Optimal Energy Management of Microgrid Based on FCCHP in the Presence of Electric and Thermal Loads Considering Energy Storage Systems

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ABSTRACT

Due to high investment costs of centralized power plants and augmentation in environmental pollutions, the use of Distributed Generations and renewable energy resources has increased rapidly. Recently, the use of FCPP and CHP generation units in microgrids and distribution systems has been attracted a lot of attention. PEM is an appropriate choice due to the fast start-up, high power density, low operating temperature, low air and sound pollution. In this paper, an optimal energy management of microgrid considering energy storage systems and the comprehensive model of PEM fuel cell units along with renewable energies such as wind and photovoltaic is investigated in two cases. The results show that the thermal power generated by FC increases proportionally to supply the demand and total operating cost is reduced by 8.65% compared to the case without thermal power of FC. The problem has been solved by BONMIN solver using General Algebraic Modeling System (GAMS) optimization package.

Keywords: Microgrid, Fuel Cell, Energy management, Renewable Energy Resources, small-scale CAES,

INTRODUCTION

due to high investment costs of centralized power plants and augment in environmental pollutions, the use of Distributed Generations (DG) and renewable energy resources (RES) has increased rapidly [1]. A Microgrid is defined as a set of controllable loads and distributed energy resources (DER) that work in an islanded or transient state [2,3].
Recently, the use of combined heat and power (CHP) generation units in microgrids and distribution systems have attracted a lot of attention toward this issue. CHP units simultaneously can provide electrical and thermal energy [4]. During the process of generating electricity in CHP units, waste heat is used to provide thermal energy [5]. In a CHP unit, the range of power generation depends on unit's heating production and the range of thermal production.
Among various types of energy resources, more research has been done on Fuel Cell Power Plants (FCPP) [6-9]. FCPP is an electrochemical device that generates heat and electricity [6]. Among various types of fuel cells, researchers have paid a lot of attention to the proton exchange membrane (PEM), especially for residential and transportation application. PEM is an appropriate choice due to the fast start-up, high power density, low operating temperature, low air and sound pollution [7]. In the reference [6] the effect of the presence of a fuel cell unit as a CHP for heat generation has been discussed but the model for the fuel cell is considered simple. In this paper, an optimal energy management to provide both electric and thermal loads simultaneously by considering energy storage systems (ESS), in order to reduce the operating cost of the microgrid is suggested. A PEM fuel cell is used as a CHP unit that has the ability to generate electric and thermal energy. Besides the aforementioned considerations, the effect of heat's presence on the optimal energy management is analyzed in this paper. In addition, microturbine and boiler units are considered to meet the demand for electric and thermal energy. In this paper, among several types of energy storage systems, a small-scale compressed air energy storage (CAES) is chosen for the simulations due to its lower capital cost, no replacement cost, lower fixed operating and maintenance cost.

ECONOMIC MODEL OF FUEL CELL

FC is a type of electrical devices that converts chemical energy into heat and electrical energy. each fuel cell normally generates a voltage between 0.5 to 0.9 volts. By combining a certain number of single cells in series mode, FC can be used as generation systems [6,9].

Recovered Thermal Energy

Both electrical and thermal energy, together, proliferate the efficiency of FC. Efficiency and ratio of electrical energy to thermal one depends on partial load ratio (PLR) [8].
Figure 1 shows efficiency and ratio of thermal to electrical and PLR. this figure can be explained by mathematical formulations as below [8,9].

$$PLR_t = \frac{P_t^{FC}}{P_{\max}^{FC}} \tag{1}$$

$$\begin{gathered} For\ \mathrm{PLR}_t < 0.05 \\ \eta_t = 0.2716, \quad r_{TE,t} = 0.6801 \end{gathered} \tag{2}$$

$$\begin{aligned} & For\ \mathrm{PLR}_t \geq 0.05 \\ & \eta_t = 0.9033\mathrm{PLR}_t^5 - 2.9996\mathrm{PLR}_t^4 + 3.6503\mathrm{PLR}_t^3 \\ & \quad -2.0704\mathrm{PLR}_t^2 + 0.4623\mathrm{PLR}_t + 0.3747 \\ & r_{TE,t} = 1.0785\mathrm{PLR}_t^4 - 1.9739\mathrm{PLR}_t^3 + 1.5005\mathrm{PLR}_t^2 \\ & \quad -0.2817PLR_t + 0.6838 \end{aligned} \tag{3}$$

