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Decentralized management of a multi-source electrical system: A multi-agent approach

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The objective of this paper was design and implementation of a self-adaptive management system of a set of production sources in a changing and unpredictable energy demand environment. The strategy proposed made it possible to achieve optimal management of the energy resource production of the electrical system facing the changing demand. After showing the need to follow «intelligently» the behavior of different entities of the electrical system by a distributed, collaborative and self-adaptive model, the emphasis was placed on the modeling of an energy management multi-agent system. The proposed model allowed the overall production to be optimized in relation with the demand profile and in function of a cost or greenhouse gas reduction criterion. The flexibility of this model could in priority allow both the integration of multi-objectives optimization and that of information.

Key words: Energy, modeling, complex system, multi-agent system, optimization, multi-source system, greenhouse gas.

INTRODUCTION

Electrical energy management goes with the protection, monitoring and control of the entire electrical network. For the operator, the question also concerns the optimizing of the energy consumption cost of different production sources without any prejudice for the activity. This requires effective and real-time control of the overall electrical system parameters. Modern solutions to this control need are products and services using information and communication technologies based on the paradigm of-smart systems, such as data loggers and supervision and control software. Research has been done on the multi-source decentralized power grid management optimization. Logenthiran et al. (2012), present a Multi-Agent System (MAS) for the real-time operation of a microgrid. The multi-agent model proposed in this paper, provides a common communication interface for the entire components of the microgrid. Implementation the MAS allows not only to maximize energy production from local distributed generators, but also to minimize the microgrid operating cost to be minimized. The recent studies by Monica et al. (2012); Mao et al. (2011); and Pipattanasomp et al. (2009) present an optimal design and implementation method for the intelligent management of electrical distribution networks. The research mentioned focuses on microgrids especially in the electrical distribution part. It would be interesting to enlarge the fieldwork and integrate both transport and production parts into energy management in order to take advantage of more room for maneuver and flexibility in the management system.

Other MAS applications allowing a diagnosis of disturbances on the grid to be made were presented in the work of Nagata and Sasaki (2002) and Wang (2001). An application that makes it possible to monitor the power system is presented in the work of Cristaldi et al. (2003), a secondary voltage control system in that of Phillips et al. (2006) and a visualization power system in that of Dimeas and Hatziargyriou (2005a).

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Some other studies, to mention only those of Dimeas and Hatziargyriou (2005b); Dimeas and Hatziargyriou (2004) and Butler-Purry et al. (2004), focus on the control of the micro network operation from a MAS. However, most of that work was applied to power grid using PV generators, batteries and controllable loads. Besides, the emphasis was more on technical than on economic and environmental aspects such as the reduction of operating costs and the amount of greenhouse gases (GHG) emitted by the electrical network.

The present paper proposes a model of generic system management of electrical systems that can be applied to a micro grid as well as to a macro grid. This model can be implemented in a real system thanks to advanced communication techniques, software agents can be embedded in different sources of power generation and loads. These agents cooperate and make decisions together to optimize system management both in technical and economic terms, taking into account technological constraints and resources availability. So, the contribution of this paper is to implement an optimal management platform of decentralized electrical systems minimizing the production cost or the amount of GHG emissions released by the power plants.

MATERIALS AND METHODS

Presentation of power grid (PG)

PG as shown in Figure 1 is a distributed system on several sites S_k. Each site consists of several power plant $C_{j\,(Sk)}$ and each plant site consists of several production generators $G_{i(Cj(Sk))}$. Each generator produces power P_i and the total power supplied by the power grid is given by Equation (1):

$$P_f^T = \sum_{k=1}^{S}\left(\sum_{j=1}^{C}\left(\sum_{i=1}^{G} P_i\right)\right) \tag{1}$$

Where, $G_{:}$ is the number of generators in power plant $C_{j(Sk)}$; $C_{:}$ is the number of power plants in a site S_k; S: is the number of network sites.

The total power demand is given by the following Equation (2):

$$P_D^T = \sum_{k=1}^{H}\left(\sum_{j=1}^{M}\left(\sum_{i=1}^{B} P_{\delta_i}\right)\right) \tag{2}$$

With: B: is the number of clients managed by a low-voltage departure d_i; M: is the number of low-voltage departures; H: is the number of high-voltage departures of the grid. The total power supplied P_S^T by the network at t time is then given by Equation (3):

$$P_S^T = P_D^T + Losses \tag{3}$$

Where, the losses are due to the technical or not technical losses. The production cost of energy sources as shown in Equation (4) takes into account the costs of fuel, oil and maintenance.

$$C_P = C_f + C_o + C_m \tag{4}$$

C_f, cost of fuel consumption; C_o, cost of oil consumption; C_m, cost of maintenance.

