Multi - Party Energy Management of Microgrid with Heat and Electricity Coupled Demand Response

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***Abstract*—Combined heat and power (CHP) based Microgrids (MG) are quite popular. They can generate electricity based on electric or thermal demand. A framework of multi -party energy management is proposed in this paper with heat and electricity demand for the CHP -MG. Paper also delves on energy management of MG provided by CHP and photovoltaic (PV) prosumers. A model of Microgrid Operator (MGO) is developed to determine the operational profit of CHP system where MGO acts as a leader and prosumers are the followers. The main objective of MGO is economic operation of MG or to minimize the net cost of generation from Distributed energy resources and purchasing energy from the grid. It is established by simulation that the CHP system operating in hybrid mode by selecting following electric load (FEL) mode and following thermal load (FTL) mode dynamically the most economic operation of CHP is achieved. A dealing process between MGO and prosumers is also modeled. Lastly, a case study with CHP -MG and 6 building users are presented to verify the effectiveness of the model and to show the economic benefit of having the MGO along with the prosumers in a MG.**

Keywords—Combined Heat Power (CHP), Microgrid (MG), energy management, photovoltaic (PV), model, Microgrid Operator (MGO), economic operation of MG

I. Introduction

Till the last decade emphasis was on centralized generation of electrical power and economics of scale. In recent years the power sector is facing various challenges like ever increasing demand of electric energy, heat energy, protection from different environmental conditions, reliability, cleanness of energy and restriction of planning. A paradigm shift is being observed for connecting small renewable energy generation system to the distribution end of the power system. The concept of Microgrid (MG) came into existence as a consequence of this change [1]. MG operates as a single unit which may include a cluster of loads and Distributed energy resources (DER) systems and operates in isolate mode or grid connected mode. The DER system may include micro turbine (MT), photovoltaic (PV) cells, fuel cells (FC), energy storage system (ESS) etc.

The MT can supply both electric power and heat from its exhaust gas. The MT based combined heat power (CHP) system is considered as one of the DERs in the MG. CHP systems can function under two different operating strategies namely generation following heat load (FEL) and generation following thermal load (FTL) [2-3]. Further, the electric appliances loads are generally classified in two groups: one the base load which is fixed & which cannot be scheduled and the other is the variable loads that is flexible and treated as variable during scheduling. Various studies have been concentrated on the operation of CHP - MG including control model [4], optimal scheduling [5-8], feasibility analysis [9-11] etc. Generally the primary energy saving and consumption [12], total profit by sending power to the end user [8] and overall cost of operation [13] are used to represent the cost efficiency of CHP system.

A micro grid operator (MGO) is proposed which decides the operation strategy of the MG as per the total energy demand of the end users. The main objective of the operation is to increase the economic benefits or reduce the net cost of generation of DER and cost of energy purchased from the grid.

Various efforts have been taken to understand the energy management problem of the microgrid with multiparties. The associating parties for the operation are mainly classified as seller or buyer [16-19] who have fixed role in the market. The buyers are generally assumed as passive consumers [14-15].

The operation of distribution system can be influenced by large scale integration of PV. Many countries have energy policies that encourages their end users to install PV energy systems. The electricity thereby generated can be consumed by themselves or can be exported to utility grid. Thus the concept of Prosumers evolved who can generate power for themselves as well as consume power.

The present work proposes a multi - party energy management system for economic operation of MG. The generation for the MG is provided from a CHP system operating in following electric load (FEL), following heat load (FHL) mode and following hybrid load (FHL) mode and a base generation capacity provided by PV sources during day time. In various studies it have been found that parties are either seller or buyer with no mixed role in the system. PV Prosumers are considered which are the end users, well equipped with PV system. The prosumers can act

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as both load and supply of electricity to the MG. However, in this paper, a prosumer can change his/her role to a buyer or a seller during different time periods, depending on the circumstance and net power requirement.

This paper considers each prosumer with same authority in the microgrid operation. Thus we consider MGO as the leader to take decision over selling and buying price of required power. Here the prosumers act as follower to adjust there energy consumption behavior under varying price condition.

The economic operation of the MG is controlled by a MGO to provide minimum cost of power to the user.

The organization of this paper is as follows. The microgrid energy management framework and CHP the power generating system with PV as the generating resource at the user end have been discussed in section II. The different model of CHP - MG being depicted in section III. Section IV describes the algorithm to define the economic model of microgrid. Different Case studies from the economic model are presented in section V. Section VI outlines the conclusion of this paper.

