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Smart DSM to Optimize Residential Load Consumption during Energy Peaks

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Abstract. Recently, Demand Side Management (DSM) has played an important role in the smart grid through the optimization of residential load consumption. Smart DSM is a very important tool that permits customers to take right decisions for their energy consumption, it also helps the energy utilities to decrease the over load demand and reshape the load curve.

This paper proposes an optimized DSM technique based on smart metering to minimize load consumption, especially during load peaks. Bat Algorithm technique is proposed to optimize the minimum consumption during peak hours according to load type for three consumers' types whom are classified based on their lifestyles. A control algorithm is applied to the proposed system to achieve load shifting according to the optimization results.

Keywords. Demand Side Management, Smart metering, Load Shedding, Smart Pricing, Bat Algorithm.

I. INTRODUCTION

According to the expectations of International Energy Agency, demand will increase by 12% in 2020, compared to 2010. High peak demands could cause generation outages and blackout. Therefore, to solve this problem smart grid gives benefits to all the following parties; to the utilities as it provides better demand management, to the customer in the picture of saving costs, and to the Environment by granting ability to reduce greenhouse gas Emissions [1].

Demand side management (DSM) is an important function in energy management of the future smart grid; it is a reliable and cost-effective tool to manage the demand according to the available generation. DSM aims at improving the energy efficiency and making less operating cost of the utility [2].

DSM strategies are verified by means of six methods including: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape. Load shifting strategy encourages customers to shift their peak load to off-peak times. Where, traditional DSM is used to find optimal allocation of resources and on the premise of some effective incentives; smart DSM realizes the effective interaction between the grid and consumers [3, 4].

Smart pricing is a smart tool to encourage users to save energy consumption by using smart metering devices. DSM includes smart pricing will cognize group's central controller about new load schedule and loads that can be reduced for each time step. The control center can place bids in the market such as some loads from the peak demand which will be shifted or shed. Any profits made through this load, DSM will be paid back to customers of the group [5, 6].

In modern smart grid, the controllable devices are needed to be utilized to execute the demand side management algorithm. Furthermore, each type of controllable load can have various characteristics regarding their consumption over few hours. In this paper, the demand side management strategy is proposed for the smart grid which is based on load shifting technique. Moreover, load shedding shall be applied to emergency cases. There is mixture in the proposed strategy between load shifting and load shedding which is used for different devices for different consumer classes.

This paper is organized as follows. Section II, describes the smart grid proposed structure. Section III presents DSM proposed strategy for residential load. Section IV studies smart DSM using bat algorithm for three consumers' classes and for different IEEE distribution test feeder at utility side. Finally, Section VI presents conclusions.

II. SMART DSM MODEL

Smart grid is very essential to create an environment that complies with infrastructure for generation, transmission and distribution, energy, information technology, and infrastructure for digital communications that enables the exchange of procedures and controls information between various segments of the power grid [4].

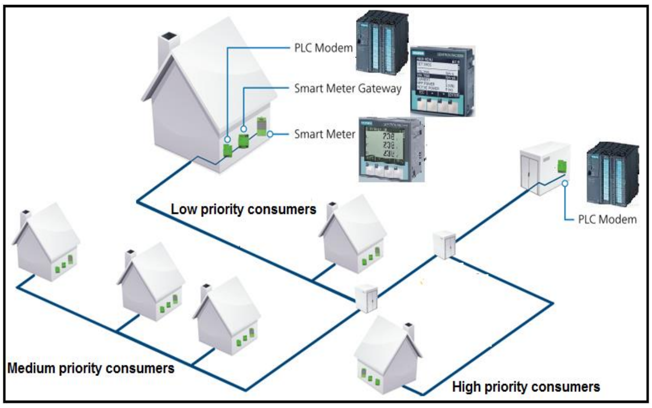

Figure.1. Structure of the proposed system

Figure.1 shows the proposed residential area and illustrates customer's control area which consists of two main parts. The first part is a programmable logic controller (PLC), which is used to execute the proposed demand response algorithm and provide an interface between the appliances, sensors, and the controller. The second part is smart metering, which is the most important device used in smart grid for obtaining information from the end users' devices and appliances.

