Energy Conversion and Management 78 (2014) 297–305

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy management in a microgrid with distributed energy resources

Linfeng Zhang *, Nicolae Gari, Lawrence V. Hmurcik

Department of Electrical Engineering, University of Bridgeport, CT 06604, USA

ARTICLE INFO

Article history:
Received 16 March 2013
Accepted 25 October 2013

Keywords:
Energy management
Distributed energy resources
Fuel cell
Solar energy

ABSTRACT

A smart grid power system with renewable energy resources and distributed energy storage shows significant improvement in the power system's emission reduction, reliability, efficiency, and security. A microgrid is a smart grid in a small scale which can be stand-alone or grid-tied. Multi microgrids form a network with energy management and operational planning through two-way power flow and communication. To comprehensively evaluate the performance of a microgrid, a performance metric is proposed with consideration of the electricity price, emission, and service quality, each of them is given a weighting factor. Thus, the performance metric is flexible according to the consumers' preference. With the weighting factors set in this paper, this performance metric is further applied on microgrids operated as stand-alone, grid-tied, and networked. Each microgrid consists of a solar panel, a hydrogen fuel cell stack, an electrolyzer, a hydrogen storage tank, and a load. For a stand-alone system, the load prediction lowers down the daily electricity consumption about 5.7%, the quantity of H_2 stored fluctuates in a wide range, and overall performance indexes increase with the solar panel size. In a grid-tied MG, the load prediction has a significant effect on the daily consumed electricity which drops 25% in 4 days, some day-time loads are shifted to the night time, and the capacity of hydrogen tank is lower than that in a stand-alone MG. In a network with multiple MGs, the control of the power distribution strongly affects the MG's performance. However, the overall performance index instead of any specific index increases with the MG's power generated from renewable energy resources.

1. Introduction

According to the U.S. Energy Information Administration, around 29.3 PWh of energy was consumed in 2008. 37% of the energy was from petroleum while 50% of the petroleum was imported – around 1.32 million tons/day. From 2006 to the present, the price of gasoline has fluctuated due to the instability in the Middle East, manipulation of energy supplies, competition over energy sources, attacks on supply infrastructure, and natural disasters. To improve the nation's energy independence and security, the best solution is to efficiently utilize renewable energy resources including solar, wind, hydro, geothermal, and tidal energy. Renewable sources of energy are plenty and vary widely in their availability across the United States. In addition, these energy resources are environmentally friendly with zero emission. In order to utilize renewable energy, wide-scale distributed renewable energy resources (DRERs) are more widespread than the large-scale centralized installations [1]. However, the traditional power grids heavily rely on the centralized power generation, around 16,000 power plants in the U.S, for instance [2,3]. Therefore, a new power grid, Smart Grid (SG), was proposed through the updating of the current grid and this SG includes technologies in the distributed energy generation (DEG), distributed energy storage (DES), advanced measurement and sensing, communications, controls, cyber security, and customer power management systems [4–7]. DEG is small-scale power generation with power less than 50 kW. It includes micro turbines (μturbine), micro combined heat and power (μCHP) systems, photovoltaic systems (PV), wind turbines, and solar thermal systems [8,9]. Electricity and on-site heat can be produced near the point of demand, allowing for production of energy with high efficiency and avoidance of the transmission and distribution losses in the conventional centralized generation model [10–12]. However, the widespread emergence of the DEG on the consumer side will significantly increase the variability of generation due to the intermittent nature of generators, especially wind turbines and photovoltaic (PV) systems. To balance supply and demand and to minimize the DEG-induced power fluctuations in the grid, compensating changes are required in the demands, DES, and output from flexible generation sources [13,14]. Here, DEG and DES are parts of distributed energy resources (DERs) [15]. Voltage and frequency within tight bands can be maintained with real-time and continuous physical adjustments to electricity generation and demand subject to complex constraints. A conservative SG approach is expected to reduce the environmental impact of the whole electricity supply system and improve the existing services efficiently [16].

* Corresponding author. Tel.: +1 203 576 4249.
E-mail address: lzhang@bridgeport.edu (L. Zhang).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.10.065

Nomenclature

S	solar panel size (m^2)
Q	overall performance index
F	price index
E	emission index
S	service quality
w_i	weighting factor
P_{supply}	energy supplied to the load
P_{demand}	power demand
e_{avg}	average atmospheric emission for electricity consumed in a MG
e_{plant}	emission from a coal-fire power plant
$\bar{P}_{dd}$	average daily day-time power demand (kW)
$\bar{P}_{dn}$	average daily night-time power demand (kW)
h_d	hours of day time
$\bar{I}$	average solar irradiance (kW/m^2)
η	efficiency

A microgrid (MG) is a small power system with a set of DEG, DES, a grid connection for two-way power flow and message exchange, heat and power distribution infrastructure, and an energy management system. In a MG, electricity and on-site heat can be produced near the point of demand, allowing for production of energy with high efficiency and avoidance of the transmission and distribution losses in the conventional centralized generation model [10–12]. Multiple MGs can form a network with a connection to the utility grid and this shows a great potential to increase the penetration of renewable and distributed energy resources. The control architecture in a MG network is distributed instead of centralized in the traditional grid and this architecture is scalable. Software with different controls, strategies, or architectures has to be developed as a management system to improve the SG's performance [17–19]. One MG can run in two modes: grid-tied and islanded [20]. In the first mode, power flows in two ways between a MG and the other MGs or the utility grid. A MG may consume the power from the outside or it may supply power for credits according to the agreement among the MGs and utility companies. An energy router, such as solid state transformers, will be developed to control power flow among MGs [21]. In an islanded or stand-alone mode, a MG is isolated from the network and this intentional "islanding" under certain circumstances, provides local reliability, stability, and security. At the same time, this operation, mode change, does not change or disrupt the integrity of the network as a whole [20]. The operation of a single MG or MG network is based on the MG energy management which includes a power generation program, an energy storage program, and a load management program. In a MG with multiple generators, such as microturbine, fuel cell stack, or PV system, power generation program will choose appropriate generators to meet the electrical and thermal load demands. The energy storage program provides an energy reserve with a stable output power, voltage and frequency, in the presence of renewable energy fluctuation [22]. The load management or demand response program determines the reduction or shift of the load demand to reduce peak-to-average ratio [23]. Demand can be categorized into different types based on whether it is can be shifted, interrupted, decreased, or cancelled. It also has different priorities in the presence of limited supply. Generally, demand is a random variable with a probability distribution in an operation time window, and it can be regarded as a series of separated and fine-grained tasks, which means each task can be completed in a sequence but not in continuous time slots. MGs should collaborate to schedule the demand shift to avoid a new peak formed in a typical nonpeak hour. The electricity price is definitely considered in this scheduling. In a grid, the price is established by the market to balance sellers' supply and buyers' demand. This balancing process should be continuous and instantaneous; since electricity must be produced at nearly the same instant it is consumed. Market trades in electricity can be: (i) bilateral transactions – short-term forward market trading in the form of a day-ahead market, and (ii) spot market trades in real-time. The first is conducted between wholesale consumers and power plants, and it provides price certainty. But consumers with DEG, DES, and AD must pursue a combination of short-term trading and spot trading. Thus, in order to maximize their benefits from the generation and consumption, consumers can balance their portfolios and adjust their generation or demand under some short-term predictable and unpredictable circumstances [13,24].

