A Multi-Agent Framework for Power System Automation

Z. Yang, C. Ma, J. Q. Feng, Q. H. Wu, S. Mann, J. Fitch

Abstract

With the growing scale of power transmission grids, the complexity of power system automation has increased dramatically during the past two decades. Over the last decade, there have been many changes in power systems in terms of their fundamental infrastructures, information management and communication approaches. These changes generate a huge amount of information and data to be managed. This paper presents a multi-agent framework with ontology based knowledge representation to tackle the problems of information management in power systems. The framework proposed in this paper introduces an agent organization model and provides a visual ontology formalizing tool. Meanwhile, mobile agents are used for portable computation.

Index Terms – *Agent, Multi-agent Framework, Power System Automation, Ontology Engineering.*

I. INTRODUCTION

In the current power supply, transmission and distribution systems, most control and automation approaches are based on the Supervisory Control and Data Acquisition (SCADA) model. Information is gathered from a series of Remote Terminal Units (RTUs), which are wired to substation switchyards and located in control components. Although the SCADA model provides stable and acceptable performance, it also has a number of restrictions due to the centralized control format, especially in the areas of flexibility and up-to-date information access.

Considering the problems generated by the distributed infrastructure of current power systems, for example, if a substation is out of service, the electricity transmission will be redirected to ensure the customers' demands. As a consequence, when such outages happen at the same time, it will take a long time to re-schedule electricity transmission routes. Furthermore, problems about connections between distributed power resources and electric grids, centralized control for a large amount of generators and substations, as well as coordination for various terminal resources (Tolbert *et al*. 2001) are also considerable.

With the growth of continued electrification, increasing geographical scale of electricity markets and high integration with information technologies, power system management requires a new approach to improve the reliability and quality for power system automation.

In today's practice, many vendors have worked on the intelligent systems of power system automation by using the technologies of client-server, internet, as well as wireless transmission. However, these centralized control approaches still cannot conquer the inflexibility and troubles of a power system. Meanwhile, the high requirement of network bandwidth, the low integration ability, which is caused by self-designed principles, is also unacceptable.

This paper aims to provide a feasible way to tackle the problems mentioned above, a multi-agent framework with distributively organized infrastructures, self-governed units and semantic based communication techniques is proposed. Agent-oriented approaches provide a local data processing and solve the problems. In comparison with traditional electric power management system, the computation times and the network consumption are rapidly reduced due to the agent-oriented approaches. The multi-agent framework also provides several fundamental services such as agent communication, agent life cycle management, and agent negotiation. A new function can be easily added to the system by just creating a specific agent.

In the context of a multi-agent system, resources (e.g., switchgears, transformers and generators) in power systems can be shared through an IP network, which can also communicate with each other crossing a geographical distance. In order to ensure the reliability and quality for power system operations, the above framework can provide satisfactory services regarding the nature of its tasks. Furthermore, using an ontology annotation, the resources in power systems can be accommodated, organized, processed, classified, linked and identified within the proposed framework.

Ontology is a mechanism that describes concepts and the relationships among resources (Baker *et al*. 1999). The

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proposed ontology-based knowledge representation has several attractive features. Ontology provides a "clear and rigorous vocabulary" (Guarino 1998) in an application domain, which is explicitly defined and separate from the application's implementation. The formal nature of ontology is used in the integration of data from heterogeneous sources, such as an approach for query processing in (Mena *et al*. 2000). Information generated from power system resources contains numerous concepts, documentations, relevant domain knowledge, etc. Therefore, ontology is chosen to organize the information. In addition, the efficiency of knowledge exchange and communication in the proposed framework is improved. An ontology editor and a visual ontology formalizing tool can be used to edit and update the information in a power system.

The rest of this paper is organized as follows: An introduction of Agent Oriented Programming (AOP) is presented in Section II. Section III introduces the multi-agent framework. Several agent communities and the services which they provide are the main content of Section IV. In Section V, technical details of ontology agent and ontology engineering are described. Section VI illustrates an actual power system application using the proposed framework. Finally, this paper is concluded in Section VII.

II. AGENT ORIENTED PROGRAMMING

Multi-agent system has been applied to a number of distributed and network-based information management domains for integration of various heterogeneous autonomous entities (Honavar *et al*. 1998; Caragea *et al*. 2001). An agent-based approach provides a flexible, robust and adaptive mechanism for large-scale distributed systems and this is especially helpful when components of the system are not known in advance, change over time, and highly heterogeneous. Moreover, agent-based methodology also offers the distributed computing solutions. Each agent is responsible for perceiving the state of environment, updating its own knowledge, deciding future actions and finishing the tasks.

