Decentralized Control and Management Systems for Power Industry via Multiagent Systems Technology

I. Zabet (Power and Water Uni. Tech)
M. Montazeri (Power and Water Uni. Tech)

Abstract—**In this paper we have done a survey over control and management challenges in modern power systems today in terms of emerging distributed power generation (DG), microgrid management, electricity marketing and power quality control toward smart grid. Intelligent agent and multiagent systems (MAS) technology are introduced, then properties and more potential benefits of MAS for power systems such as scalability, expertise and grid-computing are discussed to address MAS is a appropriate solution for power engineering challenges.**

Index Terms—**Multiagent systems technology, decentralized control, management systems, modern power systems**

I. Introduction

Today *central control systems* for power industry facing many challenges that are primary related with the huge number of control variables, the complexity of the system as well the demand of adaptability to a dynamic and uncertain environment. This means that the software developed for these applications should be more complex and extended in size.

In conventional, this is accomplished by *Supervisory Control and Data Acquisition (SCADA)* systems [1]. Current trends to control and management the operations moving toward the use of *Distributed Control Systems (DCS)*, especially nowadays an automated agent technology, which is generally known as a MultiAgent System (MAS) technology [2].

There are several standards have been proposed in order to immigrate from centralized concepts to decentralized one. Understanding this need the *International Electrotechnical Commission (IEC)* initiated development of set of standards, IEC 61499 [3] modified the IEC 61131-3 Function Block (FB) concept [4] consider as well the FB concept in field-bus standardization IEC 61804 [5]. There are some similarities and remarkably different concepts between IEC 61499 and its preceding IEC 61131 which is made it a generic standard, platform independent and suitable for distributed control applications especially agent-based technology [6] .

Another is new IEC 61850 international standard for substation communications allow [7] future development and implementation of self-configuring substation automation systems. IEC 61850 defines functions of a substation automation system (SAS) related to the protection, control, monitoring and recording of the equipment in the substation; these functions are implemented via a single or can be distributed between multiple intelligent devices within using communications interface, thus each device can be considered as an intelligent agent [8] .

Moreover the IEEE Engineering Society's (PES) Intelligent System Subcommittee has formed a Working Group to investigate and overcome challenges about using multiagent system technology in power engineering. The PES Working Group examined the potential value of MAS technology to the power industry, described fundamental concepts and approaches within the field of multiagent systems that are appropriate to power engineering applications [9], and design and implementation of such systems with a review to standards and developing tools discussed in [10]. Also multiagent solutions for distributed computing, communications, and data integration needs in power industry, presented in [11].

In this work, we have been investigating MAS approaches and applications in power systems problems and see considerable amount of potential in them for contributing power industry challenges in decentralized control and management.

The remainder of this paper is organized as follows; Section II provides an overview of the Multiagent Systems (MAS) technology as a new paradigm using in decentralized control and management. In this section also discuss about standards and tools for developing MAS and at last introduce the potential of MAS in the area of power engineering; Section III presents fields of distributed systems and control in power systems and describes solutions, previous works and potentials to implement MAS technology. Section IV argues that MAS is well suited as a management system and it is one of the best solutions for managing issues in power systems. Section V concludes the paper.

II. Multiagent Systems (MAS) Technology, Properties, and Potentials in Power Industry

A. Overview

Miltiagent Systems and intelligent agents are a new paradigm for developing software applications. Today, agents have been the focus of researches in the area such as *Distributed Artificial Intelligence (DAI)*; also they are being used in an increasingly wide variety of applications in several engineering fields. Many important computing applications such as planning, process control, communication networks and power industry will benefit from using this existing technology. An autonomous agent has the following main characteristics:

1. Reactivity
2. Pro-activeness

3. Social ability

Multi-agent system is an autonomous system, which many agents form a community together and depend on each other. Nowadays, MAS attract researcher's attention due to its possibility to handle problems flexibly that can be adopted with a single agent system operated in a single computer. So far, MAS suitable to be exploited in two ways: as an approach to construct flexible, robust and extensive hardware/software systems; and as a modeling approach. MAS have some properties as follows that provide flexibility, extensibility, and fault tolerance [9]:

1. Autonomy
2. Open architectures
3. Platform for distributed systems
4. Fault tolerance

1) AOP vs. OOP

Since implementing a flexible agent needs to develop under modular software programming in most cases, *Agent Oriented Programming (AOP)* has a higher level of encapsulation than *Object Oriented Programming (OOP)*. The agent concept is similar with software object in several ways, since OOP defines the object in terms of methods and attributes, but an agent has more general concept than an object, and in addition to properties of objects, it's defined in terms of *behavior* and *ontology*.

Behaviors implement the tasks (or intentions) of an agent. Ontology indicates the vocabulary of the symbols used in the exchange messages content between agents[12].

2) Standards & Tools

Foundation for Intelligent Physical Agents (FIPA) was first established in 1996 as an international non-profit association to develop a set of standards relating to software agent technology [13]. FIPA was reincorporated in mid-2005 as a standards committee of the "IEEE Computer Society", lending credibility to the use of FIPA as standards for industrial and commercial multi-agent system applications. FIPA standards manage the basics of an agent architecture, including agent lifecycle management, inter-agent message transport, message structure, inter-agent interaction protocols, and security.

