A PRACTICAL IMPLEMENTATION OF A DISTRIBUTED CONTROL APPROACH FOR MICROGRIDS

P.F. Lyons, P. Trichakis, P.C. Taylor, G. Coates
School of Engineering, Science Laboratories, Durham University

ABSTRACT — Public low voltage feeders containing a mixture of several micro-sources, distributed energy storage units (ESUs) and controllable loads, which appear to the upstream distribution network as controllable entities, are known as MicroGrids. Through intelligent co-ordination of micro-generators and ESUs, coupled with demand side management techniques, MicroGrids have the potential to offer significant improvements in the commercial value and environmental impact of installed micro-generators. Furthermore, using appropriate active control techniques, MicroGrids could potentially overcome the low voltage distribution network constraints associated with high levels of micro-generation. The research described in this paper builds upon previous research carried out at Durham University, which proposed a preliminary distributed control approach for MicroGrids. The first steps in this approach have now been implemented using agent technology on the laboratory based Experimental MicroGrid at Durham University. Results from this practical implementation of first-stage agent-based control are presented and discussed. Finally, the agent-based controllers are evaluated based on their suitability to satisfy the specific control requirements of MicroGrids.

Key Words: Distributed Generation, Micro-Generation, MicroGrids, Multi Agent Systems.

1 INTRODUCTION

Interest in Distributed Generation (DG) has increased greatly in recent years as fears over global warming, high oil prices, the decline of indigenous energy supplies and increasing governmental support are expected to lead to a continuous increase in electricity generated by renewable energy sources. Furthermore, the deregulation of the electricity industry in some countries has also played a key role in increasing competition and opening the market to newcomers, thus allowing more privately owned generators to be interconnected to the electricity distribution network.

In addition to the distributed generation embedded in Medium Voltage (MV) distribution networks, micro-generators installed at end users at Low Voltage (LV) levels are gaining significant momentum, due to potential advantages regarding reliability, energy efficiency and power quality. For the United Kingdom (UK), installed micro-generation capacity could grow to as much as 8GW by 2015 according to a major recent study [2], while a second study has suggested that micro-generation technologies could supply between 30 to 40 per cent of the UK's electricity demands by 2050 [3]. This is due to technologies such as domestic Combined Heat and Power (dCHP) units, small wind turbines and photovoltaic arrays having the potential to be adopted by many domestic and commercial load customers.

The anticipated growth in micro-generation will entail the introduction of large numbers of generators of different types and sizes at various locations of the low voltage electricity distribution network. However, these have been designed and operated based on planned centralized generation, and on the assumption that the current always flows from the substations to the ends of feeders. Furthermore, the growth of micro-generation is consumer-driven and not centrally planned ("fit and inform" principle). Hence, a key challenge facing the electricity industry is to accommodate the anticipated growth of micro-generation onto existing low voltage distribution networks without compromising security of supply, while at the same time minimizing costs incurred to customers and maximizing the potential benefits gained from these units. There is a consensus within industry and academia that the most appropriate way of achieving this is by active control techniques [4-7].

Public low voltage feeders containing a mixture of several micro-sources, distributed energy storage units (ESUs) and controllable loads which appear to the upstream distribution network as a controllable entity, are known as MicroGrids [8-9]. Through intelligent co-ordination of micro-generators and ESUs, coupled with demand side management techniques, MicroGrids have the potential to offer significant improvements in the commercial value and environmental impact of installed micro-generation. Moreover, it is possible that MicroGrids could be used to provide ancillary services to Distribution Network Operators (DNOs) such as local voltage control and spinning reserve. Furthermore, using appropriate control, MicroGrids could overcome the low voltage network constraints associated with high levels of micro-generation.

Currently, in relation to MicroGrids, there exists considerable research with regard to operation and analysis [16-18], protection [19-20], market operation [21-22], and control [22-26]. Furthermore, a number of demonstration projects have been commissioned internationally, in particular in Europe, USA and Japan [26-27]. However, development of these projects has mostly been undertaken independently and significant differences exist in network topology, the rating and mixture of micro-generation, as well as on their operational aims and their specific controller implementations. One such project is currently under development in Durham University with three main aims: (i) to assess the impact of micro-generation on existing passive low voltage distribution networks, (ii) to validate distribution network models that have already been developed [11, 12, 14, 15], and (iii) to implement, test and refine control algorithms for future active distribution networks. The research described in this paper builds upon previous research carried out at Durham University, which proposed a preliminary distributed control approach for MicroGrids [1]. The first steps in this preliminary approach have now been implemented using agent technology on the Experimental MicroGrid at Durham University. Results from this practical implementation of first-stage agent-based control are presented and discussed. Finally, the agent-based controllers are evaluated based on their suitability to satisfy some specific control requirements of MicroGrids.

The paper is structured as follows. Traditional, centralized control systems and modern distributed control approaches are discussed in Section 2 in terms of their capability to satisfy the specific control requirements of a MicroGrid. The use of a distributed control approach, realized through agent technology, is proposed in Section 3. Section 4 introduces the active distribution network laboratory test facilities developed at Durham University, and Section 5 describes a first-stage application of the agent-based approach to the Experimental MicroGrid. Experimental results are presented in Section 6 and discussed in Section 7 with regard to the agent-based controllers' ability to overcome issues associated with steady-state voltage rise/drop and cable thermal limits. Finally, conclusions are drawn and the scope for further work is identified.

2 CONTROL APPROACHES

The existing control approach for most DNOs is the use of a central control system executing predetermined control routines. These central control systems rarely extend down to the low voltage, 400V, network level. This means that low voltage distribution networks are currently operated as passive entities (the “fit and forget” philosophy). However, this passive approach limits the installed capacity of micro-generation that can be connected.

Since MicroGrids contain sections of public low voltage networks, these systems must be transformed from passive to active entities, in order to enable the connection and proliferation of micro-generation. At the same time, this must be achieved without impairing the ability of the DNOs to operate their networks within necessary performance standards as defined for the UK [27-28] and for Europe [29].

