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Economic Aspect of Fuel Cell Power as Distributed Generation

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ABSTRACT

According to importance and security of energy in recent years, too many research about renweable energy have been done. Among renewable energy sources, fuel cell has far attention, because the efficiency of fuel cells is always higher as compared with other distributed generation systems. Fuel cell has 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 and the ability to be placed at any site in a distribution system without geographic limitations. Management in supplying residential load with fuel cell power plant (FCPP) connected to grid is the aim of this paper. Economical fuel cell model includes Operational cost, startup cost and different tariffs on electricity during the day hour is discussed. In the present research, reformer is used to produce hydrogen for FCPP. Genetic algorithm (GA) is used to determine optimal operation of FCPP with six-minute change in load pattern. The results are discussed in conclusion.

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1. INTRODUCTION

Conventional energy sources are no longer considered as adequate due to the ever-growing increase of energy consumption, public awareness of environmental protection and hazardous nature of fossil fuels. Therefore, a lot of research work is being conducted on finding alternative renewable energy sources. In doing so, distributed generator systems are needed [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 have got some advantages over other systems. They cause less waste of energy over long transmission or distribution lines [2]. They are also quite flexible in a sense, so there is always the ability to add smaller hardware during peak times.

Wind turbine generators, photovoltaic cells, micro turbines (MT) and Fuel cells are different types of DG [3]. Although wind energy is the world's fastest growing energy source, its main disadvantage, which is variable wind speed causes voltage and power fluctuation problems at the load side, makes them technically flawed. Recently the second most widely used systems are photovoltaic wind turbine generators, but the unpredictable behavior of this kind of generation makes the use of these systems complex and very different [4].

All of these problems change humankind attitudes toward fuel cell, because the efficiency of fuel cells is always higher as compared with other distributed generation systems. Proton Exchange Membrane (PEM) fuel cells show great promise for use as distributed generation (DG) sources. They have 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 [5].

This paper presents economic model of PEM FC. In this model, we used efficiency that previously determined experimentally [6]. The GA is a good global-search technique. Therefore, it is implemented in this paper for minimized operation cost of FCPP [7-10].

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The remaining part of the paper is organized as follows. Economic model is formulated in section II. The GA algorithm and parameter adjustments are explained in section III. Finally, test results and conclusions are discussed in Sections IV and V, respectively.

2. FORMULATION OF ECONOMIC MODEL

The objective function to be minimized is defined as:

$$OF : \min \sum_{i} \left(\sum_{j} C(j) - \sum_{k} R(k) \right) \tag{1}$$

Subject to:

$$P^{\min} < P_i < P^{\max} \tag{2}$$

$$P_i - P_{i-1} < \Delta P_U \tag{3}$$

$$P_{i-1} - P_i < \Delta P_D \tag{4}$$

$$(T_{i-1}^{on} - MUT) * (U_{i-1} - U_i) \geq 0 \tag{5}$$

$$(T_{i-1}^{off} - MDT) * (U_i - U_{i-1}) \geq 0 \tag{6}$$

$$n_{start-stop} \leq N^{\max} \tag{7}$$

where, the variable P_i denote the power generation at sample time i, P^{man} and P^{min} are maximum and minimum limits of generating power of FC, respectively, ΔP_U and ΔP_D are upper and lower limits of the ramp rate, respectively, T^{on} and T^{off} are the FCPP on-time and off-time (number of intervals), MUT is the minimum up-time (number of intervals), MDT is the minimum down-time (number of intervals), U is the FCPP on–off status where $U=1$ for running and $U=0$ for stopping, $n_{start-stop}$ is the number of start–stop events, and N^{max} is the maximum number of start–stop event.

Constraint (2) presents the FCPP rated capacity, constraints (3) and (4) present ramp rate limits, constraints (5) and (6) are minimum up/down time limits, respectively and constraint (7) is the maximum number of FCPP start–stop cycles.

The objective function to be minimized (1) consist of the sum of the cost components minus incomes components. The system cost includes daily fuel cost, cost of purchased energy (electrical/thermal) if consumption exceeds the production, startup cost and operating and maintenance cost. System income is the revenue from the sale of surplus electrical energy.

2. 1. A. System Cost Component This section interpreted formulation of system cost component.