The MAS literature [14] indicates a large number of agent-oriented frameworks and the most important standardization effort in the software agent is FIPA [15]. There are a variety of the FIPA implementations (ZEUS, RETSINA, FIPA-OS, and GRASSHOPER). One of them is *Java Agent DEvelopment framework (JADE)* [16] an open-source middleware used over the last years by academic and industrial organizations which is FIPA compliant. Agent communication is also performed through message transfer; message representation is based on the *Agent Communication Language (ACL)* prepared by FIPA.

B. Properties

In multi-agent systems, agents are grouped to form communities that *cooperate* or *compete* to achieve the goals of individuals and/or of the system as a whole. Multiagent architectures as a decentralized systems have the capacity to offer several desirable properties over centralized systems. The following properties candidate MAS as a distributed solution over power industry [17].

Unit autonomy; the various agents in a Microgrid can behave mostly autonomously in a cooperative or competitive environment.

Reduced data manipulation; since in an agent-based approach the information should be processed locally and the agents should exchange knowledge with other agents, in this way, the amount of information exchanged is limited. For example the agent of a unit only knows the voltage level of its own bus and, maybe, it can estimate what is happening in specific buses, but it has no needed information about the whole design of the control system and microgrid, based on this lack of information.

Reliability; in case one of the controllers fails, other agents may adapt and continue the system function.

Openness of the Architecture; MAS allows any manufacturer of distributed sources units or loads to embed a programmable agent in the controller of its equipment according to some rules.

Performance; Agents can operate asynchronously and in parallel, which can result in increased overall performance.

Robustness; each agent is more reliable because of its reduced complexity. The failure of one or more agents does not necessarily make the overall system useless, because the control and responsibilities are shared among different agents.

C. Potential benefits of MAS in Power Industry

1) Scalability

A combination of cluster computing and multiagent systems has also been used for achieving scalability. This concept is used in a distributed multiagent model for network based, financial computing and economic analysis [18], and for developing scalable software systems on heterogeneous networks [19]. Especially for large scale power systems with hundreds of components. The size of the multiagent system used in addressing the problem and interactions among agents introduce challenges due to scalability [20].

2) Expertise and Decision Support System (DSS)

With the development of technology of large-scale network, such as computer network, computer communication network and especially power systems, power distribution network, study on agent and Multi-agent Systems (MAS) has become significant area of Distributed Artificial Intelligence (DAI) research.

DSS constitute a class of computer-based information systems including knowledge-based systems that support decision-making activities and qualitative analysis technology using *Expert System (ES)*, *Intelligent Decision Support System (IDSS)* is more effective than DSS in solving semi-structured or non-structured problems, which has got a comprehensive and successful application in many domains [21].

3) Grid-Computing

Grid computing is focused on harnessing hardware resources (computational power) to solve complex computational problems, and also algorithmic procedures for performing parallel processing and distributed computing [22].

The development of Grid Computing is analogous with the Distributed Monitoring and Control of Future Power Systems via Grid Computing early development of the Web. Levels of data security and Quality of Service (QoS) can be guaranteed through service level agreements between Grid Computing entities and Web Service Providers.

III. DECENTRALIZED CONTROL IN POWER SYSTEMS VIA MAS TECHNOLOGY

Decentralized control is a key ingredient of tomorrow's highly versatile systems, which range from microscopic sensors and actuators embedded in our environment to networked home and office appliances to large-scale network such as power systems. Since emerging distributed power generation (DG), power quality control, electricity marketplace, leads to increasing complexity on the modern power distribution network and increased number of interconnections. Using current approach like central or smaller distributed SCADA is no longer sufficient for such modern and complex systems [23], [24].

In this section we focus on approaches for implementing decentralized distributed control for power systems using multiagent systems, and various properties for control engineering over power system (esp. microgrid) such as modeling, methods, intelligence and learning investigated.

A. Distributed Control

Simulating a large-scale power system with detailed modeling of the components creates a heavy computational burden. In [25] proposed Agent-based Distributed Simulation which makes use of the networked control and distributed computing an overall system solution through separately and concurrently computing units.

Distributed control of Microgrid has three levels which are Distribution Network Operator (DNO) and Market Operator (MO) at the level of the medium voltage, MicroGrid Central Controller (MGCC) and Local Controllers (LC), which could be either micro source controllers or load controllers, agent technology can accommodated at each layer with different tasks [26], [27]. Ancillary services are those necessary to sustain the basic operation of power systems provided by generators and transmission control equipment.

Distributed Sources Control conducts to problem of placing the generation near the loads and the Microgrid concept.

A Microgrid comprises a LV or MV locally-controlled cluster of *Distributed Energy Resources (DER)* that behaves, from the grid's perspective, as a single producer or load unit. A Microgrid operates safely and efficiently within its local distribution network, but it is also capable of islanding [28].

