Optimal Operation of a Wind and Fuel Cell Power Plant Based CHP System for Grid-Parallel Residential Micro-Grid

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Abstract: -This paper presents an evolutionary programming based approach to evaluate the impact of integrating wind and fuel cell power plants (FCPP) in a combined heat and power (CHP) system on the performance and operational cost. The fluctuating nature of wind energy (WE) has a different effect on the system operational cost and constraints. Besides, FCPPs are capable of producing both electrical and thermal energy. By combining WE and FCPP in a hybrid structure for CHP system yields lower operational cost than that of individual units. An integrated cost model for FCPP and WE is constructed, which includes production cost of energy, thermal recovery from the FCPP, electrical power from WE, power trade with the local grid and maintenance cost. An hourly electrical and thermal load profile for a residential micro-grid community is employed along with the wind speed variation to determine the best cost effective strategy. The operation of the FCPP system is scheduled according to available wind power, and electrical and thermal load demand to optimize operational cost. An evolutionary programming (EP)-based technique is used to find a near-optimal solution of the problem. The method incorporates the Hill-Climbing technique (HCT) to maintain feasibility during the solution process. Results are encouraging and indicate viability of the proposed technique.

Key-Words: - Fuel Cell economics, PEM Fuel Cell, CHP, Wind Energy, Evolutionary Programming, Micro-Grid.

1 Introduction

Numerous renewable energy system applications, such as wind energy (WE) and fuel cell power plant (FCPP) systems have spread rapidly. Because of the nature WE sources (fluctuating behavior and relatively small size), they should be accompanied with conventional or other energy sources such as FCPP. The integration of WE and FCPP systems in the form of combined heat and power (CHP) system can be considered as a potential option to satisfy thermal and electrical demand of residential micro-grid. In such type of system, the electrical and thermal energy generation can be managed in a way to minimize the overall cost.

In the literature, fuel cell economics and economical aspects have been presented in references [1]-[5]. In [1], [2] an economic model has been introduced to estimate the optimal output power from the FCPP while satisfying system operational constraints. The model only considers the possibility of selling and buying energy from the local grid, and the usage of thermal power output from the fuel cell.

In this paper the model in [1], [2] has been extended to integrate WE power, which is derived from the available wind speed. Different strategies to manage the power from WE and FCPP units can be considered. In this paper, the WE system is operated at its full capacity all the time. According to available thermal load demand and remaining electrical load, FCPP is then managed in order to get minimum operational cost. The model is represented as a cost optimization problem subject to system and operational constraints. To estimate the daily optimal operational strategy for FCPP and WE a hybrid technique based on evolutionary programming (EP) and Hill-Climbing (HC) method [1], [6][6] is used. The evolutionary programming is employed to search for the near optimal solution while the HC method is used to ensure feasibility during the solution process.

The paper is organized as follows: Section 2 introduces an economic model for a fuel cell system. Section 3 presents the solution methodology. Test results are presented in Section 4. Section 5 presents the conclusions.

2 Fuel cell system economic model

At full load conditions, the FCPP produces thermal energy as a by product, approximately equal to the electrical energy [7]. Mathematical expressions to approximate the efficiency and the thermal output of the FCPP have been developed in Ref. [7] as follows:

For $PLR_j < 0.05$

$$\eta_j = 0.2716, \quad r_{TE,j} = 0.6801 \tag{1}$$

For $PLR_j \geq 0.05$

$$\begin{aligned}\eta_j = {} & 0.9033PLR_j^5 - 2.9996PLR_j^4 + 3.6503PLR_j^3 - \\ & 2.0704PLR_j^2 + 0.4623PLR_j + 0.3747\end{aligned} \tag{2}$$

$$\begin{aligned}r_{TE,j} = {} & 1.0785PLR_j^4 - 1.9739PLR_j^3 + 1.5005PLR_j^2 - \\ & 0.2817PLR_j + 0.6838\end{aligned} \tag{3}$$

where, η is the FCPP efficiency, PLR the part load ratio, r_{TE} the thermal energy to electrical energy ratio. The efficiency and the thermal energy to electrical energy ratio are functions of the part load ratio (equal to electrical generated power/maximum power). In this case, the thermal power recovered from the fuel cell according to the electrical power output can be calculated as follows:

