Evaluating a MAS Architecture for Flexible Distribution Power Flow Management

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***Abstract*— The challenges associated with controlling power networks are increasing due to integration of renewables, the potential use of storage technologies, and new dynamics introduced via technologies such as electric vehicles and demand side management. Active Network Management (ANM) is a key area to ensure that voltage and thermal limits are not breached. There has been a drive to explore flexible and extensible approaches to delivering enhanced active network management. One suitable approach is Multi-Agent System (MAS) technology that can provide a distributed solution to Smart Grid control. This paper focuses on the design and testing of a MAS able to deliver the ANM function, covering thermal constraint management as an initial application with the ability to integrate voltage control algorithms in the future. It is used to determine whether intelligent agents are the key to addressing these problems in ways that are flexible, extensible and robust. This system is built on the Presage2 MAS platform, which offers enhanced features and functionality to support the development of MAS for network control, and case studies of thermal overload management are provided for two different distribution networks.**

***Index Terms*— active network management, multi-agent system, agent communication language, power flow management, Presage2**

I. INTRODUCTION

The integration of renewable generation, demand participation and electric vehicles is increasing within distribution networks. This increase poses challenges to network control applications such as voltage control and power flow management within the distribution networks. To address these problems, Active Network Management (ANM) provides solutions to maintain voltage and power flow within statutory limits [1]. In addition, ANM allows renewable generators to connect to the distribution network without the requirement for network reinforcement [2]. Recently, there has been significant European activity in developing and demonstrating new methods to achieve ANM. Examples projects include: EU Active Distribution Network (ADINE) [3], Northern Isles New Energy Solutions (NINES) [4], Flexible Plug and Play (FPP) [5] and Autonomous Regional Active Network Management System (AuRA-NMS) [6]. Although various methods to achieve ANM have been reported, it still requires a flexible and extensible architecture which can be used to deploy the continually developing control algorithms required. Multi-agent Systems (MAS) is one of the candidates for delivering the flexible and intelligent platform. The characteristics of MAS provide a distributed solution for ANM issues, such as autonomy, reactivity, pro-activeness and social ability. The key driver for the research reported in this paper is to design a MAS which is suitable for ANM and can embed different control algorithms within intelligent agents over time. This provides an extensible and flexible platform for distributed network management intelligence. The initial implementation solves thermal constraints and will be extended to voltage violations in the future. The MAS has been implemented in the multi-agent simulation and animation platform Presage2 (Programming Environment for the Simulation of Agent Societies) [7], an extension of the original PreSage platform [8]. The scalability and "simulation" approach of Presage2 ultimately allows the effective testing of complex multi-agent interactions for network management and control. The agents developed can then be implemented in their on-line environment.

This paper presents a flexible, "plug and play", agent based ANM architecture for automatic network control. Furthermore, under the Presage2 time driven approach the system can exploit a multi-threaded implementation so that agents can run in parallel to utilize all available computing resources to solve the network control issues. Each agent has its own behaviours and rules to govern its decision making in the simulation. The developed MAS applied ANM on two different distribution networks to evaluate whether agents can operate and execute effectively to provide a flexible and extensible solution.

The paper is organised as follows. Section II will introduce the characteristics and benefits of MAS and two selected control algorithms for the agents' functionalities. It will also present the agent design of the MAS. Section III will introduce the agent design platform Presage2 and the development of the initial MAS for simulation and testing. The case studies of the MAS are undertaken on the thermal overload scenario, which will be presented in Section IV. Section V concludes the paper and describes the future work.

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II. Characteristics and Benefits of Multi-Agent Systems and Selected Control Algorithms

A. Multi-Agent System Overview

Multi-Agent Systems have been discussed widely for various applications in recent years, such as condition monitoring [9], microgrid control [10], reactive power control [11], power system restoration [12] etc. The fact is that the concept of an "agent" varies from author to author, although there are proposed definitions of agents reflecting their basic characteristics [13]-[15]. Wooldridge's [14] definition of an agent is that it can perceive the environment where it is situated and has the capability to react to changes in the environment autonomously. Furthermore, the agent can change the environment state by performing actions in the environment. Wooldridge extended the basis of an agent into that of an intelligent agent. According to Wooldridge's [14] definition of an intelligent agent, it has three main characteristics: reactivity, pro-activeness and social ability.

