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Operation Optimal Dynamics of a Hybrid Electrical System: Multi-Agent Approach

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Abstract

This paper presents a decentralized management system of a hybrid agent paradigm-based electrical system. The management strategy aims at quantifying and controlling production sources to adapt the energy consumed by consumption sources to that supplied by the system renewable production sources while reducing the operating cost of the system. A multi-agent system, where each production and consumption source is modeled by an agent, is proposed to represent the electrical system. The suggested strategy, which is based on an economic model designed to control the energy produced by the production sources and that required by the consumption sources, made it possible to reduce the system production cost. It optimizes the production cost for the operator and improves the energy use without compromising the user's energy needs and comfort.

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Keywords: Renewable energy; multi-agent system; decentralized control; behavior modeling; hybrid electrical system

1. Introduction

New renewable energy sources such as wind and solar, characterized by strong intermittency, are increasingly integrated into electrical systems. The user is more and more confronted with energy tariffs varying according to the production sources, the day and hour. It is within this varied and dynamic energy production and consumption

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context that a smart control monitoring system is all the more important from a consumption point of view as well as a tariff one (production).

Research work on the distributed control of electrical systems holds an important part of the present day bibliography [1-2]. This trend has led to the development of several distributed control systems applied to microgrids. Several architectures and methods are introduced with simulations showing their efficiency in a microgrid control. Multi-Agent Systems (MAS) applied to the distributed control of electrical systems present a major issue for the management of the control complexity and flexibility. Indeed, the Consumption Source (CS) and Production Source (PS) of an electrical network are numerous, of different types, geographically distributed and entertain several forms of interactions to ensure the operating cost balance and reduction. The balance stresses between production and consumption, taking into account local problems (shutdown, etc.) and resource availability (sunshine, wind speed etc.) and the production cost mastery require real time decentralized control and a management system permanent adaptation.

Multi-Agent Systems for the optimization of a decentralized multi-source system management was developed in our previous research work [3]. The suggested strategy has made it possible to get a decentralized management of the electrical system fossil energy production sources facing the variation of the demand. The model proposed has allowed the global production to be optimized in relationship with the demand profile and in function of a cost minimization criterion or even greenhouse gas effect reduction. Bilal et al. and Sechilariu et al. [4-5] present a method of optimal configuration of a hybrid electrical system that meets the energy demand with minimum cost. The results obtained show a significant reduction of the optimal configuration compared to other configurations. Pipattanasomp et al. [6], present a system able to adapt itself in a set of heterogeneous energy sources and loads in order to optimize several parameters such as cost and efficiency. This system is based on the multi-agent system paradigm. Each of the microgrid entity is modeled like an autonomous agent able to interact with the rest of the system and to make decisions.

This research work is particular as it mainly focuses on production while endeavoring to minimize the investment cost or annual production cost of the electrical system. So the main questions asked in the present work are:

- Is the moment chosen to exploit some energy form appropriate?
- Is it possible to find a better moment to exploit a production source without compromising the user's comfort?
- Is it possible to adapt the production sources solicitation according to the operating costs that take into account the availability of the renewable energy sources, the demand and the electrical system constraints?

The present work suggests a management model of a decentralized self-sufficient electrical network. The model presents an approach aiming at automatically selecting the best sources according to their production cost. A multi-agent system is suggested to model the electrical system.

Section two presents the methodology approach through the models of the different components of the system, the mathematical formulation of the electrical system control strategy and the typology and model of the agents. The third section presents and discusses the results achieved.

2. Materials and methods

2.1. The mathematical models of the system components

The electrical system (see fig. 1) studied in this work consists of a photovoltaic generator, an aerogenerator, storage batteries and alternative current (AC) and direct current (DC) consumption sources.

The general idea is to minimize the cost production but also the power deviation (equation (1)) between the renewable sources production and the consumption by modifying the charge profiles through its different local entities.

$$Deviation(t) = P_{PV}(t) + P_{Aer}(t) + P_{bat}(t) - P_{SC}^{DC}(t) - \left(1/\eta_{inv}\right)P_{SC}^{AC}(t) + P_{Gen}(t) \tag{1}$$

With $P_{PV}(t)$ is the power supplied by the photovoltaic generator, $P_{Aer}(t)$ that produced by the aerogenerator, $P_{bat}(t)$ that produced or consumed by the battery. $P_{bat}(t)$ is positive if the battery is a generating one and $P_{bat}(t)$ is negative if the battery is a receiving one, $P_{SC}^{DC}(t)$ is the power called by the DC loads and $P_{SC}^{AC}(t)$ is the power called by the AC loads, $P_{Gen}(t)$ that produced by the fossil generator, η_{Inv} is the inverter efficiency.

