Agent based control of Virtual Power Plants

A. L. Dimeas, *Student Member IEEE*, N. D. Hatziargyriou, *Senior Member. IEEE*

Abstract-- **The transition of traditional power systems into the flexible smart grids is under way. This paper presents a new interesting concept where Microgrids and other production or consumption units form a Virtual Power Plant. The main goal is to present the advantages of using agents for Virtual Power Plant control. More specifically this paper through examples and case studies presents how the local intelligence and the social ability of the agents may provide solutions in the optimal and effective control of a Virtual Power Plant.**

***Index Terms*—Distributed Generation, Microgrids, Multi Agent System, Virtual Power Plant, Controllable Loads.**

I. INTRODUCTION

Modern power systems are becoming more complex with time. The reason is not only the increase in the size of the system, but also the introduction of new concepts like Distributed Generation (DG), Microgrids [1,2] Market Participation (MP), Renewable Energy Resources (RES), Greenhouse Emissions (GE) reduction and Power Quality (PQ). These concepts require new control structures and schemes. This paper introduces the combination of two control structures. The first structure is the agent based control and the second is the Virtual Power Plant with aggregated load.

The Multi Agent System (MAS) technique appears to be a very useful tool for the operation and control of a power system. Although there is no strict definition about what an agent is, the literature [9,11] provides some basic characteristics. The main element of a MAS is the agent, which is a physical entity that acts in the environment or a virtual one without physical existence. In our case the physical entity is a microsource or a controllable load and a virtual one a piece of software that coordinates the agents. The cooperation of several agents forms a society called MAS. The basic element for this cooperation is the high level communication ability among the agents.

The Virtual Power Plant with the aggregated load is the result of the combined operation of production units and controllable loads. These elements cooperate in order to participate as a single entity in an energy or CO_2 market.

The authors would like to acknowledge the support received from the EC for the research projects "More Microgrids" (Contract No ENK 5-CT-2002-00610) and EU-DEEP[12]. They would also like to thank ANCO S.A., the Center of Renewable Sources and the University of Athens for their cooperation.

A.L. Dimeas is with National Technical University of Athens Greece (email adimeas@power.ece.ntua.gr)

N.D. Hatziargyriou is with National Technical University of Athens Greece (email nh@power.ece.ntua.gr)

This paper proposes the use of MAS technology in order to improve the operation of the Virtual Power Plant system, and more specifically it describes through examples how local intelligence and communication can be used in order to achieve the related complex tasks.

Section II provides a short description of the MAS technology and Section III the basic principles and Market environment for the Virtual Power Plant with the aggregated load. Section IV provides description of the test fields and Section V the operational environment. Section VI provides a description of the system architecture, Section VII describes the benefits of using this architecture for the system and Section VIII presents some technical details. Finally, Section IX concludes.

II. MULTI AGENT SYSTEM

The basic element of a Multi Agent System is the agent. An agent is capable of acting in the environment, meaning that the agent is capable to change its environment by its actions. For example, an agent that controls a storage unit and decides to store energy, rather than to inject it, alters the decision and the behavior of other agents.

Agents communicate with each other and this is part of their capability of acting in the environment. For example, agents controlling microsources communicate with the Market Operator and the other agents, in order to negotiate in the internal Microgrid market.

Agents have a certain level of autonomy. This means that they can take decisions driven by a set of tendencies without a central controller or commander. The autonomy of each agent is related to its resources, e.g. the available fuel, in case of a production unit.

Another significant characteristic of agents is that they have partial or none at all representation of the environment. Each agent only knows the state of the unit or the load it controls, it can be however informed via conversation with the other agents about the status of the neighboring system.

