Development of an Agent Based Intelligent Control System for Microgrids

S. J. Chatzivasiliadis, N. D. Hatziargyriou, *Senior Member, IEEE* and A. L. Dimeas

Abstract--**This paper presents the implementation of distributed control in Power Systems. The structure of the Microgrid and the characteristics of the Multi-Agent Systems are outlined. The control system described will be implemented and tested in the pilot Microgrid of Kythnos island, Greece. The design and development of an Intelligent Load Controller is described. The structure of the control system, together with the algorithms developed, is presented. Primary objective of this project is to test under real-life conditions the distributed control approach for the power systems. Additionally, the ability of the agents to achieve efficient use of renewable energy sources and environmental friendly technologies, in general, is investigated.**

Index Terms—**Distributed Generation, Multi-Agent System, Intelligent Load Controller, Kythnos, Microgrids**

I. Introduction

Microgrids compose a new form of a power system, which belongs to the wider concept of Smartgrids, and are likely to become a part of the future power system organizations. The Microgrid can be considered as a small-scale electricity grid, which operates in low (or medium) voltage networks. It consists of distributed generation (DG) units such as renewable energy sources, combined heat and power units, fuel cells, along with storage devices and controllable loads (e.g. water pumps, air condition). Microgrids can be operated either interconnected to the power grid, or islanded, if disconnected from the grid, offering considerable control capabilities over the network operation [1]. An important characteristic of the Microgrid is that, when interconnected, it interacts with the main grid as one entity, absorbing or supplying power to the grid.

The expected boost in small production units – and most probably in Microgrids – with the liberalization of the energy market, will increase the complexity of the grid control. Distributed control, realized in the form of multi-agent systems, might prove to be an effective solution. Thus, if managed and coordinated efficiently, a Microgrid can provide distinct benefits.

Significant research is currently carried out regarding operation and control of Microgrids [2]-[4]. In this paper we will describe the design and implementation of an intelligent load controller device, which will be tested in the pilot Microgrid of Kythnos island, Greece.

The general architecture of the Microgrid has been presented in detail in previous papers of the authors [1], [5]-[7]. Therefore, this section will focus mainly in the requirements of a control system for Microgrids. Three control levels are distinguished as shown in Figure 1.

The lower level consists of the Local Controllers (LC). They control directly the distributed energy resources as well as the loads, which are connected to the Microgrid. The second level of control comprises the Microgrid Central Controller (MGCC). MGCC's main task is to monitor the Microgrid, coordinate the actions among the local controllers and act as an interface between the Microgrid and the main grid. The main grid is represented, in the upper level of control, by the Distribution Network Operator (DNO). DNO is responsible for the technical operation of the medium and low voltage grid, where more than one Microgrids may be connected. Additionally, in a liberalized energy market environment, a Market Operator (MO) is required, who assumes the responsibility for a smooth market operation between the Microgrids and the main grid. Both DNO and MO are considered as delegates of the grid.

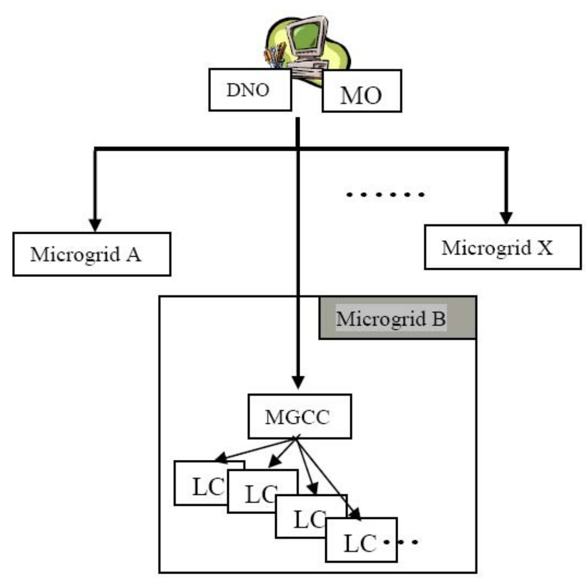

Fig. 1. Control levels of the Microgrid environment

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In order to confront with the complexity of control, resulting from the introduction of Microgrids in existing power systems, this paper adopts a distributed control approach, realized in the form of intelligent agents and Multi-Agent Systems (MAS).

The control units are given a degree of autonomy and are able to interact in order to achieve best performance. The intelligent agents are characterized from intelligence and social ability, namely the ability to communicate. Thus, they are able to take decisions locally, in order to control one unit, but they can also interact with other agents in order to accomplish goals set for the whole system, such as power availability and supply in case of islanded operation of the Microgrid.

