Abstract—This paper describes a Micro Grid Management System developed using agent based technologies and its application to the effective management of generation and storage devices connected to a LV network forming a micro grid. The micro grid is defined as a set of generation, storage and load systems electrically connected and complemented by a communication system to enable control actions and follow up surveillance. The effectiveness of the proposed architecture has been tested on laboratory facilities under different micro grid configurations. The performance and scalability issues related to the agent framework have also been considered and verified.

Index Terms— Energy management, Cooperative systems, Distributed storage and generation, SCADA systems, Power generation scheduling, Power generation control.

I. NOMENCLATURE

Micro Grid Central Controller (MGCC), Source Controller (SC), Load Controller (LC), Demand Side Management (DSM).

II. INTRODUCTION

This document describes a Micro Grid Management System developed in MICROGRIDS project (Large scale integration of micro generation to low voltage grids, ENK5-CT-2002-00610) using agent technologies.

A Micro Grid could be defined as a low voltage distribution network with distributed energy sources (micro turbines, fuel cells, PV, diesel, etc.) altogether with storage devices (flywheel, batteries, etc.) and loads. These systems could be operated, either interconnected to the main grid or either isolated from it, by means of a local management system with a communication infrastructure allowing control actions to be taken following any given strategy and objective.

In the recent years, inverter technology has matured in both functionality and efficiency while prices have decreased. Most of the micro source and micro storage equipment is connected through power electronic devices providing, to some extent, features such as active power output management, reactive power control, load balancing, voltage support and fast dynamic response without a significant harmonic distortion.

The implemented management system includes functionality to fulfill several micro grid objectives such as measurement data acquisition, DSM functions for load shifting, load curtailment and generation scheduling. Over this base system, a secondary control of generation and storage devices has been developed, in order to cope with the active power contribution of the units according to self adjustments after load changes.

At the laboratory micro grid system, each micro grid connected device including generation, storage and loads has its own local controller with its defined aims. These local controllers incorporate communication protocols, based on Internet standards, acting as gateways to the proprietary device interface.

Complementary studies have also been performed in order to ensure the performance and scalability of the agent platform used.

III. MICRO GRID MANAGEMENT SYSTEM

A Micro Grid Management System has been developed in MICROGRIDS project taking advantage of agent technologies.

A. Agent platform

Although there is not a unique definition of what intelligent agents are, there is a common view that describes them as a piece of software with: Autonomy (operate without direct intervention of humans, and have some kind of control over their own actions), Proactivity (react to external events but also have goal directed behavior) and Social Ability (co-operate with other agents by means of some communication language).

An agent platform is a software environment in which software agents run. It consists of the machines, operating system, agent management system and the agents.

The Agent Platform used for the development of Micro Grids Agents is JADE (Java Agent DEvelopment Framework, [3]).

Jade is compliant with FIPA 2000 standards (Foundation of Intelligent Physical Agents, [4]). An overview of core services specified by FIPA standards is:

- Agent Management Service (AMS)
- Directory Facilitator (DF)
- Message Transport Service (MTS)
The AMS service is in charge of maintaining a directory of AIDs (Agent IDentifier), offers white pages services and is also responsible for managing the operation of an Agent Platform (such as the creation, deletion and migration of agents to and from the platform).

The DF service provides yellow pages services to other agents. Agents may register their services with the DF and query the DF to find out which services are offered by other agents or which agents offer certain services.

The MTS is in charge of delivering messages between agents within the same Agent Platform and to agents that are running on other Agent Platforms. FIPA specifies the requirements for the MTS regarding the communications between agents in different agent platforms but does not specify the communications between agents in the same platform in this way, inter-operability between agent platforms is maintained.

B. Management functions

The agent based Micro Grid Management System provides the following functionality:

- **SCADA like system**: it is able to acquire data from the sources inside the micro grid and send commands.
- **Selling bids managing system**: the generators can produce selling bids and send them to a central market manager (based on the Spanish electricity market [5]).
- **Power schedule tracking system**: the generators’ local controller agents retrieve power scheduling information and send the set points to the generators.
- **Secondary regulation system**: it is in charge of analyzing planned generation targets and real measurements and performing suitable corrections over generation schedules.
- **Load shifting system**: the load shifting process consists in delaying the time period when a load is effectively connected in accordance with some optimization criteria.
- **Load curtailment system**: it decreases the power consumption of the loads.

The agent based management system accesses the generation scheduling patterns stored in an external conventional relational database but does not include the schedule calculation itself. This approach allows different generation schedule algorithms or strategies to be used during the research while the management system remains unmodified.

In the same way, load control functions (both shifting and curtailment) have been developed on a separate DSM (Demand Side Management) study, but only the data structures and communication infrastructure have been brought to the agent software.

