Grid-Connected Fuel Cell to Supply a Residential Load.

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Abstract :*An evolutionary programming based approach to evaluate the effect of fuel cell power plants (FCPP) on the operational and performance cost of the system is presented in this paper. Since the FCPPs are able to produce simultaneously both thermal and electrical energy, it is used to supply both thermal and electrical of a residential load in Mashhad province of Iran. A six-minute thermal and electrical load profile along with variable tariffs for purchasing and selling electricity from the local grid to satisfy the load is used. Finally encouraging results indicate that paralleling FCPP with grid in a hybrid structure for CHP system causes lower operational cost and manifest the feasibility of the proposed technique.*
Keywords *: Combined Heat and Power (CHP); Hybrid System; PEM Fuel Cell;*

2.INTRODUCTION

By eliminating subsidized energy prices in Iran, the cost of fuel severely increases. With unsubsidized utility prices, increasing energy demand, public awareness of environmental protection and hazardous nature of fossil fuels it is no wonder that environment friendly renewable energy sources are swiftly gaining in popularity. Due to the above mentioned issues conventional energy sources are no longer considered as the solely way of supplying energy then societies try to use distributed generator systems (DG) beside conventional ones [1]. The term DG means any small-scale generation which is located near the consumers load instead of being in the center or remote locations. DG's advantages, over other systems, such as less waste of energy over long transmission or distribution lines [2] and being quite flexible in a sense that there is always the ability to add smaller hardware during peak times make renewed interest in the DGs operating in parallel with the distribution network and make hybrid systems. The term *hybrid* energy system is commonly used to describe a power system with more than one type of supplier or generator, usually a generator powered by a gas or diesel engine, and a renewable energy source such as a wind, photovoltaic (PV), or hydroelectric power generator. Nowadays, the use of hybrid renewable energy systems not only due to the aforementioned disadvantages of conventional systems but also for supplying less costly the power demand of various regions has attracted some researchers' attention. For example in [3] electrical demand of the biggest island of Turkey was examined to realized how it could be possible to supply that with renewable energy sources. In [4] the viability of adding wind turbines to an existing diesel plant of a remote aria in Saudi Arabia was studied. Another feasibility study is described in [5], where hybrid systems supplied by hydrogen are evaluated for applications in Newfoundland, Canada. Therein most of these studies, and also [6], hybrid electricity generation systems are often considered less costly and more reliable than systems that rely on an individual source of energy. Recently, the combined use of renewable energy sources, especially FCPP is becoming increasingly fascinating [7]. Proton Exchange Membrane (PEM) fuel cells for having a lot of advantages such as: high efficiency (35% - 60%), low to zero emissions, quiet operation, high reliability due to the limited number of moving parts, modularity, scalability, quick installation, gives good opportunities for cogeneration operations and the ability to be placed at any site in a distribution system without geographic limitations [8, 9, 10, 11] show great promise for use as DGs. All of these advantages lead to a deep study of this type of fuel cell in order to supplying residential load.

So, this study began to investigate the feasibility of adding a FCPP to the then already present local grid of a residential house in the Khvaf, Iran.

Thermal and electrical energy generation by FCPP should be managed by a robust management strategy in a way to minimize the total cost with regard to satisfy constraints. In order to determine the optimal FCPP thermal and electrical power output a genetic algorithm is used. Finally, the algorithm will determine when the FCPP to be ON or OFF, by considering the different tariffs for electricity, constraints of FCPP, and minimization of total cost. For acquiring more information about economical aspect of fuel cell the following references are suggested [8, 9, 10, 12, 13, 14, 15]. In order to find the optimal output power from FCPP at the presence of constraints an economic model has been introduced in [8, 9]. The model of these two articles just considers the feasibility of trading energy with grid, and the usage of thermal recovery from FCPP. In [10] the amount of the stored hydrogen is also included to the model. In this paper the model of above mentioned papers with the variable tariffs for selling and buying electricity from the local grid is applied.

Different strategies such as selling electric power to the local grid or residential consumer, saving thermal energy, and etc. for managing the output power from FCPP unit can be defined. In the paper following strategies are used; in the first strategy thermal recovery from FCPP is neglected and the thermal load is supplied by natural gas. If the recovered thermal energy is less than the thermal load, the difference between these two items can be supplied by using natural gas otherwise surplus recovered thermal energy, second strategy, can be sold to other neighborhoods and third strategy can be stored and reused later based on system economics.