- *Reactivity:* An agent can react to the changes in the environment by perceiving the state of the environment and could take some actions accordingly.
- *Pro-activeness:* An agent has flexible problem-solving behaviour in order to pursue the delegated goals.
- *Social ability:* An agent has the ability to cooperate with other related agents to achieve assigned goals through a proper agent communication language.

The pro-activeness and social ability reflect the main differences between an agent and an intelligent agent. For an agent application, it is important to consider not only the role of a single agent but also how to combine several agents and intelligent agents to deliver benefits to the application under consideration. This is important for the ANM application being considered, as a MAS can deliver flexible and extensible applications. Flexibility means that an agent has the ability to adapt to a new environment, such as adding new control devices and distributed generation into the existing distribution network. Flexibility also reflects that agents can choose the appropriate action to perform in the environment depending on the current situation. Extensibility means that agent is free to add new functions or to delete unused functions in a system, potentially in real-time. As a result, the flexible and extensible features of a MAS make sure that it can integrate various control functions into the system to provide suitable solutions for ANM.

B. Selected Control Algorithms

Using agent characteristics and MAS features, the designed agent framework has to provide suitable solutions for power flow management (and voltage control in the future). Previous research has resulted in Constraint Programming (CP) [16] and Optimal Power Flow (OPF) [17] being successfully applied for power flow management. As a result, the CP and OPF control algorithms are selected for agents to solve the overload issues in this application. The CP and OPF control algorithms are briefly described below.

For the CP approach, the thermal problem is modelled as a Constraint Satisfaction Problem (CSP) with a set of variables defined within finite discrete domain of discrete values and a collection of constraints [17]. Variables determined in this paper are the controllable Distributed Generation (DG) and associated domain of discrete values for each DG is the control signal which is sent to the DG [16]. The constraints defined for the power flow management problem are: the identified solution in terms of the control signals to the DGs must keep power flow within limits; the curtailment sequence for each DG must fulfil the connection order set; and every potential solution is checked to identify which one maximizes DG access [16]. Therefore, the objective of the CP is to solve the CSP by searching suitable discrete values for each variable to make sure that all constraints are satisfied.

For the OPF approach, the power flow management problem is formulated as an optimization problem [17]. The objective of the optimization problem is to minimise the system operation costs and associated system constraints such as power balance, generation output limits, network capacity constraint and network access rights of generators [17]. As a result, the optimization problem for the power flow management problem is to calculate each DG output to minimize the power system operation costs subject to defined constraints.

C. Agent Types in the Multi-Agent System

Using the two different types of control algorithms mentioned above, the proposed MAS is required to detect the overload issues in the network and then solve them. The solutions from the two control algorithms (and any others deployed or being evaluated) may differ and as a result the system needs to manage this. Hence, the MAS is expected to contain an agent to detect the overload issues such as voltage violation and thermal overload and it also has an agent to arbitrate different solutions from the control algorithms. The schematic diagram of the MAS is shown in Fig.1. The agents communicate and cooperate with each other to realise the delegated control tasks using suitable agent communications within the agent platform. The functionalities of four different types' agents are described below.

1) Overload Detector (OD) Agent: the task of this agent is to check the overload status of the network. It detects voltage rise and thermal overload in the network. The application in this paper is to solve the thermal overload problem only.

2) CSP Solver (CSPS) Agent: this agent aims to solve the thermal constraint problems when overloads are detected in the distribution networks by invoking a CSP solver based on the CP algorithm. It is configurable at start-up with the network configuration, market constraints, etc. In the future, the CSP Solver can be used for to solve voltage control problems also.

