Role of Proactive Behaviour Enabled by Advanced Computational Intelligence and ICT in Smart Energy Grids

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Keywords: Smart Energy Grids, Computational Intelligence, Game Theory, Multi-Agent System, Proactive Behaviour.

Abstract: Significant increase in renewable energy production and new forms of consumption has enormous impact to the electrical power grid operation. A Smart Energy Grid (SEG) is needed to overcome the challenge of a sustainable and reliable energy supply by merging advanced ICT and control techniques to interact with the power grid. In SEG, distributed intelligence plays an important role to alleviate significantly consequences from uncertain power supply and changing load demand. This paper presents the state-of-the-art utilisations of distributed intelligence in SEG. Insufficient consideration of so-called proactive behaviour limits such SEG only to near real-time control functions and local optimisation of particular problems. This paper addresses a need for having a comprehensive research on anticipatory, change-oriented and self-initiated capabilities of SEG.

1 INTRODUCTION

As one of the largest and most complex engineering systems, electrical power grids spread everywhere in countries to supply electricity for myriad consumers from hundreds of thousands of producers. Secure operation of the power grid is crucial as unreliable performance can lead to grid blackouts such as the 2003 event in Europe (UCTE, 2004) and the 2012 event in India (Enquiry Committee, 2012). However, significant increase in renewable energy production (e.g. solar photovoltaic, hydro and wind power) and new forms of consumption (e.g. heat pumps, electric vehicles) has enormous impact to the electrical power grid operation. The accommodation of these so-called distributed energy resources (DER), with widely dispersed and highly stochastic natures, challenges the current power system in processing burden information, controlling the power flows properly at the right moments, and especially in balancing power supply and demand at all times.

Technically, the deviations in the power balance are caused by two main reasons including imperfect market participation and insufficient control capability. The former is the difference between the pre-scheduled values of power production and consumption, and the real contributions. In the past, conventional power plants were dispatched on the day ahead pretty well based on a sufficient knowledge of load consumption. The massive integration of DER makes the power production being hardly predictable or quite unpredictable while the load consumption is more active and flexible (Lopes, Hatziargyriou, Mutale, Djapic, and Jenkins, 2007). The latter is the limitation of the current control system arranged top-down to maintain grid stability and adequate bus voltages (Kundur, 1994). Increasing amounts of distributed, non-dispatchable, and fluctuating renewable sources reveal serious grid problems such as overloading, voltage excursions, and even instability. This classic control system is insufficient to response timely and adapt properly to the grid expansion and the significant participation of DER (Wu, Moslehi, and Bose, 2005).

Smart Energy Grid (SEG) is needed to overcome the mentioned challenges by merging advanced ICT and control techniques to interact with the power grid. This interoperability presents a chance to optimise system performance by improving the involvement of and synergy among actors, i.e. producers, consumers, and network operators. This trend takes place intensively in both US and Europe

H. Nguyen P., L. Kling W., F. Ribeiro P., K. Venayagamoorthy G. and Croes R..
Role of Proactive Behaviour Enabled by Advanced Computational Intelligence and ICT in Smart Energy Grids.
DOI: 10.5220/0004408900820087
In *Proceedings of the 2nd International Conference on Smart Grids and Green IT Systems* (SMARTGREENS-2013), pages 82-87
ISBN: 978-989-8565-55-6

(Simoes et al., 2012). In SEG, distributed intelligence plays an important role to alleviate significantly consequences from uncertain power supply and changing load demand. However, the state-of-the-art utilisations of distributed intelligence in SEG have not been focussed comprehensively in anticipatory, change-oriented and self-initiated capabilities. Insufficient consideration of this so-call proactive behaviour limits SEG to achieve only near real-time control functions and local optimisation of particular problems.

This paper discusses generally research trends in SEG as well as related limitations of the current network functions and market services. Proactive behaviour is addressed as a key to improve performance of the grid and attribute fairly benefits to involved actors.

