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Smart Load Management in Distribution Networks Incorporating Different Load Sectors using PSO

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Abstract— The excess loads nowadays arising in Egypt brings the monitoring and control of the loads to be the most complicated phenomena facing the electricity utility in Egypt. The main objective of this research is to utilize demand side management (DSM) in order to minimize the peak demand within each of residential, commercial and industrial sectors. This research takes into consideration both utility and customer benefits using particle swarm optimization PSO. Load shifting DSM technique is used to schedule controllable devices of different types at various hours of the day bringing the final load curve closer to an objective load curve. Half hourly forecasted load data and half hourly forecasted pool market price and time of day (TOD) tariff are the inputs given to the DSM program. The proposed algorithm is applied to Alexandria power grid and the simulation results show that the proposed DSM technique comprehends reasonable savings to both utility and consumers simultaneously, while reducing the system peak.

Key Terms—DSM, PSO, TOD, Load Shifting.

1. INTRODUCTION

A smart grid is the use of sensors, communications, computational ability and control in some form to enhance the overall functionality of the electric power delivery system [1].
The Classical configurations of electric energy systems are unidirectional and top-down oriented. A limited number of large power plants participate into the grid trying to preserve the balance between demand and supply. The Increasing share of volatile renewable electricity generation and peak load capacity required for relatively few hours have increased the focus on demand side participation [2],[3].

The grid capacity has raised questions about the transport of energy. Limits of the grids might be soon reached, and intelligent Demand Side Management (DSM) is one way to expand these limits a bit further [3].
Dealing with the load as an additional degree of freedom is not entirely new trend but developing communication infrastructure and embedded systems make it now relatively easy to introduce the concept of "smart" loads [3].
Demand Side Management (DSM) can be defined as a set of measures that allows the energy providers to reduce the peak load demand and reshape the load profile aiming to improve the energy system at the side of consumption [4], [5].
Programs of DSM are expanding in response to the high load growth and the increasing cost and time required bringing new generation into service [6].

As an integral function of the smart grid, DSM involves the use of smart metering technology and TOD tariffs. TOD tariffs, i.e. different prices in different times of the day, reflect electricity costs and the ability of the utility to produce the energy needed. The objective of tariffs is to motivate the customers shift their demand to off-peak period when the electricity price is lower and when it is more convenient for the utility to produce electricity [7], [8].

Researches that have been carried out in DSM utilized several algorithms to solve the problem. Some used multiagent approach as in [8], [9], some used evolutionary algorithm as in [13], [14]. Most of the techniques were developed using dynamic programming [10] and linear programming [11], [12]. However, these programming techniques cannot handle a large number of controllable devices of different types which have several computation patterns and heuristics.

In this paper particle swarm optimization (PSO) approach is tested and simulated. PSO algorithm has the ability to handle large solution space which is the case of the research as it deals with different load sectors including a large number of devices with different ratings.
Earlier researches demonstrated benefits to utilities through DSM implementation [11], [13]. In this paper, the main objective is not only the benefit of the utility but also that of the consumers.
Load shifting DSM technique is used to schedule controllable devices of the load sectors residential, commercial and industrial consumers at various hours of the day.
The daily load curve for different sectors is being built based on the summation of controllable loads for each sector.

Simulation studies are carried out on a smart grid which has different types of customers with a variety of loads. The remaining paper is organized as follows. Section II presents the proposed demand side management strategy and formulates load shifting technique mathematically. Section III briefly explains the PSO adaptation for the algorithm. Section IV provides the details of the test system. Section V presents simulation results and discussion. Section VI concludes the paper.

2. Proposed Demand Side Management Strategy

A. Problem Statement and Formulation

The principle of the proposed DSM technique is based on shifting the operation time of each controllable device in the system to bring the final load curve closer to an objective load curve.
Mathematical formulation of the proposed DSM technique is given as follows.

