APPLICATION OF MULTI-AGENT SYSTEMS TO AID THE TRANSITION TO A DISTRIBUTION SYSTEM OPERATOR

Joe COLEBROOK
Frazer-Nash Consultancy - UK
j.colebrook@fnc.co.uk

Ross CAMPBELL
Frazer-Nash Consultancy – UK
r.campbell@fnc.co.uk

Gita JUDAH
Frazer-Nash Consultancy - UK
g.judah@fnc.co.uk

ABSTRACT

There has been a significant amount of research in Multi-Agent Systems (MAS) for power system applications. The technology has reached a maturity that makes commercial applications possible. At the same time in the UK network operators are required to become System Operators and actively manage their network. This paper explores how MAS can be applied to a real distribution network and help operator's transition to an actively managed network to unlock spare capacity and embed intelligence into the network.

INTRODUCTION

The energy sector is undergoing rapid change. Power generation is becoming increasingly decentralised which requires Distribution Network Operators (DNOs) in the UK to become more flexible and actively manage their network. DNOs will be required to transition to a Distribution System Operator (DSO) which will require them to be market facilitators as well as maintaining the resilience and security of the distribution network. The generation on the network will also be more intermittent and unpredictable as renewable penetration increases. The electrification of the heat and transport sector required to meet the UKs carbon reduction targets also means the capacity of the network must increase, options to achieve this include increasing the utilisation of the network or large-scale infrastructure upgrades.

This paper explores why a MAS is a suitable Smart Grid Architecture Model (SGAM) for the flexibility, speed and scalability required to enable the DNO transition to a DSO and discusses how implementing a MAS can also help increase the utilisation of the current network. Within the paper, several MAS architectures presently in development are reviewed and a MAS architecture suitable to enable the DNO to DSO transition is proposed.

WHAT IS AN AGENT?

A good introduction to an agent is given by Wooldridge [1] which states; "an agent is a computer system that is capable of independent action on behalf of its user or owner." In a MAS, a single agent does not have complete control over its environment, it can only influence the environment through its actions and an identical action may not always have the same result. A software program can be considered an agent if it exhibits the following characteristics [2]:

- **Autonomy** - Operating without the direct intervention of humans.
- **Sociality** - Interacting with its environment, other agents and humans.
- **Reactivity** - Perceives its environment and responds in a timely manner to changes that occur in the environment.
- **Pro-activity** - Exhibits goal directed behaviour by taking the initiative.

Individual agents can work in collaboration to achieve a goal. The agents and the communication system they use to interact combine to create the MAS. *Figure 1* illustrates four agents in a power network. Each agent is independent of each other and an agent can only gain information or use an agent's functionality by messaging it. An agent can only message another agent if it knows its Agent ID. To reduce complexity of the MAS and the required communication, system agents generally only know agents in their local vicinity. As shown in *Figure 1* the agent may accept or reject another agents requests if the request conflicts with its own goals.

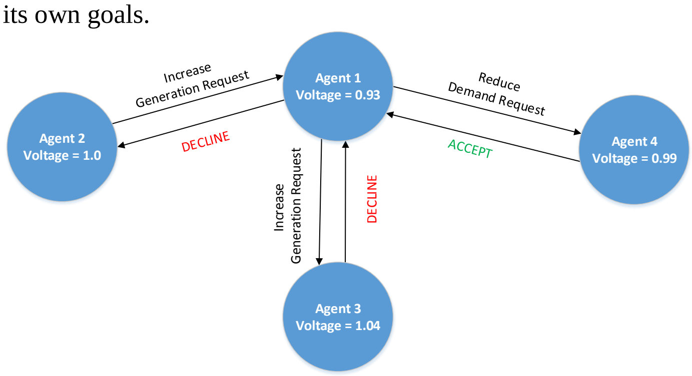

Figure 1- Abstract Agent Communication in a MAS

BUILDING A MULTI-AGENT SYSTEM

A MAS includes two agents which are visible to and can communicate with all agents in a MAS: the Agent Management Service (AMS) and the Directory Facilitator (DF). The AMS agent maintains a directory of current agents on the platform, and the DF agent maintains a register that can be used to find agents with services to offer. For example, an agent on a power network may have a generation service, Demand Side Response (DSR), or control of reactive power. A MAS uses a standardised and open sourced Agent Communication Language (ACL) which allows transparent communication between agents and humans. This type of architecture is called an open architecture as it places no restrictions on the programming language or origin of agents joining the platform.

The IEEE Power Engineering Society's MAS working group have discussed the applications of MAS in power engineering and the technical issues that need to be addressed to facilitate the uptake of the technology within the power and energy sector [3] [4]. The working group believes that using a central Supervisory Control And Data Acquisition (SCADA) system is no longer sufficient for certain control operations.