2. 1. 1. Cost of Fuel Cost of fuel is related to the cost of fuel for producing electrical energy by the FCPP and can be written as follows :

$$C_{fuel-i} = c_f \frac{P_i}{\eta_i} \tag{8}$$

where, c_f is the price of natural gas for FCPP ($/kWh), P_i is total electrical power produced at sample time i by FCPP (kW), and η_i is fuel cell electrical efficiency.

2. 1. 2. Purchased Electrical Energy Cost System to satisfy its electrical load shortfall must buy electrical energy from Grid. Purchasing cost of electrical energy lack obtain as follow :

$$C_{ELP-i} = c_{elp-i} \; T \max(L_{EL-i} - P_i, 0) \tag{9}$$

where, c_{elp-i} is purchasing electricity tariff ($) from grid which varies at day hour, T is the length of time interval (h), L_{EL-i} is the electrical load demand corresponding to time interval i (kW).

2. 1. 3. Startup and Maintenance Cost Two important items in startup cost formula are temperature and the FCPP off time. So, it can be defined as follows:

$$C_{start} = \alpha + \beta \left(1 - \exp\left(-\frac{t_{off}}{\tau}\right)\right) \tag{10}$$

where, α and β are hot and cold startup cost, respectively, t_{off} is the off time, that FCPP has been off (h) and τ is the fuel cell cooling time constant (h).

2. 2. B. System Income In this section, FCPP incomes from sold surplus energy are explained and formulated.

The surplus electrical energy sold by FCPP is calculated as follows:

$$I_{ELS-i} = c_{els-i} \; T \max(P_i - L_{EL-i}, 0) \tag{11}$$

where, c_{els-i} is the tariff for selling electricity ($/KWh).

Part Load Ratio (PLR) is used to determine efficiency. This is calculated in two categories by considering PLR as follow:

$$\begin{aligned} &for \;\; PLR_i < 0.05 \\ &\eta_i = 0.2716, \qquad r_{TE-i} = 0.6801 \end{aligned} \tag{12}$$

$$\begin{aligned} &for \;\; PLR_i \geq 0.05 \\ &\eta_i = 0.9033PLR_i^5 - 2.9996PLR_i^4 + 3.6503PLR_i^3 \\ &\qquad - 2.0704PLR_i^2 + 0.4623PLR_i + 0.3747 \\ &r_{TE-i} = 0.0785PLR_i^4 - 1.9739PLR_i^3 + 1.5005PLR_i^2 \\ &\qquad - 0.2817PLR_i + 0.6838 \end{aligned} \tag{13}$$

3. GENETIC ALGORITHM OPTIMIZATION TECHNIQUE

In the last three decades, heuristic methods have been rapidly developed to solve optimization problems. These methods are based upon the principles of natural biological evolution; they are called Evolutionary Computations (EC). Heuristic methods and expert systems such as Genetic Algorithms (GAs), Simulated Annealing (SA), Tabu Search (TS), Artificial Neural Networks (ANNs), fuzzy logic and combinations of these provide general ways to search for a good solution. Among these methods, the GA is implemented in this paper to define the optimal settings by minimizing the cost function (1) subjected to the constraints given by (2)–(7).

The basic advantage of the GA solution is the flexibility that it provides in modeling both time-dependent and coupling constraints. In this method, process and results are transparent in comparison to many other methods. They reveal both important and non-important variables. Automation is straight forward; so, applicable to analysis of large numbers of species, being parallel and more likely to find global maximum are the other advantages of this method which made this paper to use GA as an optimization technique.

GA starts searching design space with a population of designs (solutions), which are initially created over the design space at random. In the basic GA, every individual of population (design) is represented by a chromosome which is an array of genes. A gene is an array of bits and each gene represents some data.
A simple genetic algorithm follows the following steps:

1. Generate randomly a population of initial population within the feasible ranges of the decision variables.
2. Calculate the fitness for each string in the population.
3. Create offspring strings through reproduction, crossover, and mutationoperation.
4. Evaluate the new strings and calculate the fitness for each string (chromosome).
5. If the search goal is achieved, or an allowable generation is attained, return thebest chromosome as the solution; otherwise go to step 3. Flowchart of a simple GA can be shown in Figure 1. GA uses selection, creation of the mating pool, crossover and mutation as four main operators to direct the population of designs towards the optimum design. In the ***selection*** process, some designs of a population are selected by randomized methods for GA operations. In ***creation of the mating pool***, some good designs in population are selected and copied to form a mating pool.