The remaining part of the paper is organized as follows: Section 2 gives a complete structure of the system besides the type of FC. Formulation of economic model is presented in section 3. The solution methodology and GA algorithm with its parameter adjustments are explained in section 4. Test results and conclusions are discussed in Sections 5 and 6, respectively.

2.SYSTEM CONFIGURATION AND ENERGY UNITS.

2.1SYSTEM CONFIGURATION

The diagram of a PEM Fuel Cell hybrid energy system connected to grid is indicated in Fig. 1. The system is constituted of wind energy turbine, local grid, heat pump, PEM Fuel Cell stack and load unit.

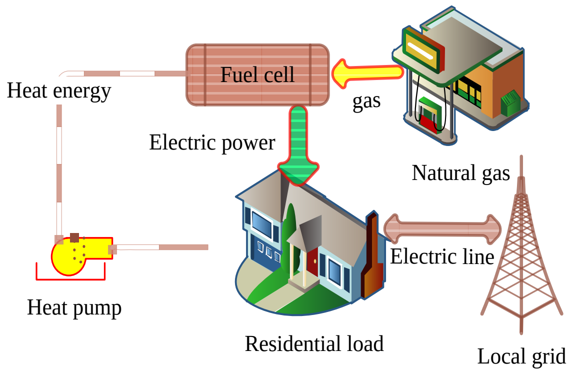

Figure 1. System configuration of the proposed hybrid energy system

2.2FUEL CELL UNIT

PEM stands for polymer electrolyte membrane or proton exchange membrane. Advantages of PEM fuel cells can be mentioned as: their high efficiency compared with other energy conversion devices [16], low operation temperature cause to reach the operation point rapidly and allows rapid start-up [17], inexpensive materials than high temperature fuel cells [18]. PEMs can be made extremely thin and the thinner the polymer electrolyte the higher the conductance and lower the ohmic resistance losses. Therefore this type of fuel cell presently receives the most attention among all kind of fuel cells. Hence, in this paper 6.3 KW PEM fuel cell power plant due to its advantages is used. When FCPP works at full load it can produces thermal energy as much as electrical energy [19]. In order to manage excess thermal or electrical energy, it is vital to have a robust management strategy. In PEM FCPP, due to the lower operating temperature, thermal recovery from the stack is abandoned so, thermal energy is just recovered from the reformer where the temperature goes up to about 360 C. Hot water and space heating considers as thermal load in this paper and adds to electric loads of PEM FCPP. The thermal load is fulfilled by using the recovered thermal energy from the FCPP and, if necessary, by use of natural gas.

3.FORMULATION OF ECONOMIC MODEL

The mathematical representation of the cost optimization problem consists of the overall operational cost and the total system income, subject to operational and system constraints can be specified as follows:

$$Objective\ Function = Min\sum_{i}^{m}(\sum_{j} Cost_j - \sum_{k} Income_k) \quad (1)$$

Subject to:

$$P^{\min} \le P_{Fc,i} \le P^{\max} \quad (2)$$

$$P_{FC,i} - P_{FC,i-1} \le \Delta P_u \quad (3)$$

$$P_{FC,i-1} - P_{FC,i} \le \Delta P_D \quad (4)$$

$$(T_{i-1}^{on} - MUT)(U_{i-1} - U_i) \ge 0 \quad (5)$$

$$(T_{i-1}^{off} - MDT)(U_i - U_{i-1}) \ge 0 \quad (6)$$

$$n_{start-stop} \le N^{\max} \quad (7)$$

The first term of (1) represents the overall operational-cost, which is completely discussed in section 3.1 while the second term is the total system income relating to daily income from the sale of excess thermal and electrical energy.

