Optimal Management of Fuel Cell Power Plant by Using Genetic Algorithm

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Abstract—This paper presents an energy management strategy to supply residential load in hybrid fuel cell power plant (FCPP) using genetic algorithm. Economical fuel cell (FC) model includes thermal load, local electrical load, operational cost, start-up cost and different tariffs on electricity during the day hour is discussed. The proposed energy management strategy has been modelled as a multi-tasking optimization problem. Also, the extended Genetic algorithm (GA) is used to determine optimal operation of FCPP with respect to six-minute time steps in load pattern change.

Keywords—Energy management, Fuel Cell power plant, Intelligence optimization, Genetic algorithm, Multi-tasking optimization

I. INTRODUCTION (HEADING 1)

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. Therefor a lot of research activities are 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], and they are quite flexible in a sense that 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 and also it has the potential capability of providing both heat and power.

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[5–9]. All of these advantages lead to a deep study of this type of fuel cell in order to supplying residential load.

Energy management in supplying residential load with fuel cell power plant (FCPP) connected to grid is the aim of this paper. The economic models of fuel cell are presented in the literature [6–9]. In [6] and [7], the operational cost of grid-parallel fuel cell is optimized with a simplified approach. In these papers authors used efficiency and thermal to electrical ratio that previously determined experimentally in [10]. In [8] the economic model presented in [6] and [7] are expanded until the amount of the stored hydrogen is included in it. Also the effect of different selling and buying tariffs of electricity and natural gas is presented in [9].

The safety is the most important factor in residential fuel sources. In [11] hazard of hydrogen-air mixtures is expressed. Leakage in hydrogen tank and its pipes can cause hydrogen-air mixture and made a sever combustion. Therefore storing
hydrogen is dangerous for residential applications. All of previous studies assumed selling and buying tariffs of electricity is constant, while practically these tariffs are not constant during day hours. The main advantage of this paper with respect to the previous works is the introduction of variable tariffs on electricity into the model.

A robust management strategy is the key in minimizing the operational costs. The most important point to choose management strategy is the recovered thermal energy. In this paper three different cases based on recovering thermal energy from FCPP are studied. The GA is a good global-search technique. Therefore, it is implemented in this paper for minimized operation cost of residential load [12–15].

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

II. FORMULATION

Residential load can be supplied from different sources of energy. Fuel cells show great promise for use in residential application. They have a lot of advantages such as: high efficiency (35%-60%), low to zero emissions, quiet operation, scalability, quick installation, and etc. Beside these advantages, thermal energy can be recovered as a by-product from FCPP. This recovered thermal energy can be used for supplying residential thermal load such as cooking, heating and etc.

The objective function to be minimized is defined as:

\[
OF : \min \sum_i (\sum_j C(j) - \sum_k R(k))
\]

Subject to:

\[ P_{min} < P_i < P_{max} \]  
\[ P_i - P_{i-1} < \Delta P_i \]  
\[ P_{i-1} - P_i < \Delta P_i \]  
\[ (T_{on} - MUT) * (U_{i-1} - U_i) \geq 0 \]  
\[ (T_{off} - MDT) * (U_i - U_{i-1}) \geq 0 \]  
\[ n_{start-stop} \leq N_{max} \]  

Where, the variable \( P_i \) denote the power generation at sample time \( i \), \( P_{min} \) and \( P_{max} \) are maximum and minimum limits of generating power of FC, respectively, and 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 events.

Constraint (2) present the FCPP rated capacity, third and fourth constraints 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 summation 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 incomes are the revenue from the sale of surplus electrical and thermal energies.

A. Cost Components

This section interpreted formulation of system cost com1.

Cost of fuel: Cost of fuel is related to the efficiency of the FCPP and its cost function which can be written as follows:

\[
C_{fuel} = c_f P_i T \max(L_{EL,i} - P_i, 0)
\]

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 \( T \) is fuel cell electrical efficiency.

Purchased electrical energy cost:

In proposed structure to satisfy its electrical load shortfall must buy electrical energy from Grid. Purchasing cost of electrical energy lack is computed as follow:

\[
C_{GPP,i} = c_e P_i T \max(L_{EL,i} - P_i, 0)
\]

Where, \( c_e \) is purchasing electricity tariff ($/kWh) 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).

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

\[
C_{GP,i} = c_f T \max(L_{TH,i} - P_{TH,i}, 0)
\]

Where, \( c_f \) is price of natural gas for thermal load ($/kWh), \( P_{TH,i} \) is the thermal recovered energy from FCPP and \( L_{TH,i} \) is thermal load demand at interval \( i \) (kW). Term of illustrate requested electrical energy for storing surplus thermal energy.