Three examples of current research into the operations a MAS are presented here to consider different DSO issues; including micro-grid control, energy trading and power flow forecasting.

Example 1: A MAS for Micro-grid Control

The thesis by Feroze on MAS in micro-grids is a demonstration of a well implemented MAS to control a micro-grid in MATLAB© Simulink and the MAS development platform ZEUS [5]. The micro-grid consists of one Distributed Energy Resource (DER) and five houses which contain critical and non-critical loads, each house has a user agent that can interact with the homeowner. There is a control agent which monitors the voltage level from the main grid and price signals from the utility to inform the control of the main grid circuit breaker. The DER capacity must be selected such that it can secure all critical loads during outages. Battery storage within the DER is implied as it can increase power output to satisfy the critical loads.

The system was tested to illustrate the proposed agents' ability to manage the supply from the DER when in islanded operation, secure critical loads during an emergency, and to share the excess DER capacity among the non-critical loads.

The Feroze paper provides an excellent framework on which to base a MAS for use in a distribution network, particularly if micro-grids become more common. The research can be expanded upon by integrating parameterised energy storage within the DER and increasing the number of DERs within the micro-grid. The research demonstrates a MAS that can autonomously isolate parts of the grid during a fault and continue to operate them as an island. This could be developed further to explore the potential for the network to become a self-healing grid.

Example 2: A MAS for Energy Trading

Another application of a MAS in Active Distribution Networks (ADNs) is presented by Lopez et al [6], which uses the idea of a MAS to execute a DSR strategy based on an optimisation problem, where the profit maximisation of all agents is pursued. The research focus demonstrated a planning tool rather than performing real time control.

The expected demand was known over a set time period. The system sought to optimise the power allocation to mitigate demand peaks and troughs. Every DER, Electric Vehicle (EV), storage unit and load was represented by an agent in a fully decentralised architecture. For a given period, each agent decided the quantity of power it could buy or sell. Agents could then choose to negotiate with other agents in an internal auction or to trade with the upstream grid. Once the whole system supply and demand was balanced, the solution was passed through a power flow solver and results checked against technical constraints, i.e. nodal voltages. If the voltage constraints were not satisfied a correction was applied to the system and the result passed through the power flow solver again.

The paper proposed an interesting application of a MAS for peer-to-peer energy trading but it did not use a standardised ACL or a standard architecture. The research by Lopez et al demonstrates a MAS is a suitable control mechanism to buy and sell network flexibility services on localised networks.

Example 3: A MAS for Power Flow Forecasts

A team at the University of Strathclyde Institute for Energy and Environment considered a MAS to control a fully decentralised autonomous ADN [7]. An agent was placed at each node in the network to estimate the load and generation profile for a given period and monitor the voltage at that node. Each agent, via communication with its neighbours, was given information about different network parameters such as upstream generators or grid connection points and thus built up a local model of the system.

Starting with the agents at the end of each branch, the load profiles for a specific period were compiled and communicated to upstream agents where these were combined; this led to an overall load profile at the grid connection point and each agent knowing its downstream load profile. Similarly, the generation profile was compiled and communicated upstream where this was subtracted from the downstream load profile of each agent resulting in either an import or export at the grid connection point.

If the aggregate power was above the grid connection threshold the agent would reduce all generation sources by a given percentage and propagate this information back down the branches. In the event of the actual power flow exceeding the power limits of a given branch, the agent managing that node, using its inbuilt local model, could communicate with the closest generation agent and request immediate corrective action.

The authors did not simulate the proposed method but assuming it works as expected this process could be developed further to help each agent predict when local network constraints will be reached. Agents could then take proactive steps to procure local flexibility services. The model could also be improved by including the line losses and therefore its effect on voltage as the load profiles are exchanged.

THE DSO COORDINATED MODEL

The characteristics of a MAS are well suited to meeting the requirements of a DSO and the research discussed highlights how a MAS can be used for the SGAM. A MAS could be implemented for distribution network applications as they display the following characteristics:

- Many entities need to interact.
- Sufficient data available locally to undertake an analysis or decision.
- New services need to be implemented that incorporate existing infrastructure or control systems.
- Functionality will be continually extended over time.
- There is interaction between distinct conceptual entities.

A particular benefit of MAS for distribution networks is the ability to introduce new agents and services to the system without disrupting the current system, and then updating the services they offer through remote updates as the requirements of the MAS change. There is no central SCADA that would need to be updated which, for non-redundancy systems, may risk a partial or complete outage.