II. Energy Management Framework

The CHP operator with heat and electric power flow to the user is shown in “Fig. 1”. The architecture of MG is shown in “Fig. 2”. The different entities involved in the MG are-

1. CHP power generating system
2. PV generating resources of the prosumers.
3. The energy management system MGO.

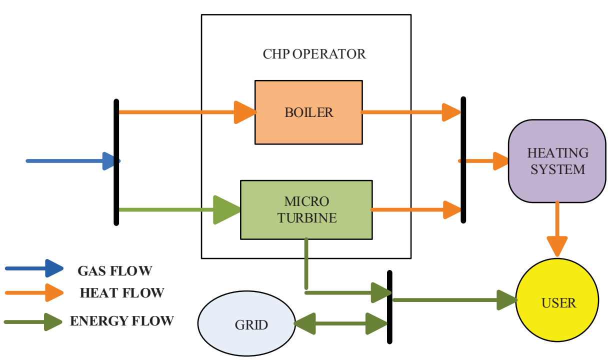

Fig. 1. Schematic diagram of CHP

CHP system is basically the combination of MTs and Boilers. The output of CHP system is of two types namely the electric energy from the MTs and the thermal energy from its exhaust and from the boiler depending upon the requirement of the end users. This frame work is considered for the joint operation of FTL/ FEL modes of CHP and the PV prosumers inside the grid connected MG with the interaction between MGO and prosumers.

PV Prosumers are the end users well equipped with PV system on the roof top. The prosumers can act as both load and supply of electricity to the MG. Extra energy required by the prosumers can be drawn from the MGO with an internal buying price P_mb when the total consumption is greater than the self-produced PV energy. There is an internal selling price P_ms by which prosumers can sell their surplus energy to MGO.

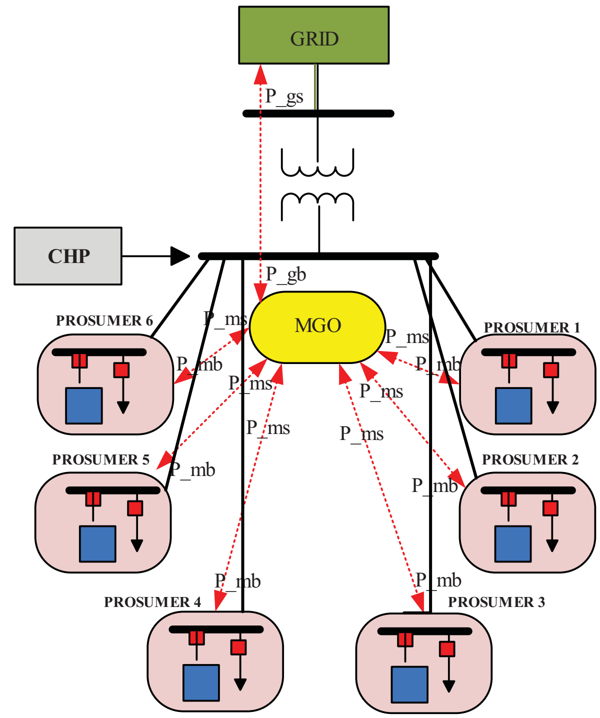

Fig. 2. The Framework of Energy Management of MG

MGO is responsible for energy sharing optimization among the PV prosumers. The MGO is given the charge of supplying heat load (in winter) to the prosumers in MG. It also purchases electric power from the grid and from the prosumers with surplus power output and then sell the surplus power to the end users within the MG. The MGO schedules the demand from the grid to balance the demand and generation when there is some internal power mismatch between demand from load and generation from PV. The price of exporting and importing energy are denoted as P_gs and P_gb respectively. The internal selling and buying price denoted with P_ms and P_mb with the prosumers are also set by the MGO.

An optimization model of the MGO system is established for profit of the CHP system by selecting FTL and FEL mode dynamically which includes the cost of gas, profit from the selling energy to the end users/ consumers and by selling the extra electricity to the utility grid. Another operating mode based on both heat and electricity, namely generation following hybrid load (FHL) is also proposed.

The paper further discusses the framework of energy management inside the grid connected MG for the combined operation of CHP and PV prosumers by considering the interrelation between prosumers and MGO with autonomous demand response (ADR).