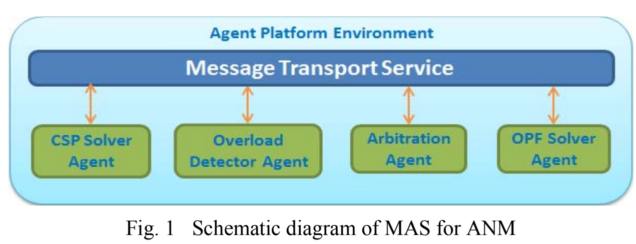

Fig. 1 Schematic diagram of MAS for ANM

3) OPF Solver (OPFS) Agent: this agent provides a solution to any detected thermal overload through invoking the OPF solver in the Power World Simlulator software [18].

4) Arbitration Agent: this agent checks if it requires to arbitrate between solutions when an overload occurs. If it identifies that it requires to arbitrate, it will check for conflicting actions and make a decision based on its knowledge base and network control priorities after receiving the solutions from the CSPS Agent and OPFS Agent.

III. Multi-Agent System Implementation

A. Presage2

An agent design and implementation platform is needed to allow the multi-agent active network management system to be implemented. The agent design platform used in this paper is Presage2.

There are numerous platforms to support Agent-based Modelling (ABM) or Multi-Agent Based Simulation (MABS) (see [19] for an extensive survey), or for developing multi-agent systems, e.g. JADE. In this paper, the multi-agent animation and simulation platform Presage 2 [19] is selected to achieving these purposes. Presage2 is a highly customisable and extensible programming environment that provides support for:

- 'large' numbers of arbitrarily 'complex' heterogenous agents, which can be run in multi-threaded or cloud computing environments for improved performance;
- soft-wired or dynamic agent behaviours which can be changed at run-time;
- conventional communication, and in particular the exercise of institutionalised power [20] (whereby a distinguished agent, normally occupying an identified role, performs a designed action (often a speech act), in the context of an institution, to establish a fact of conventional significance)

The authors have moved to Presage2 for a number of reasons. Firstly, it may be more scalable and offer a platform for a much larger set of agents. It can support more effective agent communication by allowing greater control by the designer over the autonomous behaviours and communication interaction. In addition, Presage2 has been designed to overcome some limitations within the FIPA-ACL. One of the limitations of FIPA-ACL is the agent autonomy ability. For example, an agent under the FIPA-ACL only makes a request to another agent which will then undertake a task for it. Theoretically, an agent has the ability to refuse to take an action when other agents request it. Consequently, a FIPA agent is not able to operate under the settings where sincerity and trust cannot be taken for granted [21]. Presage2 provides greater flexibility to design self-organising systems where richer interactions and the ability to clearly identify if a requested action will be taken or not is available [22].

Presage 2 offers the possibility for an ACL that can fully accommodate the flexible, extensible and autonomy needs of applications in electric power systems. There are three main components in the Presage2 platform, which are Agents, the Environment and the Network.

- *Agents:* An agent has an internal state to record information about the environment state and other agent states in the platform. The internal state consists of private and public parts. The private state is used to keep some information hidden from other agents.
- *Environment:* This represents a shared state between all the agents and agents can access the shared states via the environment service's function. An agent can change the environment state by performing the actions in the environment.
- *Network:* This is the central switchboard for messaging in the platform, rather than letting the agents communicate with each other directly. A user can add constraints to allow the blocking of messages or modify the messages before delivery. A key element in the use of Presage2 for ANM will be the ultimate distribution of the network functionality.