B. Power Quality Control

The industrial processes are susceptible to power quality problems outside the scope of conventional interruptions. The information is critical in detecting, resolving and preventing power quality problems and is essential for evaluating total system performance. A power-quality agent can read the measured data from the process, compute power quality indexes, and shared the processed data with other agents. A distributed system is more available then one centralized to detect incidents like transients (frequency and amplitude changes in voltage and/or current waveforms), sags and swells, flicker, noise, harmonics or frequency variations.

Flexible Alternating Current Transmission Systems (FACTS) devices can use for power flow control and/or node voltages dynamically control. They may increase the controllability in power systems and offer opportunities to agent approaches [29]. *Intelligent Electronic Devices (IEDs)* are the standard in new or upgraded integrated substation protection. Microprocessor based *protective relays* protect substation equipment, but also provide additionally functions like metering, event recording or built in fault analysis tool. Embedded software agents are an artifact of the need to exhibit some degree of autonomy and mobility. The IEDs must provide necessary computational and I/O capabilities needed to support a software agent.

The real-time regulation between generators consider to demands, would be performed by *Automatic Generation Control (AGC)* to keep the frequency of the system within safe operating limits and the interchanges between the areas at the scheduled value.

C. Strategies and Modeling Approaches

In this section we discuss about control strategies, modeling and introduce some methods using in control of parts of power systems.

The strategies of decentralized control, divided into two categories; Competitive and Cooperative. These categories based on behavior of an agent to reach their goal respect to other agents.

Since power system immigrates to modern power system with huge interconnected devices and more complexity, traditional modeling approaches will not applicable more. In this part 3 of this section we introduce some modeling issues which will be appropriate for sophisticated systems.

1) Competition

Market-based control is an example of competitive model of MAS which a large number of agents are competitively negotiating and trading on an electronic market; optimally achieve their local control action goals [30].

In market-based control, many control agents competitively negotiate and trade on an electronic market to optimally achieve their local control action goals. Each device is supervised by a control agent who tries to operate the device process in an economically optimal way conform to process's constraints. The agents negotiate prices on an electronic exchange market either their consumption or electricity production, and the resulting price determines the power volume allocated to each device.

Regulation is one of the ancillary services traditionally provided by the generating units, under the authority of a balancing area, to continually compensate for the difference between load and generation. There are several forms of competitive markets for regulation. These markets have usually been markets for capacity reserves and have variously been called regulation, balancing, load-following, frequency control or even combined with spinning reserve markets.

In [12] defines three types of regulation market for participating generators in power systems, as follows:

- A flat-rate regulation market
- A price based regulation market
- A response based regulation

2) Cooperation

Over the last decades *MPC* (also known as receding horizon control or moving horizon control) has become an important strategy for finding control policies for complex, dynamic systems. MPC in a single-agent control structure has shown successful application in power networks. In a *multi-agent MPC* structure, there are multiple control agents, each of them controlling only its own subnetwork, i.e., a part of the overall network since the agents cooperating with each other to meet a global goal. In the *multi-layer multi-agent MPC* case there are multiple control layers in the control structure, i.e., there are authority relationships between the agents in the sense that some agents provide set-points or directions to other agents. The agents at higher layers typically consider a larger region of the network and consider slower time scales than agents in lower layers [31].

3) Modeling

Preceding standards and technologies in the industrial software domain are based principally on functions whereas IEC 61499 introduces the OO paradigm in this domain. Moreover, it can be foreseen to be a tool in integrating the Holonic and Agent-based concepts into industrial applications [6].

There are 3 types of control technologies that exist today and will continue to be available to power system control engineers: generation controls, power-electronic based transmission controllers, and management and protection schemes. As long as the first two, have continuous dynamics, using continuous feedback control action; the third exerts discrete open-loop control action. Thus, power system control is a typical hybrid system naturally, which consists of both continuous and discrete control [32].

Traditional modeling methods of *Hybrid System* can be divided into two main groups: methods based on *Discrete Event Dynamical System (DEDS*) and methods based on *Continuous Variable Dynamical Systems (CVDS)*. The former considers hybrid system as a kind of expansions of DEDS by zoning continuous system state space [33] .

Now power system is hierarchical, which can be divided into subsystems such as primary system, secondary system, SCADA, Energy Management System (EMS) and Office Automation (OA). But sophisticated model is needed to describe the characteristics under big disturbances, including continuous and discrete dynamical characteristics. For example, the behaviors of power generator and load can be regarded as continuous dynamical behaviors complying with physical laws which are often described with a group of differential and algebraic equations, while protection and remote control of power system show discrete characteristics driven by events complying with logical rules relevant to continuous dynamical signals. In [33] power system is modeled with method based on *Controlled General Hybrid Dynamical Systems (CGHDS)*. The global and local systems which are described with different models can be treated as continuous subsystems.