A SG with multiple MGs is a distributive system. There are different criteria to evaluate the performance of a MG. Current evaluation methods and indicators only consider one particular aspect of the system, such as economic benefits, energy use efficiency, and environmental benefits [25].

The objective of this paper is to introduce MG performance metrics for the MG performance evaluation from comprehensive aspects: cost, environmental effect, and the service quality. Here, service quality is supply/demand ratio. With the performance metrics, the optimum design and operation of the MG can be achieved. Models of a stand-alone MG, a grid-tied MG, and a MG network with multi-agents are designed for the simulation on the power generation, distribution, consumption, and storage on the energy level while the topology of these models does not limit the simulation. The whole system is developed with Java and each unit is implemented as a thread.

2. The MG model

Fig. 1 shows the structure of a MG with a radial distribution type and the location is assumed to be in the city of Bridgeport, Connecticut, U.S.A (longitude 73, latitude 41). Each MG consists of a solar panel, an electrolyzer, a hydrogen (H_2) fuel cell (FC) stack, a H_2 tank, and loads with different priorities. In addition, there are two circuit breakers and one local agent. The MG can be connected to an external distribution system, grid, through a point of common coupling (PCC). There is also a separation device, a static switch, which has the capability to island the MG when faults or events described in the standard IEEE 1547 occurs, or for maintenance purposes [16,26]. Line 1, 2, and 3 are for bi-directional power distribution and their directions depend on the local load, supply, and electricity price. The local agent is responsible for the energy management: it monitors the grid and the MG status through smart meters with two-way communication; it schedules the power/heat generation, energy storage, and load demands; it also determines the power flow within the MG and between the MG and the outside. In Fig. 1, electricity can be generated from the solar panel to be supplied to the local loads. The spare can either be stored as H_2 in a compresses tank through an electrolyzer or be supplied to the utility grid. When more electricity is needed later, the FC stack will run with the stored H_2 or the power can be

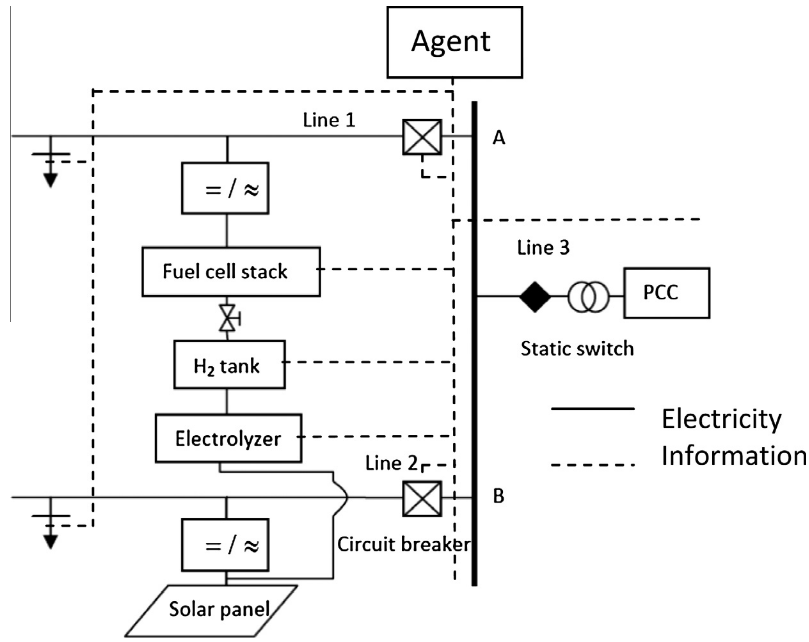

Fig. 1. The structure of a MG.

from the grid. In this paper, the simulation is based on the energy level and it is not limited to this topology.

2.1. Solar panels

The solar position is calculated via reference [27]. Without the consideration of the investment in solar panels, the size (m^2) of the solar panels should be at least:

$$S = \frac{\bar{P}_{dd} h_d \eta_{el} \eta_{fc} + \bar{P}_{dn}(24 - h_d)}{\bar{I} h_d \eta_{sp} \eta_{el} \eta_{fc}} \tag{1}$$

where $\bar{P}_{dd}$ and $\bar{P}_{dn}$ are the average power demand (kW) in the day time and night time, respectively. h_d is the number of hours of day time with sun light. η_{fc}, η_{sp}, and η_{el} are the efficiencies of the FC stack, solar panels, and the electrolyzer, respectively. $\bar{I}$ is the average solar irradiance (kW/m^2).

Fig. 2(a) shows the solar azimuth and altitude on February 26, 2010 without consideration in environmental temperature change. The sun rises at 6 O'clock and sets at 17 O'clock and this result is verified with the reference [27]. Fig. 2(b) shows the output power from a 120 m^2 solar panel.

