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The Future of Electrical and Computer Engineering Education

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Abstract—This is the first part of a 2-part paper that has arisen from the work of the IEEE Power Engineering Society's Multi-Agent Systems (MAS) Working Group.

Part 1 of the paper examines the potential value of MAS technology to the power industry. In terms of contribution, it describes fundamental concepts and approaches within the field of multi-agent systems that are appropriate to power engineering applications. As well as presenting a comprehensive review of the meaningful power engineering applications for which MAS are being investigated, it also defines the technical issues which must be addressed in order to accelerate and facilitate the uptake ofthe technology within the power and energy sector.

Part 2 of the paper explores the decisions inherent in engi- neering multi-agent systems for applications in the power and energy sector and offers guidance and recommendations on how MAS can be designed and implemented.

Index Terms—Multi-agent systems

INTRODUCTION

FOR over a decade the proposed use of multi-agent sys- tems (MAS) to address challenges in power engineering has been reported in IEEE transactions and conference papers. MAS technology is now being developed for a range of applications including diagnostics [1], condition monitoring [2], power system restoration [3], market simulation [4], [5],

network control [6], [7] and automation [8]. Moreover, the technology is maturing to the point where the first multi-agent systems are now being migrated from the laboratory to the utility, allowing industry to gain experience in the use of MAS and also to evaluate their effectiveness [1].

Nevertheless, despite a growing awareness of the technol- ogy, some fundamental questions often arise from other researchers and, in particular, industrial partners when discussing multi-agent systems and their role in power engineering. Theseare: what benefits are offered by multi-agent systems? What differentiates them from existing systems and approaches? To what sort of problem can they be applied?

If and when MAS technology is deemed appropriate for a particular power engineering application, then other questions naturally follow: how should multi-agent systems be designed?

How should multi-agent systems be implemented? Are there any special considerations for the application of MAS in power engineering?

The IEEE Power Engineering Society's (PES) Intelligent System Subcommittee (within the PSACE Committee) hasformed a Working Group to investigate these questions about the use of multi-agent systems. Its first remit is to definethe drivers for and benefits gained by the use of multi-agent systems in the field of power engineering. As MAS are a rela- tively new technology, a number of technical challenges need to be overcome if they are to be used effectively. The WorkingGroup's second remit is to identify and disseminate details of those challenges. Its third and final remit is to provide technicalleadership in terms of recommendation and guidance on the appropriate use of the standards, design methodologies and implementation approaches which are currently available.

This paper reports on the research of the Working Group. It begins by describing key concepts and approaches associated with multi-agent systems. As a result of research and discus- sions by the Multi-Agent Systems Working Group, definitionsof MAS terminology and concepts have been tailored for use by the power engineering community.

The engineering drivers behind the use of MAS and the benefits they may offer are presented. The recent increase in activities in this area has led to some inappropriate usesof the technology; hence it considers the principal problems which can be tackled by MAS. Comparisons with existing technologies, such as web services, grid computing and intel- ligent systems techniques are drawn to illustrate how MAS differ.

Additionally, this part of the paper (part 1) presents a comprehensive review of the power engineering applications for which

MAS technology is being investigated, and outlines the key technical issues and research challenges which the authors believe need to be addressed if MAS technology is to be deployed within the power industry.

The uptake of multi-agent systems has increased over the last few years, in terms of number of research projects. How- ever, it is essential at this stage of maturity of research into the application of MAS that appropriate standards and guidance are available for those developing multi-agent systems in the power engineering community; these are discussed in the companion Part 2 paper.

CONCEPTS: TERMINOLOGY AND DEFINITIONS

In order to explore the potential benefits of MAS to power engineering and the areas where their application may be justified, the basic concepts and approaches associated with multi-agent systems need to be understood. This leads us to a basic but essential, and unfortunately difficult, question: what is an *agent*?

The definition of Agency

The computer science community has produced myriad definitions for what an *agent* is [9]–[13]. The fact that so many different definitions exist, testifies to the difficulty in defining the notion of agency. A comparison of these definitions and discussion of their relative merits and weaknesses, from a computer science perspective, can be found in [14].

While all the definitions referenced above differ, they all share a basic set of concepts: the notion of an *agent*, its *environment*, and the property of *autonomy*. Wooldridge's basic definition of an agent [13] echoes that of Russell and Norvig [9] and Maes [10]. According to Wooldridge an agent is merely "a software (or hardware) entity that is situated in some *environment* and is able to *autonomously* react to changes in that *environment*."