Petri nets (PNs) are mathematical models, which can be used to describe and analyze distributed systems. A petri net can describe the interaction of multiple agents in wide-area nets. As a visual modeling tool for distributed systems, PNs have some advantages over traditional methods, such as the ability to capture behavior in the form of *rule sets*, *flowcharts*, and *Finite State Machines (FSM)*. To overcome state calamities, colored and object-oriented PNs have been studied in [34]. The G-Net is an object-based extension of PNs, which is defined in terms of a set of independent and loosely coupled modules in. *Agent-oriented PNs (AOPN)*, based on the G-Net, have been used to express the perception and collaboration of agents in [35], [36], [37]. Some intelligent elements, such as goal processing, knowledge processing, environmental data, sensor data, and decision-making, are introduced to make an agent autonomous and goal driven. But the decision-making and sensor modules are abstract, and message processing is not based on the current running state of the agents. PNs have been successfully applied in power systems in areas, such as electric power markets, fault diagnosis, and power system restoration [38], [39], [40], [41].

An agent-oriented peer-to-peer negotiating colored petri net (AOPCPN) also for a wide-area backup protection system is proposed in [42] , which combines the principles of colored PNs and AOPN. The autonomy, cooperation, concurrency, and robustness of wide-area backup protection agents are embodied in modules.

4) Methods

Decoupling power system network into subsystems and solve them independently by subsystem's agent, and then gather the results to make solution for the overall power system, one possible way to reduce computational cost [43]. The way to decouple network and represent the missing parts will affect the result greatly. In [25] describes the algorithm extended from the DC coupled method to distributed simulation in the power system.

A fundamental problem in *graph theory* and *combinatorial optimization* is the *maximum flow problem* for which many different sequential and parallel algorithms have been developed. This algorithm has been implemented to find a solution to maximum amount of flow from a source to a sink node and will be useful in the design of the energy management system. The power flow problem of the electric shipboard system is presented in [44]. The *Optimal Power Flow (OPF)* problem consists of obtaining magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line of a power system, traditionally solve with *Transmission System Operators (TSOs)* which operate on interconnected electrical power systems [45].

The *Reactive Power Dispatch* is to minimize the active power loss in the transmission network which can be described as an optimization problem subject to voltage and power flow constraints. For solving the problem a *Multi-Agent based Particle Swarm Optimization (MAPSO)* approach, was adopted in [46], and considered an agent a particle from the *Particle Swarm Optimization (PSO)* and a candidate solution to the optimization problem.

To provide damping to system oscillations, *power system stabilizers (PSSs)* have been used for many years. But in modern interconnected power system, *transient stability* becomes a complex and more sophisticated issue. One of solutions will be implementing agent-based stabilizers via power network [47], [48].

D. Intelligence and Learning

Given a large power system operating with the aid of new control devices, advanced communications, and computer hardware a learning to control approach emerges as an attractive way to cope with increasing complexity in power system stability control [49].

A basic question that was often asked by researchers in the field of Game Theory and Artificial Intelligence (AI) is how to design a learning algorithm that allows an agent to learn about the environment in which it resides and to maximize its chances of success.

Some of the key algorithms developed for single-agent learning are *Artificial Neural Networks (ANN)*, *Bayesian Learning (BL)*, *Computational Learning Theory (CLT)*, *Genetic Algorithms (GA)*, *Analytical Learning (AL)*, and *Reinforcement Learning (RL)*. The applications of these algorithms range widely. In recent years, multi-agent learning takes the place of single-agent learning as cooperative learning [50]. Learning algorithms are divided into 3 approaches; Model-based Approaches, Model-free Approaches and Regret Minimization Approaches

IV. Management in Power Systems via MAS Technology

A. Marketing

In recent years, many countries around the world have modified their electricity supply frame, and constructed types of electricity market. Agent technology as a useful tool, offers to construct agent-based market simulators for electricity marketing. These models have hinted at the potential of agent-based models for the analysis of electricity markets [51].

B. Distributed Energy Resources (DER)

The large-scale use of distributed energy resources (DERs) will change the way that electric energy is dispatched through the utility power grid, enabling the electricity consumers to have some degree of energy independence and the bulk power system to open to small distributed energy suppliers. The benefits of DERs are seen to be the reliability of service, the quality of power supply, and greater efficiency of energy use by utilizing the waste heat from power generation systems. In addition, DER systems can benefit electric utilities by reducing congestion on the grid, reducing the need for new generation and transmission capacity, and offering ancillary services such as voltage support and demand response [52].

C. Microgrid Management and Automation

Microgrid management system consists of many items that should have to manage a microgrid such as acquire data, send parameters, marketing, and retrieve power scheduling information and send set points to generators by agents, planning of generations and etc [53].

The agent based management system accesses the generation scheduling procedures by means of an external conventional relational database but does not include the schedule calculation itself. This approach allows different generation schedule algorithms or strategies to be used during the research while the management system remains unmodified [54].

D. Condition Monitoring & Maintenance

Effective condition monitoring and asset management plays a significant role in improving the performance, reliability and longevity of electrical plant. In [55], describes a condition monitoring architecture that can support the capture and interpretation of UHF diagnostic data using agent-based and intelligent system technologies.

A real time condition monitoring multi agent system (COMMAS) developed to facilitate the task of monitoring the performance of a gas turbine, proposed in [56]. The agents collect measurements from the turbine sensors and an existing engine management system (EMS), analyze abnormal measurements and perform fault diagnosis.

