Ain Shams Engineering Journal (2016) 7, 855–866

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
www.sciencedirect.com

ELECTRICAL ENGINEERING

Operation optimization of distributed generation using artificial intelligent techniques

Mahmoud H. Elkazaz *, Ayman A. Hoballah, Ahmed M. Azmy

Electrical Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

Received 15 August 2015; revised 16 January 2016; accepted 29 January 2016
Available online 18 February 2016

KEYWORDS
Distribution automation;
Energy management;
Fuel cells;
GA optimization;
Home automation;
Smart grid

Abstract Future smart grids will require an observable, controllable and flexible network architecture for reliable and efficient energy delivery. The use of artificial intelligence and advanced communication technologies is essential in building a fully automated system. This paper introduces a new technique for online optimal operation of distributed generation (DG) resources, i.e. a hybrid fuel cell (FC) and photovoltaic (PV) system for residential applications. The proposed technique aims to minimize the total daily operating cost of a group of residential homes by managing the operation of embedded DG units remotely from a control centre. The target is formed as an objective function that is solved using genetic algorithm (GA) optimization technique. The optimal settings of the DG units obtained from the optimization process are sent to each DG unit through a fully automated system. The results show that the proposed technique succeeded in defining the optimal operating points of the DGs that affect directly the total operating cost of the entire system.

1. Introduction

The smart grid and its promising features for a better intelligent and automated energy infrastructure are under study in several researches and projects [1]. Home automation (HA) and home energy management (HEM) systems are one of the main branches of the future smart grid [2]. Regarding home automation, optimizing the operation of DG units within the residential homes is a new face of home automation. Nowadays, achieving coordination between the operation of various DG units within the residential homes in order to satisfy the customer's needs and minimize operating cost is the first desire of all homeowners. Due to the environment pollution and lacking of energy resources, distributed renewable energy resources such as PV systems and FC units are attracting more attention as alternative energy resources. PV/FC hybrid generation system is one of the most effective methods to make use of renewable energy sources [3]. The power generated by a PV system is highly dependent on climate conditions. Also, it is difficult to store the power generated by PV system for future use. To overcome this problem, integration of a PV system with other alternatives DG such as FC systems in order to maintain a reliable energy supply is an encouraging solution [4].

* Corresponding author. Tel.: +20 1283640306, +20 1119057706.
E-mail addresses: mahmoud.elkazaz@f-eng.tanta.edu.eg (M.H. Elkazaz), ayman.hoballah@f-eng.tanta.edu.eg (A.A. Hoballah), azmy.ahmed@hotmail.com (A.M. Azmy).
Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2016.01.008
2090-4479

The literatures presented a lot of researches that rely on minimizing the total daily energy costs within the smart homes based on advanced techniques. In [5], the author presented a novel technique for determining the optimal output of FC systems supplying a residential loads in order to minimize the total energy consumption. However, the authors built their strategy based on a fixed assumed forecasted household demand without considering the frequently changes in daily load curve over the day. Thus, the uncertainty effect of the forecasted demand has not been investigated.

The author in [6] presented an approach for reducing the daily total operating costs of a proton exchange membrane fuel cell (PEMFC) supplying a residential load under electrical demand uncertainty. In order to minimize the total daily operating costs of the FC, a cost model is developed. This model takes into account the various operational and technical constraints associated with the unit. The author used particle swarm optimization approach to define the optimal outputs of the FC. However, this research did not take into account the methods of data collection and role of communication technology to facilitate the implementation of this algorithm.

In [7], a two-phase approach to manage the daily operation of PEMFCs for residential applications is presented. This approach depends on two stages. The first performs offline optimization processes for different load demands and electricity and natural gas tariffs using a GA optimization technique. In the second, the obtained results are used for offline training and testing of ANN, which can be used on-site to define the settings of the FC in the online mode.

In [8], an operational algorithm that maximizes the advantages of all residential cogeneration systems is proposed, where the technique is evaluated from the viewpoint of energy conservation and economic effectiveness based on the energy demand characteristics.

This paper introduces a new approach to manage the operation of DG units within smart homes in order to minimize the total daily operating cost and also to satisfy all home's needs. The proposed approach depends on a strong communication infrastructure that enables the two way flow of information between the consumers and the control centre and also remote control of DG units and appliances within the smart homes [9].

The optimization problem is formulated as an objective function that is solved using GA optimization technique. The influence of changing purchased/sold electricity tariffs on the optimal settings of the DG units is investigated in addition to highlighting the effect of using time-based tariff strategy. Therefore, a simple comparison between applying a fixed purchased tariff and a time-based purchased tariff is introduced.

2. The proposed system description

Fig. 1 represents the general structure of the proposed system. The proposed system consists of four smart homes with each home containing one PEMFC and one PV system with a certain capacity. Each home has its own electric and thermal loads demand.

The FC and the PV systems are responsible for feeding the electric loads of the home. The output power of the DGs may be less than the home's electric load, which is an economic decision, where the remaining power can be purchased from

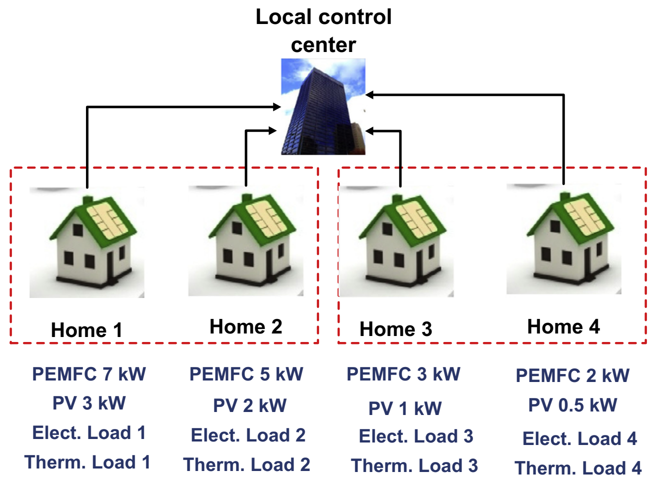

Figure 1 The general structure of the proposed system.

the grid. In certain periods, the output power of the DGs is more than the home's electric load, where the excess power can be sold to the grid to achieve an economic profit. Each home has one two-way smart meter that enables measuring the electric energy purchased from or sold to the grid. The thermal loads include water and space heating. The FCs produce thermal energy that is used to feed the thermal loads. If the FC couldn't satisfy the thermal loads of the home, the remaining thermal power can be obtained by burning natural gas from the utility. Regarding the possibility of interchanging thermal power, the proposed system assumes that the homes are separated into two groups. This assumption considers that each group has homes that are close to each other and hence, the interchange of thermal power is possible. On the other hand, the two groups are assumed to be far from each other, which prevents the interchange of thermal power between them.

Fig. 2 illustrates the electrical and thermal power flow through each smart home. In each home, two separate natural

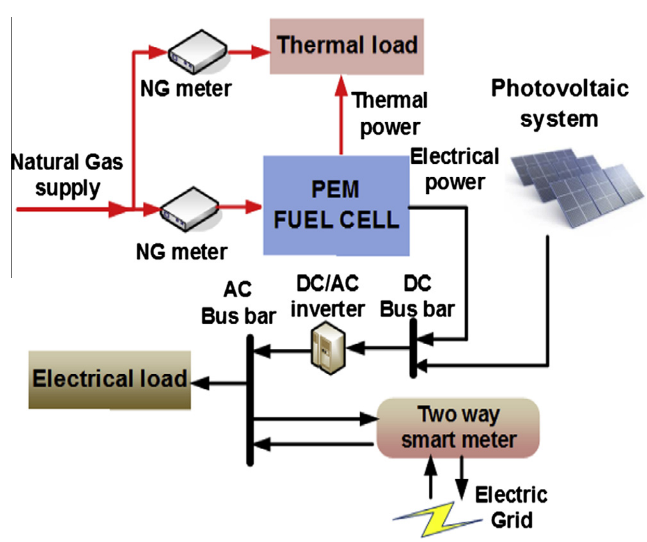

Figure 2 The electrical and thermal power flow through the smart home.