2.1 Specific control requirements of a MicroGrid

The specific control requirements that have been identified [1] are associated with (i) overcoming the low voltage network constraints associated with micro-generation, and (ii) the ability to provide predictable and controllable power input/export from the MicroGrid. In turn, satisfying these requirements could lead to increased economic benefits due to group interaction with energy markets and the potential provision of ancillary services to DNOs. These increased economic benefits could potentially facilitate the proliferation of micro-generation and hence offer significant environmental benefits due to increased renewable energy production.

2.1.1 Low Voltage Network Constraints

The low voltage network constraints considered in this research are: (i) voltage rise limits [10-11], (ii) voltage unbalance limits [12], (iii) operating distribution network circuits above their thermal limits [13], and (iv) reverse power flow through distribution transformers exceeding their thermal limits [14]. The first two constraints are determined by statutory regulations [28-30], while the other two constraints are determined by equipment ratings. The rationale for choosing these four particular network constraints is based on the results shown in Table 1 from simulations run in a generic UK distribution network model that have identified them as the main technical barriers to the operation of high levels of micro-generation to low voltage distribution networks [11, 12, 14, 15].

The UK generic distribution network contains six 11kV feeders, each supplying eight 11/0.4kV 500kVA ground mounted distribution transformers and 400V substations. The results shown in Table 1 focus on the uniform connection of micro-generators on just one 400V substation of the distribution network, which represents a 1.2km long, underground cable, urban LV distribution system serving 384 evenly-distributed customers.

The simulation package PSCAD/EMTDC™ has been used to model the distribution network as a multi-grounded three-phase four-wire system. Installed micro-generators were modeled as current sources, with the power factor of each generator set by adjusting the phase angle of the generator relative to the phase angle of the supply voltage. Results shown in Table 1 assumed that all micro-generators are operating at unity power factor.

Finally, constant power load models were used for all single-phase customer loads. Maximum and minimum domestic load figures were taken from Electricity Association sources, which show that, including diversity of demand, the minimum and maximum demand figures of each domestic single-phase load are 0.16kVA and 1.3kVA respectively. Results presented in Table 1 assume minimum loading conditions and unity power factor for all customers in the network.

Table I
Threshold micro-source rating per customer for each of the four LV network constraints

LV Network Constraint	Rating per customer
Voltage Rise	0.5 kW[1]
Voltage Unbalance	1.5 kW/phase
Thermal Limits	~2.5 kW[1]
Reverse Power Flows	~ 1.4 kW

In order to overcome voltage rise issues, the control system needs to be able to measure the magnitudes of all single-phase voltages at the remote point of each feeder. These values should then be compared with the +10/-6% statutory limits defined in [28]. If the magnitude of a single-phase voltage falls outside the statutory limits, the control system must be able to change the power flows in the MicroGrid so that this voltage can return to within the statutory limits.

With regard to overcoming voltage unbalance, measurement of the magnitudes and angles of each of the phase voltages at the remote end of the MicroGrid's feeders must be processed and compared with the maximum 1.3% of voltage unbalance defined in [29]. In the event that voltage unbalance exceeds this limit, the control system would change the single-phase power flows to restore balance to the voltages.

Overcoming thermal issues within the MicroGrid requires the control system to measure the Root Mean Square (RMS) values of the currents at known "hot spots" within the MicroGrid, and compare them to the appropriate cable ratings. For reverse power flow issues, the control system must be able to compare RMS current values to transformer ratings. If values exceed equipment ratings, the control system needs to be able to change the power flows in the network to address these issues. The difference between addressing thermal and reverse power flow issues in a MicroGrid is the single-phase nature of the former compared to the three-phase nature of the latter.

2.1.2 Operational goals

For the MicroGrid to be able to provide predictable and controllable power input/export, the control system must be able to measure the three-phase power flows at the connection point of the MicroGrid with the distribution network and then modify the power flows within the MicroGrid according to the desired operational goal. Depending on network conditions, five different possible operational goals for the operation of a MicroGrid have been identified: (i) zero power export, (ii) zero power import, (iii) zero power import and export (self-sufficiency), (iv) constant power import, and (v) dispatchable power export [1]. This should be done at half-hourly intervals, in accordance with UK electricity market procedures. For power dispatch, communication links between the control system and the local DNO need to be established to allow the MicroGrid to receive a central request from the DNO to specify the required change in power exchange with the distribution network. In line with this central request, the control system will then determine if it is capable of delivering the specified power to the distribution network and will then decide how best to achieve this.

[1] This figure is based on the assumption that there is a uniform distribution of micro-generation throughout the LV network under study.

2.2 *Potential approaches for control*

Two potential control approaches for a MicroGrid have been identified, namely centralized and distributed. With regard to a centralized control approach, limitations have been identified in its application to Microgrids [5, 30]. As such, a distributed control approach has been proposed and selected in [1]. The work described in this paper represents a first stage practical implementation of this distributed control approach using a Multi-Agent System (MAS).

3 DISTRIBUTED CONTROL USING AGENTS

A Multi-Agent System is the combination of one or more agents, each exhibiting a range of attributes, within a co-operative system [31]. Through a detailed examination of the MicroGrid control problem, four key attributes have been identified: autonomy, social ability, reactivity, and pro-activeness [1]. Furthermore, each of these key attributes is described along with specific examples of their value within the MicroGrid control problem. In order to satisfy the specific control requirements of a MicroGrid and adhere to the specifications developed by the Foundation of Intelligent Physical Agents (FIPA) [35], three types of control agent are required: direct, indirect and utility.

Direct agents explicitly control a power system entity within the MicroGrid. Within this distributed control approach three categories of direct agent are used, namely Generator Agent (GA), Consumer Demand Agent (CDA) and Energy Storage Agent (ESA). The direct agents act autonomously where possible, though in certain situations they will be required to respond to requests from indirect agents.

Indirect agents implicitly control a power system entity within the MicroGrid. Three categories of indirect agents, which are able to influence the actions of direct control agents, are used: Thermal Limits Agent (TLA), Operational Goals Agent (OGA) and Unbalance Agent (UA).