Finally, an agent has a certain behavior and tends to satisfy certain objectives using its resources, skills and services. One skill could be the ability to produce or store energy and a service could be to sell power in a market. The way that the agent uses its resources, skills and services defines its behavior. As a consequence, the behavior of each agent is formed by its goals. An agent that controls a battery system aiming to provide uninterruptible supply to a load has a different behavior than a similar battery system, whose goal is to maximize profits by participating in the energy market. The concept of the behavior is a significant part of the agent technology and is further analyzed in the next section. It is already obvious however, that the MAS technology can satisfy the requirements for Microgrids control, as specified in Section II. More specifically:

- Unit autonomy. Depending on the goals of the unit owners, the various units in a Microgrid can behave mostly autonomously in a cooperative or competitive environment.

On the other hand, an industrial Microgrid might be best controlled in a centralized manner, in which case the approach presented in this paper is clearly not preferable .
- Reduced need for large data manipulation. The agent based approach suggests that the information should be processed locally and the agents should exchange knowledge. In this way, the amount of information exchanged is limited and so is the demand for an expensive communication network. This feature is common to the traditional distributed computing. Moreover, the Multi Agent System is characterized by the fact that agents have partial or none at all representation of the environment. In our application the agent of a unit only knows the voltage level of its own bus and, maybe, it can estimate what is happening in specific buses, but it has no information about the whole Microgrid and the design of the control system is based on this lack of information.
- Increased reliability of the control system. In case one of the controllers fails, other agents may adapt and continue the system function.
- Openness of the system. Multi Agent Systems allow any manufacturer of DER units or loads to embed a programmable agent in the controller of his equipment according to some rules. In this way, the required ‘‘plug and play’’ capability for installing future DER units and loads can be provided.

III. Virtual Power Plant With Aggregate Load

The introduction of energy markets is followed by several new concepts. One if the is the idea of the Virtual Power Plant where various power production units that are not in the same bus cooperate and behave as a single unit in the Market. In this Virtual Power Plant controllable load is also included.
The main goal of this entity of course is to maximize the economical benefits. The Virtual Unit that is created, having larger capacity may participate in the energy market more aggressively. On the other hand the loads may have access to better prices via the long term cooperation with Virtual Power Plant.
It should be mentioned that is not the scope of this paper to define the optimal form of the market or the optimal policy of the system. The authors assume a realistic operation of the market and suggest a control model that will be able to provide advanced functionalities and profitable operation of the system. The main goal is reached by using Multi Agent System technology that will help the Virtual Power Plant to take decisions.
In the following, the installations comprising the pilot Virtual Power Plant in the region of Athens are described. The Multi Agent System is developed for and applied in this real system.

IV. Test Sites

Laboratory Microgrid of the National Technical University of Athens

In figure 1 the Microgrid installed in the Power System Laboratory of the National Technical University of Athens is shown. This is a modular system, comprising a PV generator and a Wind Turbine as the primary source of power. The micro sources are interfaced to the 1-phase AC bus via DC/AC PWM inverters. A battery bank is included, interfaced to the AC system via a bi-directional PWM voltage source converter. The Microgrid is connected to the local LV grid. Furthermore, a panel with controllable loads is available[3].

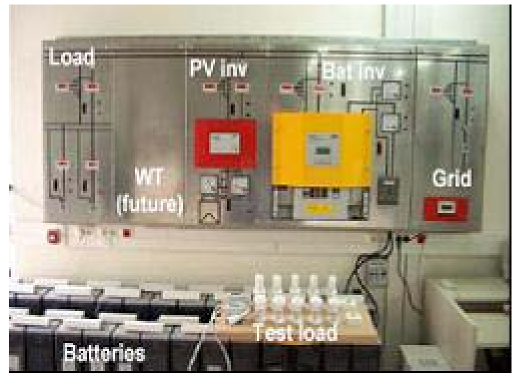

Figure 1. The Laboratory Microgrid in the Power System Laboratory of National Technical University of Athens.

Combined Heat and Power unit in the University of Athens

The CHP installation at the Athens University Campus provides energy to the school of science and the school of philosophy. It is formed by two CHP units with total electrical capacity 2 x 1365 = 2730 kWe.