Part load ratio (PLR) is used to determine efficiency and thermal to electrical ratio [19]. These are calculated in two categories by considering PLR as follow:

$$\begin{aligned} &For \quad PLR_i < 0.05 \\ &\eta_i = 0.2716 \ , r_{TE,i} = 0.6801 \end{aligned} \quad (8)$$

$$\begin{aligned} &For \quad PLR_i \ge 0.05 \\ &\eta_i = 0.9033\times PLR_i^5 - 2.9996\times PLR_i^4 + 3.6503\times PLR_i^3 \\ &\quad - 2.0704\times PLR_i^2 + 0.4623\times PLR_i + 0.3747 \\ &r_{TE,i} = 1.0785\times PLR_i^4 - 1.9739\times PLR_i^3 + 1.5005\times PLR_i^2 \\ &\quad - 0.2817\times PLR_i + 0.6838 \end{aligned} \quad (9)$$

3.1SYSTEM COST COMPONENT

Cost of fuel: Cost of fuel for producing electrical energy by the FCPP:

$$C_{fuel,i} = c_f \frac{P_{FC,i}}{\eta_i} \quad (10)$$

Purchased electrical energy cost: Electrical energy purchased from grid when FCPP is the only supplier of demand energy.

$$C_{EL,pi} = c_{el,pi} T.\max(L_{el,i} - P_{FC,i}, 0) \quad (11)$$

Electrical energy purchased from local grid for storing surplus thermal energy when FCPP supply demand energy.

$$C_{EL,pi} = c_{el,pi} T.\max(L_{el,i} + 0.2max(P_{th,i} - L_{th,i}, 0) - P_{FC,i}, 0) \quad (12)$$

Term of $0.2max(P_{th,i} - L_{th,i}, 0)$ illustrates requested electrical energy for storing surplus thermal energy.

Gas cost for purchasing thermal energy*:* Gas cost can be added to the cost function if thermal load is more than recovered thermal energy and it is calculated as follow:

$$C_{Gas,pi} = c_g T.\max(L_{th,i} - P_{th,i}, 0) \quad (13)$$

Startup and maintenance cost:

$$C_{\sup} = \alpha + \beta(1 - e^{-\frac{t_{off}}{\tau}}) \quad (14)$$

3.2SYSTEM INCOMES COMPONENTS

***Selling surplus electrical energy*:** Surplus electrical energy sold by FCPP is calculated as follows:

$$I_{EL,Si} = c_{el,si} T.\max(P_{FC,i} - L_{el,i}, 0) \quad (15)$$

If the surplus recovered thermal energy is stored and reused and FCPP be the solely source of supplying energy, income of selling surplus electrical energy give as:

$$I_{EL,Si} = c_{el,si} T.\max(P_{FC,i} - 0.2max(P_{th,i} - L_{th,i}, 0) - L_{el,i}, 0) \quad (16)$$

Surplus thermal energy incomes: If recovered thermal energy from FCPP is more than thermal load the surplus can be sold to other neighborhoods.

$$I_{TH,Si} = c_{th,si} T \max(p_{thi} - L_{thi}, 0) \quad (17)$$

If the surplus recovered thermal energy is stored and reused, income of selling the saving of thermal energy at the end of day give as.

$$I_{TH,Si} = c_{th,si} P_{th-storage} \quad (18)$$

4.AN OVERVIEW OF GENETIC ALGORITHMS

As genetic algorithms software is the most widely used for purposes of optimization, to optimize the fitness function (1) a genetic algorithm is used. Since six minute time interval is used, 240 variables are defined for 24 hours. Linear equalities and inequalities (Equation 4 to 11) with their bounds are also defined. A double vector population type is used to specify the type of the input to the fitness function. Population size, which specifies how many individuals there are in each generation, is selected 450.In order to create the initial population a uniform function is used that creates a random initial population with a uniform distribution. For removing the effect of the spread of the raw scores a scaling function should be defined, so in this paper rank function is used. Rank function scales the raw scores based on the rank of each individual, rather than its score. The rank of an individual is its position in the sorted scores. For example the rank of the fittest individual is 1, the next fittest is 2, and so on. Appropriate parents based on their scaled values from the fitness scaling function for the next generation should be selected. Therefore stochastic uniform is used as selection function, and lays out a line in which each parent corresponds to a piece of the line of length proportional to its expectation. The algorithm moves along the line in the same size steps, one step for each parent. At each step, the algorithm allocates a parent from the section it lands on. The first step is a uniform random number less than the step size.