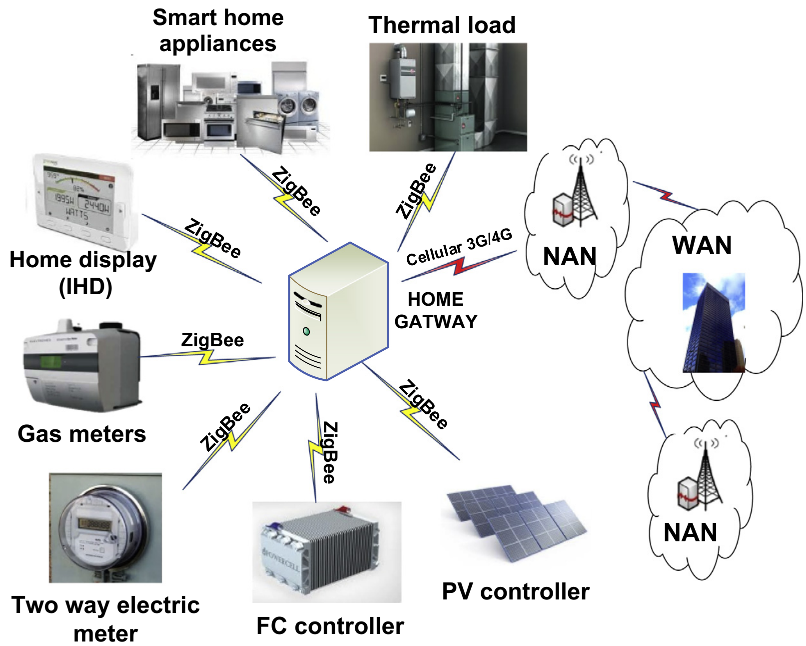

Figure 3 The general structure of the communication system.

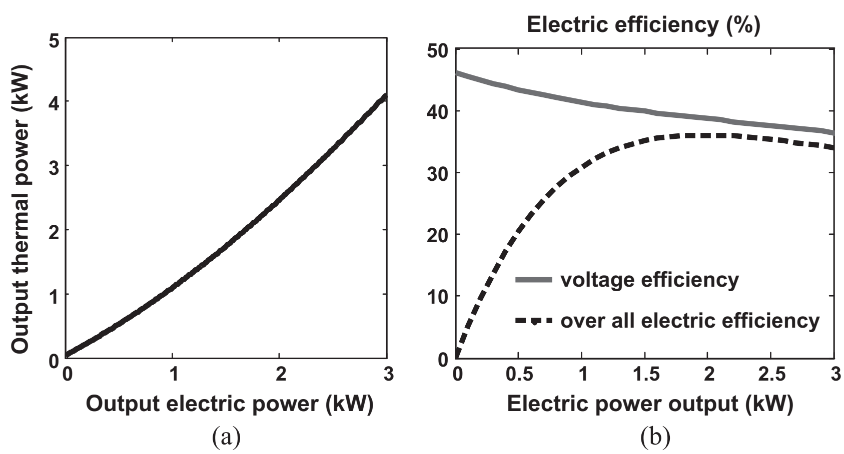

Figure 4 Thermal power and efficiency curves of a 3 kW fuel cell.

gas smart meters are used. This is because most natural gas companies offer different tariffs for natural gas usage, e.g. residential, industrial or electricity generation. It is assumed that each home has a home energy gateway (HEG). The HEG controller includes a central hub that links smart meters, smart home appliances, and smart devices such as FC and PV controllers in the home area network (HAN) [10]. The controller also collects and reports power usage data and enables two way flow of information between the consumers and the utility. The HEG allows every point of the smart home to be connected and controlled from a central point. HEG can use many communication technologies for wireless communication within the home. The most recommended one is ZigBee technology [11,12]. The HEG links to a wide area network (WAN) for remote control and monitoring through Internet connection. Fig. 3 shows the general structure of the communication network of the proposed system.

3. FC/PV configuration

The two types of DG units used in this paper are PEMFC and PV system. These two types will be discussed as follows.

3.1. Proton exchange membrane fuel cell

PEMFC is low-temperature type of FCs which can be used safely in residential homes. It shows a great potential in hybrid energy system applications [13]. PEMFC not only produces electric energy, but also exhaust heat. The exhaust heat is circulated via water, which can be used as hot water or a heating medium such as floor heating or bath ventilations. The relation between the thermal and the electric output power of the PEMFC is shown in Fig. 4(a) [14]. The electric efficiency of the PEMFC can reach 40%, while the overall efficiency can reach 80% if the output thermal power is used in water and space heating to form a combined heat and power system (CHP). In Fig. 4(b) the electric efficiency of the PEMFC is illustrated. The concern of this paper is on the economic model rather than the dynamic model. The rating of the FCs used in this model was based on the maximum electrical load demand of each home over one year. The ratings of the FCs used in this paper are 2, 3, 5 and 7 kW for the four homes.

3.2. Photovoltaic system

The PV system is chosen in this paper to be the second DG unit that contributes in feeding the electric load demand during sunshine hours. About 40% of the home's electric loads are consumed during the sunshine hours [15]. The rest is consumed during the night. The rating of the PV is selected in order to cover the demand only during the sunshine hours, i.e. 40% of the total electric load during the day. Any shortage in electric energy can be fed from the FC or from the electric grid according to the economic benefits. Any excess of electric power can be sold to the electric grid. The ratings of the PV used are 0.5, 1, 2 and 3 kW. No storage devices are used in this paper

4. Operation optimization of the hybrid PEMFC-PV system

The target of this paper is to determine the optimal operating scenario of the FC units in combination with the PV system. The optimal operation can reduce the total operating cost of the DG units and also achieve an economic benefit for both the customer and the utility. In this paper, the optimal settings of the four homes are obtained simultaneously, rather than defining the optimal operation of each home individually. In another words, the optimal operation is set in order to reduce the total daily operating cost of the four homes together as one group. The following steps show the proposed procedure in order to determine the optimal settings:

- HEG communicates with all home appliances in order to receive and store the total electric and thermal loads during the day.
- HEG sends this information periodically to the control centre in order to form a complete database of the consumption of each home, which enables the control centre after that to forecast the electric and thermal loads of each home.
- Before a new day begins, the control centre forecasts the daily electric and thermal load curves for each home.
- The control centre receives the appropriate tariffs of exchanging electricity between the grid and consumers and the appropriate price of natural gas to supply the FCs and residential thermal load from service vendors.
- The control centre receives the status of each DG unit in the system, i.e., in service or out of service.
- Based on a predefined database, the control centre retrieves the status of each DG unit within the four smart homes (i.e. in-service units) and also all technical information about these units.
- Based on the calculation of the daily radiation and ambient temperature in this area, the control centre can estimate the output electrical power of each PV system within the four homes.
- The PV systems operate according to a maximum power point tracking (MPPT) strategy in order to obtain the maximum possible power from the PV.
- Based on a proposed objective function, the control centre performs the optimization process using GA optimization technique to get the best settings of the FC units in order to satisfy the customer needs and minimize the total daily operating cost of the system.
- After getting the best settings of the FC units, the control centre sends these settings to each FC controller within the smart home through the HEG.
- The control centre repeats the above tasks periodically to avoid any uncertainty and achieve high reliability.
- The control centre facilitates the two-way information flow between customers and service vendors and displays energy usage data to end users through their HEG and their home smart meters.