Three classes of consumers are proposed within this study, and categorized according to consumers' priorities [7, 8].

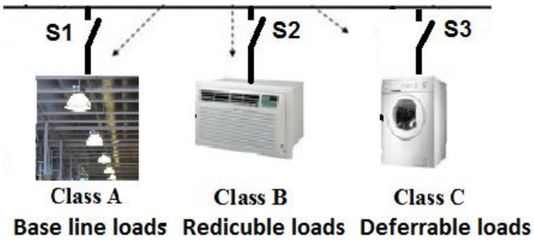

Figure.2. proposed system with control action [10]

In a lower level, Figure.2 shows the categorization of loads inside consumers' home according to loads priority for any of the classes. Loads are categorized into three types: A- Base line loads whose power consumption must be continuous for all time, such as lightning, refrigerator and fans, B- reducible loads, whose power consumption can be decreased for some time periods, such as air conditioning and Water heater, C- deferrable loads, whose operation or charging time can be deferred, such as washing machines, Electrical oven and Microwave oven [12].

III. PROPOSED SMART DSM STRATEGY

The proposed optimization algorithm aims at reshaping the final load curve to achieve the objective of load minimization at peak time using load shifting as the primary technique that can be utilized by the central controller of the smart grid. The DSM strategy is applied to three different levels of consumers which are classified according to consumers' lifestyles and each consumer has three types of loads. The first level is the high consumer level which needs the three types of loads to be operated regardless of the cost. The second level is the medium consumer level which needs at least a base line and reducible loads to be operated. The third level is the low consumer level which needs to reduce electricity bill as much as possible.

I) Problem Formulation

The main objective of each consumer is to minimize his electricity bill. This can be achieved through the following objective equations [9].

Minimize: $EC = \sum_{i=1}^{24} a*P_i*E_h + b*P_i*E_m + c*P_i*E_l$ (1)

$$P_i = C\,E_i\,\log(E_i+1) \quad (2)$$

Subject to:

$$a+b+c = 100\% * n \quad (3)$$

$$E_i < \text{Feeder load power} \quad (4)$$

$$a <= .3,\ b <= 1,\ c <= 1 \quad (5)$$

EC: Electricity cost during a day.
P_i: Energy price in hour i.
E_h: Energy for high priority consumers in hour i.
E_m: Energy for medium priority consumers in hour i.
E_l: Energy for low priority consumers in hour i.
E_i: Energy consumption in hour i.
C: Price parameter is calculated using Egyptian Electric utility and Consumer's Protection. Price parameter in this paper has varied in different periods around the 24 hours as the first period (from 8AM up to 2PM and from 2AM up to 8AM are OFF Peak periods with reduced tariff) and the second period (from 2PM up to 8PM and from 8 PM up to 2AM) are Over Peak periods with another, which applies monthly tariff as an hourly tariff with scaled results [10, 15].
n: no. of consumers connecting to distribution feeder.
a: percentage of high priority consumers = maximum 30% of n.
b: percentage of medium priority consumers.
c: percentage of low priority consumers.

II) DSM Proposed Algorithm

This algorithm allows implementation of features that model the load demand which is based on the lifestyles of the customers, so that the disturbance to the customers can be minimized. Within this paper, Smart DSM model is based on load shifting technique and, load shedding for emergency cases. This can be executed by handling several devices of different load types to minimize consumer's electricity bill. We can find the modeling steps of smart DAM system as follow:

