MultiCraft

International Journal of Engineering, Science and Technology
Vol. 2, No. 3, 2010, pp. 60-68

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY
www.ijest-ng.com

Requirement analysis for autonomous systems and intelligent agents in future Danish electric power systems

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Abstract

Denmark has already achieved a record of 20% penetration of wind power and now moving towards even higher targets with an increasing part of the electricity produced by distributed generators (DGs). In this paper we report work from a sub activity "subgrid design" of the EcoGrid.dk[1] project. First we review innovative control architectures in electric power systems such as Microgrids, Virtual power plants and Cell based systems. We evaluate application of autonomous systems and intelligent agents in each of these control architectures particularly in the context of Denmark's strategic energy plans. The second part formulates a flexible control architecture for electric power systems with very high penetration of distributed generation. This control architecture is based upon the requirements identified in the first part. We also present development of a software framework to test such flexible control architectures.

Keywords: Electric power system, distributed control, autonomous systems, intelligent agents

1. Introduction

Electric power systems is one of the most critical and strategic infrastructures of industrial societies and is currently going through a revolutionary change. Deregulation, security of supply, environmental concerns and rapid growth in Information and Communication Technologies (ICT) are basic driving factors behind trends like renewables and distributed generation, free market, decentralized control, self healing and automatic (dynamic) reconfiguration in today's' power systems. Deregulation aims at ultimately providing a competitive market based environment which can offer energy to customers at a favorable price. Environmental Concerns primarily deals with CO2 emissions and global warming. Security of supply ensures the smooth delivery of energy to customers. Electric power industry has traditionally been slower to adopt modern ICT compared with other industries e.g. telecommunication. But recently, a rapid growth and significant reduction in price of ICT tools and technologies has made it inevitable for electric power industry to take initiatives to adopt ICT more effectively. This situation has created an incentive among both distribution utilities as well as network operators to develop long term strategies and plans that address above mentioned challenges.

Denmark has already achieved a record of 20% penetration of wind power (2007 data), and innovative control architectures like microgrids, virtual power plants (VPP), cell based systems, vehicle to grid, are under consideration and development in electric power system. Furthermore, Denmark is now moving towards a target set out by a new national energy strategy which implies 50% wind power penetration for the electric power system by 2025.

With the valuable experiences accumulated so far, it has been anticipated that the technical challenges for a 2025 scenario of 50% wind penetration will be in balancing the power system, development of new market services and the need for new strategies for operational security and control. Accomplishing these challenges require that future power systems are of a distributed nature, consisting of autonomous components or subsystems, are able to coordinate, communicate, compete and adapt to emerging

[1] EcoGrid project: http://www.ecogrid.dk/

situations and self heal themselves. Efforts are underway to meet these challenges. EcoGrid.dk is a principal research program on the national level initiated by the Danish TSO (Transmission System Operator) Energinet.dk, and comprised a consortium of stake holders including power distribution and generation companies, manufacturers, consultants and research institutes both in and outside Denmark, to propose a strategy for transforming the Danish power system into the world best renewable based electricity network. In this paper we report work from a sub activity "subgrid design" of the Ecogrid.dk project (phase 1). This activity is part of the work package II dealing with System Architecture.

The paper is composed of three main parts. In the first part we make a review of innovative control architectures in electric power systems such as microgrids, virtual power plants and cell based systems. In the second part we evaluate the approach of using autonomous systems and intelligent agents in each of these control architectures particularly in the context of Denmark's strategic energy plans. We identify specific requirements and respective capabilities of intelligent agents for each of these control architectures. In the third part we formulate a generic and flexible subgrid control architecture for the future Danish electric power system. We base this architecture on the requirements identified in the second part and suggest that power systems with high penetration of distributed generation may be controlled as a loose aggregation of energy units -- *the subgrid control*. Finally we present a multiagent software platform for design and test of the subgrid control concept which is currently under development.

The structure of the paper is as follows: section II presents the review of innovative control architectures in the context of the Danish Power System and a requirement analysis for the use of intelligent agents and autonomous systems. Section III presents the generic sub-grid based control architecture and section IV presents our work on developing a software framework for designing and testing the flexible control strategies mentioned in section III. Section V contains conclusions of the work.