Minimize

$$\text{Fitness} = w_{res} * \text{fit}_{\text{res}} + w_{comm} * \text{fit}_{\text{comm}} + w_{ind} * \text{fit}_{\text{ind}} \quad (1)$$

And since there are three main loads which are Residential, commercial and industrial
The fitness equations are stated as follows

$$\text{fit}_{\text{res}} = \sum_{t}^{n}\left(\text{R}_\text{x}(\text{t}) - \left(\text{w}_1 * \text{obj}_{\text{res}_{\text{cu}}}(\text{t}) + w_2 * \text{obj}_{\text{res}_u}(\text{t})\right)\right)^2 \quad (2)$$

$$\text{fit}_{\text{com}} = \sum_{t}^{n}\left(\text{C}_\text{x}(\text{t}) - \left(\text{w}_1 * \text{obj}_{\text{com}_{\text{cu}}}(\text{t}) + w_2 * \text{obj}_{\text{com}_u}(\text{t})\right)\right)^2 \quad (3)$$

$$\text{fit}_{\text{ind}} = \sum_{t}^{n}\left(\text{I}_\text{x}(\text{t}) - \left(w_1 * \text{obj}_{ind_{\text{cu}}}(\text{t}) + w_2 * \text{obj}_{ind_u}(\text{t})\right)\right)^2 \quad (4)$$

Where,

$R_x(t)$, $C_x(t)$, $I_x(t)$ are the consumption of power after shifting at time **t** of Residential, Commercial and industrial, respectively.
$\text{obj}_{\text{res}_{\text{cu}}}(t)$, $\text{obj}_{\text{com}_{\text{cu}}}$, (t) $\text{obj}_{ind_{cu}}(\text{t})$ are consumer objective consumption at time t that was chosen to be inversely proportional to TOD tariff in the residential, commercial and industrial sectors.
$\text{obj}_{\text{res}_{\text{u}}}(t)$, $\text{obj}_{\text{com}_{\text{u}}}$, (t) $\text{obj}_{ind_u}(\text{t})$ are utility objective consumption at time t that was chosen to be inversely proportional to pool electricity market price which aims to benefit utility.
W_{res}, W_{com} and W_{ind} are weights used to balance the fitness equation.W_1 and W_2 are weights that achieve either the utility objective curve or the customer objective curve. Weights were made equal in order to benefit both customer and utility such that $W_1 = W_2 = 0.5$.
The fitness function to be minimized, which is represented in Eq. (1), is the summation of Residential, Commercial and industrial fitness functions.
Objective curves of both customer and utility are first added with a ratio (weight) then subtracted from consumption of power after shifting at time (t). The difference is then squared and summed from t=1 to N=48 which is the number of half hourly time steps.

B. The Algorithm of Load Shifting

The two main elements in the proposed algorithm are (i) Percentage of load reduction at time t and (ii) number of time steps at which the remaining of the reduced load will be shifted. In order to ensure customer comfort, Reduction Percentage range was not to exceed 50% and shifting intervals was not to exceed 10 steps i.e. 5 hours. After several trials, the percentage range is to be taken between 0 and 50% and time the step is between 2 and 10.
Load shifting is carried out as follows: at any time t, load power (number of devices) is reduced by a certain percentage and the remaining power consumption is shifted with a certain time step.
The minimization function of the algorithm is a constrained problem. The constraint was created according to the range of load reduction percent and range of time step.
It must be stated that load shifting is applied only to controllable loads which are the loads that are flexible to be shifted.

3. PSO Adaptation For The Algorithm

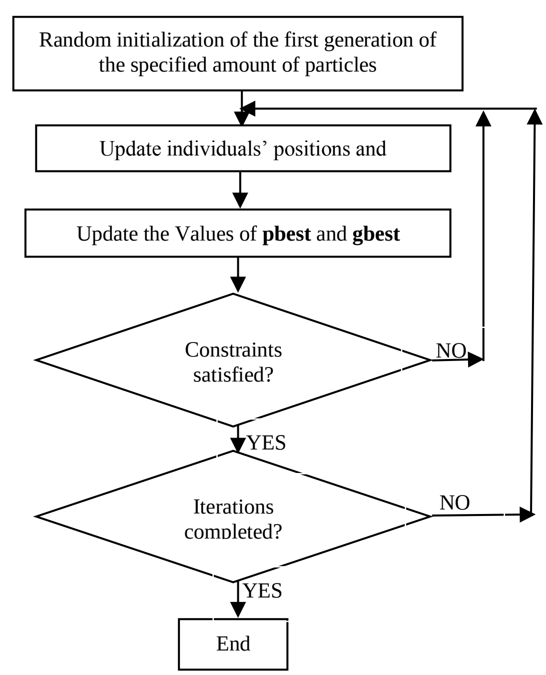

Fig. 1 .Flowchart for PSO

PSO emulates the swarm behavior and the individuals represent points (solutions) in the D-dimensional search space. Each individual is composed of a number of parts equal to the number of controllable devices. Each part consists of 2N values. The first group of N values represents the percentage of devices to be shifted each hour. The second group of N values represents the number of intervals (hours) to shift the load forward. Figure 1 shows the flowchart for PSO.