Startup and maintenance cost: the two important items in start-up cost formula are temperature and the FCPP off time so it can be defined as follows:

\[
C_{start} = \alpha + \beta (1 - \exp(-\frac{t_{off}}{\tau}))
\]

Where \( \alpha \) and \( \beta \) are hot and cold startup cost, respectively, \( t_{off} \) is the off time, that FCPP has been off (h) and \( \tau \) is the fuel cell cooling time constant (h).

B. Income Components

In this section FCPP incomes from sold surplus energy (both of electrical and thermal) are explained and formulated.

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

\[ I_{ELS-i} = c_{els-i} \cdot T \max(P_i - L_{el-i}, 0) \]  

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

**Surplus thermal energy incomes**: if recovered thermal energy from FCPP is more than thermal load demand the surplus can be sold to other neighbors and income is calculated as follow:

\[ I_{THS-i} = c_{ths-i} \cdot T \max(P_{TH-i} - L_{TH-i}, 0) \]  

Where, \( c_{ths-i} \) is the tariff for selling thermal energy to other neighbors ($/KWh).

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

\[ \eta_i = 0.2716, \quad r_{TE-i} = 0.6801 \]  

for \( PLR_i < 0.05 \)

\[ \eta_i = 0.9003PLR_i^4 - 2.9996PLR_i^4 + 3.6003PLR_i \]
\[ -2.0704PLR_i^2 + 0.4623PLR_i + 0.3747 \]  

\[ r_{TE-i} = 0.0785PLR_i^4 - 1.9739PLR_i^3 + 1.5005PLR_i^2 \]
\[ -0.2817PLR_i + 0.6838 \]  

for \( PLR_i \geq 0.05 \)

**III. GENETIC ALGORITHM**

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 straightforward 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 that 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, a chromosome is an array of genes and 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 mutation operation.
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 the best chromosome as the solution; otherwise go to step 3. Flowchart of extended GA based solution methodology is 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.

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.

![](image)

Fig. 1. GA based solution methodology

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) is 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.

IV. CASE STUDY

The proposed strategies tested for supplying both electrical and thermal load which is given in figure 2 and figure 3 respectively. Total daily electrical and thermal consumptions are 91.33 KWh and 149.63 KWh respectively.

To supply residential load a 6.3 KW FCPP is used while its data with GA parameters and thermal energy trading tariffs are given in Table 1. Electricity trading tariffs are shown in Table 2. As FCPP run, thermal energy is produced as a by-product beside electrical energy. This amount of energy should be recovered and used. In order to encourage other neighborhoods 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 is considered lower than fuel price for residential load.

Case1: In this case both thermal and electrical load are supplied through the local grid and natural gas, respectively. Base case shows the cost of supplying residential load without running FCPP. After calculating this cost without considering FCPP daily cost of supplying both thermal and electrical energy will lead to 18.5809$.

Case2: In this case thermal energy is recovered from FCPP as by-product. It means that in addition to use electrical output power from FCPP its thermal energy is also use for supplying residential thermal load. If the recovered thermal energy is less than thermal load this lack can be supplied by using natural gas while surplus recovered energy is being sold to other neighborhoods.

For the sake of determine optimum operating point of FCPP GA is implemented. The convergence of GA is shown in figure 4. Proposed optimization converged after 3000 iteration. While, in other works convergence is taken place after 20000 iterations [6,8,9]. Electrical load and power generation is shown in figure 5. Electrical energy trade with local grid is shown in figure 6. Thermal load and thermal energy which is recovered from FCPP is shown in figure 7.

A robust management strategy should consider different transient change in FCPP production. This transient change can cause different condition in electricity trade with local grid. Therefore, the FCPP generation can be divided into 5 parts. As the figure 4 shows, the first part is from 0:00 to 6am that management strategy ordered FCPP to be off then in order to supply electrical load electrical power is purchased from local grid.
During the fourth part, which is between 1pm and 5pm, FCPP generated electrical power is just for supplying electrical load. In this part excess recovered thermal energy is sold to the neighbors. This excess recovered thermal energy is shown in fig 4. In the last part, from 5pm till 0:00, both selling and buying electrical power take place.

Daily cost of energy supplying is equal to 14.5356$. Daily cost reduction is equal to 4.04526$ in this case. Total yearly saving is equal to 1476.5231$.

V. CONCLUSION

In this paper, FCPP is used as DG to supply residential load. The economic model of the FCPP by considering thermal energy recovery and electrical power trade with the local grid is presented here. During day hour different tariffs for purchasing/selling power electricity is assumed. Since the GA is a robust global-search technique, it is used to minimize operating cost of FCPP. The proposed extended GA has converged in less iteration than previous optimization method. The results show that operating FCPP with recovering thermal energy lead to 1476.5231$/year reduction in cost.

REFERENCES