5. Objective function formulation

The aim of this section was to formulate the objective function needed to be optimized. Before introducing the proposed objective function, many constraints associated with the balance of electric and thermal power within the system should be presented.

The balance equation of the total electric power within the proposed system can be written as follows:

$$\sum_{i=1}^{n}\left(P_{\mathrm{pv,i}}+P_{\mathrm{fc(elect.),i}}\right)=\sum_{i=1}^{n}\left(P_{\mathrm{load(elect.),i}}+P_{\mathrm{grid,i}}\right) \tag{1}$$

where

n: Number of homes used in the proposed system.

$P_{\mathrm{pv,i}}$: Electric output power produced by the PV system in home "i" (kW).

$P_{\mathrm{fc(elect.),i}}$: Electric power produced by the FC in home "i" (kW).

$P_{\mathrm{grid,i}}$: Electric power purchased from (negative) or sold to (positive) the grid by home "i" (kW).

$P_{\mathrm{load(elect.),i}}$: Electric load demand of home "i" (kW).

On the other hand, the balance equation of the total thermal power within the proposed system can be written as follows:

$$\sum_{i=1}^{n}\left(P_{\mathrm{fc(therm.),i}}+P_{\mathrm{ng,i}}\right)=\sum_{i=1}^{n}P_{\mathrm{load(therm.),i}}+P_{\mathrm{excess}} \tag{2}$$

where

$P_{\mathrm{fc(therm.),i}}$: Thermal output power produced by the FC in home "i" (kW).

$P_{\mathrm{ng,i}}$: Thermal power produced by burning natural gas in home "i" (kW), used to feed the remaining part of thermal loads that is not covered by the FC.

$P_{\mathrm{load(therm.),i}}$: Thermal load demand of home "i"(kW).

P_{excess}: The excess thermal power that can be stored in a form of hot water or can be lost in a form of steam.

The daily operating cost "$C_{\mathrm{(TOTAL)}}$", which has to be minimized, can be developed in terms of payments, for natural gas needed to feed the FC and burners and purchased electricity from the grid, and incomes, from the sold electric power produced by the PV or FC systems, as follows:

$$C_{\mathrm{TOTAL}} = \sum_{i=1}^{n} \left(C_{\mathrm{NGFC,i}} + C_{\mathrm{NGRL,i}} + C_{\mathrm{purc,i}} - C_{\mathrm{sold,i}} + C_{\mathrm{o\&mfc,i}} + C_{\mathrm{o\&mpv,i}} + \mathrm{SC_i} \right) \quad (3)$$

where

C_{TOTAL}: The total daily operating cost of the whole proposed system (\$/day).
$C_{\mathrm{NGFC,i}}$ and $C_{\mathrm{NGRL,i}}$: Daily cost of natural gas consumed by the FC and burner, respectively, in home "i" (\$/day).
$C_{\mathrm{purc,i}}$: Daily cost of purchased electricity by home "i" (\$/day).
$C_{\mathrm{sold,i}}$: Daily income of the sold electricity by the home "i" (\$/day).
$C_{\mathrm{o\&mfc,i}}$: Daily operating and maintenance cost of the FC in home "i" (\$/day).
$C_{\mathrm{o\&mpv,i}}$: Daily maintenance cost of the PV system at home "i" (\$/day).
$\mathrm{SC_i}$: Daily start-up cost of the FC in home "i" (\$/day).

The above terms in the objective function can be described as follows:

$$C_{\mathrm{NGFC,i}} = T_{\mathrm{ng-fc}} \times \Delta T \sum_{J=1}^{96} \frac{P_{\mathrm{J,i}} + P_{\mathrm{aux,i}}}{\eta_{\mathrm{J,i}}} \quad (4)$$

$$C_{\mathrm{NGRL,i}} = T_{\mathrm{ng-rl}} \times \Delta T \sum_{J=1}^{96} \max(L_{\mathrm{th,J,i}} - p_{\mathrm{th,J,i}}, 0) \quad (5)$$

$$C_{\mathrm{sold,i}} = T_{\mathrm{el-s}} \times \Delta T \sum_{J=1}^{96} \max(P_{\mathrm{el,J,i}} - L_{\mathrm{el,J,i}}, 0) \quad (6)$$

$$C_{\mathrm{purc,i}} = T_{\mathrm{el-p}} \times \Delta T \sum_{J=1}^{96} \max(L_{\mathrm{el,J,i}} - P_{\mathrm{el,J,i}}, 0) \quad (7)$$

$$C_{\mathrm{o\&mfc,i}} = \mathrm{FC_{o\&m}} \times \Delta T \sum_{J=1}^{96} P_{\mathrm{J,i}} \quad (8)$$

$$C_{\mathrm{o\&mpv,i}} = \frac{PV_{\mathrm{o\&m}}}{365} \times \mathrm{I.C_{PV,i}} \quad (9)$$

$$\mathrm{SC_i} = € + \varphi \left(1 - e^{\frac{-T_{\mathrm{off}}}{\tau}} \right) \quad (10)$$

where

$T_{\mathrm{ng-fc}}$: Natural gas tariff for supplying the FCs (\$/kW h).
ΔT: Time duration between two sequential settings of the FC (15 min).
$P_{\mathrm{J,i}}$: Electrical power produced by the FC in home "i" at interval "J" (kW).
$P_{\mathrm{aux,i}}$: Electric power (kW) required for auxiliary devices of the FC, e.g. pumps, fans.
$\eta_{\mathrm{J,i}}$: Electrical efficiency of FC in home "i" at interval "J".
$T_{\mathrm{ng-rl}}$: Natural gas tariff for supplying the thermal loads (\$/kW h).
$L_{\mathrm{th,J,i}}$: Thermal loads of home "i" at interval "J" (kW).
$P_{\mathrm{th,J,i}}$: Thermal power produced by the FC in home "i" at interval "J" (kW).
$T_{\mathrm{el-s}}$: Tariffs of the purchased electricity (\$/kW h).
$T_{\mathrm{el-p}}$: Tariffs of the sold electricity (\$/kW h).
$P_{\mathrm{el,J,i}}$: Electrical power produced by the DG units in home "i" at interval "J" (kW).
$L_{\mathrm{el,J,i}}$: Electrical load demand of home "i" at interval "J" (kW).
$\mathrm{FC_{o\&m}}$: Daily operation and maintenance constant of PEMFC; 0.003\$/kW h.
$\mathrm{PV_{o\&m}}$: Annual maintenance constant of PV system, 0.12%.
$\mathrm{I.C_{PV,i}}$: Initial capital cost of PV system installed at home "i".
$P_{\mathrm{J,i}}$: Electrical power produced by the FC in home "i" at interval "J" (kW).
€: Hot start-up cost.
$€ + \varphi$: Cold start-up cost.
T_{off}: The time duration, where the unit is off (h).
τ: The cooling time constant (h) of the DG unit.

