COMMUNICATIONS
IN
DEPENDABILITY AND
QUALITY
MANAGEMENT
An International Journal

CDQM, An Int. J., Volume 19, Number 4, 2016, pp. 40-51

UDC 005.591.1:620.9

Application of Demand Side Management Techniques in Successive Optimization Procedures

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accepted December 19, 2016

Summary: *Smart grid technologies give opportunities to customers and utilities to manage power system, make decisions on energy consumption and load demand time, so as to control the expenses. These possibilities are used through application of various Demand Side Management (DSM) techniques. DSM techniques are based on improvement of the load factor and load curve, whereas lowering the expenses. It can be done by using various optimization tools. In this paper are applied load shifting and peak clipping methods, so as MS Excel Solver as an optimization tool. The problem of a daily load curve in the case of some controllable loads is solved. This method may be applied to various practical cases.*

Key words: *Demand side management, load curve, load factor, objective function, optimization tools.*

1. INTRODUCTION

Demand Side Management (DSM) is one of the fundamental up-to-date solutions to manage electricity consumption in the developing world of insufficient electricity capacity, increasing fuel costs and problems of environmental polution. DSM provides measures to reduce consumption and expenses. In order to apply various DSM options and strategies, analytical and optimization tools are used. This also requires detailed information about dynamics of electricity consumption, system functioning and planning, understanding on peak loads and their variations due to environmental factors. Energy demand side management includes activities made by end-users to modify their consumption in a best possible way for both utility and the customers, but this does not necessarily lead to decrease in the total energy consumption. Demand Side Management is made through implementation of activities in order to produce the desired daily, monthly or seasonal load curves [2, 4].

For utilities, DSM means avoiding or delaying the need to invest in new capacities, improving the power quality, ensuring efficient generation, transmission and distribution of energy [7]. For the residential customer, it means reduced bills and taking advantage of the financial incentive provided by utility company. For commercial and industrial customers, it means lower costs included in their products price, making them more competitive on the market. DSM gives the customer a new role and freedom in shifting the demands to off-peak periods to reduce the electricity bill, whereas providing lower costs per kWh to the utility.

The main DSM techniques are valley filing, load shifting, peak clipping, load building and energy conservation programs [6]. Such programs are different from one utility to another, as they depend on number of customers, load type (commercial, industrial or residential), benefit from that program, level of customer's reaction or satisfaction with the applied program, etc. However, benefits from applying are on both sides of customers and utility, so that such activities have grown over the past decades. Many utilities are implementing DSM programs and other are considering it in planning processes.

After the introduction, different DSM techniques are presented and governing equations in Section 2. In Section 3 the objective functions and constraints are given, together with the defined optimization problem. In Section 4, two practical problems are defined and analyzed using MS Excel Solver and, based on this, the conclusions are given.

2. IMPLEMENTATION OF DEMAND SIDE MANAGEMENT TECHNIQUES

DSM techniques may be implemented by utilities through direct or indirect load control. In the case of direct load control, utility can modify load pattern by switching-off the power supply to specific category of customers at chosen time intervals, or for specified types of electric loads. In the case of indirect control, the utility may use some special methods as loads time schedule, thermal energy storage, efficient end-use technologies, tariff system and electrification technologies (Figure 1).

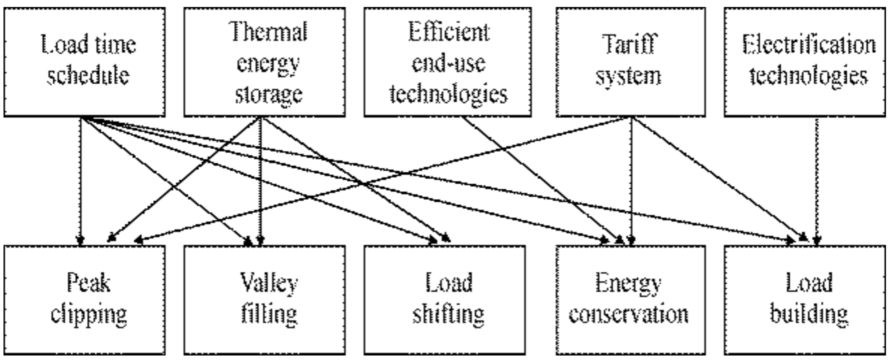

Figure 1. Scheme of Load Shape Objectives

Valley filling (Figure 2) is one possible DSM method applied in order to change load curves so to obtain grater load factors in predefined time margins. In such a way the utility may increase its profit, whereas it decreases the costs per kWh of energy. Greater demand in off-peak hours is achieved by encouraging end-customer to spend energy with paying lower tariffs, or to change time schedule of the load demand distribution over the day. This is possible if some controllable devices may operate in different time intervals during the day and the chosen time interval is not relevant to the customer, e.g. for a residential or industrial consumer these might be boilers or storage heaters.