1. Firstly, the data regarding the devices of one consumer, which are used during any normal day of the year, shall be collected. These devices shall be using the smart meters, then to categorize them in three classes: base line loads (lightning, refrigerator and fans), reducible loads (air conditioning and Water heater), deferred loads (washing machines, Electrical oven and Microwave oven).
2. Secondly, three types of consumers shall be determined according to consumers' load priorities, then to calculate the maximum power limit for each consumer type.
3. Thirdly, the total power consumption for each hour is to be compared with the maximum power limit by using PLC device which can control the switches which may occur to the above load types.
4. Fourthly, if total power consumption at any hour is larger than maximum power limit, then the objective function no (1) will be applied. It will calculate the amount of power which can be shifted to the off peak hours by using bat optimization technique.
5. If total power consumption at the same hour during another day is still larger than maximum power limit, the objective function no (1) will be applied once again, and to calculate the amount of power which will be shaded by using bat optimization technique again.
6. Finally, we shall calculate the electricity cost during one day after applying the optimization technique and reshaping consumer's daily load curve.

IV. APPLICATION OF TH E PROPOSED SMART DSM

The system consists of utility and distribution system. IEEE distribution test feeder on one hand and test consumer (1) on the other hand [11].

a) Optimization at Consumer side

In order to simulate real life consumption with accessible data, we concludes average Egyptian consumption throughout the year for one consumer and categorized loads for each consumer according to loads priority mentioned previously in smart DSM model.

Table.1: Daily load consumption for consumer (1):

Time	Class A	Class B	Class C	Total power consumption	Total cost before optimization
8am	455	500	1100	2055	0.77317
9am	455	510	0	965	0.1728
10am	455	10	250	715	0.0904
11am	455	1010	0	1465	0.3755
12pm	455	1010	0	1465	0.3755
1pm	455	1010	0	1465	0.3755
2pm	455	1500	310	2265	1.07
3pm	400	1555	1060	3015	1.966
4pm	470	1000	110	1580	0.4965
5pm	470	1010	10	1490	0.438
6pm	470	1010	10	1490	0.438
7pm	480	40	1440	1960	0.78634
8pm	480	520	810	1810	0.6635
9pm	480	520	1060	2060	0.8743
10pm	480	20	360	860	0.15
11pm	480	20	250	750	0.11173
12am	480	20	250	750	0.1117
1am	340	10	100	450	0.48265
2am	320	0	0	320	0.2305
3am	300	0	0	300	0.2
4am	300	0	0	300	0.2
5am	300	0	0	300	0.2
6am	300	500	0	800	0.1155
7am	300	500	0	800	0.1155
maximum load	480	1555	1440	3015	10.81312

Table.1 shows daily load consumption for an Egyptian customer with base line loads, reducible loads and deferrable loads according to consumer's lifestyle.

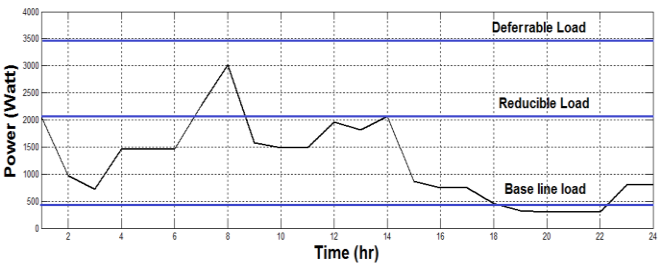

Figure.3 power comsumption for one consumer

Figure.3 shows that Base line load = 480 Watt, Reducible Load = 1560 Watt, and Referable Load = 1440 Watt. Total loads = 3480 Watt.

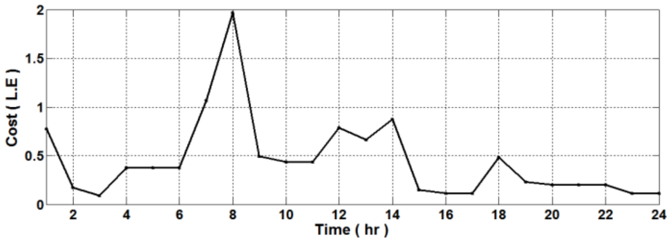

Figure.4 cost before optimization

Figure.4 gives the daily cost of a typical customer according to table number 1. The average cost before optimization = 10.3 L.E/day.