III. Model of CHP – MG

A. Model of the Prosumers

1) Requirements of Electric Loads

All prosumers connecting with MGO are having a particular proportion of flexible load, which means they can adjust the time as well as the size of the load. Generally, the electric load of the prosumers is comprised of two types which are fixed load and shiftable loads.

a) Fixed loads

The different requirements of fixed loads are high reliability and a fixed or unchanged power supply. The different loads such as televisions, refrigerators, lights, fans etc. are taken as the fixed loads for the daily life convenience. The fixed loads (EFL_i^h) of i[th] buildings in h[th] time slots are given as:

$$EFL_i^h = \left[efl_1^1, efl_2^2, efl_3^3 \ldots\ldots efl_n^h \right] \ldots\ldots\ldots\ldots (1)$$

Where n is the total number of prosumers.

b) Shiftable loads

In case of shiftable loads the prosumers can select the time of electricity use as per the price of the electricity. In this paper the end users have some of shiftable loads (equipment or appliances) for their use. Such appliances may include dryer, washer, etc. The shiftable loads (ESL_i^h) of i[th] buildings in h[th] time slots are given as:

$$ESL_i^h = \left\lfloor esl_1^1, esl_2^2, esl_3^3 \ldots\ldots esl_n^h \right\rfloor \ldots\ldots\ldots\ldots (2)$$

Where n is the total number of prosumers.

So, the total electric load $\left(TEL_i^h\right)$ is given as:

$$TEL_i^h = EFL_i^h + ESL_i^h \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Net electrical load (NEL_i^h) is given as

$$NEL_i^h = TEL_i^h - PV_i^h \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where PV_i^h is the amount of total generated solar based electrical energy for i[th] building in h[th] time slot and can be given as:

$$PV_i^h = \left[pv_1^1, pv_2^2, pv_3^3 \ldots\ldots\ldots pv_n^h \right] \ldots\ldots\ldots (5)$$

Where i varies from 1 to n.

2) Requirement of Heat Load

The thermal demand of prosumers is met using the heat produced by the CHP. The thermal demand of the end user may consist of hot water in winter and heat for other domestic work. The total heat demand (HL_i^h) of the prosumer in h[th] time slots can be defined as:

$$HL_i^h = \left\lfloor hl_1^1, hl_2^2, hl_3^3 \ldots\ldots\ldots hl_n^h \right\rfloor \ldots\ldots\ldots\ldots\ldots (6)$$

Where i varies from 1 to n.

IV. Economic Model of MG and Algorithm

A. Basic profit model of MGO

MGO is uses a model to maintain the profit of prosumers and also for MGO who is given the charge of supplying heat load to the prosumers in MG. It also purchases electric energy from the grid and from the prosumers with surplus power output and then sell the surplus power to the end users within the MG.

Profit of MGO (Pro_m_g) by selling/ buying power to/ from grid in h[th] time slot is given as:

$$\begin{aligned} &\Pr o\_m\_g(1,h) = -P\_gs(1,h) * \min(Net\_load(1,h) \\ &ep\_chp(1,h),0) - P\_gb(1,h) * \max(Net\_load(1,h) - \\ &ep\_chp(1,h),0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7) \end{aligned}$$

Profit of MGO (Pro_m_u) by selling/ buying power to/ from prosumers in h[th] time slot is given as:

$$\begin{aligned} &\Pr o\_m\_u(1,h) = (P\_ms(1,h) * \max(Net\_load(1,h) \\ &,0)) + (P\_mb(1,h) * \min(Net\_load(1,h),0)) \ldots\ldots\ldots (8) \end{aligned}$$

Profit of MGO (Pro_m_ht) by selling heat load to the prosumer in h[th] time slot is given as:

$$\Pr o\_m\_ht(1,h) = ht\_r * P\_ht\_sum(1,h) \ldots\ldots\ldots (9)$$

Running cost of the CHP (C_chp) plant in h[th] time slot is given as:

$$C\_chp(1,h) = p\_gas * (ep\_chp(1,h) * L * n\_chp) \ldots (10)$$

The total profit of MGO (Pro_m) by selling power /buying power to/from grid is given as:

$$\begin{aligned} &\Pr o\_m(1,h) = \Pr o\_m\_g(1,h) + \Pr o\_m\_u(1,h) + \\ &\Pr o\_m\_ht(1,h) - C\_chp(1,h) \ldots\ldots\ldots\ldots\ldots\ldots (11) \end{aligned}$$

Where P_gs is the selling price of power by MGO to the main grid, ep_chp is the electrical power generated by CHP, P_gb is the buying price of power by MGO from the main grid, P_ms is the selling price of power by MGO to the prosumers, P_mb is the buying price of power by MGO from prosumers, ht_r is the price rate of supplied heat load, P_ht_sum is the total heat demand of prosumers, p_gas is the price of natural gas, L is the heat content of natural gas and n_chp is the electrical efficiency of the CHP plant.