2 SEG'S RESEARCH TRENDS

2.1 Network Optimisation

2.1.1 State Estimation and Prediction

Real-time control and operation are playing an important role to reduce consequences of intermittency and uncertainty in such new context of smart grids. These functions require advanced techniques to not only estimate system state variables but also predict their trends steps ahead (Venayagamoorthy et al., 2012). By improving the monitoring capability of the grid, control action will be trigger in real-time thus improve system reliability and stability. While Static State Estimation (SSE) based on Weighted Least Square (WLS) provides only a snapshot of the current state vector (Schweppe and Wildes, 1970),

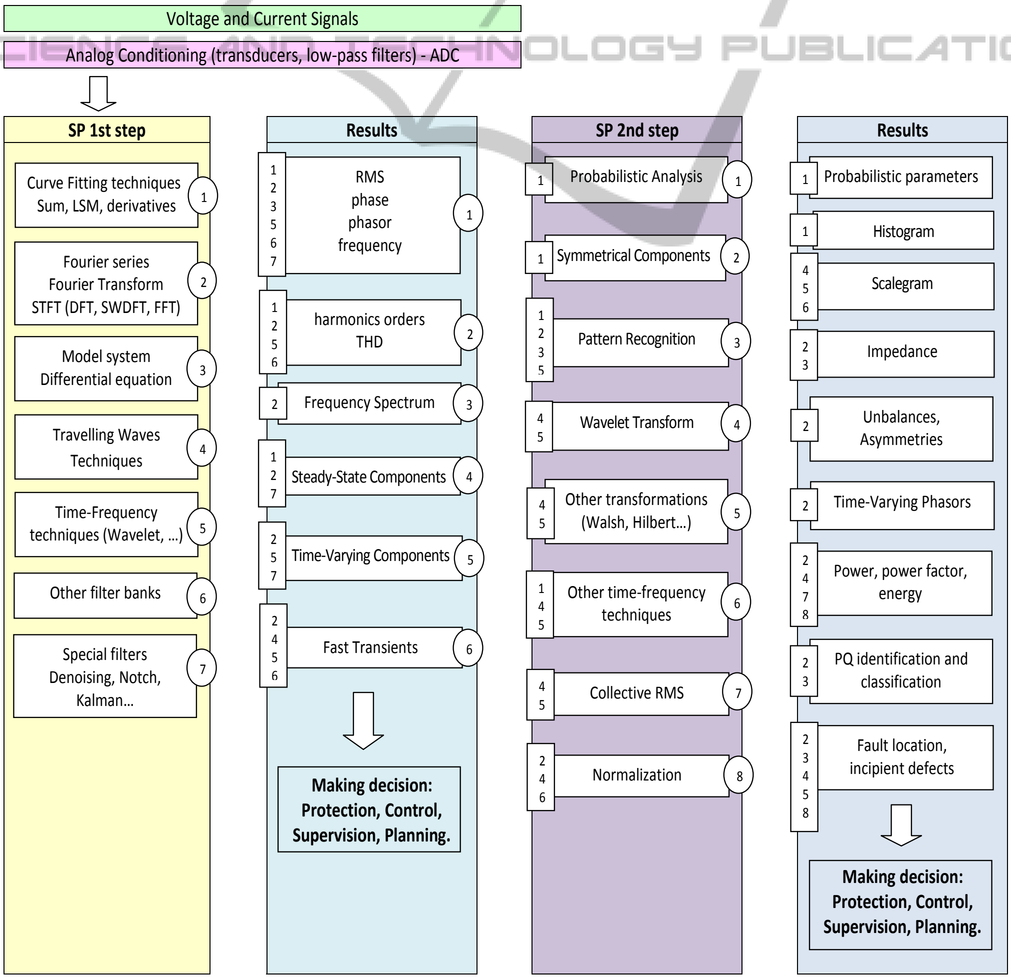

Figure 1: Illustrates the basic concept of the signals and parameters can that be processed and derived.