Estimation of the quantities of greenhouse gas emissions

The estimation of emissions from fossil fuels combustion in fossil energy sources is presented in three levels of approaches in the 2006 Guidelines (Amit et al., 2006).

Level 1 approach

It requires the knowledge of data such as the quantity of fuel burned per unit of energy and a default emission factor. The associated equation is:

$$E_{G,F} = Q_F \times F.E_{G,F} \tag{5}$$

The total emission of greenhouse gases due to combustion (E_G) is obtained by adding the GHG emissions attributable to the combustion of each fuel (Richalet, 1987). This results in the following Equation (6):

$$E_G = \sum_F E_{G,F} \tag{6}$$

Level 2 approach

In Level 2, the default emission factors from Level 1 are simply replaced by specific emission factors of the corresponding country (Amit et al., 2006).

Level 3 approach

The Level 3 approach considers an emission factor per fuel and per technology (Amit et al., 2006). The mathematical model associated with this approach is given by Equation (7):

$$E_{G,F,T} = Q_{F,T} \times F.E_{G,F,T} \tag{7}$$

The total emission of GHG generated by different technologies is given by Equation (8):

$$E_{G,F} = \sum_T E_{G,F,T} \tag{8}$$

Typology and structure of agents

The approach is to translate the problem of vector processing exchanges of energy flow in an agent space where the system entities cooperate with each other. A situated approach, cooperative and decentralized, is proposed for power system management. This is an approach into which an agent «Source Agent» (Ag_S) is associated with each energy source and an agent

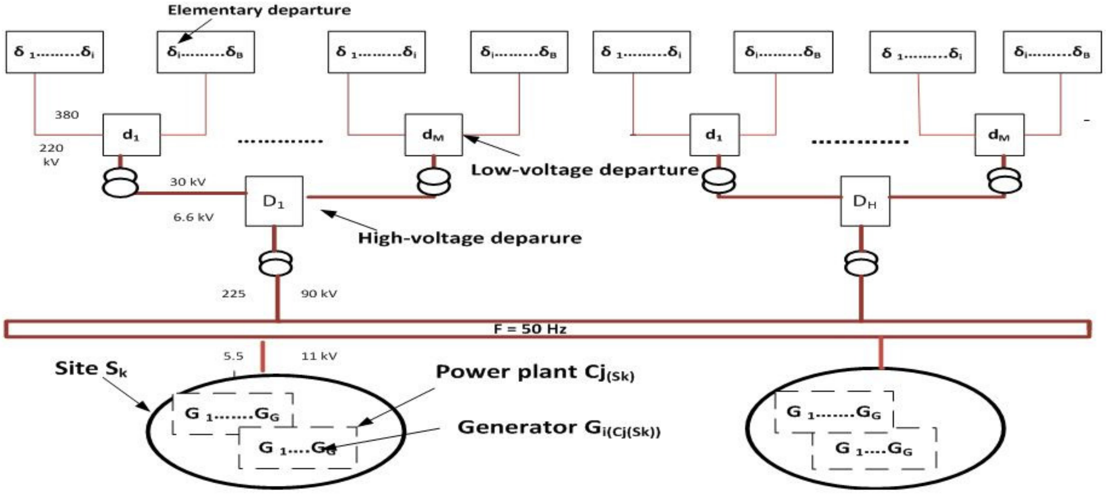

Figure 1. Power grid.