The *environment* is simply everything external to the agent. In order to be situated in an environment, at least part of the environment must be observable to, or alterable by the agent. The environment may be physical (e.g. the power system), and therefore observable through sensors, or it may be the computing environment (e.g. data sources, computing resources, and other agents), observable through system calls, program invocation, and messaging. An agent may alter the environment by taking some action: either physically (such as closing a normally-open point to reconfigure a network), or otherwise (e.g. storing diagnostic information in a database for others to access).

The separation of *agent* from *environment* means that agents are inherently distributable. Placing copies of the same agent in different environments will not affect the reasoning abilities of each agent nor the goals it was designed to achieve; rather, the specific actions taken by each may differ due to different observations from the two environments. This means that an agent can operate usefully in any environment which supports the tasks the agent intends to perform.

Under Wooldridge's definition, an entity situated in an environment is only an agent if it can act autonomously in response to environmental changes. *Autonomy* is a somewhat elusive term, used in all definitions of agency, but rarely defined. The loosest definition of autonomy says that an agent "exercises control over its own actions" [14], meaning that it can initiate or schedule certain actions for execution. Russell and Norvig go further, by requiring the scheduling of actions to be in response to some change in the environment, and not simply the result of the agent's in-built knowledge [9]. This requirement for environmental change is in agreement with Wooldridge, and makes intuitive sense; can an agent really be considered autonomous if it takes action at times prede- fined by the agent designer, regardless of external changes in circumstance? *Autonomy* is therefore the ability to schedule action based on environmental observations.

From an engineering perspective this definition is problem- atic: it does not clearly distinguish agents from a number of existing software and hardware systems. Arguably, under the definition above some existing systems could be classed as agents. For example, a protection relay could be considered as an agent. It is situated in its *environment*, i.e. the power system. It reacts to changes in it environment, i.e. changes to voltage or/and current. It also exhibits a degree of *autonomy*. Similar arguments can be made for software systems such as Unix daemons and virus checkers.

Renaming existing systems or new systems built using existing technologies as "agents" offers nothing new and no concrete engineering benefit. While Russell and Norvig [9] argue that "The notion of an agent is meant to be a tool for analyzing systems, not an absolute characterization that divides the world into agents and non-agents", being able to distinguish agent systems from existing systems is important. There is a need to know how agents and multi-agent systems differ from existing systems and system engineering approaches. Moreover, it is the potential advantages gained through these differences that interest us as power engineers and that have motivated the exploration of the application of MAS to power engineering problems.

Definition of an Intelligent Agent

In order to help differentiate MAS from existing systems the authors have adopted the definition of agency as proposed by Wooldridge [13]. Wooldridge extends the concept of an agent, given above, to that of an *intelligent agent* by extending the definition of autonomy to *flexible autonomy*. An agent which displays flexible autonomy, i.e. an intelligent agent, has the following three characteristics:

Reactivity: an intelligent agent is able to react to changes in its environment in a timely fashion, and takes some action based on those changes and the function it is designed to achieve.

Pro-activeness: intelligent agents exhibit goal directed behavior. Goal directed behavior connotes that an agent will dynamically change its behavior in order to achieve its goals. For example, if an agent loses communication with another agent whose services it requires to fulfill its goals, it will search for another agent that provides the same services. Wooldridge describes this pro-activeness as an agent's ability to "take the initiative".

Social ability: intelligent agents are able to interact with other intelligent agents. Social ability connotes more than the simple passing of data between different software and hardware entities, something many traditional systems do. It connotes the ability to negotiate and interact in a cooperative manner. That ability is normally underpinned by an agent communication language (ACL), which allows agents to *converse* rather than simply pass data.

While an *agent*, in terms of our earlier definition, and many existing systems display the characteristic of reactivity, in order to be classed as an *intelligent agent* under Wooldridge's definition, an agent must also have some form of pro-activeness and some form of social ability. It is the goal-directed behavior of individual agents and the ability to flexibly communicate and interact that set intelligent agents apart.

Not only do the characteristics of reactivity, pro-activeness and social ability help us distinguish agents from traditional hardware and software systems, it is from these characteristics, as shall be discussed in the following sections, that many of their benefits are derived.