The proposed PSO based algorithm is then applied to a part of the distribution network of Alexandria. The network is composed of 45 busses, 33 residential busses, 3 commercial busses and 9 industrial busses with total peak demand of 2001.1 MW. Each individual is now composed of a number of sectors equal to the number of system buses. It should be noted that, for Alexandria distribution network, the first group of N values represents the percentage of bus load to be shifted each hour while the second group of N remains representing the number of intervals (hours) to shift the load forward.

4. Details Of The Test System

In this article, forecasted hourly load consumption of each area of the smart grid is given in Table I [13]. The hourly forecasted load consumption was turned first to half hourly by doubling each consumption at each hour to two half hours. Such that power at 1hrs-2hrs will the first two half hours and so on.

TABLE I
FORECASTED LOAD DATA

Time	Hourly Forecasted Load Kw		
	Residential Load	Commercial Load	Industrial Load
1 hrs-2hrs	412.3	375.2	876.6
2 hrs-3hrs	364.7	375.2	827.9
3 hrs-4hrs	348.8	404.0	730.5
4 hrs-5hrs	269.6	432.9	730.5
5 hrs-6hrs	269.6	432.9	779.2
6 hrs-7hrs	412.3	432.9	1120.1
7 hrs-8hrs	539.1	663.8	1509.7
8hrs-8hrs	729.4	923.5	2045.5
9 hrs-10hrs	713.5	1154.4	2435.1
10 hrs-11hrs	713.5	1443.0	2629.9
11 hrs-12hrs	808.7	1558.4	2727.3
12hrs-13hrs	824.5	1673.9	2435.1
13 hrs-14hrs	761.1	1673.9	2678.6
14hrs-15hrs	745.2	1673.9	2678.6
15 hrs-16hrs	681.8	1587.3	2629.9
16 hrs-17hrs	666.0	1558.4	2532.5
17 hrs-18hrs	951.4	1673.9	2094.2
18 hrs-19hrs	1220.9	1818.2	1704.5
19 hrs-20hrs	1331.9	1500.7	1509.7
20 hrs-21hrs	1363.6	1298.7	1363.6
21 hrs-22hrs	1252.6	1096.7	1314.9
22 hrs-23hrs	1046.5	923.5	1120.1
23 hrs-24hrs	761.1	577.2	1022.7
24 hrs-1hrs	475.7	404.0	974.0

Total types of controllable devices subjected to control in the three load areas Residential , Commercial and Industrial are 14, 8 and 6 respectively , with a total number of over 3500 device. The data containing the consumer classification (type) and the corresponding devices and their rating was derived from [13].

The primary objectives are to reduce the peak consumption utility bills and customer bills in these areas. Therefore, an objective load curve was chosen to be inversely proportional to both pool price and electricity market prices.

Whole sale price [13] and forecasted half hourly pool electricity price [14] are shown in figure 2.These data were used in the simulation but it had to be normalized first before applying on Alex Distribution Grid.

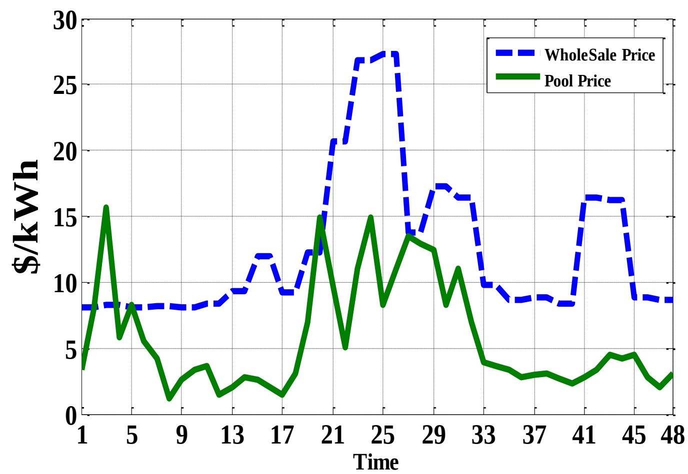

Fig.2. Whole sale price vs. Pool Price

5. Simulation Results And Discussion

There are two possibilities: Performing optimization of all three types at the same time or each load type optimized alone. It seems that the more appropriate choice is the first choice since the grid is treated as a whole unit especially regarding a large interconnected grid “large complicated grid” like the Alexandria distribution grid. Though most of researches preferred the second choice which is to get the optimal solution by performing the algorithm for each load type alone. That is because each load type is supposed to be distinguished by its own busses in the grid and can be dealt with alone since there are busses for only residential load, and busses for commercial etc.

