Exploiting Multi-agent System Technology within an Autonomous Regional Active Network Management System

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***Abstract*-- This paper describes the proposed application of multi-agent system (MAS) technology within AuRA-NMS, an autonomous regional network management system currently being developed in the UK through a partnership between several UK universities, distribution network operators (DNO) and a major equipment manufacturer. The paper begins by describing the challenges facing utilities and why those challenges have led the utilities, a major manufacturer and the UK government to invest in the development of a flexible and extensible active network management system.**

The requirements the utilities have for a network automation system they wish to deploy on their distribution networks are discussed in detail. With those requirements in mind the rationale behind the use of multi-agent systems (MAS) within AuRA-NMS is presented and the inherent research and design challenges highlighted including: the issues associated with robustness of distributed MAS platforms; the arbitration of different control functions; and the relationship between the ontological requirements of Foundation for Intelligent Physical Agent (FIPA) compliant multi-agent systems, legacy protocols and standards such as IEC 61850 and the common information model (CIM).

***Index Terms*— Cooperative systems, distributed control, intelligent systems.**

I. Introduction

With an increasing number of generators wishing to connect to existing distribution networks, the proliferation of distributed energy resources (DER) is changing the way distribution networks in the UK are designed and operated. While the renewable obligation certificate (ROC) scheme has provided the incentive for generators to connect to the distribution networks, the burden of any requisite network reinforcement can be prohibitive. As a result utilities are looking to active network management solutions [1] which allow generators to connect to existing networks under a range of connection agreements, while avoiding, or at least reducing or deferring, the costs associated with network reinforcement.

The register of active management pilots, trials, research, development, and demonstration activities [2] details over 100 distinct activities in the UK, with the most mature activities in areas of distributed coordinated voltage control [3] and active power flow management [4].

In this paper we discuss the exploitation of multi-agent system (MAS) technology with AuRA-NMS, an autonomous regional network management system currently being developed by several UK universities, distribution network operators and a major power industry equipment manufacturer.

AuRA-NMS represents a move from bespoke network specific solutions to more generic solutions which can be applied quickly to a variety of networks and offer an increased degree of flexibility and extensibility in the face of future changes to the networks once in place. AuRA-NMS also aims to integrate different control and network management tasks, such as voltage control and power flow management. Moreover, if control hardware and communications infrastructure is already in situ for the sake of increasing network access, there is an opportunity to use that as a platform for other forms of network automation, such as automatic restoration or network reconfiguration, which aim to reduce customer interruptions (CI), minimize customer minutes lost (CML) and minimize losses.

This paper describes the proposed use of multi-agent systems technology within AuRA-NMS. While the use of MAS technology for distribution system automation and network control has been mooted by several authors [5][6][7][8][9], AuRA-NMS is different in that it does not map an agent architecture onto the existing topology of the power system, i.e. in AuRA-NMS agents do not represent specific generators, circuit breakers, feeders or busbars: MAS technology is used simply as a flexible, extensible, distributable software integration framework.

In addition to introducing the AuRA-NMS concept and the rationale behind the use of MAS technology, we highlight some of the challenges inherent in using MAS for network management and control, challenges that we believe have yet to be discussed in the literature.

II. Industry Challenges Driving The Development of AuRA-NMS

While in the US active network management is being driven by the need for congestion management, in the UK and Europe active network management is being driven by the need to provide network access to small scale generators to traditionally passive distribution networks that cannot support firm connections.

A. Network Access and Connection Agreements

Under the current regulatory framework in the UK, utilities are motivated to minimize the capital expenditure required to meet their license obligations. Active network management can be one means of doing so.

Take the network in figure 1 as an example. The network has a number of embedded generators. The 33kV side of the network has almost 85 MW of installed generation with the minimum total local load of 10 MW. As a result, under certain contingencies the network cannot support the connection of all the generation. If, for example, one of the

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two 45MVA transformers was to be removed from service while the hydro plant and all the wind farms are at full output, the remaining transformer would be heavily overloaded.