Utility agents perform administrative duties, in accordance with the FIPA specifications [36]. The Agent Management System (AMS) and Directory Facilitator (DF) enable the efficient operation of direct and indirect agents.

4 EXPERIMENTAL MICROGRID

A laboratory based Experimental MicroGrid is currently under development at Durham University with three main aims: (i) to assess the impact of micro-generation on existing passive low voltage distribution networks, (ii) to validate distribution network models that have already been developed [11, 12, 14, 15] and (iii) to implement, test and refine control algorithms for future active distribution networks. The Experimental MicroGrid consists of one load emulator, one wind turbine generator emulator, one PV generation emulator, one dCHP emulator, one ESU and one network connection emulator, as shown in Figure 1.

Figure 1: View of the Experimental MicroGrid at Durham University

4.1 Design of the Experimental MicroGrid

Figure 2 illustrates the topology of the Experimental MicroGrid and the location of the six measurement nodes. The network has a radial layout and its impedances are primarily resistive, in accordance with public low voltage networks where X/R ratios are low.

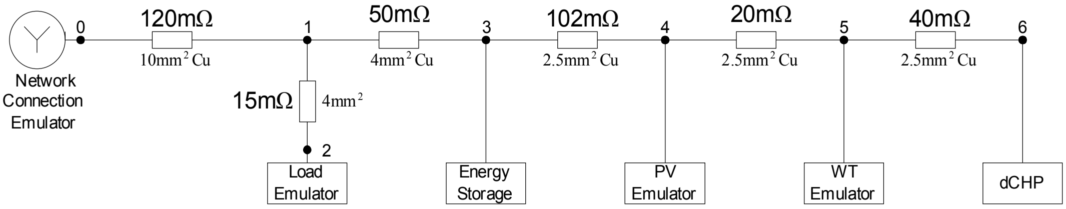

Figure 2: Single line diagram of the topology of the Experimental MicroGrid

A more detailed schematic of how load, single-phase micro-generators and single-phase energy storage are coupled with the three phases of the ac bus is shown in Figure 3. The micro-sources are interfaced directly in the case of the dCHP emulator or using inverter interfaces when the wind turbine generator emulator, PV generation emulator and energy storage unit are coupled to the network.

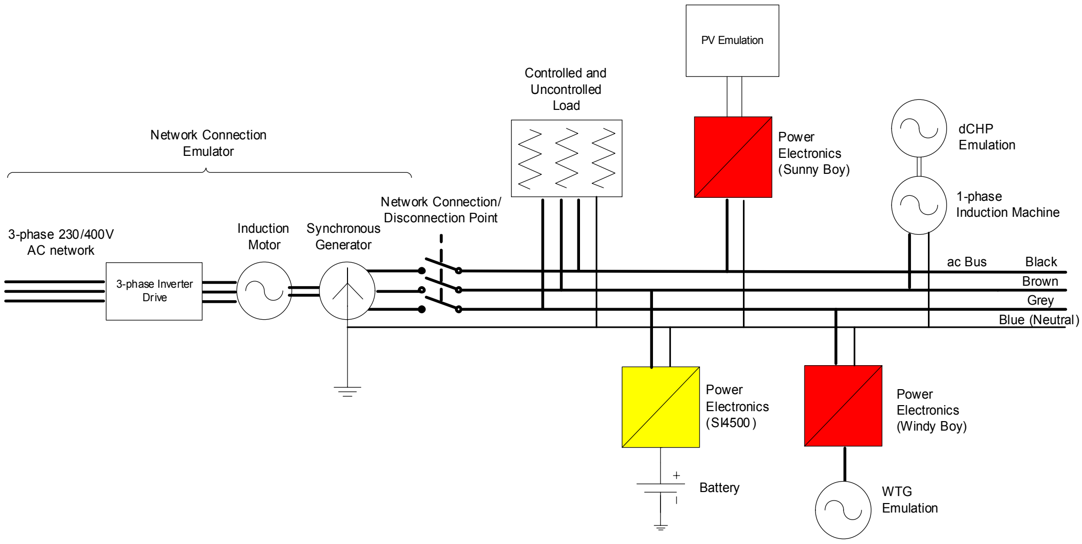

Figure 3: Electrical Layout of the Experimental MicroGrid

Sophisticated monitoring and control systems have been developed using the LabVIEW™ visual programming environment [37]. The LabVIEW™ system has been adopted by Durham University for the following reasons. It enables the flexible, real-time measurement of system parameters (voltage, current, frequency etc) from the ESU emulator, wind turbine generator emulator and three-phase load system. The system can control the micro-source and ESU inverter interfaces in order to regulate active power flow. Reactive power flow into and out of the energy storage system may also be controlled. Finally, the LabVIEW™ control panel supervises the control of the micro-source and load emulation system that enables repeatable controlled testing to be carried out in order to test the control algorithms developed.

Load balancing for the network is achieved using a 30kW, 400V three-phase synchronous machine. The prime mover for this machine is a 15kW induction machine driven by a 4-quadrant mains fed inverter drive.

An Elecsol 48V, 110Ah long life (5.28kWh), carbon fiber battery bank is used to provide energy storage within the Experimental MicroGrid. An SMA Sunny Island 4500™ (SI4500) battery charger/single-phase bi-directional inverter is used to invert the 48V dc from the battery bank and interface with the Experimental MicroGrid low voltage network. Communication between control algorithms, running in LabVIEW™ and the SI4500 is achieved using OPC (OLE for Process Control where OLE stands for Object Linking and Embedding) servers/clients, utilizing the DataSocket™ I/O interface technology in LabVIEW™ [38]. Control of the real and reactive power flow from the energy storage system is achieved by utilizing the droop control functionality of the SI4500 [38-40].

To emulate a small scale wind turbine generator, a three-phase axial flux synchronous machine designed at Durham University for use in a vertical axis wind turbine [41] is used in conjunction with a computer controlled induction machine to emulate the mechanical characteristics of a wind turbine. The V-I characteristic of a PV array is simulated using a computer controlled dc power supply. These micro-sources are coupled to the LV network of the Experimental MicroGrid using G83 compliant [42] grid tied inverters from SMA [43, 44], the real power output of which can be regulated using the same OPC technology used to control the ESU.