Each DG unit has a number of constraints that restrict its operation. Mathematically, minimization of the objective function (3) is limited by the following operational and technical constraints:

Upper and lower capacity constraints:

$$P_{\mathrm{min}} \leqslant P_{\mathrm{j}} \leqslant P_{\mathrm{max}} \quad (11)$$

Constraints of upper ramp rate:

$$P_{\mathrm{(j,t)}} - P_{\mathrm{(j,t-1)}} \leqslant \Delta P_{\mathrm{u}} \quad (12)$$

Constraints of lower ramp rate:

$$P_{\mathrm{(j,t-1)}} - P_{\mathrm{(j,t)}} \leqslant \Delta P_{\mathrm{D}} \quad (13)$$

where

P_{min}, P_{max}: The minimum and maximum limits of the generated power from FC.
ΔP_{u} and ΔP_{D}: The upper and lower limit of the ramp rates.
$P_{\mathrm{(j,t)}}$ and $P_{\mathrm{(j,t-1)}}$: The power generated at intervals "t" and "$t-1$".

6. GA-based optimization technique

In order to solve the proposed optimization problem and obtain optimal settings of the DG units, a strong evolutionary algorithm is needed such as GA. It represents an effective evolutionary search algorithm that can search a population of points in parallel. The GA optimization technique is selected due to its ability to deal with models that comprise many constraints. Consequently, it shows a great success in getting the best solution between different conflicting objectives [16].

The main implementation steps of the GA-based optimization are summarized in the flowchart as shown in Fig. 5.

In this paper, a population of 384 chromosomes is randomly formulated to represent the electrical output power from the four FCs (i.e. 96 chromosomes for each FC) through one day. It is assumed that the setting of the FCs is updated for each 15 min. Each chromosome in the randomly created population is tested for violating the constraints. A suitable additional penalty cost is assigned to the chromosome if the solution is infeasible.

The performance of each chromosome is evaluated by calculating the total cost and then ranked depending on their corresponding costs. After that, a suitable fitness value is assigned to each chromosome depending on the situation of this chromosome within the population. The new generation is produced by means of two main processes: crossover and mutation. The above procedure is repeated for many iterations

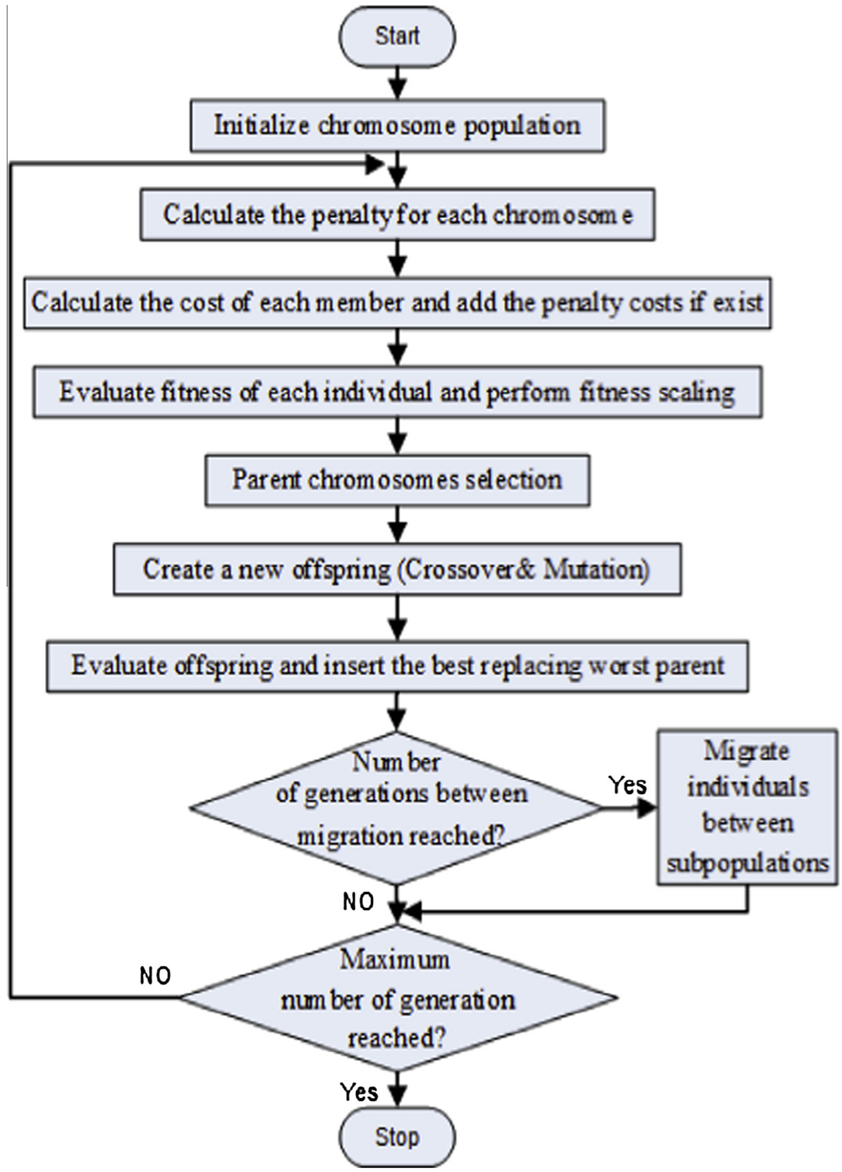

Figure 5 The main implementation steps of the GA-based optimization.

until the best solution is obtained. In this paper, the obtained optimal settings of DGs, that represent the best solutions, result from the optimization process after a number of iterations. These optimal settings ensure a complete satisfaction of customer's needs at minimum operating cost. In order to improve the quality of the obtained results, multi-population structure is used. The use of subpopulation scheme and multi-population structure, which improves the quality of the obtained results, is also known as island scheme. The population is divided into a number of subpopulations and each forms an independent searching space. Thus, each subpopulation is evolved individually over generations by a traditional GA. According to this strategy, a number of individuals migrate periodically between subpopulation to exchange information between them. The amount of migration of individuals and the pattern of that migration determine how much genetic diversity can occur.

All the parameters of the GA used in this work are summarized in Table 1.

Table 1 Parameters of the GA-based optimization process.

Number of subpopulations	30
Number of individuals per subpopulation	100
Total population size	3000
Generation gap Insertion rate	0.9
Insertion rate	0.8
Probability of crossover	0.95
Probability of mutation	0.11
Maximum number of generations	1500
Number of generations between migration	50

7. Simulation results and discussion

In this section, the optimal settings of the DG units within the four residential homes will be discussed. The optimization process is carried out using 8 different electric and thermal load curves for the different four homes, i.e. each home has one electric and one thermal load curve. The output of the above mentioned PV system is considered in this section and it is assumed to cover only 40% of the electric loads of the home.

In this study, different values of tariffs are used. The used tariffs of purchasing or selling electricity and the tariffs of natural gas to supply the homes are assumed based on real values for overall many countries [17]

The following tariffs in \$/kW h are used as base values.

$$T_{\text{el-s}} = 0.06 \text{ (\$/kW h)}, \quad T_{\text{el-}p} = 0.14 \text{ (\$/kW h)},$$
$$\text{O\&M} = 0.003 \text{ (\$/kW h)}$$

$$T_{\text{ng-fc}} = 0.07 \text{ (\$/kW h)}, \quad T_{\text{ng-rl}} = 0.05 \text{ (\$/kW h)}$$

Fig. 6 shows the electrical and the thermal output power of the 7 kW FC and also the electric output power of the PV array located in home 1. It is obvious that the FC covers most of the thermal load. Any excess thermal power is used to feed the thermal loads of the neighbour's house. The electric output of the PV system is used first to feed the electric loads of the home because the PV system works with MPPT mechanisms in order to get the maximum power of available solar energy. If the electric output of the PV system and the FC is more than the electric load of the home, the excess power can be sold to the grid as shown in the figure. The shortage in electric power can be purchased from the grid in order to satisfy the load needs.