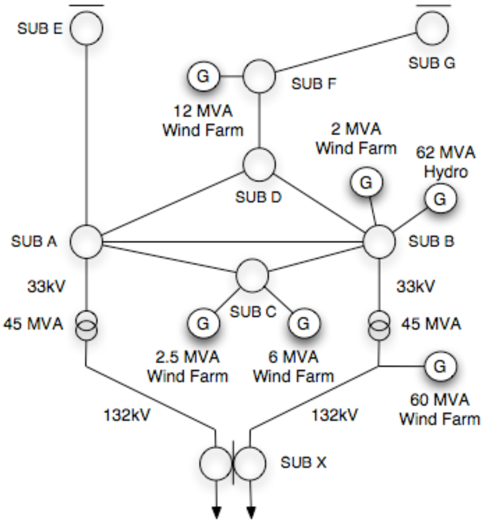

Fig. 1. Example network with distributed energy resources.

As generation has been connected to the network, the utility has employed a number of network automation schemes to deal with different contingencies.

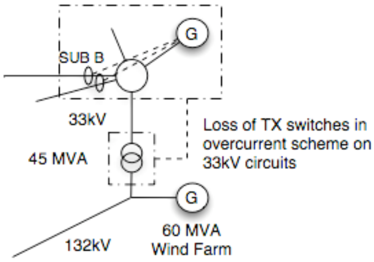

Fig. 2. One of nine network automation schemes deployed on the example network. This scheme activates an over-current scheme that will trip the generator if the 33kV lines are overloaded.

Figure 2 shows one such automation scheme. Since the loss of the transformer could leave the other 45MVA transformer heavily overloaded, an automatic control scheme has been put in place that automatically switches in an over-current scheme that will trip the hydro generator if the 33kV lines become overloaded.

Network automation must also take into account the nature of the generator's connection agreement and network access rights with respect to the access rights of other generators connected to the network. As new generators connect, the appropriate actions to take under certain contingencies may change and the installed network automation must reflect this.

In the future the nature of connection agreements may change depending on the rules put in place by the regulator. A practical active network management system must be flexible enough to implement a control scheme which satisfies existing connection agreements but can be adapted in the future in the face of changes to commercial agreements, rules for market participation of the generators or even use of system charging.

B. *Complexity of Control Schemes*

As more generators connect to the network, the complexity of a control scheme developed incrementally using the approach above increases. Over the years, additional layers of network automation have been put in place to trip generation in the case of certain contingencies, such as the example in figure 2. At the time of writing nine schemes are in place on the network above.

From the control engineer's perspective, as additional layers of automation are added, operation of the network becomes more complicated. Schemes may interact in a manner that may make it difficult to discern root cause. In some cases the complexity of control and the possible negative impact on network performance can become the main barriers to additional generation being connected to the network.

C. *Network Performance*

The deferral of network reinforcement may be seen as the key driver for employing an active management system such as AuRA-NMS, however regulatory pressure to reduce customer interruptions, customer minutes lost and losses means that network performance is also a concern.

There may be ancillary benefits of levels of automation if, as well as increasing DG access, it can improve network performance, i.e. reduce customer minutes lost (CML), customer interruptions (CI) and minimize losses, through automated restoration or automated network control which takes action to minimize losses.

AuRA-MNS is being designed to address these challenges while meeting requirements distribution network operators in the UK have for practical active network management systems. Understanding those requirements is key to understanding the rationale behind the use of MAS technology within AuRA-NMS.

III. The Distribution Network Operators' Requirements

One of the first tasks during the initial development of AuRA-NMS was the specification of the DNOs' requirements. These are summarized below:

- **Safety and security:** Safe operation is paramount; hence any regional network management and control system must meet the utilities' standards for both safety and security.
- **Flexibility and extensibility:** Flexibility connotes the ability to easily reconfigure the control system in the face of:
    - Changes to network topology and plant ratings;
    - The connection of new generation or energy storage;
    - The removal of generation or energy storage;
    - Changes to protection and control equipment;
    - The installation of new measurement and monitoring equipment; and
    - The removal of measurement and monitoring equipment.