$$P_{th,j} = r_{TE}(P_j + P_a) \tag{4}$$

In Refs. [1], [2], the authors introduced an economic model for the FCPP operating strategy. In this paper, the model has been extended to include wind energy (WE). The model considers the electrical power output, the thermal power recovery, and the power trade with the local network. The economic model consists of two main parts i.e. firstly, the costs due to energy production, which are purchased energy to compensate unsupplied electrical and thermal power demand and the cost of operation and maintenance, and secondly the savings from excess electrical energy sale. This economic model can be represented as a cost optimization problem subject to system technical and operational constraints, and can be summarized as follows:

$$Objective\ Function = \min\left(\sum_{\mathrm{i}} \mathrm{C_i} - \sum_{\mathrm{i}} \mathrm{P_i}\right) \tag{5}$$

where,

$$\begin{aligned}\sum_{\mathrm{i}} \mathrm{C_i} = {} & c_{n1}T\sum_j \frac{P_j + P_a}{\eta_j} + c_{el,p}T\sum_j \max(L_{el,j} - P_{W,j} - P_j, 0) + \\ & c_{n2}T\sum_j \max(L_{th,j} - P_{th,j}, 0) + c_{om}T\sum_j (P_j + P_{W,j}) + (\alpha + \beta(1 - e^{-\frac{t_{off}}{\tau}}))\end{aligned} \tag{6}$$

$$\sum_{\mathrm{i}} \mathrm{P_i} = c_{el,s}T\sum_j \max(P_j + P_{W,j} - L_{el,j}, 0) \tag{7}$$

Subject to:

$$P^{\min} \leq P_j \leq P^{\max} \tag{8}$$

$$P_j - P_{j-1} \leq \Delta P_u \tag{9}$$

$$P_{j-1} - P_j \leq \Delta P_D \tag{10}$$

$$(T_{j-1}^{on} - MUT)(U_{j-1} - U_j) \geq 0.0 \tag{11}$$

$$(T_{j-1}^{off} - MDT)(U_j - U_{j-1}) \geq 0.0 \tag{12}$$

$$n_{start-stop} \geq N^{\max} \tag{13}$$

where,

c_{n1} : price of natural gas for FCPP ($/kWh)
T : length of time interval (h)
P_j : electrical power produced at interval j (kW)
P_a : power for auxiliary devices (kW)
$P_{W,j}$: power from wind energy at interval j (kW)
η_j : cell efficiency at interval j
$c_{el,p}$: tariff for purchasing electricity ($/kWh)
$c_{el,s}$: tariff for selling electricity ($/kWh)
$L_{el,j}$: electrical load demand at interval j (kW)
c_{n2} : fuel price for residential loads ($/kWh)
c_{om} : operation and maintenance cost ($/kWh)
$L_{th,j}$: thermal load demand at interval j (kW)
$P_{th,j}$: thermal load produced at interval j (kW)
α,β : hot and cold start up cost respectively
t_{off} : time the FCPP has been off (h)
τ : fuel cell cooling time constant (h)
P^{min} : minimum limit of generating power (kW)
P^{max} : maximum limit of generating power (kW)
ΔP_u : upper limit of the ramp rate
ΔP_D : lower limit of the ramp rate
T^{on} : FCPP on-time (number of intervals)
T^{off} : FCPP off-time (number of intervals)
MUT : minimum up-time (number of intervals)
MDT : minimum down-time (number of intervals)
U : FCPP on-off status, U = 1 for running, U = 0 for stopping
N^{max} : maximum number of start-stop events
$N_{start-stop}$: number of start-stop events

First term of the Eq. (6) is the daily fuel cost for the fuel cell ($). Second term is the daily cost of electrical energy purchased if the demand exceeds the electrical energy produced ($). The third term is the daily cost of purchased gas for residential thermal loads if the thermal energy produced is not enough to meet the thermal energy demand ($). The forth term is the operation and maintenance cost of the FCPP and WE ($). The last term is the start up cost ($) of the FCPP. Eq. (7) represents the daily income from the electrical energy sale if the electrical energy produced exceeds the demand ($).