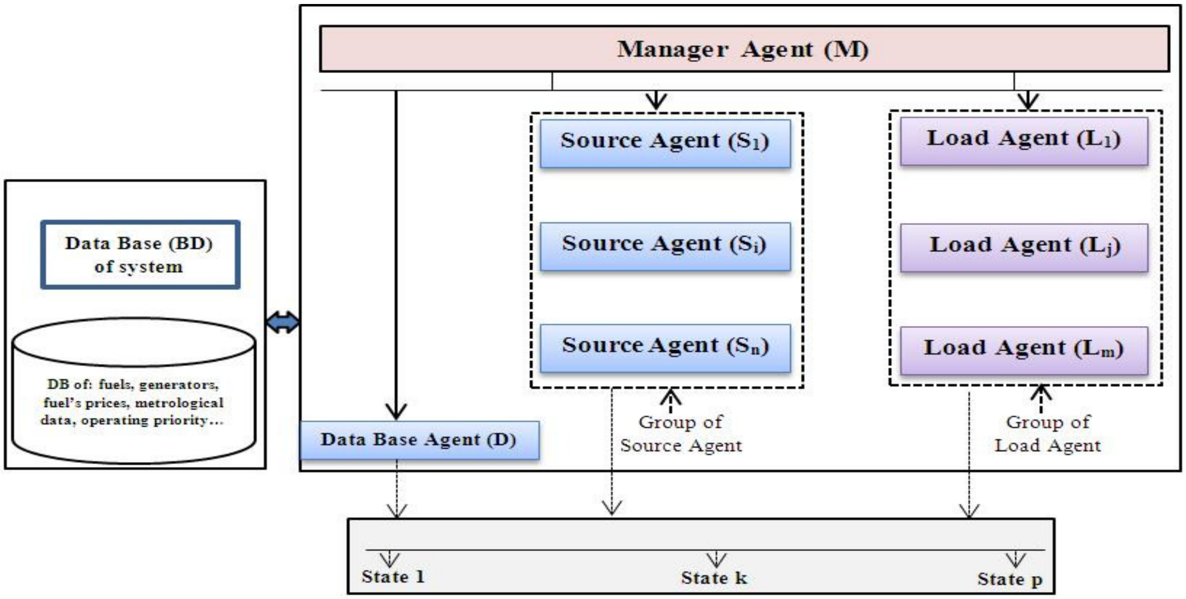

Figure 2. General architecture of the platform developed by a multi agent development kit (MADKIT).

«Load Agent» (Ag_L) is associated with each low-voltage departure.

The proposed architecture (Figure 2) is hybrid and is divided in two layers: the first layer consists of two types of reactive agents (Source Agent and Load Agent). Each Ag_{S_i} (i ∈ [1 - N]) and each Ag_{L_k} (k ∈ [1 - K]), have their own characteristics (Table 1). The second layer consists of a cognitive agent called «Manager Agent» (Ag_M) and a reactive agent called «Data Base Agent» (Ag_D), which manages the database of information handled by Source Agent and Load Agent.

Agent priority is a decisive parameter in the working of the management system. It allows the agents, depending on their priority, to participate or not in meeting the demand. Priority (p_{Si}) of Source Agent is a parameter which depends on the optimization criterion, the availability of the source, the source production cost and / or the amount of GHG released (Equation 9). This is a real value between zero (0) and one (1). A production source has all the higher priority as the value of its priority is closer to one (1).

The priority of Load Agent varies between zero (0), one (1), two (2) and three (3). A Load Agent has all the higher priority as the priority value of its priority is greater. Departures supplying sensitive areas (major national institutions, hospitals, etc.) have a higher priority equal to three (3). Departures supplying secondary areas (industrial, etc.) have a priority equal to two (2). Departures supplying non-priority areas (residential, etc.) have a priority equal to one (1).

Table 1. Attribute of source agent and load agent.

Source agent (Ag_{S_i})	**Load agent (Ag_{L_k})**
I_{S_i} : Identification number	I_{D_k} : Identification number
Comb **:** consumed fuel	P_{L_k} : Power demand (MW)
P_{S_i} : Power supply (MW)	p_{Lk}**:** operation priority
A_{Si} : availability	
C_{Si} : cost per kWh (FCFA/kWh)	
Q_{Si} : quantity of CO_2 released to produce 1 kWh (g/kWh)	
p_{Si} **:** operation priority	

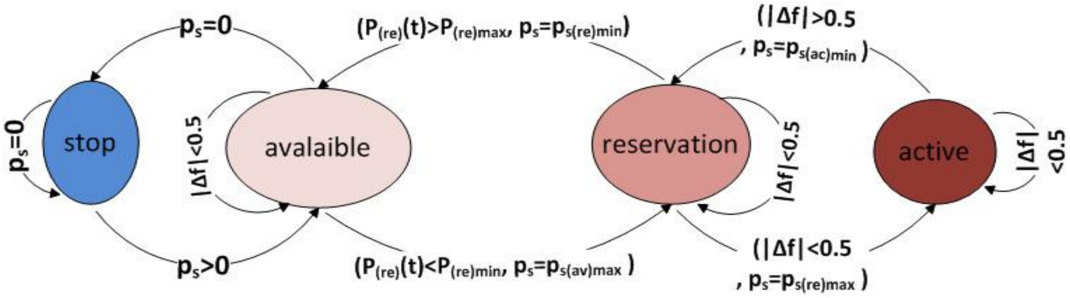

Figure 3. Behavioral model of source agent.