The total profit of prosumers consists of the following paramters: expenditure of buying electric and thermal load from MGO, selling electricity to MGO and the subsidy provided by government for using of PV generation.

Profit of Prosumers (Pro_prosumers) can be written as:

$$Pro\_prosumer(1,j) = ki * \ln(1 + total\_load(1,j)) - P\_ms(1,j) * \max(Net\_load(1,j),0) - P\_mb(1,j) * \min(Net\_load(1,j),0) - ht\_r * P\_ht\_sum(1,h) + pv\_sum(1,j) * pv\_rate \qquad (12)$$

Where pv_sum is the electric energy provided to the distribution system systems and pv_rate is the subsidy rate per kWh from government.

The algorithm for the profit of MGO and prosumers are given below:

1. Set MGO selling & buying price with external grid.
2. Set MGO selling & buying price to and from prosumers.
3. Calculation of hour slot wise total heat load using equn.6.
4. Calculation of hour slot wise total electrical fixed load using equn. 1.
5. Calculation of hour slot wise total electrical shiftable load using equn. 2.
6. Calculation of PV output from the prosumers.
7. Calculation of total load and net load using PV output.
8. For each user $i \in n$

(a) If (net load > 0) then

MGO profit from prosumer = (P_ms * 0.4 * net load + (P_ms+2.5) * 0.6 * net load)

(b) Else

MGO profit from prosumer = -[P_mb * 0.4 * net load + (P_mb+2.5) * 0.6 * net load]

(c) End if

(d) Consider MGO profit by selling heat load using equn. 9.

(e) Consider the running cost of CHP plant using equn. 10.

9. Calculation of total MGO profit.
10. End for
11. For each user $j \in n$
12. Calculation of prosumer profit using equn. 12.
13. End for

V. Case Study

A. Basic Prosumer data

This paper considers 6 residential buildings as prosumers who are members of the MG. The electrical fixed load, electrical shiftable load and heat load are given in fig. 3, fig. 4 and fig. 5 respectively of the prosumers. In this paper, a day is categorized in 6 slots, where each slots depicts 4 hours. Slot 1 represents time from 6am to 10am, slot 2 from 10am to 2pm and the 6th & last slot ends at 6am on the next day. The peak of electric fixed load and shiftable load is considered about 19:00 to 22:00 hours as shown in fig. 3 and fig. 4 respectively.