The further addition of generation scheduling and demand side management algorithms performed by other agents should not create any problem other than the algorithm software development itself.

C. Software architecture

The Micro Grids Management System is developed on top of Jade Agent Platform; Jade’s container architecture allows the deployment of agents in a distributed environment. Under normal circumstances, each micro source, storage or load control system has a devoted local controller agent although the distributed architecture enables any of those agents to be executed on a physically different hardware.

The management system architecture (see Fig. 1) may be depicted into:

- **Relational Data Base Server**: It holds real time measurements, generation schedules and demand side management data. It is accessed using standardized and platform independent communication protocols (Java Data Base Connectivity, JDBC).
- **Micro Grid Agent Platform**: It provides the basic infrastructure and services where the Micro Grid Central Controller (MGCC), Micro Source Controller (SC) and Load Controller (LC) agents are executed.
- **Source and Load device controllers**: Local device controllers have been adapted to support not only proprietary protocols but also the XML-RPC standard.

![Management System Architecture](image)

The Micro Grid Agent Platform includes the following components:

1) **Micro Grid Central Controller**

The MGCC executes the Agent Platform Main Container where the basic DF and AMS are found. It includes the following agents and functions:

- **Pulling Agent**: It is in charge of getting source measurements (active & reactive power, frequency, voltage and status) and sell bids periodically for database storage. It is also in charge of checking for generation schedules updates at the persistent storage backend.
- **Database Agent**: It interfaces the relational data base
and the remaining agents for measurement, bid, generation schedule and demand side management data storing, updating and browsing.

- **Control Agent**: It enables the secondary regulation functions modifying generation schedules on an as needed basis.
- **Shifting Agent**: It manages shiftable load connection requests and assigns a connection period accordingly to the DSM produced schedule.
- **Curtailment Agent**: It ensures the curtailment actions following DSM output.

2) **Micro Source Controller**

The MSC executes in an Agent Platform Container:

- **Generator Agent**: It is used by other agents to send power set points and retrieve data working as an interface to the XML-RPC server (see Fig. 2).
- **Schedule Agent**: It is in charge of the active power output tracking to apply the generation schedule.
- **Bid Agent**: It sends active power selling bids. The default reference implementation reads it from the file system.

![Fig. 2: Generator control architecture.](image)

3) **Load Controller**

The LC runs in an Agent Platform Container providing:

- **Load Agent**: It registers shiftable and curtailable loads into the system and enables demand side management actions.
- **Status Agent**: It controls the on/off status of the load.
- **Switch Agent**: It is in charge of receiving and executing shifting and curtailment commands.

D. **Secondary regulation**

The Secondary Regulation Control System is implemented using the developed Agents Software whose basic functionalities (data acquisition, scheduling, load curtail and load shifting systems) have already been tested in laboratory environment with real devices.

The implementation is done by implementing a control algorithm in the agent (Control Agent running at the MGCC) that collaborates with the previously deployed agents in order to execute the new control functionality.

The Secondary Regulation Control System is in charge of adjusting the current power schedules of the generators taking into account real time measured active power generation, initially planned schedules and micro source configuration settings.

The available schedules and last measurements are retrieved from the database, this data, as well as configuration information (such as maximum & minimum power limits and fixed schedule flag), is processed calculating the deviation of the produced power from the planned power output. Then the estimated error is assigned to each micro source proportionally to each generator power change capacity.

The calculation procedure is as follows:

1) **Calculate the total power deviation**:

   \[ \Delta P_{\text{Tot}} = \sum (P_{\text{sch}}^i - P_{\text{meas}}^i) \]

   Where:
   - \( i \): is the time step.
   - \( P_{\text{sch}}^i \) is the planned power output for a generator
   - \( P_{\text{meas}}^i \) is the measured active power output.

2) **Calculate the total power change capacity of the generators**:

   \[ \Delta P_{\text{max}} = \sum (P_{\text{max}}^i - P_{\text{sch}}^i) \]

   Where:
   - \( P_{\text{max}}^i \) is the maximum power limit of the generator.
   - Repeat the same for minimum power outputs.

3) **For each generator the deviation to be assigned over its previous schedule is**:

   \[ \Delta P_{\text{Assig}} = \left( \frac{P_{\text{max}}^i - P_{\text{sch}}^i}{\Delta P_{\text{Tot}}} \right) \times \Delta P_{\text{Tot}} \]

   The solving procedure takes into account non dispatchable sources (for instance renewable and intermittent sources), those with fixed schedules (i.e. units linked to heat demand links or contracted schemes), maximum and minimum limits, and resources availability.

   The new generation schedules are produced adding the calculated power correction to the initial planned output and stored into the data base. Updated schedules are managed by other agents without any additional request from the Control Agent.