The dCHP emulator consists of a computer controlled three-phase induction machine to emulate the prime mover of a dCHP unit and a capacitor compensated, single phase induction machine to couple the system to the LV network.

A computer controlled three-phase load bank has been developed, which independently varies power demand on each of the three-phases independently from 0 to 2.2kW in 0.2kW steps.

5 APPLICATION OF AN AGENT-BASED CONTROL APPROACH TO THE EXPERIMENTAL MICROGRID

As mentioned previously, the Experimental MicroGrid consists of one load emulator, one wind turbine generator emulator, one PV generation emulator, one dCHP emulator and one ESU emulator. A first-stage application of the proposed agent-based control approach to the Experimental MicroGrid is presented in this section in accordance with the system agents identified in Section 3.

5.1 System agents

The following agents have been implemented in the Experimental MicroGrid using the LabVIEW™ visual programming platform, as shown in Figure 4:

- Generator Agent (GA – Direct Agent) ~ the GA controls the wind turbine generator emulator.
- Consumer Demand Agent (CDA – Direct Agent) ~ the CDA controls the load emulator.
- Energy Storage Agent (ESA – Direct Agent) ~ the ESA controls the ESU emulator.
- Thermal Limits Agent (TLA – Indirect Agent) ~ the TLA controls the power flow through Node 1.

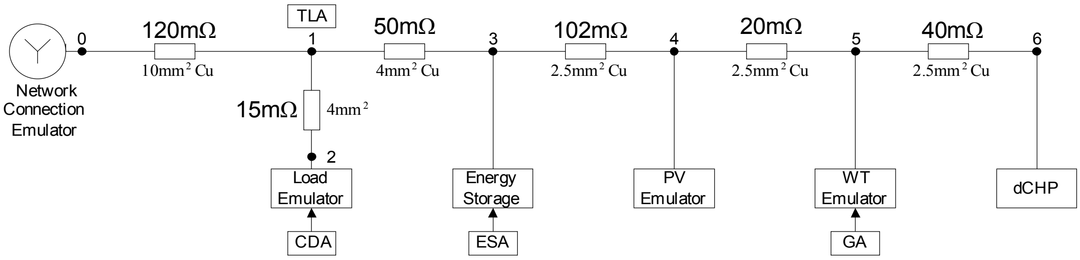

Figure 4: First-stage application of the agent-based control approach to the Experimental MicroGrid

5.2 Functionality of the control system

The control requirements of the first-stage control system, which has been developed, are associated with (i) overcoming steady-state voltage rise/drop issues within the Experimental MicroGrid (+10/-6% according to [28]), and (ii) protecting system cables from being thermally overloaded.

Steady state voltage rise can be mitigated by: (i) reducing the power output of the wind turbine micro-generator through the GA, (ii) diverting power into the ESU through the ESA, and/or (iii) increasing the load in the locally affected area through the CDA. Similarly, steady-state voltage drop issues can be mitigated by: (i) exporting power from the ESU through the ESA, and/or (ii) reducing the load in the locally affected area through the CDA. These interventions can be performed individually or collectively by the three direct control agents in the system.

Furthermore, the control system also contains a TLA, which uses current measurements from Node 1 of the Experimental MicroGrid such that it can intervene to protect cables from thermal damage. This can be achieved by establishing communication links between the TLA and the direct control agents in order to: (i) reduce the power output of the wind turbine micro-generator through the GA, (ii) divert power into the ESU through the ESA, and/or (iii) increase the load through the CDA.

For a MicroGrid where the operation of micro-sources results in reverse power flows to the distribution transformer, an agent responsible for protecting that transformer from thermal damage may also be required. The TLA implemented in the Experimental MicroGrid could be used as such an agent by measuring and comparing three-phase currents instead of single-phase for cable thermal limits.

6 EXPERIMENTAL RESULTS

First-stage agents were developed in accordance with the framework outlined in the previous section. Four agents (GA, CDA, ESA and TLA) were developed in LabVIEW™. The ability of the agents to overcome the following technical constraints was investigated:

- Voltage rise
- Voltage drop
- Cable thermal limits

The Experimental MicroGrid was operated such that each of the three constraints were exceeded/experienced. In all cases, agents then intervened in an attempt to restore satisfactory operation of the MicroGrid. Satisfactory operation means that the agents ensure that all relevant electrical parameters are within defined limits.

6.1 *Steady-state voltage rise*

The Experimental MicroGrid was firstly operated such that it exceeded the steady-state voltage rise limit at no load. For the purposes of the test, this was defined at 225.5V + 3.5V = 229V. At time t=10s the prime mover of the wind turbine generator emulator is instructed to operate at a speed that results in a power output of 0.6kW to the system. The Windy Boy™ detects the resultant DC voltage and initiates a synchronization sequence with the Experimental MicroGrid low voltage network. Once synchronization is achieved, the system starts to export power. At time t=70s the prime mover is instructed to accelerate to a speed that results in a power output of 1.2kW from the wind turbine generator emulator to the system. Figure 5(a) illustrates the effect of the operation of the wind turbine generator emulator on the remote end network voltage, without any agents deployed in the system. It can be seen that the voltage in this case exceeds the defined voltage rise limit of 229V following the increase in generation.

Figure 5(b) shows the individual operation of the GA, CDA and ESA in order to mitigate against this steady-state voltage rise. In all the cases, system agents intervened in an attempt to restore satisfactory operation of the Experimental MicroGrid. This was achieved through: (i) the GA instructing the grid interface inverter of the wind turbine generator emulator to curtail its power output (ii) the ESA instructing the bi-directional inverter of the ESU to import power thus charging the batteries, and (iii) the CDA instructing the load emulator to increase demand.

Figure 5(c) illustrates the joint operation of the GA and CDA to reduce the voltage rise at the remote end of the system. In this case, the agents operate in a similar manner to the individual case, but the contribution of each is reduced as the agents are sharing the duty of restoring satisfactory operation.

