A developed Energy Management System for a Microgrid in the Competitive Electricity Market

Alireza Bagherian, S.M.Moghaddas Tafreshi

***Abstract*--This paper presents a developed energy management system for a microgrid (MG). This Microgrid Management System (MMS) generates an optimum operation plan for a microgrid on next day. This planning is optimized from economical view point based on profit maximization while abiding by system constraints and regulatory rules. The MG considered in this paper consists of wind turbine, microturbines, photovoltaic array, fuel cell, electrolyzer, H_2 storage tank, reformer, a boiler, electrical and thermal loads. Also in the model possibility of selling and buying electrical energy from the local grid is considered. This system includes the operational cost, thermal recovery, power trade with the local grid, and hydrogen production.**

***Index Terms*--Microgrid, Energy Management, Power Market, Distributed Generation**

I. NOMENCLATURE

$P_G(t)$	Power that is allocated for sale or the power that is bought from the grid (kW)
$p_G(t)$	Predicted tariff for purchasing or selling Electricity (¢)
$P_{L\text{-}i}(t)$	Electrical load demand *i* at interval t (kW)
$p_{L\text{-}i}(t)$	Price for Electrical load demand *i* at interval t (¢)
$P_{therm}(t)$	Thermal load demand at interval t (kW)
$p_{therm}(t)$	Price for thermal load demand at interval t (¢)
$P_j(t)$	Power bid of independent DG *i* for interval *t* (kW)
$p_j(t)$	Price bid of independent DG for interval *t* (¢)
$C_{mt\text{-}k}(\ )$	Costs of producing microturbine *k* (¢)
$C_{fc}(\ )$	Costs of producing fuel cell (¢)
$C_L(\ )$	Costs of curtailment strategy in controllable Loads (¢)
$C_{therm}(\ )$	Costs of thermal energy producing (¢)
$\alpha_{mt}, \beta_{mt}, \gamma_{mt}$	Cost coefficients of microturbine
$\alpha_{stmt\text{-}k}, \beta_{stmt\text{-}k}$	Hot and cold start up cost for MTs
$\alpha_{el}\ \beta_{el}$	Hot and cold start up cost for electrolyzer
OM_{el}	Operation and maintenance cost for electrolyzer (¢/h)
α_{fc}, β_{fc}	Hot and cold start up cost for fuel cell
OM_{fc}	Operation and maintenance cost for fuel cell (¢/h)
c_{Ng}	Daily price of natural gas for reformer (¢)
$\dot{G}$	Natural gas consumption of reformer (m^3/h)
β_L, γ_L	Cost coefficients of curtailment strategy in controllable loads
P_{sh}	Curtailed power at controllable load (kW)
T_{shed}	Shedding duration for controllable load (h)
P_{wt}	Predicted power from wind turbine (kW)
P_{pv}	Predicted power from PV (kW)
P_{boi}	Thermal power produced at boiler (kW)
$P_{thMT\text{-}k}$	Thermal power produced at microturbine k (kW)
$P^{\min}, P^{\max}$	Minimum/maximum generating capacity (kW)
MUT	Minimum down-time
MDT	Minimum up-time
T_i^{on}	Microturbine on-time
T_i^{off}	Microturbine off-time
$\dot{H}_{el}$	Hydrogen production rate of the electrolyzer (m^3/h)
$\dot{H}_{fc}$	Hydrogen consumption rate of the fuel cell (m^3/h)
$H_v(t)$	Hydrogen storage level at the beginning of time interval t (m^3)
$u_j(t)$	On/off state of DG j at interval t
$u_{mt}(t)$	On/off state of MT at interval t
$u_{el}(t)$	On/off state of electrolyzer at interval t
$u_{fc}(t)$	On/off state of fuel cell at interval t
x, y, z	Number of consumers, DGs and MTs, respectively

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II. INTRODUCTION

INTERCONNECTION of small, modular generation and energy storage to low or medium voltage distribution systems forms a new type of power system, the microgrid (MG)[1]. Microgrids can be connected to the main power network or be operated autonomously, similar to power systems of physical islands. In other words, the microgrid concept assumes an aggregation of loads and microsources (<500 kW) operating as a single system providing both power and heat. The aim of operating microgrid sub-systems is to move away from considering Distributed Generation (DG) as badly behaved system components, of which a limited amount can be tolerated in an area, to 'good citizens' [2]. From the grid's point of view, a Microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load and as a small source of power supporting the network [3]. In this work, The MG is centrally controlled and managed by a MG central controller (MGCC) installed at the medium voltage/low voltage (MV/LV) substation.