The characteristics and the benefits one can gain from the implementation of Multi-Agent Systems are described in detail in Section II. The rest of the paper is organized as follows. In Section III the pilot Microgrid on the island of Kythnos is presented, in Section IV the Intelligent Load Controller (ILC) is introduced, in Section V the algorithms developed for the MGCC and the ILCs are described, and in Section VI the reliability tests carried out in the laboratory are presented.

II. Introduction to Multi-Agent Systems

Although there is no strict definition about what an agent is, the literature [8], [9] provides some basic characteristics.

Apart from the ability of the agent to act in its environment, either by taking decisions locally or by communicating with other agents, as already stated, an agent has a certain degree of autonomy. This suggests that the agents take decisions driven by a set of tendencies without a central controller or commander. For a battery system a tendency could be: “charge the batteries when the price for the kWh is low and the state of charge is low”. Thus, the agent is capable of taking certain initiatives based on its own rules. The autonomy of each agent is related to the resources it possesses, for example the available fuel for a diesel generator.

Another significant characteristic is that the agents have partial or none at all representation of the environment. The agent has knowledge only of the status of the unit it is controlling. However, it can be informed via conversation with other agents of the status of a neighboring system.

Finally, an agent is characterized by a certain behavior. This behavior is formed from the tendency to accomplish the goals set, satisfy objectives and use the resources, skills and services available. For example, an agent controlling a battery has the skill to store and supply energy to the grid. A service it provides may be the ability to sell power to the grid. The way that each agent uses its resources, skills and services define its behavior.

The characteristics outlined above allow for several benefits that the Multi-Agent Systems can offer, as far as the control of the Microgrid is concerned.

Taking into account that a Microgrid is comprised mostly from small-size production units, a centralized control approach would prove to be a quite expensive choice with relevance to the cost of the production units. Although in large production plants, the control units reflect only a small percent of the overall cost, this is not the case for small-size production units. Thus, low-cost innovative solutions must be investigated. The implementation of an intelligent agent requires only a processing unit with a microprocessor, similar to those found in every PC. Furthermore, depending on the intelligence of the agents, they are able to act without being constantly supervised, and, therefore, there is no need for an operator of the system.

Additionally, the agents allow for advanced “plug and play” capabilities. Based on their characteristics, the agents can adapt to their environment and act accordingly in order to accomplish the goals set. For example, in the future electricity grids, power production units are expected to connect and disconnect from the grid in a stochastic manner. The agents are able to recognize autonomously when a new production unit has been connected to the grid, and adapt their behavior in order to optimize their operation. A traditional control system, on the other hand, should have its central controller reprogrammed in order to take into account the new production unit, or at least, be human-aided to some extent. In this way, only by embedding a programmable agent in a DER unit or load, they are able to take part in this future possible electricity grid.

It should be finally noted, that the agents offer, as well, reduced need for large data manipulation and increased reliability of the control system. If one agent fails, the rest are able to adapt to this new state and continue the system function.

III. The Kythnos Island Microgrid

The pilot Microgrid in the island of Kythnos, shown in Figure 2, electrifies 12 houses in a small valley of Kythnos, an island in the Aegean Sea, Greece [4], [10]. The generation system comprises 10 kW of PV, a nominal 53-kWh battery bank, and a 5-kW diesel genset. A second PV array of about 2 kW, mounted on the roof of the control system building (System House), is connected to an SMA inverter and along with a 32-kWh battery bank provide power for monitoring and communication. Residential service is powered by three SMA battery inverters, connected in a parallel master-slave configuration, forming one strong single-phase circuit. More than one of the 3.6-kW battery inverters is used only when more power is demanded by consumers. The battery inverters can operate in frequency droop mode, allowing information flow to switching load controllers if the battery state of charge is low, and limiting the power output of the PV inverters when the battery bank is full.

In the Kythnos Microgrid, switching load controllers connected to the point of power input to each house have already been installed. These controllers have the ability to measure the frequency, and disconnect the house from the grid when they detect that the frequency falls below a certain threshold.