In this multi-agent framework, agents are grouped with a hierarchical structure. There are several different levels of intelligence in software agents, ranging from Information Service Agent, Ontology Annotation Agent, User Service Agent to Control Agent, Mobile Agent and Database Agent. Therefore, the framework provides a powerful problem solving mechanism through the task decomposition and agent interactions. Agents from different communities can coordinate with cooperation (agents have established and mutually agreeable objectives), negotiation (agents negotiate until agreement is reached) and mediation (agents resolve conflicts that cannot be resolved by negotiation by appeal to a third, neutral agent) (Lind 2001).

The negotiation mechanism (Zhang *et al.* 2002; McCalley *et al*. 2003) in the framework is established with coded negotiation models, which represent different decision makers of agents. Via the intercommunication, they can exchange information among the system until an agreement is achieved. Furthermore, the negotiation mechanism provides the technology to facilitate actual negotiation scenarios. By comparing solutions obtained assuming full information and centralized optimization with those obtained based on sequential, bilateral negotiations, it also provides the ability to study the effects of varying degrees of decentralization in decision problems.

III. THE MULTI-AGENT FRAMEWORK

A distributed system can be defined as a collection of autonomous processors and data storages that interact cooperatively to achieve an overall goal (Sloman 1994). Therefore, during the period of designing an efficient multi-agent framework for information management, monitoring of devices and real-time control of power systems, it is essential to consider the mission nature and provide a common knowledge representation for the collaboration of autonomous processors (domain objects, agents). The common knowledge context should address the problems of knowledge acquisition, meta information storage, information access and computing context diffusion. Agents are embedded into power system plants as their representatives, which are directly connected to their siblings and communicate with the agents that belong to their upper and lower layers.

It is an engineering process to formalize an ontology, which needs to consult the guidance of a domain expert. Therefore, it is essential for the experts to format information fragments as an organized formal ontology, using a toolkit or a wizard. In order to create an ontology for using in a specific domain, many efforts are taken to analyze various concepts and relationships which are exhibited in the domain. Considering, for example, the electrical insulation of a transformer is related to its internal temperatures. It is important for an expert to assess the condition of the transformer based upon its insulation state, thermal conductivity, thermal diffusivity and specific heat capacity. The decision making process can be regarded as a reasoning process, which also involves knowledge expression. It is quite difficult to mimic such a decision making process using a computer programming language. Therefore, it is useful to provide a structured mechanism for knowledge representation, which can describe the key characters of an automated reasoning system.

An ontology explorer is specifically developed for this purpose. It provides a friendly graphical user interface, which domain experts can edit, update, query, generate and abandon an ontology. Once an ontology is created, the domain experts can use the explorer to specify the concept and relationships of this ontology within the existing ontology communities by using a set of 3-D graphical view which includes tree view,

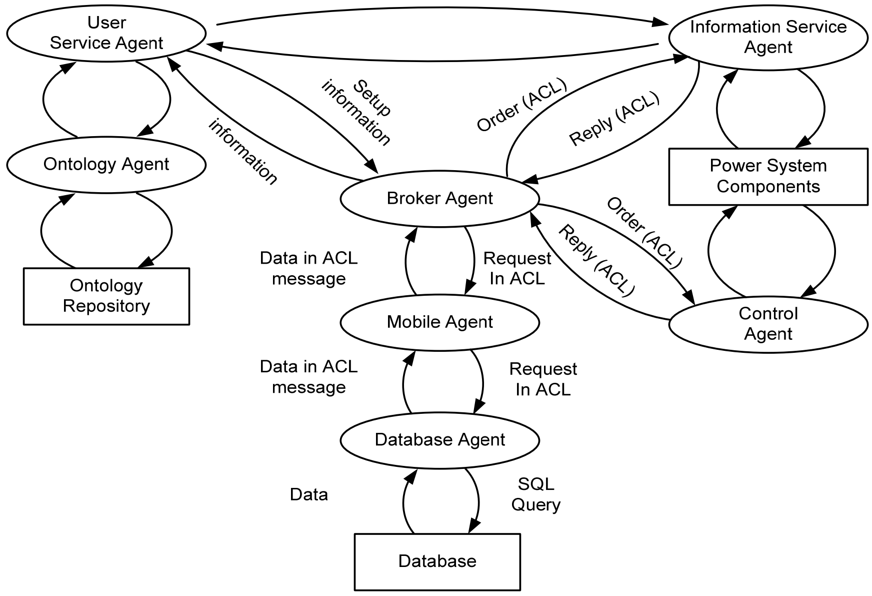

Fig 1. System Framework

table view as well as RDF (W3C 2004a) view. For instance, ontology O_A is *SubClassOf* another ontology O_B, the sensible *weight* of connection between O_A and O_B will be clearly displayed on the 3-D graphical view of explorer. Slots and constraints are also visualized to give a direct understanding from the viewpoint of engineering.