The MGCC includes several key functions, such as economic managing functions and control functionalities, and is the head of the hierarchical control systems. MMS is the main aspect of a MGCC that specifies the best strategy for a microgrid to achieve its objects.

The purpose of the Energy Management System (EMS) is to make decisions regarding the best use of the generators for producing electric power and heat in the microgrid, the best schedule of storage system, proper load management and appropriate selling or purchasing from local grid.

This paper is organized as follows: Section III introduces microgrid model. Section IV presents the Microgrid Management System. Solution methodology, test results and conclusions are presented in Sections V, VI and VII respectively.

III. MICROGRID MODEL

The proposed microgrid consists of generators, loads and storage system. The MG architecture studied in this paper is shown in Fig. 1.

A. Generators

In this work, generators consist of two following types:

1) Distributed generation (DG) units inside the microgrid control area which managed or owned independently from the microgrid manager. From the market point of view these units send energy offers (price and quantity or other data such as constraints) to MMS.
2) Distributed generation units inside the Microgrid control area, which are owned by microgrid manager. These units have the microsources consisting of renewable energy sources (wind turbine WT, photovoltaic PV) and conventional type (microturbine). To ensure system reliability, the forecasting uncertainty must be considered in the incorporation of wind or sun power capacity into generation planning.
3) In addition to electrical load, the Microgrid has thermal load and can burn natural gas by a boiler to supplement the recovered heat of the microturbine (or fuel cell), therefore we have considered the boiler in generator units' category.

B. Loads

The four types of loads in our Microgrid are critical load, controllable load, sensitive to price load and thermal load.

1) Critical load: it describes demands that must be met at all times, such as servers and loads related to essential processes.
2) Controllable load: the magnitude of certain demands might be flexible. Controllable demands have a preferred level, but the demand level can be lowered if a certain cost is associated with the load shedding. (a penalty for MMS)
3) Price sensitive load: the magnitude of these loads depends on energy price. In this type, the load specifies for MMS a price as margin price. If energy price is higher than the margin price, load demand decrease to a predefined value or to zero.
4) Thermal load: their required thermal energy is provided by boiler and recovered heat from microturbines.

C. Storage System

In this work storage system consists of electrolyzer, storage tank, fuel cell, reformer and relative accessories. In the mentioned system an Electrolyzer is used for splitting water into H_2 and O_2 by the supply of direct current to its electrodes. Produced hydrogen is compressed and then stored in pressurized tanks. Hydrogen also is obtained by reformer with natural gas feed. Fuel cell (PEM type) converts hydrogen energy to electrical energy by oxidizing H_2 in required times. one of the advantages of the storage system in this work (from economical view points) is to store energy (H_2) by electrolyzer and reservoir in low price times or when generation rate is more than consumption rate and converting H_2 to electrical energy by fuel cell in high price times.

Each component of the MG system is modeled separately based on its characteristics and constraints.

IV. MICROGRID MANAGEMENT SYSTEM

A. Problem Description

Objective function for the mentioned microgrid is based on profit maximization over 24 hours for next day. The function of Microgrid Management System (MMS) is somedeal similar to a day-ahead local energy market, aimed to maximize its profit regarding to following parameters (as the inputs of objective function);

The bids from independent DGs (price/quantity), start-up and operation cost of the units belong to microgrid manager (owner), consumers demand, energy price forecast in wholesale power market, weather forecast data, historical weather data etc.

Objective Function (OF) is;