The definition of a Multi-Agent System

A *multi-agent system* is simply a system comprising two or more *agents* or *intelligent agents*. It is important to recognize that there is no overall system goal, simply the local goals of each separate agent. The system designer's intentions for the system can only be realized by including multiple intelligent agents, with local goals corresponding to sub-parts of that intention.

Depending on the definition of agency adhered to, agents in a multi-agent system may or may not have the ability to communicate directly with each other. However, under Wooldridge's definitions, intelligent agents must have social ability and therefore must be capable of communication with each other.

For the sake of this paper the authors have focused on MAS where this communication is supported. This clearly differentiates the type of MAS discussed in this paper from other types of systems.

THE POTENTIAL BENEFITS OF MAS TECHNOLOGY AND DRIVERS FOR ITS USE IN POWER ENGINEERING APPLICATIONS

To answer the question of how (and why) MAS may be applied in power engineering requires an understanding of the basic ways MAS can be exploited. In this paper the authors have called these "approaches".

To date MAS have a tendency to be exploited in two ways: as an approach to building flexible and extensible hardware/software systems; and as a modeling approach.

MAS as an approach to the construction of robust, flexible, and extensible systems

There are many power engineering application areas for which flexible and extensible solutions are beneficial.

Flexibility connotes the ability to respond correctly to dynamic situations, and support for replication in varied situations (environments). This sounds very similar to autonomy and therefore intelligent agents should automatically be flexible; but if autonomy is the ability of an agent to schedule its own actions, flexibility relates to having a number of possible actions from which to select the most appropriate. Some specific examples of flexible behavior would be correct handling of different formats of one type of data (such as temperatures in Centigrade or Fahrenheit); or the ability to construct a new plan if a particular control action fails; or a

system that can be deployed on any feeder, which senses the connection of distributed generation and changes protection settings accordingly.

Extensibility connotes the ability to easily add new functionality to a system, augmenting or upgrading any existing functionality. For example, a condition monitoring system may gain a new type of sensor, and require a new data analysis algorithm. A state-estimator system may be upgraded to use a faster load-flow calculation algorithm. For distribution networks, a distributed network control and management system responsible for voltage control may be extended to also automate restoration and the management of distributed generation. Importantly, a truly extensible system will allow new functionality to be added without the need to re-implement the existing functionality.

Across many applications in power engineering there is also a requirement for fault tolerance and graceful degradation: should part of the system fail for whatever reason, the system should still be able to meet its design objective or, if that is not possible, it should accomplish what it can without interfering with other systems.

MAS can provide a way of building such systems. Indeed, the ability of MAS to be flexible, extensible, and fault tolerant is often part of the justification for their use. However, in order for that justification to be valid, the way in which MAS provide flexibility, extensibility, and fault tolerance needs to be understood. The properties of agents and MAS that produce these qualities are examined below.

Benefits of autonomy and agent encapsulation: An agent encapsulates a particular task or set of functionality, in a similar way to modular or object-oriented programming. This means that the benefits of standard interfaces and information-hiding are also available with agent programming through the use of messaging with a standard agent communication language, but there is also the additional capability of autonomousaction.

Recall that autonomous action means each agent is ableto schedule its own activity in order to achieve its goals. Ina modular programming situation, external modules can call functions which the module *has no choice* but to execute. Withagent programming, external agents can only send messages *requesting* the agent take some action: the autonomous agent can decide whether to fulfill the request, the priority of the task, and if other actions should also be scheduled. This can beuseful in situations when an agent is receiving many requests and cannot fulfill them all within a reasonable timescale, such as with multiple requests for a processing-intensive task likea load-flow calculation.

The autonomy of each agent and the messaging interface are what contribute most to flexible and extensible systems. Because agents are not directly linked to others, it is easy to take one out of operation or add a new one *while the others are running*. Any agents interacting with the stopped one can use the standard service location facilities to locate another agent that performs the same task, and by this mechanism new agentscan be included within the system. The agent framework provides the functionality for messaging and service location, meaning that new agent integration and communications are handled without effort from the system designer.

This allows systems to be extensible: extra functionality can be added simply by deploying new agents, which use service location to find others to communicate with; and parts of systems can be upgraded by deploying a replacement agent and removing the obsolete one. Flexibility also follows: the appropriate mix of agents can be deployed to fit the details of individual situations, and flexible handling of messages between agents allows the system to self-configure. Finally, legacy systems can be incorporated within the system simply by wrapping legacy functionality in a layer of agent messag- ing.