Source Agent can be in four (4) different states (Figure 3): active (ac), reserve (re) or standby, available (av) and stop (st). In each state, the instantaneous power of the source agent is delimited by a minimum and a maximum allowable power ($P_{(state)min} \leq P_{(state)}(t) \leq P_{(state)max}$). The numbers of source agents in state ac, re, av and st are respectively denoted N_1, N_2, N_3 and N_4. Equation 10 gives the instantaneous power reserve which is the sum of the powers of sources agents in the reserve state at t time. The reserve instantaneous power $P_{(re)}(t)$ should always be remaining between a minimum value $P_{(re)\min}$ and a maximum value $P_{(re)\max}$. Production sources that are in the reserve state can regulate the frequency around 50 Hz.

$$f:\{1,-1\}\times\{0,1\}\times[0\,1]\rightarrow[0\,1]$$
$$v_1,v_2,v_3\rightarrow p_s=f(v_1,v_2,v_3)=v_2\left(1-\left|v_1\times v_3\right|\right) \tag{9}$$

v_1 is optimization criterion, v_1 =1 or -1, $v_1 \in \{-1\ 1\}$; v_2 is the source availability, v_2=1 if the source is available otherwise v_2=0, $v_2 \in \{0\ 1\}$; Let $\{C_{S_i}\}$ be the set of kWh costs associated with energy sources of the system and $Max\{C_{S_i}\}$ the maximum of this set. Let $\{Q_{S_i}\}$ be the set of all the amounts GHGs released associated with energy sources of the system and $Max\{Q_{S_i}\}$ the maximum of this set. v_3 is equal to the following value:

$$v_3=\frac{C_{S_i}}{Max\{C_{S_i}\}} \text{ or } v_3=\frac{Q_{S_i}}{Max\{Q_{S_i}\}} \quad i=\{1,2,.....,N\} \text{ by}$$

construction $v_3 = [0\ \ 1]$.

$$P_{(re)\min} \leq P_{(re)}(t)=\sum_{i=1}^{N_2} P_{(re)i}(t) \leq P_{(re)\max} \tag{10}$$

Model system management

The main objective of the management system is to minimize the cost per kWh or reduce the amount GHG generated by the system with the constraint of maintaining the equilibrium of the system which requires the frequency in a fixed interval. Satisfaction function of system (SF) is a Boolean variable, it is equal to one (1) if the frequency of the electrical system is in [49.5 50.5] otherwise it is equal to zero (0). The Manager Agent is a cognitive agent and supervises staff departures and production sources, and their associated states (Figure 4). It plays a major role in the timing and coherence of the activities of different agents. It is involved in the cooperation between the different agents of the system. It supervises and coordinates the operation of the system agents.

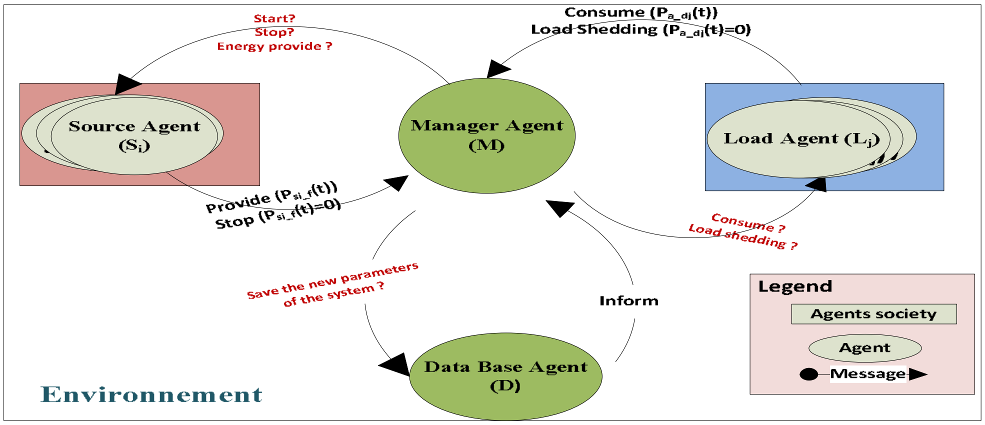

Figure 4. Model of energy management system.