B. Implementing the Multi-Agent System using Presage2

For this implementation and test of the active network management MAS, the CSPS Agent and OPFS Agent are the initial control agents implemented within Presage 2. They are applied to thermal load management at this stage. In addition, an environment service is created in order to allow agents enquiring on overload information from the network, known as the Overload Service (OS). The initial MAS within the Presage2 platform, linked to the simulation environment, is shown in Fig.2. For the simulation, it requires a power network simulator to run the electricity network model and to provide the data from the network. The simulator embeds the IPSA software [23] within it to run the network models and the generator and load profiles is imported from external files during the simulation. Then, the data in the network model is written into the OPC server. In addition, the simulator reads the control signals by means of employing the OPC server, where the control signals are sent from the agents running on the Presage2 platform after the solutions are found. The CSPS Agent and OPFS Agent have their own behaviours and rules to govern their decision making. A brief description of each

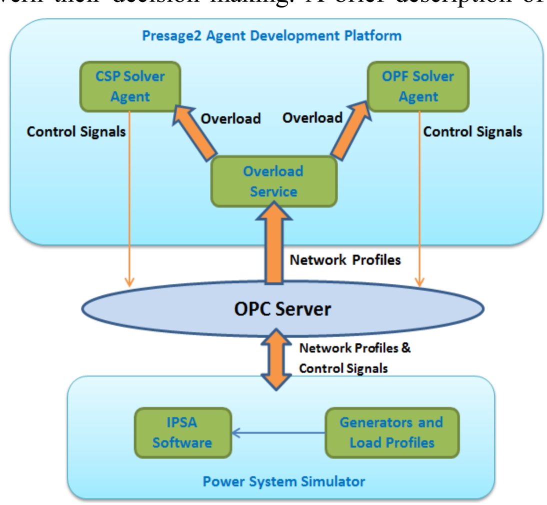

Fig.2 MAS simulation diagram

agent's behaviours and the functionality of the Overload Service are described below.

1) Overload Service (OS): this environment service is responsible for monitoring overload in the network. In order to check for overload, it invokes the IPSA software to perform load flow analysis after receiving the network profile through the OPC server. Then, it compares the value such as line thermal rating or bus voltage with the set system value. It is a global environment service which all the agents in the Presage2 platform can use to enquire about the overload service.

2) CSP Solver (CSPS) Agent: this agent finds a solution through the CP algorithm to solve a thermal overload issue and is coded in Python language. As a result, it invokes an external related Python program to find a feasible solution, which is saved for later application after it has been found. Then, it reads the saved solution file to record it as an internal solution state, the state indicates the system the solution is found and recorded.

3) OPF Solver (OPFS) Agent: this agent aims to seek an alternate solution by using the OPF approach to solve the optimization problem through invoking the OPF solver on the Power World Simulator software using a Python script. When it receives the overload information, it invokes the external related Python program to find an solution and save the contents of the solution into an external file. After that, the state of the agent procedded to the internal solution state.

IV. MAS Thermal overload Case Study and Results

The MAS was tested on thermal overload case studies which were undertaken on two distribution networks, a 33kV interconnected network (Fig.3) and an 11kV radial network (Fig.4) which were previously used in the AuRA-NMS project [16, 17]. Since Presage2 is a discrete time-driven simulator, each agent executes its actions and updates its environment and the agents' state every time step. During the simulation, the power system simulator updates the network profile to the OPC server and reads the control signals from the OPC server every second. The OS in Presage2 reads the network profile from the OPC server and checks for thermal overload through a defined function every time step. When a thermal overload is identified, it updates the overload state of the overload service environment. The CSPS Agent and OPFS Agent, on the other hand, enquire about the overload status using the OS every time step. When an overload occurs, they start to find a solution with the associated control algorithms. However, solutions determined by the CSPS Agent and OPFS Agent could be different for some scenarios. Moreover, the speed of the agent solvers can be different too. We expect that the basis for designing appropriate arbitration strategies can be found through the case studies. In this paper, the designed MAS and simulation is running on one PC platform. The thermal overload case studies and results are illustrated below.