The process of querying the power system information includes the following steps:

1. Query request submitted: The explorer provides a query interface to assist the user for submitting query request.

2. Query processed: The explorer is equipped with an inference engine to convert semantic representation into a machine readable expression, which can be used by agents to query information in the power system.

3. Resource searched: Since the query result must be included in a resource or component of power system, therefore, explorer will locate its representative agent in

   the agent communities and get athirst information.

4. Results displayed: Finally, the explorer shows the detailed information on an information panel.

IV. AGENT COMMUNITIES

In order to specify the tasks of agents, the multi-agent system has divided the multiple agents into several individual agent communities. As can be seen from Figure 1, it includes: a user service agent community, a broker agent community, a mobile agent community, an information service agent community, a database agent community, a control agent community and an ontology agent community.

A. The community of user service agents

Agents from this community are concerned with the ontology explorer interface. They afford monitoring, assistance as well as intercommunication approaches (e.g., Personal Assistance Agent (PPA)) to users. Roles defined in this community and their distributions depend on the additional specifications of the functions.

USer Service Agent (USSA) can be used in the user interface and user profile managements:

1. User interface management: As mentioned above, a friendly user interface are provided in the multi-agent system. It is a PPA which allows the human users to control the power resources and components dynamically.

2. User profile management: This service endeavors on the management of user's profiles. The user profile agent can be regarded as an archivist. The archives of users are described as ontology annotations and deposited in an ontology repository.

On the other hand, they also focus on the interactions between the human user and other agents based on thefollowing design principles:

1. Goal oriented: The USSA accepts the query request from human users and autonomously decides how and when to process the problem;

2. Charitable: The USSA should understand the semantic meaning of the request and translate it into an agent readable format using ontological annotations;

3. Balanced: The USSA will balance the cost of finding a piece of information and avoids the nuisance of pestering the human user with any question;

4. Compatible: Under the direction of Directory Facilitators (DF), the USSA can contact with other agents by means of FIPA (Foundation for Intelligent Physical Agents) ACL (Agent Communication Language) (FIPA 1996) messages in order to make the communication compatible.

B. The community of broker agents

In many scenarios of information management implementation, the "distributed I/O devices" such as IEDs (Intelligent Electronic Devices) and RTUs have many obvious limitations, for example, private communication protocols, difficulties of re-configuration and lack of flexibility for coordination. Broker Agent (BA) is just a suitable solution for the case. It organizes the functionalities of various agents who have provided the subscription services and then advertises the functions as the services that itself provides.

This function is named Yellow Page Service (YPS) which is based on the FIPA specification and uses the JADE (Bellifemine 2003) platform. All the gathered agent function information is stored in the DF which is the core component of broker agent community.

In this community, two broker agents, i.e. a query broker and a request broker, are included. They allow users and other agents to submit a query or request an action. When a particular event notification is obtained, the broker agent creates a subscription with the service provider agent and forwards the received notification.

With the DF, it is guaranteed for broker agents to find the suitable service provider agents. In addition, the locations of these agents are also precisely ensured.

C. The community of mobile agents

With the cooperation between broker agents and static agents, various tasks can be preformed in power system automation. However, the slow network links and limited bandwidth between grids and substations, substations and substations can greatly reduce the system performance. This situation especially occurs when it is necessary to monitor a long period action.

Mobile Agent (MA) is designed for the above problems. The MA is implemented on the J2ME (Java 2 Micro Edition) platform over a strong arm microchip with mature mobile devices and an embedded operating system. It can be launched by any agent in the multi-agent system and provided with specific task configurations.

The MA moves the computational load onto more powerful plants when the system is lowly configured. Moreover, transferring a mobile agent to an isolated plant and let it perform a series of tasks locally is strongly recommended.

Considering the limited data links between various apparatuses, the MA should transfer as little data as possible. Therefore, it is not recommended that the MA moves between different plants, unless it is necessary. Normally, the MA should generate the optimal result in one plant before it moves to the sender or the next destination.