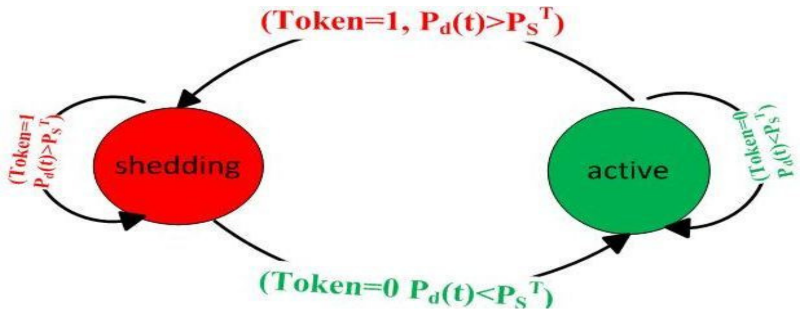

Figure 5. Behavioral model of load agent.

Source agent

According to the demand and the characteristics of the source, a Source Agent can be in four (4) different states: active, reserve, available and stop (Figure 3). A Source Agent

(i) is in the «stop» state when it cannot run because of a maintenance case following a breakdown, incident, etc., Its priority is then zero (p_s = 0). It goes into the available state as soon as it is functional again.
(ii) changes from the stop state to the available state when it can run, its priority is then evaluated and is positive. It may at any time switch to the reserve state according to the request and its priority.
(iii) is in the reserve state when it is ready to provide energy. Its production is equal to zero (0). This allows regulation of the frequency by continuous adaptation of the production level to that of the consumption. It goes into the active state according to the demand and its priority.
(iv) is in the active state when it supplies energy. In this state its priority is the greatest of all those of the agents that are in other states.
With:
(v) Δf (Hz) is the variation of the system frequency, it is equal to the absolute value of the difference between the frequency (f) (Hz) of the system at t time and the reference frequency (f_0 = 50 Hz) ($\Delta f = | f - f_0 |$ Hz). It is the direct image of the imbalance between the production and the consumption.
(vi) $p_{s(re)min}$ is the lowest source priority among the sources that are in the reserve state.
(vii) $p_{s(re)max}$ is the priority of the most favorable source among the sources that are at the reserve state.
(viii) $p_{s(av)max}$ is the priority of the most favorable source among the sources that are in the available state.
(ix) $p_{s(ac)min}$ is the lowest source priority among the sources that are in the active state.

Load agent

Load Agent (Ag_L) of the system is in an active state or in a shedding state as shown in Figure 5. The management of load shedding is done following attribution of a token «shedding». Load agents having the token « shedding» can pass from the active state to the load shedding state.
Where: P_d *(t)* is equal to the instantaneous power called by all departures; P_S^T is the total power available in the electrical network.

Power system

An electrical grid similar to that of Senegal was deliberately chosen (Table 2). This table provides a description of the power plants and generators, types of fuel, power installed. More than 88% of the production are of thermal origin. This makes it possible to get closer to reality.

Table 2. Production park of power network.

Power plants	Generators	Fuels	Installed power (MW)	Power plants	Generators	Fuels	Installed power (MW)
C1	Source1 1	Heavy fuel	15.95	C5	Source5 2	Diesel oil	18
	Source1 2	Heavy fuel	15.95		Source5 3	Kerosene	36
	Source1 3	Heavy fuel	15.95		Source5 5	Diesel oil	30
	Source1 4	Heavy fuel	15.95	C6	Source6 1	Diesel oil	15
C2	Source2 1	Heavy fuel	18		Source6 2	Diesel oil	15
	Source2 2	Heavy fuel	18		Source6 3	Diesel oil	15
	Source2 3	Heavy fuel	18		Source6 4	Diesel oil	15
	Source2 4	Heavy fuel	15	C7	Source7 1	Hydraulic	60
	Source2 5	Heavy fuel	15	C8	Source8 1	Heavy fuel	20
C3	Source3 1	Heavy fuel	67.5		Source8 2	Heavy fuel	13
C4	Source4 1	Naphtha	50		Source8 3	Heavy fuel	20

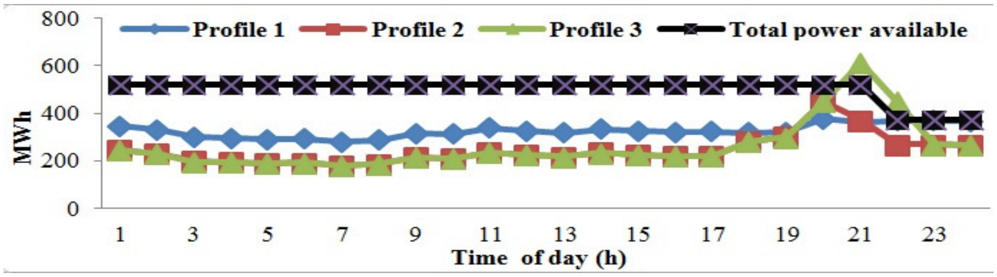

Figure 6. Profiles of the power demand of the network.

