Multi Agent System for cooperative energy management in microgrids

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***Abstract*—In the last years the microgrid are emerged as the key component able to increase the efficiency, reliability, and sustainability of traditional electrical infrastructures. Micro distribution systems aggregate small, modular renewable power source, distributed storage and local loads as autonomous entities that can exchange power with the traditional electricity if operating in connected mode. A prime task in microgrid operation is the dynamic balance of local supply and power demand due to the intermittent nature of renewable energy resource and the variability of load demand during the day. However the power transfer among each microgrid and the main grid is always associated with a cost due to the loss of power over the distribution line. In this paper, a multi-agent systems (MAS) for the optimal coordination of multiple distributed energy resources is presented. The agents, associated with each microgrid, implement a cooperative strategy to minimise the power loss over the distribution lines and to maximise the economic income by sharing the surplus of the generated power between the microgrids belonging to the same coalition. The simulation results show the effectiveness of the proposed control strategy demonstrating that the MGs payoff increases up to 30% when microgrids cooperate to gain the power balance.**

***Keywords*—Smart grid, micro grid, multi-agents, cooperative TU game, distributed energy management**

I. Background

The smart grids are the evolution of the traditional power grid in a complex and more interconnected cyber-physical system, which optimizes asset utilization and improves power quality operating resiliently against system disturbances and faults [1]-[3]. These challenges need the development of:

- advanced monitoring and communication systems to collect data for timely decision making;
- renewable energy sources, located at a distribution level, to defer the construction of new plants and transmission lines;
- distributed artificial intelligence systems for demand management and control of energy bills.

With respect to these goals, microgrids are emerged as a potential way to supply customer and critical loads with the energy locally produced offering considerable control capabilities [4]. In fact, microgrids are defined as complex systems at LV or MV distribution network comprising small power generators, energy conversion devices, intelligent static control switches and confined cluster of loads. The microgrids generally work as controlled single entities within the traditional electricity grid and can operate as a small source of power or an aggregated load according to the required local power needs. Clearly, microgrids require smart control architectures to manage the uncertainty of renewable power generation and the hourly fluctuations of energy demand with high reliability and cost effectiveness.

This paper discusses the development of a Multi-Agent System (MAS) for the control and dispatch of the power flows within a district of the distribution network including N microgrids linked to the primary substation of a public utility grid. The microgrids (MG) agents interact each-other to find the optimal feeder reconfiguration that allows to redistribute locally the energy surplus of the microgrids, minimizing the burden on the main grid and the technical losses [5] in a cost effective way.

The logic control of the MG agents is designed to implement a TU-cooperative game enabling the formation of coalitions between microgrids to achieve the power balance.

This approach allows the primary advantage to distribute decision making capabilities facilitating dynamic demand response. Moreover, the asynchronous operation of the agents and the distributed energy management allow microgrids to easily leave or enter each coalition as conditions permit. This leads to an improvement of the overall reliability of the distribution network, an increment of resiliency to faults and accelerate service restoration.

The proposed MAS for cooperative energy management is simulated using the middleware JADE (Java agent development Environment) by TILAB (Telecom Italy Lab) for the development of distributed multi-agent applications based on peer-to-peer communication architectures [6].

This middleware allows distributing the intelligence, the initiative and the control on different terminals in order to implement the parallel interactions between *peers* (called agents) with different behaviours in compliance with the FIPA (Foundation for Intelligent Physical Agents) standards [7] [8]. JADE enables the communications between the agents both in wireless or wireline networks allowing the exchange of asynchronous messages.

Results from simulation studies show the effectiveness of the approach followed in designing the proposed MAS for the cooperative distributed power management of the microgrids located in the same geographical area of a smart grid.

The rest of the work is organized as follows. The second section briefly presents the model for the distribution network, the MAS components and the control strategy based on a TU game. The third section describes the study environment and the main experimental results. The fourth section is devoted to conclusions.