D. The community of information service agents

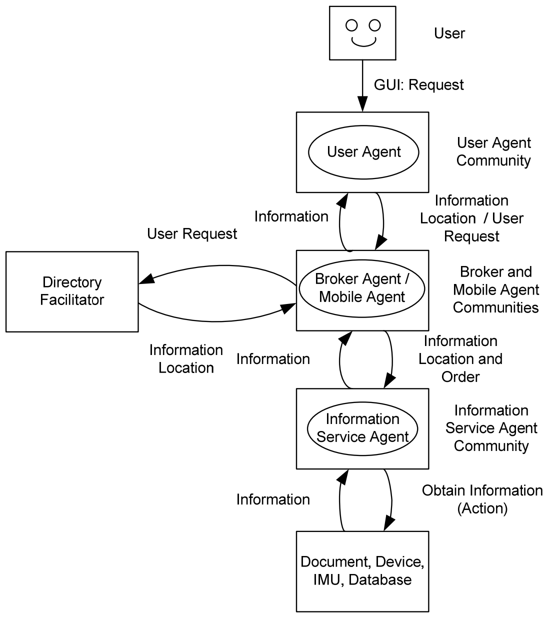

Fig. 2. Information Retrieval

Agents from this community are responsible for collecting information (e.g., average values of voltage and current, active and reactive powers, or perhaps even the real-time voltage and current waveforms) from existing heterogeneous information resources, such as IMU (Information Management Unit), databases, documents as well as hardware within a power system.

At the same time, they also provide intercommunication mechanisms for other agent communities and perform surveillance on the on-line and idle devices, documentations, work flow status and control procedures, etc. As shown in Figure 2, the user agent retrieves the information by sending a request to a broker agent or a mobile agent. Then the available information is brought back with the assistance of the Information Service Agents (ISA).

E. The community of database agents

Database Agent (DA) accesses a database with FIPA ACL. It is responsible for interacting with individual databases. This agent updates the static databases with data from the plants of a power system. This task, although trivial, is vital for the system performance, as it relieves humans from manipulating a huge amount of information.

When the DA receives a message from the broker agent or mobile agent, it establishes a connection to the related databases and stores all information and configurations in the FIPA ACL format on a corresponding table.

In addition, the DA also provides information to the Ontology Agent (OA) as the materials of ontology annotations, which will be used as the knowledge base of the multi-agent system.

F. The community of control agents

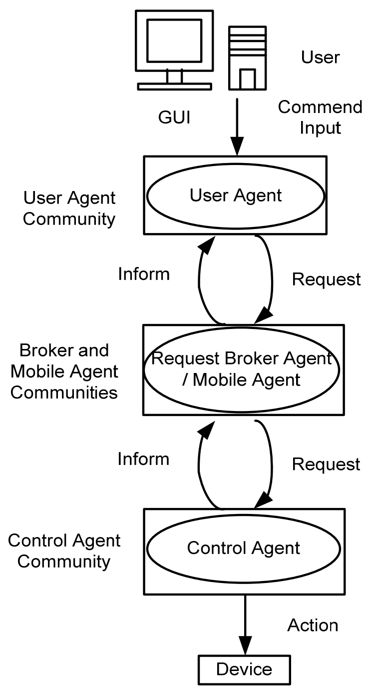

Fig. 3. Inclusion of Control Agents

Control Agents (CA) from this community are embedded into devices (e.g., substation, generator, electric motor, etc) of a power system and provide the input and output channels for contacting with the broker agents and the mobile agents, which are used to deliver the operator's orders of operation, as shown in Figure 3. Via the output channel, the CA can negotiate with broker and mobile agents requesting further information of actions as well as sending feedback of finished operation results and failure information.

According to the obtained action information, the CA dynamically changes the conditions, environments, parameters of electric power plants. Meanwhile, CAs also set up a communication with the plants of the power system and alert corresponding configurations in order to make sure that all parts of the power system work in a normal functional mode.

V. Ontology Engineering in The Framework

Comparing with static databases, the ontology annotations have composed the real knowledge repository of the multi-agent system. The OA provides a common knowledge context as a semantic ground for inter-operation and communication of agents in the multi-agent system. At the same time, it also supports access to the ontology annotations of power system's plants, manages the distributed evolutions and controls the growth of ontology in the ontology repository.

Moreover, the OA can be embedded into the ontology explorer to support information download and update services as well. It involves mapping raw information into ontology and monitoring services for ontology change notifications, etc. In order to display the concepts and relationships between concepts of the power system, the OA chooses the “DAML+OIL” (W3C 2001) and “RDF schema” (W3C 2004b) for mapping the information corresponding to the ontology annotations.