- Storage system model

The calculation of the current supplied and received ($I_{bat}(t)$), the voltage ($V_{bat}(t)$) and state of charge (SOC) of the battery is given by the following block diagram of Fig. 2. The power at the battery terminals and the ambient temperature (input data of the model) make it possible to calculate the current imposed on the block and to update the state of charge.

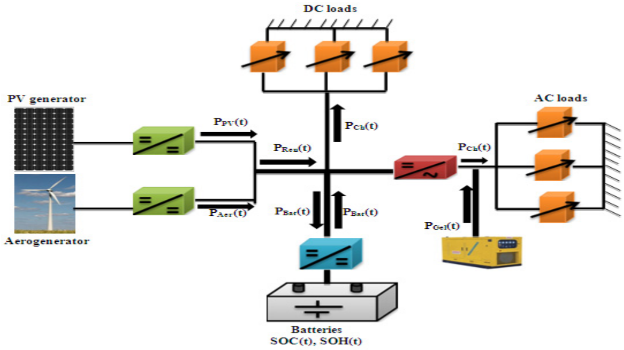


Fig. 1. The electrical system studied.

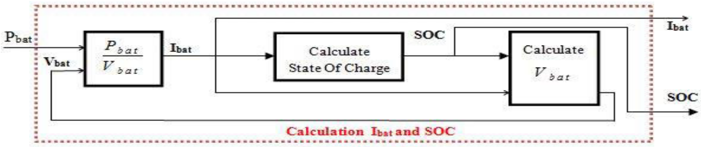


Fig. 2. Synoptic of the current and state of charge determination, in an operation mode imposed power (charge or discharge).

Equation (2) determines the battery state of charge [7].

$$SOC(t) = \frac{1}{C(t)}\int_0^t \eta_c(t) I_{bat}(t)dt \tag{2}$$

Where C (t) represents the battery capacity at instant t, η_c (t) is the battery faradic output. The battery is subject to a constraint given by equation (3).

$$-P_{bat}^{Max} \le P_{bat}(t) \le P_{bat}^{Max} \tag{3}$$

Where P_{bat}^{Max} is the maximum power supplied by the battery.

- Photovoltaic generator model

The power delivered by the PV module when going out is given by equation (4) [8].

$$P_{PV}(t) = \frac{\dfrac{V_{oc}(t)}{nKT(t)/q} - FF_0}{1 + \dfrac{V_{oc}(t)}{nKT(t)/q}} \bullet \left(1 - \frac{R_S}{V_{oc}(t)/I_{sc}(t)}\right) \bullet I_{sco}\left(\frac{G(t)}{G_0}\right)^{\alpha} \bullet \frac{V_{oco}}{1 + \beta ln\dfrac{G_0}{G(t)}} \bullet \left(\frac{T_0}{T(t)}\right) \tag{4}$$

Where G(t) and G_0 are respectively the radiance and the standard radiance. I_{sc0} and V_{oc0} are respectively the short circuit current and the open circuit voltage of the PV module at radiance G_0, whereas $I_{sc}(t)$ and $V_{oc}(t)$ the short circuit current and the open circuit of the module PV at radiance G(t). The constant parameters α, β, γ depend on the module technology, n represents the ideality factor included between 1 and 2, and the ideal form factor independent from resistor R_s is represented by FF_0.