  Extensibility, on the other hand, connotes the ability to easily:
    - Add additional network control and management functionality in the future; and
    - Replace existing functionality when improved network control and management techniques or algorithms are developed.

  Flexibility and extensibility are key attributes that utilities require in future active network management systems if they are to be manageable over the longer term.
- **Tolerance of failure:** A degree of tolerance of failure is required, with respect to:
    - Communications;

- o The hardware platform the control software is deployed on;
- o The distribution network control and management software used within the active network management system;
- o The failure of primary system plant, i.e. the failure of a breaker or switch to move when instructed; and
- o Measurement and monitoring equipment, e.g. tolerance of spurious or erroneous measurements.

- **Graceful degradation:** The concept of graceful degradation is common in intelligent systems. Graceful degradation, within the context of active network management, can be thought of as follows: if failures outside those that can be mitigated through redundancy occur, then the active network management system's performance should degrade gracefully, fulfilling as many of the network operator's goals as possible or sacrificing the attainment of lesser goals for higher priority goals, e.g. keeping customers on supply. The system should not "fall over".
- **Integration with the existing distribution management system:** Integration with the DMS in the control centre is essential. Through appropriate interlocking the control engineer should be able to override any automation.
- **Interfacing with existing equipment**: The DNOs require any future network management and control system to interface with existing measurement, protection and control equipment while also supporting the next generation of protection and control equipment, i.e. IEC 61850 compliant devices.

IV. AuRA-NMS: An Overview of its Properties

As its name suggests, AuRA-NMS is an autonomous regional active network management system. Within AuRA-NMS network management and control decisions are taken locally, in the substation, by software communicating with software running in other substations when necessary.

AuRA-NMS can be viewed as a distributed network control and management software solution running on a distributed and networked hardware platform.

A. Hardware Platform

The hardware platform on which the AuRA-NMS software will be initially deployed is ABB's COM 600 series substation automation product, an industrial computer designed for robustness which runs Window XP and has no moving parts. Details of the product can be found on ABB's website [10].

Fig 3: The ABB COM 600 industrial computer

The COM 600 has been designed to act in part as a substation gateway which translates between various protocols using IEC 61850 as a common data model and OPC clients and servers [10]. It currently supports a number of inter and intra substation communication protocols including: DNP3, MODBUS and IEC 61850. As a result, the COM 600 comes with a readymade software interface to existing protection, control and monitoring systems as well as existing communication networks.

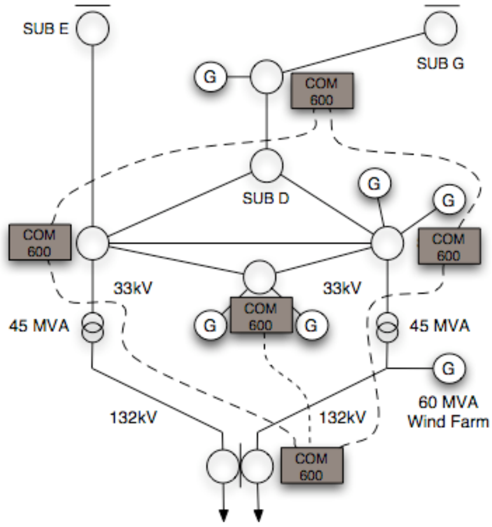

Fig. 4. A networked set of COM 600 units provide a hardware platform on which autonomous network management and control software can be deployed.

Networked using either the existing communication systems or, if cost effective, additionally installed communication channels, a network of COM 600s across several substations can provide a distributed hardware platform on which power system management and control software can be deployed (fig. 4).

Before considering the software which will run on the COM 600 as part of AuRA-NMS, the functionality of that software is discussed below.