II. MAS FOR OPTIMAL POWER DISPATCH

In the recent years multi-agent technologies are applied in various areas of smart grid, such as frequency control, load scheduling, system faults detections and system restoration [9]-[13]. In this section, it is presented a Multi-Agent System (MAS) for the efficient managing of the power flows among microgrids. This MAS constitutes the technological solution to the multi-objective problem of reconfiguring the distribution lines that interconnect a set of N microgrids. The pursued goals are the power balance and the reduction of the energy cost minimizing the Line Power Loss (LPL). Specifically, the intelligent agents cooperate exchanging message to achieve the efficient redistribution of locally generated power by implementing a control strategy, based on cooperative coalitional game with transferable utility.

The distribution architecture under the study includes N_{mg} microgrids and N_{sub} primary substations. Each microgrid comprises modular energy sources (photovoltaic, small wind turbines, thermal generators, etc.,) and both critical and non-critical loads (such ad schools, hospitals, residential users) that can notify their energy demands to the microgrid control system.

The power flows of this complex architecture are managed by a MAS, characterized by agents with different rules and functionalities. To model the distribution network scenario four kinds of agents are defined, namely the Point of Common Coupling (*PCC*) agents, the Grid Facilitator (*GF*) agents, the Grid Management (*GM*) agent and the MicroGrid (*MG*) agents.

PCC Agents: They are generally associated with the substations and they coordinate the overall power operations between the utility grid and each linked microgrid. They reveal any technical violations in the point of common coupling and communicate to the *MG* agents the price of electricity at any given time period.

GM Agent: Given an area of the distribution network, this agent is responsible for the creation and deletion of *MG* agents from the corresponding MAS platform, complying to the FIPA specifications. In fact, each MG agent needs to be registered at *GM* agent and related to a unique identifier (called Agent IDentifier - AID) within a specific distribution network area. The AID is retained in the *GM* agent directory with both the *MG* agent description and its current state. The MG agent may be active or inactive if the controlled microgrid is in connected mode or island mode.

GF Agent: It maintains a complete and timely list of the MG agents and provides information about their offered services and coalitions that are defined. This agent implements a yellow pages service, used by the MG agent wishing to sell or buy power in a given time interval. The MAS can include multiple *GF* agents to provide the yellow pages service to different sub-areas of the distribution network. In this case, the *GF* agents need to establish cross-registrations with one another to be able of propagating the MG service requests or the modifications of the defined MG coalitions.

MG Agents: These agents are responsible for the power balance of each microgrids integrated at the distribution level. They collect information about micro-source operation status, their response time and their output power. The primary objective is to evaluate the amount of power that each microgrid needs to transfer or acquire from the others microgrids to minimize the technical power losses.

A. MAS Control Strategy

The control strategy of the MG agents is designed on the basis of coalitional game theory with transferable utilities as proposed by the recent literature [14]-[15]. Each MG agent is a player which makes agreements with others players to share the power surplus and to distribute the payoffs incurring for the corresponding power transfer.

The evaluation of the available power surplus is made by the MG agents considering the power demand and generation inside the microgrids over time t.

Given a time period δt, the power demand P_{load_i} and the power supply P_{gen_i} of the i^{th} microgrid, denoted by MG_i, can be formally expressed as:

$$P_{load_i}(\delta t) = \sum_{j=1}^{Nk_i} l_{j,i}(\delta t) \tag{1}$$

$$P_{gen_i}(\delta t) = \sum_{j=1}^{Nh_i} g_{j,i}(\delta t) \tag{2}$$

where Nk_i is the number of loads with power demand $l_{j,i}(\delta t)$, and Nh_i is the number of power generators $g_{j,i}(\delta T)$.

Therefore, each microgrid MG_i needs to exchange an amount of power $P_{exch_i} = P_{gen_i} - P_{load_i}$ to balance its power needs. In traditional distribution architecture, each microgrid operates autonomously, selling or buying the power P_{exch_i} directly from the utility grid.