Fig. 7 shows the electric and thermal output power of the 5 kW FC and also the electric output power of the PV array (2 kW) located at home 2. It is obvious that the FC thermal output covers only a part of thermal load, while the other part is fed from the excess thermal power imported from the neighbour's home or through burning natural gas from utility. Any excess electric energy is sold to the grid. Any shortage can be compensated by purchasing electric energy from the grid.

Fig. 8 shows the electric and the thermal output power of the 3 kW FC and also the electric output power of the PV array (1 kW) located at home 3. It is obvious from the figure that the optimal settings of FC are to cover the thermal loads. In order to cover all home's thermal loads, it produced a great amount of electric energy which covers the home's electric load and the excess power is sold to the grid. The excess power of the PV array is sold to the grid.

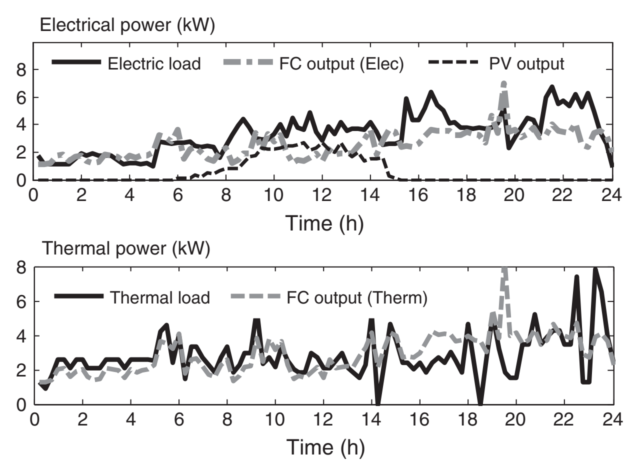

Figure 6 Electric and thermal output of FC (7 kW) and the electric output of PV (3 kW).

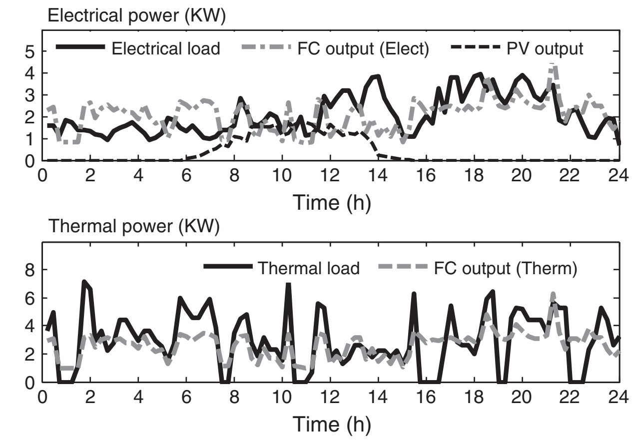

Figure 7 Electric and thermal output of FC (5 kW) and the electric output of PV (2 kW).

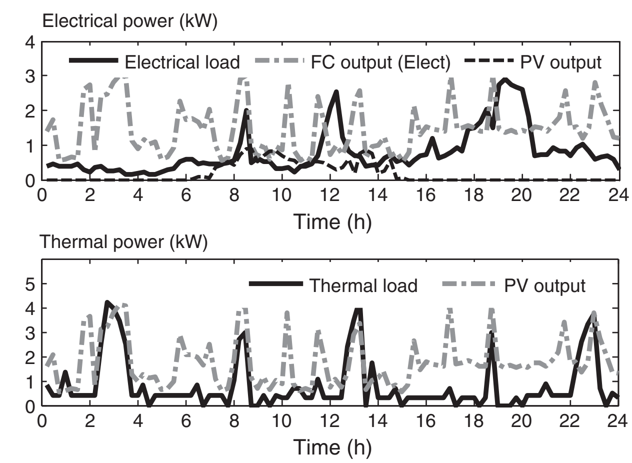

Figure 8 Electric and thermal output of FC (3 kW) and the electric output of PV (1 kW).

Fig. 9 shows the electric and the thermal output power of the 2 kW FC and also the electric output power of the PV array (0.5 kW) located in home 4. It is obvious from the figure that the FC covers all electric loads except the interval between 18.5 pm to 19.5 pm where the economic benefits advice to purchase the remaining power from the grid during this period. The excess thermal power is used to feed the neighbour's home.

Fig. 10 shows the total electric and thermal output of all FCs and all PV in the proposed system. It is obvious from the figure that the FC covers all thermal loads for all homes. The excess thermal power can be stored in a form of hot water to be used later or it will be lost in the form of steam.

The total FCs capacity is 17 kW (electric) which means that it can cover all the electric loads, but from an economic point of view and based on the above mentioned tariffs; the settings of the FCs shown in the above figures are the optimal settings which minimize the total daily operating cost of the proposed system.

After performing cooperation optimization process and obtaining the optimal settings of each DG, the daily operating cost of each home and the total daily operating cost of the

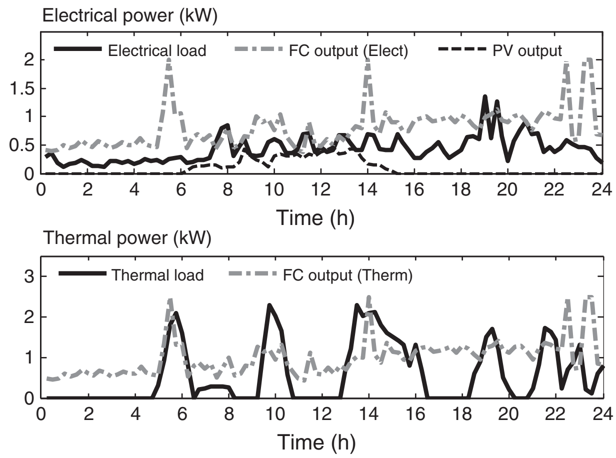

Figure 9 Electric and thermal output of FC (2 kW) and the electric output of PV (0.5 kW).

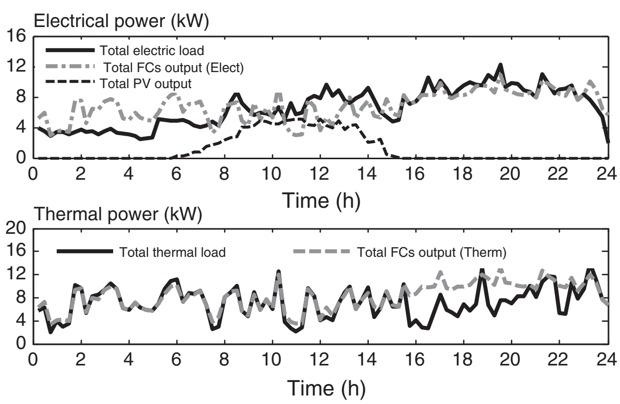

Figure 10 Total electric and thermal output of all FCs and all PV in the proposed system.

whole system must be calculated in order to compare between using this methodology of optimization and the old methods. Table 2 shows the daily operating cost of each home and also the total daily operating cost of the whole system after performing cooperation optimization process.