B. Network Control and Management Functionality

Although AuRA-NMS will be flexible and extensible, allowing functionality to be added and removed as required, the core network management and control functionality it should have has been identified through discussion with DNOs. That functionality has been split into two families: reactive network management and control; and proactive network management and control.

Reactive network management and control takes place notionally over a zero to five-minute timescale. As the name suggests, control actions are applied in reaction to network events, e.g. the loss of a transformer due to a fault or the imminent infringement of a power flow or voltage constraint.

Proactive network management and control, on the other hand, is associated with wider timescale from 5 minutes to hours ahead. Based on forecasts of load and generation, proactive network control looks to optimize network performance over longer periods, placing the network in the optimal state which reduces losses if appropriate or mitigates the effect of possible contingencies. Depending on the DNOs' requirements, proactive actions could be taken by the AuRA-MNS controller without control engineering supervision or be offered as decision support, allowing the control engineer to decide whether or not to employ certain proactive measures.

For its initial deployment AuRA-NMS will have the following core network management and control functionality:

- Management of steady state voltage;
- Automated restoration;

- Operation of the network within thermal limits, e.g. power flow management;
- Management of constrained connections; and
- Proactive network optimization strategies, e.g. minimization of losses.

Some of the control functionality will be purely reactive, e.g. automated restoration, or purely proactive, as in the case of network optimization strategies. Other functionality, such as the management of steady state voltage and the operation of the network within thermal limits will have both reactive and proactive elements.

The development of methods for achieving the functionality above and how that functionality will be incorporated into AuRA-MNS are discussed later in the paper.

The way the control engineer will use the system is as important as the network management and control functionality AuRA-NMS will have.

C. Selectively Devolved Goal Driven Network Control

At the heart of the AuRA-NMS concept is the notion of selectively devolved goal driven network control. The control engineer will be able to assign AuRA-NMS an area of network and set the control goals for that area. These goals may be: the regulation of voltage within certain limits; operation of the power system within thermal limits; automatic restoration; and the reduction of losses.

From the control engineer's perspective, selectively devolved goal driven control means that goals can be assigned to AuRA-NMS which best suit the control engineer at that time, providing more flexibility than having a control scheme that can be simply enabled or disabled (although these options will also be available).

D. Explanation of Control Actions

Increased network automation can lead to networks with increasingly complex behavior. From the control engineer's perspective, transparency is key: why AuRA-NMS has taken a certain set of actions needs to be clear to the control room staff. As a result, reporting of action taken to the control centre must be accompanied by a description of the goal the system is trying to achieve. For example, if AuRA-NMS decides to trip a generator to alleviate a thermal constraint then the rationale behind that action and details of the constraint need to be sent to the control room.

If proactive network control is in place, the provision of explanations for control actions is even more important, especially if AuRA-NMS takes action for reasons which are not immediately obvious to the control engineers, e.g. the reconfiguration of the network based on forecast generation and load for hours ahead.

V. The Application of MAS within AuRA-NMS

In this paper we wish to explore the application of MAS within AuRA-NMS and illustrate why, with respect to the DNOs' requirements, MAS technology is attractive. First and foremost is the distributable, flexible, and extensible software architecture MAS can provide.

A. MAS as a distributable 'plug and play' architecture

The development of AuRA-NMS is being carried out by several teams at UK universities in collaboration with two DNOs and ABB. Each team is focused on delivering software which will provide AuRA-NMS with its reactive and proactive network management and control functionality, such as: voltage control; automatic restoration; and power flow management. By wrapping that software as autonomous intelligent agents and augmenting it with the functionality required to display the properties associated with agents, MAS technology is being used as a flexible and extensible way of both integrating and distributing the software across the hardware platform.

The use of Foundation for Intelligent Physical Agents (FIPA) compliant multi-agent systems to provide open, flexible, and extensible software solutions has been reported previously [11][12] and the arguments for how MAS provides flexibility and extensibility can be found in [13].

Existing standards provide a basic architecture which can be run on one COM 600 or over several. The FIPA Agent Management Reference Model defines the "framework within which FIPA agents exist", defining standards for creating, locating, removing, and communicating with agents [14] (Fig. 5). A FIPA compliant platform offers an implementation of this model underpinned by standards for inter-agent communication [15].