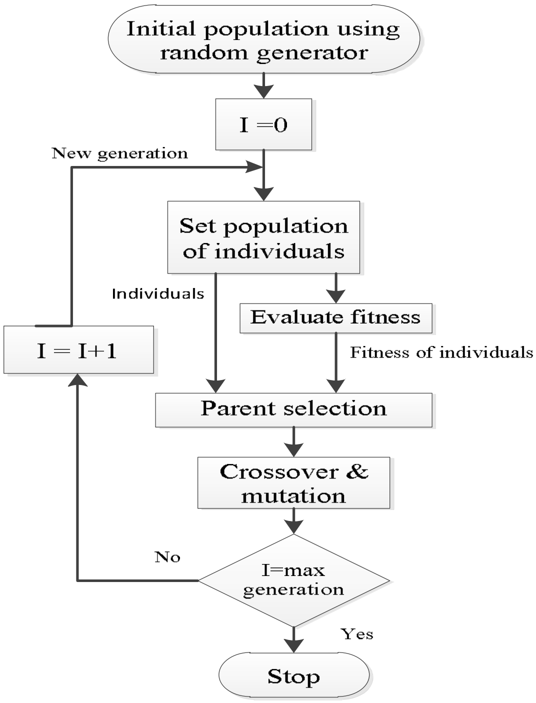

Figure 1. GA Based solution methodology

Crossover allows the characteristics of the designs to be altered. In this process, different digits of binary strings of each parent are transferred to their children. Crossover probability represents how often crossover will be performed. For better results, the crossover rate is taken to be much larger than the mutation rate (generally 20 times greater). The crossover rate generally ranges from 0.25 to 0.95.

Mutation is an occasional random change of the value of some randomly selected design variables. The mutation operation changes each bit of string from 0 to 1 or vice versa in a design's binary code depending on the mutation probability. Mutation probability represents how often parts of a chromosome will be mutated. If there is no mutation, offspring are generated immediately after crossover (or directly copied) without any change. If mutation is performed, one or more parts of a chromosome are changed. Mutation can be considered as a factor preventing from premature convergence. In this paper, crossover occurs with probability of 0.8 while mutation depend on constraints.

Stopping criterion is the last stage of GA method. In this stage, the main GA loop is terminated when there is no significant improvement in the solution after a pre-specified number of generations. It can also be terminated when a given maximum number of generations (iterations) are reached. In the current work, the latter method (i.e., a given number of iterations) is employed. In this paper, maximum number of evolutionary generation is 8000 while number of individuals are 450. The GA optimization toolbox (GAOT) in MATLAB proposed in [15] is used for solving the minimization problem. The binary GA with different mutation and crossover functions available in the toolbox were tried on this problem.

4. CASE STUDY

The proposed strategies tested for supplying electrical load which is given in Figure 2. Total daily electrical consumptions is 91.33 KWh. To supply residential load, a 6.3 KW FCPP is used while its data with GA parameters are given in Table 1. Electricity trading tariffs are shown in Table 2.

Case1: In this case, electrical load is supplied through the local grid. This case shows the cost of supplying residential load without running FCPP. After calculating this cost without considering FCPP daily cost of supplying electrical energy will lead to 9.6031$.

Case 2: In this case, a combination of FCPP and local grid is used to supply electrical load. During 0 to 11am purchasing electricity tariff from grid is too low then the management strategy order FCPP to be off and supply electrical load from local grid. The amount of FCPP power generation is depicted in Figure 3 and the difference between this generation and load demand has been supplied from local grid. In this strategy, daily cost of supplying electrical energy has a reduction of 1.2321 $, so it is 8.371$. This strategy can result in a save of 450.0245$ per a year. In Table 3, the outcome of each case is given.