RESULTS AND DISCUSSION

To test the simulation model presented previously, three scenarios were set up to show the behavior of the system as clearly as possible.

Load profiles

To test the simulation model presented previously, three different load profiles were used (Figure 6). The first load profile is characterized by a nearly constant demand around 350 MW. The second profile is characterized by a peak power high demand of more than 37% within an interval of one hour. The third profile is characterized by a power demand exceeding the available power equal to 522.3 MW. Several scenarios were simulated in order to show the behavior of the system as clearly as possible.

Scenarios

The simulations were carried out following three criteria: An optimization criterion based on minimizing the production cost, a criterion based on the minimization of the amount of GHG emissions released and a criterion based on random rules. A test scenario consisted in simulating the behavior of the system when the power system presented below, a given load profile (1, 2, 3) and a given optimization criterion (minimizing the production cost or minimization of the amount of GHG) were applied. Several simulations of each load profile were also performed with a generator assessment criterion based on random rules. The results of various simulations were then compared. Those scenarios made it possible to highlight the robustness and effectiveness of the management system.

Simulation results

The results obtained with the first two criteria (cost and GHG) are compared to the third criterion (random). Figures 7, 8, 9, 10, 11, 12 and 13 show the results of different simulations with the platform.

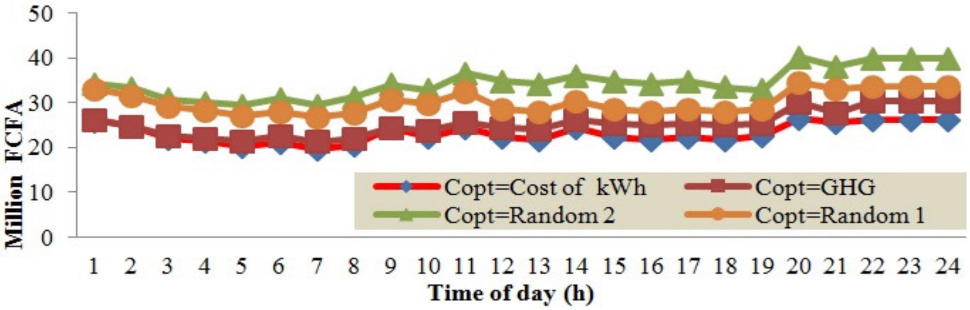

Figure 7. Production sources operating costs (Profile 1).

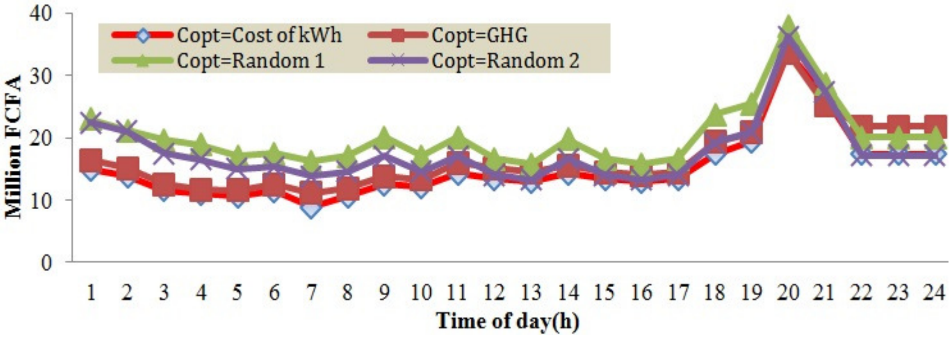

Figure 8. Production sources operating costs (Profile 2).

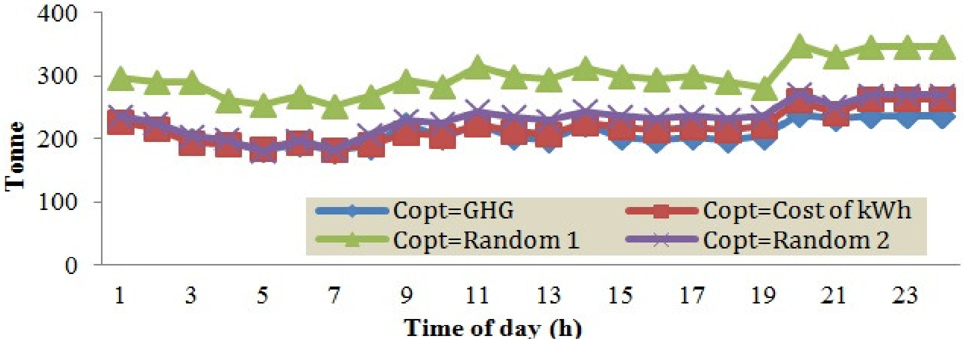

Figure 9. CO_2 quantity (Profile 1).