2.2. Hydrogen FC stack

Hydrogen FC stack generates electricity through the reaction between hydrogen and oxygen without emission. Therefore, the environment can be protected. In the meantime, heat, as by product, can also be provided to the building or local community. In this work, the parameters of the FC stack are shown in Table 1.

The FC stack is simulated through the equations in the reference [28] with the consideration of a double-charge layer on the surface of the cathode. Fig. 3(a) is the voltage–current and power–current curves from the FC stack at 70 °C. The maximum output power is 27 kW if the current is around 200 A. The electric power is close to the heat generated for a FC stack with 50% efficiency. This rated capacity is one constraint imposed on the operation of the FC stack in the next time step and another constraint is the maximum

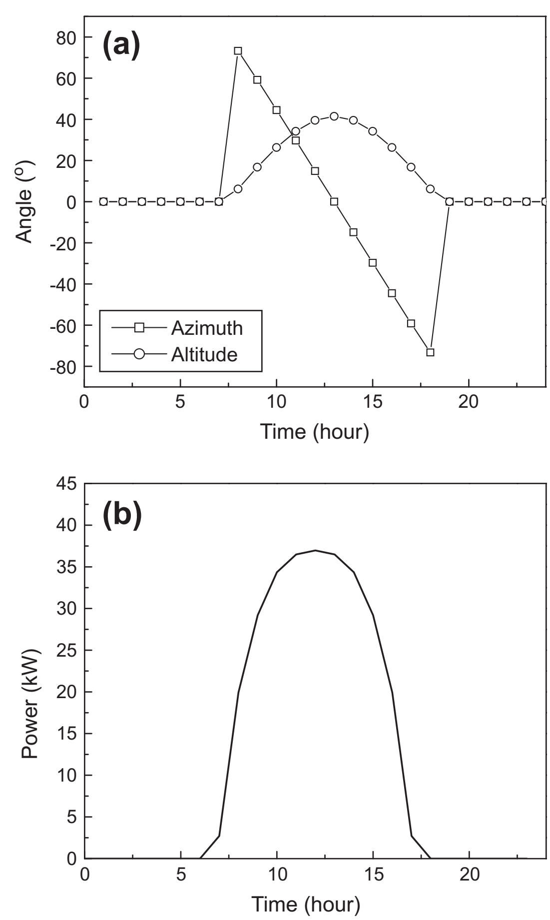

Fig. 2. Solar position at different time (a) and power generated from the solar panel (b).

power with the available hydrogen in the tank. In this paper, the necessary power from the FC stack in the first day is predicted as:

$$P_{FCn+1} = c_1 P_{FCn} + c_2 P_{needn} \tag{2}$$

Table 1
Parameters of a FC stack.

Parameter	Value
Number of cells	300 (in series)
Active area per cell	200 cm^2
Operating temperature	70 °C
Cathode pressure	2 atm
Anode pressure	2 atm

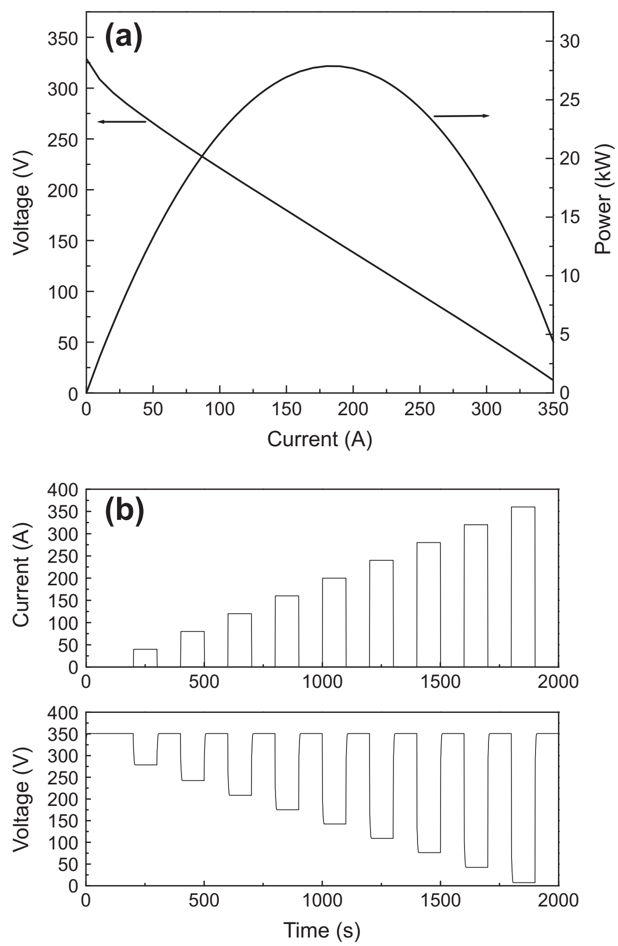

Fig. 3. Voltage–current and power–current curves of a PEM FC stack at 70 °C (a) and its dynamic voltage response (b).

where c_1 and c_2 are weighting factors. $P_{FCn+1}$and P_{FCn} is the power from the FC stack in the next and current time step, respectively. P_{needn} is the power still needed to meet the total demand in the current time step.

From the second day, the power needed from the FC stack will be predicted according to load demand and generation in the previous days.

Fig. 3(b) shows the dynamic behavior of the stack at different currents. There is a transient process in the voltage when there is a sudden change in the current. The time constant in this transient process is around 10 s which can be neglected for any current constant in a long period. In this work, the operating point the FC stack is predicted based on the current power demand (more than 2 kW) and the current output power from the FC stack. Moreover, the operating current is equal to or below the one corresponding to the maximum output power.

Maximum power point (MPP) tracking strategy with perturbation and observe will be used in the operation of solar panel and FC stack. It can be implemented with a MPP tracking controller and a DC–AC inverter [21]. The whole system is a distributed system and is implemented through Posix threads in Java. In one MG, there are four threads for an agent, a FC stack, a solar panel, and an electrolyzer, respectively.