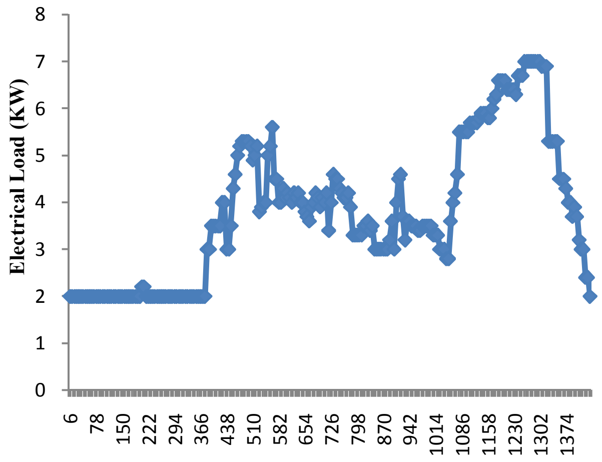

Figure 2. Electrical Load

TABLE 1. FCPP and Genetic Algorithm Parameters

Parameter	Value
Maximum limit of generating power (kW)	6.3
Minimum limit of generating power (kW)	0.0
Hot startup cost, $\alpha(\$)$	0.05
Cold startup cost, $\beta(\$)$	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 (kW)	0.5
Upper limit of the ramp rate (kW)	0.4
Length of time interval, *T* (h)	0.1
Maximum number of starts-stops,	5
Maximum number of evolutionary generation	8000
Number of individuals	450
Price of natural gas for FCPP ($/kWh)	0.4

TABLE 2. Tariff of Trading Electrical Energy with Local Grid

Time /h	Purchasing Tariff	Selling Tariff
0-6	0.05	0.03
6-8	0.07	0.05
9	0.09	0.07
10-11	0.1	0.07
12-16	0.11	0.08
17	0.13	0.09
18-19	0.14	0.1
20	0.17	0.14
21	0.15	0.1
22	0.1	0.07
23	0.07	0.05

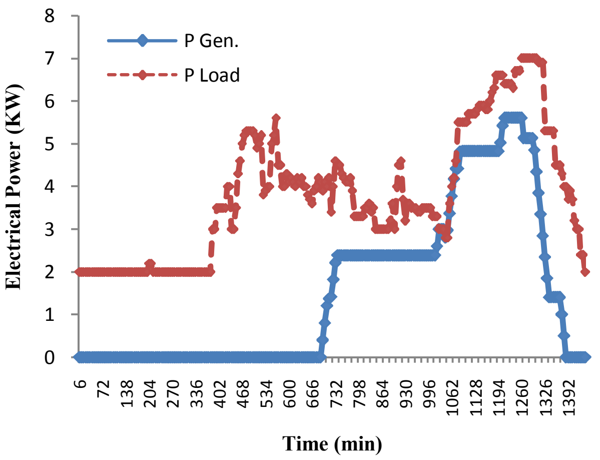

Figure 3. Electrical power consumption and generation

5. CONCLUSION

In this paper, FCPP is used as DG to supply residential load. The economic model of the FCPP by considering electrical power trade with the local grid is presented here. Different tariffs for purchasing/selling power electricity is considered, but selling tariffs are taken lower than purchasing tariffs, inorder to encourage neighbours to buy electricity from fuel cell. GA is used to minimize operating cost of FCPP. The results show that using hybrid system (FC & Grid) can result in lower cost than using them individually. Finally FCPP lead to 450.0245$ annual saving in costs, and make the hybrid system cost effecive to implement in most places.

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چکیده

به دلیل اهمیت و امنیت انرژی در سالهای گذشته، تحقیقات زیادی در راجع با منابع انرژی های تجدید پذیر صورت گرفته است. در میان این منابع انرژی، پیل سوختی به دلیل راندمان بالاتر در مقایسه با دیگر منابع مورد توجه زیادی قرار گرفته است. پیل های سوختی دارای مزایای زیادی از قبیل راندمان بالا (۳۵–٦٠٪)، آلودگی کم یا در حد صفر، عملکرد سریع، اطمینان بالا به دلیل تعداد قطعات متحرک کم و قابل نصب در هر مکان بدون محدودیت مکانی می باشد. هدف این مقاله تامین بار خانگی توسط پیل سوختی متصل به شبکه می باشد. مدل اقتصادی پیل سوختی ارائه شده در این مقاله شامل هزینه بهره‌برداری، هزینه ی راه اندازی و تعرفه های جریان الکتریکی متفاوت در طول روز می‌باشد. جهت تولید هیدروژن از ریفرمر استفاده شده است. از الگوریتم ژنتیک جهت بهینه سازی عملکرد پیل سوختی با در نظر گرفتن تغییرات شش دقیقه ای در الگوی بار استفاده شده است.

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