2. Review of Innovative Control Architectures

The objective of this section is to review existing Danish and international proposals for future systems structures e.g. microgrids, cell based systems and virtual power plants and perform a requirement analysis for the use of intelligent agents and autonomous systems in these architectures. One purpose of this task within the EcoGrid.dk project was to provide input to other tasks in the project and to provide inputs to the electric power industry for their future planning and application of intelligent control technologies.

2.1 Intelligent Agents and Multiagent Systems:

“An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives” (Wooldridge 2002).

To further explain:

- Agents are encapsulated in a belief, desire, intention BDI metaphor
- Agents are situated in physical or software environments
- Agents are autonomous and can exercise control over their state and behavior
- Agents are proactive and can take initiatives by themselves rather than passively responding to changes in their environment
- Agents are social and can communicate in high level dialogues

This definition of agents and the metaphore presented in Figure 1 is analogous to the notion of engineering autonomous systems which can react intelligently and flexibly on changing operating conditions and demands from the surrounding processes (Rehtanz 2003). Such intelligent and autonomous systems provide capabilities like decomposition, reasoning, dynamic, flexibility (dynamic reconfiguration) and cooperation modeling. The remaining part of this section indicates that such capabilities are critical for realization of innovative control architectures in electric power systems.

It has been suggested to use intelligent agents and multiagent systems from a requirements rather than a technological perspective. Intelligent agents are considered appropriate for applications that are modular, decentralized, changeable, ill-structured, and complex (Wernstedt & Davidsson 2002) because multiagent architecture directly supports design and development of systems with such features.

We investigate innovative control architectures in electric power systems and argue that they have specific characteristics which makes them candidates for application of intelligent agents. We base our analysis primarily on the three most noteworthy and emerging concepts: microgrids, virtual power plants and cell based systems. It is important to note that the terminology *cell based systems* has been used in very general meaning in electric power system literature. For our study we refer to a concept applied by *the cell project*[2] of Danish TSO Energinet.dk, which falls within the general notion of cell based energy systems.

[2] The Danish Cell Project: www.energinet.dk

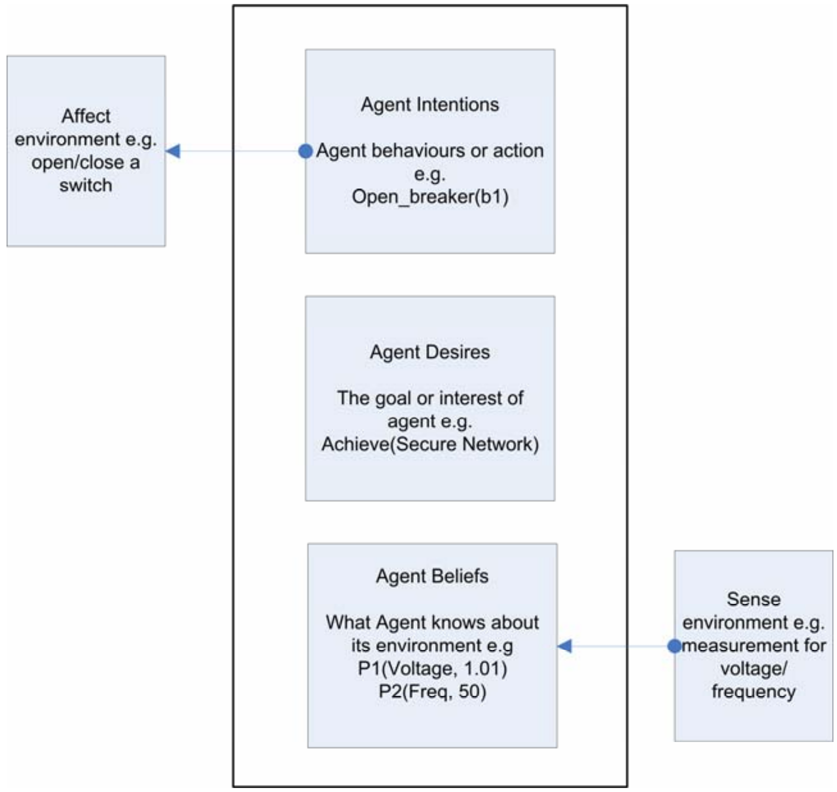

Figure 1. *Belief, Desire, Intention BDI* based abstract intelligent agent metaphor