Smart DSM for different consumers' types:

The Bat Algorithm (BA) is a metaheuristic algorithm for global optimization. It is based on the phenomenon of echolocation bat which can find insects and discriminate their different types in full darkness. New studies indicate that this algorithm is very hopeful (Yang 2010) [13, 14].

In simulations, naturally, virtual bats are used. E_i (Total Energy consumption per hour t) is their positions and Pi (Energy price per hour t) is their speeds in a d-dimensional space which are updated. The new solution E^t_i and speed P^t_i at time t are given by

$$EC_i = EC_{min} + (EC_{max} - EC_{min})\,\beta \qquad (6)$$

$$P^t_i = P_i^{t-1} + (E^t_i - E_*)\,EC_i \qquad (7)$$

$$E^t_i = E_i^{t-1} + P^t_i \qquad (8)$$

Where,
β Є[0, 1] is a random vector derived from a regular distribution.
E_* is the best presented solution that is found after comparing all solutions.

$$E_{new} = E_{old} + \alpha A^t \qquad (9)$$

α Є [−1, 1] is a random number and $A^t = \langle A^t_i \rangle$ is the average loudness of all the bats at this time step.
Bats fly randomly with velocity P_i at position Ei with a fixed frequency EC_{min}, varying wavelength λ and loudness A_o to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission r Є [0, 1], depending on the proximity of their target; although the loudness can vary in many ways, we assume that the loudness varies from a large (positive) A_o to a minimum constant value A_{min}.

Table.2 Switches Sequence after optimization for different consumer classes in peaks:

Time	**Control Action**		
	Low priority	Medium priority	High priority
8AM: 2PM	Base line Load operates.	Base line and Reducible Load operate.	Base line, Reducible and Referable Load operate.
2PM: 8PM	Base line Load operates.	Base line and Reducible Load operate.	Base line, Reducible and Referable Load operate.
8PM: 2AM	Base line Load operates.	Base line and Reducible Load operate.	Base line, Reducible and Referable Load operate.
2AM: 8AM	Base line Load operates.	Base line and Reducible Load operate.	Base line, Reducible and Referable Load operate.

i. For High Priority Consumers

High priority consumers need the three types to be operated of loads regardless the cost.

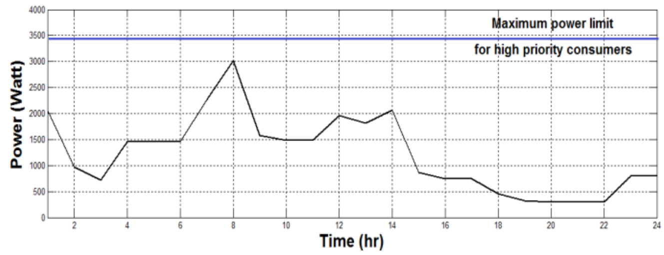

Figure.5. Consumer's load curve for high priority class

Figure.5 shows the consumer's load curve and the maximum power limit which was calculated from table.2. As all switches for different load categories are closed, any power more than power limit line will be shed in peak hours.

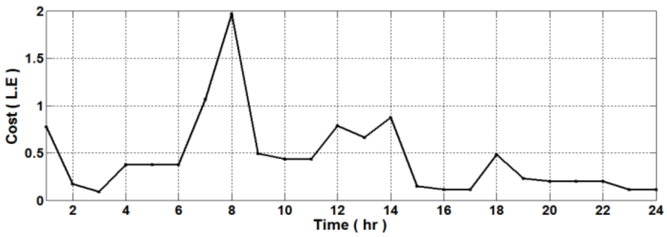

Figure.6. daily electrical price for high priority consumer

Figure.6 shows the total electrical price for one consumer in high priority class = 10.3 L.E/Day.

ii. For medium priority consumers:

To optimize medium priority consumption; load shifting optimization technique will be used to reshape medium priority consumer's load curve in peaks.