The electric power output of the wind turbine, P_{Wj} at interval j with respect to wind speed v_j can be expressed as below [8]:

$$P_{W,j} = \begin{cases} 0 & 0 \le v_j < v_{c-i} \\ P_N \cdot \left(a + b \cdot v_j + c \cdot v_j^2\right) & v_{c-i} \le v_j < v_N \\ P_N & v_N \le v_j < v_{c-o} \\ 0 & v_j \ge v_{c-o} \end{cases} \tag{14}$$

where, $v_{c\text{-}i}$, v_N and $v_{c\text{-}o}$ are the cut-in, nominal and cut-out wind speeds respectively for wind turbine generator. The constants, a, b and c are determined by the following equation.

$$\left.\begin{aligned} a &= \frac{1}{\left(v_{c-i} - v_N\right)^2} \cdot \left[v_{c-i}\left(v_{c-i} + v_N\right) - 4 v_{c-i} v_N \cdot \left(\frac{v_{c-i} + v_N}{2 v_N}\right)^3 \right] \\ b &= \frac{1}{\left(v_{c-i} - v_N\right)^2} \cdot \left[4\left(v_{c-i} + v_N\right) \cdot \left(\frac{v_{c-i} + v_N}{2 v_N}\right)^3 - \left(3 v_{c-i} + v_N\right) \right] \\ c &= \frac{1}{\left(v_{c-i} - v_N\right)^2} \cdot \left[2 - 4\left(\frac{v_{c-i} + v_N}{2 v_N}\right)^3 \right] \end{aligned}\right\} \tag{15}$$

3 The evolutionary programming (EP)-based solution methodology

Evolutionary programming can be traced back to the early 1950's when Turing discovered a relationship between machine learning and evolution [9]-[11]. Later, Bremermann, Box, Friedberg, and others developed evolutionary computation as a tool for machine learning and optimization. Great attention was given to EP as a powerful tool when Fogal, Burgin, Atmar, and others used it to predict the events of finite state machines on the bases of old observations. During the 1980's evolutionary programming, with advances in computer technology was used to solve difficult real-world optimization problems. In the power systems area, EP has been used to solve a number of power systems problems[11].

Evolutionary programming is a search optimization method. It moves from one solution to another using a probabilistic search technique. Evolutionary programming starts with random individuals. Each individual represents a complete solution for the problem under study. The individuals are moved from one generation (or iteration) to the other after passing through two main steps, mutation and competition. During a mutation step a new individual is produced when a Gaussian random variable with uniform probability is added to the current individual. The competition step is a probabilistic selection scheme used to assign a weight to each individual according to a comparison between current individual and a randomly chosen one. It may happen that the new solution is infeasible. Therefore, using EP alone may require a long time to reach the optimal solution or it may get trapped in a local optimum. This limitation was overcome by the use of the Hill-Climbing technique (HCT) [12] to move new infeasible solutions into the feasible region. The following algorithm details the proposed approach to solve the problem:

1. Generate initial random solutions for the output power from the FCPP at each interval.

   $$S_i = \{x\} \quad i = 1,\ldots,m \tag{16}$$

   where, x is a set of output power from the FCPP at each interval, m is the number of individual in the current generation.

   The random solution is expected to satisfy the system constraints.
2. For each individual in the current generation, calculate the objective function value using (5).
3. Mutate each individual and assign it to S_{i+m} according to (17).

   $$S_{i+m} = S_i + N(0, \beta_i\, v(S_i) + z_i) \tag{17}$$

   where, S_i is the ith individual, $N(\mu,\sigma^2)$ is Gaussian random variable with mean μ and variance σ^2, β_i is a constant to scale $v(S_i)$, z_i is an offset to guarantee a minimum amount of variance.
4. Check the feasibility of each new individual against the constraints. If there is no violation go to step 5. Otherwise go to step 6.
5. Calculate the objective function value for the feasible solution using (5) and go to step 7.
6. Use the Hill-Climbing algorithm to drive the infeasible individuals into feasibility. If no feasible solution can be found go to step 3.
7. Assign a fitness score $v(S_i)$ to each individual S_{i+m} (i=1,…,2m). The score is assigned equal to the cost function.
8. Using (18), calculate a weight W_i for each

individual S_i, i = 1,…,2m. These weights are to be calculated during a random competition between individuals based on the objective function value.