2.2 Microgrids:

Microgrids are small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage. A microgrid can be connected to the main power network or be operated autonomously, similar to an island operation. Sources in a microgrid are usually small (< 100 kw) units with power electronic interfaces (Hatziargyriou 2008). Microgrids can be characterized by following specifications based upon current implementation and test efforts:

- Different resources in a microgrid may be owned by different owners, thus making environments where the components have competing goals, while still serving the common goal of ensuring "security of supply"
- Resources in a microgrid are of a heterogeneous nature
- In a grid connected mode, all the resources in microgrid participate in the market, whereas in islanded mode microgrid have its own market managed by local microgrid controller
- A microgrid has to be able to shift to (and from) islanded mode to grid-connected mode

Considering this characterization, intelligent software agents have a very obvious case for application in microgrid control and operation. Intelligent agents have sophisticated cooperation mechanism (Jennings 1995; Liu et al. 2006) which could help implement the required cooperation between different DGs in a microgrid. The adaptive nature of intelligent agents (Bernon et al. 2003) can help to implement dynamic adaptability in microgrids e.g., from grid-connected to islanding mode. The autonomous nature of agents is vital for the local and distributed control of microgrids and to facilitate the economic interest of individual DG owners. The ability of agents to coordinate, communicate and resolve issues can help to implement market mechanism. Also agents have the capability to strike a balance between individual and collective system goals which is relevant for implementing the above scenario of maintaining a balance between individual economic goal of DG owners and overall system goal of security of supply and balancing.

There are several efforts and demonstrations for utilizing intelligent agents and autonomous systems for design and control of microgrids (Dimeas 2004; Farred 2008).

2.3 Virtual Power Plants:

Unlike a microgrid which is a geographical aggregation, a virtual power plant is a commercial aggregation of distributed energy resources. VPP is a group of DG units which are controlled to function together like a single power plant, thereby improving the market function and providing valuable flexibility to the power system. Through the VPP concept, individual DGs will be able to gain access and visibility across the energy markets, and benefit from VPP market intelligence in order to get their revenue maximized, which otherwise would have not been able to participate in the market due to their small size or stochastic energy supply. Virtual power plants can be characterized further as following:

- Same as microgrids, different components in a VPP may be owned by different owners with competing goals/interests
- The resources in a VPP may be geographically dispersed at long distances, making the communication requirements more significant
- All nodes participate in the market, individually in the local market and in the main grid through a central facilitator (controller) of VPP
- Nodes of a VPP should have enough level of intelligence to take local decisions and perform well in the market

Besides the requirement of autonomy, local control capability, high level communication and decision making as in microgrids, it is apparent that VPP has a higher requirement for (real time) market mechanisms. Current research has shown that economic feasibility of VPP is very much dependent on good local market mechanisms, ability of the DGs inside a VPP to respond intelligently to price signals, and negotiation patterns of DGs for participating in the market (Shi 2009). Intelligent agents and other reasoning mechanism has been used widely in different market processes e.g., stock exchanges and has great potential to be used in VPP particularly enabling for individuals DGs to participate effectively in the market.

2.4 Cell based systems:

A cell is defined as the portion of a distribution system below 150/60 KV sub station typically consisting of 20-100 MW of conventional loads and a mix of CHP and wind turbine generators (Lund 2007; Cherian & Knazkins 2007).
A cell has two main operational modes:

- In the case of a cell-area operating in parallel with the HV-grid, the main focus of control is a fully automated VPP operation on existing and the future market conditions. It should also be possible for TSO to interact with cells from a control center just as they would interact with a conventional power plant

- In emergency situations in a 400 KV grid, it performs intentional islanding i.e., on receiving a signal from the control center it quickly manages a balance between generation and load within the cell and restarts itself using local resources (< 60 KV)

In the case of a cell-area operating in parallel with the HV-grid, the focus of control can be fully automated VPP operation on existing and the future market conditions. It should also be possible for TSO to interact with cells from a control center just as they would interact with a conventional power plant. In emergency situations in a 400 KV grid, it performs intentional islanding i.e., on receiving a signal from the control center it quickly manages a balance between generation and load within the cell and restarts itself using local resources (< 60 KV)

In the first case of VPP operation the control is commercially motivated and can incorporate both active and reactive power at the same time. Furthermore the controller can be asked to do voltage control in a certain grid point utilizing all available generators under its control. During the second case of emergency islanding situations, islanding occurs and control is transferred to local cells. In such cases each cell behaves like a microgrid (or island) which is not connected to the main network. When cells are islanded (in emergency situations) they are disconnected from the main grid and are no longer able to participate in the normal market.