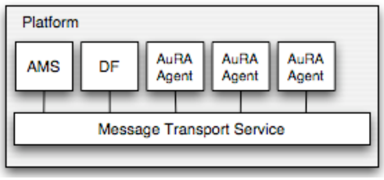

Fig. 5 The FIPA agent management reference model.

When an agent is launched on the platform, it registers with the agent management system (AMS) and registers the services it can offer with the directory facilitator (DF). For example, if a voltage control agent is introduced into the architecture it will proactively seek out the services of other agents it requires to fulfill its goal, (i.e. keeping voltage within certain limits) using the agent and service discovery provisions of the AMS and directory facilitator. Agents can be easily added or removed, so when new control or management functionality is developed it can be added to the system. Older functions can be easily removed and replaced at run time.

Different networks may require different functionality to be located in different substations. We believe that MAS technology offers the ability to deploy that functionality flexibly depending on the particular case at hand.

B. Mapping goal driven network control to MAS

According to Wooldridge autonomous intelligent agents should exhibit the three characteristics associated with flexible autonomy: reactivity, pro-activeness and social ability [16]. The second characteristic, pro-activeness, is the agent's ability to perform goal-directed behavior. Goal driven network control could be achieve in MAS by launching agents which proactively pursue the goals the control engineers wish to achieve. By deploying different agents within the hardware platform provided by a network of COM 600 units, a selectively devolved network control system can be created at runtime.

C. Building in Redundancy

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 a voltage control 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 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 COM600 units. As discussed in [13], this does not defend against faults in the code for a particular agent. Again, similar techniques used in good engineering practice can be employed: agents with the same functionality could be implemented differently, in an analogous manner to the way protection engineers may use distance relays from different manufacturers for first and second main schemes.

VI. Challenges in Applying MAS to Network Automation

If MAS technology is to be deployed on real power systems for network automation then a number of issues need to be addressed. In this paper we briefly examine two issues. The first is general and the second applies to AuRA-NMS.

A. Robustness and Reliability

MAS technology is often cited as being inherently robust, primarily through the ability of multi-agent systems to exploit redundancy. Many papers have claimed that MAS eliminates single points of failure. However, this not as straightforward as it might first appear. A MAS comprises not only a community agents but also the platform on which the agents run. By way of an example consider how the Java Agent Development Environment (JADE) [15], a firm favorite amongst MAS developers in the power engineering community, implements the agent management reference model (Fig. 6.).

There are several potential points of failure. Failure of the main container, i.e. the Java virtual machine (JVM) on which the container is running, can result in failure of the entire system. Problems with the RMI connection between additional containers can also cause failures.

From the perspective of a distributed control system, such as AuRA-NMS, this is problematic. If a single platform is run over several COM 600 units and the communication links between the COM 600 units are lost, agents may lose the ability to communicate with the DF or AMS and thus lose the ability to discover new services. They may also lose the ability to communicate with agents running in other containers (if those containers continue to run).

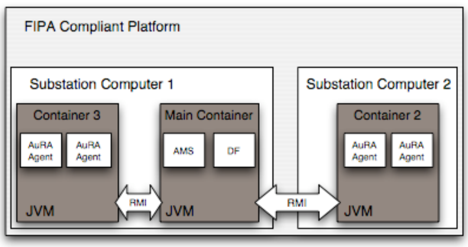

Fig. 6. The JADE implementation of a distributed FIPA compliant platform. Agents run within java virtual machines using remote method invocation (RMI) as a (non-FIPA compliant) message transport service.

The developers of JADE have built a number of platform specific features into their software to try to mitigate some of these issues [16]. Whether or not these solutions are adequate for this and other network control applications is a point which needs to be discussed by those reliant on a single JADE platform.

