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Interfacing applications for uncertainty reduction in smart energy systems utilizing distributed intelligence

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A R T I C L E I N F O

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A B S T R A C T

Under the transition towards sustainable smart energy systems (SES), utilization of distributed intelligence has been gradually proposed along with the expansion of Information and Communication Technology (ICT) infrastructure and advanced control services. Distributed intelligence (DI)-based control and management solutions proved a perfect complement to the existing control structures to handle the SES' uncertainty which is getting quite complex with different system layers and involved stakeholders. Advanced modelling and simulation techniques are crucial here to realize and enable the applications of DI to enhance grid reliability while optimize market operation. However, several challenges arise while modelling DI applications and integrating them in the simulation platform due to the complexity of the multi-disciplinary smart grids. As an activity of IEEE Task Force on Interfacing Techniques for Simulation Tools, this paper mainly reviews the interface issues between modelling and simulation of physical, ICT, and application layers, as well as business processes of the whole smart energy systems. By means of a conceptual framework for SES development, this paper aims to position most of DI-based control applications in specific research domain and elaborate on their interface with the whole SES context.

1. Introduction

DEVELOPMENT of smart grids, or Smart Energy System (SES) in a broader sense, is facing challenges related to uncertainty in both securing the electricity networks and balancing energy supply and demand [1,2]. The anticipated massive integration of stochastic renewable energy sources (RES) and the introduction of new energy-intensive appliances, e.g. electrical vehicles or heat pumps, aggravates these challenges because of larger uncertainties on all time scales [3]. Distributed intelligence (DI) has been considered, among other computation intelligence methods, as an enabler for bottom-up modelling and control solutions to handle the SES' uncertainty which is getting quite complex with different system layers and involved stakeholders. Considering the increasing interest in DI-based applications from the research community, the IEEE Task Force on Interfacing Techniques for Simulation Tools carried out the task to assemble a comprehensive overview of DI-based applications in SES, as well as to address interface issues between modelling and simulation of DI within a conceptual framework for SES development.

1.1. Uncertainty in smart energy systems

The most obvious source of uncertainty in future SES comes from the intermittency of RES, which is way harder to predict and schedule than on-demand sources [4]. Meanwhile, stochastic behaviour of DERs changes energy demand levels and their patterns over time, as a result of heavy appliances such as EV, HP's and CHP installations. Therefore, the uncertainties make it increasingly difficult to both perform supply and demand matching (SDM), as well as to operate the electricity network within secure operation limits [3,5]. Besides these obvious uncertainties and notwithstanding the promising capabilities of proposed control applications and functionalities in future SES [6], the information and communication systems (ICT) in next generation power systems will face a greater variety of cyber vulnerability as those of today [7,8]. Security and privacy aspects will be stressed more, since the customers will participate actively in the whole energy supply

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chain. The increasing involvement of ICT systems and advanced control mechanisms also reveals uncertainty in the interoperability of SES [5]. Therefore, solving these uncertainty problems requires a comprehensive insight on the relevant system layers. These layers include the physical power grid, ICT, as well as the control functions and services deployed on top of this, to ensure safe, reliable and efficient operation of the electricity supply chain.

1.2. A variety of DI based applications

Besides the conventional centralized control applications and services, utilization of distributed intelligence (DI) has been gradually proposed [9,10]. These DI-based solutions proved a perfect complement to the existing control structures to handle complexity and uncertainty of the system which is getting quite complex with different layers and many involved stakeholders. In general, DI can be realized as embedded hardware and software with sensing, communication and decision-making capabilities [11]. This way, it can provide advanced control functionalities in transmission and distribution networks, facilitate network ancillary services, as well as dispatch of flexibility and demand side management (DSM) and demand response (DR) programs. To realize these functionalities in a scalable and efficient way for large size future SES, enabling technologies are required including distributed control, computation intelligence, distributed optimization and multi-agent technology, also called a multi-agent system (MAS) [12,13].

After the publication by IEEE MAS Working group [12] in 2007, there is still an increasing interest from the research community to address DI-based applications as illustrated in Fig. 1. This research portfolio is based only on the IEEEXplore database, while searching for the keywords smart energy system or smart grid together with multi-agent system. This gives a wide variety of DI-based applications in this record, addressing different aspects of SES development including both grid and market operation. Some highlighted works will be discussed in more detail in Section 2.