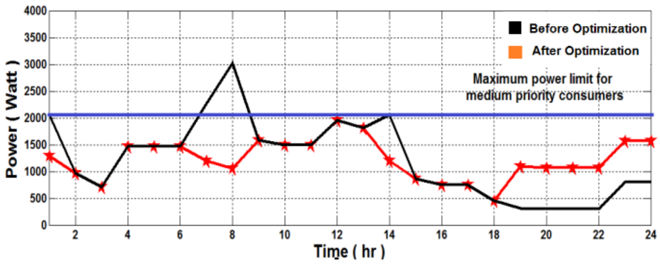

Figure.7. Power consumption before and after optimization

Figure.7 shows the consumer's load curve before and after optimization for one consumer (table.2 and maximum power limit which was calculated from table 1).

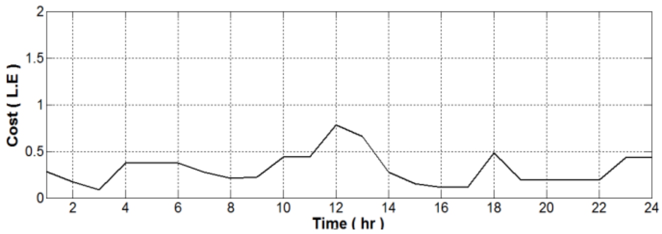

Figure.8. Daily electrical price for a medium priority consumer

Figure.8 shows the total electrical price for one consumer in a medium priority class = 7.22 L.E/Day.

iii. For Low Priority Consumers:

In low priority consumer's load, load shifting and shedding optimization techniques will be used so as not to exceed maximum power limit.

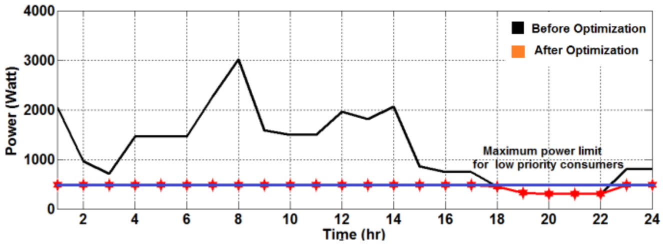

Figure.9 Power consumption before and after optimization

Figure.9 shows the consumer's load curve before and after optimization for one consumer (table.2 and maximum power limit which was calculated from table 1).

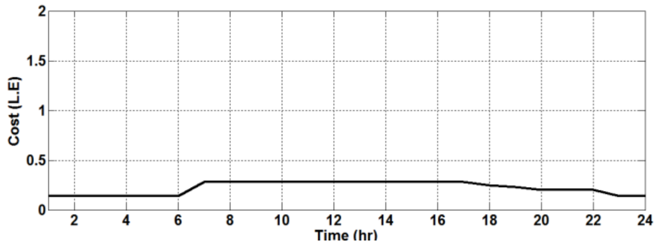

Figure.10 Daily electrical price for low priority consumer

Figure.10 shows the total electrical price for one consumer in a low priority class = 5.3 L.E/Day.

b) Optimization at utility side

The utility side is represented by IEEE distribution standard test systems, these systems were designed to evaluate and benchmark algorithms in solving unbalanced three-phase radial systems. Each of these systems represents reduced-order models of an actual distribution circuit [15].

1. 4-Bus Test Feeder.
2. 13-bus Feeder.
3. 34-bus Feeder.
4. 37-bus Feeder.
5. 123-bus Feeder.

The optimization function will be applied to determine the power capacity of each IEEE distribution test feeder. Moreover, if we have a specific power value for each feeder, then the number of consumers at the different consumer levels could be calculated by evaluating the maximum percentage of consumers in each consumer's priorities level using the linear programming.