Combined Heat and Power unit in the National Technical University of Athens

This site includes an 80 kW tri-generation CHP. Its installation is in progress within EU-DEEP[12]. There is possibility to include controllable loads.

Hybrid DER Laboratory at the Center of Renewable Sources (CRES)

The test plant at the DER Laboratory of the Center of Renewable Sources includes:

a. Two photovoltaic units with a nominal power of 1.1kWp and 4.4kWp respectively.
b. A battery storage unit with a nominal capacity of 40kWh, connected to the grid via a three phase inverter.
c. A battery storage unit with a nominal capacity of 40 kWh connected to the grid via three single phase inverters.
d. A 12kVA diesel-generator set. The speed regulator of the generator can operate in isochronous or droop mode.
e. A variety of controllable loads.

Meltemi Camping

Meltemi is a seaside resort located 15 km north-east to Athens. It consists of 170 cottages used as a holiday resort mostly

during summer. Meltemi has an interesting load curve which varies a lot between summer and winter. Furthermore due to the small size of each cottage the electrical consumption of each house is lower than in an ordinary house in Greece.
The Meltemi camping is equipped with a 40 kVA diesel genset, currently used as a backup generation and few PVs that are planned to be expanded. These on-site generation facilities form the basis for its transformation to an interesting Microgrid. This is also aided by the fact that the whole installation is fed by one MV/LV transformer making testing of island mode of operation or experimenting with special communication methods, like Power Line Carrier possible.
The primary target is optimal use of the power sources assuming its participation in the open energy market. However in order to optimize the use of energy as well the production the special characteristics of the installation should be identified, like the large variations in its load curve.

V. The Operational Environment

In order to define the test cases and the scenarios the market environment should be introduced first. The main assumption is that an hourly price schedule is announced every day 12 hours in advance. The various units as well the loads are assumed to participate in the market in order to produce or consume energy, respectively. In order to define a general strategy the main goal of the system should be introduced:

Should we optimize the aggregated production and load or each production unit or load should optimize each own operation?

The answer to that question is complicated, however the authors believe that it is a deceptive question. Definitely each unit and load wants to maximize each own profit since they are independent entities. So the real question for each entity, production unit or load, should be:

Am I gaining more by participating in the market independently or by being in cooperation with others?

The answer to this question is even more complicated and far beyond the scope of this paper. Giving a simple example, consider a PV unit that should decide to sell its production. Is it more profitable to consider only the market prices or occasionally to cooperate with a battery in order to store energy and sell it later when prices are higher?

Another critical question is:

Small DG units and small residential loads, like those described before, are real market players?

To rephrase this question, were these units installed in order to participate exclusively in the energy market? The answer is generally negative, although it is recognized that some distributed production units, for example PV plants >10kW could be installed for this purpose taking advantage of the favorable feed-in tariff schemes. However a CHP in a building or a factory or some controllable loads are installed to minimize the cost of energy consumption (including heat) and not to maximize benefits from market participation. For example occasionally in a factory it is more profitable to pay a penalty rather than reducing production or there are special needs that the load should play far more important role than bidding in the market. To further explain this situation, consider also the case where some loads and production units have common goals. For example the CHP installed at NTUA as well as the loads and the Microgrid are owned by the same legal body and therefore they will cooperate as a single entity for a common goal. The conclusion is that t*here are special needs in each installation that should be taken into account.*

It is important therefore to provide a flexible control structure that is difficult to be satisfied by a centralized decision mechanism.

VI. System Architecture

The solution proposed in this is based on a Multi Agent System based architecture in order to control the system. Due to the complexity of the system the main principle is that several levels of control should be introduced. Before describing the structure consider the Meltemi test site. The Meltemi consists of 170 houses that cannot participate in the market independently. They will have to create a small local MAS system and they will operate in the overall system as a single entity, as shown in Figure 2.