All the other agents could interact with the OA when they need information for specific tasks, for instance, the initialization of the user agent, configurations of data acquisition for mobile agent and update of database agents, etc.

A. The definitions of ontology levels

In the multi-agent system, ontologies are distinguished according to their roles for information services:

1. Top-level ontology describes general concepts. These concepts are broad classification of the objects existing in the system. In the multi-agent framework, the top level concepts are Device, User, Agent and Operation.

2. Domain ontology is used to define vocabularies about the entities, attributes and relations within a knowledge domain. In the framework, domain ontology builds the internal relationships and annotations within a specific knowledge domain.

3. Operation ontology defines an operation or behavior such as the behavior “Log-Retrieve” for data log retrieval operations, the behavior “Onto-Query” for a certain ontology request, etc.

4. User ontology provides information on user characteristics, such as user's domain knowledge, records, identities, daily operations, etc.

B. The life-cycle of an ontology

The life-cycle of an ontology is an iterative process: “composing”, “utilization” and “abandonment”. Since the ontology approach is used to achieve the global sharing of knowledge, the “composing” procedure can be interpreted as “rewrite” or “update” of an existing ontology. The outcome of information collection is restricted by nature languages as a set of terms and relations. Therefore, it is called semi-informal ontology. It can be encapsulated into axioms of knowledge representations using OWL (W3C 2004c), which captures concepts and their meanings by describing object classes and relations between the objects. “Utilization” is a significant stage of an ontology's life-cycle. It is the major contribution for a knowledge inference and information management in implementations. The third step of an ontology is “abandonment”. Unvalued ontology will be given up after they have finished their tasks. The existence of life-cycle of an ontology ensures the multi-agent system to reach a desired state in a particular time scale. Knowledge consultation, acquisition and evaluation are carried out throughout these three stages as well.

VI. APPLICATION IN POWER SYSTEMS

An example is described here to illustrate the proposed framework, which is applied to the power substation information management. For the simulation purposes, a power system is composed of 100 substations and each substation contains several IEDs, which are embedded into substation plants (e.g., transformers, switchgears and other equipments) and responsible for control and monitoring tasks.

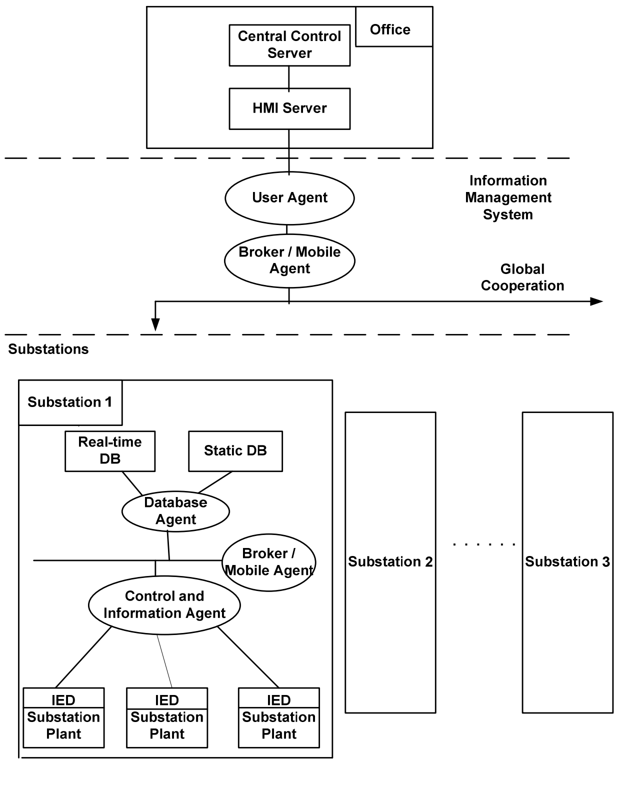

Fig. 4. Substation Information Management

As shown in Figure 4, a central control platform is provided for administrators to input their commands. With the cooperation of Human-Machine Interface (HMI) and USSA, such commands are changed into a machine readable format in order to make them processable in the following actions. Useful information then is transported to the broker agent and the mobile agent for further operations based upon the principles stated earlier.

The substation contains two databases, a static database and a real-time database. Both of them are tailed by the database agent. The static database is designed for depositing substation topology information and the real-time database is used for providing work condition monitoring, security checking as well as logging services.