Objective function:

$$\text{Minimize } P = P_h{*}a + P_m{*}b + P_l{*}c \qquad (10)$$

Subject to:

$$a+b+c = 1, \qquad (11)$$

$$a<= 0.3,\ b<= 1,\ c<=1 \qquad (12)$$

P_h: Maximum power limits for high priority consumers.
P_m: Maximum power limits for medium priority consumers.
P_l: Maximum power limits for low priority consumers.

Firstly, we will determine the power capacity by using the pervious maximum power limit values. The minimum power value that may achieve a suitable number of consumers in each consumer level (a = 0.3 = 30% of n, b = 0.7 = 70% of n, c = 0 = 0% of n) can be calculated through applying the objective function using the linear programming method, so the minimum power value equals 2472 Watt. It shall be taken into consideration that these percentages are the maximum limits for both the high and the medium priority consumers with the minimum power consumption calculated.

Secondly, we will calculate the maximum percentage of the number of consumers in each consumer's priorities level at each test feeder having a specific power value. Initially, the power consumption of spot loads in each distribution test feeder system shall be evaluated; that shall be executed for 400 consumers then, to determine the maximum percentage limit for the number of high, medium and low priority consumers.

1. For IEEE 4 node test feeders:

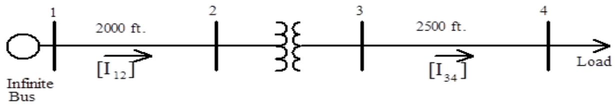

Figure.11 IEEE 4 Node Test Feeder

Figure.11 shows the system to be used in testing transformer models. Loads are connected in grounded wye for four wire line configurations with P=1800KW and connected in closed delta for three wire line configurations with P=1200KW. As the transformer must be loaded with 80%; So Maximum power consumption is 1800KW*80% = 1440 KW (wye load connected), 1200 KW * 80% = 960 KW (Delta load connected) according to load data in the table, if we have 10 buildings, each building has 40 consumers, so power consumption for one consumer in wye load connected = 1440 KW/400consumer = 3600 Watt, however, in delta load connected = 960 KW/400consumer = 2400Watt.

2. For IEEE 13 node test feeders:

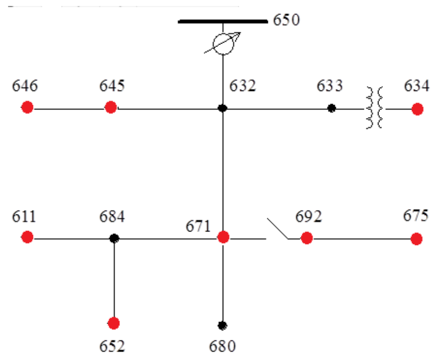

Figure.12 IEEE 13 Node Test Feeder

Figure.12 shows the system which is characterized by being short, relatively highly loaded, a single voltage regulator at the substation, overhead and underground lines, shunt capacitors, an in-line transformer, and unbalanced loading. The figure also shows the spot load points number 646, 645, 634, 652, 692, 675 671, and 611 with power of 1158 KW per phase (1), 973 KW per phase (2) and 1135 KW per phase (3). If we have 400 consumers, so, power consumption for one consumer = 1158KW/400consumers = 2895 Watt per phase (1), 973KW/400consumers = 2432.5 Watt per phase (2), 1135KW/400consumers = 2837.5 Watt per phase (3).