- Aerogenerator model

The aerogenerator power expressions in function of the wind speed are given by equation (5) [9]. Parameters v(t), V_s, V_n and V_c respectively represent the instantaneous wind, start, nominal and cut off speed. P_n is the aerogenerator nominal power; k is the form factor (without any dimension characterizing the Weibull distribution dissymmetry).

$$\begin{cases} P_{Aer}(t) = P_n \times \dfrac{V^k(t) - V_s^k}{V_n^k - V_s^k}, & V_s < V(t) < V_n; \\ P_{Aer}(t) = P_n, & V_n < V(t) < V_c; \\ P_{Aer}(t) = 0, & \text{elsewhere.} \end{cases} \tag{5}$$

2.2. Mathematical formulation of the control strategy consumption sources

This section presents the mathematical formulation of the system management strategy. The control strategy is modeled mathematically by means of an optimization problem under constraints inspired by the work of Thillainathan [2]. The question is to minimize the distance standard between production and consumption (equation (6)).

$$\sqrt{\sum_{t=1}^{N} \left(P_{SC}(t) - Production(t) \right)^2} \tag{6}$$

With Production (t) is the system production at instant t. The P_{SC} (t) is consumption at instant t, which is given by equation (7).

$$P_{SC}(t) = Prediction(t) + Connexion(t) - Deconnexion(t) \tag{7}$$

With *Prediction(t)* is the consumption predicted at instant t, *Connexion (t)* and *Deconnexion (t)* are respectively the amounts of energy consumed by the CS connected and disconnected at instant t during the displacement in the temporary space. *Connexion (t)* and *Deconnexion (t)* calculation is inspired by the works Thillainathan [2].

2.3. Evaluation economic model of the system production sources cost

This section presents costs assessment model that make it possible to find a combination of production sources which minimizes the production cost (or use) of the hybrid electrical system. It passes by the determination of each source cost over a reduced time interval to calculate the best possible combinations. The no use cost (C_{nu}) is the source cost if its production is zero. The use cost (C_u) makes it possible to assess the source cost in relation to its production at instant t and it equals the ratio no use cost and the supply power by production source (P_{PS}) if P_{PS} is higher than P_{PS}^{Min} which is the minimal power supplied by the source. The function C_{nu} of each source is composed of four cost types (see equation (8)): acquisition cost (C_{acq}), maintenance cost (C_{main}), replacement cost (C_{rep}) and exploitation cost (C_{exp}) [10]. In this paper the exploitation costs is considered to equal zero for the aerogenerator, PV and battery.

$$\begin{aligned} C_{nu} = & \sum_{e=1}^{N_{Aer}} \left(C_{acq}^{e} + C_{main}^{e} + C_{rep}^{e} \right) + \sum_{p=1}^{N_{PV}} \left(C_{acq}^{p} + C_{main}^{p} + C_{rep}^{p} \right) + \\ & \sum_{b=1}^{N_{bat}} \left(C_{acq}^{b} + C_{main}^{b} + C_{rep}^{b} \right) + \sum_{g=1}^{N_{Gen}} \left(C_{acq}^{g} + C_{main}^{g} + C_{rep}^{g} + C_{\exp}^{g} \right) \end{aligned} \tag{8}$$

Where N_{Aer}, N_{PV}, N_{bat} and N_{Gen} are respectively the number of aerogenerators, photovoltaic generators, batteries and fossil generators. The assessment method uses the updating mechanisms of inflation rate (R). The annualized cost of each component is calculated using equation (9).

$$C_{acq}^{a} = \frac{C_{acq}}{L_S}\left(\frac{R(1+R)}{(1+R)^{L_S}-1}\right) \tag{9}$$

Where $\left(C_{acq}^{a}\right)$ is the annualized acquisition cost and L_S the source lifetime. The annualized maintenance cost is given by equation (10).

$$C_{main}^{a} = C_{main}(1+R)^{L_S} \tag{10}$$

The annualized replacement cost of a system source is the annualized value of all the replacement costs occurring throughout the lifetime of the project (equation (11)).

$$C_{rep}^{a} = C_{rep} * \frac{R}{(1+R)^{L_S} - 1} \tag{11}$$

For the specific case of the fossil generators, the operating cost needs to be assessed and annualized based on the inflation rate. The annualized operating cost is given by equation (12).

$$C_{\exp g}^{a} = C_c \frac{1-(1+R)^{L_S}}{L_S R} \tag{12}$$

Where C_c is the fuel cost at full throttle.

So, for each source, the cost depends on the lifetime (L_S), and can be updated yearly $\left(C_{nu}/L_S\right)$, monthly $\left(C_{nu}/L_S^m \text{ where } L_S^m = 12 * L_S\right)$, *daily* $\left(C_{nu}/L_S^d \text{ where } L_S^d = 12*30*L_S\right)$, *hourly* $\left(C_{nu}/L_S^h \text{ where } L_S^h = 12*30*24*L_S\right)$.