$$W_i = \sum_{j=1}^{N} W_{i,j} \tag{18}$$

where, N is a randomly generated competition number, $W_{i,j}$ is either 0 or 1 depending on the competition of the individual with another individual selected randomly from the population. The value of $W_{i,j}$ can be calculated as follows:

$$W_{i,j} = \begin{cases} 1 & \text{if } v(S_i) \le v(S_p) \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

where $p = [2mu_1 + 1]$, $p \ne i$ and $u_1 \sim U(0,1)$.

9. Rank the solution S_i (i=1,…,2m) in descending order according to their values of W_i (if more than one solution has the same W, use the actual score of $v(S_i)$ to rank them). Use the first m solutions along with their score values $v(S_i)$ as a new generation for the potential optimal solution.
10. Check for convergence. Criteria used for convergence include the maximum generation number and the average/maximum fitness ratio being less than a predetermined small value. If convergence is achieved, stop; otherwise go to step 3.

4 Tests and Results

The proposed model has been applied to a 250 kW FCPP and 50 kW WE unit, which are grid-parallel and supply a residential micro-grid. The IEEE-RTS load profile with a peak of 250 kW [13] is used to simulate the hourly electrical load profile of the micro-grid. The winter hot water usage and space heating load for Atlanta, Georgia [7] is considered to represent the thermal load profile. Due to the lack of thermal load information for the summer and spring/fall, thermal load data are estimated from the available winter data. The thermal load is used along with the electrical load profile to simulate total hourly operation of the FCPP and WE. Table 1 gives gas prices and FCPP/EP parameters for the case studies for different seasons.

Base Case: In this test case, the model is tested without considering the WE for winter, spring/fall and summer seasons. Cost components for different seasons are given in Table 2.

Table 1. FCPP and evolutionary program parameters.

Maximum limit of generating power, P^{max} (kW)	250
Minimum limit of generating power, P^{min} (kW)	0.0
Length of time interval, T (h)	0.25
Upper limit of the ramp rate, ΔP_u (kW)	25
Lower limit of the ramp rate, ΔP_D (kW)	30
Price of natural gas for FCPP, c_{n1} ($/kWh)	0.04
Tariff for purchasing electricity, $c_{el,p}$ ($/kWh)	0.13
Tariff for selling electricity, $c_{el,s}$ ($/kWh)	0.08
Fuel price for residential loads, c_{n2} ($/kWh)	0.05
Operation and maintenance cost, c_{om} ($/kWh)	
Hot start up cost, α ($)	0.05
Cold start up cost, β ($)	0.15
The fuel cell cooling time constant, τ (h)	0.75
Minimum up-time, *MUT* (intervals)	2
Minimum down-time, *MDT* (intervals)	2
Maximum number of start-stop time, N^{max}	5
Maximum number of evolutionary generation	20000
Number of individuals	200

Case 1: In this case, in addition to the FCPP unit the model is tested using a total capacity of 50 kW WE system, which is operated at its full capacity all the time. Same synthetic wind speed data, Fig. 1, is used to calculate the power output of WE for all seasons. The different cost components and savings for using WE and FCPP are presented in Table 2.

Table 2. Cost comparison between Base case and Wind case.

Daily cost components ($)	**Base Case**		
	Winter	**Summer**	**Spring/Fall**
Fuel cost	613.91	602.90	539.72
Profit from electricity sold	0.00	0.00	2.31
Purchased electricity	76.60	115.82	99.48
Residential natural gas	149.79	29.16	45.55
FCPP O&M cost	26.37	26.04	23.79
Total cost	**713.47**	**542.27**	**511.88**
	Case 1		
Fuel cost	611.33	603.16	496.54
Profit from electricity sold	0.00	0.00	0.06
Purchased electricity	145.18	185.68	139.81
Residential natural gas	151.26	29.01	50.59
FCPP O&M cost	26.30	26.05	22.04
Wind O&M cost	4.36	4.36	4.36
Total cost	**648.07**	**476.91**	**433.78**
	Savings of Case 1 versus Base Case ($)		
Total cost	**65.4**	**65.36**	**78.1**