The recovered thermal power from the fuel cell as a function of the electrical power output can be calculated as Eq. (4) [6]:

$$\mathrm{H}_t^{FC} = r_{TE,t}\ (P_t^{FC}) \tag{4}$$

in the full load condition, thermal efficiency is equal to 1. Figure 1 demonstrates output electrical power to input gas power. Their efficiencies are 30 to 40 percent regardless of thermal power in calculating the efficiency and if FCPP is used as CHPH, its efficiency will increase. Authors of [7-9] introduce a mathematical model for operating cost of FCPP. The operating cost represents as Eq. (5):

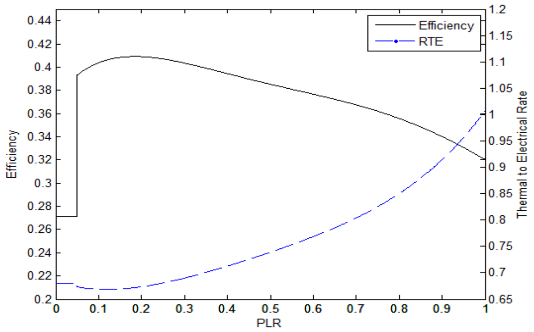

Figure 1:Performance curves of the FCPP

$$C_{FC} = \sum_{t=1}^{T}\left(\frac{P_t^{FC}}{\eta_t}\times C_{ng}\right)+\left(P_{\max}^{FC}\times OM\right) \qquad (5)$$

The aforementioned operation cost can be divided into two separate parts. The first part is the daily overall fuel cost of FC unit and the second part is related to operation and maintenance cost of FC units.

MATHEMATICAL MODELING

The objective goal of this paper is optimal energy management of microgrid to supply electrical and thermal loads considering energy storage system.

Wind Turbine (WT)

The electrical energy produced by the wind farm is a function of wind speed and turbine characteristics. This model is non-linear but according to linear approximation, equation 6 can be replaced in small linear parts instead of non-linear ones as Eq. (6):

$$P_t^{WT} = P_{\max}^{w} \times \begin{cases} r_1(w_t - v_{ci}), & v_{ci} \le w_t \le v_1 \\ r_1(v_1 - v_{ci}) + r_2(w_t - v_1), & v_1 \le w_t \le v_2 \\ r_1(v_1 - v_{ci}) + r_2(v_2 - v_1) + r_3(w_t - v_2), & v_2 \le w_t \le v_r \\ 1 \quad v_r \le w_t \le v_{co} \\ 0 \quad \text{otherwise} \end{cases} \qquad (6)$$

In Eq. (6), the maximum power of wind turbine defines as P_{max}^{w}, v_i and r_i demonstrate the slope and breaking point of the i-th section of wind turbine curve respectively [6]. v_{ci}, v_{co} and v_r are cut in speed, cut off and rated power respectively.

Photovoltaic systems (PV)

The Output power of the photovoltaic system can be expressed as equation (7). The power produced by photovoltaic system relies on solar radiation, surrounding temperature and module specifications [6].

$$P_t^{PV} = \begin{cases} P_{sn}\dfrac{G_t}{G_{std}R_c} & 0 < G_t < R_c \\ P_{sn}\dfrac{G_t}{G_{std}} & G_t > R_c \end{cases} \qquad (7)$$

Where G_t, G_{std}, P_{sn} , and R_c are forecasted solar radiation, solar radiation in the standard radiation $(1000\, W/m^2)$, rated power for PV systems and the certain radiation point $(150\, W/m^2)$, respectively.