Dynamic State Estimation (DSE) aims to provide not only time-varying solutions but also predict the future operating points of the system (Debs and Larson, 1970). However, DSE approaches normally based on Extended Kalman Filter (EKF) need to collect recursively time-historic data, to update covariance vectors, and to treat heavy computation matrices. Computation burden mitigates the state-of-the-art utilizations of DSE in real large-scale networks although DSE was introduced several decades ago. Recent improvement of DSE by using Unscented Kalman Filter (UKF) can alleviate significant computation burden while outperform the former EKF-based method in terms of accuracy and robustness. This application opens a possibility to improve monitoring capability in SEF, especially at the distribution system level in a wide-range of dynamic conditions.

A fine-grained solution can be obtained by support from advanced signal processing technique. By measuring and analysing the signals at different points of the system the condition of the grid can be fully assessed. Figure 1 illustrates the basic concept of signals and parameters that can be processed and derived in steps. First, three-phase signals are decomposed into time-varying harmonics and then these are processed by symmetrical components. The result allows the engineer to have a unique means to visualize the nature of time varying unbalances and asymmetries in power systems.

Improvement of dynamic state estimation and prediction is important for situation awareness (SA) that needs for secure and efficient operation of SEG. SA is defined in (G. K. Venayagamoorthy, 2011) as the perception of environmental elements within a volume of time and space, the understanding of their meaning, and the prediction of their states in the near future. In near future, SA with its capability of state estimation and prediction is critical in distribution networks to provide distribution network operators insight about their grids.

2.1.2 Stability of SEG

SEG is facing an increasing replacement of conventional rotating-machine based power production by decentralised power-electronic based renewable energy production. Due to the decrement of available rotating generators, instability in the grid can be increased. Virtual Synchronous Generator (VSG) gives an opportunity for inverter-interfaced units to emulate virtual inertia ("VSYNC project," n.d.). Figure 2 illustrates a simplified model of a VSG.

Emulation of rotational inertia by VSG can be implemented with adjustment of active power in the way similar to a synchronous machine in the swing equation. However, normal capacity of storage is small compared with the large moment of inertia of the system. To have and solid effect on the inertia of the grid, one needs to use multiple units of VSG together. Figure 3 illustrates relatively impact of numbers of VSG units on grid stability.

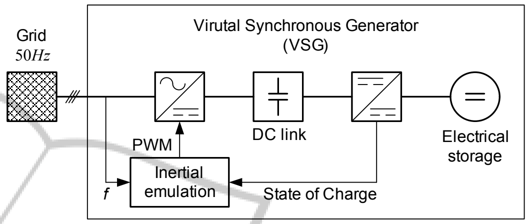

Figure 2: A simplified model of a Virtual Synchronous Generator.

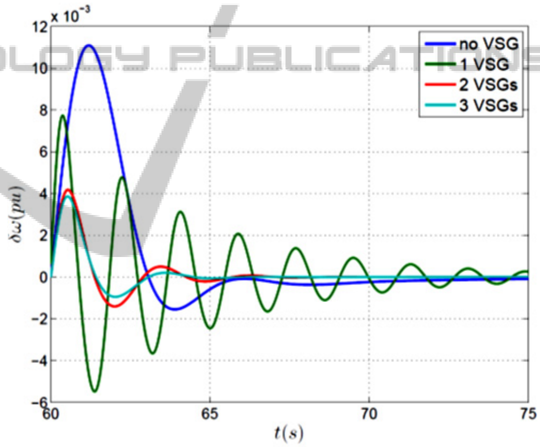

Figure 3: Contribution of virtual synchronous generators of damping oscillation of the grid.