2.3. Performance index

In order to comprehensively evaluate the performance of a MG with the consideration of electricity price, atmosphere emission, and service quality, an overall performance index Q for each MG is proposed as:

$$Q = w_1 F + w_2 E + w_3 S \tag{3}$$

Here, F is a price index of electricity, E is an environmental effect index due to atmospheric emissions, and S is the service quality. All of these indexes are between 0 and 1. 0 is the worst and 1 the best. w_i (i = 1, 2, 3) are weighting factors and $\sum w_i = 1$. The values of the weighting factors are flexible and they depend on the consumer's preference or government incentives. Thus, the operating of any specific MG may be different for the consumers. However, the ultimate objective for each MG operation is to maximize its overall performance index. Although this performance index is introduced for one MG, it can be applied for an entire SG under certain circumstances. In this simulation, w_1, w_2, w_3 are set as 0.5, 0.3, and 0.2, respectively. The dynamic price of electricity from a SG central dispatch is assumed to be 3 units during peak times (between 8 O'clock and 18 O'clock), and it is 1 unit during off-peak times. The price of electricity from solar panels or FC stack is 2 units. Note, the price index may be more than 1 if the electricity from solar panels is much less than that from the grid during the peak hour. Therefore, the price index of electricity, F, can be calculated as:

$$F = \frac{c_{SG-off-peak}}{c_{avg}} \tag{4}$$

Here, $c_{SG\text{-}off\text{-}peak}$ is the price of electricity from a SG central dispatch in off-peak time, and c_{avg} is the average cost of electricity for a MG.

The service quality index can be calculated as:

$$S = \frac{1}{T}\sum_{t=0}^{T}\sum_{i=1}^{3}\left(w_i \frac{P_{supply,i}}{P_{demand,i}}\right) \tag{5}$$

Here, T is a period of time, and i is the priority of the load (high, normal, or low). $P_{supply,i}$ is the energy supplied to the load demand with a priority i, and $P_{demand,i}$ is the load demand with a priority i. i can be 1, 2, and 3 for the critical, shiftable, and cancelable loads, respectively. w_i (i = 1, 2, 3) is a weighting factor for the load with priority i, and $\sum w_i = 1$. In this simulation, w_1, w_2, w_3 are set as 0.5, 0.3, and 0.2 for the loads with high, normal, and low priorities, respectively.

The air emission index is defined as:

$$E = 1 - \frac{e_{avg}}{e_{plant}} \tag{6}$$

where e_{avg} is the average atmospheric emission for electricity consumed in a MG, and e_{plant} is the emission from a fire power plant. In this paper, the emission is set as 3 units for electricity from the fire power plant and 0 unit for electricity generated from a solar panel or a fuel cell stack in a MG.

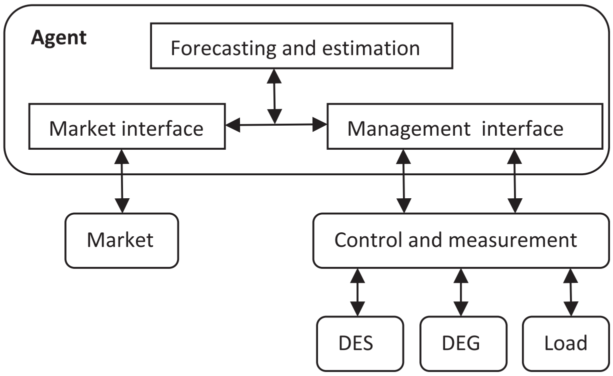

Fig. 4. The structure of an agent-based energy management system.

2.4. Energy management

The structure of agent-based energy management is shown in Fig. 4. The agent can be the weather forecast or the estimated energy generation/consumption pattern for a local DEG and loads for the upcoming time period. This agent communicates with its regional manager which is also an agent but voted by its neighbors to be the manager. The regional manager then aggregates the energy profiles and trade with the other managers through bids and auctions in order to balance the supply and demand and determine a price. A two-layer hierarchical structure will ensure scalability and reduce communication overhead. Thus, with the information from the regional manager, an agent can make a decision to optimize the operation of the system through real-time control with advanced measurement infrastructure.

3. Results and discussion

3.1. A stand-alone MG

A stand-alone MG is an off-the-grid electricity system for locations that are not fitted with an electricity distribution system. However, a grid-tied MG can also operate in “islanded” for security and reliability.

Table 2 shows the parameters of the system and Fig. 5(a) is the results in the first day. At the very beginning, 0 O’clock, there is no power supply although the demand is 20 kW. Around 6 O’clock, solar panel starts to generate electricity and the power demand in the day time can be met. As the maximum power from a solar panel is 60 kW and the demand is 40 kW, the spare electricity is supplied to the electrolyzer and H_2 quantity starts to increase. In the night time, the power is only from the FC stack till 23 O’clock and its output is less than the rated power, 27 kW, due to the hydrogen available. There is no power after 23 O’clock and before the sun rises in the second day. One problem can be observed is that both the electrolyzer and the FC stack work between 10 O’clock and 17 O’clock. This is due to the insufficient data available for prediction of demand. In the 10th day, as show in Fig. 5(b), the electrolyzer and the FC stack do not run simultaneously and there is sufficient power supplied to the day-time demand. In addition, the FC stack only works when the power from the solar panel is below the demand. Similar to the result in the 1st day, there is no enough power supplied in the nigh time.

