted the need for effective methods of decentralized optimal reactive power control (DORPC), especially based on the new available frameworks which have emerged along with the smart grids. This paper presents a novel approach to the DORPC problem based on a Holonic architecture. The Holonic architecture has some unique features by which the objective of the DORPC problem could be optimized through a timely proposed strategy. In order to demonstrate the features of the proposed approach, it is compared with two other methods considering a set of indices. Accordingly, the proposed approach has great potential to reduce the active power losses and to fully exploit the available reactive power resources. It requires a limited set of data while improves the fault tolerance of the network.

Introduction

Motivation

The proliferation of distributed energy resources (DERs) in future distribution networks brings about formidable challenges regarding their reactive power control. Roughly speaking, the advent of future smart grids changes the paradigm in power system operations. One of the most fundamental prerequisites of such grids is to employ distributed algorithms by means of data exchange among several entities [1]. Traditionally, power systems are operated on the basis of a control center where a certain set of quantities of the network is gathered via a supervisory control and data acquisition (SCADA) system. Such schemes, nonetheless, will no longer effectively manage a distribution network hosting the sheer number of meters, sensors, actuators, and DERs [2]. In the centralized schemes, the burden associated with a large number of entities could bring about congestion of communication infrastructure or crash of central processors. Moreover, the power system operation becomes more vulnerable in case of a fault occurrence in the communication link. Indeed, the heavy dependence of centralized methods to the communication link leads to a significant interruption in the system control if any fault occurs in the communication link. Consequently, shifting from a centralized operation to a decentralized one would considerably enhance the real-time control of smart grids and improve their supply resilience [1,3].

The reactive power control plays a vital role in the optimal operation of power systems. Insufficient reactive power is considered to be one of the major reasons for recent blackouts and voltage collapses around the world [4]. Generally, an optimal reactive power control scheme seeks to determine the optimum values of controllable variables (e.g., the voltage of generators, on-load transformer tap-changers (OLTC), reactive power compensators, distributed generations (DGs), and smart parks) so as to minimize an objective function. From a computational perspective, reactive power control is a nonlinear optimization problem with a set of complicated constraints. The main goals of the reactive power control problem, which have been addressed in the literature, are reduction of active power losses, minimization of voltage deviations, and enhancement of voltage stability margin [5].

Literature review and contributions

A large body of literature has investigated the reactive power control problem. In [5], a novel method is presented in order to solve a multi-objective reactive power control problem. The method considers bus voltage limits, the limits of branches power flow, generator voltages, transformer tap changers and the amount of compensation on weak buses. The objectives of the optimization problem are real power losses and voltage deviations from their corresponding nominal values. In [6], the authors have proposed a probabilistic algorithm for optimal reactive power provision in

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hybrid electricity markets. The proposed algorithm is a six-stage multi-objective optimization problem which also takes the load forecasting errors into account. The authors in [7,8] have used smart grid technologies in order to collect measurements and send directions through a secure communication infrastructure. In these papers, a hierarchal intelligent voltage control framework based on incident command system (ICS) is proposed in two different structures: a central control scheme and a local control scheme. Note that these structures are proposed in order to provide a real and reactive power support at the end-use level.

In the decentralized scheme proposed in [9], agents are allowed to determine the injection of reactive power in the network. Fazio et al. [10] proposed a decentralized approach which is mainly based on an off-line coordination and optimal set-point design for the reactive power control scheme of the DGs. In [11], a model-free decentralized voltage control algorithm is proposed with the aim of minimizing the power loss of an islanded microgrid. The algorithm works well even when the configuration of the microgrid changes. In [12], a distributed multi-agent scheme is presented for reactive power management in smart coordinated distribution networks with DERs. A multi-agent method is proposed for emergency control of long-term voltage instability in a multi-area power system [13]. In this study, the overall problem is partitioned into a set of sub-problems, each to be tackled by an individual agent.