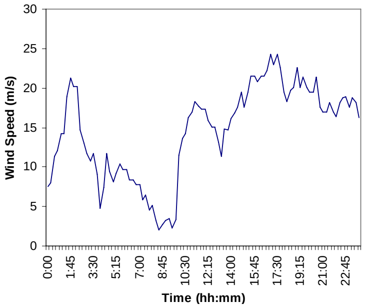
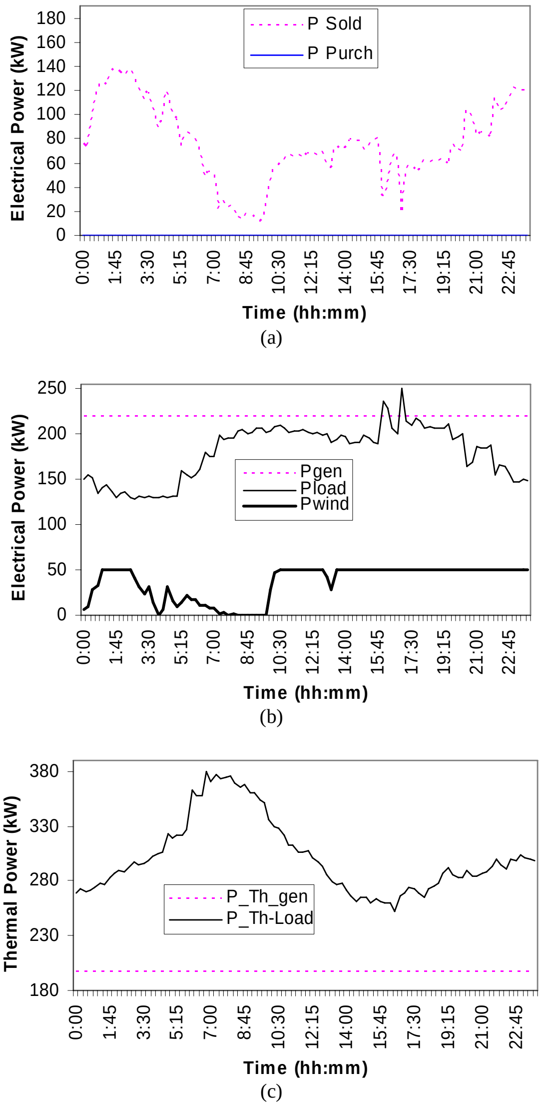


Fig. 1, Wind speed data for 24-hours.

Power trade with the local network, electrical load/electrical outputs from FCPP and WE, and thermal load/thermal power outputs from the FCPP for different seasons are shown in Figs. 2, 3 and 4, respectively.



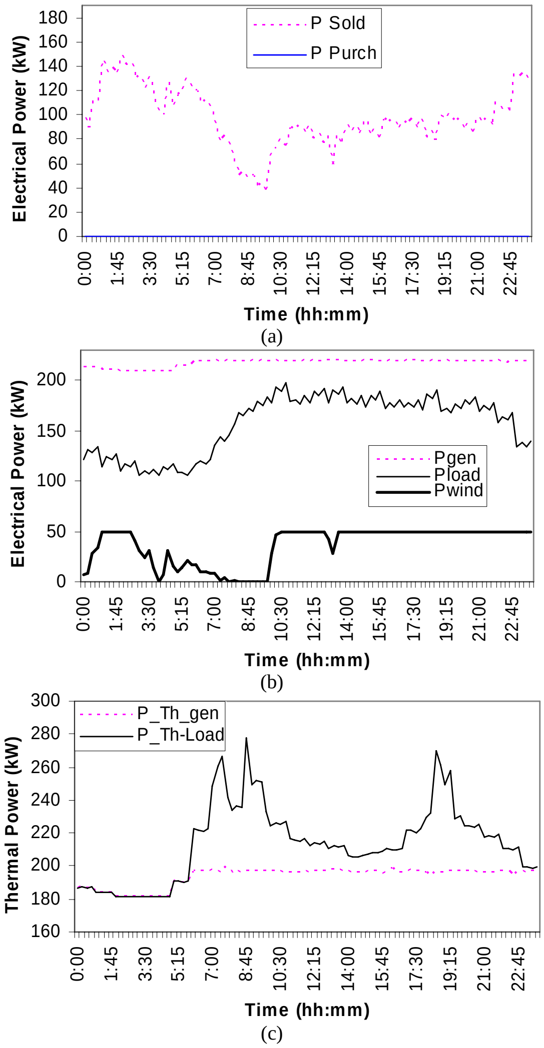
(a)