Both approaches were taken into consideration in case study one which is the first part of the simulation. In case study one: the PSO technique was applied using forecasted data of table 1,price of figure 2 and devices data from [13]. The second part of the simulation is case study two which covers the application of the proposed algorithm on part of the Alexandria distribution grid, where the optimization is carried out for all the three types at the same time as it is more suitable for this grid as previously explained.

a. Case Study One

1) Performing optimization of each load sector alone

Applying the proposed PSO algorithm to devices of different types resulted in reduction in peak load and in energy cost as shown in Table II & III. In this section results are also compared with results of [13].Data from [13] were used to perform load shifting using a heuristic-based Genetic Algorithm.

TABLE II
PEAK REDUCTION

Load Type	Peak Load without DSM **KW**	Peak Load with DSM **KW**		Percentage Reduction	
		(PSO)	*(Genetic) [13]*	**(PSO)**	*(Genetic) [13]*
Residential	1363.6	**1084.1**	*1114.4*	**20.5%**	*18.3%*
Commercial	1818.2	**1381.9**	*1485.2*	**23.99%**	*18.3%*
Industrial	2727.3	**2145.0**	*2343.6*	**21.35%**	*14.2%*

TABLE III
COST REDUCTION

Load Type	Cost without DSM **$**	Cost with DSM **$**		Percentage Reduction	
		(PSO)	*(Genetic) [13]*	**(PSO)**	*(Genetic) [13]*
Residential	2302.8	**2123.8**	*2188.3*	**7.77%**	*5.0%*
Commercial	3626.6	**3129.0**	*3424.3*	**13.72%**	*5.8%*
Industrial	5712.0	**5500.0**	*5141.6*	**3.71%**	*10.0%*

Simulation results shows that for the same forecasted, objective curves and same devices numbers and ratings; the proposed PSO technique produced better results in both peak and cost reduction than using Genetic algorithm as in [13].

2) Performing optimization of all load sectors at the same time

In this section PSO algorithm is applied the same as the previous but optimization was performed for all devices of different types at the same time. In addition, both utility and customer sides financial benefit was studied. Results are presented in Table IV.

TABLE IV
PEAK AND COST REDUCTION

ALL Load Sectors optimized at the same time					
Load Sector	Peak Reduction			Cost Reduction	
	Before shifting (kW)	**After shifting (kW)**	**%**	**Customer**	**Utility***
Residential	1363.6	1139.8	16.4%	8.97%	6.47%
Commercial	1818.2	1236.6	22.99%	25.12%	25.58%
Industrial	2727.3	2100.2	31.98%	11.05%	10.55%
ALL Sectors	5113.6	4196.6	17.93%	15.03%	14.51%

*** Cost of energy produced by utility**

According to Table VI, substantial peak and cost reduction for all load sectors are achieved. The residential sector has lower results as it has lower peak than the other sectors which is reason that made the PSO more concerned with the other two sectors; commercial and industrial. The peak reduction results are better than table II due to the ability of PSO to handle larger search space as in case study two.