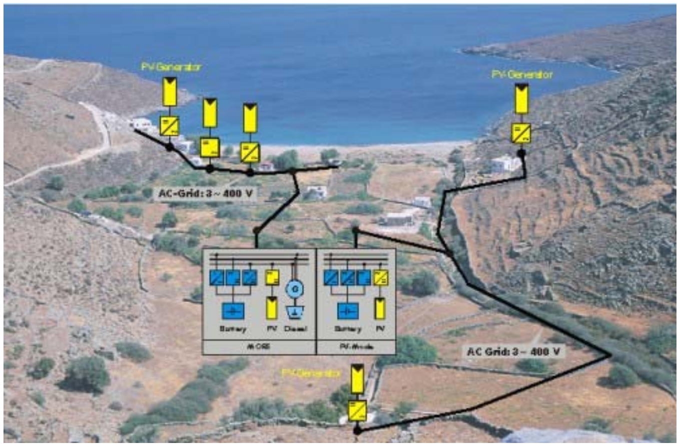

Fig. 2. The Kythnos Island Pilot Microgrid

Main objective of this paper is to present a new, more “intelligent” load controller, for the power management of the system. During its initial design, it was decided that the new controller should fulfill certain requirements.

Firstly, it should have the capability to control not the whole house as one entity, but groups of loads in the house (e.g. water pump, air-condition). In this way, in case of power shortage, only the non-important loads are first disconnected.

Additionally, a central Personal Computer will be installed in the System House of the settlement, in order to assume the role of the Microgrid Central Controller. Therefore, the PC should be able to operate in an agent environment, capable of sending setpoints and policies, if needed, to the Local Controllers and collecting from them measurements as well. The MGCC should be also able to publish the collected data to authorized remote users via Internet.

The final prerequisite has been the minimal intervention of the controller to the inner house electrical installation. Therefore, communication via PLC (Power Line Communication) between the controller and uniquely identified controllable switches has been proposed.

The development and functions of this Intelligent Load Controller, fulfilling the above requirements, will be described in detail in the following section.

IV. The Intelligent Load Controller

A. Description of the Intelligent Load Controller

The Power Systems Laboratory of the National Technical University of Athens (NTUA) in cooperation with ANCO S.A., have designed and developed an Intelligent Load Controller (ILC), which will be tested in the Kythnos Microgrid. Software has been developed, which allows the implementation of Multi-Agent Systems. Namely, every ILC will be controlled and represented in the system by an intelligent agent.

The ILC is a system that can be used to monitor the status of a power line and take Voltage, Current and Frequency measurements. In addition it can remotely control up to 256 PLC A10 devices (PLC load switches) connected to the power line. As far as the houses of the settlement are concerned each ILC will control two PLC switches. Main objective of this application is to control the operation of non-important loads. Each house in the Kythnos Microgrid is equipped with a water pump, which is responsible for replenishing a water tank and in this way supplying water to the residents of the house. The water pump is considered as a non-important load and therefore, in case of power shortage, it should be disconnected if needed. Therefore, the first PLC Switch controls the water pump, while the second PLC Switch controls a power socket and any load connected to it (e.g. air-conditioning unit).

Additionally, the ILC features a Wi-Fi interface that enables it to wirelessly connect to a Local Area Network. This eliminates the need of a data-cabling infrastructure and simplifies the installation of the units.

The core of the unit is an integrated computer module that runs the Windows CE 5.0 operating system. The integrated computer module is driven by the powerful Intel® Xscale™ PXA255 processor at 400MHz and features 64MB of RAM and 32MB FLASH Memory (instead of a hard disk drive). Thus, it is suitable for demanding applications.

The operating system supports the installation of a Java Virtual Machine. Therefore, an agent environment based on the JADE platform [11] can be easily embedded in the controller. In this way, along with the MGCC installed in the System House in the Kythnos Microgrid, we schedule to perform the first actual field test of Multi-Agent Systems in a Microgrid.

The ILC hosts an integrated Web Server, as shown in Figure 3, through which we are able to control the operation of each controller.

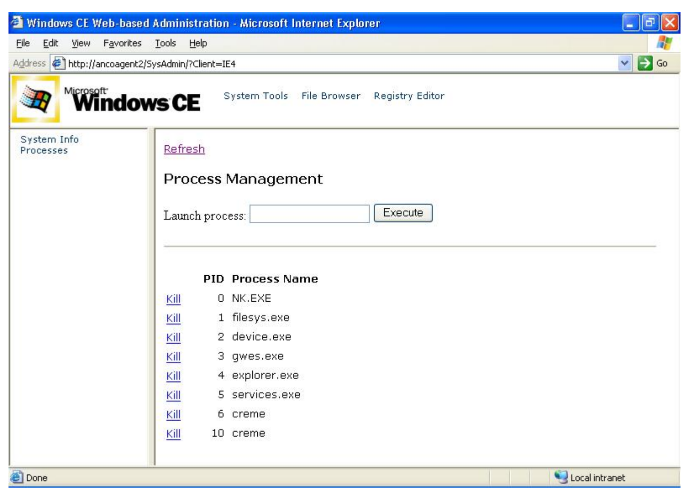

Fig. 3. ILC Integrated Web Server

During the installation in the Kythnos Microgrid, a broadband Internet connection will allow for remote control through a Virtual Private Network. As a result, commands can be sent and data can be exchanged among the ILCs, the