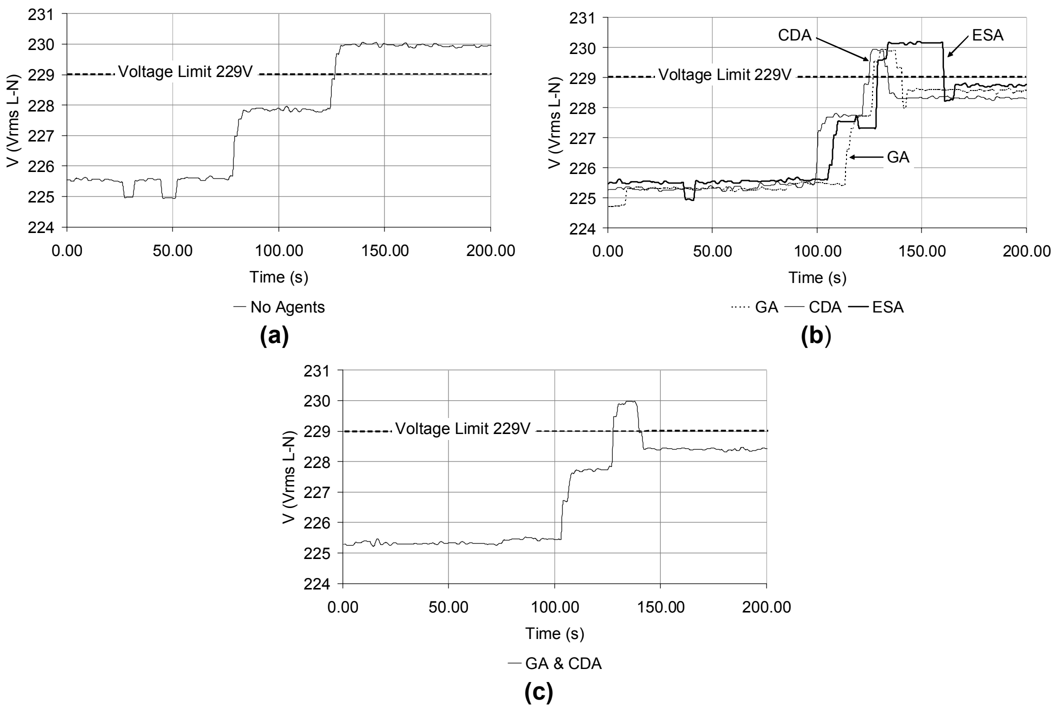

Figure 5: Effect of agent deployment in overvoltage conditions

6.2 *Steady-state voltage drop*

The Experimental MicroGrid was then operated such that it violated the lower voltage limit when there was no generation present in the system. This was defined at 225.5V - 3.5V = 222V. At time t=10s, the demand of the load emulator is increased from 0kW to 0.75kW and, at time t=70s, the demand increases further to 2kW. Figure 6(a) illustrates the effect of the load increase on the remote end network voltage without any agents deployed in the system. It can be seen that the voltage in this case drops below the defined lower voltage limit of 222V following the increase in demand.

Figure 6(b) illustrates the individual deployment of the CDA and ESA in order to mitigate against this steady-state voltage drop. The system agents detected that the voltage dropped below acceptable limits and intervened in an attempt to restore satisfactory operation of the Experimental MicroGrid. This was achieved through (i) the ESA instructing the bi-directional inverter of the ESU to export power thus discharging the batteries, and (ii) the CDA instructing the load emulator to reduce demand.

In Figure 6(c) the joint operation of the GA and CDA is shown. In this instance, the agents intervene to increase the voltage at the remote end of the system. The agents operate in a similar manner to the individual case, but again the contribution of each is reduced as the agents are collaborating to ensure that voltage at node 5 is above the defined limit.

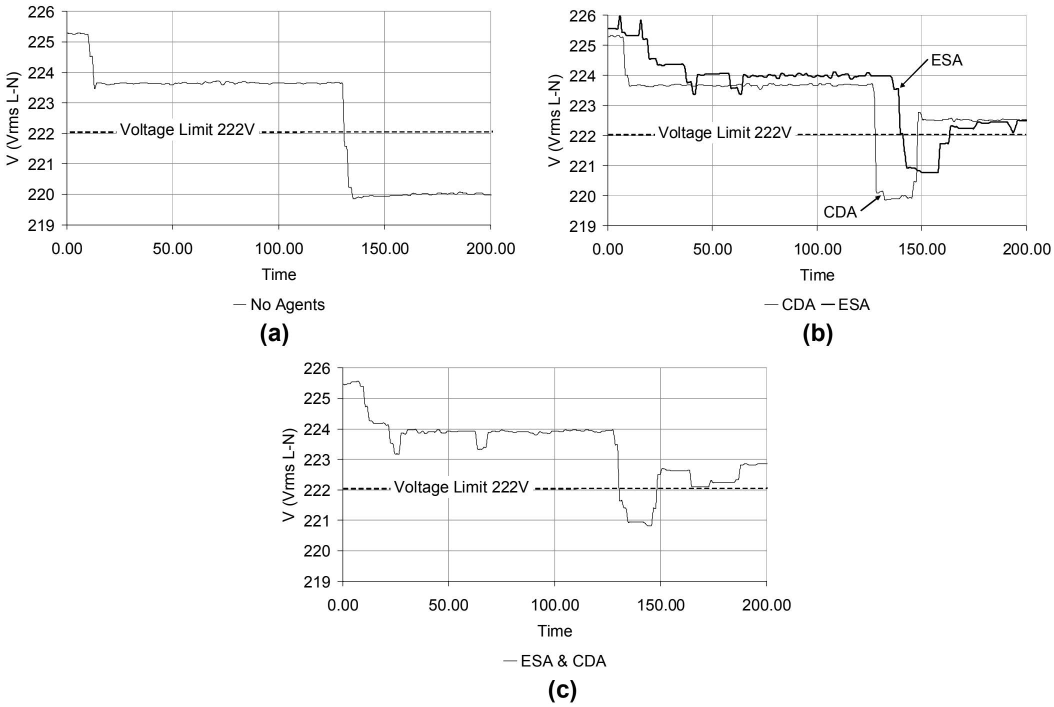

Figure 6: Effect of agent deployment in undervoltage conditions

6.3 Cable thermal limits

The Experimental MicroGrid was firstly operated such that it exceeded the defined cable thermal limit (4A) under no load conditions. As the Experimental MicroGrid under consideration is a radial network, the most thermally stressed cable section is between node 0 and node 1. A similar test sequence was devised to that of the steady-voltage rise investigation. Figure 7(a) illustrates the effect of the operation of the wind turbine generator emulator on the current of the cable section under consideration, without any agents deployed in the system. It can be seen that the current in this case exceeds the defined current limit of 4A following the increase in generation.