The source use cost is given by the non use cost / production. Finally, the system use cost is the sum of all the source use cost.

$$C_u = C_{uA} + C_{uP} + C_{uB} + C_{uG} \tag{14}$$

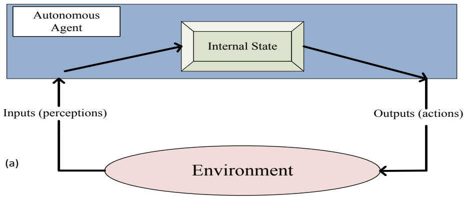
Where C_{uA}, C_{uP}, C_{uB} and C_{uG} respectively represent the aerogenerator use cost, the PV use cost, the battery use cost and the fossil generator use cost.

2.4. Typology and model of agents

In the approach adopted, a Production Source Agent $(Ag_{PS})_i$ ($i \in [1 - N]$) is associated with each energy production source and a Consumption Source Agent $(Ag_{CS})_j$ ($j \in [1 - M]$) is associated with each consumption source. The suggested architecture is hybrid and is distributed into two layers: the first layer consists of two types of reactive agents (fig. 3 (a)) (the production and consumption source agents). The second layer consists of three cognitive agents (fig. 3 (b)) such as the Manager Agent (Ag_M), the Service Agents (Ag_{Sv}) and the Facilitator Agent (Ag_F) and one reactive agent called Database Agent (Ag_B). Ag_B manages the information database manipulated by the production and consumption source agents.

- Ag_M**:** the manager agent supervises the production and consumption source agents; and their associated states. It plays a major role in the synchronization and coherence of the different agents' activities. It interferes in the cooperation between the different agents of the system. It supervises and coordinates the functioning of the system agents. It evaluates the deviation between the production and the consumption and starts the connection and/or disconnection process of the consumption sources.

- Ag_F: the Facilitator Agent facilitates the transaction between consumption sources (one or several) and production sources. It permanently discusses with Ag_M to verify the demand and production power balance. It gives the list of energy suppliers (production sources) to each energy buyer (consumption source). It is up to a buyer to find the best offer according to its needs (energy quantity, required service duration, etc.).
- Ag_{Sv}: the service agents locally supervise the different consumption source agent groups. They are associated with each distinct service by activity supervision of service groups and the determination process of the Ag_{CS} priorities. The priority determination process is started when there is a conflict between consumption sources.
- Ag_{CS}: the system consumption source agents are in an active or inactive state. A consumption source agent is in an active as long as it consumes energy. It can be shifted, changed or interrupted in function of the availability or not of the energy, of the user's comfort, of his priority and electrical constraints.
- Ag_{PS}: the finite automaton state models of renewable production sources such as the aerogenerator, the photovoltaic generator are inspired by our previous works [3].



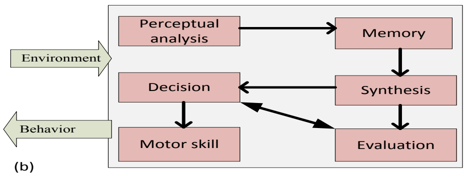


Fig.3 (a) operation reactive agent, (b) operation cognitive agent.

3. Results and discussions

3.1. Electrical system studied

The electrical system consists of a 16.5 kWc photovoltaic park made up of one hundred and ten 150 Wc modules, a 20.5 kW Wind Park consisting of forty one 500 W aerogenerators and a 7200 Ah storage system made up of 160 of 180 Ah batteries, 12 V. The DC bus voltage is 48 V. The critical discharge level is 30%. The profile is studied in this work (fig. 4). The charge profile corresponds to the use of public and commercial equipment (refrigerators, mills, water pumping, radios, televisions, fans, computers, etc.). The total demand total energy is 94 kWh/day; the maximum power is 20 kW and is observed about 10 p.m.

3.2. Simulation results from the energy point of view

To implement our architecture, we chose the MADKIT (Multi-Agent Development Kit) platform [11]. This platform is reserved for the development of the distributed multi-agents applications based on paradigm oriented organization.