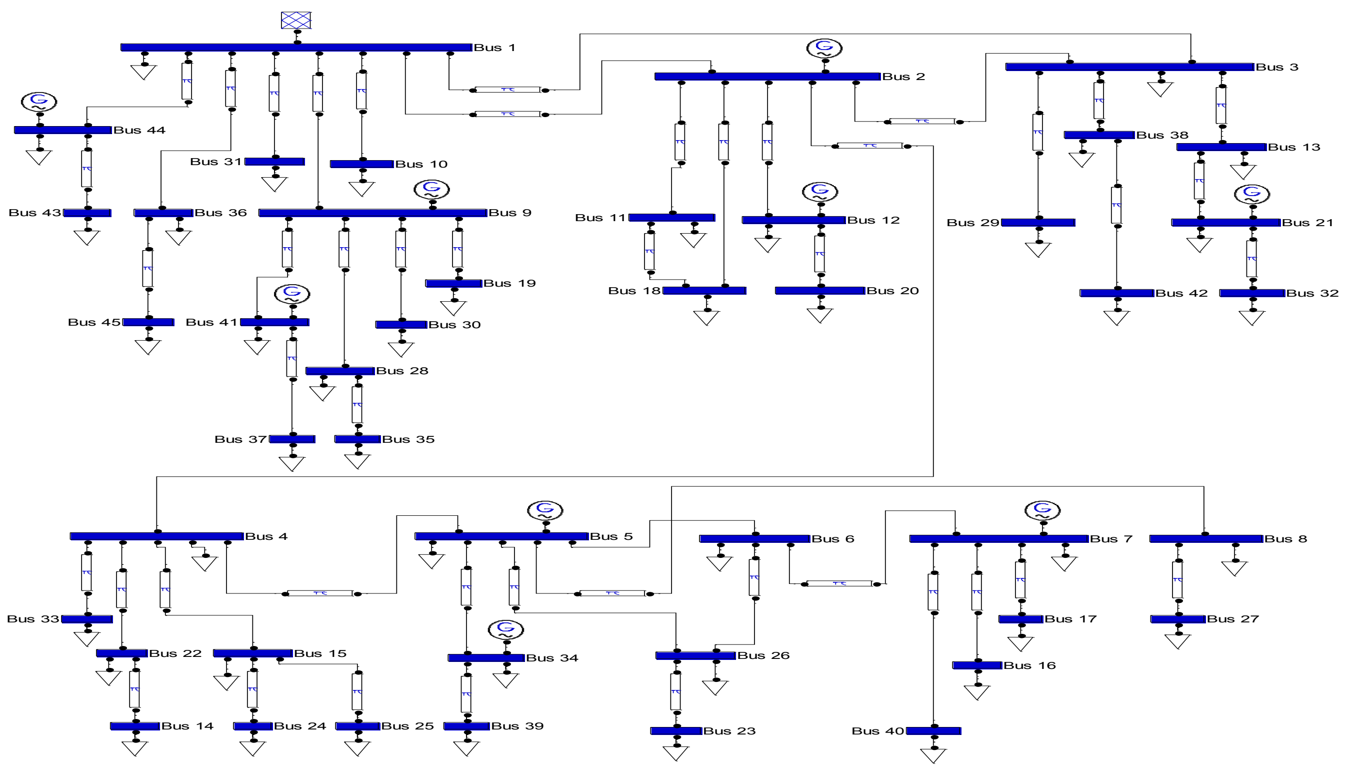

Fig. 3 .The 66kV, 45 bus system (part of Alex. distribution grid)

b. Case Study Two

The effectiveness of the proposed approach is verified on both peak reduction and cost reduction of utility and customer by applying the proposed demand side management strategy on Alexandria distribution network.

Electrical network diagram of Alexandria distribution grid is shown Fig. 3

Unlike case study one; the residential load buses have a combined peak of nearly 1700 MW which is larger than the other two sectors peaks. The industrial load sector has a peak of 470 MW while busses of commercial load have a total peak of almost 110MW.

Applying the proposed PSO algorithm to the buses within different load types resulted in reduction in peak load and energy cost as given in Table V.

TABLE V
PEAK AND COST REDUCTION

All load sectors optimized at the same time					
Load Type	Peak Reduction			Cost Reduction	
	Before shifting (MW)	After shifting (MW)	%	Customer	Utility*
Residential Busses	1688	1171.5	30.59%	16.54%	11.14%
Commercial Busses	111	106.419	4.13%	21.97%	21.54%
Industrial Busses	469	419.197	10.62%	19.67%	16.32%
ALL Sys. Busses	2001.8	1690.6	15.54%	17.59%	12.99%

*** Cost of energy produced by utility**

It could be noted that using the proposed algorithm resulted in a reduction in the peak demand for residential busses reaching 30.59 % and minimal variation in commercial and industrial busses, but as most of the busses is residential this caused a total reduction of the peak load of about 15.54 %. As for the cost of energy, the proposed algorithm has shown reduction for both of the utility and the customer.

The daily load curves of the three types of loads of each type before and after applying the DSM algorithm are shown in Fig.3, 4 & 5. It can be noticed that the application of DSM algorithm resulted in reduction of the peak load of all types of load due to load shifting especially in case of residential load. Fig.6 illustrates the overall daily load curve of the network. It also proves that the proposed DSM algorithm succeeded in reducing the peak load of the network.