Fig. 6 shows the change of H_2 mole number in the first 10 days and this number starts to increase at around 10 O’clock and decrease at 15 O’clock. The peak value of the H_2 quantity fluctuates between 2250 mol and 750 mol, which is in the 1st day due to

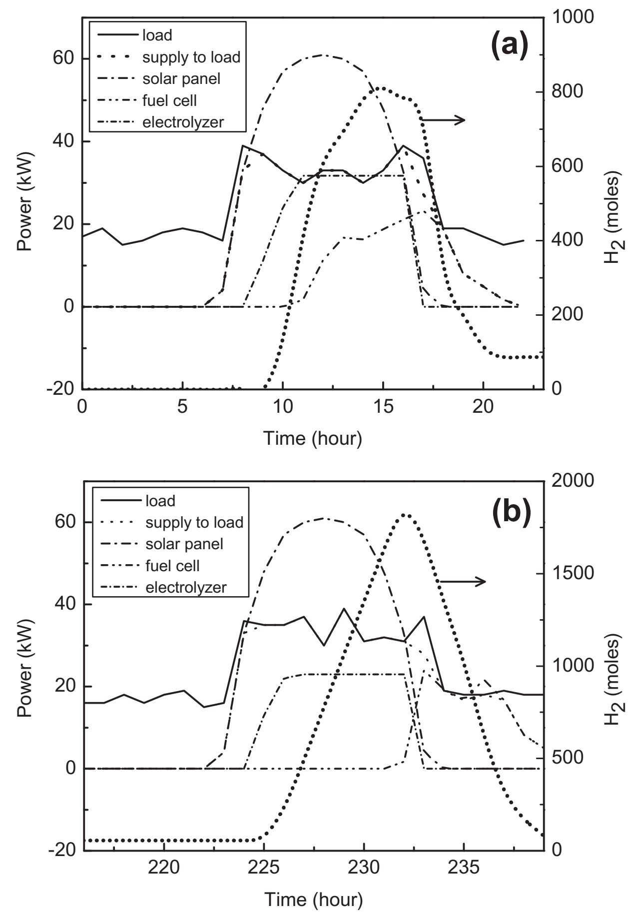

Fig. 5. The power flows in the 1st day (a) and the 10th day (b) in a stand-alone system with a 200 m^2 solar panel.

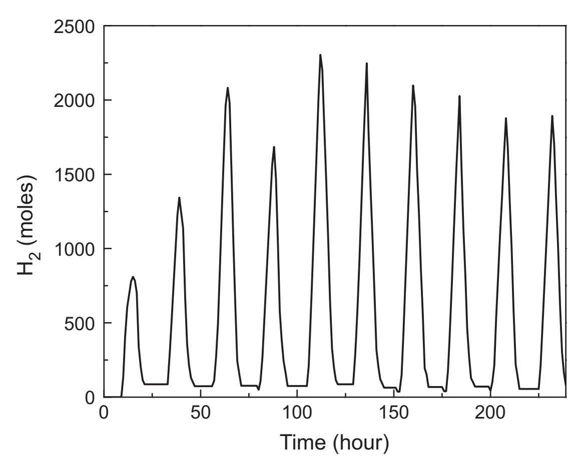

Fig. 6. H_2 in the system with a 200 m^2 solar panel.

Table 2
The parameters of the MG.

	Solar panel (m^2)	Load			H_2 tank		
		Day time (kW)	Night time (kW)	Priority distribution	Initial (moles)	Pressure (psi)	Volume (L)
MG-0	200	40	20	0.6, 0.2, 0.2	0	3000	260

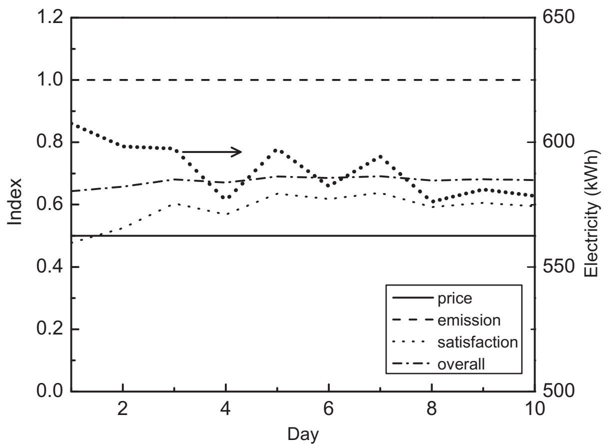

Fig. 7. The performance index and electricity for a system with 200 m^2 solar panel.

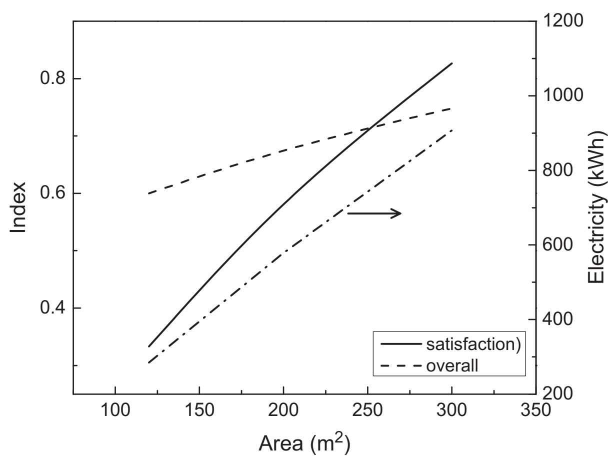

Fig. 8. The performance index and the electricity used in the systems with different solar panel sizes.

the inefficient system operation. According to the H_2 quantity, the volume of a H_2 tank should be at least 260 L to store H_2 under 3000 psi.

Fig. 7 shows the electricity and the performance indexes in the first 10 days. The daily electricity supply decreases from 610 kW h on the 1st day to 575 kW h on the 10th day as the MG runs more and more efficiently. Thus, service quality index increases from 0.49 to 0.60. However, there is no much change in the overall performance index, around 0.63. Since the all power is from the solar panel, the price and the emission indexes are constants as 0.5 and 1, respectively, and both of them are not affected by the size of the solar panel. However, the total daily electricity consumption, service quality index, and overall index increase with the solar panel size as showed in Fig. 8.

3.2. A grid-tied MG

For a grid-tied MG, there are two-way power transmission and communication between the MG and the utility grid. The power flow direction is determined by the service quality and cost. For example, A MG can obtain electricity from the grid if this MG does not generate sufficient power locally and/or the dynamic electricity price on the grid is low; A MG can also supply its spare power to the grid when there is a power shortage and/or the price is high. In addition, the MG loads are smart and they can also communicate with the MG agent for the demand response. Based on the load information, e.g., priority, a MG agent determines the power supply to the loads. As a real application in peak hours, the high-priority loads will be guaranteed for its supply, the medium-priority loads will be shifted to off-peak hours for peak-shaving and cost-reduction, and the low-priority loads will be cancelled. For the same peak-shaving purpose, a MG can store electricity in the night time and deliver it in the day time or peak hours.