However, in the proposed smart distribution network, the distributed MG agents coordinate the cooperation of set of neighboring microgrids to transfer efficiently power within them. Specifically, the MG agent monitors the DER assets closing or opening the ties and sectionalizing switches [16] to provide the relative microgrid with the power P_{exch_i} from the coalition of linked microgrids characterized by the minimum power loss.

To accomplish this goal the MG agent takes account of three factors: the power loss associated with the transfer to the main grid, the power waste over the interconnecting lines to the other microgrids, the utility payoff related to each possible coalition.

For a microgrid MG_i, the technical power loss LPL_i is a function of the power exchanged over each k^{th} bus ($Pq_{k,i}$) and can be expressed as:

$$LPL_i = \sum_{k=1}^{K_i} R_{k,i} \frac{(Pq_{k,i})^2}{V_k^2} + \beta Pq_{k,i} \tag{3}$$

where V_k is the line voltage, $R_{k,i}$ the line resistance, and β the loss factor of the transformer eventually involved [17].

The equation (3) models all the power waste incurred in transfer to the main grid or other microgrids.

In addition, the amount of power P_{exch_i} required by the microgrid MG_i satisfies the eq.(4),

$$P_{exch_i} = \begin{cases} \sum_k Pq_{k,i} & if \quad P_{gen_i} > P_{load_i} \\ \sum_k P_{0r_{k,i}} & if \quad P_{gen_i} < P_{load_i} \\ 0 & otherwise \end{cases} \tag{4}$$

where $P_{0r_{k,i}}$ represents the amount of power that needs to be generated to ensure that the microgrids MG_i receives the power $Pq_{k,i}$ over the line k.
Thus the power $P_{0r_{k,i}}$ can be described as :

$$P_{0r_{k,i}} = R_{k,i}\frac{P^2_{0r_{k,i}}}{V^2_{k,i}} + \beta P_{0r_{k,i}} + \mid P_{q_{k,i}} \mid \tag{5}$$

For each microgrid MG_i, the optimal coalition which belong to is derived by each i^{th} microgrid agent as the solution of a TU game (N, v) on N players [18], [19].
This TU game is defined to have cost function $v(S)$ proportional to the power losses :

$$v(S) = \min_{S \subseteq N} u(S, \Sigma) \tag{6}$$

$$\begin{aligned} u(S,\Sigma) = \sum_{i \in S_s, j \in S_s} LPL_{i_j} + \sum_{i_u \in S_s} LPL_{i_u} + \\ + \sum_{j_u \in S_b} LPL_{j_u} \end{aligned} \tag{7}$$

In eq.(6) $S = S_b \cup S_s$ is any coalition of Σ microgrids constituted by a set S_b of Σ_b microgrids that acquired power and a set S_s of Σ_s microgrid that sell power.
In eq. (7), the first term $LPL_{i,j}$ describes the losses over the lines interconnecting pair of microgrids, while the second and third terms (LPL_{i_u} and LPL_{j_u}) represent the losses incurred in power transfer to and from the utility grid.
It is assumed to divide the extra utility among the cooperating agents following a proportional approach. Therefore, the payoff ϕ_i of the agent MG_i belonging to the coalition S is chosen as:

$$\phi_i = v(\{MG_i\}) + \gamma_i \Big(v(S) - \sum_{MG_j \in S} v(\{MG_j\}) \Big) \tag{8}$$

where $v(S)$ is the best cooperative cost of the coalition S including MG_i, $v(\{MG_j\})$ is the cost of the coalition constituted of one microgrid MG_j, γ_i described in (9) is the MG_i quota of the exchanged power among the Σ microgrids joining to S.

$$\gamma_i = \frac{\sum_{k \in S, k \neq i} P_{exch}(MG_i, MG_k)}{\sum_{j \in S} \sum_{k \in S, k \neq j} P_{exch}(MG_j, MG_k)} \tag{9}$$

The above mathematical expressions describe the cooperative strategy implemented by each intelligent MG agent to accept or reject a temporary request of power transfer.