In [57] considered how software agents might be applied in the scenarios of circuit breaker maintenance from the viewpoint of facilitating the tasks of the management personnel and the maintenance crews.

E. Protection Management and Fault Diagnosis

Protection and *fault management* systems are today an important part of the automation process in power systems, they should include the knowledge about failure modes and their causes and also, they should give, as soon as possible, information about the presence of faults in the processes. This is the task of timely detection of an abnormal event, diagnosing its causal origins and then taking appropriate supervisory control decisions and actions to bring the process back to a normal, safe, operating state or, at least, with minimal process operation degradation.

Thus, there exist a need of new protection systems in the actual industry and it will be a good option to make use of the Distributed Artificial Intelligence (DAI) techniques. Namely, the methodologies based on the multi-agent systems (MAS) can be a good option to create a distributed, modular and collaborative fault management system for the industrial processes [58], [59].

An innovative Fault Tolerant Networked Control System based on Multi-agent Systems (FTNCS-MAS), is proposed in [60] with a framework involving simultaneously decentralized and centralized topology. Extensive researches in protection and fault management have been done in the area of power system protection [61], power distribution network protection [62], [63], [64] and shipboard power system protection [65].

The MAS protection coordination system presented in [66] consists of relay agents, distributed generator agents and equipment agents. The agents can communicate with each other within the same agent society or within different agent societies. By example, a distributed generator agent communicates with relay agent to provide connection status.

F. Reconfiguration and Restoration

An efficient switch operation scheme that restores the power to an optimal target network configuration is referred to power system restoration. The problem can be formulated as an objective function satisfying the system constraints, where the objective is to maximize the supply of power to as many loads as possible. There are many algorithms and most of the restoration techniques are centralized, but the decentralized approaches within implementing MAS also exist.

Nagata et al. in [67], [68] obtained interesting results with multi-agents for power restoration problem. There are several works on power distribution network [69], and power system restoration [70], [71], [72], [73], [74], [7], and shipboard power system reconfiguration [76], [77], [78], [79] implementing MAS technology and various algorithms within multiple platforms.

G. Security

The electric power sector, all around the World, is undergoing a series of very important changes which have strong impact on power systems security. Among these changes, the most well known one is due to the restructuring of the electrical power sector towards a market-based environment.

The intimate role that electricity plays in today's societies implies that the power system security is to remain the most important aspect of power system operation which cannot be compromised in a market-driven environment [80], [81].

V. Conclusion

This paper focused on a research of multiagent systems (MAS) technology potential as acting decentralized control and management applications in power industry infrastructure today and future. We conclude that intelligent agent technology has significant potential benefits for facilitating many decentralized control strategies, system modeling and better performances in power management.

References

[1] D. Bailey and E. Wright, Practical SCADA for industry. Newnes, Oxford, UK, 2003.

[2] M.Pipattanasomporn, H.Feroze, S.Rahman, "Multi-Agent Systems in a Distributed Smart Grid: Design and Implementation", PES 2009 Power Systems.

[3] IEC 61499-1: Function Blocks – Part 1: Architecture, IEC Standard, 2005.

[4] K. H. John and M. Tiegelkamp, IEC 61131-3: Programming Industrial Automation Systems, Heidelberg: Springer-Verlag, 2001.

[5] IEC 61804-2: Specification of FB concept and Electronic Device Description Language (EDDL), IEC Standard, 2004.

[6] Frey, G.; Hussain, T.: "Modeling Techniques for Distributed Control Systems based on the IEC 61499 Standard - Current Approaches and Open Problems". Proceedings of the 8th International Workshop on Discrete Event Systems (WODES 2006), Ann Arbor, Michigan, USA, pp. 176-181, July 2006.

[7] R. Lewis, Modelling control systems using IEC 61499, London, United Kingdom: The Institution of Electrical Engineers, 2001.

[8] C.Costea, A.Petrovan: Agent-Based Systems in Power System Control, 9th International Conference on Development and Application Systems, Suceava, Romania, May 22-24, 2008

[9] Mcarthur S.D.J., Davidson E.M., Catterson V.M., et al. "Multiagent systems for power engineering applications. Part I: Concepts, approaches, and technical challenges", IEEE Trans. Power Syst., 22, (4), pp. 1743–1752, 2007

[10] Mcarthur S.D.J., Davidson E.M., Catterson V.M., et al. "Multiagent systems for power engineering applications. Part II: Technologies, standards, and tools for building multiagent systems", IEEE Trans. Power Syst., 22, (4), pp. 1753–1759, 2007

[11] Z. Zhang, J. McCalley, V. Vishwanathan, and V. Honavar, "Multiagent system solutions for distributed computing, communications, and data integration needs in the power industry," Power Engineering Society General Meeting, 2004. IEEE, pp. 45–49, June 2004.

[12] C.C. Liu, Project Leader, "Agent Modeling for Integrated Power Systems", Final Project Report, Power Systems Engineering Research Center, PSERC Publication 08-17, September 2008

[13] F. Bellifemine, G. Caire, and D. Greenwood, "Developing multi-agent systems with JADE," John Wiley & Sons, Feb. 2007.