Table 3
The parameters of the MG.

	Solar panel (m^2)	Load			H_2 tank		
		Day time (kW)	Night time (kW)	Priority	Initial (moles)	Pressure (psi)	Volume (L)
MG-0	200	40	20	0.6, 0.2, 0.2	0	3000	85

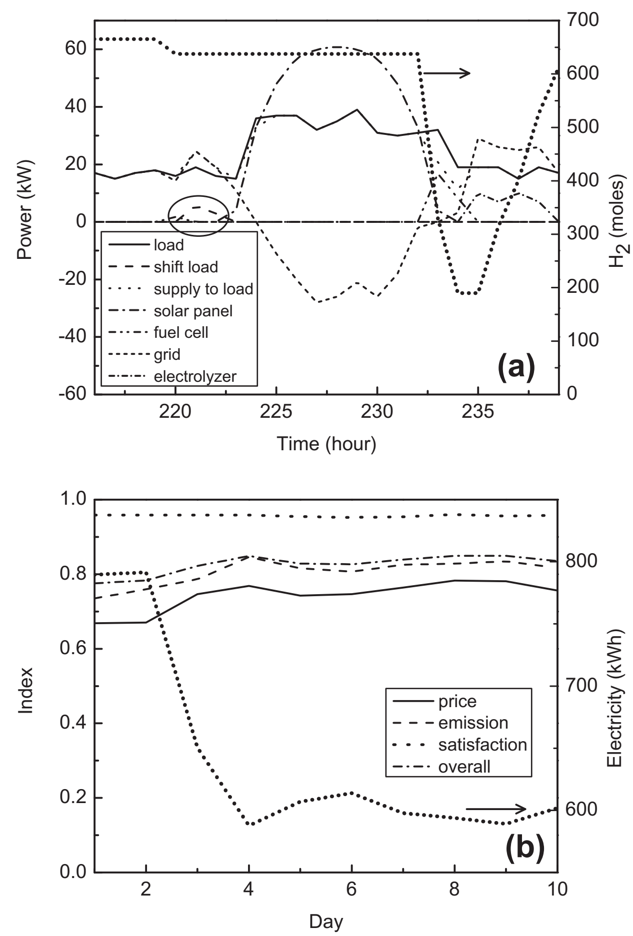

Fig. 9. Power flow (a) and performance index (b) in a MG.

One grid-tied MG is simulated with the parameters shown in Table 3. The power demand and supply in the 10th day are shown in Fig. 9(a). In the night time, the electricity from the grid is supplied to the load and also to the electrolyzer for H_2 production to store energy. Although around 50 mol H_2 is consumed by the FC stack at the 220th hour (4 AM) for the shifted load with medium priority, H_2 quantity is constant until the 235th hour (7 PM). In the day time, power is mainly from the solar panel and the FC stack. The spare electricity goes to the grid due to the limit volume of the H_2 tank. In Fig. 9(b), the total electricity used drops from 800 kW h to 600 kW h in the first 4th day and this 25% drop is due to the efficiency improvement of the MG operation. Due to

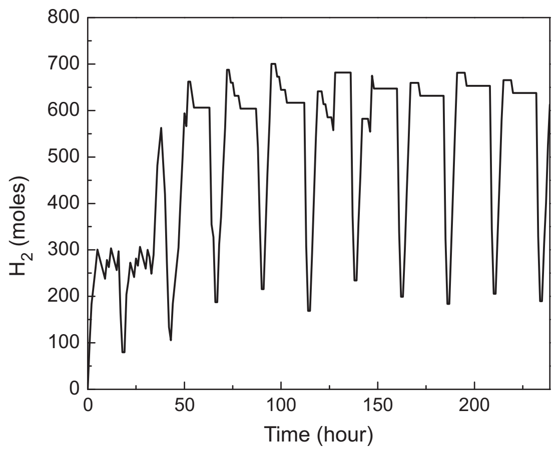

Fig. 10. H_2 quantity in the MG.

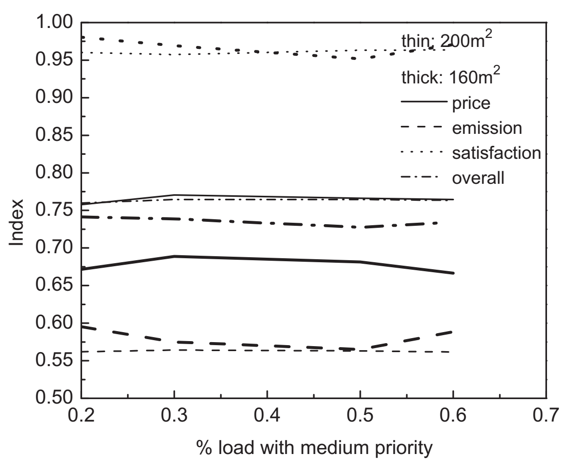

Fig. 11. The performance of the two MGs with different percentage of medium-priority load.

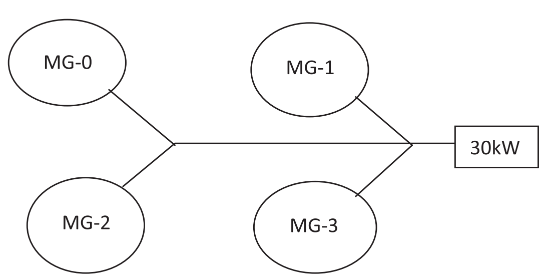

Fig. 12. A model of a smart grid with five MGs.

the electricity transmitted from the grid, emission index, 0.8, is lower than that in a stand-alone MG, but service quality, 0.8, and overall performance, 0.92, are higher.

Fig. 10 shows the available H_2 in the tank. Except the first 2 days, the H_2 quantity fluctuates and shows a maximum value, 650 mol, at 8 AM and a minimum value, 200 mol, at 7 PM. Here, the volume of the H_2 tank is 85 L, which is one third of that in the stand-alone MG discussed before.