The simulations are carried out following two scenarios and two day types. Day type I where the battery is fully charged and day type II where the battery discharge level is at a critical state (around 30%). In the first simulation scenario (S1) the system is managed without production source cost. The second scenario (S2) applies the decentralized control model. The two simulation results are then compared.

Fig. 5 (a) shows the production source behavior for the day type I. The demand is always inferior to maximum power (P_{bat}^{Max}) that supplies the battery which is equal to 38.4 kW. During the day, the fossil generator is not solicited whereas the battery contributes to meet the demand from 0 a.m. to 5 a.m. and 5 p.m. to 11 p.m. During these periods, the aerogenerator and the PV units do not manage to satisfy the demand fully. Fig. 5 (b) illustrates the production sources behavior for the day type II where the battery SOC is about 30%, which starts the contribution of

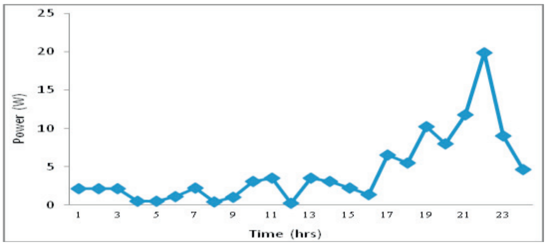


Fig. 4. The profile of the consumption sources

fossil generator if the aerogenerator and PV units together do not manage to meet the demand. From the energy point of view, the curves represented in fig. 5 (a) and (b) show the production source different behaviors, the battery SOC and loads profile on the analyzed two type day. Overall the PV and the aerogenerator the same way, the small differences noted are explained by the potential variations. On day type I we observe that the storage system is much requested between 6 p.m. and 11 p.m. Whereas day type II starts by the inferior limit of the battery SOC (30%) which has less contributed in the day, which explains the fossil generator great request.

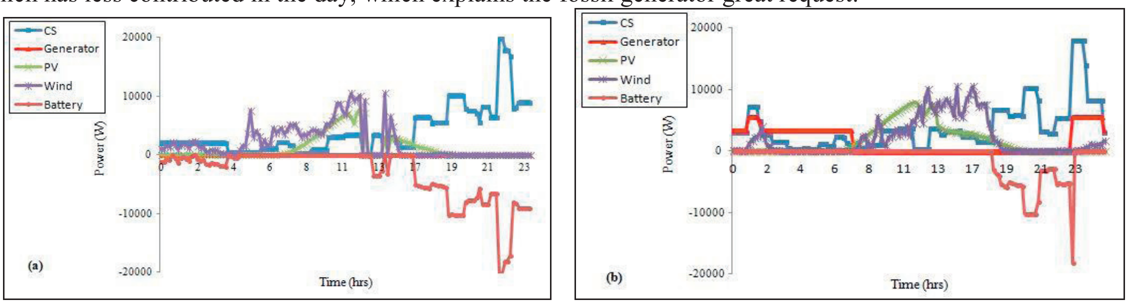


Fig.5 (a) Production sources behavior in real-time: day type I, (b) Production sources behavior in real-time: day type II.

From the economic point of view, a comparative analysis between the implemented control system and a scenario which does not include the production source costs is made.

Table 1 results show that the production and the PV and aerogenerator (Aero) cost remain constant for a same day whether the management strategy is applied or not. However a variation is observed depending on the day type. The cost depends on the production which is highly correlated with the potential. The battery (Bat) mean production increases when the cost control is applied. As for the battery kilowatt-hour cost, it decreases from 25.88 \$/kWh to 18.47 \$/kWh during the day type I and from 62.07 \$/kWh to 33.86 \$/kWh for the day type II. The production of the generator (Gen) is equal to zero (0) for the day type I whether the control applied or not and the kilowatt-hour cost is not defined (ND).

Table 1: Energy cost and production of Sources Parks.