It is clear that cell operation can either be commercially motivated, the first case of VPP operation where more centralized approach and competitive market mechanisms are required, or it can be technically motivated, the second case of emergency islanding where a decentralized (or local) control with cooperative behavior of individual resources is anticipated.

Cell based systems have a high requirement for situation awareness and being able to reconfigure in a changed situation e.g., when going to cell mode. The behavior of cell components has to be different during islanding and VPP operation modes. Thus it is anticipated that characteristics of intelligent agent technology like knowledge representation, situation reasoning and cooperative decision models can facilitate realization of this concept. Aspects of agent technology are already under testing in the cell project demonstrations (Lund 2007; Cherian & Knazkins 2007). Because of the requirement for more centralized nature of control during VPP operation and more decentralized one during islanding, it should be interesting to consider heterarchical control strategies where different modes of control are implemented at different control levels.

Table 1 summarizes a mapping of intelligent capabilities into innovative power systems control requirements. It shows the important characteristics of intelligent based systems which have a potential for application in innovative control architectures. The application cases have been analyzed with two levels of significance: high requirement and low requirement.

Table 1. Mapping of intelligent system capabilities into innovative power systems control requirements

Agent Capabilities	Innovative power systems control architectures			
	Microgrid	Virtual Power Plants	Cell based Systems	
			VPP operation	Emergency Islanding
Local/Distributed Control	H	H	L	H
Modularity	H	H	H	H
Self organization/Adaptability	L	H	L	H
High level cooperation and communication structures	H	H	H	H
Market mechanism	H	H	L	H
Robust/no single point of failure	H	H	H	H
Hybrid control mechanisms	L	L	H	H
H: high requirement L: low requirement				

3. Subgrid Architecture

As the second part of this work, a generic flexible control architecture was envisioned for future scenarios where the electric power system is a loose aggregation of units that could be a microgrid, virtual power plant or cell like structure. These subgrids not only have to optimally perform local control within the subgrid, but also must comply with responsibilities towards the main grid. This two way responsibility is particularly interesting for scenarios of electric power systems with very high penetration of distributed generation and where a large part of the grid are sub-aggregated units -- the subgrids. The subgrid control architecture tries to organize the grid in a flexible way which allows dynamic aggregation and de-aggregation of resources at different control levels. The process of (de)aggregation is supposed to be flexible enough to incorporate both technical and commercial motivations for aggregation and should have a mechanism for capturing semantics for differentiating these modes. Figure 2 shows a symbolic presentation of such a scenario. The concept of subgrid based control has been motivated and based upon the capabilities of intelligent systems e.g., modularity, decomposition, local/distributed control and its implementation is anticipated to be done using sophisticated mechanisms of coordination, cooperation and competition provided by multiagent technology.

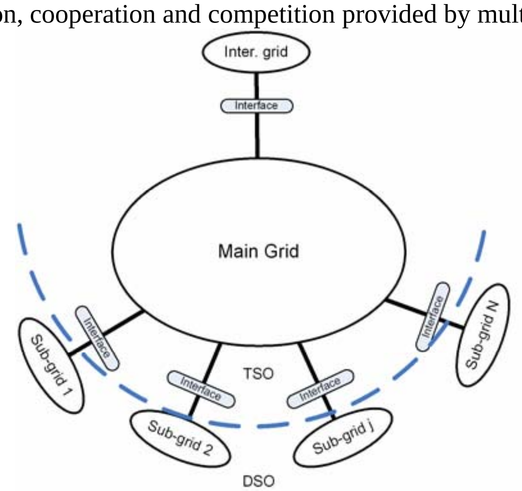

Figure 2. Decomposition of the power grid into a main grid interconnected with a number (N) of sub-grids (Lind et al. 2008; Xu et al. 2008)

Figure 3 presents different the modes of operation, and transition among these modes for a subgrid. In the following we briefly describe these modes and their operation. It should be noted that "connected", "islanding" and "commercially aggregated" are stable modes, whereas "blackout", "connected alert", "synchronization" and "aggregated alert" are modes of transition.