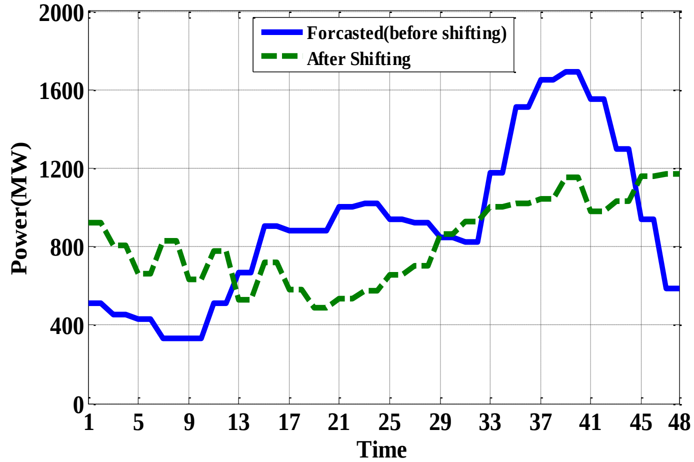

Fig.4. Load curve of Residential Busses: Before and after shifting.

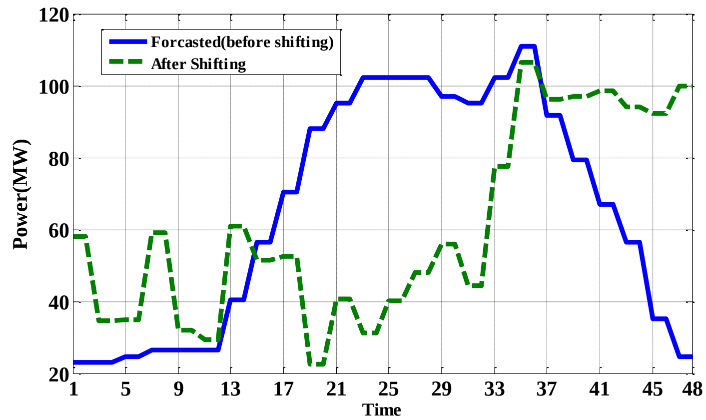

Fig.5. Load curve of Commercial Busses: Before and after shifting.

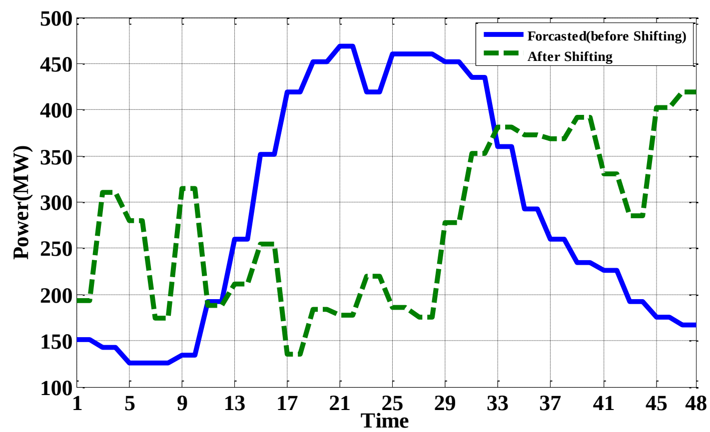

Fig.6. Load curve of Industrial Busses: Before and after shifting.

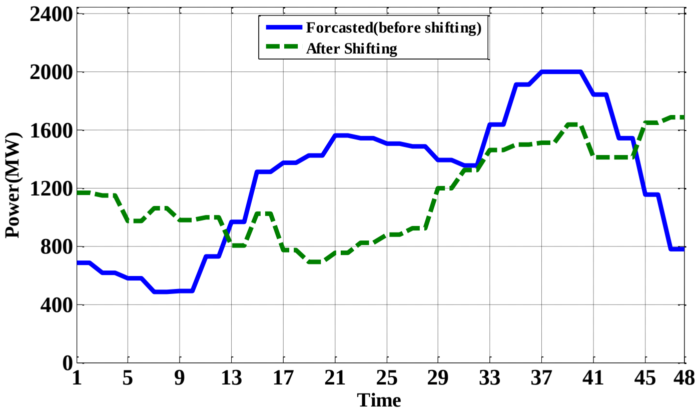

Fig.7. Load curve of Alex Grid: Before and after shifting.

6. CONCLUSION

In this study, demand side management (DSM) was utilized in order to minimize the peak demand within each of residential, commercial and industrial sectors. Load shifting DSM technique was used to schedule controllable devices of different types at various hours of the day bringing the final load curve closer to an objective load curve. Both utility and customer benefits were taken into consideration using particle swarm optimization PSO. The proposed algorithm was applied to Alexandria power grid and the simulation results showed that the proposed DSM technique succeeded in reducing the system peak and energy cost.

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