Benefits of open MAS architectures: An open agent ar- chitecture places no restrictions on the programming language or origin of agents joining the system, and allows flexible communication between any agents. This is achievable through adherence to messaging standards: the separation of an agent from its environment means that the messaging language an agent understands is important for inter-agent communication, rather than the programming language in which it was imple- mented.

An example of a set of standards for an open architecture is that defined by the Foundation for Intelligent Physical Agents (FIPA) [15]. The FIPA Agent Management Reference Model covers the *“framework within which FIPA agents exist”*, defining standards for creating, locating, removing, and communicating with agents. This is more generally called the *agent platform*, and is simply one part of an agent’s environment. One requirement of an open agent architecture is that the platform places no restrictions on the creation and messaging of agents, while a second is that some mechanism must be available for locating particular agents or agents offering particular services within the platform. Under the FIPA model, this is achieved through a separate agent called the Directory Facilitator: an agent which manages a searchable list of services offered by other agents within the platform.

Early agent systems tended to be closed architectures, as one set of agents would be deployed every time the system was run, with all communication explicitly defined by the system creator. An example is the ARCHON system for distribution network management, originally built to integrate four legacy systems [16]. Such an architecture is said to be closed because new agents cannot be added to the community: even if a new agent is created and run, other agents have no way of locating it and communicating with it. A closed architecture removes the possibility of an extensible or flexible system, severely limiting the benefits of using agents.

How to specifically design an open agent architecture is discussed in detail in Part 2 of this paper.

Platform for distributed systems: An agent is distinct from its environment, meaning that it can be placed in different environments and still have the same goals and abilities. However, the environment impacts upon which actions an agent takes and in what order, as the agent autonomously schedules action in response to sensor inputs and messages.

For this reason an agent is inherently distributable, having no fixed ties to its environment. In practice, distribution of agents across a network is supported by the agent platform: the

platform is run on every computer that will host an agent, and the agents are deployed within the platform as usual. To agents within one platform, there is no difference between agents on the same computer and agents on a different computer, as the instances of the platform running on separate machines seamlessly connect and appear as a single instance.

This means that the same set of agents can be deployed on one computer, and alternatively on multiple networked computers, without modifying or changing the agent code.

Fault tolerance: Building redundancy into systems is one of the standard engineering approaches to gaining fault tolerance. Building redundancy into MAS simply involves providing more than one agent with a given set of abilities. If an agent needs the services of a second agent in order to fulfill its goals, and the second agent fails, the agent can pro- actively seek an alternative agent (perhaps using the Directory Facilitator) to provide the services it requires.

This redundancy may be provided by simple duplication of each agent, possibly with distribution of duplicates across different computers. This would provide a tolerance to physical faults, such as the loss of a network connection, or damage to a computer. Tolerance to programming-related faults would require a more design-intensive solution: rather than simply running two copies of a single agent, the same functionality would be coded differently in two agents. Various applications and operating environments will have differing requirements for levels of robustness and fault tolerance, and so the approach taken must be application-specific.

However, the flexibility offered by an open architecture of agents with good social ability easily leads to the design of a fault tolerant system.

Multi-agent systems as a modeling approach

Multi-agent systems are more than a systems integration method, they also provide a modeling approach. By offering a way of viewing the world, an agent system can intuitively represent a real-world situation of interacting entities, and give a way of testing how complex behaviors may emerge.

Natural representation of the world has previously been given as an advantage of object-oriented (OO) systems design, where entities in a system are modeled as *objects*. This has recently found favor with the power engineering community in standards such as the Common Information Model (CIM)

[17] and IEC 61850 [18]. The main benefit of the object approach is data-encapsulation: the particular data structures used to hold attributes of an object are hidden from external objects, but are indirectly accessible through method calls and standard interfaces. Agent-based design adds another level of abstraction to this: not only are internal data structures hidden, but the “methods” (actions) an agent can perform are also hidden, yet indirectly accessible through standard messaging interfaces.

This is a very natural way of modeling actors in somesystems such as markets: in a real market actors have attributes(such as desired price and lowest price for a seller) and possible actions (e.g. start auction, accept bid) which other actors cannot manipulate directly. Indirect access is available by, for example, presenting the seller with a high bid, in the hope that it will be accepted. By modeling each market participant as a separate agent in a multi-agent system, it is easy to run simulations of different market scenarios; the attributes of single or multiple market participants can bealtered by changing the initial conditions of one or more agents.