In order to show the role of the proposed methodology in minimizing the total daily operating cost of the entire system through cooperation optimization of DGs operation, a comparison between the daily operating cost of each home before and after cooperation optimization process is introduced.

Table 2 Daily operating cost of each home and of the whole system after performing cooperation optimization process.

	Home 1	Home 2	Home 3	Home 4
C_{purc} ($)	2.11	0.90	0.36	0.07
C_{sold} ($)	0.57	0.89	1.21	0.61
C_{NGFC} ($)	7.95	6.49	4.26	2.37
C_{NGRL} ($)	0.72	1.42	0.27	0.23
$C_{o\&m}$ ($)	0.18	0.15	0.10	0.05
C_{HOME} ($)	10.39	8.01	3.78	2.11
C_{TOTAL} ($)	24.29			

Table 3 A comparison between the daily operating cost of each home before and after cooperation optimization process and the net saving of each home.

	Home 1	Home 2	Home 3	Home 4
C_{HOME} ($) before cooperation	11.45	8.62	4.38	2.7
C_{HOME} ($) after cooperation	10.39	8.01	3.78	2.11
Net saving ($)	1.06	0.63	0.6	0.59
Saving percentage (%)	9.25	7.29	13.69	21.85

Before cooperation optimization, it is assumed that each home is fed through its own DG units only in cooperation with the grid without any coordination between these DGs and the other DGs at the neighbourhood's homes. The NG is used to feed the remaining part of residential thermal loads (water and space heating) where no thermal power is shared between homes. No electric or thermal power is shared between neighbour's homes. Table 3 shows this comparison and the net saving of each home.

8. Effect of changing tariffs on the optimal settings of FCs

Changing any tariff of the previously mentioned tariffs can greatly affect the optimal setting of the DG units. This section investigates the effect of changing each of purchased and selling electricity tariffs on the optimal setting of the DG units and also on the total daily operating cost of each home.

8.1. Changing of purchased electricity tariff

In this section, three different tariffs of purchased electricity from the grid are used. These tariffs are $T_1 = 0.05$ \$/kW h, $T_2 = 0.09$ \$/kW h and $T_3 = 0.13$ \$/kW h.

It is assume that all other tariffs are constant and equal:

$$T_{el\text{–}s} = 0.09 \text{ \$/kW h}, \quad T_{ng\text{–}fc} = 0.04 \text{ \$/kW h}$$

$$T_{ng\text{–}rl} = 0.07 \text{ \$/kW h}, \quad O\&M = 0.003 \text{ \$/kW h}$$

It is assumed that all loads are constant and the output power of all PV systems is zero in order to focus only on the effect of changing tariffs on the optimal settings of the FCs. Fig. 11 shows the variation of the optimal settings of the FCs with three different tariffs of purchased electricity for a certain load curve. It is obvious from this figure that the optimal settings of the FC are greatly affected by varying of the purchased electricity tariff. As the purchased electricity tariff increases, the FC output increases in order to cover all electric load and avoid purchasing any electric energy from the grid.

In case of tariff $T_1 = 0.05$ \$/kW h, the output of FCs is small since the cost of purchasing electricity from the grid is less than producing electric power from FC. So from an economic point of view, it is better for the home to purchase electricity from the grid than producing a large amount of electricity from the FC.

In case of $T_2 = 0.09$ \$/kW h, in which the purchasing electricity tariff is equal to the selling of electricity, it is obvious that as the purchasing electricity tariff increases, the output

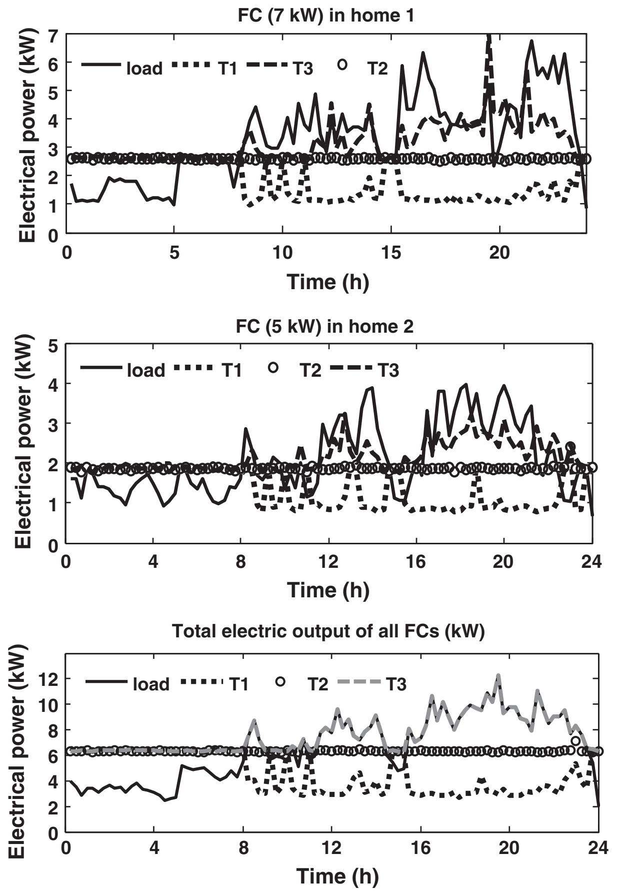

Figure 11 Effect of varying the purchased electricity tariff on the optimal settings of the FCs for a certain load curve.

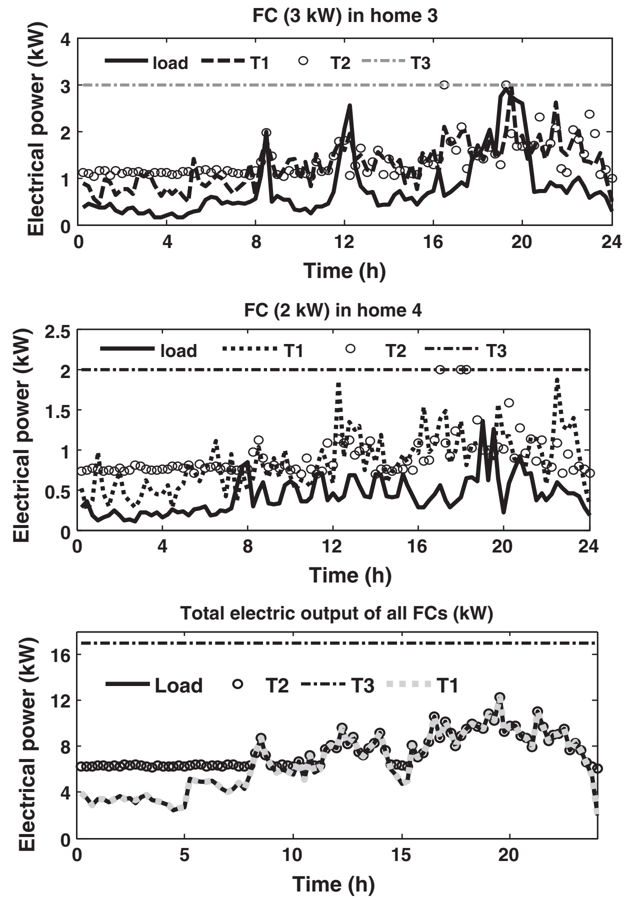

Figure 12 Effect of varying the sold electricity tariff on the optimal settings of the FCs for a certain load curve.

Table 4 Variation of total daily operating cost of each home and of the whole system with the three different purchased electricity tariffs.