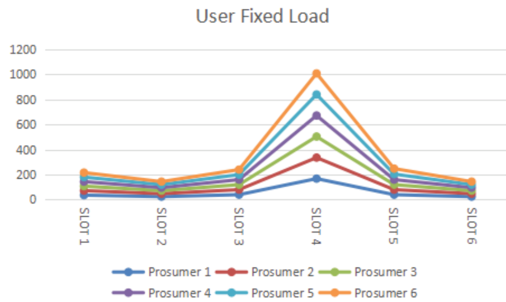

Fig. 3. Prosumer Electric Fixed Load

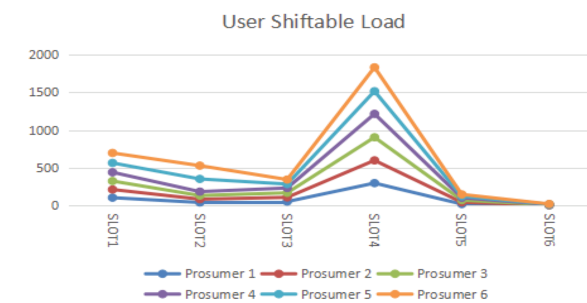

Fig. 4. Prosumer Electric Shiftable Load

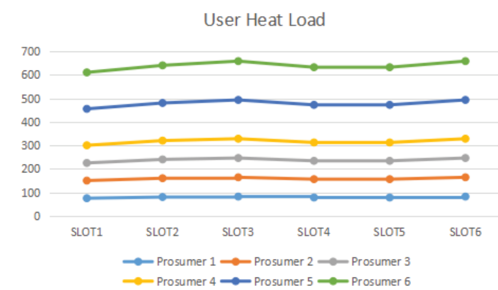

Fig. 5. Prosumer Heat load

B. Simulation and Results

The above model is implemented on MATLAB platform and is used for analyzing and solving the issue. Fig. 9, Fig. 10 and Fig. 11 indicate the profit of MGO under different mode of operation like following thermal load (FTL), following electric load (FEL) and following hybrid load (FHL) without source at user end. Fig. 6, Fig. 7, Fig. 8 represents the profit of MGO under different mode using net demand from the prosumers.

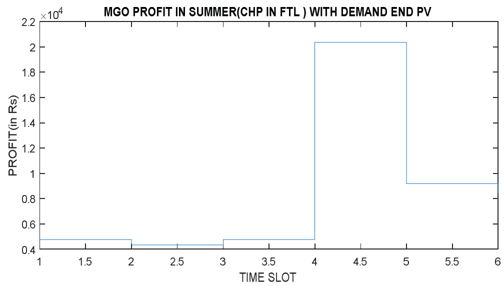

Fig. 6. Profit of MGO at FTL mode with user end PV source

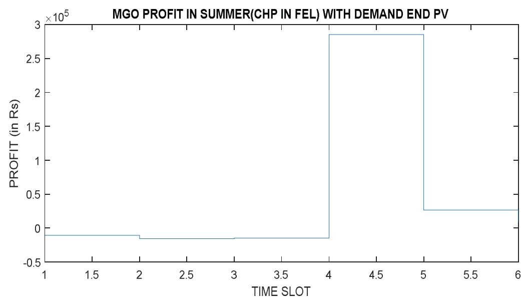

Fig. 7. Profit of MGO at FEL mode with user end PV source

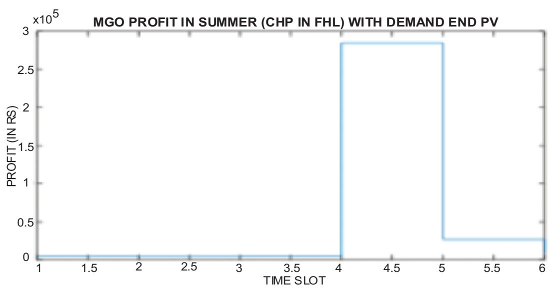

Fig. 8. Profit of MGO at FHL mode with user end PV source

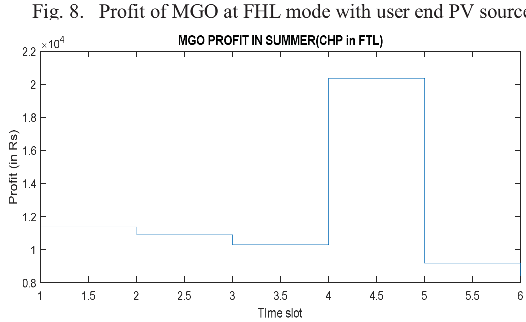

Fig. 9. Profit of MGO at FTL mode

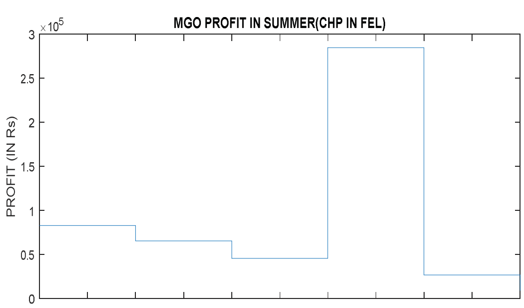

Fig. 10. Profit of MGO at FEL mode

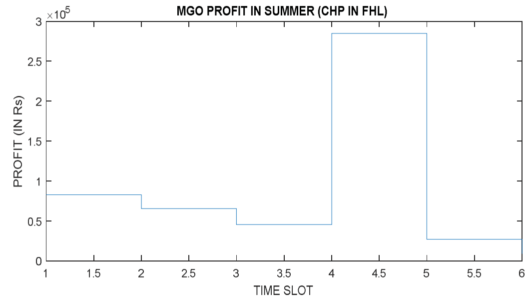

Fig. 11. Profit of MGO at FHL mode

C. Profit results

The total profit of prosumers at FEL, FTL mode without PV and with PV connection is shown in TABLE I. And the total profit of MGO at FEL, FTL and FHL mode are shown in TABLE II. The positive sign in Table I indicates the profit of prosumers when they are using PV source to mitigate their demand but the negative sign shows the expenditure of the prosumers when running without PV source and buying all the required energy (thermal/ electric) from MGO.