3. For IEEE 34 node test feeders:

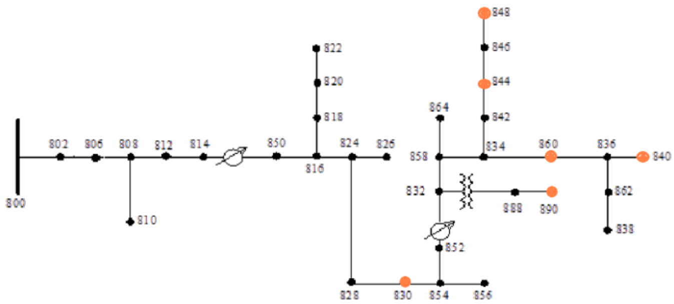

Figure.13 IEEE 34 Node Test Feeder

Figure.13 shows the system which is characterized by being long and lightly loaded, two in-line regulators, in-line transformer for short 4.16 kV section, unbalanced loading, and shunt capacitors. The figure also shows the spot load points number 848, 844, 860, 840, 890 and 830 with 344 KW per phase (1, 2) and 359 KW per phase (3). If we have 400 consumers, so, power consumption for one consumer = 344 KW/400consumers = 860 Watt per phase (1, 2) and 359KW/400consumers = 897.5 Watt per phase (3) [16].

4. For IEEE 37 node test feeders:

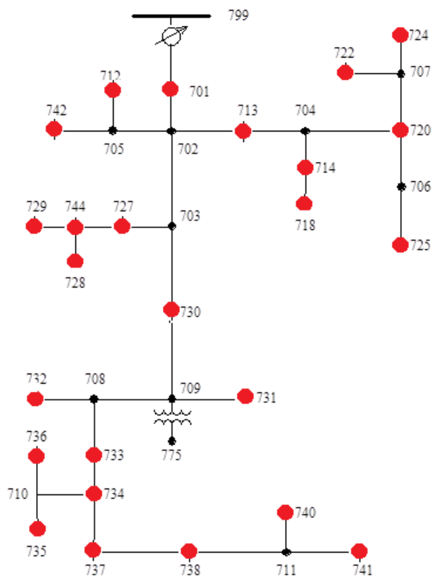

Figure.14 IEEE 37 Node Test Feeder

Figure.14 shows the system which is characterized by delta configured, all line segments are underground, and substation voltage regulation is two single-phase, open-delta regulators. Spot loads are very unbalanced. The figure also shows the spot load points number 724, 722, 701, 712, 742, 713, 714, 718, 720, 725, 727, 744, 729, 728, 730, 731, 732, 733, 736, 734, 735, 737, 738, 740 and 741 with power 727 KW per phase (1), 639 KW per phase (2) and 1091 KW per phase (3). If we have 400 consumers, so, power consumption for one consumer = 727KW/400consumers = 1817.5 Watt per phase (1), 639KW/400consumers = 1579.5 Watt per phase (2), 1091KW/400consumers = 2727.5 Watt per phase (3).