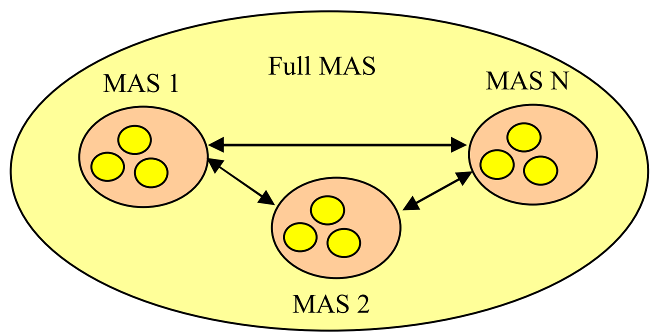

Figure 2. The organization of the MAS

The system includes a large number of agents forming small groups of MAS organized in three levels. The three levels are presented in Figure 3.
In the following a high level description of the system under development is only provided. All the agents associated with the control of the production units or controllable loads belong to the ***Field Level***. These agents directly communicate and control a production unit or a load. Furthermore these agents are organized in MAS according to physical constraints of the system. For example the agents that are situated in the Meltemi Camping. Each of these MAS has also an agent that has the responsibility to communicate with other similar MASs in order to cooperate with them. These agents belong to the ***Management Level***. Furthermore, these MASs may form larger MASs in order to participate in the energy market at the ***Enterprise Level***. This implies that there is one agent in each one of them that takes responsibility for Market Participation.

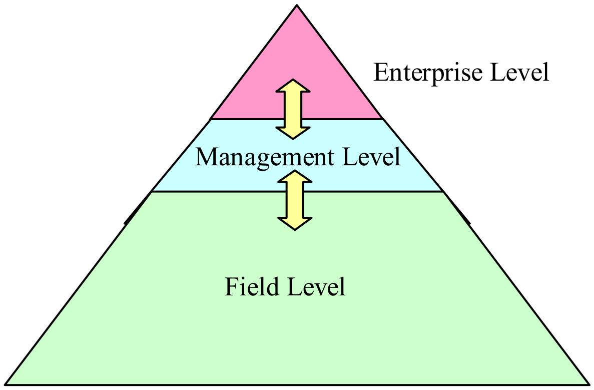

Figure 3. The various levels of organization.

However it should be mentioned that the agents that participate in the management level or in the enterprise level may be one of the field agents and not necessarily a special agent in a separate computer. The main advantage of this architecture is that the reliability of the system increases, since all the agents of the system operate as redundant agents.

VII. BENEFIT OF USING MAS TECHNOLOGY

In previous papers several advantages of the MAS technology were presented. In this section the authors intend to discuss the advantages that this architecture introduces into the system.

The most critical question is whether the final solution is optimal like in a centralized system. A more technical explanation is whether the communication delays the incomplete information available at each agent in a MAS are leading the system to a sub optimal solution. It is claimed by the authors that

Taking into account the operation of the centralized systems, a MAS system provides ***a better solution*** *but does not always provide the optimal solution.*

The justification of this statement is simple, although it is very complicated to prove it mathematically. The main idea is that each optimization problem has an objective function subject to several constraints. The MAS solution is better because it incorporates far more information than a centralized solution. For example, a centralized solution would consider a CHP as a production unit with a specific cost that is currently in operation, but it would not incorporate information, like local temperature or estimation for the heat needs of the specific unit. This type of information is critical in order to define parameter like actual maximum power or rate of production change. For a centralized system these variables are simple constant values, otherwise the mathematical model would be extremely complicated and most possibly not solvable in reasonable time. On the other hand, the MAS system may include a more simple solution mechanism in order to avoid excessive communication delays, however it can include a large set of constraints, in other words includes local information.