Figure 7(b) illustrates the operation of the GA, CDA and ESA individually in conjunction with the TLA in order to protect the cable from thermal damage. In all cases, system agents intervened in an attempt to reduce current flow in the cable section below the defined limit. This was achieved through: (i) the GA instructing the grid interface inverter of the wind turbine generator emulator to curtail its power output (ii) the ESA instructing the bi-directional inverter of the ESU to import power thus charging the batteries, and (iii) the CDA instructing the load emulator to increase demand.

Figure 7(c) illustrates the collective operation of the TLA, GA and CDA to reduce the current flow through the cable section. As before, the agents operate in a similar manner to the individual case, but the contribution of each is reduced as the agents are collaborating to restore desired system operation.

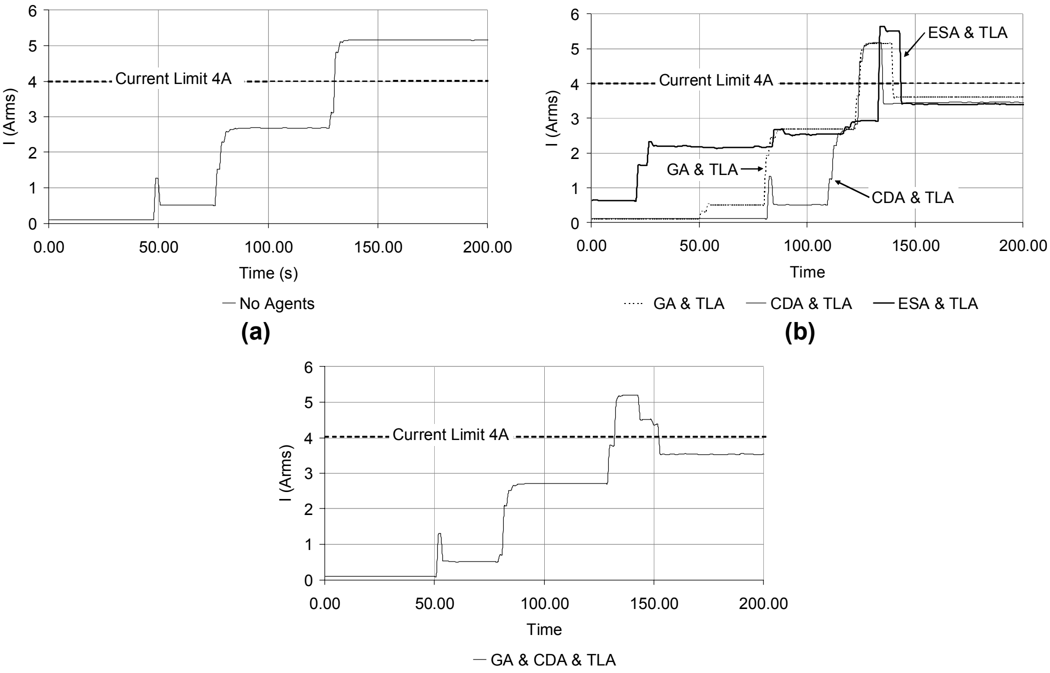

Figure 7: Effect of agent deployment in overcurrent conditions

7 DISCUSSION OF RESULTS

It can be seen from the results presented in Figures 5 - 7 that the agents successfully operate individually to solve the technical problems associated with high levels of micro-generation described in Section 2. Moreover, the collaborative behavior of the agents was also found to solve these technical problems with no degradation in the speed of response of the controllers to the disturbance in the system. The priority and weighting of each of the agents were defined to be equal in this implementation. These priorities are not expected to be the same in practical implementation since end customers are likely to have preferences for the operation of particular MicroGrid entities rather than others. For example, certain end customers may wish to adopt a low priority setting for their non-critical loads in favor of increased energy yields from their installed micro-generation.

The time responses of the agents were found to be reasonably consistent. The CDA and the GA took approximately 10s to detect the system disturbance, instruct the appropriate entity (controllable consumer demand or micro-generator) and for the entity to alter its power import or export as illustrated in Figure 5(b), Figure 6(b) and Figure 7(b). The GA took slightly longer than 10s to react due to the LabVIEW™, OPC, RS485 and power electronics taking longer to react to the control instruction than the time taken for the load emulator to respond to an instruction from the CDA. The ESA was more inconsistent in its operation. This is due in part to the number of control parameters that must be exchanged between the LabVIEW™ platform, in which the agents have been developed, and the bi-directional inverter to complete the control operation. In addition, LabVIEW™ is also used to control the reactive power from the ESU, which can increase the burden on the communications interfaces. The combined operation of the agents is illustrated in Figure 5(c), Figure 6(c) and Figure 7(c). It can be seen that the time responses in these cases were approximately the same as when the agents were deployed individually.