Marketplace simulation is an application in which the benefits of using intelligent agents to represent autonomous actors are fairly clear. By modeling the behavior and commu- nication of individual agents, operation of the market can be studied for emergent behavior patterns. However, many other power engineering applications can usefully apply this wayof viewing the world, such as power systems operation and control. Generators have a degree of autonomy and cannot be directly affected by external system actors, lending themselves to being represented by agents. Such an application would be using agents for both their modeling properties and also as a way of building a flexible, extensible system.

Through their use for systems integration or modeling, MAS offer significantly different approaches to designing systems for typical power and energy applications.

M. Pěchouček and S. Thompson provide interesting per- spectives on industry applications of multi-agent systems in a report from the Industry Track of the Fourth International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2005) [19]. They indicate that most industrialists are interested in agents for the following applications: planning; scheduling; resource and strategic decision making; diagnos- tics; control and real-time replanning; software systems integration; interoperability; knowledge integration; ontologies; and simulation and modeling. Many of these underpin the applications of multi-agent systems within the power industry which are discussed in this paper.

MAS, GRID COMPUTING, WEB SERVICES, AND ARTIFICIAL INTELLIGENCE TECHNIQUES

Before exploring the applications of MAS technology inpower engineering, it is worthwhile considering the relation-ship between multi-agent systems, grid computing [20], web services [21], and artificial intelligence techniques; what the technologies have in common and what makes them different.The commonality between the first three is easiest to deal with: all three technologies offer a perspective on the prob- lems associated with distributed computing, i.e. harnessing distributed hardware and software resources to complete aspecific objective or task. They all tend to support some form of messaging between their component parts.

How do they differ? Firstly, they differ in scope of ap- plication. Grid computing is normally focused on harnessing hardware resources (computational power) to solve compu- tationally complex problems. Web services, on the other hand, are designed to offer interoperability between software systems, providing the mechanisms for the discovery of those systems and their communication across a network.

At first glance, web services and multi-agent systems look deceptively similar. Similar styles of interaction diagrams areoften used to describe web services and to describe agentinteractions. The ideas of the “services” and the “brokerage ofservices” are common to the technologies. However, standards for multi-agent systems (e.g. [15]) support a richer set of interactions, i.e. support for negotiation, than those required for the brokerage of services as supported by web services.So while web services support the interoperability between software systems, the nature of that interoperability is more limited than that for multi-agent systems.

The key differentiator between multi-agent systems, grid computing and web services is the notion of *autonomy*. Under the current standards there is no provision for autonomy in web services [22]. Similarly there is no requirement for nodes in computational grids to exhibit autonomy.

It is also the social ability and pro-active nature of agents that set them apart from grid computing and web services. So much so that MAS technology has been mooted as a mechanism for delivering improved web services [22] and grid computing systems.

Hence, applications where the use of agents is justified are normally cases where the characteristic of autonomy offers tangible benefits.

Another common question regards the difference between MAS and AI techniques per se, i.e. expert systems, model- based reasoning (MBR) systems, case-based reasoning sys- tems, artificial neural networks (ANNs).

This question is understandable from the perspective thatthe techniques above have been applied to similar problems (fault diagnosis, condition monitoring, decision support) and that MAS are often seen as another AI technique. However, this question also represents a misunderstanding, as MAS are not an alternative or competitor to classical AI techniques. Indeed, there are many cases in the literature where expert systems, ANNs, and MBR systems are used to provide agents with their abilities to reason and achieve the goals for which they were designed.

What MAS do provide is a framework for building hybrid systems which integrate different AI techniques. Examples of where such an approach can be beneficial are fault diagnosis and condition monitoring [2].

BIBLIOGRAPHICAL ANALYSIS OF AGENT RESEARCH

A bibliographical analysis of agent research was undertaken in the preparation of this paper. Its aim was to provide an indication of the active areas of agent research, with respect to power systems and related applications. For conferences, the sources were restricted to the Proceedings of the Intelligent Systems Application to Power Systems conferences for 2001, 2003 and 2005 [23]–[25]. This is a representative forum for agent based research in the power industry. In addition, papers from relevant IEEE and IEE journals were sought and categorized. These included the IEEE Transactions in Power Systems, Power Delivery, Energy Conversion, and Evolution- ary Computing. Further searches included the IEEE Power and Energy Magazine and relevant IEE journals. All searches dated from 1998 onwards. These sources and timescales are representative of the body of research undertaken in this field.