2.1.3 Decentralised Control and Operation

Decentralisation becomes an important trend for control and operation at distribution system level, although essential centralised systems are still be used. In this transition, distributed intelligence plays an important role to handle the consequences from uncertain and variable power supply and changing load demand. As an evolution from conventional artificial intelligence into the mainstream of distributed systems, distributed intelligence in SEG is formed by pieces of software with communication capabilities (Wooldridge and Jennings, 1995). A so-called agent can simplify the way in which local entities interact with the power system as they can bring together reactive, proactive, and social behaviour (Li, Poulton and James, 2010). Reactivity is the agent's capability to react timely to change within its environment that needs for real-time control functions in smart grids such as coordinated voltage regulation (Nguyen, Myrzik, and Kling, 2008), or power flow management (Nguyen, Kling, and Myrzik, 2009). Sociality is the agent's capability to interact with other intelligent agents that is preferred for Microgrid applications (Dimeas and Hatziargyriou, 2005), balancing a local area network (Kok, 2011), or large-scale integration of DER units in Virtual Power Plants (Hommelberg, Warmer, Kamphuis, Kok, and Schaeffer, 2007). The state-of-the-art utilisations of this technology in SEG exploit mainly reactive and social capabilities of the intelligence agent.

Though proactivity is the most important behaviour to be driven by a set of tendencies, it has not been considered thoroughly in SEG's applications. This fact limits distributed intelligence to achieve only near real-time control functions and local optimisation.

2.2 Market Optimisation

2.2.1 Very Short-term Forecasting

Very short-term forecasting is expected to alleviate the consequences of uncertainty from active small-scale producers and consumers. Over- or under-forecasting the wind power generation has different consequences on the value of wind power generation in power system (Ortega-Vazquez and Kirschen, 2010). Forecasting tool, therefore, is crucial functional block to predict the stochastic behaviour of involved actors. With capability of mapping non-linear input-output relations, artificial neural network (ANN) based models are widely accepted for enabling very-short forecasting tools (Peng, Hubele and Karady, 1992). With high integration of renewable energy, on-line training with mutual information of input data selection is desired to reduce forecasting error.

2.2.2 Real-time and Scalable Market

Power supply and demand matching is a continuous system-wide problem that must be solved at all times. Until now this matching process has been centrally organised, based on generators which follow the passive loads in a coordinated way. With a massive amount of intermittent power sources and more stochastic patterns of new forms of load, the uncertainty increases significantly. The PowerMatcher concept, for instance, is an application of agent-based technology for power matching via a bottom-up market approach (ECN, n.d.). Similar approach with additional capability for taking also network congestion into account has been presented in (Greunsven, Veldman, Nguyen, Slootweg and Kamphuis, 2012). The principle of this application is that software agents connected to electricity generating or consuming devices are involved in an electronic market that also contains an aggregator, who determines the market equilibrium between demand and supply via pooling or an event based mechanism.

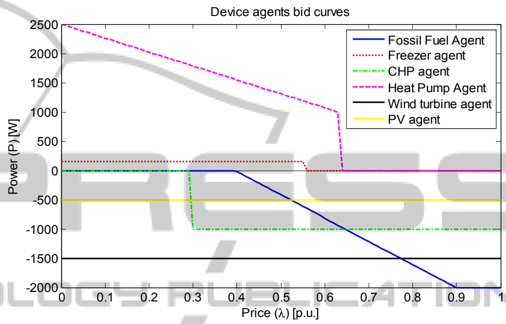

Figure 4: Example of bidding curves for power supply-demand matching.

2.3 System Optimisation

Consideration of the interrelated problems of both network and market optimisation in a dual way leads to conflicting interests between the actors involved. The elaboration of these issues is novel and not considered in most research works. To achieve an overall optimal performance of the supply system, priori knowledge about system states and market trends will be exploited and suitable strategies for allocating capacities from the resources will be formulated via the agent-based platform. One possibility to achieve optimisation of dual-objectives is the utilisation of game theory. A combination of a multi-agent model and game theory to resolve coalition formation in multilateral trade was mentioned (Yeung, Poon and Wu, 1999) - (Saad, Han and Poor, 2011). In a preliminary study, mainly cooperative game theory to dedicated conflicting problems in SEG has been developed.

A more generic method needs to be developed for dealing with complete aspects to help system overcome local optimisation traps to achieve global ones. Developed algorithms must take dynamic characteristics and constraints of the physical grid into account. Performances of these algorithms will be compared with conventional optimal power flow results in term of dynamic and fast event-based responses.