Reproduction determines how the genetic algorithm creates children at each new generation. This process consists of the number of elite, crossover and mutation fraction. In the paper elite count has been set to 20 while crossover and mutations have been set to 0.8 and 0.2 respectively. Crossover combines two parents to form a new child, for the next generation. Scattered crossover is applied in the article. The crossover at first creates a random binary vector then selects the genes by the help of this vector, where an element of the vector is 1 a gene will be selected from the first parent, otherwise it will be selected from the second parent, and finally combines the genes to form the child. For example:

p1 = [a b c d e f g h] ,
p2 = [1 2 3 4 5 6 7 8]
Random crossover vector = [1 0 0 1 1 0 0 1]
Child = [a 2 3 d e 6 7 h]

In order to enable the genetic algorithm to search a broader space a uniform mutation function is used. It has two-step process, in the first step the algorithm picks out a fraction of the vector entries of an individual for mutation, where each entry has the same probability as the mutation rate of being mutated. In the second step, the algorithm replaces each selected entry by a random number selected uniformly from the range for that entry. Given the population size as a vector of length 450, algorithm should create a movement of individuals between subpopulations which is called migration. In

migration every so often, related to interval control, the best individuals from one subpopulation replace the worst individuals in another subpopulation. A forward migration with 20 intervals is used. That is the nth subpopulation migrates into the (n+1) th subpopulation and migration between subpopulations takes place every 20 generations. In order to control the number of individuals move between subpopulations a fraction of 0.2 is defined. For instance if individuals migrate from a subpopulation of 50 individuals into a population of 100 individuals and Fraction is 0.2, 10 individuals (0.2 * 50) migrate. Individuals that migrate from one subpopulation to another are copied; they are not removed from the source subpopulation.
After all of aforementioned process a set of stopping criteria, which are related to the number of generations, time and fitness limit, are determined to allow the algorithm to terminate. Eventually fitness and constraint functions in serial form are evaluated. Serial form means the fitness and constraint functions are evaluated separately at each member of a population. Flowchart of extended GA based solution methodology is displayed within the figure 2.

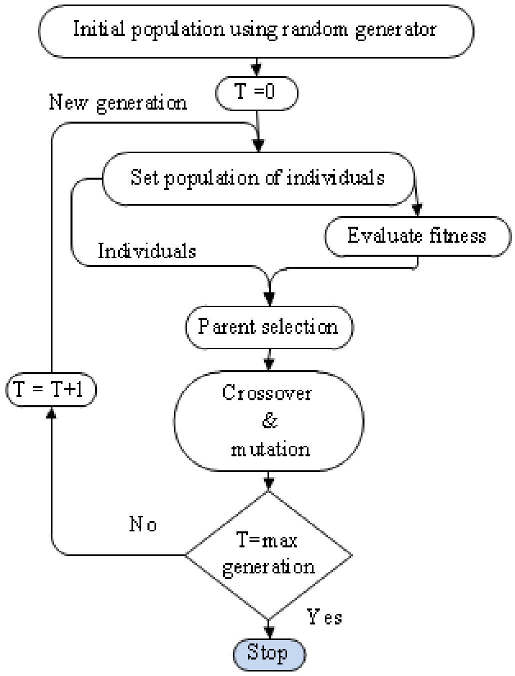

Figure 2 genetic algorithm

5.CASE STUDY

For the base case residential load demand is supplied by local grid. In the first three cases a 6.3kW PEM FCPP is applied beside local grid to supply residential load. Electricity trading tariffs are shown in Table 1. Data for PEM FCPP with GA parameters and thermal energy trading tariffs are given in Table 2.
In each case (except base case) GA defines optimal electricity output power of the FCPP with respect to consider electricity trading tariffs, thermal and electrical load, FCPP constraints
As table 1 shows selling price at all the time is cheaper than purchasing price then it is encourage grid and neighbors to buy electricity from FCPP. Electrical and thermal residential load are depicted, in figure 3. When FCPP runs, thermal energy is produced as a by-product besides electrical energy. After recovering this energy we must be sure it will be used by neighborhoods. Hence in order to encourage them to use this energy, its price should be lower than other ways of supplying thermal energy. So, as it is obvious from Table 1, thermal energy selling price with FCPP is considered lower than fuel price for residential load.