TABLE I
BIBLIOGRAPHIC SURVEY OF AGENT PAPERS

Conferences	ISAP 2001	ISAP 2003	ISAP 2005	IEEE & IEE Journals	Totals
Protection	1	0	1	5	7
Modeling & Simulation	1	3	3	16	23
Distributed Control	0	3	8	15	26
Monitoring & Diagnostics	2	2	2	6	12
Totals	4	8	14	42	68

Four categories of applications were discovered: monitoring and diagnostics, distributed control, modeling and simulation, and protection. From the survey results in Table I, it is clear that most papers have concerned the use of agents for modeling and simulation or distributed control. This is unsurprising, as these are two complex fields where the power industry faces real challenges.

Protection applications represent the least active area interms of journal publications, with only five journal papers [26]–[30]. All the journals focused on monitoring and diagnos-tics have arisen from the research activities at the Universityof Strathclyde [1], [2], [31]–[34]. In terms of journal papers, there is a wide diversity of authors publishing work in the areaof distributed control [3], [6], [8], [35]–[46] and modeling and simulation [47]–[62].

THE APPLICATION OF MAS IN POWER ENGINEERING

As described in Section III, agent technology offers two main approaches to developing innovative applications. The four broad fields of agent applications in power, identified through the bibliographical analysis, each use the propertyof flexible autonomy to bring a new suite of techniques and abilities to bear on traditional issues and problems in the industry.

Based on this, multi-agent systems should be considered for applications which display one or more of the following characteristics:

There is a requirement for interaction between distinct conceptual entities, such as different control subsystems and plant items e.g. controlling a microgrid while tak-ing account of thermal constraints, voltage control and renewable energy sources;

A very large number of entities must interact, where it would be impossible to explicitly model overall system behavior, e.g. simulation of an energy marketplace whereeach individual generator, independent system operator and customer is modeled;

There is enough data/information available locally to undertake an analysis/decision without the need for com- munication with a central point e.g. substation-based diagnostics from transformer, switchgear and protection analysis systems;

New functions need to be implemented within exist- ing plant items and control systems, e.g. extending substation-based condition monitoring systems by addingdata interpretation functions;

Over time, there is a requirement for functionality to be continually added or extended, e.g. asset managementthrough the use of real-time condition monitoring on multiple plant items.

The specific benefits of MAS technology for the four fields of application are considered below.

Monitoring and Diagnostics

A key application area for multi-agent systems is the management and interpretation of data for a wide variety of power engineering monitoring and diagnostic functions. MAS technology is an excellent tool for collecting and manipulatingdistributed information and knowledge.

Condition Monitoring: Condition monitoring of equip- ment and plant items offers a number of challenges:

Gathering data from a variety of sensors;

Interpreting the data to extract meaningful information. This often requires the use of multiple algorithmic and intelligent system-based approaches;

Combining the evidence and information from different interpretation algorithms to generate an overall diagnosticconclusion;

Delivering the diagnostic information in the correct for- mat to relevant engineers; and

Automatically altering power system and plant settings based on the condition of the plant.

If we consider plant items such as transformers, there are various sensors which can be used to monitor them, suchas UHF monitoring of partial discharge, acoustic monitor- ing of partial discharge, and on-line dissolved gas in oil measurement. Furthermore, operational information about the circuit loading and fault conditions from digital fault recorderscan also be used to inform the diagnostic process. Agent technology allows the combination of data from all these sources in a flexible manner: information is used *when it is available and relevant* by delegating the task of monitoring each source to an autonomous agent.

As an example, an agent responsible for monitoring the output from UHF sensors can inform the engineer or diag- nostic algorithms when significant partial discharge activity has been detected. The autonomy of the agent allows it to determine when such information should be communicated, and to whom. The property of flexibility allows integrationof as much diagnostic data, information and knowledge as is currently available. New sensors and interpretation algorithms can also be introduced seamlessly into the overall system,since the open architecture allows extensibility.

Using these principles, some of the authors have developed a transformer condition monitoring multi-agent system [2].

As a further idea, condition monitoring agents could also be capable of modifying the measurement set-up by, for example, altering the data acquisition rate. While the physical instrument connection can rarely be changed, in a framework of virtual instrumentation (e.g. LabVIEW), the monitoring agent cancontrol execution of specific virtual instruments. This wouldbring advantages such as the optimization of resources like battery and computation power.