[14] Rafael Bordini, L. Braubach, M. Dastani, A. E. Fallah Seghrouchni, J.Gomez-Sanz, J. Leite, G. O'Hare, A. Pokahr, A. Ricci, "A Survey of Programming Languages and Platforms for Multi-Agent Systems", in: Informatica 30, 2006.

[15] FIPA, The Foundation for Intelligent Physical Agents, http://www.fipa.org.

[16] JADE - Java Agent Development Framework, [online] http://jade.tilab.com.

[17] A. L. Dimeas, N. D. Hatziargyriou, "Agent Based Control for Microgrids," presented at the IEEE PES General Meeting, Tampa, FL, June 24–28, 2007.

[18] J. Yen, A. Chung, H. Ho, B. Tam, R. Lau, M. Chua, and K. Hwang, Collaborative and scalable financial analysis with multi-agent technology , in Proceedings of the 32nd Annual Hawaii International Conference, vol. Track5, 1999.

[19] K.P. Chow, and Y.K. Kwok, On load balancing for distributed multiagent computing, in IEEE Transactions on Parallel and Distributed Systems, vol. 13, no. 8, pp. 787-801, 2002.

[20] S.Moheuddin, A.Noore, and M.Choudhry, "A Reconfigurable Distributed Multiagent System Optimized for Scalability", International Journal of Computational Intelligence 5:1, 2009

[21] Yu-jiong Gu, Xiao-feng Dong, Jian-jun Wu, Kun Yang, "Study on multi-agent based maintenance decision support system used for power plant equipment", IEEE International Conference on Industrial Engineering and Engineering Management, pp. 2167 - 2171, Dec. 2008.

[22] G.A. Taylor, M.R. Irving, P.R. Hobson, C. Huang, P. Kyberd, and R.J. Taylor, Distributed monitoring and control of future power systems via grid computing, in IEEE Power Engineering Society General Meeting, 2006.

[23] D. Ernst, M. Glavic and L. Wehenkel, "Power Systems Stability Control: Reinforcement Learning Framework", IEEE Transactions on Power Systems, Vol. 19, No. 1, Feb 2004.

[24] A. Al-Hinai, "Multi-Agent Control and Operation of Electric Power Distribution Systems", PhD thesis, College of Engineering and Mineral Resources, West Virginia University, 2005

[25] J. Wu, N N. Schulz and W. Gao, "Agent-based distributed simulation", IEEE Power Engineering Society General Meeting, Oct, 2006.

[26] T. Logenthiran, D. Srinivasan and D. Wong, "Multi-Agent Coordination for DER in MicroGrid", ICSET 2008.

[27] I.M. Elmarkabi"Control and protection of distribution systems with distributed generators", PhD thesis, North Carolina State University, 2004

[28] J. Liu, X. Jin and Y. Wang, "Agent-Based Load Balancing on Homogeneous Mini grids; Macroscopic Modeling and Characterization", Ieee Transcations on parallel and Distributed Systems, Vol 16, No. 7, July 2005.

[29] G. Hug-Glanzmann, R. Negenborn, G. Andersson, B. De Schutter, and H.Hellendoorn, "Multi-area control of overlapping areas in power systems for FACTS control," Proceedings of Power Tech 2007, Lausanne, Switzerland, 6 pp., July 2007. Paper 277.

[30] J.K. Kok, C.J. Warmer, I.G. Kamphuis, "PowerMatcher: Multiagent Control in the Electricity Infrastructure", International Conference on Autonomous Agents, archive Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems, pp. 75-82, 2005

[31] R. Negenborn, "Multi-Agent Model Predictive Control with Applications to Power Networks", PhD thesis, Technische Universiteit Delft, 2007

[32] Frey, G.; Hussain, T "Modeling Techniques for Distributed Control Systems based on the IEC 61499 Standard - Current Approaches and Open Problems", Proceedings of the 8th International Workshop on Discrete Event Systems (WODES 2006), Ann Arbor, Michigan, USA, pp. 176-181, July 2006.

[33] W. Wang, X. Bai, W. Zhao, J. Ding and Z. Fang , "Hybrid Power System Model and the Method for Fault Diagnosis", IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific, Dalian, China, 2005

[34] Q. Bai, M. Zhang, and H. Zhang, “A colored petri net based strategy for multi-agent scheduling,” in Proc. Rational, Robust, Secure Negotiation Mechanisms Multi-Agent Systems, 2005, pp. 3–10.

[35] S. Hammami, I. Tnazefti, M. Moalla, and A. Chaillet, “Designing control and diagnosis for flexible manufacturing systems as a multi-agent system using blackboard and object petri nets,” in Proc. INRIA/IEEE Symp. Emerging Technologies Factory Automation, 1995, pp. 373–382.

[36] H. Xu and S. M. Shatz, “An agent-based petri net model with application to seller/buyer design in electronic commerce,” in Proc. 5th Int. Symp. Autonomous Decentralized Systems, 2001, pp. 11–18.