Table 1 Tariff of trading electrical energy with local grid

Time(h)	*Purchasing Tariff $/Kw*	*Selling Tariff $/Kw*
0-6	0.05	0.03
6-8	0.07	0.05
8-9	0.09	0.07
9-11	0.1	0.07
11-16	0.11	0.08
16-17	0.13	0.09
17-19	0.14	0.1
19-20	0.17	0.14
20-21	0.15	0.1
21-22	0.1	0.07
22-23	0.07	0.05

Table 2 FCPP and genetic algorithm parameters

Maximum limit of generating power, P^{max} (kW)	**6.3**
Minimum limit of generating power, P^{min} (kW)	**0.0**
Hot start -up cost, α($)	**0.05**
Cold start- up cost, β($)	**0.15**
The fuel cell cooling time constant, τ (h)	**0.75**
Minimum up-time, *MUT* (number of intervals)	**2**
Minimum down-time, *MDT* (number of intervals)	**2**
Lower limit of the ramp rate, Δp_D (kW)	**0.5**
Upper limit of the ramp rate, Δp_u(kW)	**0.4**
Length of time interval, *T* (h)	**0.1**
Maximum number of starts-stops, N^{max}	**5**
Maximum number of evolutionary generation	**5000**
Number of individuals	**450**
Fuel price for residential load, c_g ($/kWh)	**0.6**
Price of natural gas for FCPP, c_f ($/kWh)	**0.4**
Thermal energy selling price $c_{th,s}$ ($/kWh)	**0.4**
Thermal storage efficiency, $\eta_{st,th}$(%)	**90**

5.1Test and results

A load profile of Khavaf province with a peak of 6.3 kW is used to simulate 6 minute load profile of the residential house. The space heating and winter hot water usage is considered as the thermal load profile for residential house in Khavaf, Khorasane Razavi. The electrical load is used along with the thermal load profile to simulate total 6 minute operation of the FCPP. The necessary parameters are given in table 1 and 2.

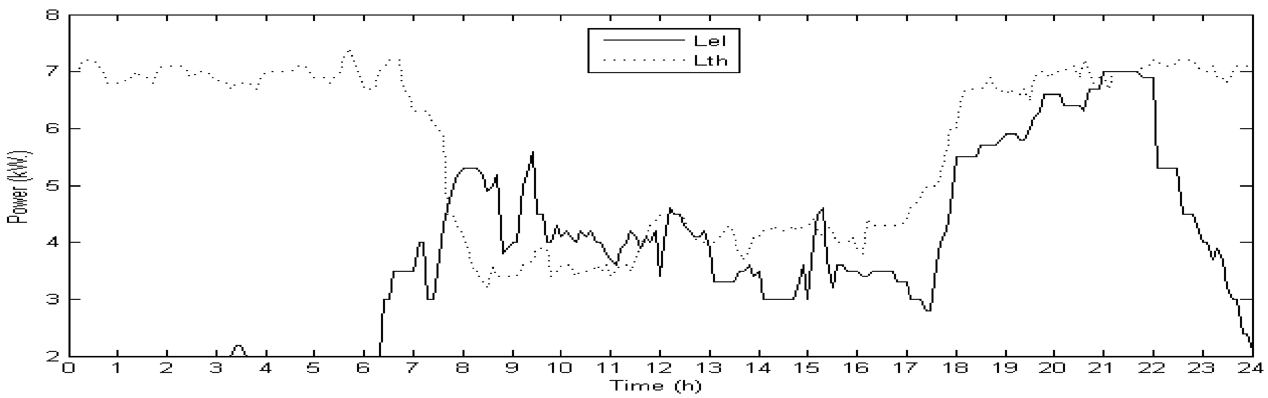

Figure 3 **Electrical and thermal load**

Base case: In this case both electrical and thermal load are supplied through the local grid and natural gas, respectively. Base case shows the cost of supplying residential load without considering the FCPP. In this test case daily cost of supplying both thermal and electrical energy will lead to 17.0693$.