It can also be seen that one of the undesirable effects of the GA is that generation is curtailed when overvoltage conditions exist as shown in Figure 5. However, this reduction in generation is much more desirable than when the micro-generators are installed using a “fit and forget” philosophy. If one considers that an overvoltage condition may exist on a low voltage distribution network with a high penetration of micro-generation, fifty times in one year, this could result in the complete disconnection of the micro-generators during these voltage excursions. Thus, the power output from the microsources is zero during these periods in contrast to the partially curtailed generation of the micro-generator under the control of a GA. It can be seen therefore that the GA actually increases the annual energy yield from the micro-generator, which is both economically and environmentally desirable. These benefits are greater when the CDA is used in collaboration with the GA as the duty of mitigating against the overvoltage condition is shared between the micro-generator and the controllable load. This would have the effect of further increasing the annual energy yield of the micro-generator. When implementing the CDA it is necessary that controllable or deferrable loads, such as thermostatically controlled heating or cooling systems, are available for control. Moreover, even if loads are available for demand side management, the CDA may also need to know the nature of these loads as it may be only possible to alter the demand for a limited time duration or that that load may be available for control in the future.

When mitigating against undervoltage conditions, the ESA needs to ensure when instructing a control action for an ESU that the State of Charge (SOC) is suitable. This is because the energy export or import from the ESU is finite, and is a function of the SOC and the Ah rating of the battery. Collaborative operation of multiple agents results in less of a burden on the ESU in alleviating the undervoltage condition. The duty is now shared between the ESU and the controllable load as illustrated in Figure 6(c). The GA does not intervene during undervoltage conditions. This is because an increase in power export from a micro-generator is not possible unless its generation has already been curtailed. Generation is most likely to be curtailed within a MicroGrid when an overvoltage condition exists on the low voltage network or if there is a violation of the thermal limits in the reverse direction. Therefore, the probability of the intervention of the GA being required to solve an undervoltage problem is extremely low.

The agents are also used to restore system operation after a disturbance in the system that results in excessive current flow through a cable section. The agents are used individually and collectively to return the system to an operating point within the defined limits as illustrated in Figure 7. This cooperative behavior illustrated in Figure 7(c) illustrates the ability of multiple collaborating agents to overcome multiple technical constraints as the GA and CDA, which had previously been used to manage the overvoltage condition illustrated in Figure 5(c), operate in conjunction with the TLA to ensure that the current levels within the cable section fall below the defined limits.

8 CONCLUSIONS

This paper has presented an implementation of a first-stage agent-based control approach for the Experimental MicroGrid currently in development at Durham University. It has been shown that the controllers developed have been successfully employed to: (i) overcome steady-state voltage rise/drop issues encountered within the MicroGrid, and (ii) protect system cables from thermal damage. This has been achieved through both individual and collective agent deployment. Furthermore, the controllers ensured that system entities remain connected, with modified power outputs/inputs, in the event of power flow and voltage excursions. Satisfying this requirement could result in the total energy yield, and hence the economic benefits, increasing without compromising system performance.

Given that the consumer-driven growth of micro-generation is dynamic and unforeseen, one of the main requirements for the control of MicroGrids is for the customers to be able to connect their microsources, ESUs or demand units quickly and easily ("plug and play" capabilities), without affecting system performance. An agent-based approach offers a means of managing the growth of entities, such as customers, micro-generators, storage devices and network infrastructure within the MicroGrid through the instantiation of the corresponding number and type of agents. This can be achieved without the need for rewriting software. In comparison, using a centralized approach, the additional connection of new units to the network would require permission to be granted and software modifications to be made every time a new entity is added.

Two main areas have been identified in terms of scope for further work. The first is to extend the functionality of the agent-based controller in LabVIEW™ to include the two remaining low voltage network constraints under consideration (voltage unbalance and reverse power flows to distribution transformers), as well as the five identified operational goals. Again, this will be achieved through both individual and collective agent deployment of the four previously developed agents (GA, CDA, ESA and TLA) and two further agents (OGA, UA) that have been described in Section 3.

The second area for further work is the development of a fully FIPA-compliant MAS [36], with the same control requirements as the controllers developed in LabVIEW™. The MAS will first be interfaced with a power system simulation package in order to evaluate its functionality and will then be implemented in the Experimental MicroGrid in order to compare it against the controllers developed in LabVIEW™.

REFERENCES

1. Trichakis, P., Taylor, P.C., Coates, G. and Cipcigan, L. "A distributed control approach for small scale energy zones", *Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy*
2. *System Integration of Additional Micro-Generation Costs and Benefits – Final Draft Report*, Mott McDonald, June 2004.
3. *Potential for Micro-generation - Study and analysis*, Energy Saving Trust, 2005
4. Power Technologies International, "Embedded Generation on Actively Managed Distribution Networks", DTI, 2001
5. Roberts D. A.; "Network Management Systems for Active Distribution Networks – A Feasibility Study", DTI, 2004
6. Smart, P., Dinning, A., Maloyd, A., Causebrook, A. and Cowdry, S.; "Accommodating Distributed Generation", Econnect, DTI, March 2006
7. Taylor, P.C.; "Active Network Management as an enabler for the proliferation of domestic combined heat and power", *Proceedings of 12th International Stirling Engine Conference,* Durham, UK, September 2005.
8. EU Research Project: "More MicroGrids". Available at: http://microgrids.power.ece.ntua.gr
9. Lasseter, R.H., "Microgrids", *IEEE Power Engineering Society Winter Meeting*, 2001, vol. 1, pp. 146-9
10. Jenkins, N., Allan, R., Crossley P., Kirschen, D. and Strbac, G. *Embedded Generation*, IEE Power and Energy Series 31, London, UK, 2000.
11. Lyons, P., Taylor, P., Cipcigan, L. and Trichakis, P.; "Small Scale Energy Zones and High Concentrations of Small Scale Embedded Generation" *Proceedings of 41st UPEC 2006*, 6-8 September 2006, Newcastle, UK.
12. Trichakis, P., Taylor, P.C., Cipcigan, L.M., Lyons, P.F., Hair, R. and Ma, T., "An Investigation of Voltage Unbalance in Low Voltage Distribution Networks with High Levels of SSEG". *Proceedings of 41st UPEC 2006*, 6-8 September 2006, Newcastle, UK.
13. Hadjsaid, N., Canard, J.F. and Dumas, F., "Dispersed generation impact on distribution networks", *IEEE Computer Applications in Power*, April 1999, 12 (2), 22–28.
14. Cipcigan L. and Taylor P.C., "Investigation of the reverse power flow requirements of high penetrations of small scale embedded generation". *IET Renewable Power Generation*, 1(3), September 2007, 160-166.
15. Trichakis, P., Taylor, P.C., Lyons, P.F., Hair, R., "Predicting the technical impacts of high levels of small-scale embedded generators on low-voltage networks". *IET Renewable Power Generation,* 2(4), December 2008, 249-262.
16. Georgakis, D., Papathanassiou, S., Hatziargyriou, N., Engler, A., Hardt, C., "Operation of a prototype Microgrid system based on micro-sources equipped with fast-acting power electronics interfaces". *Proceedings of PESC'04*, June 2004, Aachen, Germany.
17. Peças Lopes, J.A., Tomé Saraiva, J., Hatziargyriou, N. and Jenkins, N., "Management of Microgrids" *JIEE Conference 2003*, Bilbao, 28-29 October 2003
18. Soultanis, N.L., Papathanasiou, S.A. and Hatziargyriou, N.D. "A stability algorithm for the dynamic analysis of inverter dominated unbalanced LV Microgrids". *IEEE Transactions on Power Systems*, 22(1), February 2007, pp. 294-303
19. Xueguang, W., Jayawarna, N. Zhang, Y., Jenkins, N., Peças Lopes, J., Moreira, C., Madureira, A., and Pereira da Silva, J., "Protection Guidelines for a MicroGrid", *Deliverable DE2 for EU MicroGrids project*, June 2005
20. Jayawarna, N., Jenkins, N., Barnes, M., Lorentzou, M., Papthanassiou, S., Hatziagyriou, N., "Safety analysis of a MicroGrid", *International Conference on Future Power Systems*, November 2005, pp. 1-7
21. FIPA English Auction Interaction Protocol. Available on line:http://www.fipa.org