III. Case Study and Simulation environment

The effectiveness of the proposed MAS for an efficient cooperative power management, is demonstrated by multiple tests carried out on a simulation platform, developed to demonstrate how the integration of technical data about the available distribution lines and feeders makes the decentralized power management controls of microgrids more effective.
The simulation platform models a distribution network in which the mesh structure guarantees a high level of service.

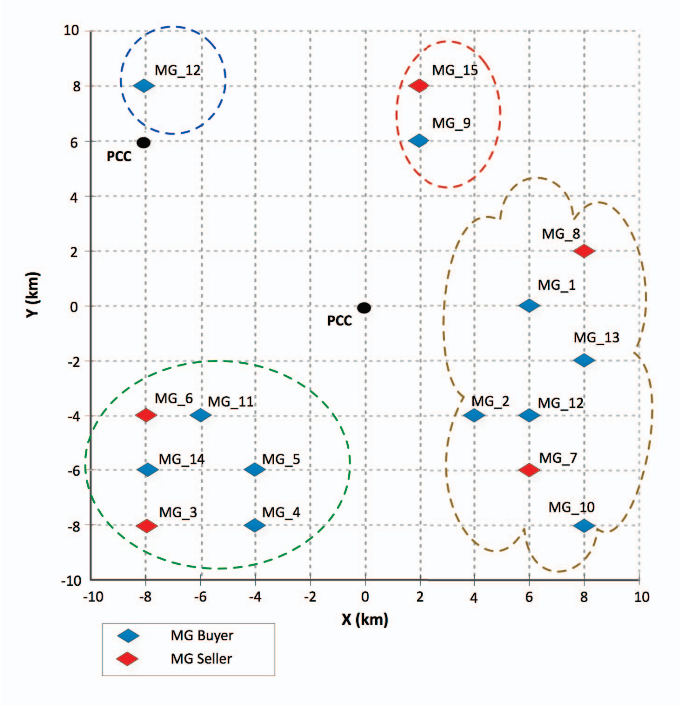

Fig. 1. Distribution network scenario with multiple substations (PCC) and microgrids (MG_i) in a 20km x 20km square geographical area

It is assumed that the portion of distribution grid covers 400 km^2 and includes N microgrids randomly located around the substations of the utility grid, with $2 <= N <= 25$. The microgrids are linked to the main electrical system through Points of Common Coupling (PCC) at High Voltage (HV) side (380/150 kV). Moreover the interconnection lines among microgrids operate at Medium Voltage (MV) with voltage set to 10 kV, 15 kV or 20 kV.
Consequently, it is expected that a certain quantity of electric power is lost inside the distribution network by the leakage currents, the corona effect, the dielectric losses, the heat dissipated in the distribution line conductors as well as the magnetic losses in the power transformers.
These technical losses are modelled by the equation (3) for each line, assuming values of the equivalent resistance $R_{k,i}$ is in the range $[0.2 - 0.4]$ Ω /km and values of the transformer loss factor $\beta = 1.8\%$.

Different topologies of the distribution network are analyzed in simulation test varying both the distances among the neighbouring microgrids and their positions respect to the point of common coupling (PCC). The power needs P_{exch_i} of each microgrid MG_i is described as a random factor due to the fluctuation over time of the local power generation and load. According to the the probability distribution of the power needs P_{exch_i} can be assumed Gaussian with zero mean and standard deviations σ_i in the range [0.5, 10] MW [20].
The MAS architecture, implementing a distributed power control system for the set of N microgrid, is developed on JADE framework, an open source JAVA based middleware distributed under the LGPL (Library Gnu Public Licence) licence. JADE is based on the IEEE FIPA (Foundation for Intelligent Physical Agents) standard and ensures the interoperability among the different agents [7]. To achieve this ability, the agents live in

Java process containers, provided by the JADE run-time and distributed over the network.