Small-Scale CAES

Constraints for small-scale CAES are expressed as below:

$$V^{inj}(t) = \alpha^{inj} . P_{c,p}(t) \quad \forall t \le T \qquad (8)$$

$$P_{c,s}(t) = \alpha^{p} . V^{p}(t) \quad \forall t \le T \qquad (9)$$

$$V_{min}^{inj} . u^{inj}(t) \le V^{inj}(t) \le V_{max}^{inj} . u^{inj}(t) \qquad (10)$$

$$V_{min}^{p} . u^{p}(t) \le V^{p}(t) \le V_{max}^{p} . u^{p}(t) \qquad (11)$$

$$u^{p}(t) + u^{inj}(t) \le 1 \qquad (12)$$

$$A(t+1) = A(t) + V^{inj}(t) - V^{p}(t) \qquad (13)$$

$$A^{min} \le A(t) \le A^{max} \qquad (14)$$

Technical constraints for small-scale CAES are presented in (8) -(14). [10]. The amount of injected air into storage in this model is expressed by constraint (8), where $P_{c,p}(t)$ is the consumed energy of CAES at time t for compressing and injecting air (KW), $V^{inj}(t)$ is the amount of injected air into storage and α^{inj} is the yield of injected power to CAES. Equation (9) explains the amount of energy produced by CAES $P_{c,s}(t)$, where α^{p} is the yield of produced power from CAES and $V^{p}(t)$ is the amount of pumping air into the the combustion chamber by CAES (KWh). The efficiency factors α^{inj}, α^{p} for compression and generation are assumed 90% in this paper. Equation (10) and (11) present the mathematical model of the air stored in storage and then pumped from the storage to the combustion chamber. $u^{inj}(t)$ and $u^{p}(t)$ are used for preventing CAES from simultaneous operation in the above two modes (only for pumping or injecting air into combustion chamber). Constraint (13) is the dynamic model of energy for CAES at each time. The last constraint in Eq. (14) is the restrictions of storage tank, where $A(t)$ is the level of stored energy in CAES at time t in and A^{min} and A^{max} are the minimum and maximum energy stored CAES (KWh). The assumed parameters are expressed at Table 1 as follows.

Objective Function

In this section the objective function, operating cost of the microgrid, consists of 3 main parts, operating cost for FC, operating cost of microturbine and boilers that are considered linear

Table 1: Small-Scale CAES characteristics

unit	A_{min}	A_{max}	V_{min}^{inj}	V_{max}^{inj}	V_{min}^{p}	V_{max}^{p}
CAES	40	200	40	100	40	100

.

$$OF = \sum_{t=1}^{T}\left\{\left(\sum_{i=1}^{N_{FC}} C_{FC,i}\right)+\left(\sum_{j=1}^{N_{MT}} P_{t,j}^{MT}\times C^{MT}\right)+\left(H_t^{bl}\times C^{bl}\right)\right\} \qquad (15)$$

Where $P_{t,j}^{MT}$ is electrical power generated by the j-th microturbine at t-th hour. $C^{MT}(\$/kWh)$ is microturbine unit power price. H_t^{bl} is boiler unit power at the t-th hour. $C^{bl}(\$/kWh)$ is boiler unit power price.

Constraints

Power balance constraint:

$$\sum_{i=1}^{N_{FC}} P_{t,i}^{FC} + \sum_{j=1}^{N_{MT}} P_{t,j}^{MT} + \sum_{w=1}^{N_{Wind}} P_{t,w}^{WT} + \sum_{v=1}^{N_{PV}} P_{t,v}^{PV} + P_{c,s} - P_{c,p} \quad (16)$$

$$= P_t^{elec} \quad \forall t.$$

Thermal load balance constraint:

$$\sum_{i=1}^{N_{FC}} H_{t,i}^{FC} + H_t^{bl} = P_t^{ther} \qquad \forall t. \quad (17)$$

RESULTS AND DISCUSSION

The proposed model has been analyzed in two cases. In case 1, Fuel cell units are assumed to generate only electrical power. In case 2, Fuel cell units are considered as CHP unit and simultaneously generate electrical and thermal power.