3 PROACTIVE BEHAVIOUR OF SEG

Proactive behaviour with its anticipatory capability is expected to provide the best strategy to integrate and attribute conflicting interests among actors. In the past, this feature has been hardly obtained in distribution networks due to lack of information and monitoring capabilities. In near future, SEG will be enforced with robust, redundant ICT infrastructure to enrich information thus monitoring capability of the distribution network will be improved.

On the one hand, distributed control systems need proactive behaviour to perform distributed control in real-time or even before a possible event occurs (before event occurring time). Conventional approach to the sequence of measuring, detecting and responding causes always time delays. Distributed control with very fast communication can significantly reduce this time delay to enable near real-time functions. Nevertheless, the remaining time delay is still a barrier that limits technical solutions (Wu et al., 2005). Distributed intelligence with its proactive behaviour can predict unsecure tendencies from learning its historic data and exchange information to enrich its priori knowledge about network situations.

On the other, distributed intelligence was considered particularly for either technical or commercial aspects of the power grid. Naturally, those agent-based applications can achieve only local optimisation due to its self-interests, as illustrated in dash-bold lines in Figure 5.

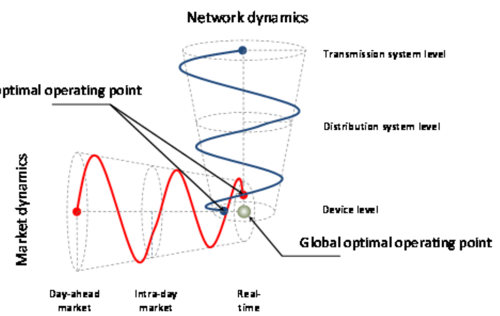

Figure 5: Limitations in SEG.

It needs to bring together cross-cutting issues related to different technical, economic and social disciplines, including advance control strategies and information and communication techniques. More specifically, by enabling proactive behaviour, distributed intelligence in SEG can mimic human intelligence by number of intelligent agents to cope with complexity, uncertainty, and variety of circumstances.

The first focus of proactive behaviour's utilisation is about a local support tool to react in real-time or on event occurring in time. Priori knowledge as a core of the tool will be obtained by using set of advanced computational intelligent techniques, such as recurrent ANN or other machine learning techniques. Via suitable Kalman Filter-based models, dynamic system states can be estimated and predicted adequately in steps ahead. In addition, proactive behaviour can enhance system optimisation to solve better conflicting interests of involved actors in an emerging multidisciplinary environment. As a classic but rich mathematic applied technique, the game theory and especially its cooperative branch could reveal innovative solutions for such complex behaviour of SEG. Novel algorithm supported by priori knowledge will yield unique optimal strategy for entities to allocate their local resources. Research's innovation is illustrated in Figure 6 that is extended from two local optimal points depicted in Figure 5.

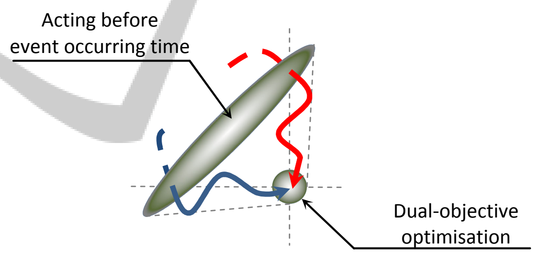

Figure 6: Innovative solutions of the research.

4 CONCLUSIONS

This paper addresses on-going research activities related to technical aspects of Smart Energy Grids. It aims to show a need of having coordinating framework in which integrated functions can be harmonised. Priori knowledge about system and perdition of system states will be a key to enable the framework, as so-called proactive behaviour. This feature could help SEG to achieve global optimal performance while system reliability and security are ensured.

Besides technical challenges, SEG needs to concern also on societal challenges as consumer comfort, mondial economic changes, (absence of) human resources, legal matters and, financial possibilities and barriers. Societal issues might turn into showstoppers. Co-operation is necessary to stand the world-wide economic changes. This is an concern for all involved stakeholders with massive knowledge and strength in the field of ICT and power systems.

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