In the UK, the Energy Networks Association (ENA) has developed five possible 'Future Worlds' which define potential DSO models [8]. This paper considers the 'DSO coordinated' Future World. In the 'DSO coordinated' model, the DSO enables a market whereby connected generation/demand customers can utilise their flexible capacity to meet the network constraints or demand conditions. This scenario is used because the author considers it the most decentralised Future World. In this scenario the SGAM employed by a DSO will have the following roles and responsibilities [9]:

1. Maintain distribution network resilience and security.
2. Provide an interface with the TSO to support whole system stability and optimisation.
3. Provide fair and cost-effective distribution network access.
4. Provide capacity in an efficient, economic, coordinated and timely manner.
5. Enable and facilitate competition in energy markets.

THE IMPLEMENTATION OF A MAS FOR POWER DISTRIBUTION NETWORKS

Different MAS architectures could be used to control a distribution network. The key differences between them are the network visibility of each agent and the level of interconnectivity/communication between different numbers of agents.

This paper proposes a MAS architecture to meets the Future World DSO requirements in a scalable manner to enable phased roll-out.

The Proposed MAS Architecture

To join the MAS an agent would require permission to register with the AMS and DF agents. The new agent would have to be approved by another agent with a high enough authority level for the type of service the connecting agent is offering. Once the agent joined the MAS it would need to provide information about itself to its neighbours and gather information about the local network by exchanging messages with neighbouring agents.

Agents could send different types of messages including INFORM, REQUEST, REFUSE, and AGREE. An ontology could be developed that enables the agents to understand the concepts and actions required to run the network, based on the ontology outlined by the IEEE MAS working group. The concepts include ID, direction, power and voltage. An action could be to increase real power flow or to disconnect from the network. The use of an ontology allows an agent to send a request e.g. Increase Power, and the recipient agent to know the senders ID, sender's direction and the value of the power increase required.

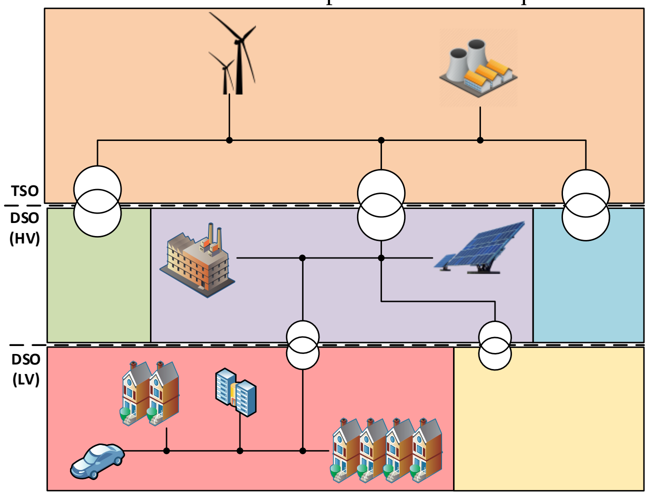

Figure 2- Agent visibility for a DSO coordinated architecture

There would be an agent at each substation and each private connection point on the network, these agents would be able to directly influence the DSO controlled environment. *Figure* 2 illustrates the visibility of each agent. This model assumes the distribution network has a radial topology during normal operation. An agent would be able to communicate with another agent of the same coloured group. The groups are split by voltage levels and then by each branch of the radial network. Agents on the voltage boundaries, i.e. Substations Agents, would be able to communicate with multiple MAS groups. The Substation Agents, which are controlled by the DSO, are dominant agents and could command agents to disconnect as a last resort to ensure network security.

DSO controlled agents aim to keep the network within the given constraints using the flexibility services provided by the agents connected to the network. The DSO Agents could request the agents to vary generation, loads, or reactive power to change the voltage and current profiles on the network to ensure the distribution network stays within the voltage and thermal constraints. Due to the agent's local visibility they would communicate with agents electrically close to them first which prioritises solving power flow or constraint issues locally.

Network Resilience and Security

In this model, agents owned or acting on behalf of the DSO would be able to monitor key parameters of the network such as voltage, current and frequency.

Some DSO agents would be able to reconfigure the network by operating switchgear. This would be important if there was a fault on the network and could permit isolated areas to operate in islanded mode using local generation and load control to maintain all or essential services.

Due to the decentralised nature of a MAS it would be difficult for an attacker to compromise the network. Gaining control of a single agent would only allow limited control as each agent is an independent piece of software from its environment and other agents. An attacker would need to control a significant proportion of the agents to have a meaningful impact on the network and this would be difficult to do undetected.