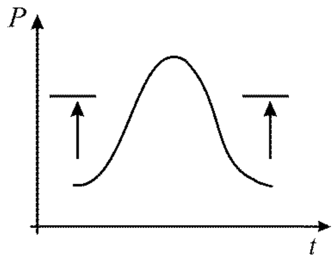

Figure 2. Valley Filling Technique

Load shifting (Figure 3) is the best solution from the point of view of utility companies. With this DSM technique the part of demand is shifted from peak to off-peak hours. Customers are encouraged for this by cheaper tariff in off-peak hours.

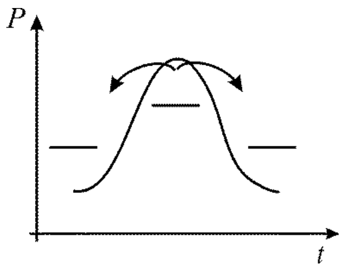

Figure 3. Load Shifting Technique

Peak clipping (Figure 4) is also aimed at decreasing the demand during peak hours, especially if the installed capacity is not enough to cover the peak demand. This is very important in the developing countries and if there is the problem with investments for the new installations and generation capacities.

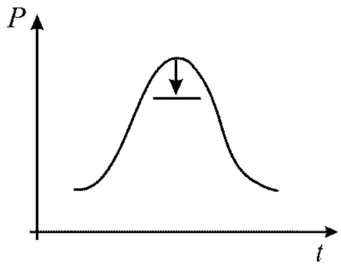

Figure 4. Peak Clipping Technique

Energy conservation (Figure 5) is also very important in power systems and, nowadays, there are many novelties announced in this field. If it is required to decrease the overall energy consumption, it may be achieved by using more efficient devices and appliances, which is very important at the global level.

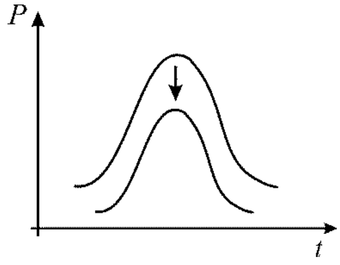

Figure 5. Energy Conservation Technique

Increasing the overall energy consumption (Figure 6) is useful if some utility has surplus capacity or available energy to sell with lower costs per kWh. This load building technique is achieved with the encouragement of consumers to spend electrical energy where needed for the operation of power system. There are examples of power utilities which gave customers storage heaters as great loads where this was desirable to maintain the power system capacities in the area.

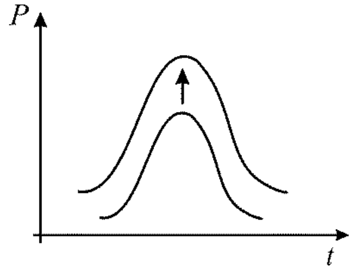

Figure 6. Load Building Technique

3. OBJECTIVE FUNCTIONS AND OPTIMIZATION PROBLEM

For all of the five mentioned DSM techniques, some objective functions, either maximum of the load factor for the utility, defined by (1) or (2), or minimum of the total cost for the customers, defined by (3), are optimized using the corresponding constraints for that technique.