Simulations are implemented on modified microgrid as shown in figure 2[11] that comprised of two Fuel Cells, two microturbine, three wind turbines, two PV systems, one boiler (in order to compensate for the lack of thermal energy) and one small-scale CAES. In this paper, the loss of lines assumed to be zero. The parameters of fuel cells are expressed in table 1[7]. The linear coefficients of the cost function for microturbine and boiler are 0.06. the load profile is shown in the figure 3. In each feeder, the thermal load is 40% of the electrical load [9]. Maximum output power for wind turbines and PV systems are 80 and 70 kw, respectively. All the simulations were carried out using BONMIN solver running under GAMS software.

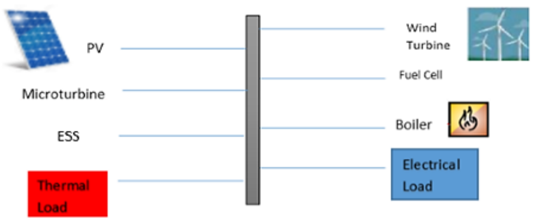

Figure 2: Microgrid test system

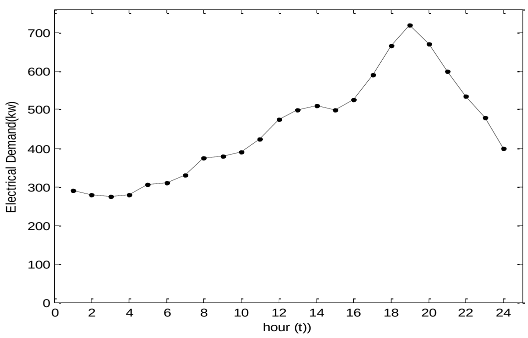

Figure 3: Daily load profile

Table2 : Data of fuel cell unit

Characteristic	Value	Characteristic	Value
$P_{min}^{FC}\ (kW)$	20	$P_{max}^{FC}\ (kW)$	100
$OM\ (\$/kWh)$	0.01	$C_{ng}(\$/kWh)$	0.04

Case1: Energy management without considering thermal energy of Fuel Cell

Figure 4 shows the total electrical power of units. wind turbine and photovoltaic units also generate electrical power depending on the speed and radiation respectively for each hour. Due to the fact that these units do not have any operating cost, they use their maximum power.

In this case, the operating cost is 773.89 $. In this case, since fuel cell units do not produce thermal power and its generation cost is more than microturbine units, the power of the fuel cell is at its lowest level. Only in the last hours of the day which photovoltaic power is zero and demand is high, the capacity of fuel cell generation increases to supply load and boiler lonely provides thermal loads.

Case2: Energy management with considering thermal energy of Fuel Cell

The results of the electrical and thermal generation of total units are shown in figure 6 and 7. In this case, since the fuel cell unit is used as CHP, therefore, the electrical power of fuel cell units is greater than that of using its thermal power, compared to the first case. It can be seen from PLR diagram and thermal coefficient that the higher the power generated by the FC is, the higher the thermal coefficient becomes Thus, with regard to the relationship between the PLR and FC efficiency, it can be observed that the efficiency of FC is at its maximum level at one point and with augment of PLR, the efficiency decreases and this, leads to a higher operating cost of FC. During the peak hours, the power generated by fuel cell and microturbine units increases proportionally to supply the demand. In this case, total operating cost is reduced by 8.65% and reached to 706.9863 $. Since, the FC is operated as CHP unit and generate thermal energy.