The local information concerns not only what is happening in the specific unit but also what is the correlation of this unit with its neighbors. For example for a CHP unit, the local information derived from nearby agents controlling loads is available. In other words the agent uses information of the area that is installed in order to define its own status.

The next argument against the centralized approach concerns social reasons. For an average consumer the idea of a local controller installed in his premises and controlling his installation in cooperation with the outside world is acceptable. Furthermore, the installation owner, who is not a dedicated market player, will not easily accept the idea that his installation is monitored and controller from an external point. Therefore the idea of taking the final decisions locally is far more acceptable.

Another critical issue concerns the optimization method and the decision process. In a main power system with the large units controlled and monitored by one the market operator, sophisticated algorithms like genetic algorithms can be used in order to reach the optimal solution. This kind of algorithms cannot be easily used in this type of system not only due to the size but because there should be a mechanism that can easily justify any decision. A simple mechanism should be able to explain to a load, why it should be interrupted at a specific hour and not its neighbor. Therefore since the decision mechanism is based on simple strict rules the only way to improve the performance of the system is to add more information in order to know more precisely the status of the system.

Finally the system should be adaptable to new changes. The FIPA compliant technology platforms, like Jade, provide tools to the agent to announce it existence to others, as well to search for agents with specific characteristics. The adaptability is far beyond a simple "plug n' play" capability. Consider that the system includes a large number of different types of units that are not easily modeled in a centralized system. For example the introduction of a Fuel Cell may require significant changes in the centralized control system. On the contrary in a MAS system only the agent that controls the Fuel Cell should have full knowledge of the characteristics of the system.

VIII. TECHNICAL ISSUES

The development of the system is based on the Jade[7] platform. Jade is a Java based tool for developing MAS systems. The development of the application is in conformity with the standards proposed by the international Foundation of Intelligent Physical Agents (FIPA) [8]. This organization aims to standardize the development of such systems, especially in the area of communication between the agents and the organization of the MAS.

The most interesting part of the implementation is the load controller [9]. The core of the unit is an embedded computer that runs Windows CE 5.0 operating system. The embedded computer is driven by the powerful Intel Xscale PXA255 processor at 400MHz. The controller is possible to execute the Jade-LEAP runtime. Another interesting feature is the usage of Power Line Carrier in order to control various loads within the installation.

Furthermore the installation requires some personal computers and Programmable Logical Controllers (PLC), especially for controlling the CHP units or the inverters. Especially for CHP, due to the complexity of the system, the agents will run on a PC and will collect measurements via the PLC. The procedure for controlling the CHP units is still under investigation.

The most interesting part of the system is the design of the agent itself. The MAS includes operations that require different response times like market participation, local control, message handling etc. The authors have proposed the following architecture for the agents in order to organize all these operations.

Accordingly, the behaviors of the agent are grouped into three levels as shown in table 1. In this table behaviors for communication purposes or other strictly software engineering tasks are omitted. The main idea is that the behaviors are grouped depending on the effect on the environment.

Level	Agents	Behavior	Example
1	1	Single	Battery management
2	Many	Multi Agent	Resource Allocation
3	Many/All	Team	Market Participation

Table 1. Control levels of the MAS behaviours.

The first level includes all the actions and decisions that are necessary to control and manage locally the unit. For example, in the battery management operation, if the agent detects low state of charge (SOC) decides to stop the injection of energy to the grid. This is an action that was decided locally without asking permission from other agents. On the other hand, the decision of starting the charging is not local and for this reason the decision should be taken on a higher level.

The second level includes simple tasks that should be completed by more than one agent. For example, after clearing of the market, the Microgrid receives an order to inject certain kWh in the grid as well, to feed the local loads. The decision of the production of each unit can be taken by a small internal auction as described in [4,5,6].

In the highest level the agent should accomplish a complex task which may have the following characteristics:

- The state of the system is important for the decision, however is not fully known.
- There is demand for management of huge amount of information with very limited resources.
- The outcome of various actions may be random and unknown.
- The decision does not affect the current step only, but also several steps later.