A. Scenario 1: 33kV Interconnected Network

The first scenario is undertaken on the 33kV interconnected distribution network. There are eight generators (DGs) connected to the network. The network

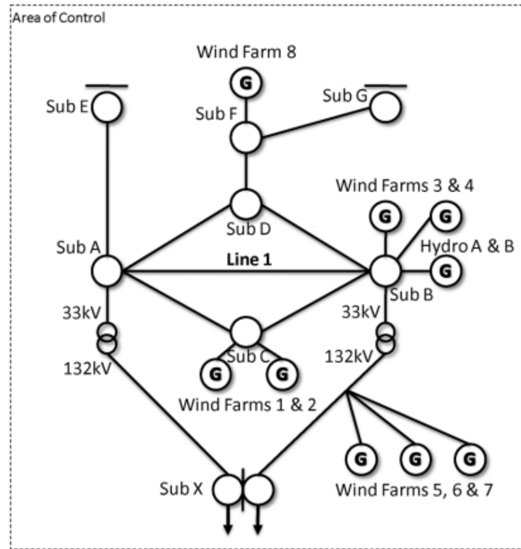

Fig.3 33kV interconnected network

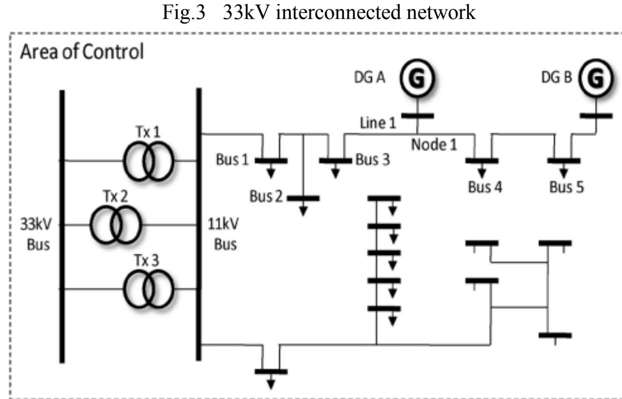

Fig.4 11kV radial network

access rights applied for this case study is the Last In First Off (LIFO) principle. LIFO is the common connection order in the UK which means the last generator connected to the network will be the first curtailed when overload issues occur. The details of the generator on this network are shown in Table I [16]. From the connection order in Table I, the first curtailed generator is Gen 5. As mentioned in Section II concerning the CP control algorithm, the domain of discrete values for the generator is configured as {1, 0.8, 0.5, and 0} which represent curtailment bandings, with exception of Hydro generations [16]. The activities of the hydro generators are indicated by {1, 0}. The value 1 means that this generator provides its scheduled output and 0 means that this generator has to be switched off. The value 0.8 and 0.5 represent the generator output needs to be curtailed to 80% and 50% of rated output.

For this scenario, all generators produce at rated output except Gen 5 which produces varying output and one of the loads at Sub A is increased to force a thermal overload at

TABLE I. Generator Data for 33kV IntercontED Network

DG Name	*Gen 1*	*Gen 2*	*Gen 3*	*Gen 4*	*Gen 5*	*Gen 6*	*Gen 7*	*Hydro A&B*
Maximum Power (MW)	5.0	4.35	23	12	23	10.2	2.4	20
Access Order	2	3	6	7	8	5	4	1