This paper aims to establish a decentralized optimal reactive power control (DORPC) scheme in smart grids. The proposed methodology is developed based on a Holonic architecture which is capable of combining both autonomous and cooperative behaviors efficiently in order to attain the system goals. Such capabilities would considerably alleviate the concerns associated with the centralized approaches. Employing the proposed architecture, system operators will be able to operate the network near to the optimal point. Considering the two unique features of the Holonic structure (i.e., the Holon dynamics and the Holonic negotiations), this methodology would fully exploit the available reactive power sources in the network. The prevailing uncertainties pertaining to renewable energy sources (RES) are also taken into account. In order to evaluate the performance of the proposed approach, it is compared with two other methods. Meanwhile, the authors of this article have previously proposed a decentralized architecture for optimal reactive power dispatch in their prior work [14]. As a follow-up, this paper presents a more refined use case to illustrate the effectiveness of the proposed scheme in the context of smart grids. Generally speaking, some main contributions of the proposed DORPC structure is as follows:

- Developing a hierarchical decentralized approach in order to control the reactive power flows.
- Proposing an approach to avoid a surplus of communication between different areas of the system.
- Obtaining a DORPC by a low time-consuming method together with few control actions during the proposed strategy.
- Developing an appropriate test bed to validate the scheme in a realistic setting by linking MATLAB and java agent development framework (JADE) platforms to each other.

Paper organization

The rest of this paper is organized as follows. Section ‘‘Multi-agent systems (MASs) in smart grids” briefly introduces the basic concepts of the Holonic structure as a novel MAS in power grids. Section ‘‘Formulation of the DORPC problem” is devoted to the mathematical formulation of the problem. The decentralized approach used to solve the problem is presented in Section ‘‘DORPC based on the Holonic structure”. The prevailing uncertainties along with the Plug-in electric vehicle (PEV) modeling are presented in Section ‘‘Formulation of the DGs and PEVs”. Simulation results are discussed in Section ‘‘Numerical studies”. Finally, relevant concluding remarks are provided in Section ‘‘Conclusion”.

Multi-agent systems (MASs) in smart grids

MAS concept

A MAS is composed of intelligent agents for harmonization of their behavior. The residence in an environment and autonomy are the common concepts expressed for agents [15]. The agent's environment is all things located at its outside and surroundings. Generally, the agent's interaction with its environment can be seen as a succession of perception, decision-making, and measures [16]. An autonomous agent is an agent whose decisions depend not only on the perception of environment, but also on the prior knowledge (a set of predesigned actions) provided in the design step [17]. The reactivity, pro-activity and social ability are other features of agents [16]. Reactivity means agents' ability to perceive their environment and respond timely to the changes occurred in the environment so as to satisfy design objectives. The agents' proficiency to mutate their behavior dynamically means the pro-activity. For example, if the connection between agent-1 and agent-2 is lost, agent-1 will look for another agent which serves the same services. This feature indicates the agent's initiative. The social ability is beyond the data transfer between various software and hardware. In fact, it shows agent's ability for cooperative negotiation and interaction.

Now, the obvious question that may come to mind is: when MAS can be suitable for solving a problem? This question is answered by defining several determinant indexes including: (1) the environment should be uncertain, complex and open and/or high dynamic, (2) using agents should be seen natural, (3) data, control and authority must be distributed, (4) the system must possess tolerance and strength and (5) it should be able to execute calculation simultaneously in parallel.

MAS organization

The MAS organization is a set of roles, interactions and authority structure that handles MAS's behavior. Analogous to human organizations, a MAS organization determines how agents interact with each other not only in real time, but also in long-term interactions. This organization can touch the authority relationships, resources allocation, information flow, coordination patterns and other system characteristics. Thus, a simple group of agents may represent complex behavior and/or a sophisticated group of agents reduces the complexity of their behavior. This definition shows that the shape, size, and features of an organizational structure can impress the system behavior. Many organizational structures are presented by researchers in this filed. A comprehensive review of these organizations is provided in [18].

Notion of Holon

The concept of ‘‘*Holon*” was introduced for the first time by a Hungarian philosopher for describing recursive and self-similar structures in the biological and social organizations [19]. A Holon is a self-similar structure and a stable integrated fractal which can be composed of several smaller Holons (i.e., sub-Holons) and on the other hand, it can be a component of a bigger Holon (i.e., super-Holon). According to this recursive definition, a Holon can be seen, depending on the level of observation, either as an autonomous "*atomic*" entity, or as an organization of Holons. A