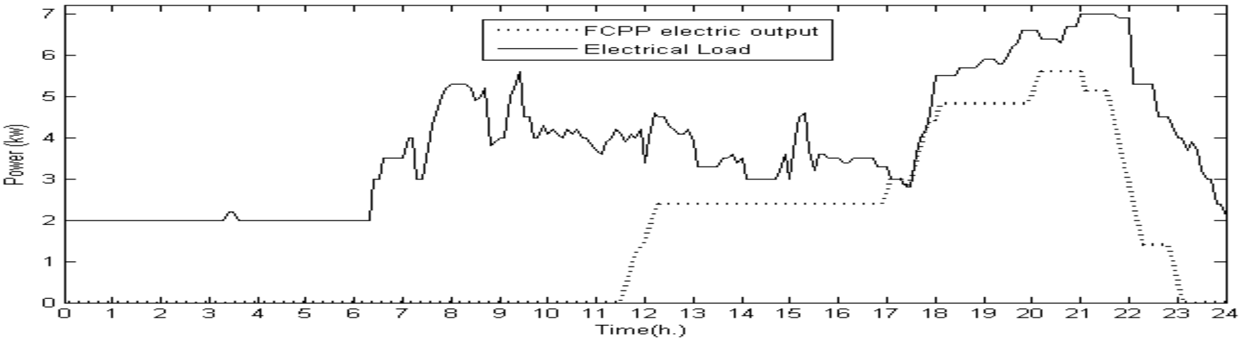

Figure 4. Supplying electrical loads by combination of FCPP and local grid

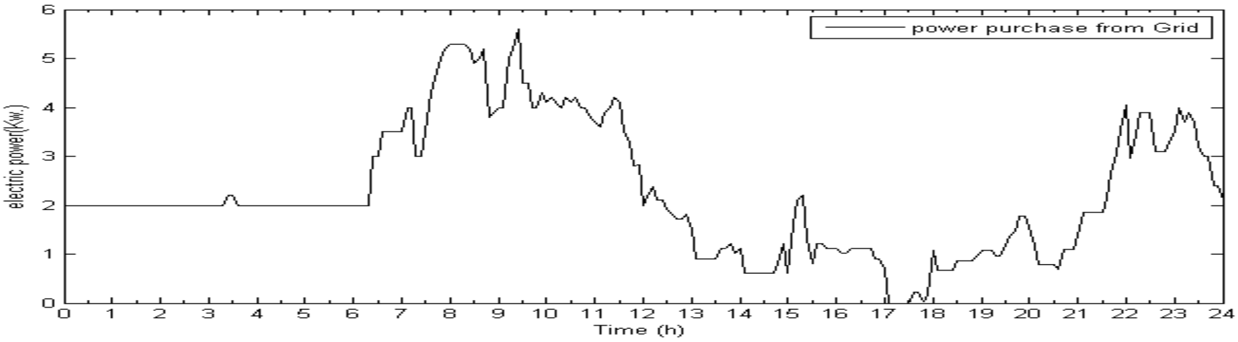

Figure 5. Purchasing electricity from local grid

Case 1: In this case a combination of FCPP and local grid is used to supply just electrical load. Recovering of thermal energy from FCPP is neglected. The amount of FCPP power generation is depicted in figure 4 and the difference between this generation and load demand has been supplied from local grid which is shown in figure 5. As figure 4 shows, during 0 to 11 purchasing electricity tariff from grid is too low then the management strategy order FCPP to be off and supply electrical load from local grid so in this period the shape of figure 5 is exactly like electric load profile. In this strategy daily cost of supplying both thermal and electrical energy has a reduction of $0.9293 so total cost in this case for one day is 16.14$. This strategy can result in a save of $339.1965 per a year.

Case 2: In this case thermal energy is recovered from FCPP as a by-product. It means that in addition to use of electrical output power from FCPP its recovering thermal energy is also used for supplying residential thermal load. If the recovered thermal energy is less than thermal load the lack can be compensate by using natural gas otherwise surplus recovered thermal energy is being sold to other neighborhoods. Electrical load and power generation is shown in figure 6 while electrical energy trade with local grid is shown in figure 7. Thermal load and recovered thermal energy is depicted in figure 8.