(b)

(c)

Fig. 2, (a) Winter electrical power trade with the grid (b) Winter electrical load and power generation (c) Winter thermal load and generation.

It is evident from Figs. 2, 3 and 4 that integrated generation system buys almost zero electrical energy for all seasons, instead the system sells excess electrical energy all the time. This excess electrical energy is high during the low thermal load for summer and winter cases. For the spring/fall case, surplus electrical energy is low during the low thermal load intervals and high during the low thermal load periods.



(a)

(b)

(c)

Fig. 3, (a) Summer electrical power trade with the grid (b) Summer electrical load and power generation (c) Summer thermal load and generation.

5 Conclusions

This paper introduces the integration of FCPP and WE system in an economic model which includes power trade with the local grid and thermal recovery from FCPP. The paper offers practical concepts concerning operational cost modeling of the system. Two test cases were evaluated using IEEE test system load profiles for different seasons. Based on the available power from WE, the fuel cell power plant supplies both electrical and thermal power to a small micro-grid community. Based on the system economics, results shows that, WE runs at full capacity most of the time based on wind speed. Thermal load is the main factor that affects the operation of the FCPP. For example, based on the system economics, FCPP tends to produce electrical energy more than the electric load during high thermal load periods and generates low electrical energy during low thermal periods. Test results on a 50 kW WE and 250 kW fuel cell power plants indicate the viability of the proposed approach and its potential to find the optimal power output from the fuel cell power plant subject to the associated constraints and WE power.

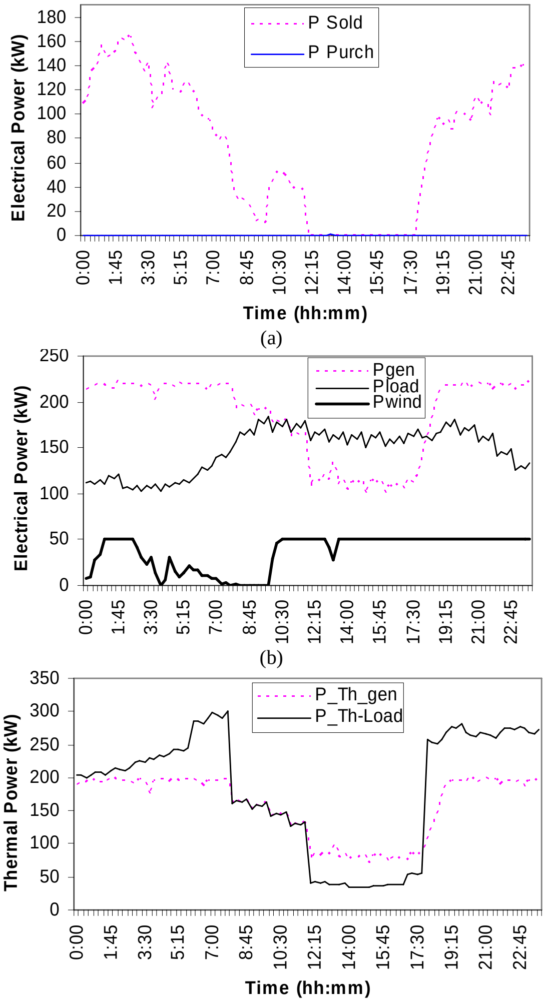


Fig. 4, (a) Spring/fall electrical power trade with the grid (b) Spring/fall electrical load and power generation (c) Spring/fall thermal load and generation.

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