Daily operating cost ($)			
Tariff ($/kW h)	T_1 0.05	T_2 0.09	T_3 0.13
Home 1	7.63	8.14	8.87
Home 2	4.71	5.18	5.52
Home 3	2.42	2.47	2.54
Home 4	1.37	1.32	1.39
Total	16.13	17.12	18.31

power of the FC increases in order to reduce the purchased electricity from the grid and reduces the total operating cost.

In case of $T_3 = 0.13$ \$/kW h, the purchased electricity tariff is high. All FCs work effectively in order to cover all electric loads. In this case, the cost of producing electricity from the FCs is much less than purchasing electricity from the grid.

As the purchasing electricity tariff increases, the optimal settings of the FCs increase also to cover most of the electric load and to maintain the total daily operating cost almost at minimum available values. Table 4 shows the variation in the daily operating cost of each home and the total daily operating cost of the whole proposed system with the three different purchased electricity tariffs.

8.2. Changing of sold electricity tariff

The cost analysis is repeated using three different tariffs of selling electricity to the grid. These tariffs are $T_1 = 0.02$ \$/kW h, $T_2 = 0.09$ \$/kW h and $T_3 = 0.13$ \$/kW h

It is assumed that all other tariffs are constant and equal:

$$T_{el-p} = 0.16\ \$/\text{kW h},\quad T_{ng-fc} = 0.04\ \$/\text{kW h}$$

$$T_{ng-rl} = 0.07\ \$/\text{kW h},\quad \text{O\&M} = 0.003\ \$/\text{kW h}$$

It is assumed that all loads are constant and the output power of all PV systems is zero in order to focus only on the effect of changing tariffs on the optimal settings of the FCs. Fig. 12 shows the variation of the optimal settings of the FCs with the three different tariffs of the sold electricity.

Fig. 12 shows that the optimal setting of the FC is highly affected by changing the sold electricity tariff.

As the sold electricity tariff increases, the FCs output increases in order to maximize the income of selling electricity to the grid. In case of tariff $T_1 = 0.02$ \$/kW h, each FC tends to cover its load and also sell the excess power to the next home in order to satisfy the proposed system needs and avoid purchasing electricity from the grid. No electricity is being sold

Table 5 Variance of the total daily operating cost of each home and of the whole system with the three different tariffs of sold electricity.

Daily operating cost ($)			
Tariff ($/kW h)	T_1 0.02	T_2 0.09	T_3 0.13
Home 1	10.24	9.33	6.72
Home 2	6.51	5.80	3.83
Home 3	3.62	2.59	0.97
Home 4	2.19	1.37	0.40
Total	22.56	19.09	11.92

to the grid because the cost of producing more electric energy from the FCs will exceed the income of the sold energy to the grid.

In case of $T_2 = 0.09$ $/kW h, as the sold electricity tariff increases, the electric output of the FCs increases also in order to increase the income of the sold electricity to the grid.

In case of $T_3 = 0.13$ $/kW h, the FCs output increases in a very rapid way such that each FC operates at its full rated power. This means that at this tariff, or higher values, all FCs will work with their full capacity to maximize the income of the sold electricity.

Table 5 summarizes the variation of the daily operating cost of each home and of the whole system with the three different tariffs of the sold electricity. The results show that as the tariff of the sold electricity increases, the operating cost of each home decreases.

9. Customer's comfort level

Nowadays, applying time-based tariff strategy or demand-side management techniques within SG environment comes over customer's comfort and satisfaction of consumer's needs. The proposed technique of cooperation optimization of different DG units avoids any load rescheduling or load shifting techniques and, thus, ensures a high degree of comfort for all customers. This is accomplished through the cooperation of various DG units within the different residential applications in feeding the overall load. This cooperation makes the electric grid covering all electric and thermal loads and also providing a high reserve power, which can be used in critical condition.

To emphasis this view, it is assumed that a time-based tariff strategy for purchased electricity is applied over the proposed system. Hence, the success of the proposed strategy in dealing with this situation will be evaluated through satisfying all customers' needs with high degree of comfort.

Then, the proposed system has been studied under two cases:

Case 1: applying a time-based tariff strategy for purchased electricity.

Case 2: operating at a constant tariff of purchasing electricity.

The study is performed only on the first home that contains a 7 kW FC with zero output power from the PV unit. The following tariffs in $/kW h are assumed to be constant for both cases:

$$T_{el-s} = 0.07, \quad T_{ng-fc} = 0.07, \quad T_{ng-rl} = 0.09, \quad O\&M = 0.005$$

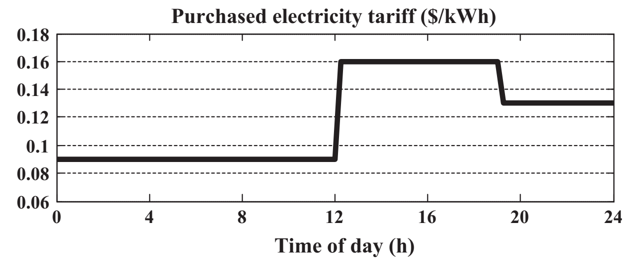

Figure 13 Time-based purchasing electricity tariffs used in case 1.

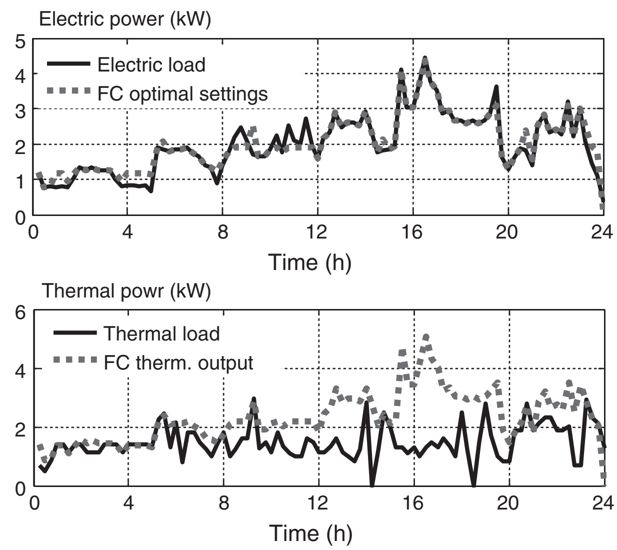

Figure 14 Optimal settings of the FC through case 1.

In case 1, time-based purchased electricity tariff is being varied as in Fig. 13.

If the optimization process satisfied all load demands without any load shifting or load rescheduling with minimum operating cost, then we can say that the cooperation optimization process insures a high degree of comfort for customers.

The optimization process is performed and the desired optimal settings are obtained. Fig. 14 shows the optimal settings of the FC for this case.

In the interval from 12 pm to 19 pm, the purchased electricity tariff increases and this is reflected on the optimal settings of the FC in order to cover all electric loads without any purchased electricity from the grid. In this period, there is no excess of produced electricity since the selling electricity price is not increased but only the purchased electricity tariff. For the other intervals, in which the purchased tariffs are quiet lower, the optimal settings are based on satisfying the load needs and achieving minimum operating cost.

In case 2, a constant value of purchasing electricity tariff along the day is used, which is assumed to be 0.12 $/kW h.