[37] W. Han and M. A. Jafari, “Controller synthesis via mapping task sequence to petri nets in multi-agent collaboration applications,” in Proc. IEEE Int. Conf. Robotics Autom., 2003, pp. 4312–4317.

[38] N. Lu, J. H. Chow, and A. A. Desrochers, “A multi-layer petri net model for deregulated electric power systems,” in Proc. Amer. Control Conf., Anchorage, AK, 2002, pp. 513–518.

[39] P. S. Georgilakis, J. Katsigiannis, and K. P. Valavanis, “Petri net based transformer fault diagnosis,” in Proc. Int. Symp. Circuits Systems, 2004, pp. V-980–V-983.

[40] J. Sun, S.-Y. Qin, and Y.-H. Song, “Fault diagnosis of electric power systems based on fuzzy petri nets,” IEEE Trans. Power Syst., vol. 19, no. 4, pp. 2053–2059, Nov. 2004.

[41] N. A. Fountas, N. D. Hatziargyriou, and K. P. Valavanis, “Hierarchical time-extended petri nets as a generic tool for power system restoration,” IEEE Trans. Power Syst., vol. 12, no. 2, pp. 837–843, May 1997.

[42] X. Tong, X, Wang and K.M. Hopkinson, “The Modeling and Verification of Peer-to-Peer Negotiating Multiagent Colored Petri Nets for Wide-Area Backup Protection”, IEEE Transaction on Power Delivery, Vol. 24, NO. 1, Jan 2009

[43] J.Wu and N.N.Schulz, "Generalized Three Phase Coupling Method for Distributed Simulation", Proceedings of North America Power System Conference, Iowa, Oct. 2005.

[44] A. Feliachi, K. Schoder, S. Ganesh, and H. J. Lai, “Distributed control agents approach to energy management in electric shipboard power system,” Power Engineering Society General Meeting, 2006, June 2006.

[45] S.Talukdar and V.C.Ramesh, “A multi-agent technique for contingency constrained optimal power flows,” IEEE Trans. Power Syst., vol.9, no.2, pp.855–861, 1994.

[46] B. Zhao,C.X.Guo,Y.J.Cao, “A Mutiagent-based Particle Swarm Optimization Approach for Optimal Reactive Power Dispatch”, IEEE Transactions on Power Systems, Vol.20, No.2, May 2005

[47] H. Ni, G. T. Heydt, and L. Mili, “Power system stability agents using robust wide area control,” IEEE Trans. Power Syst., vol. 17, no. 4, pp. 1123–1131, Nov. 2002.

[48] I. Kamwa, R. Grondin, and Y. Hebert, “Wide-area measurement based stabilizing control of large power systems—a decentralized/hierarchical approach,” IEEE Trans. Power Syst., vol. 16, pp. 136–153, Feb. 2001.

[49] D.Ernst, M.Glavic, and L.Wehenkel, "Power systems stability control: reinforcement learning framework", IEEE Transactions on Power Systems, pp.427 - 435, Feb. 2004

[50] L.M. Gao, J. Zeng, J. Wu, M. Li, "Cooperative reinforcement learning algorithm to distributed power system based on Multi-Agent", 3rd International Conference on Power Electronics Systems and Applications, pp. 1 - 4, 20-22 May 2009

[51] J. Yu, J. Z. Zhou, J. J. Yang, W. Wu, B. Fu, R. T. Liao, “Agent-Based Retail Electricity Market: Modeling and Analysis”, Proceedings of 2004 International Conference on Machine Learning and Cybernetics, pp. 95-100, Aug. 2004.

[52] Z. Jiang, “Agent-Based Control Framework for Distributed Energy Resources Microgrids”, Proceedings of the IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT'06), 2006

[53] J. Oyarzabal, J. Jimeno, A. Engler, C. Hardt and J. Ruela “Agent based Micro Grid Management System”, International Conference on Future Power Systems, Nov, 2005.

[54] D.P.Buseand, Q.H.Wu, "IP Network-based Multi-agent Systems for Industrial Automation Information Management, Condition Monitoring and Control of Power Systems", The University of Liverpool, Springer-Verlag, 2007

[55] S. D. J. McArthur, S. M. Strachan, G. Jahn, “The design of a multi-agent transformer condition monitoring system”, IEEE Trans. on Power Systems, Vol. 19, Issue 4, Nov. 2004, pp.1845 – 1852.

[56] Mangina, E. E., S. D. J. McArthur, A. Montlebert, and J. R. McDonald. 2001a. “A multi agent system for monitoring industrial gas turbine start-up sequences.” IEEE Power Transactions in Power Systems, 16(3):396-401.

[57] X. Xu, M. Kezunovic, D. Wong, "Agent-Oriented Approach to Work Order Management for Circuit Breaker Maintenance", IEEE PES Summer Meeting 2002, Chicago, July 2002.

[58] M. Albert, T. L¨angle, H. W¨orn, M. Capobianco, and A. Brighenti, “Multi-agent systems for industrial diagnostics,” in Proc. of 5th IFAC SAFEPROCESS’2003, Washington D.C., U.S.A, June 2003, pp. 483–488.