Fig.2 shows an example of the coalitions formed by the MAS controlling a distribution area with 15 microgrids with the power needs of Table I in a given time period δT.

TABLE I. POWER NEEDS OF N MICROGRIDS

Microgrid ID	Exchanged Power (kW)
MG_1	12000
MG_2	-3000
MG_3	-6000
MG_4	-7000
MG_5	-4000
MG_6	-4000
MG_7	-3000
MG_8	-6000
MG_9	-7000
MG_10	14000
MG_11	14000
MG_12	-3000
MG_13	12000
MG_14	-2000
MG_15	-2000

To decide which coalition to join, the MG agents exchanged messages with the GM agent, GF agent and PCC agent acquiring information on the amount of power provided or required by the different buyers or sellers inside each potential coalition. Therefore the MG agents run a negotiation process behaving like players of the cooperative game described by eqs. (6)-(7).

This process ended at the Pareto equilibrium and gave the stable set of coalitions presented in Table II.

TABLE II. STABLE COALITIONS

S_i	Players
S_1:	$\{$ MG$_2, MG_4, MG_{13}, MG_{15}\}$
S_2	$\{$ MG$_1, MG_3, MG_5, MG_8, MG_9, MG_{11}, MG_{12}, MG_{14}\}$
S_3	$\{$ MG$_6, MG_7, MG_{10}\}$

Table III presents the power losses of each microgrid for both non collaborative and collaborative power management among the microgrids.

TABLE III. POWER LOSSES (KW)

Microgrid ID	Non Collaborative Power Management	Collaborative Power Management
MG_1	1230	120.7
MG_2	104	18
MG_3	252	90
MG_4	400	98
MG_5	112	39.4
MG_15	50.1	11.3
MG_6	100	45.2
MG_7	128	27
MG_8	293.5	113.8
MG_9	319	109.5
MG_10	1600	544.7
MG_11	1470	237.8
MG_12	104.3	18
MG_13	1203	127.3
MG_14	56,1	8,2
MG_15	50.1	11.3

In computing these results, it is considered the power transfer among the utility grid and the microgrids as well as and the power exchanges between couple of microgrids. Also, it is assumed $R_{k,i}$=0.25 Ω/km for the links between the PCC and each microgrid, while $R_{k,i}$=0.4 Ω/km for the interconnecting lines between two microgrids.

Note that all the surplus of power generation of microgrid MG_13 is shared locally to the microgrids MG_2, MG_4 and MG_15 reducing to zero the power transfer to the utility grid. Similarly, the microgrids MG_1 and MG_11 distributed almost the totality of their power surplus to the microgrids of coalition S_2. As results, the power loss of the coalitions S_1 and S_2 are improved of about 85% , while the power loss reduction of S_3 is about 66%.