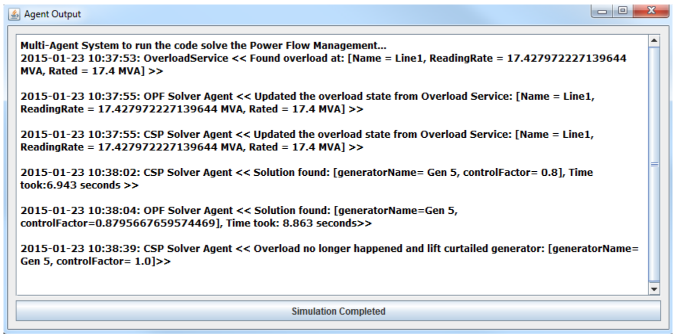

Fig.5 MAS simulation outputs for scenario1

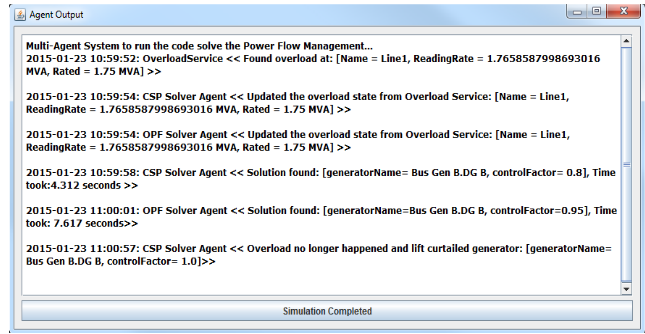

Fig.7 MAS simulation outputs for scenario2

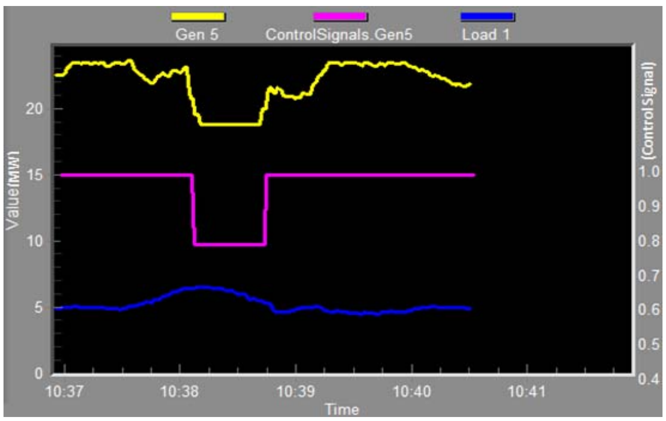

Fig.6 Gen5 output response, control sginal and load curve for scenario1

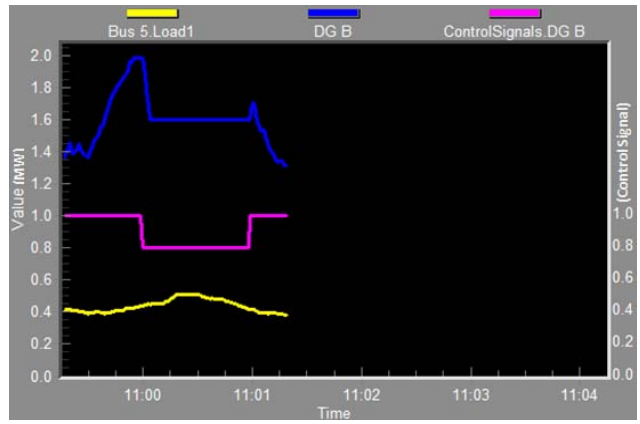

Fig. 8 DG B output response,control signal and load curve for scenario2

Line1 [16]. The MAS simulation outputs are given in Fig.5. Fig.6 illustrates Gen 5 output response, control signal, and varying load curve during the simulation. When the thermal overload occurred on the network, Fig. 5 presents the OS can capture this overload and update the overload state. The CSP Solver Agent and OPF Solver Agent updated this overload state through accessing the OS and started to find suitable solutions. As shown in MAS simulation outputs, the solutions determined by the CSPS Agent and OPFS Agent are to curtail the Gen 5 output to 80% and 87.95667%, respectively, under this situation. The calculation time for the CSPS Agent and OPFS Agent are 6.943 seconds and 8.863 seconds (Fig.5). The first found solution is applied in this implementation, but an Arbitration Agent will select and adapt the solutions to find the best in terms of curtailment in the future. Therefore, Gen 5 is curtailed to 80% of rated output. The corresponding control signals and Gen 5 output response under this situation are indicated in Fig .6 shown as pink (middle) line and yellow (upper) line, respectively. After applying the solution found by the OPFS Agent, it solves the overload issue through decreasing the output of Gen 5 by a smaller amount compared to that provided by the CSPS Agent. Following this, as the load at SUB A is reincreased (shown in the blue (lower) line in Fig.6) the CSPS Agent allows the DG B to run unconstrained by sending the control signal with value 1 shown in Fig.5 and Fig.6.