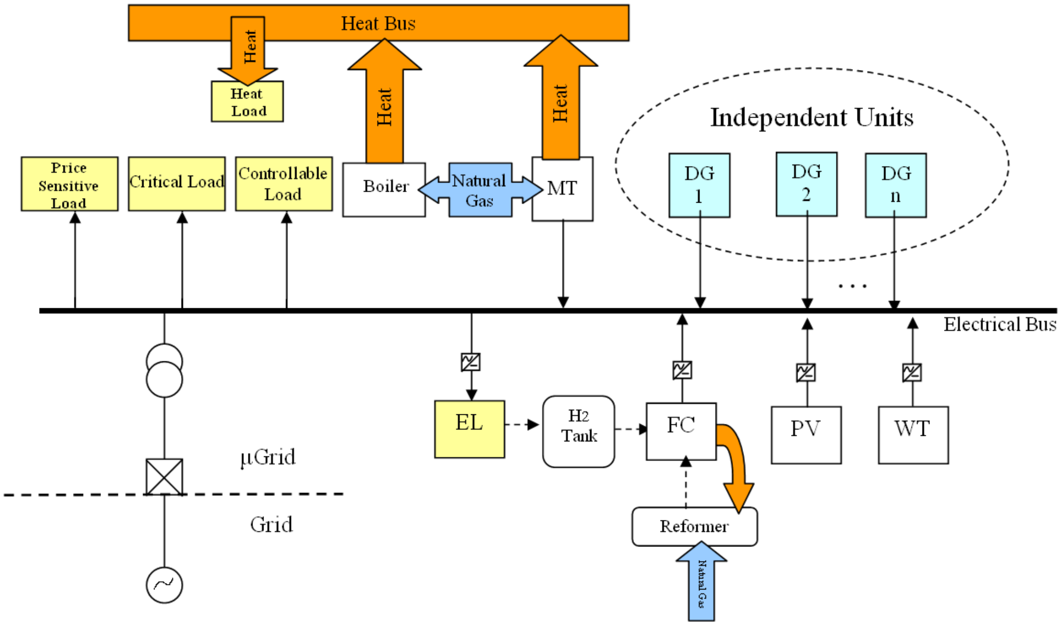

Fig. 1. Microgrid Architecture

$$OF = Max \sum_{i=1}^{24} (Income_i - Cost_i) \tag{1}$$

The first term of the objective function is the total system income pertaining to income from the sale of electrical energy to local grid and consumers in microgrid control area and income from the sale of thermal energy. The second term of the objective function is the overall operational cost. This cost includes the cost of purchased electrical energy from independent generator units, the cost of purchased energy from local grid, the cost of purchased gas for thermal loads if there is insufficient production of thermal energy (included in boiler cost function), the cost of energy produced by generator units belongs to micro grid such as microturbine, fuel cell, PV and wind turbine and the cost of energy storage system. We also consider a penalty for MMS when load management strategy is applied to controllable loads.

It is important that the above function subject to the various constraints.The MMS must handle the technical coordination among the MG units, the interconnected power grid, independ units and Loads.

The extended state of the (1) is presented in (2) as follow;

$$\begin{aligned} OF = Max \sum_{t=1}^{24} \{ & P_G(t) \cdot p_G(t) \\ & + \sum_{i=1}^{x} (P_{L\text{-}i}(t) \cdot p_{L\text{-}i}(t)) + P_{therm}(t) \cdot p_{therm}(t) \\ & - \{ \sum_{j=1}^{y} u_j(t) \cdot P_j(t) \cdot p_j(t) + \sum_{k=1}^{z} C_{mt\text{-}k}(P_{mt\text{-}k}(t)) + C_{fc}(P_{fc}(t)) \\ & + C_{el}(P_{el}(t)) + C_{therm}(P_{therm}(t)) + C_{L}(P_{sh}(t)) \} \} \end{aligned} \tag{2}$$

In the above equation we encounter to following terms:

- **Power trade with the local grid:** The model considers the possibility of selling and buying energy from the local grid. The power (P_G) with positive sign means that we are selling energy to local grid and vice versa.
- **Microturbine:** In this work the following convex quadratic function cost is used for MT units:

$$\begin{aligned} C_{mt\text{-}k} = {} & \alpha_{mt\text{-}k} + \beta_{mt\text{-}k} P_{mt\text{-}k} + \gamma_{mt\text{-}k} P_{mt\text{-}k}{}^2 + \\ & (\alpha_{stmt\text{-}k} + \beta_{stmt\text{-}k}(1 - e^{-\frac{t_{off}}{\tau}})) \times u_{mt\text{-}k}(t)(u_{mt\text{-}k}(t) - u_{mt\text{-}k}(t-1)) \end{aligned} \tag{3}$$

First term of the (1) is operation cost and second term considers start-up cost for MT units that belong to MG.

In this work, the thermal load is satisfied by utilizing the recovered thermal energy from the microturbine and, if necessary, through the direct use of natural gas by boiler. Thermal energy for the MT is considered as a by-product, which is a function of electrical power output of MTs [4].

- **Electrolyzer:** The following equation can be used to define the H_2 production cost for electrolyzer:

$$\begin{aligned} C_{el} = {} & \\ & [(\alpha_{el} + \beta_{el}(1 - e^{-\frac{t_{off}}{\tau}})) \times u_{el}(t)(u_{el}(t) - u_{el}(t-1))] + OM_{el} \end{aligned} \tag{4}$$

Where C_{el}, does not depend on the power (since the electrolyzer and the fuel cell lifetimes have been considered as not dependent on the power) [5]-[7].