MGCC and authorized users who are not required to be on-site. It should be noted that an ILC communicates with the MGCC through a Local Area Network and the Wi-Fi interface they both feature.

Figure 4 shows how the ILCs are connected in the electricity grid. Each ILC unit is connected to the Power Line outside the house, before the kWh-meter and the house's electrical panel. After the electrical panel and near the loads, the PLC switches are installed. Each PLC switch has a unique address, so that it can receive commands from the Intelligent Load Controller.

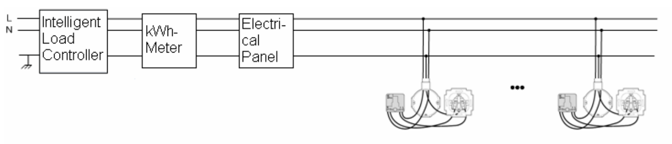

Fig. 4. Typical Installation of an ILC Unit

B. Power Line Measurements

The Intelligent Load Controller built-in software provides the following functionalities regarding the power line measurements:

- Frequency measurement.
- Voltage RMS measurement.
- Current RMS measurement.
- Sag events detection and announcement.
- Overvoltage events detection and announcement.
- Overcurrent events detection and announcement.

The RMS values are calculated by sampling the power line at a rate of 3,500 SPS (samples/second). As far as the events detection functionalities are concerned, the controller announces the event start and termination, records the duration of the event and, depending on the event, records the maximum or minimum value measured. It is important that, with the software we have developed, the controller is capable of processing these measurements. As a result, the agent who is implemented in the controller is able to identify certain events and take the relevant actions. For example, the agent can recognize an overcurrent event resulting from an engine start and can distinguish it from an overcurrent event due to a failure.

In the following section, the algorithms we developed in order to implement the Multi-Agent System and achieve the effective control of the Microgrid is presented.

V. Algorithms for the ILCs and the MGCC

Our main objective in this application is the minimization of the use of the diesel generator. In order this goal to be accomplished, the agents are required to cooperate so that they make efficient use of the power supplied from the PV units and the battery banks.

The MGCC is responsible for monitoring the operation of the Microgrid and coordinating the Local Controllers. Therefore, it gathers information from the Intelligent Load Controllers and the inverters who control the PVs output and the batteries, regarding the amount of energy consumed and the amount of energy produced respectively. The MGCC is also informed about which controllable loads are in operation every moment. (Controllable loads comprise the two loads in each house equipped with a PLC switch). If the production units of the Microgrid (i.e. the PVs and the batteries) are able to supply the requested power, then the MGCC takes no action. If the PVs are capable of producing more power than the loads request, then the MGCC sends a message to the batteries informing the relevant agents that there is a surplus of power. The agents controlling the batteries are able to decide if there is need for the batteries to be charged, according to their state of charge.

If, on the other hand, the loads on operation demand more power than the production units can offer, the MGCC informs the Intelligent Load Controllers that there is need for load shedding. The ILCs, equipped with intelligent agents, and, hence, with communication skills, are required to interact with each other and most probably negotiate in order to decide which load is going to be disconnected from the grid. Finally, the possibility the produced power not to be sufficient while all the non-important loads have already been disconnected should also be anticipated. In this case, the diesel genset is started to supply the additional power. Figure 5 illustrates the course of action of the algorithm presented.