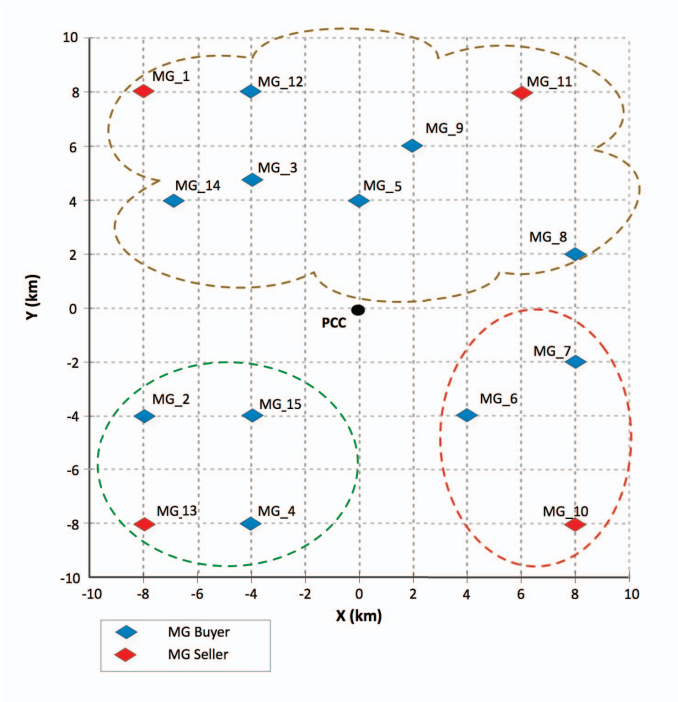

Fig. 2. Proposed coalitions in a given time slot for a distribution network with 15 microgrids (4 power sellers and 11 power buyers). One substation (PCC) is located at the center of the considered geographical area

In order to evaluate the performance of the proposed MAS in the optimization of the local energy distribution, the power loss reduction per microgrid is computed over a large number of set ups of the simulated distribution network. The tests were performed varying the number of microgrids, their position respect to the point of common coupling as well as their power demand P_{exch_i}. In addition, a fully connected graph for the interconnection lines between microgrid is considered.

The performance of the MAS are assessed in terms of average power loss per microgrid resulting in the various tests.

Fig. 3 shows the obtained results when the microgrids operate autonomously or in cooperative way through the MAS. It should be noted that there is a significant improvement of the power loss reduction, when the MAS energy management is implemented and the number of microgrids increases. The power loss reduction is made possible by the higher number of possible coalitions in which the set of microgrids can partitioned. In fact, the MAS has more chance to split the neighboring microgrids in groups able to mutually satisfy the power needs.

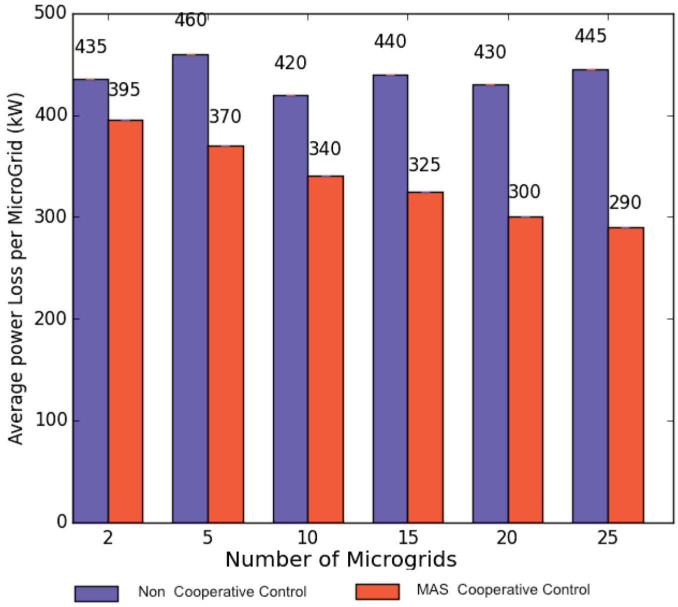

Fig. 3. Average power loss per microgrid in presence/absence of the MAS for cooperative energy management

IV. Conclusion

This paper discusses the design of a MAS implementing cooperative control strategies for the efficient distribution of energy locally produced by a set of microgrids. The interaction among agents are based on a cooperative TU-game to maximize the economic income of each microgrid by minimizing the power losses. Moreover, a proportional criteria is adopted to divide the payoff function among the cooperative microgrids preserving the individual rationality of the MG agent in making the more convenient choice of the coalition. The agent interoperability is ensured developing the system in a platform compliant with FIPA standard.

The outcome of the proposed MAS in terms of technical power loss reduction have demonstrated the effectiveness of the proposed framework in contrast with a distribution network dominated by conventional, non cooperating microgrids. The probability of creating efficient coalitions of microgrid to share their power and gain an economic revenue with the significant reduction of the power loss, is strictly associated with the number of microgrid operating at the distribution level.

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