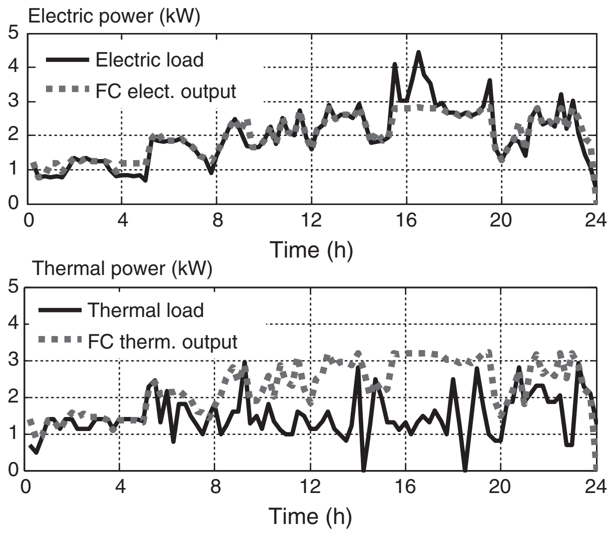

Figure 15 Optimal settings of the FC through case 2.

Table 6 A comparison between the daily operating cost of home 1 in the two cases.

Daily operating cost of home 1 ($)		
	Case 1	Case 2
C_{purc}	0.21	0.28
C_{sold}	1.22	1.01
C_{NGFC}	6.53	6.57
C_{NGRL}	0.05	0.04
$C_{o\&m}$	0.20	0.21
C_{TOTAL}	8.21	8.11

As in the previous case, the PV system is zero. The optimization process is performed in order to obtain the optimal settings of the FC as shown in Fig. 15.

Comparing the obtained optimal settings in case 2 with that obtained in case 1 during the period from 12 pm to 7 pm, it is observed that the electric output of the FC in case 1 is higher than that in case 2. This means that the optimization process increases the electric output of the FC in this period "in which the purchasing electricity tariff is high" to avoid buying any electricity from the grid at this period in order to minimize the daily operating costs. In this case, the customer gets two benefits, minimum operating cost and high comfort level without load shifting or load rescheduling.

Table 6 gives a comparison between the daily operating costs of home 1 in the two cases. The comparison shows that there is a small difference in the daily operating cost in the two cases. This means that when converting from the constant purchasing tariff to the time-based tariff, the optimal settings of the FCs are changed in order to maintain a minimum operating cost for the home and also the same comfortable condition for customers without any load rescheduling or priority selection. The results show that the optimization process, not only succeeded in satisfying all the load needs, but also with minimum operating cost in spite of changing the method of the tariff used.

10. Conclusion

The proposed technique, which optimizes the operation of the DG units within the residential applications, shows a great success in reducing the total daily operating costs of the residential system and satisfying the load needs. The simulation results show that the optimal settings of the DG units are greatly affected by the efficiency curve of each DG unit, purchasing and selling electricity tariffs, natural gas tariffs and the constraints associated with each DG unit. Changing the values of purchasing or selling electricity tariffs affects the optimal settings of the FC in such a way to maintain minimum operating cost for each home. The results show a great success for the proposed methodology in dealing with time-based purchasing electricity tariffs. This success appears in satisfying all the customers need with a high degree of comfort and also with minimum operating cost without any load rescheduling. With the aid of advanced communication technologies, implementation of the above proposed system in wide scale becomes more easy and reliable.

References

[1] Karnouskos S. Smart houses in the smart grid and the search for value-added services in the cloud of things era. In: Proc IEEE int conf ind technol; 2013. p. 2016–21.
[2] Nallathambi B. Low cost home energy management with security and automation; 2014.
[3] Li W. Modeling, control and simulation of a small photovoltaic fuel cell hybrid generation system. In: Int conf comput intell softw eng; 2009. p. 1–6.
[4] Mohsenian-Rad AH, Leon-Garcia A. Optimal residential load control with price prediction in real-time electricity pricing environments. IEEE Trans Smart Grid 2010;1(2):120–33.
[5] Taniguchi Y. Determination of optimal operation plans of fuel cell system in residential house with PV system; 2012. p. 2–5.
[6] Pappala VS, Erlich I. Management of distributed generation units under stochastic load demands using particle swarm optimization. IEEE Power Eng Soc Gen Meet 2007:1–7.
[7] Azmy M, Erlich I. Online optimal management of PEM fuel cells using neural networks. IEEE Trans Power Deliv 2005;20 (2):1051–8.
[8] Yamagishi Y, Sugihara H, Saeki O, Tsuji K. An operational algorithm for residential cogeneration systems based on the monitored daily-basis energy demand. Electr Eng Jpn 2010;170 (2):37–45 [English Transl. Denki Gakkai Ronbunshi].
[9] Kailas A, Cecchi V, Mukherjee A. A survey of communications and networking technologies for energy management in buildings and home automation. J Comput Netw Commun 2012;2.
[10] Jacobsen RH, Mikkelsen SA. Infrastructure for intelligent automation services in the smart grid. Wirel Pers Commun 2014;76(2):125–47.
[11] Zhang Q, Sun Y, Cui Z. Application and analysis of ZigBee technology for Smart Grid. In: Proc ICCIA 2010–2010 int conf comput inf appl; 2010. p. 171–4.
[12] Kuzlu M, Pipattanasomporn M. Assessment of communication technologies and network requirements for different smart grid applications. In: IEEE PES innov smart grid technol conf, ISGT 2013; 2013.
[13] Feroldi D, Basualdo M. PEM fuel cells with bio-ethanol processor systems. Green Energy Technol 2012;87:49–72.
[14] Neto RC, Teixeira JC, Azevedo JLT. Thermal and electrical experimental characterisation of a 1 kW PEM fuel cell stack. Int J Hydrogen Energy 2013;38(13):5348–56.

[15] Imam S, Azmy A, Rashad E, Husi G. Assessing the effect of design parameters on optimal size of isolated PV systems for residential utilizations; 2014. p. 234–9.
[16] Jones G. Genetic and evolutionary algorithms. Encycl Comput Chem 1998.
[17] www.statista.com/statistics/263492/electricity-prices-in-selected-countries; 2015.

Mahmoud H. Elkazaz was born in El-Gharbia, Egypt. He received the B.Sc. degree in electrical engineering with honor from the Tanta University, Egypt, in 2008. He is now pursuing M. Sc. in "Artificial Intelligent-Based Optimal Utilization of Automated Distributed Generation for Residential Applications". Currently, he is a demonstrator at faculty of engineering, Tanta University, Egypt. His research interests include smart grid, home automation and renewable energy sources.

Ayman A. Hoballah was born in in El-Gharbia, Egypt, in 1973. He received his B.Sc. degree in Electrical Engineering from Tanta University in 1996. He was awarded M.Sc. degrees in electrical engineering from Tanta University at 2003. He was awarded the Ph.D. Degree in renewable energy from Duisburg-Essen, Germany, in 2011. His current interests are renewable energy, smart grid control and analysis of power system.

Ahmed M. Azmy was born in El-Menoufya, Egypt. He received the B.Sc. and M.Sc. degrees in electrical engineering from the El-Menoufya University, Egypt, in 1991 and 1996, respectively. He received the Ph.D. degrees in electrical engineering from the university Duisburg-Essen, Germany, in 2005. He is the head of department of Electrical Power and Machines Engineering- Tanta University, director of the automated library project in Tanta University- director of the quality assurance unit and executive director of the continuous improvement and qualification for accreditation program. His research topics are directed to the intelligent techniques, dynamic simulation, smart grids, distributed generating units and renewable energy resources. He has been awarded Tanta University Incentive Awards (2010) and Prizes for international publishing in 2010, 2012 and 2013.