   The secondary regulation control system is designed for the isolated operation of the micro grid, but it could be possible to apply it to the grid connected mode by adding a dummy source controller, monitoring the power exchange between the micro grid and the mains and then adding the desired import/export balance as its planned schedule. This approach would translate into the effective control of the micro grid sources and into satisfying a contracted behavior of the micro grid with the distribution grid.

E. **Laboratory micro grid**

The experiments where performed at ISET’s laboratory (DeMoTec) located in Kassel, Germany. The diagram of the used equipment is shown in Fig. 3.

![Fig. 3: Electrical Schema of the test bed.](image)

The following devices are used:
- **Variable speed diesel aggregate**: It consists of a diesel motor (30kW), a synchronous generator...
(400V, 50 Hz, PME 20kVA) and a three-phase inverter.

- Battery system 1: The system contains three battery bi-directional inverters (Sunny-Island; each 3.3kW) with battery bank (14 kWh).
- Battery system 2: Same as the previous one.
- Controllable loads: A set of two load banks (lamps, compressor, etc.) remotely controlled.

The diesel aggregate and the two battery systems are controlled by means of standard PCs with Linux operating system. Each control PC communicates with the inverter control by means of a serial link under a proprietary communication protocol and behaves as a gateway providing XML-RPC access to the data.

The XML-RPC is an Internet standard that encapsulates information under XML (eXtensible Markup Language) and uses HTTP (HyperText Transfer Protocol) as communications protocol.

The controllable load bank uses a Netsyst NetMaster device supporting the XML-RPC protocol to enable and disable individual load consumption.

### F. Study Case: Single storage system

The first test consists in taking the diesel aggregate system, one battery inverter and the load bank in grid isolated mode. The battery inverter is configured as voltage source (being responsible for frequency and load following) while the diesel aggregate is working as current source (producing a given power output). Load bank is operated manually connecting and disconnecting individual consumptions at random.

This layout is aimed at having the battery inverter reacting to consumption changes immediately adjusting its own power output to recover the generation-load balance from the energy stored. Then, the secondary regulation should detect the change in the power output of the battery inverter and assign the difference to the diesel generator.

The data acquisition system is running every 20 seconds, the secondary control system is configured to be executed every 30 seconds; the battery inverter schedule is loaded into the database to have a fixed zero power output.

The recorded measurements are stored in the database and exported to a spreadsheet. A summary of the obtained result is shown in Fig. 4.

As it can be seen in Fig. 4:

- When a micro grid load changes the battery inverter modifies its power output (magenta line) until a new generation-consumption balance is achieved.
- The linear frequency drop characteristic of the battery inverter becomes apparent noticing that the battery output and the frequency (yellow line) are mirror images to one another: as the power output raises the frequency is reduced and the opposite.
- Once the new diesel unit schedule has been produced and set, the unit increases its power output (blue line) following a ramp. An opposite ramp is observed at the battery inverter reducing its power output as there is an excess of power in the system. The secondary control is able to restore the desired storage system output.
- System frequency is recovered automatically, once the battery inverter has reached its initial state.

It is worth stressing that the secondary regulation system seems to be requiring two executions to restore the storage output to the planned value. This apparent misbehavior is due to the secondary regulation coming into operation before the equilibrium has been obtained after the load step (notice that measured battery outputs are systematically lower than the diesel final active power output).

This fact implies that it is possible to reduce the secondary regulation timing in order to decrease the use of the battery inverter storage or increase it to allow the full equilibrium before any action is taken. Both approaches would affect the number of cyclic operations of the battery and its long term life.

### G. Study Case: Multiple storage systems

This test includes the diesel aggregate system, two battery inverters and the load bank in grid isolated mode. The battery inverters are configured as voltage sources sharing the feed load according to their frequency droops characteristics. The diesel aggregate is used as a current source. The load bank is operated automatically after a load schedule is uploaded to the load controller device.

This layout focuses on the multi inverter coordination and self adjustment to address load changes immediately. Afterwards, the secondary regulation is expected to find the deviation in the battery inverters power output and then to correct it by modifying the diesel generator output.

The micro grid management system is configured as in the previous study case (20 seconds period for data acquisition, 30 seconds period for secondary control and both battery inverters scheduled to produce no power at any time step). The measurements recorded at the database are brought to a spreadsheet and summarized in Fig. 5).
From Fig. 5:

- Micro grid load changes are handled by the battery inverters adapting their power output (magenta and yellow lines) until the generation-consumption balance is recovered again. Both inverters are able to share load changes without any external signal.
- The frequency (cyan line) shape mirrors the battery inverter active power.
- The secondary control restores the planned storage system output.
- Diesel system power output (blue line) changes are observed at the battery inverters reducing their output.
- System frequency is again automatically reestablished. Maximum frequency swings are defined by the battery inverters capacity.