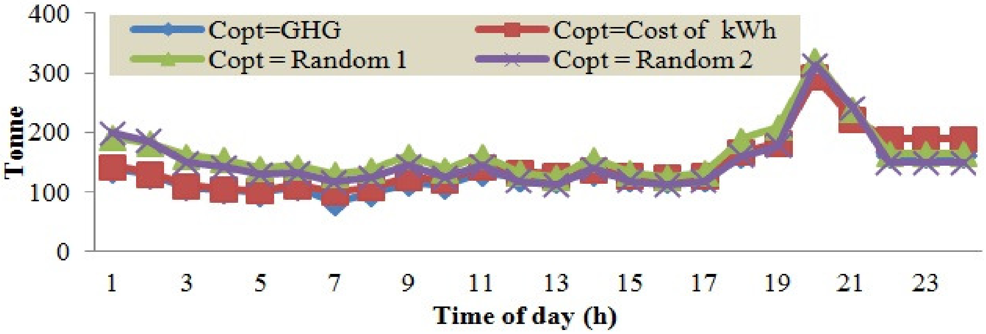

Figure 10. CO_2 quantity (Profile 2).

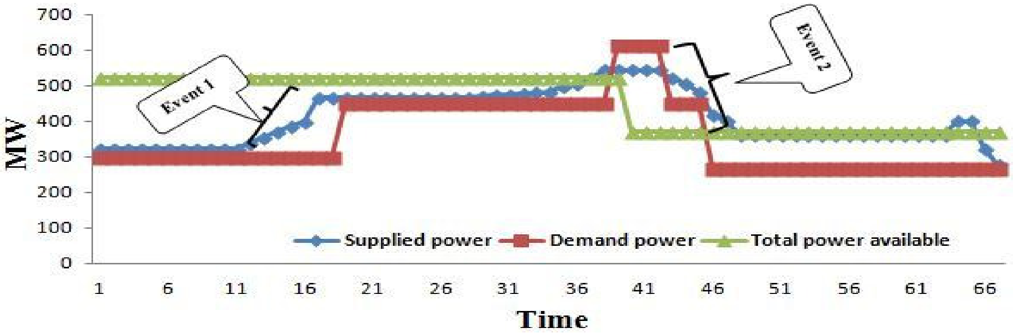

Figure 11. Behavior of management system on the critical moments of the day (between: 19 to 23 h).

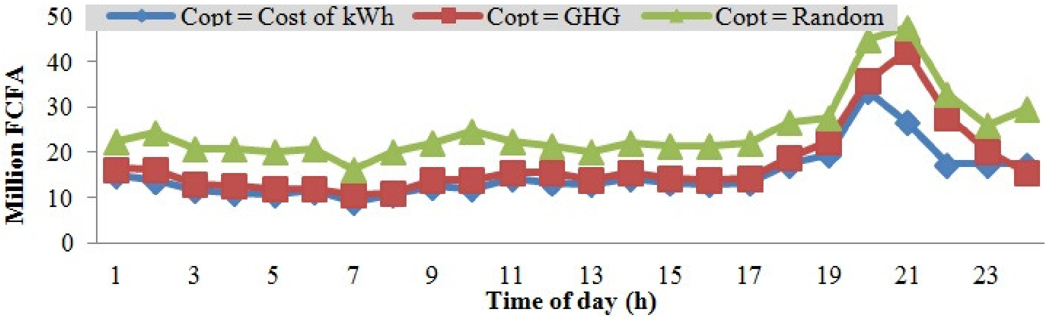

Figure 12. Production sources operating cost (Profile 3).