- **Fuel Cell**: the cost function for fuel cell can be formulated as following equation:

$$\begin{aligned} C_{fc} = {} & c_{Ng} \cdot \dot{G} + \\ & [(\alpha_{fc} + \beta_{fc}(1 - e^{-\frac{t_{off}}{\tau}})) \times u_{fc}(t)(u_{fc}(t) - u_{fc}(t-1)] + OM_{fc} \end{aligned} \tag{5}$$

The first term of the (5) is the cost of the hydrogen production in reformer unit that is proportional to natural gas price and natural gas consumption rate of the reformer.

The second term represents the start up cost and the last term is the operation and maintenance cost of the FC.

H_2 fuel cost is not considered in (5), because the fuel cell consumes H_2 previously produced by the electrolyzer. We have not included the H_2 tank costs, since we have considered both the lifetime and the O&M costs as fixed, therefore, they do not depend on the performance of the electrolyzer and the fuel cell [5]-[7].

- **Load Shedding**: Curtailment options of final retail customers are also modeled as a convex quadratic cost function

$$C_L = \beta_L P_{sh} + \gamma_L P_{sh}^{\ 2} \tag{6}$$

On the other hand, C_L is a penalty for MMS because the MMS cannot supply energy for controllable load [8].

B. Remarks

- Since the WT and PV deliver free cost power, the output power is not considered in optimization function, instead output power of these units are treated in power balance equality constraint.
- Power output of WT is calculated according to the relation between the wind speed and the output power [9].
- Power output of PV is calculated according to the effect of the temperature and the solar radiation that are different from the standard test condition [9].
- For DG units, Bid of price and capacity is important for MMS, so generator type and other details of these units are not required for MMS.
- Since the renewable sources characteristic is far from reliably predictive, the integration of wind and solar resources into generation planning requires the consideration of generation uncertainty, so we considered uncertainty for renewable energy generators to prevent overestimation of mentioned units [10].

C. System Constraints

The proposed OF exhibits equal, unequal, linear, and nonlinear constraints that can be summarized as follows:

- Power Balance: To meet the active power balance and heat energy balance, two equality constraints are imposed (in each hour)

$$\sum_{i=1}^{x} P_{L\text{-}i} + P_{el} = \tag{7}$$

$$P_G + \sum_{j=1}^{y} P_j + \sum_{k=1}^{z} P_{mt\text{-}k} + P_{wt} + P_{pv} + P_{fc}$$

$$P_{boi} + \sum_{k=1}^{z} P_{thMT\text{-}k} = P_{therm} \tag{8}$$

- Microturbine constraints

$$P^{\min} \le P_{mt\text{-}k} \le P^{\max} \tag{9}$$

$$(T_{i-1}^{on} - MUT)(u_{i-1} - u_i) \ge 0 \tag{10}$$

$$(T_{i-1}^{off} - MDT)(u_i - u_{i-1}) \ge 0 \tag{11}$$

- Fuel cell constraint

$$P^{\min} \le P_{fc} \le P^{\max} \tag{12}$$

- Electrolyzer constraint

$$P^{\min} \le P_{el} \le P^{\max} \tag{13}$$

- H_2 tank constraints

$$\frac{H_v(t+1) - H_v(t)}{\Delta t} = \dot{H}_e - \dot{H}_f \tag{14}$$

$$V^{\min} \le H_v \le V^{\max} \tag{15}$$

- Controllable load constraints

$$P_{\min} \le P_L \tag{16}$$

$$T_{shed} \le T_{\max} \tag{17}$$

V. SOLUTION METHODOLOGY

In this paper, the PSO algorithm was utilized mainly to determine the optimal operation plan of Microgrid components on next day. We use the HPSO algorithm process to solve the objective function, since the objective function contains binary and continue parameters [11], [12].

PSO, as an optimization tool, provides a population-based search procedure in which individuals called particles change their positions (states) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and the experience of neighboring particles, making use of the best position encountered by itself and its neighbors. The swarm direction of a particle is defined by the set of its neighboring particles and its history experience.

VI. TEST AND RESULT

We considered three MTs with different cost function coefficient and capacity. Main specification for MTs is presented in Table I.