Post-fault diagnosis of power system faults: When oper- ational engineers investigate the causes and impact of power system faults, they employ a number of data sources. These include Supervisory, Control and Data Acquisition (SCADA) system data, digital fault recorder data, and traveling-wave fault locator data. In a similar fashion to the condition monitor- ing problem discussed previously, automation of the analysis of such data provides essential decision support to operational engineers. For example, [1] reports on work with a UK utility which experienced an influx of 15,000 SCADA alarms and 1,695 digital fault records during a single storm. The engineersrequire effective supporting analysis tools to combat such situations.

Research into the application of intelligent systems for the analysis of power systems data has been ongoing for the best part of two decades and has produced a variety of tools and techniques for analyzing individual data sources. Multi-agent system technology can be used to integrate legacy data analysistools in order to enhance diagnostic support for engineers, giving a holistic view of the performance of power systems based on a variety of data sources.

Distributed control

With the introduction of distributed power generation, load control, market operations, increasing complexity in the distribution network and an increased number of interconnections, the operation of a modern power system is extremely complex. Multi-agent systems provide a technology for flexibly con- trolling the modern power system. The current approach ofusing a central SCADA system and several smaller distributed SCADA systems is no longer sufficient for certain control operations. An approach that provides intelligent, fast and adaptable local control and decision making is required. Applications currently being investigated in this field include:

Power system restoration,
Active distribution networks operation,
Microgrid control, and
Control of shipboard electrical systems.

Taking the example of active distribution networks, man- agement and control of complex networks present a numberof challenges, not least in the scalability and flexibility of solutions. A number of researchers are considering agent- based approaches as an alternative to centralized power system management and control [6], [7]. By distributing management and control functionality using intelligent agents, decision- making regarding network restoration, reconfiguration, the dispatch of generation, and the management of loads can be locally managed.

Local decision-making would require agents capable of a range of actions, such as monitoring local conditions, control- ling switchgear and other plant, and coordinating with other regions of the network.

Modeling and simulation

Within modern power systems, several operations are toocomplicated to model and simulate using traditional methods.For this reason, the use of agent systems as a modeling ap- proach, introduced in Section III-B, could be beneficial to the simulation of complex power systems, energy markets, overallenergy networks, and energy utilization. These applicationsall have a common property: overall system behavior is verycomplex, but is generated by the interaction of simpler entities.This approach to modeling has been applied to energy mar- ketplace simulation, where agents model suppliers, brokers,generators, and customers [4], [5]. Another such area is theplanning of transmission [62]. A further simulation applicationuses an agent to provide simulated data to the rest of the multi-agent system for the purpose of “what if” scenario analysis—an approach used within research concerning the control ofshipboard electrical systems [63], [64]. This is similar todata driven simulation, and poses new problems regarding the dynamic real-time interaction of agents and the real world.

More recently, agent technology has been suggested for the integration and co-ordination of different models and modeling software packages [47], [50].

Protection

Power system protection is an area where the analoguebetween agents and protective devices is being explored [26]–[30]. In all the papers above protection relays and associated equipment are seen as agents and their functionality aug- mented accordingly. In doing so, researchers are investigating MAS technology as a way of developing novel protectionschemes which are fault tolerant and self coordinating.

Maturity of Multi-Agent Systems in Power

While the potential application of MAS technology to power engineering spans a diverse range of applications, some applications are more mature than others. Here, three particular examples are highlighted to demonstrate the current maturity of such systems.

The first is an agent system for the control of microgrids, developed at the National Technical University of Athens (NTUA) [6]. This system has progressed to a physical demon-strator, which has been employed successfully on a test electrical network.

Secondly, the Protection Engineering Diagnostic Agents (PEDA) were developed at the University of Strathclyde for automating the analysis of power systems data [1]. This system was successfully transferred from the laboratory todeployment at a utility, indicating that MAS technology is maturing to the point where meaningful industrial applicationsare achievable. Results of the trial and the issues surrounding the implementation of an industrial strength MAS are reportedin [1].

The third system is a commercial product: the IntelliTEAM II by S&C Electric Company [65].