3.1 Connected:

This is a mode of normal operation when the subgrid is part of the main grid and taking part in normal operations. From this state the subgrid can either go to "connected alert ", in the case where early warning systems work (emergency), directly go to "blackouted" state when early warning systems does not work, or to "aggregation alert" state where it starts planning/synchronizing for commercial aggregation.

3.2 Connected Alert:

An alert message may come from a PMU based early warning system informing about some disturbance or fault and the subgrid goes to the connected alert state. The subgrid controller suggest an optimized plan for islanding operation at this state which may include reconfiguration and load shedding schemes based on the current situation. From "connected alert" mode the subgrid can go to one of following states:

- Connected mode: In the situation when a disturbance is not very severe, e.g., under-voltage signal and the grid was able to overcome it without any need to go in islanded mode (restoring)
- Islanded mode: In the situation when the system has prepared a (partial) optimized plan for islanding operation and goes safely to islanding (optimized islanding)
- Blackouted mode: in the case of a very severe disturbance and there was not enough time to prepare a plan for islanding.

3.3 Islanded:

The sub-grid may enter this mode from one of following:

- Connected mode: when early warning systems don't work and subgrid directly goes to islanded (non optimized islanding)
- Connected alert mode: when an alert message from early warning system takes subgrid to connected and it comes to islanded state with already prepared (semi) optimized plan for islanding operation
- Blackouted mode: when system was blackouted initially but then was able to prepare an optimized plan for islanding operation and blackstarts later

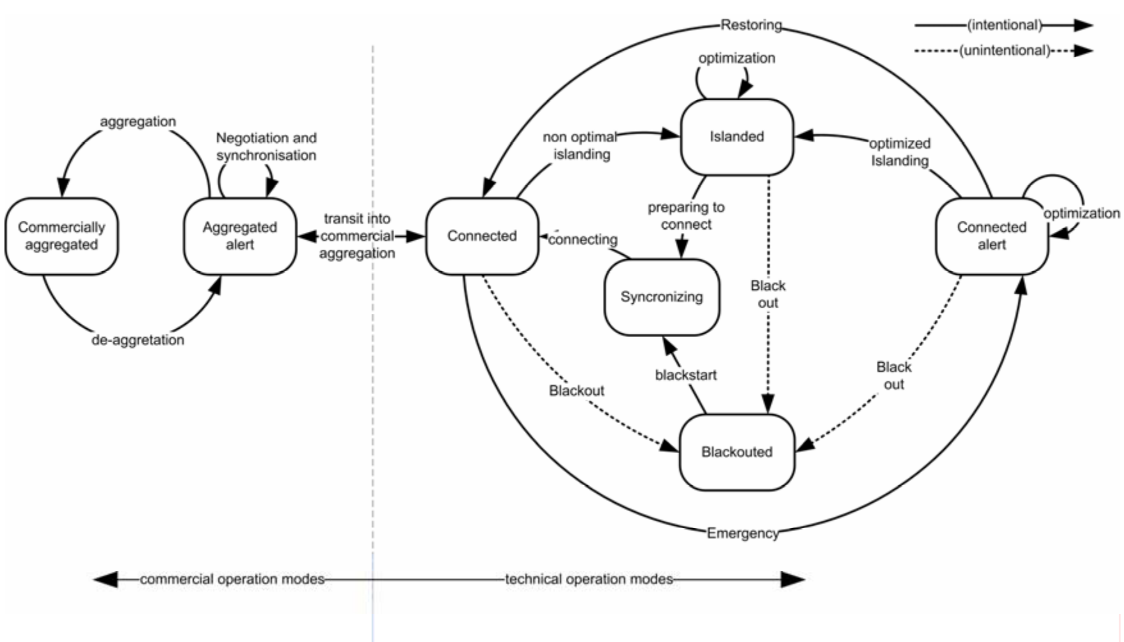

Figure 3. Control modes and transition for subgrid operation

3.4 BlackOuted:

In this subgrid operating mode there is no operation going on in the subgrid and the power is lost by all the loads. The system tries to make an optimal islanding plan at this state and tries to blackstart.

3.5 Aggregated alert:

It is a transitional mode and is reached when some agents controlling the grid resources decide to create a dynamic aggregation based upon some commercial motives. During this mode synchronization and planning is performed to prepare for commercial aggregated operation.

3.6 Commercially Aggregated:

This is a stable mode where aggregated resources perform a commercial operation e.g. VPP operation or market based intentional islanding of microgrid.