TABLE I
MTs Specification

	P_{min} (kW)	P_{max} (kW)	α (¢)	β (¢/kW)	γ (¢/kW^2)	α_{mtst} (¢)	β_{mtst} (¢)
MT 1	0	300	3	0.1	0.0003	10	20
MT 2	0	300	5	0.3	0.0004	12	24
MT 3	0	200	9	0.7	0.0005	12	18

Table II gives specifications of FC and electrolyzer , in this table unit capacity and start-up costs are presented.

Table III present the main parameters for controllable load. These parameters include minimum allowable demand, maximum duration of curtailment strategy and penalty coefficients.

Also we have considered a PV array with 40 kW capacity and a wind turbine which have 100 kW rated power. Forecasted power from these units are illustrated in Fig. 2.

As mentioned before, 4 load type considered in this work. electrical energy price for sensitive to price load and controllable load is the same and is lower than critical load price, also Long term bilateral contracts specify heat energy price for these consumers. Requested demand for next day is shown in Fig. 3.

The price of electrical and thermal energy for loads and forecasted price for exchange with local grid (selling/purchasing) is shown in Fig. 4.

In the microgrid model two independent DG is considered in MG control area. In Fig. 5 and Fig. 6, we illustrated capacity and price offer for DG 1 and DG 2 respectively.

Operation schedule (as output of Objective Function) for proposed microgrid is shown in Fig. 7.

TABLE II

FUEL CELL AND ELECTROLYZER SPECIFICATION

	P_{min} (kW)	P_{max} (kW)	α_{el}, α_{fc} (¢)	β_{el} , β_{fc} (¢)
Fuel Cell	0	200	5	15
Electrolyzer	0	140	5	17

TABLE III

CONTROLLABLE LOAD SPECIFICATION

	P_{min} (kW)	T_{max} (h)	β_L (¢)	γ_L (¢)
Controllable Load	50	4	6	0.001

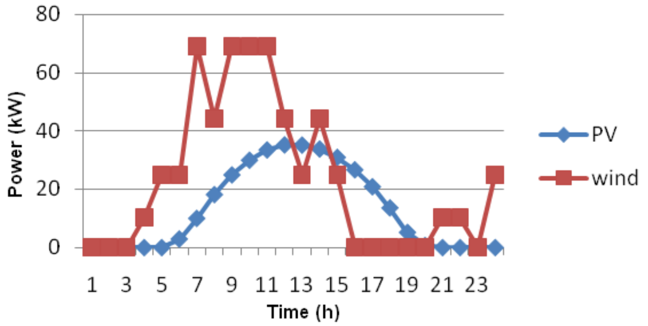

Fig. 2. PV and WT forecasted power (kW)

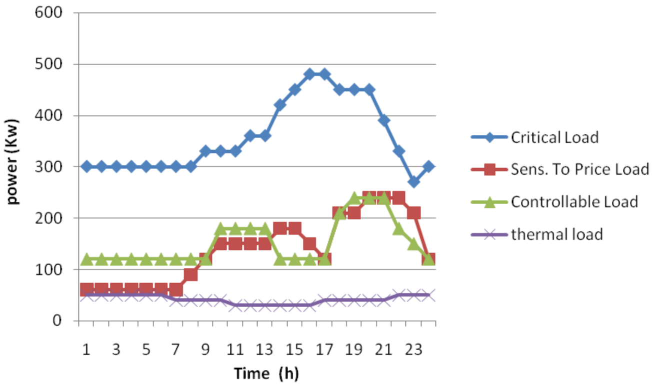

Fig. 3. Requested demand for MG loads (kW)

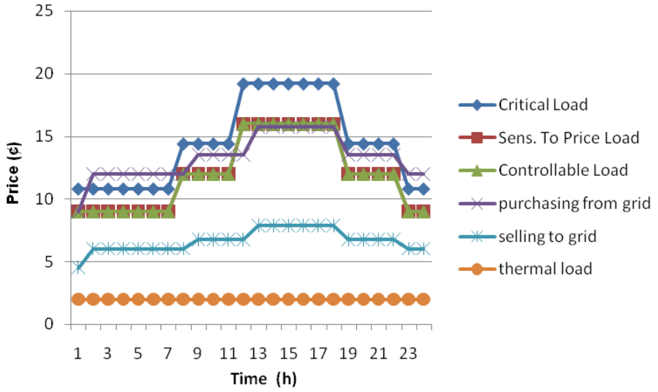

Fig. 4. Price of electrical and thermal energy (¢)