TECHNOLOGY CHALLENGES FOR POWER ENGINEERING

While the potential benefits of agent technology have been thus far described, it is important to identify the key technical challenges that are yet to be overcome to allow most effec- tive implementation of multi-agent systems within the power engineering community. These include:

Platforms: a number of multi-agent system platforms exist. However, judicious selection is required to ensure long-term compatibility and the required robustness for on-line applications. The necessity to develop agents that can interact with each other, irrespective of the platform they run on, is fundamental to the development of flexible, extensible, open architectures. For this reason,platform choice for standards-adherence is extremely important.

Toolkits: based on the increasing amount of agent re- search within the power engineering community, there is the opportunity to re-use agent designs and functionality for the benefit of the whole community. Therefore, there is a role for toolkits which allow the re-use of existing agent behaviors and capabilities.

Intelligent agent design: new researchers and industrial implementers need guidance on how exactly an agent should be designed or, at very least, knowledge of the available options. A number of different concrete ar- chitectures for intelligent agents can be found in the literature: Belief Desire and Intention (BDI) agents [13], reactive agents [13], agents with layered architectures[13], and agents implemented using model-based pro- gramming [66]. Each of these implementation strategies will produce agents with differing degrees of reactivity, pro-activeness and social ability. What is not readily understood is how flexible autonomy varies across these implementation strategies and their suitability for differ- ent power engineering applications.

Agent communication languages and ontologies: Un- derpinning the social ability of agents are agent commu- nication languages. These define how agents exchange information, communicate and negotiate. Within them areprotocols and content languages which allow meaningful messages to be composed and interpreted. International standards are set by the Foundation for Intelligent Physi- cal Agents (FIPA) [15]. A key aspect of using agent-based technology is that all agents within power engineering applications should be able to co-operate and interop- erate, and this should be independent of the individual developer. Therefore, the community must agree on the adoption of appropriate agent communication language standards. This extends to the area of ontologies [67] which define the terms and concepts which agents are able to exchange, interpret and understand.

Data Standards: The power engineering community has expended significant effort in defining data standards for various application areas. One example is the Common Information Model (CIM) for data exchange between Energy Management Systems and related applications [17]. Another is the IEC 61850 Communication Networksand Systems in Substations standard for data exchange between Intelligent Electronic Devices (IEDs) [18]. These standards cannot be directly applied for agent communi- cation, as the conversational abilities of agents require a richer language than a data-passing standard. However, there is potential to use them as a foundation for anontology. This is explored further in Part 2 of this paper.

Security: due to the peer-to-peer nature of agent systems, security can be a key concern. If agents are to seamlessly join an agent community, there must be measures in place to determine the level of trust between agents and the security of messaging. Agents from a rival utilitymay be offered fewer services, for example, indicatingthe lower trust placed in them. Similarly, communication between two agents is open to attacks such as sender spoofing (the message purports to be from a more trusted agent) and message modification (a message is changed while traveling between agents, particularly in negotiation situations).

Mobility: A number of researchers are interested in mobile agents, which move completely (source code and data) from machine to machine [8]. While this has been suggested within a few power engineering applications, as of yet no credible reason for using this approach is apparent. In [19], Pěchouček and Thompson state “People often claim that agent mobility is inevitable and more essential than is actually the case. Often, migration ofdata or simple communication is sufficient, rather than migration of an agent’s code”.

Beyond technical and implementation issues described above, the lack of experience in the use of multi-agent system technology in industry is an obvious concern of both utilities and manufacturers considering MAS solutions. According to Wooldridge and Jennings [68], the migration of an agent system from prototype to a solution that is robust and reliable enough to be used in practice is a non-trivial step. This naturally leads to a requirement for the demonstration of MAS technology in the industrial environment for a range of applications. Furthermore, there is also a requirement for clear communication of results from industrial trials of MAS technology, highlighting failures and problems as well as successes, to the wider power engineering community.

CONCLUSIONS

This paper opened by posing two sets of questions sur- rounding multi-agent systems: broadly, “what are they?” and “how should they be used?” In this paper (Part 1 of two)the first question has been answered, by defining the keyterminology and concepts associated with multi-agent systems, and identifying the important contributions that can be made in the field of electrical power systems. Drivers and benefits have also been identified, and a survey of publications in IEEE and IEE journals and relevant conferences has been used to highlight the application areas for which MAS technology is currently being investigated. As well as the potential benefits of MAS technology, this part has also considered the technical challenges which must be overcome through further research ifMAS technology is to be successfully employed and deployedin the power industry.

Part 2 will tackle the second question, giving detailed technical recommendations of how MAS should be employed by those building systems for power engineering applications.

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