Two MGs with different solar panel sizes, 160 m^2 and 200 m^2, are simulated separately under different medium-priority load percentage and their performance indexes are shown in Fig. 11. Except the price index, the other indexes are very close. Therefore, the solar panel size only strongly improves the price index in our simulation environment. In both MGs, the effects of the medium-priority load percentage on the performance are not significant. Further study of the MG structure on the MG performance will be carried out in the future.

3.3. A network of multiple MGs

A network of four MGs is simulated with the structure shown in Fig. 12 and each MG consists of the similar components as shown in Fig. 1 with parameters listed in Table 4. In addition, the load shift in one MG is scheduled through this algorithm: it checks the shared network schedule and chooses the time slots to make load demand evenly distributed, broadcast an new schedule for the rest of MGs to update their information. Therefore, the distribution of the electricity from the grid or other MGs follows the first-come first-served rule. It should be noted that the power from the grid itself is limited at 40 kW.

Fig. 13(a) shows the power transmitted in two ways between the MGs and the grid. Due to the size of the solar panels, MG-0 and MG-1 only obtain electricity from the main dispatch, but MG-2 and MG-3 can supply their spare electricity to the grid and further to MG-0 and MG-1.

Fig. 13(b) shows the H_2 quantity of different MGs. In the night time, 620 mol H_2 is stored in MG-0 at 0 AM and this is produced with the electricity from the main dispatch. In MG-2 and 3, around 900 mol H_2 is used up by their FC stacks between 5 PM and 0 AM. For MG-1, there is no H_2 to run its FC stack and no power from the grid. Thus, all loads in this MG stop working. In the day time, the electricity price is high on the grid and the electricity from the grid is only supplied to the loads with high priority. MG-0's power is from the solar panel and the FC stack and around 400 mol H_2 is gradually consumed between 8 AM and 4 PM. MG-1 obtains most electricity available on the grid but generates any H_2. While, MG-2 and 3 have large solar panels and both of them generate electricity to the loads and electrolyzers. Thus, their H_2 quantities increase to around 900 mol.

The performance indexes of the MGs are shown in Fig. 13(c). MG-0 is a special case and its high service quality index, 0.94, is due to the rule of the power distribution from the grid and this can be observed from its low emission index, 0.5. In MG-1, all indexes are low, less than 0.5, because this MG neither generates electricity nor gets much electricity from the grid. For MG-2 and

Table 4
The parameters of the MGs.

	Solar panel (m^2)	Load			H_2 tank		
		Day time (kW)	Night time (kW)	Priority	Initial (moles)	Pressure (psi)	Volume (L)
MG-0	120	40	20	0.6, 0.2, 0.2	0	3000	150
MG-1	0						
MG-2	200						
MG-3	300						

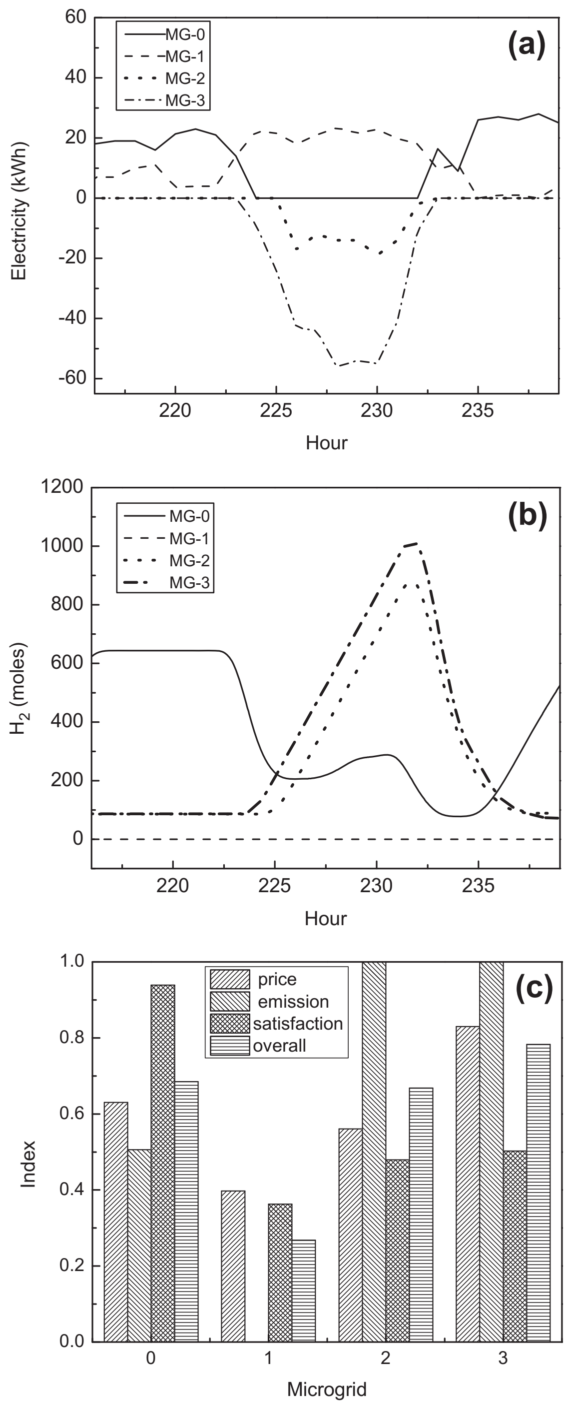

Fig. 13. Energy transmission between the MGs (a), H_2 stored in each MG (b), and the MG performance indexes (c).

3, their emission indexes are the same as 1 since both of them do not need any power from the grid. But, their price indexes, 0.56 and 0.8, respectively, are higher than that in MG-1. Compared with the MG-0's service quality index, the MG-2 and MG-3's are lower. The reason is that both MGs do not obtain electricity from the grid in the night although they supply much power to the grid in the day time. Further, the MG-2's price index is lower than the MG-0's. From the four MGs' indexes, the overall performance index is generally higher if the solar panel size is bigger. However, the overall performance index depends on the weighting factors and it is affected by the weather, the electricity price, the MG structures, the operation, and the rules on the power distribution.