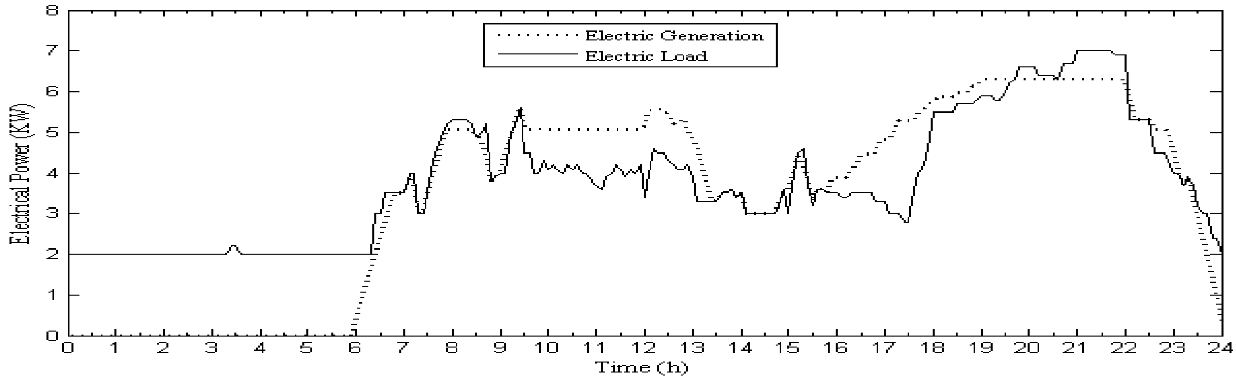

Figure 6. Electrical load and generation

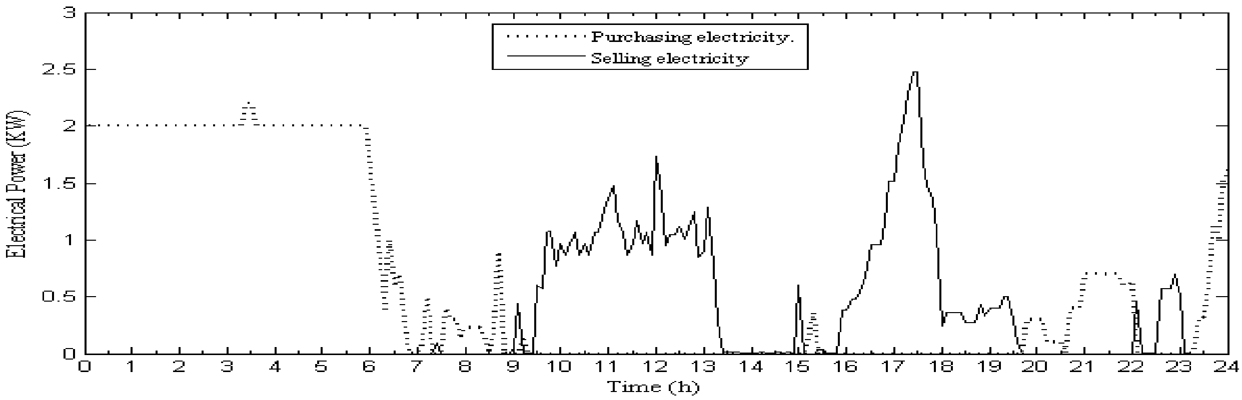

Figure 7. Electrical power trade with local grid

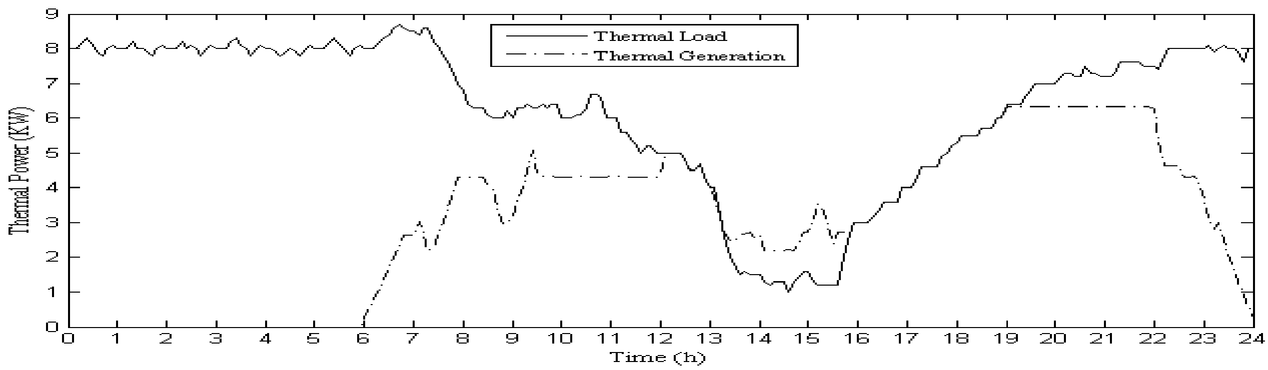

Figure 8. Thermal load and generation

A robust management strategy should consider different transient changes in FCPP production. This transient change can cause different conditions in electricity trade whit local grid. Therefore, the FCPP generation can be divided into 5 parts. As figure 6 shows, from 0:00 to 6 that management strategy ordered FCPP to be off because purchasing electricity from local grid, during this period, is more economical than generating power by FCPP then in this period

