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COMPUTATIONAL INTELLIGENCE APPLICATIONS IN SMART GRIDS

Enabling Methodologies for Proactive and Self-Organizing Power Systems

Editors

Ahmed F Zobaa | Alfredo Vaccaro

Imperial College Press

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To Giulia and Antonella

Preface

The large-scale deployment of the smart grid (SG) paradigm could play a strategic role in supporting the evolution of conventional electrical grids toward active, flexible and self-healing web energy networks composed of distributed and cooperative energy resources. From a conceptual point of view, the SG is the convergence of information and operational technologies applied to the electric grid, providing sustainable options to customers and improved security. Advances in research on SGs could increase the efficiency of modern electrical power systems by: (i) supporting the massive penetration of small-scale distributed and dispersed generators; (ii) facilitating the integration of pervasive synchronized metering systems; (iii) improving the interaction and cooperation between the network components; and (iv) allowing the wider deployment of self-healing and proactive control/protection paradigms.

However, several studies have highlighted open problems and ongoing technological and methodological challenges that must be addressed for the full exploitation of these benefits to be possible.

SG technologies include advanced sensing systems, two-way high-speed communications, monitoring and enterprise analysis software and related services for collecting location-specific and real-time actionable data, in order to provide enhanced services for both system operators (i.e. distribution automation, asset management, advanced metering infrastructure) and end-users (i.e. demand side management, demand response). The cornerstone of these technologies is the ability for multiple entities (e.g. devices or software processes) to manage accurate and heterogeneous information. It follows that the development of reliable and flexible distributed measurement systems represents a crucial issue in both structuring and operating smart networks.

To address this complex issue, Chapter 1 analyzes the strategic role of wide-area monitoring, protection and control (WAMPAC). WAMPAC involves the use of system-wide information to avoid large disturbances and reduce the probability of catastrophic events by supporting the application of adaptive protection and control strategies aimed at increasing the network capacity and minimizing wide-area disturbances. The adoption of accurate phasor and frequency information from multiple synchronized devices installed at various power system locations allows WAMPAC to monitor power flows in interconnected areas and/or heavily loaded lines and offers the opportunity to reliably operate the SG closer to its stability limits. Additionally, these systems can monitor the dynamic behavior of the power system and identify inter-area oscillations in real-time. The ability to detect and reduce inter-area oscillations could allow the system operator to exploit transmission and generation capacity more efficiently. As a result, renewable power generators can be used more effectively, and the marginal cost of power generation can be reduced.

Effective WAMPAC operation requires intensive numerical analysis aimed at studying and improving power system security and reliability. To achieve this aim, the streams of data acquired by the field sensors, (i.e. phasor measurement units), should be effectively processed in order to provide SG operators with the necessary information for better understanding and reducing the impact of perturbations. For large-scale networks, this process requires massive data processing and complex and NP-hard problem solutions in computation times that should be fast enough for the information to be useful in a short-term operation horizon. In solving this challenging issue, the development of advanced computing paradigms based on metaheuristic and bio-inspired algorithms could play a strategic role in supporting rapid power systems analysis in a data-rich, but information-limited, environment.

Armed with such a vision, Chapter 2 proposes an advanced optimization algorithm integrating both soft and hard computing techniques for optimal network reconfiguration in smart distribution systems. The proposed computing paradigm can be easily integrated in conventional processing architectures since it is based on pieces of information usually available at a control center and relies on common actuators. For the same reason, it is expected to be easily implementable in the extended real-time framework of power system distribution operation. These features are particularly useful in SGs where the constant growth of interactive software processes (i.e. WAMPAC, energy management systems, distribution management systems, demand side managements systems) will raise the interdependency between distributed processing systems. For these systems, data heterogeneity, a non-issue in traditional electricity distribution systems, must be addressed since data growth over time is unlikely to scale with the same hardware and software base. Manageability also becomes of paramount importance, since SGs could integrate hundreds or even thousands of field sensors. Thus, even in the presence of fast models aimed at converting the data into information, the SG operator must face the challenge of not having a full understanding of the context of the information and, consequently, that the information content cannot be used with any degree of confidence.

To address this problem, Chapter 3 analyzes the important role of metaheuristic optimization for solving multi-objective programming problems in SG. Four different evolutionary algorithms have been proposed to solve a complex SG operation problem, namely the economic emission dispatch problem of thermal power generators by considering the simultaneous minimization of cost, NOx (mono-nitrogen oxide) emission and active losses. The main idea is to deploy a non-dominated sorting technique along with a crowded distance ranking to find and manage the Pareto optimal front. The obtained results show that, compared to traditional optimization methods, the adoption of evolutionary computing exhibits several intrinsic advantages making them an ideal candidate for solving complex optimization problems in SGs.