5. For IEEE 123 node test feeders:

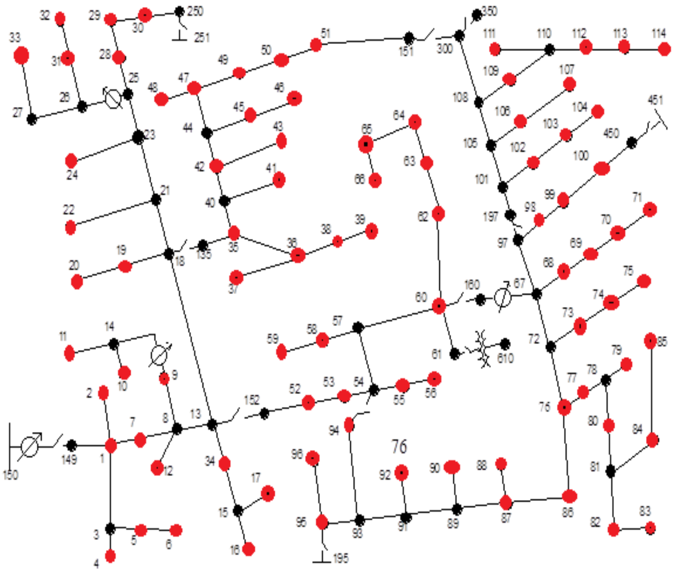

Figure.15 IEEE 123 Node Test Feeder

Figure.15 shows the system which is characterized by being overhead and underground lines, unbalanced loading with current constant, impedance, and power of four voltage regulators, shunt capacitor banks, and multiple switches. The figure also shows the spot load points number 1, 2, 4, 5, 6, 7, 9, 10, 11, 12, 16, 17, 19, 20, 22, 28, 29, 30, 31, 32, 33, 34, 35, 37, 38, 39, 41, 42, 43, 45, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56, 58, 59, 60, 62, 63, 64, 65, 66, 68, 69, 71, 73, 74, 76, 77, 79, 80, 82, 83, 84, 85, 86, 87, 88, 90, 92, 94, 95, 96, 98, 99, 100, 102, 103, 104, 106, 107, 109, 111, 112, 113 and 114 with power of 1420 KW per phase (1), 915 KW per phase (2) and 1155 KW per phase (3). If we have 400 consumers, so, power consumption for one consumer = 1420KW/400consumers = 3550 Watt per phase (1), 915KW/400consumers = 2287.5 Watt per phase (2), 1155KW/400consumers = 2887.5 Watt per phase (3).

Table.3. the maximum percentage limits for three consumers' priorities at spot loads:

	Phase (1)	Phase (2)	Phase (3)
4 Feeders	P=2400W	P=2400W	P=2400W
	a= 30% b= 65% c= 5%	a= 30% b= 65% c= 5%	a= 30% b= 65% c= 5%
13 Feeders	P= 2895W	P= 2432.5W	P= 2837.5W
	a= 30% b= 70% c= 0%	a= 30% b= 67% c= 3%	a= 30% b= 70% c= 0%
34 Feeders	P= 860W	P= 860W	P= 897.5W
	a= 0% b= 0% c= 100%	a= 0% b= 0% c= 100%	a= 0% b= 0% c= 100%
37 Feeders	P=1817.5W	P= 1579.5W	P= 2727.5W
	a= 30% b= 28% c= 42%	a= 30% b= 14% c= 56%	a= 30% b= 70% c= 0%
123 Feeders	P= 3550W	P= 2287.5W	P= 2887.5W
	a= 30% b= 70% c= 0%	a= 30% b= 58% c= 12%	a= 30% b= 70% c= 0%

Table no. 3 shows the maximum percentage limits for a total number of 400 consumers of high and medium priority consumers with the minimum power consumption which can be calculated at spot loads in different distribution systems. The above shows that if P => 2472 Watt, thus the high and the medium priority consumers can load with the power they need, but at 34 IEEE test feeder, the low priority consumers are the only ones who can load as spot load value which almost covers the base line loads.

The main advantage of this objective function and these calculations is that we can re-plan consumers according to their different priority levels at distribution feeders without overload at distribution points.

V. CONCLUSION

This paper presents a comprehensive study of a proposed smart DSM controller. The controller consists of two parts; the first part is smart metering and communication system which consist of smart meters, while the second part is PLC devices and optimization DSM technique. The proposed smart meter has the ability of a two-way communication between customer and utility central control as it enables both customer and utility to take a planned decision based on loading information. The DSM technique allows consumers to control their loads in order to operate the system more efficiently, as this technique supports both customer's and utility's decisions regarding energy management, especially during peak hours.

Throughout the paper, different test systems are used. The proposed smart DSM is applied to three levels of consumers, who are classified according to their life styles. Each consumer has three categories of loads inside his own home. The proposed DSM uses bat algorithm that provides optimized load shifting values according to the preset constraints of the utility. The proposed smart meters receive the optimum values, then apply a control action to consumer's level to achieve the overall purpose of energy management of the whole system. In addition, the proposed smart meters give the opportunity to measure, observe, and control customer's appliances through the central utility control, which is a new concept for smart grid. Based on the above, customers can achieve their target of electricity price saving, taking into consideration the different tariffs during the different operating hours. We shall note that the proposed system proves controllability at the different levels "customer's and utility's" with economic approach.

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