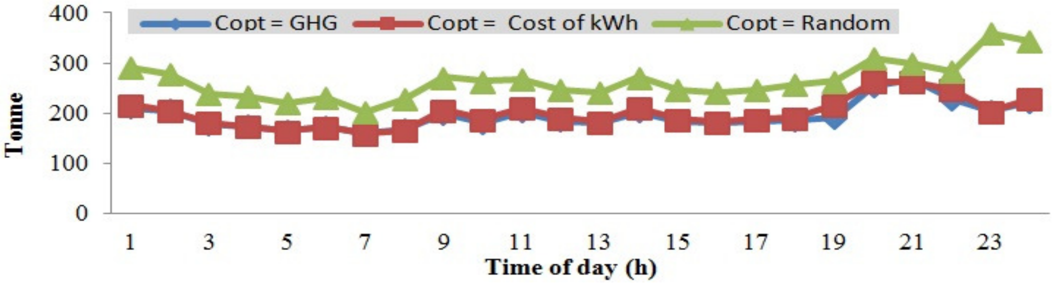

Figure 13. CO_2 quantity (Profile 3).

Results obtained with the first and second scenarios

Optimization criterion: The kWh production cost: Figures 7 and 8 show the operating costs of generation sources obtained respectively with Profile 1 and 2. The results show that the optimal cost is always lower than the cost obtained with the criterion based on random rules.

Optimization criterion: The amount of greenhouse gas emissions: Figures 9 and 10 show the amount of CO_2 released by the sources of production respectively with Profile 1 and 2. The difference between the results obtained by random criterion and optimized criterion remains significant for the amount of GHG released.

Results obtained with the third scenario

The third load profile shows the behavior of the system facing load shedding. Figure 11 shows many fluctuations between 19 to 23 h with a power peak of the demand exceeding the total power available (P_S^T) of the electrical network, a power loss in the production facilities and a departure opening (load shedding). The management system always tries to balance the inbalance between the energy production and consumption quickly. For the disturbances brought to the electrical network, the reaction time always remains in the interval [0 50] seconds.

Event 1: satisfaction of the 20 h demand (duration of the event 35.39 s); Event 2: peak (exceeding the total power PT), shedding load, satisfaction of demand, (duration of the event 48.9 s).

Optimization criterion: The kWh production cost

Figure 12 shows the operating cost of generating sources obtained with the simulation. The input data of the system are those of Profile 3. Costs obtained with the optimization criterion kWh cost are still lower than all other costs.

Optimization criterion: The amount of greenhouse gas emissions

Figure 13 shows the amount of CO_2 emitted by the sources of production respectively with Profile 3.

Conclusion

The work presented in this paper proposed a design and implementation of a simulation platform for decentralized management based on a multi-agent system. Using a located multi-agent paradigm built model seemed then to be an innovative and promising option for the development of decision support tools. The methodology adopted in this paper set up a control strategy over the agents in order to organize, schedule and interpret the amount of information exchanged between the different entities of the system. The results later achieved with the established platform showed that the optimized production costs of the arrangements of the energy sources by the platform were always better than any other arrangement. The platform also made it possible to assess and minimize the amounts of GHG released by the electrical system. Some incompatibility on the simultaneous satisfaction of the two optimization criteria was noted. The explanation is that generators, whose production cost is cheapest, are the most polluting of the power source.

One of the prospects of this work is to find an arrangement of production sources for optimal operation, taking into account two optimization criteria: the network operation cost and the quantity of greenhouse gas emissions. The other prospect focuses on the diversification of the production sources by integrating the renewable energies. Indeed, new energy sources such as wind, solar generators, are getting into our electrical systems and the user will increasingly be confronted with energy prices varying according to the supplier, the date and the time. It is in this varied and dynamic context of production and energy consumption that a «smart» control system takes all its importance from both consumption and pricing points of view (production).

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NOMENCLATURE

Ag_D Database Agent
Ag_L Departure Agent
Ag_M Manager Agent
Ag_S Source Agent
C_{S_i} Cost of kWh of the energy source
Q_{S_i} Quantity of fuel burned in the energy source
E_G Total emission of greenhouse gases (kg)
$E_{G,F}$ Emission of a given GHG per fuel type (kg)
$E_{G,F,T}$ Emission of a given GHG per fuel type and per technology (kg)
$E.F_{G,F}$ Emission factor of a given GHG per type of fuel used (kg/GJ)
$E.F_{G,F,T}$ Emission factor of a given GHG per fuel and per technology (kg/GJ)
P_D^T Total power Demand (W)
P_S^T Total power Supplied (W)
$P_{(state)min}$ Minimum power allowable in a state (W)
$P_{(state)max}$ Maximum power allowable in a state(W)
p Operating priority of a system agent (GJ)
Q_F Quantity of fuel burned in energy unit
$Q_{F,T}$ Quantity of burned fuel per energy unit per technology type (GJ)
GHG Greenhouse Gases

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