[59] M. J. G. C. Mendes, J. M. F. Calado, and J. M. G. S´a da Costa, “Fault diagnosis system based in agents,” in Proceedings of the 6th IFAC symposium on fault detection, supervision and safety of technical processes (SAFEPROCESS’ 2006), vol. 6-1, Beijing, china, August 2006, pp. 396–401

[60] M.J.G.C. Mendes, B.M.S. Santos and J. da Costa, “Multi-agent Platform and Toolbox for Fault Tolerant Networked Control Systems”, Journal of Computers, VOL. 4, NO. 4, pp. 303-310, April 2009

[61] H. Wan, K.P.Wong, C.Y.Chung, "Multi-agent Application in Protection. Coordination of Power System with Distributed Generations," Proceeding in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, pp. 1-6, July 2008.

[62] H. Wan, Li, K.K.; Wong, K.P.,"Multi-agent application of substation protection coordination with distributed generators",Future Power Systems, 2005 International Conference on, 16-18 Nov. 2005, Pages: 6 pp.

[63] I.S. Baxevanos, and D.P. Labridis, “Implementing Multiagent systems technology for power distribution network control and protection management”, in IEEE Transactions on Power Delivery, vol.22, no.1, pp.433-43, 2007.

[64] I.S. Baxevanos, and D.P. Labridis, “Software Agents Situated in Primary Distribution Networks: A Cooperative System for Fault and Power Restoration Management”, Transactions on Power Delivery, vol 22; No 4, pages 2378-2385, 2007

[65] K.C. Alfred, "A Framework of a Multi-agent System for Detection and Diagnosis of Fault on Shipboard Power Systems", Master thesis, Howard University, 2008

[66] H. Wan, Li, K.K.; Wong, K.P.,"Multi-agent application of substation protection coordination with distributed generators",Future Power Systems, 2005 International Conference on, 16-18 Nov. 2005, Pages: 6 pp.

[67] T. Nagata, Y. Tao, H. Sasaki, H. Fujita, “Decentralized Approach to Power System Restoration by means of Multi-agent Approach”, Bulk Power System Dynamics and Control - VI, August 22-27, 2004, Cortina d’Ampezzo, Italy

[68] T. Nagata, H. Sasaki, “A Multi-Agent Approach to Power System Restoration”, IEEE Transactions on Power Systems, Vol. 17, No. 2, May 2002

[69] J. G. Gomez-Gualdron, M. Velez-Reyes and L. J. Collazo, “Self-Reconfigurable Electric Power Distribution System using Multi-Agent Systems,” Electric Ship Technologies Symposium, pp 180 – 187, May 2007

[70] P.Tulpule, "Multiagent Approach for Power System Reconfiguration", Master thesis, West Virginia University, 2007

[71] J.M. Solanki, "Multi-Agent based Control and Reconfiguration for Restoration of Distribution systems with distributed generators", PhD thesis, Mississippi State University, 2006

[72] T. Nagata and H. Sasaki, “A multi-agent approach to power system restoration,” IEEE Trans. Power Syst., vol. 17, no. 2, pp. 457–462, May 2002.

[73] H. Qi, W. Zhang, L.M. Tolbert, "A Resilient Real-Time Agent-Based System for a Reconfigurable Power Grid"

[74] K. Huang, S. Srivastava and D. Cartes, “Decentralized Reconfiguration for Power Systems using Multi Agent System,” 1st Annual IEEE Systems Conference, pp 1 – 6, April 2007

[75] K. Moslehi, A.B.R. Kumar, H. D. Chiang, M. Laufenberg, A. Bose, P. Hirsch, L. Beard, “Control Approach for Self-Healing Power Systems: A Conceptual Overview”, 2004.

[76] S.K. Srivastava, "Multi-Agent System for Predictive Reconfiguration of Shipboard Power Systems", PhD thesis, Texas A&M University, 2003

[77] K. Huang, "Shipboard Power System Reconfiguration using MultiAgent System", PhD thsis, The Florida State University, 2007

[78] K. Huang, D. A. Cartes, and S. K. Srivastava, “A multi-agent based algorithm for mesh-structured shipboard power system reconfiguration,” in Proc. 13th Int. Conf. Intelligent Systems Application to Power Systems, 2005, pp. 188–193.

[79] G. Morejon, S. K. Srivastava and D. A. Cartes, “Integrating Virtual Test Bed and JADE Agent Platform using CORBA for Reconfiguration of shipboard Power System,” IEEE Power Engineering Society General Meeting, June 2006

[80] L.Wehenkel, M.Glavic, D.Ernst, "On multi-area security assessment of large interconnected power systems", Proc. of Second Carnegie Mellon Conference in Electric Power Systems, 6 pages, 2006

[81] D. Kechagias A. Symeonidis, M. P. (2002). Towards improving Multi-Agent Simulation in safety management and hazard control environments, Simulation and Planning in High Autonomous Systems - AIS 2002. , Lisbon, Portugal.