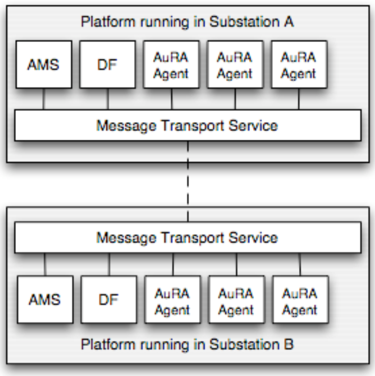

Fig. 7. Federated FIPA compliant platforms.

An alternative approach is to federate platforms (Fig. 7). Should the communication links between the platforms be lost, the platforms can still function independently. When the communication link is in place, platforms can be federated, allowing agents in substation A to discover agents and services offered by agents in substation B. This approach may also have the advantage of being a FIPA compliant solution which can be used for JADE and other FIPA compliant platforms. This does not mitigate the effect of failure of the DF and while the FIPA standards provide a mechanism for agent discovery within an individual platform through the DF and AMS, there is currently no standard way of discovering and managing federated platforms.

B. The Problem of Arbitration

The approach of using a number of disparate tools and techniques taken in AuRA-NMS creates a challenging problem: the problem of arbitration.

AuRA-NMS is predicated on the concept of a “plug and play” network management system where network control and management functionality can be wrapped as agents and easy added and removed for the overall AuRA-NMS system. In certain situations problems may arise when agents responsible for voltage control, power flow management, restoration or some other yet undefined service, wish to carry out conflicting actions in order to achieve their goal: some method of arbitration is required. Figure 8 shows an arbitration agent receiving proposed actions for a number of other agents.

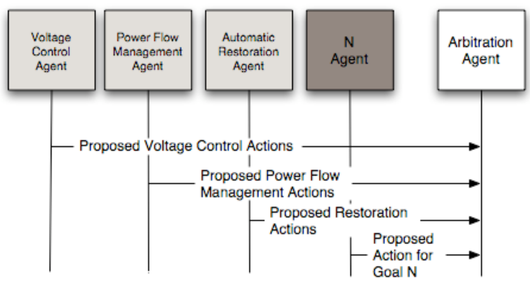

Fig. 8. The problem of arbitration. The arbitration agent must decide on which action or actions to implement based on its knowledge and information sent to it by the other agents.

In order to arbitrate between the goals of the different agents the arbitration agent needs to be able to detect conflict and have some knowledge of the DNO’s priorities.

A MAS technique called reflection may have a role to play in this type of situation. Reflection is the ability of an agent to reflect on the knowledge, abilities and goals of other agents.

Reflection has already been applied successfully in the COMMAS system [19] and employs probabilistic methods based on Bayesian belief networks for enhancing the evaluation of competing classifications of partial discharge data. The use of weightings or some measures of preference to discriminate between competing sets of action may not be appropriate within AuRA-NMS as such methods do not provide the rationale for the selection of one set of actions over another. For the control engineer to be comfortable with the choice of one set of actions over another some level of rationale may be required. Hence, symbolic forms of reflection which capture rationale may be needed to provide an appropriate level of transparency for arbitration decisions.

C. Ontological Requirements

In FIPA-compliant MAS, inter-agent communication is supported by: FIPA ACL [15], a shared content language and a shared ontology. While the content language is standardized, developers must pick an appropriate content language and, in most cases, develop a domain problem specific ontology.

The agents deployed within AuRA-NMS will have to communicate with existing substation devices. As a result, the ontology used by the agents will be based on existing standards. IEC 61850 will be used for device addressing and the common information model (CIM) will provide the data model for capturing details of the network. Unfortunately CIM and IEC 61850 do not cover all the ontological requirements AuRA-MNS will have. Hence the ontology will contain additional concepts and predicates which will not have equivalents in CIM or IEC 61850.

VII. Conclusions

This paper has described the AuRA-NMS concept and the drivers behind its development. The use of MAS technology to provide a flexible, extensible, and distributable software architecture has been discussed along with the challenges associated with deploying MAS for network management and control applications.

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