The objective functions are defined as the following:

$$LF_{\max} = \left[\left[\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} t_{(j)}\right] / \sum_{j=1}^{J} t_{(j)}\right] / \sum_{i=1}^{N} P_{(i,k)} \qquad (1)$$

$$LF_{\max} = \left[\left[\sum_{j=1}^{J} P_{tot(j)} t_{(j)}\right] / \sum_{j=1}^{J} t_{(j)}\right] / P_{tot(k)} \qquad (2)$$

$$C_{\min} = \left[\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} t_{(j)} c_{e(i,j)}\right] + \left[\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} c_{d(i,j)}\right] \qquad (3)$$

for $LF_{\max}$ – the maximum load factor value,
$P_{(i,j)}$ – power demand of the load type *i* at the time interval *j*, for *i* = 1,..., *N*, and *j* = 1,..., *J*,
N – the total number of load types,
J – the total number of time intervals,
$P_{tot(j)}$ – the total demand power for all types of loads, where *j* denotes time interval number,
k – time interval of the maximum demand of all load types $i = 1,..., N$, over all intervals $j = 1,..., J$,
C – the total cost of the electrical demand and energy consumption,
$c_{e(i,j)}$ – the cost of energy for load type *i* at the time interval number *j*,
$c_{d(i,j)}$ – the cost of demand for load type *i* at the time interval number *j*.

The imposed constraints depend on the chosen DSM technique, on the particular load specifications and the power system [1]. For the valley filling technique (Figure 7), the effect is obtained by building loads in off-peak periods.

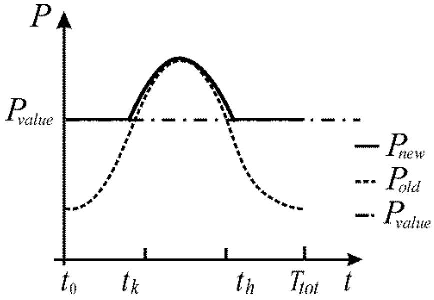

Figure 7. Load Curve Before and After Applied Valley Filling Technique

Either (1) or (2) is optimized by applying equality constraint:

$$P_{new(i,j)} = P_{old(i,j)}, \quad \forall t \in \{t_k, t_h\}, \tag{4}$$

and inequality constraints:

$$P_{new(i,j)} \geq P_{old(i,j)}, \forall t \in \{t_0, t_k\} \cup \{t_h, T_{tot}\}, \tag{5}$$

$$P_{new(i,j)} \leq P_{value}, \forall t \in \{t_0, t_k\} \cup \{t_h, T_{tot}\}, \tag{6}$$

for $P_{new(i,j)}$ – the demand of load type *i* at time interval *j* after applying DSM technique,

$P_{old(i,j)}$ – the demand of load type *i* at time interval *j* before applying DSM technique,

P_{value} - the limiting value given by the planner of the system.

k is the time interval at which the total demand of all load types $P_{tot(k)}$ is of the maximum value, so that

$$P_{tot(k)} > P_{tot(j)} \forall j = 1,..., J; j \neq k, \tag{7}$$

and the sum of all time intervals is $T_{tot} = \sum_{j=1}^{J} t_{(j)}$.

In the load shifting technique (Figure 8) there is no change of the total energy consumption, but there is a decrease in peak demand.

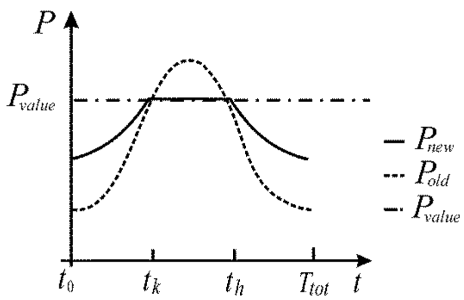

Figure 8. Load Curve Before and After Applied Load Shifting Technique

Eqs. (2) and (3) are optimized by applying equality constraints:

$$\sum_{i=1}^{N}\sum_{j=1}^{J} P_{new(i,j)} t_{(j)} = \sum_{i=1}^{N}\sum_{j=1}^{J} P_{old(i,j)} t_{(j)}, \quad (8)$$

$$P_{new(i,j)} = P_{value}, \quad \forall t \in \{t_k, t_h\}, \quad (9)$$

and inequality constraints:

$$P_{new(i,j)} \geq P_{old(i,j)}, \forall t \in \{t_0, t_k\} \cup \{t_h, T_{tot}\}, \quad (10)$$

$$P_{new(i,j)} \leq P_{value}, \forall t \in \{t_0, t_k\} \cup \{t_h, T_{tot}\}. \quad (11)$$

For the peak clipping technique, the effect is reduction of load demand during peak period from t_k to t_h and reduction of the total energy consumption up to T_{tot} (Figure 9).