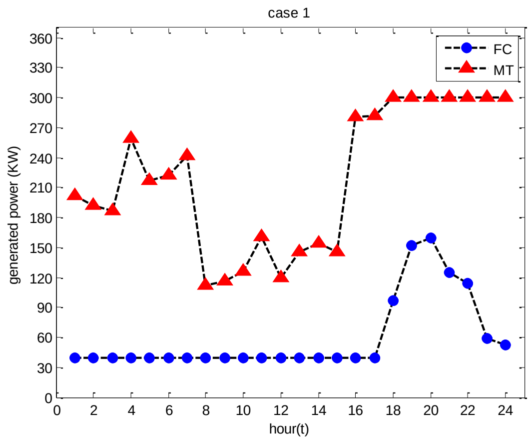

Figure 4: Generated power of units in case 1

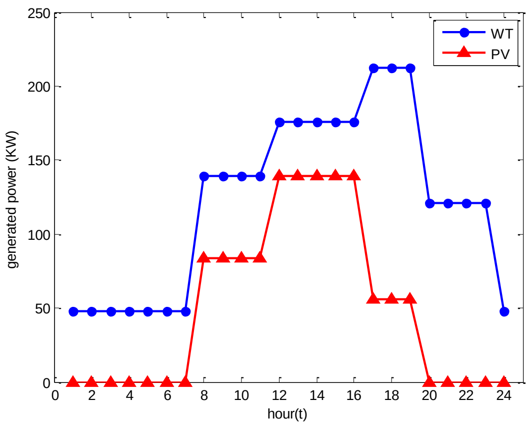

Figure 5: Generated power of renewable resources

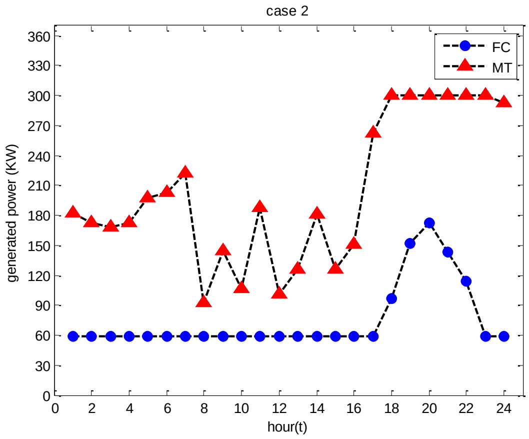

Figure 6: Generated power of units in case 2

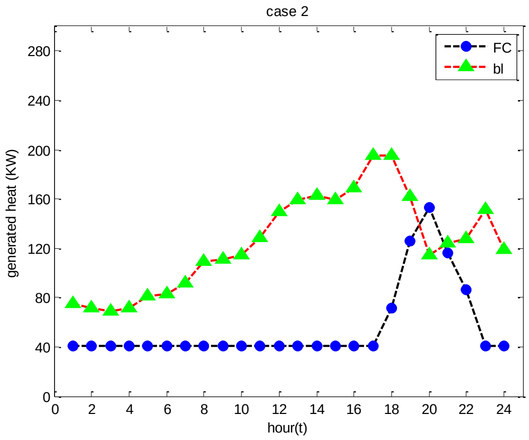

Figure 7: Generated heat of units in case 2

thermal power produced by boiler decreases and as a result, the consumption of gas is going to be lower. Therefore, this action leads to a significant reduction in operating cost compared to the previous one.

CONCLUSION

In this paper, optimal energy management of microgrid considering the comprehensive model of PEM fuel cell units along with renewable energies such as wind and photovoltaic is investigated. The objective function of this problem is to minimize the operation cost of microgrid. By comparing two cases, it can be found that the case study with considering thermal energy of Fuel Cell is more beneficial than the other one and operation cost decreases by 8.65%. simulation results demonstrate that if FC units are not used as CHP, it cannot be efficient due to its high operating cost. Therefore, in order to provide thermal loads, a boiler unit should be used which will increase the operating cost, but if the FC unit is used as a CHP, it produces electrical and thermal power in proportion to its efficiency and reduces the operating cost of microgrid.

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