This conclusion has been confirmed in Chapter 4, where a case-based reasoning system for voltage security assessment and optimal load-shedding scheme is described. This is a complex issue in SG operation control, since voltage collapse can occur suddenly and there may not be sufficient time for analysis of system operating condition and operator actions to stabilize the system. In such emergencies, load shedding is the most effective and practical way to mitigate the voltage collapse. Therefore, after voltage security assessment, providing a real-time optimal load-shedding plan for insecure operating states can help the SG operators to avoid the voltage collapse. Solving this problem in near real-time is still a challenging task. In this context there is a need for fast detection of the potentially dangerous situations of voltage instability so that necessary corrective actions can be taken to avoid voltage collapse. To face this problem, the application of decision support systems based on artificial intelligence represents a very promising research direction.

Chapter 5 addresses another challenging task in SGs control and monitoring, namely the deployment of fast and reliable state estimation procedures. To solve this problem, iterative numerical algorithms based on iterative numerical techniques have traditionally been deployed. These solution paradigms usually work quite well in the presence of well-conditioned power system equations but they could become unstable or divergent in the presence of critical operating points. A manifestation of this numerical instability is an ill-conditioned set of linear equations that should be solved at each iteration. To try and overcome these limitations, this chapter conceptualizes two solution paradigms based on the dynamic systems theory. The challenging idea is to formulate the state estimation equations by a set of ordinary differential equations, whose equilibrium points represent the problem solutions. Starting from the Lyapunov theory it will be rigorously demonstrated that this artificial dynamic model can be designed to be asymptotically stable and exponentially converges to the state estimation solution.

The experimental deployment of the solution strategies discussed in these chapters requires the definition of advanced control architectures aimed at acquiring and processing all the power system measurements. A debate on the requirements of these architectures in the context of the modern SGs has been recently undertaken in the power systems research community. In particular, it is expected that the large-scale deployment of the SGs paradigm will massively

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increase the data exchange rate leading centralized control architectures to become rapidly saturated. Consequently, the streams of data acquired by distributed grid sensors may not provide system operators with the necessary information to act on in appropriate timeframes. To address this issue, SGs researchers are reviewing the design criteria and assumptions concerning the scalability, reliability, heterogeneity and manageability of SG control architectures. These research works conjecture that the hierarchical control paradigm would be not affordable in addressing the increasing network complexity and the massive pervasion of distributed generators characterizing modern SGs. In this context, the research for distributed multi-agent optimization paradigms has been identified as the most promising enabling technology. This is mainly due to the successful application of decentralized and cooperative agent networks in enhancing operational effectiveness of complex systems. Armed with such a vision, Chapter 6 outlines the important role played by multi-agent systems equipped with a novel fuzzy inference engine, named timed automata based fuzzy controller, in solving the optimal voltage regulation problem in the presence of a massive pervasion of distribution generation systems. As shown in the experiments, the proposed strategy results in an effective and suitable method for solving voltage regulation problem in SGs by improving the grid voltage profile and reducing power losses. It is expected that this multi-agent-based solution strategy will exhibit several advantages over traditional client server-based paradigms, including less network bandwidth use, less computation time, and ease of extension and reconfiguration.

The cornerstone of multi-agent frameworks is the ability for multiple entities (e.g. devices or software processes) to interact via communication networks. It follows that the development of a reliable and pervasive communication infrastructure represents a crucial issue in both structuring and operating the SG. A strategic requirement in supporting this process is the development of a reliable communications backbone, establishing robust data transport wide-area networks (WANs) to the distribution feeder and customer level. Existing electrical utility WANs are based on a hybrid mix of technologies including fiber optics, power line carrier systems, copper-wire line, and a variety of wireless technologies. They are designed to support a wide range of applications as far as SCADA/EMS (supervisory control and data acquisition/energy management system), generating plant automation, distribution feeder automation and physical security are concerned. As outlined in Chapter 7, these communication infrastructures should evolve toward nearly ubiquitous transport networks able to handle traditional utility power delivery applications along with vast amounts of new data from the SG. These networks should be scalable in order to support the new and future sets of functions characterizing the emerging SGs technological platform, and highly pervasive in order to support the deployment of last-mile communications (i.e. from a backbone node to the customer locations).

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