B. Scenario 2: 11kV Radial Network

The second scenario is undertaken on the 11kV radial network with two generators. The maximum output and connection order for these two generators are: DG A (last-off) with 1.6 MW maximum output and DG B (first-off) with 1.9 MW maximum output [17]. The domain of discrete values of the generators is the same as the 33kV interconnected network {1, 0.8, 0.5 and 0}.

Under this scenario, the DG A is configured at its rated output and DG B has varying output and circuit flow changed by varying the load at Bus 5 resulting in a thermal overload occurring at Line1 [17]. Fig. 7 gives the MAS simulation outputs. The DG B output response, control signal, and varying load profile at Bus 5 in the simulation duration are shown in Fig.8. From the MAS simulation outputs, the OS can detect the thermal overload and update the overload state of the environment once the thermal overload occurred on the network. The CSPS Agent and OPFS Agent updated the overload information through accessing the OS and started to find solutions. The suitable solutions determined by the CSPS Agent and OPFS Agent (Fig.7) are to curtail the DG B generator to 80% and 95% of the rated output, respectively. The computation time for the CSPS Agent and OPFS Agent are 4.312 seconds and 7.617 seconds, respectively. In a similar manner, the first solution found is employed without considering arbitration. Therefore, the DG B is curtailed to 80% of rated output. The corresponding control signals of DG B and its output response after receiving the control signal can be observed in Fig.8 shown as pink (middle) line and blue (upper) line as well. Alternatively, if the OPFS Agent's solution is applied, it is found that the solution can solve the current thermal overload issue by a smaller reduction of DG B output. When the load at Bus 5 is reduced (shown in yellow (lower) line in Fig.8), the CSPS Agent allows the DG B to generate at rated output by sending the control signal with value 1 given in Fig.7 and Fig.8.

C. Discussion of Results

From the thermal overload case studies above, it is clear that a MAS, with multiple control algorithms deployed as agents, can effectively provide active network management functionality for thermal load management. This can be applied to multiple network configurations and voltage levels. However, the solution granularity and computation time of the different types of solver agents inside the MAS are varied. The CSPS Agent and OPFS Agent both can determine useful solutions, but the OPFS Agent's solution is more effective at ensuring that less generation is curtailed due to its optimisation formulation. The CSPS Agent is based on the CP control algorithm which assigns discrete values set in advance for each generator. The CSPS Agent is quicker than the OPFS Agent to reach a solution. The computation time is based on the network size and objective function. As the 33kV network is more complex than the 11kV network, the computation time for the 11kV radial network scenario is always quicker than the 33kV interconnected network scenario, and even the computation time for the OPFS Agent is close for both scenarios. In addition, the OPFS Agent always took longer than the CSPS Agent to find a more accurate solution on both scenarios.

These simulation results prove the viability of a flexible, "plug and play", agent based architecture for active network management. They inform and drive the next stages of the research. For example, current work is focusing on a knowledge based Arbitration Agent to decide which solution is more suitable and to apply it appropriately.

V. Conclusion and Future Work

This paper proves the suitability of a MAS for ANM and the suitability of Presage2 as a programming environment for simulating MAS for electrical power systems. It presents the approach to implementing agents on the Presage2 platform, which is underpinned by the desire to integrate different control algorithms into agents. Using agent simulation, it implements agent behaviours and functionalities to tackle the power flow management problem. It is clear that the designed MAS can detect the thermal overload accurately and the agents can compute and execute feasible solutions effectively within various distribution networks. The next step will consider the Arbitration Agent and the resolution of conflicts between the CSPS Agent and OPFS Agent based on the thermal overload simulation results. The authors also aim to expand the agent communications in the system to allow a wider set of agents to cooperate more flexibly. Voltage control agents will also be implemented within the MAS to solve voltage violations. Ultimately, the plan includes a test of the proposed MAS within a physical microgrid laboratory for validation and verification of MAS applications in power engineering.

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