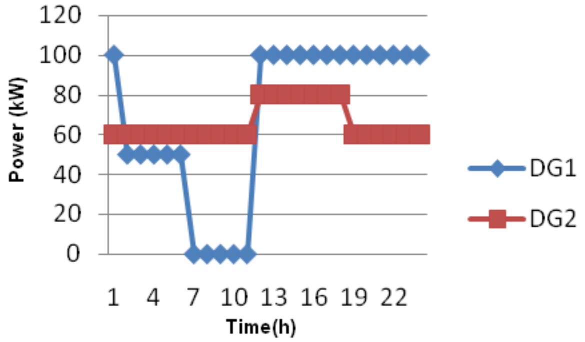

Fig. 5. Offered capacity of DG units (kW)

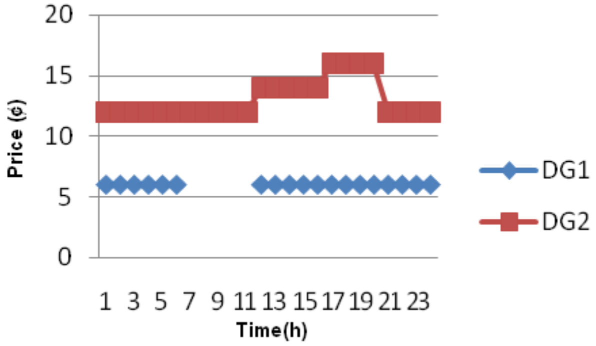

Fig. 6. Offered price of DG units (¢)

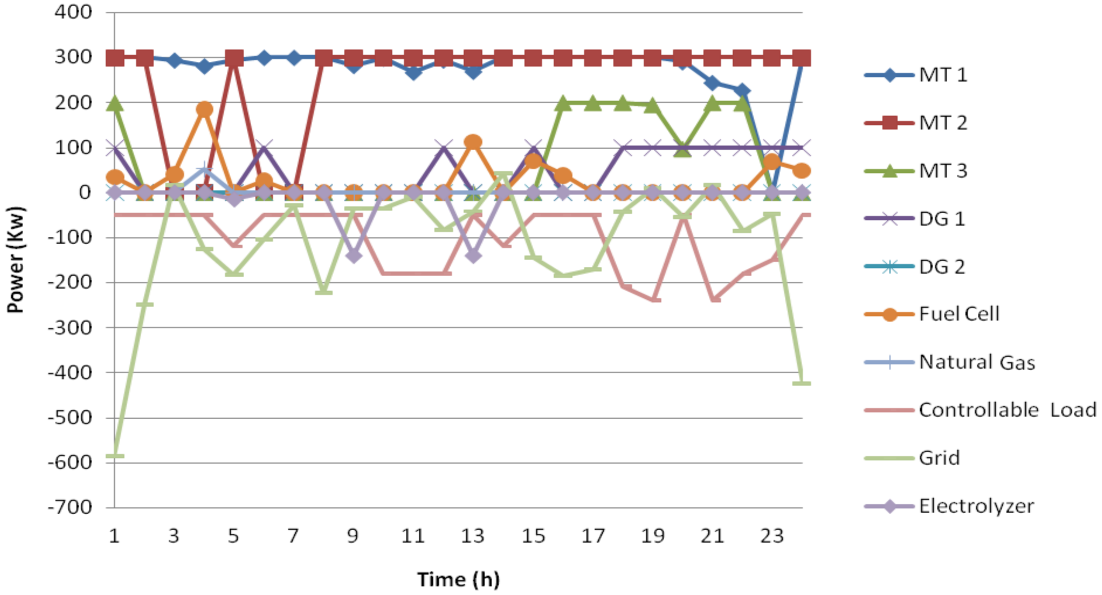

Fig. 7. Microgrid Operation Schedule

VII. CONCLUSION

In this work an objective function is constructed to determine the optimum operation of proposed MG. The optimization problem includes a variety of power system components that are likely to be found in a microgrid: a fuel cell, a microturbine, PV arrays, wind generators, electrolyzer, H_2 tank, boiler, reformer and electrical and thermal loads. Also this system considers possibility of power trade with local grid. Constraint functions are added to the optimization problem to reflect some of the additional considerations often found in a small-scale generation system. Because of the microgrid is a novel concept in power system, we didn't have a reliable reference for results comparison, but from the results obtained in previous section, it is clear that operation schedule for the MG is acceptable and reasonable.

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