TABLE I. PROSUMER PROFIT IN DIFFERENT MODE OF OPERATION

DIFFERENT MODE	PROFIT (Rs.)					
	SLOT 1	***SLOT 2***	***SLOT 3***	***SLOT 4***	***SLOT 5***	***SLOT 6***
	WITHOUT PV SOURSE					
FTL	-7665.8	-7686.7	-7718.1	-7547.9	-7761.6	-7850.5
FEL	-82958	-65560	-45325	-287032	-26633	-9086
	WITH PV SOURSE					
FTL	10511.8	12970.6	11299.5	-7547.9	-7761.6	-7850.5
FEL	-1931.1	-3500.7	-5228.4	-287032	-26633	-9086.9

TABLE II. MGO PROFIT IN DIFFERENT MODE OF OPERATION

DIFFERENT MODE	PROFIT (Rs.)					
	SLOT 1	***SLOT 2***	***SLOT 3***	***SLOT 4***	***SLOT 5***	***SLOT 6***
	WITHOUT PV SOURSE					
FTL	11374.6	10898.2	10304.1	20352	9185.53	8424.22
FEL	82761.2	65520	45461.1	284820	26923.1	8959.9
FHL	82761.2	65520	45461.1	284820	26923.1	8959.9
	WITH PV SOURSE					
FTL	4768.73	4348.45	4762.53	20352	9185.53	8424.22
FEL	-10598	-15230	-14522	284820	26923.1	8959.94
FHL	4768.73	4348.45	4762.53	284820	26923.1	8959.94

D. Comparison with the Existing System

Fig. 12 shows the profit of MGO for the existing system which considers only FEL mode of operation. The profit earned by the proposed system using FHL mode is depicted in fig. 8. The hour slot wise and the total profit of MGO for the existing system and the proposed model is depicted in Table III. It is observed that the total profit of MGO is greater than that of existing system considering a complete 24 hours of a day.

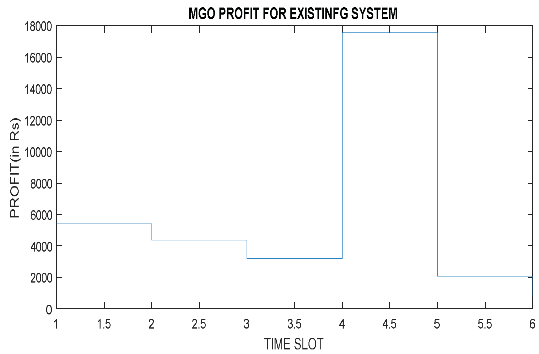

Fig. 12. Profit of MGO for Existing System

TABLE III. COMPARISON OF MGO PROFIT

DIFFERENT MODE	PROFIT (Rs.)						
	SLOT 1	***SLOT 2***	***SLOT 3***	***SLOT 4***	***SLOT 5***	***SLOT 6***	***TOTAL PROFIT***
WITHOUT PV SOURSE							
FHL	82761.2	65520	45461.1	284820	26923.1	8959.9	514445.3
WITH PV SOURSE							
FHL	4768.73	4348.45	4762.53	284820	26923.1	8959.94	334582.75
EXISTING SYSTEM							
FEL	11806.6	11466.6	11070.3	23560.6	10693.1	10284.1	78881.3

There is a decrements of profit earned by the MGO when PV is connected at prosumer end. This is due to the savings earned by the prosumer by consuming power generated by its PV source.

VI. Conclusion

This paper proposes an energy management system for prosumers having CHP and PV sources and are placed in a grid connected MG. Two operating modes are possible namely FEL and FTL. An hybrid of the two mode is also possible by selectively using FEL and FTL in different slots. This method considers the MGO's viewpoint to coordinate between CHP and PV prosumer to maximize profit of end users and MGO. The results shows that the profit of MGO is increased in FHL mode in comparison to FEL and FTL mode of. Similarly on the basis of profit of MGO it is depicted that the proposed methodology generates more profit with respect to the existing models. The end users earn saving during day time when they are connected with PV sources on the roof top whereas at night with PV not generating energy there is no saving.

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