Generation and load match, even if at the graph, it seems that when adding battery inverters output (0 kW) and diesel unit output values there is always a difference to the load consumption. This is due the load schedule being represented taking data from nominal load consumption but not from real measurements (not measured nor recorded).

This time the secondary regulation system acting in two consecutive time periods only happens once: at the higher load change the network is still moving to achieve the balance when the fist cycle is executed. In the remaining load steps the system with two master storages balances faster.

Multiple master inverter operation manages any load step with two apparently abnormal situations:

- After the first load rise and the second regulation cycle has been performed, measurements suggest that one battery inverter starts feeding the other one (both output curves seem to be diverging with positive and negative slopes); the possible evolution is interrupted by a load step down.
- After the last load rise and the secondary control cycle the frequency is slightly higher than in the previous equilibriums.

In any case, those behaviors are due to the automatic multi master synchronization and therefore they are out of the scope of the micro grid management system or the used secondary regulation algorithm; it could be possible to add some new functionality to the management system to identify these cases and tackle them through control actions.

IV. PERFORMANCE AND SCALABILITY

To assess the ability of the agents’ architecture to fulfill Micro Grid Management System requirements, a performance evaluation of the current Jade v3.3 platform was carried out from the points of view of response time and scalability. Various communications scenarios were considered, both for intra and inter-platform communications. The analysis and comparison of results is summarized below.

Jade provides mechanisms called Message Transport Protocols (MTP) for inter-platform communications. Jade MTPs use IIOP (Internet Inter-ORB Protocol) associated with CORBA or HTTP. Three MTPs (SUN ORB, ORBACUS and HTTP) have been compared.

For intra-platform communications, FIPA does not mandate the use of a specific MTP. When agents reside in the same container, Jade supports Java events for message passing; Java RMI (Remote Method Invocation) is used when sender and receiver agents run in different containers.

The Contract Net Protocol (CNP) [6] was selected for the performance and scalability tests. CNP is a negotiation protocol for the establishment of contracts between agents. It is based on two types of agents: Initiator and Participant. The Initiator announces tasks to a group of Participants that are potential executers of these tasks and that bid for their execution. The Contract Net Protocol is executed by two Java Applications that have been developed and run on the Jade Platform. Other Java applications were also created for the generation of simulation scenarios, starting the negotiation and launching a number of agents automatically.

A study with similar goals is described in [7]. Test conditions were different (based on a circular exchange of messages), and only two MTPs were used (SUN ORB and ORBACUS).

The parameter of interest in the simulations is the negotiation time as a function of the number of participating agents – the negotiation process requires a number of messages exchanged between the Initiator and each Participant (Responder).

For intra-platform communications, the negotiation time increases almost linearly with the number of agents and this was observed in tests with up to 7000 agents (with an average of 10 ms for a complete dialogue between the Initiator and each Responder). Best performance is achieved with HTTP; this is observed both in the accumulated negotiation time and in the point where degradation starts to occur, which is shown by a sharp increase in the negotiation time (for HTTP, this occurs for about 6500 agents). This confirms the choice of HTTP as the current default MTP in Jade.

For inter-platform performance is worse than in the intra-platform case for all MTPs, that is, there is a higher negotiation (response) time and a lower number of agents supported when degradation becomes noticeable (for HTTP this occurs for about 3500 agents). Once again, performance is better and degradation less pronounced with HTTP.

For inter-platform communications two sets of tests were carried out, as well – agents residing in two platforms in the same computer and agents residing in two platforms in
different computers. Performance is worse than in the intra-platform case for all MTPs, that is, there is a higher negotiation (response) time and a lower number of agents supported when degradation becomes noticeable (for HTTP this occurs for about 3500 agents). Once again, performance is better and degradation less pronounced with HTTP and worse with SUN ORB. Performance is better when the containers reside in two computers, since the computational load is divided between the machines.

Results show excellent scalability properties, which allow concluding that Jade is capable of fulfilling Micro Grid Management System requirements and HTTP is the best choice for MTP.

V. CONCLUSIONS

This paper reports a Micro Grid Management System based on intelligent software agent technologies and its application to the effective management of generation & storage devices connected to a LV network forming a micro grid. The micro grid, defined as a set of generation, storage and load systems electrically connected and complemented by a communication system, is successfully monitored, controlled and operated by means of the developed software.

The software modular architecture enables additional services for advanced control, such as the deployed generation secondary control system. The effectiveness and applicability of the introduced software has been evaluated by a twofold strategy: on one hand, the management system has been tested on a laboratory environment where real generation, storage and load devices are being monitored and controlled, while on the other hand, performance and scalability issues related to the agent framework have been assessed.

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VII. REFERENCES

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VIII. BIOGRAPHIES

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