		With cost control applied					Without cost control applied				
	Sources Types	Aero	PV	Bat	Gen	Total	Aero	PV	Bat	Gen	Total
first type day	Cost ($/kWh)	0.739	7.28	18.47	ND	26.486	0.739	7.28	25.88	ND	33.899
	Production (kWh)	0.289	0.169	3.022	0	3.480	0.289	0.169	1.9	0	2.358
Second type day	Cost ($/kWh)	1.449	10.52	33.86	0.014	45.843	0.149	10.52	62.07	0.001	72.740
	Production (kWh)	0.165	0.117	1.308	0.179	1.769	0.165	0.117	0.796	1.680	2.758

Fig. 6 shows for the day types I and II, over a time interval of twenty four hours (24 h), the ratio evolution between the system operation overall costs when the proposed strategy and the operating cost when the strategy is not applied. The no use cost presented in section 2.3 is assessed based on a ten-minute time interval, and is equal to \$ 3.356for the storage system, \$1.576 for the PV park, \$ 0.384 for the aerogenerator park and \$ 0.002 for the fossil generator.

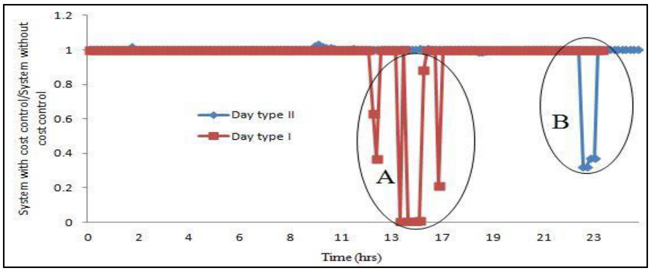


Fig. 6. The ratio between operator global cost of system applied the strategy proposed and the operator cost without applied the strategy.

4. Conclusion and perspectives

This paper presented a hybrid electrical system decentralized management strategy based on renewable energies. The management strategy was implemented in a multi-agent architecture where different self-sufficient entities cooperated and controlled cost fluctuations and energy flows exchanged within the system to reduce the energy produced by the renewable sources. It relied on the production source dynamic and consumption source control flexibility to reduce the system operation cost. Two day types were selected for the simulations in the order to evaluate the results obtain. The simulation results showed a production cost source when the strategy is applied. The control system applied results in a cost reduction from 25.88 \$/kWh to 18.47 \$/kWh during the day type I and from 62.07 \$/kWh to 33.86 \$/kWh for the day type II. The prospects will be about integration (user's habit, user priority charges, etc.) and of interactivity with the user in the demand control strategies. It would be interesting to open the system for other production sources conventional networks.

References

1. Hernandez L, Baladron C, Aguiar J M, Carro B. A multi-agent system architecture for smart grid management and forecasting of energy demand in virtual power plants. Communications Magazine, IEEE 2013. Volume: 51, Issue:1 pp : 106-113.
2. Thillainathan L, Ashwin M K. Multiagent System for Real-Time Operation of a Microgrid in Real-Time Digital Simulator. IEEE Transactions on smart grid, vol. 3, NO. 2.
3. Mbodji A K, Ndiaye M L, Ndiaye P A. Decentralized management of a multi-source electrical system: A multi-agent approach. Academic Journals 2013; ISSN 1992-1950.
4. Bilal B O, Ndiaye P A, Kébé C M F, Sambou V and Ndongo M, Methodology to Size an Optimal Standalone Hybrid Solar-Wind-Battery System using Genetic Algorithm, International Journal of the Physical Sciences Vol. 7(18), pp. 2647-2655, 9 May, 2012.
5. Sechilariu M, Wang B C, Locment F, Jouglet A. DC microgrid power flow optimization by multi-layer supervision control. Design and experimental validation, Energy Conversion and Management 82 2014.
6. Pipattanasomp M, Feroze H, Rahman S. Multi-Agent Systems in a Distributed Smart Grid: Design and Implementation. IEEE PES Power Systems Conference and Exposition (PSCE'09), Seattle, Washington, USA, 2009.
7. Guasch D and Silvestre S. Dynamic Battery Model for Photovoltaic Applications. Prog. Photovolt: Res. Appl. 2003; 11:193–206
8. Zhou W, Yang H, Fang Z. A novel model for photovoltaic array performance prediction. Applied Energy 2007; 84 1187–1198.
9. Diafa S, Belhamel M, Haddadic M, Louche A. Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island. Energy Policy 2008; 36 743–754.
10. Hongxing Y, Wei Z, Chengzhi L. Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. Applied Energy 2009; 86 163–169.
11. Gutknecht O, Ferber J. Madkit: a generic multi-agents platform. AGENTS'00: 4th International Conference on Autonomous Agents, pp. 78-79, 2000.