4. Conclusions

A distributed model of a MG with the proposed performance index is presented in this paper and each MG can consist of a solar panel, an electrolyzer, a FC stack, and dynamic loads. With the assumed weighting factors and dynamic electricity price, the operation of a stand-alone MG, a grid-tied MG, and a MG network is simulated with a multi-agent infrastructure. For a stand-alone system, the load prediction lowers down the daily consumed electricity about 5.7%. The quantity of H_2 stored fluctuates dramatically and the capacity H_2 tank is high. In our case, since the electricity generated is not enough to meet the daily demand, there is no load shift. Moreover, both the service quality and overall performance indexes increase with the solar panel size, but the emission index is always equal to 1, zero emission and the price index is also a constant which depends on the cost of the solar panel. In a grid-tied MG, the load prediction has a significant effect on the daily consumed electricity which drops 25% in four days and some loads in the day time are shifted to the night time. Due to the connection to the grid, the capacity for H_2 storage system is lower than that in a stand-alone MG. Solar panel size has negligible effect on the emission and service quality indexes but it does improve the price index. In a network with multiple MGs, the control of the power distribution strongly affects the MG's performance. However, the overall performance index instead of any specific index increases with the MG's power generated from renewable energy resources. Based on the current platform, the distributed and dynamic network with multiple MGs can be simulated and this model can be developed future with the focuses on the load demand and energy production predication and scheduling with the real-time dynamic price. In addition, the pattern behavior of the DEG will be also considered in the power/heat generation management for the transient response of the system.

References

[1] Huang AQ, Crow ML, Heydt GT, Zheng JP, Dale SJ. The future renewable electric energy delivery and management (FREEDM) system: the energy internet. Proc IEEE 2010;99(1):133–48.
[2] <http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/3.pdf>.
[3] Zhang L, Gari N, Xiong X, Hu J, Hmurcik L. Understanding smart power grid systems by a course project, in ASEE 2010 annual conference. Kentucky: Louisville; 2010.
[4] FOA: recovery act – workforce training for the electric power sector (DE-FOA-0000152). U.S.D.o. Energy, Editor. 2009.
[5] FOA: recovery act-smart grid demonstration U.S. Department of. Energy, Editor. 2009.
[6] Grose TK. The cyber grid. ASEE Prism, October 2009. p. 26–31.
[7] Hawkes AD, Leach MA. Modelling high level system design and unit commitment for a microgrid. Appl Energy 2009;86:1253–65.
[8] Wu Z, Gu W, Wang R, Yuan X, Liu W. Economic optimal schedule of CHP microgrid system using chance constrained programming and particle swarm optimization. In: Power and Energy Society General Meeting, 2011 IEEE. 2011.
[9] Pedrasa MAA, Spooner TD, MacGill IF. Coordinated scheduling of residential distributed energy resources to optimize smart home energy services. IEEE Trans Smart Grid 2012;1(2):134–43.
[10] Alsayegh O, Alhajraf S, Albusairi H. Grid-connected renewable energy source systems: challenges and proposed management schemes. Energy Convers Manage 2010;51:1690–3.
[11] Lasseter RH. MicroGrids. In: IEEE Power Engineering Society Winter Meeting. 2002.
[12] Lopes JAP, Moreira CL, Madureira AG. Defining control strategies for MicroGrids islanded operation. IEEE Trans Power Syst 2006;21(2):916–24.
[13] Molderink A, Bakker V, Bosman MGC, Hurink JL, Smit GJM. Management and control of domestic smart grid technology. IEEE Trans Smart Grid 2010;1(2):109–19.
[14] Sechilariu M, Wang B, Locment F. Building-integrated microgrid: advanced local energy management for forthcoming smart power grid communication. Energy Build 2013;59:236–43.
[15] You S. Developing virtual power plant for optimized distributed energy resources operation and integration. Lyngby: Department of Electrical Engineering, Technical University of Denmark; 2010.
[16] Hledik R. How green is the smart grid? Electric J 2009;22(3):29–41.
[17] Hommelberg MPF, Warmer CJ, Kamphuis IG, Kok JK, Schaeffer GJ. Distribute control concepts using multi-agent technology and automatic markets: an

indispensable feature of smart power grid, In: Power Engineering Society General Meeting, 2007. 2009, IEEE. p. 1–7.
[18] Nunna KDS. Multiagent-based distributed-energy-resource management for intelligent microgrids. IEEE Trans Ind Electron 2013;60(4):1678–87.
[19] Chen Y, Wu Y, Song C, Chen Y. Design and implementation of energy management system with fuzzy control for DC microgrid systems. IEEE Trans Power Electron 2013;28(4):1563–70.
[20] Lasseter RH, Piagi P. Microgrid: a conceptual solution. In: PESC. Germany: Aachen; 2005. p. 20–5.
[21] Zhong Zhi-dan HH-b, Xin-jian Zhu, Guang-yi Cao, Yuan Ren. Adaptive maximum power point tracking control of fuel cell power plants. J Power Sour 2008;176:259–69.
[22] Kanchev H, Lu Di, Colas F, Lazarov V, Francois B. Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications. IEEE Trans Ind Electron 2011:4583–92.
[23] Wong VWSJ, Schober R, Leon-Garcia A. Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid. IEEE Trans Smart Grid 2010;1(3):320–31.
[24] <http://www.iso-ne.com/nwsiss/grid_mkts/how_mkts_wrk/whlsle_elec_trad/index-p2.html>.
[25] Gu W, Wu Z, Bo R, Liu W, Zhou G, Chen W, et al. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Int J Electric Power Energy Syst 2014;54:26–37.
[26] Llaria A, Cureaa O, Jiménezb J, Camblonga H. Survey on microgrids: unplanned islanding and related inverter control techniques. Renew Energy 2011;36(8):2052–61.
[27] <http://www.srrb.noaa.gov/highlights/sunrise/azel.html>.
[28] James Larminie AD. Fuel cell systems explained. 2nd ed. Wiley; 2003.