22. Dimeas, A.; Hatziargyriou, N. “A multiagent system for MicroGrids”. IEEE Power Engineering Society General Meeting, vol. 1, June 2004, pp. 55 – 58

23. Piagi, P.; Lasseter, R.H. “Autonomous control of MicroGrids”, IEEE Power Engineering Society General Meeting, June 2006, Montreal, Canada.

24. De Brabandere, K., Vanthournout, K., Driesen, J., Deconinck, G. and Belmans, R., “Control of Microgrids”, *Power Engineering Society General Meeting, 2007*, IEEE, 24-28 June 2007.

25. Oyarzabal, J. Jimeno, J., Engler, A., Hardt, C., and Ruela, J.; “Agent based Micro Grid Management System”, *International Conference on Future Power Systems*, Nov. 2005, Page(s) 1-6

26. Barnes, M. Kondoh, J., Asano, H., Oyarzabal, J., Ventakaramanan, G., Lasseter, R., Hatziargyriou, N. Green, T. “Real world MicroGrids – An overview”, *IEEE International Conference on System of Systems Engineering*, April 2007, San Antonio, Texas, US.

27. Morozumi, S., “Overview of Microgrid Research and Development Activities in Japan”, *International Symposium on Microgrids*, Montreal, June 2006.

28. “The Electricity Safety, Quality and Continuity Regulations 2002”, *Statutory Instrument 2002, No. 2665*

29. *Engineering Recommendation P29 - Planning Limits for Voltage Unbalance in the United Kingdom*, The Electricity Council, 1990

30. CENELEC, *EN 50160: Voltage characteristics of electricity supplied by public distribution systems*, Brussels, Belgium, November 1999

31. Botting, D. “Technical Architecture – A First Report: The Way Ahead”, *IEE Power Systems and Equipment Professional Network*, June 2005.

32. Wooldridge, M and Jennings, N.R., *Intelligent Agents: Theory and Practice - The Knowledge Engineering Review*, 10 (2), 115 – 152, 1995,

33. Jennings, N.R. and Bussmann, S., “Agent-Based Control Systems”, *IEEE Control Systems Magazine*, June 2003, 23 (3), 61 – 74.

34. Bradshaw, J.M. “An introduction to software agents”, *Software Agents*, J.M. Bradshaw (Ed.), Cambridge, MA: MIT Press, 1997, pp. 3-46.

35. The Foundation for Intelligent Physical Agents (FIPA), available from: http://www.fipa.org/

36. The Foundation for Intelligent Physical Agents. FIPA Agent Management Specification, available from http://www.fipa.org/specs/fipa00023/SC00023K.pdf

37. LabVIEW™, User Manual, National Instruments, April 2003, www.ni.com

38. *Sunny Island – Installation and Operating Instructions. Bidirectional Battery Inverter SI4500 for stand-alone applications, V.3.1.* SMA Regelsysteme GmbH.

39. Barnes, M., Dimeas, A., Engler, A., Fitzer, C., Hatziargryriou, N., Jones, C., Papathanassiou, M. and Vandenbergh, M., “MicroGrid Laboratory Test Facilities”, *International Conference on Future Power Systems, 2005*, page(s): 2032 – 2033, Vol.2 16-18 Nov. 2005.

40. Osika O., Degner T., Hardt C., Lange H., Vandenbergh M., Dimeas A., Georgakis D., Kamarinopoulos A., Papathanassiou S., Goodwin A. J., Elmasides K., Iliadis G., Barnes M., Fitzer C., Kariniotakis, G. “Description of the laboratory micro-grids”, Microgrids project report DH1.

41. Bumby, JR and Martin, R; “An axial flux, permanent magnet, air-cored generator for small scale wind turbines”, *Proc. IEE – Electrical Power Applications*, Vol. 152, No. 5, Sept 2005, pp1065-1075

42. *Engineering Recommendation G83/1, Recommendations for the connection of small-scale embedded generators (up to 16 A per phase) in parallel with public low-voltage distribution networks*, Energy Networks Association, London, www.energynetworks.org.uk, September 2003.

43. *Windy Boy WB 2500/3000 – Inverter for Wind Energy Power Plants – User Manual Version 1.2*, SMA Regelsysteme GmbH.

44. *Sunny Boy 1700 - Installation Manual Version 1.1*, SMA Regelsysteme GmbH.