In comparison with centralized management applications, the multi-agent information management framework demonstrates the services of relay control, information retrieval, work flow monitoring and real-time information display with the following advantages: the agent based approach provides increasing flexibility of power system extensions with a standard framework; agents are loosely connected with a central control platform physically, therefore, errors can be fixed locally without any influence of other components; and, the utilization of the mobile agent has greatly reduced network jams.

VII. CONCLUSIONS

This paper presents an ontology embedded multi-agent system framework for information management in power systems. Under this framework, a dynamic graphical ontology explorer has been designed for intercommunications between system operators. In addition, it supports rapid communication and control responses with internal agents from different agent communities. In comparison with the traditional management technologies of electric power systems, the proposed multi-agent framework has been identified as a feasible solution to tackle the complexity of modern power systems under various requirements.

REFERENCES

BAKER, P.G.; GOBLE, C.A and BECHHOFER, S., 1999. An Ontology for Bioinformatics Applications. *Bioinformatics.* 15 (6), 510-520.

BELLIFEMINE, F., GAIRE, G., RIMASSA, G., 2003. *JADE, A White Paper* [online]. JADE. Available from: http:// jade.tilab.com/papers/2003/ White Paper JADEEXP.pdf

CARAGEA, D.; SILVESCU, A. and HONAVAR, V., 2001. Towards a Theoretical Framework for Analysis and Synthesis of Agents that Learn from Distributed Dynamic Data Sources. *In: S. WERMTER, J. AUSTIN, D. WILLSHAW, eds. Emergent Neural Computational Architectures Based on Neuroscience.* Berlin: Springer-Verlag, 547-559.

FIPA, 1996. *Agent Communication Language Specification* [online]. FIPA. Avaible from: http://www.fipa.org/repository/aclspecs.html

GUARINO, N., 1998. Formal Ontology and Information Systems. *In: 1st International Conference on Formal*

Ontologies in Information Systems, June 1998, Trento, Italy. Trento: IOS Press, 3-15.

HONAVAR, V.; MILLER, L. and WONG, J., 1998. Distributed Knowledge Networks. *In: IEEE Information Technology Conference, 1-3 Sept, 1998, Syracuse, NY* . New Jersey: IEEE Press, 87-90.

Lind, J., 2001. *Iterative Software Engineering for Multiagent Systems : The MASSIVE Method (Lecture Notes in Computer Science / Lecture Notes in Artificial Intelligence).* Berlin: Springer-Verlag.

MCCALLEY, J.D.; ZHANG, Z.; VISHWANATHAN, V. and HONAVAR, V., 2003. Multiagent Negotiation Models for Power System Applications. *In:* C. REHTANZ, ed. *Autonomous Systems and Intelligent Agents in Power System Control and Operation.* Berlin: Springer-Verlag, 49-74.

MENA, E.; KASHYAP, V.; SHETH, A.P. and ILLARRAMENDI, A., 2000. OBSERVER: An Approach for Query Processing in Global Information Systems based on Interoperation across Pre-existing Ontologies. *International Journal of Distributed and Parallel Databases.* 8 (2), 223-272.

SLOMAN, M., 1994. *Network and Distributed System Management.* Boston: Addison-Wesley.

TOLBERT, L.M.; QI, H. and PENG, H., 2001. Scalable Multi-Agent System for Real-Time Electric Power Management. *In: IEEE Power Engineering Society Summer Meeting, 15-19 July, 2001, Vancouver, Canada.* New Jersey: IEEE Press, 1676-1679.

W3C, 2001. *DAML+OIL(March 2001) Reference Description* [online]. W3C. Available from: http://www.w3.org/TR/daml+oil-reference.

W3C, 2004a. *Resource Description Framework (RDF)* [online]. W3C. Available from: http://www.w3.org/RDF

W3C, 2004b. *RDF Vocabulary Description Language 1.0: RDF Schema* [online]. W3C. Available from: http://www.w3.org/TR/rdf-schema.

W3C 2004c. *OWL Web Ontology Language Reference* [online]. W3C. Available from: http://www.w3.org/TR/owl-ref.

ZHANG, Z.; VISHWANATHAN, V.; MCCALLEY, J.D. and HONAVAR, V., 2002. A Multiagent Security Economy Decision Support Infrastructure for Deregulated Electric Power Systems. *In: 7th Probabilistic Methods Applied to Power Systems (PMAPS), 22-26 Sept, 2002, Naples, Italy.* New Jersey: IEEE Press, 39-44.

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