TSO Interface

The Grid Supply Point (GSP) is a substation that connects the distribution network to the transmission network. In *Figure 2* there are three GSPs that sit on the DSO and TSO boundary. A DSO controlled agent and a TSO agent at the GSP would manage this interface. The DSO agent would provide aggregated information to the TSO agent such as the forecasted power flows through the GSP. The DSO MAS could use a variation of the process described by Korbik et al from the University of Strathclyde [7]:

1. The agents compile forecasted power flow profiles which are aggregate as they are passed between agents and up voltage levels.
2. The DSO agent informs the TSO agent of this power flow profile.
3. The TSO agent checks that the forecasted profile is within the network constraints and accepts or rejects the profile accordingly.
4. The TSO agents' goals are to keep the transmission network within the network constraints.

The DSO and TSO agents cooperate to mutually achieve their respective goals. When two agent's goals are conflicting, they would be able to negotiate so that both networks stay within imposed constraints. If a conflict cannot be resolved with negotiation, the TSO agent would be dominant due to the higher voltage on the transmission network, and could command the DSO agent to limit the power flowing through the DSO/TSO interface.

Fair and Cost-Effective Network Access

With a significant penetration of DERs the control and monitoring of a MAS would provide the ability to reduce and increase power flows at all points on the network. The DSO could have a much higher utilisation of its assets and this in turn could reduce the investment required for large-scale network reinforcement. The main investment to enable deployment of a MAS would be the required communication infrastructure at all substations and private connection points.

A MAS would allow different stakeholders' goals to be achieved in a transparent, fair and cooperative way:

- Demand Agents aim to minimise the amount of money spent on electricity.
- Generator Agents aim to maximise the money earned from selling electricity.
- EV Agents must be able to ensure charging availability but may have a secondary goal of minimising costs.
- DSO Agents must ensure the network is reliable within constraints and to minimise costs.

These different and conflicting goals, solved locally for each specific network point should ensure the network has efficient allocation of resources.

EVs, large scale batteries and heating are examples of flexible electrical loads where some of their demand can be shifted to different times or temporarily reduced. Smoothing out the peaks and troughs in the demand profile is a cost-effective way to increase the total utilisation of the network.

Provide Capacity in an Efficient, Economic, Coordinated and Timely Manner

A MAS architecture is inherently designed to be scalable. A MAS could be implemented on small parts of the distribution network in trials before being rolled out across the whole network. This is possible if the MAS uses open source communication and can interface with other systems or humans. A MAS interface point could have power flow limits set to ensure it does not adversely impact the rest of the network. Because the agents only have local visibility of the network the solution can be efficiently scaled up throughout the network in a coordinated manner as individual substations were added to the MAS.

The installation of MAS communication infrastructure could be coordinated in a similar way to smart meters and benefit from the lessons learnt during the rollout. There are significantly fewer substations than domestic houses and the use of a standardised open source communication system should assist with ensuring a smooth deployment.

Enable and facilitate competition in energy markets

A MAS helps facilitate a highly competitive market. Every consumer and producer of power could have an intelligent agent controlling it which participates in energy markets by communicating with the market platform.

A MAS could also be combined with other innovative technologies such as a peer-to-peer energy trading platform. Blockchain technology could be used for smart contracts and asset registers that build trust into system. The ability for millions of electrical devices to participate in the energy market could create a competitive market. A MAS is designed for negotiation with agents exchanging messages with each other and could follow a similar process to the current wholesale energy market in the UK. Human interaction would be replaced by agent interaction and the ability for high frequency communication would allow for millions of participants.

CONCLUSION

The way energy is produced and consumed is changing rapidly. Generation and load profiles are harder to predict. Power now flows in novel directions and can be significantly variable even across one day. The distribution network must be actively managed and this is recognised by the current UK transition from DNOs to DSOs.

An MAS architecture can be considered an intelligent society and can cooperate and integrate with current human focused systems. At the same time the MAS can solve the optimisation problems of the network faster and more efficiently than human based control methods. By designing agents with appropriate services and by aligning their goals they can efficiently and transparently allocate energy resources whilst staying within the physical constraints on the network. The independence of each agent from its environment in a MAS acts as a natural Demilitarized Zone (DMZ) and therefore it is inherently resilient to cyber-attacks. The MAS architecture proposed in this paper could enable network operators to make the transition to DSO and achieve the key roles and responsibilities required of them by the regulator.

Agent architectures and power system ontologies have been developed by the IEEE MAS working group to allow the standardisation and interoperability of agents and competing MAS platforms. This paper demonstrates that MAS remains a viable option for network management and should be investigated further through the following next steps to enable the characteristics of MAS to be demonstrated at scale:

1. Model the system based on a real network.
2. Optioneering of the communication method.
3. Live trials on small parts of the network.

The IEEE MAS working group also highlighted the need for industrial trials to build on the wealth of research and prove a MAS can work in a commercial environment.

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