electrical load supplied by local grid and recovered thermal energy is zero. Start-up cost can be another factor that management strategy considered to keep the fuel cell off. From 6 to 10 the optimum power generation, according to management strategy is to supply electrical load by FCPP. Sometimes supplying thermal load just by generating extra power from FCPP is not cost-effective, unless the excess power generation will be sold to local grid and thermal load supplied by natural gas. 10AM to 1PM is the time period that this operation may take place since electricity price is almost high. Fortunately in the period generated power from FCPP is more than residential electrical demand so surplus electrical power can be sold to local grid by a lower price. The action depends on management strategy, maybe supplying thermal load or electricity tariffs be factors for the operation. During the time period 1PM to 5PM (780-1020 min.), generated electrical power by FCPP is just for supplying electrical load. In this period excess recovered thermal energy is sold to the neighborhoods. From 5PM to 0:00, trading electrical power with local grid take place while not only does FCPP can't sell thermal energy, but also need to buy natural gas to supply thermal load.
In this case daily cost of energy supplying is equal to $14.5385 it means a 2.5308 $ reduction in each day that result in 923.7420$ saving per year. So, this strategy is more effective than the previous strategy.

Case 3: This case is like the second case except that surplus recovered thermal energy from FCPP is stored and reused at the end of the day. If the recovered thermal energy is less than thermal load, thermal load is supplied from thermal reservoir otherwise it will be stored and sold to other neighborhoods at the end of the day. Both FCPP power generation and recovered thermal energy will be like figure 6 and figure 8 in case 2 respectively. Since our desire is supplying residential load, unlike case 2 surplus recovered thermal energy between 13-16 h. of figure 8, is stored and reused at the end of the day unless recovered energy is less than thermal load. Daily cost of supplying energy in this case is equal to $14.5334 so daily cost reduction will be 2.5359$. Total yearly saving is equal to 925.6035 $.
The effect of using FCPP as a DG system for supplying residential demand is being analyzed. The results prove that recovering thermal energy is the most effective strategy. Although storing surplus thermal energy is seems to be more affordable than case 2, it is not viable for residential use since storing thermal energy needs higher technology and expensive equipment.
Finally the results are depicted in figure 9.

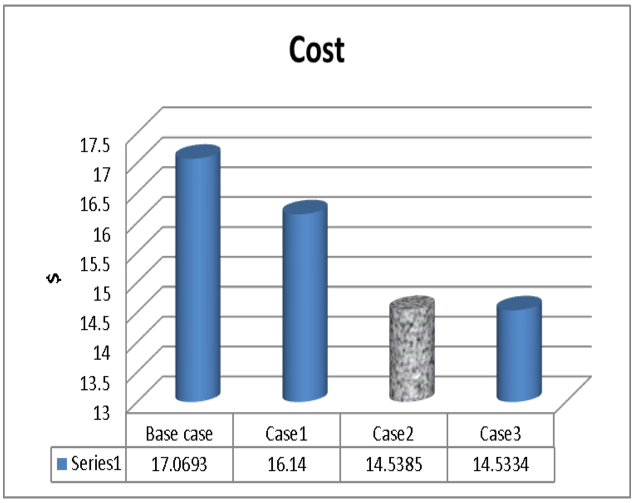

FIGURE 9 COST OF EACH CASE

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6.CONCLUSION

The paper suggests practical concepts regarding operational cost modeling of the system. Three test cases were evaluated using a residential load profile of Khavaf province in Khorasane Razavi, Iran. The main factor that affects the operation of the FCPP is thermal load. For instance some times, based on the system economics, FCPP inclines to generate electrical energy more than the electric load during high thermal consumption periods and produces low electrical energy during low thermal periods. . Test results on a 6.3 kW fuel cell power plants indicate the feasibility of the suggested approach.

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