An example for this level is the market participation where the decision to sell or buy energy from the grid may be very complex, since the selected action is affected by the decisions of other players in the main grid. Furthermore a policy may be proved correct after several days or months, but not in the next step.

IX. Conclusions

The paper presents on-going work concerning the application of a real Multi Agent System. This is a large scale MAS implementation that aims to satisfy the new, complex control needs created by the increased penetration of small distributed generators and controllable loads in the system. The MAS technology through the advantages that are described in the paper seems to be a suitable solution.

X. References

[1] http://microgrids.power.ece.ntua.gr

[2] R. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Meliopoulos, R. Yinger and J. Eto, "White Paper on Integration of Distributed Energy Resources. The CERTS MicroGrid Concept.," Consortium for Electric Reliability Technology Solutions (CERTS), CA, Tech. Rep. LBNL-50829, Apr. 2002.

[3] S. Papathanassiou, D. Georgakis, N. Hatziargyriou, A. Engler, Ch. Hardt, "Operation of a prototype Microgrid system based on micro-sources equipped with fast-acting power electronics interfaces, 31th PESC 2004, Aachen, 20-25 June 2004

[4] A.Dimeas and N.D. Hatziargyriou "Operation of a Multiagent System for Microgrid Control Power Systems", IEEE Transactions on Volume 20, Issue 3, Aug. 2005 Page(s):1447 – 1455 Digital Object Identifier 10.1109/TPWRS.2005.852060

[5] N.D. Hatziargyriou, A.Dimeas and A. Tsikalakis. "Centralised and Decentralized control of Microgrids", International Journal of distributed Energy Resources, Volume 1 No 3 July September 2005 pages 197-212.

[6] A.Dimeas and N.D. Hatziargyriou, "*A MultiAgent system for Microgrids*", presented at the IEEE PES General Meeting, Denver, CO, June 6–10, 2004, paper -PESGM2004-001244.

[7] Jade (Java Agent DEvelopment Framework) at http://jade.tilab.com/

[8] FIPA: www.fipa.org

[9] ANCO: www.anco.gr

[10] Jeffrey M. Bradshaw. Software Agents. MIT Press.

[11] Jacques Ferber. Multi-Agent Systems. An introduction to Distributed Intelligence. Addison-Wesley.

[12] EU-Deep Research program: http://www.eudeep.com/

XI. Acknowledgments

The authors would like to acknowledge the support received from the EC for the research projects "More Microgrids" (Contract No ENK 5-CT-2002-00610) and EU-DEEP[12]. They would also like to thank ANCO S.A., the Center of Renewable Sources and the University of Athens for their cooperation.

XII. Biographies.

Aris L. Dimeas (S'04) was born in Athens, Greece, in 1977. He received the diploma in electrical and computer engineering (2001) and his PhD (2006) from the National Technical University of Athens (NTUA), Athens, Greece. He is currently senior researcher at the Electric Energy Systems Laboratory of NTUA. His research interests include dispersed generation, artificial intelligence techniques in power systems, and computer applications in liberalized energymarkets. Dr. Dimeas is student member of IEEE and member of the Technical Chamber of Greece.

Nikos D. Hatziargyriou (S'80–M'82–SM'90) was born in Athens, Greece. He received the diploma in electrical and mechanical engineering from the National Technical University of Athens (NTUA), Greece, and the M.Sc. and Ph.D. degrees from UMIST, Manchester, U.K. He is currently Executive Vice-Chairman & Deputy CEO of the Public Power Corporation of Greece and Professor at the Power Division of the Electrical and Computer Engineering Department of NTUA . His current interests include transmission and distribution systems, dispersed and renewable generation and artificial intelligence techniques applied in power systems. Dr. Hatziargyriou is member of the EU SmartGrids Technology Platform, of CIGRE SCC6 and of the Technical Chamber of Greece.