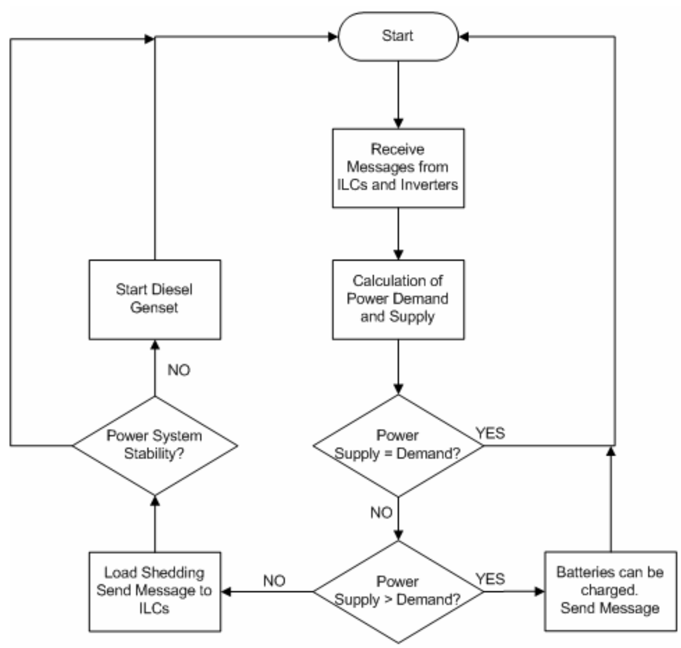

Fig. 5. Flow Chart of the MGCC Algorithm

The algorithm for the implementation of the intelligent agent in the ILC has as main objectives the collection of measurements and the development of negotiation skills. Thus, every ILC agent has been programmed to collect periodically voltage, current and frequency measurements and inform the MGCC. Furthermore, the ILC agent has the ability to negotiate with fellow ILC agents in order to decide, when needed, which load will be disconnected.

Goal of this part of the algorithm has been the minimal intervention in the residents' decisions. Therefore, if a resident has decided that he needs to operate the water pump, or another controllable appliance (load), the agents are required to interfere to the minimum possible extent with this decision. On this account, the algorithm developed can be illustrated as a baton passed from one agent to another. When an agent has the baton in its possession, then it is not allowed to operate its non-important loads (i.e. the water pump). The baton is passed from one agent to another in predefined time intervals (e.g. 10 minutes). In this way, load shedding does not burden only one house, but is equally divided among the whole settlement. In case more than one load need to be disconnected, an additional "digital baton" is created, also following the aforementioned cyclic behavior. More advanced negotiation algorithms, such as the auction algorithm presented in [5], are also going to be tested in the field.

Finally, an important property of the JADE platform needs to be acknowledged. JADE platform provides the agents with a Yellow Pages service. This characteristic becomes important, if we need to offer the "plug and play" capability to the agents. A Yellow Pages service allows agents to publish one or more services they provide so that other agents can find and successively exploit them [12]. Every agent who comes into operation (i.e. a load or a production unit is connected to the grid) is registered in the Yellow Pages service. For example, when a battery bank is connected to the grid, it informs the Yellow Pages service accordingly. When another agent desires to communicate with agents controlling a battery, it refers to the Yellow Pages service, which, in turn, provides information about all agents performing such a service. As a result, an agent does not need to be reprogrammed or notified every moment a load or a production unit connects or disconnects from the grid. Instead, whenever it needs to be informed, the agent consults the Yellow Pages service. This procedure was also followed for the implementation of the Multi-Agent System in our application. The ILC agents and the MGCC are registered in the Yellow Pages service when the units they control connect to the grid, and they respectively de-register when they disconnect.

VI. Reliability Tests

The algorithms presented were tested in the Power Systems laboratory, NTUA, in order to investigate their reliability. The application of the described control system in the Kythnos Microgrid must be as reliable as possible, since it is going to be tested under real-life conditions and affect the residents' daily routine. The rate of message exchange capability has already been tested and found that two agents are able to exchange more than 5,000 messages per minute. It is forecast that for the actual operation conditions in Kythnos a rate of no more than 100 messages per minute is sufficient. More tests will take place, while the whole system is going to be tested on the field for six months, starting from December 2007, in the Kythnos Microgrid.

VII. Conclusions

This paper contributes to the investigation of the benefits distributed control can offer to future electricity grids. It describes the first field test (the results will be available for the conference) of a Multi-Agent System in a Microgrid. It proposes a possible low-cost approach for the maximization of the use of Renewable Energy Sources and environmental friendly technologies in an electricity power supply grid. This is achieved through the coordination of actions from the MGCC and the negotiation skills of the Local Controllers. The Intelligent Load Controller, apart from its participation in the agent environment as a controllable load, might prove to be most useful in the islanded operation of a Microgrid. In this case, where power availability and supply is the primary goal, the ILC allows for advanced load shedding functionalities when needed.

VIII. Acknowledgment

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X. Biographies

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