1.3. Modelling and simulation of DI based applications

Despite its proven advantage in handling system complexity and uncertainty [12], some applications of DI require intensive support from ICT and advanced control mechanisms [9,10]. Therefore, advanced modelling and simulation techniques are necessary for simultaneous simulation of the physical power system, ICT and the distributed intelligence applications. Simulations form a cost effective approach for repeatedly investigation of the system behaviour under various conditions. Due to the complexity of the multi-disciplinary nature of SES, several challenges arise in the interfaces between simulation of the physical, information and communication, as well as application layers of the whole system. These issues are extensively addressed by the IEEE Task Force on Interfacing Techniques for Simulation Tools [14,15].

Because of the diversity in deployment of DI-based applications, the challenge of modelling and integrating them in the simulation platform remains due to a lack of a common and comprehensive development framework [16]. This hinders also the evolution of DI-based applications towards commercial hardware/software design practices [17]. As a consequence, an advanced simulation environment is required to address comprehensively the complex interactions between the various business processes [18,19], and the different smart grid layers from the household level [20], microgrid management system [21,22], coordination of multiple microgrids [23,24], to the whole distribution grid as a cyber-physical system [25]. Developed simulation platforms are expected to be highly extensible and able to perform different grid control strategies [26,27], take into account the integration of distributed energy resources [28] as well as to deploy various market mechanisms [29,30].

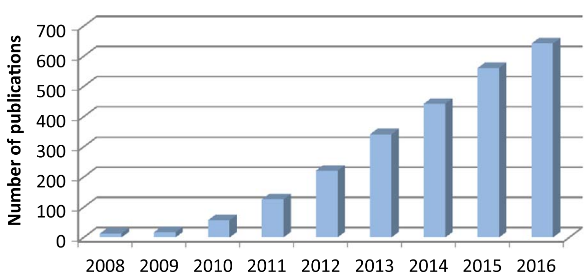

Fig. 1. Number of publications related to DI-based applications in SES accumulated by years.

1.4. Proposed approach and contributions of the paper

To follow up the research thus far, this article aims to specify on issues related to modelling and simulation of DI based business processes for uncertainty reduction in SES related to the mentioned challenges for grid operation and balancing. For this purpose, the paper will use a conceptual framework to classify applications and their modelling and simulation approach for the two aspects of grid operation and system balancing, including details regarding the relevant system layer, simulation domain and interfacing method. This way, it gives an overview on interfacing different simulation solutions for power systems, ICT systems, as well as the business processes themselves. It includes both non real-time and real-time simulations platforms, as well as simulation platforms supporting hardware-in-the-loop (HIL) configurations.

In this paper, a four-step approach as visualized in Fig. 2 has been applied including (1) a selection of DI-based applications, (ii) categorization of the application based on the proposed smart grid application framework; (iii) specification of DI-based application with associated modelling and simulation platforms; (i) identification of interfacing challenges.

The remaining part of the paper is organized as follows: in Section II, different advanced applications of distributed intelligence have been categorized within a conceptual framework of SES; Section III addresses challenges in modelling and simulation of such DI-based applications to reveal and cope with the uncertainty of SES; in Section IV, interfacing issues regarding individual simulations and their interaction with the whole system context are elaborated with different types of simulation platforms; finally, conclusions are drawn and an outlook is presented in Section V.

2. Conceptual framework for smart grid applications for uncertainty reduction

In this work, the various applications of distributed intelligence for uncertainty reduction in smart grids are categorized in two parts: 1) applications related to network operation and optimization; and 2) applications related to (local) market operation and optimization. Their relations and mutual interfaces are displayed in Fig. 3.

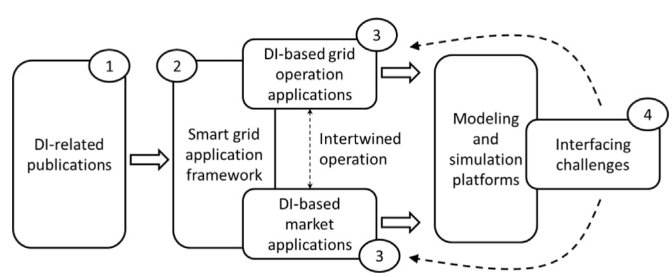

Fig. 2. The four-step approach to address interfacing challenges for various DI-based applications.