A more detailed description of the subgrid based control architecture and discussion on its usability in electric power systems with very high penetration of distributed generation can be found in (Lind et al. 2008).

4. Development of Software platform for design and testing of Flexible Control

Section II performed a requirement analysis for applying intelligent agents and autonomous systems in electric power systems with high penetration of distributed generation, a flexible control architecture was presented for such systems in section III. This section describes development of a software platform to design and test such multiagent based flexible control strategies. A dynamic multiagent platform has been implemented in the Java agent development framework (JADE)[3]. The platform consists of one main container, and several sub containers. Each sub container represents a sub-aggregation unit in a electric power network consisting of one load shedding agent LS and several DG and load agents. Both DG and load agents can join or leave the network dynamically according to the changes in the network. New such sub-aggregation units can also be created following any situation in the network. The software platform also includes JADE utility agents and services. Some of the important utilities and agents are: i) DF (directory facilitator) agent which provides yellow page services. DG and load agents interact with this agent to register and discover agent services, ii) AMS (agent management services) agent which provide white page services. This agent is responsible for creating, destroying and managing agents and containers in a JADE platform, iii) MTS (message transport service) is a service responsible for message transportation between agents within a container and across containers. This service also enables synchronization of messages when several messages are sent and received from different agents in parallel. In order to take full advantage of agent capabilities such as autonomy, local control, scalability and high level communication, the software platform is implemented as fully compliant with FIPA (foundation for physical intelligent agents)[4] standards. Figure 4 shows the structure of the software platform. It presents a symbolic representation of containers which represent electrical islands in a distribution system, the agents inside these containers and the JADE utility services described above. Detailed discussion on development and effectiveness of this platform has been described in (Saleem et al. 2009), where results have been presented from several experiments of using this platform in distributed control scenarios.

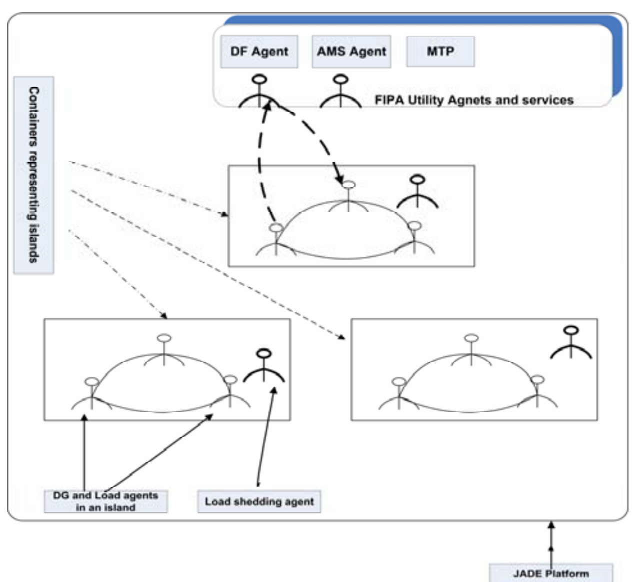

Figure 4. Software platform for design and testing of flexible control strategies

[3] Java Agent Development Framework (JADE): http://jade.tilab.com
[4] Foundation for Physical Intelligent Agents (FIPA): http://www.fipa.org

5. Conclusions

A requirement analysis has been performed for utilization of intelligent agents and autonomous systems in innovative control concepts of electric power system. A flexible subgrid based control architecture has been proposed for control of electric power systems with very high penetration of distributed generation. A multiagent software platform has been described. The purpose of this software platform is to support design and test of multiagent based flexible control strategies. This platform has been based on the requirement identified in section II and the control architecture envisioned in section III.

The approach of the paper is to identify requirement and to map them into the capabilities of intelligent systems. Subsequently, to suggest a control architecture based upon these requirements and present the development of a software platform for design and test of such control architecture.

Nomenclature

DG	Distributed Generation
VPP	Virtual Power Plant
JADE	Java Agent Development Framework
FIPA	Foundation of Physical Intelligent Agents
PMU	Phasor Measurement Unint

Acknowledgement

The authors acknowledge the support obtained from Energinet.dk and the inspiration and insights gained from discussions with members of the EcoGrid.dk work package II team. It is emphasized that the paper represents the personal views and conclusions of the authors and not that of Energinet.dk.

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Received December 2009
Accepted March 2010
Final acceptance in revised form March 2010