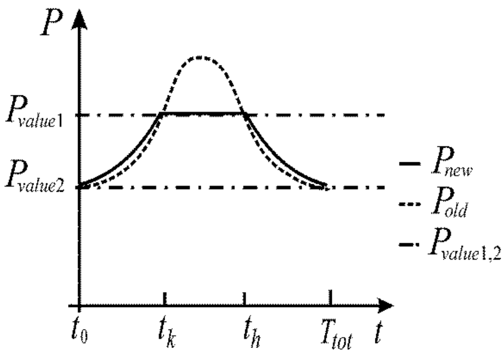

Figure 9. Load curve before and after applied peak clipping technique

Eq. (2) is optimized by applying equality constraint:

$$P_{new(i,j)} = P_{old(i,j)}, \ \forall t \in \{t_0, t_k\} \cup \{t_h, T_{tot}\}, \quad (12)$$

and inequality constraints:

$$P_{new(i,j)} \leq P_{value\ 1}, \quad \forall t \in \{t_k, t_h\}, \quad (13)$$

$$P_{new(i,j)} \geq P_{value\ 2}, \quad \forall t \in \{t_k, t_h\}, \quad (14)$$

$$P_{value\ 2} \leq P_{value\ 1}, \quad (15)$$

for $P_{value\,1}$ and $P_{value\,2}$ the limiting values given by the planner of power system.

For the energy conservation technique, the peak demand and total energy consumption are reduced over the whole period of interest (as given in Figure 10).

Eq. (3) is optimized, as it is representing the minimum cost of the electrical demand and energy consumption, by applying inequality constraint:

$$P_{new(i,j)} \leq P_{old(i,j)}, \quad \forall t \in \{t_0, T_{tot}\}. \tag{16}$$

In the load building technique (Figure 11) the effect is that peak demand and total energy consumption are increased over the whole period of interest. Eq. (3) is optimized, as it is representing the maximum revenue, by applying inequality constraint:

$$P_{new(i,j)} \geq P_{old(i,j)}, \quad \forall t \in \{t_0, T_{tot}\}. \tag{17}$$

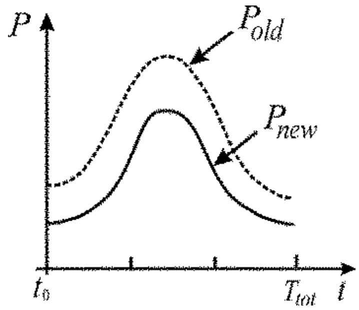

Figure 10. Load curve before and after applied energy conservation technique

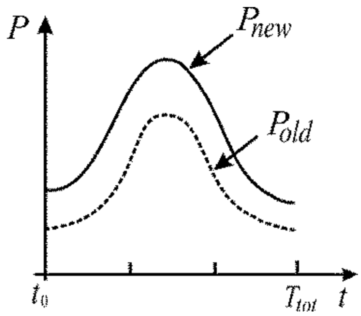

Figure 11. Load curve before and after applied load building technique

4. PRACTICAL EXAMPLES AND OPTIMAL SOLUTIONS

For a given daily load curve in Figure 12, the demand P_{old} is presented in the second column of Table 1. The old time schedule should be changed if there are any controllable loads, so to obtain an optimum load curve P_{new} (given also in Figure 12) and determine the new time schedule. Suppose there are some controllable loads such as three electrical boilers having P=20kW, which have to work for four hours continuously in order to achieve the desired temperature. They may be turned on at any time and turned off four hours later, so the possibility to change their demand time should be exploited.

After applying load shifting and peak clipping techniques, the new load curve and load time schedule as given in Table 1 are obtained by using Solver. It is the MS Excel based tool (Figure 13) for solving optimization problems. The objective function is written in the target cell, and constraints and variables in the changing cells. Results of the optimization are given in Figure 14 and in Table 1.

The maximum value from the old daily load curve is $P_{\max old} = 120\,\text{kW}$ and the minimum value is $P_{\min old} = 20\,\text{kW}$. Their ratio value is $P_{\max old} / P_{\min old} = 6$. After applying two of the DSM techniques, the obtained limiting values are $P_{\max new} = 80\,\text{kW}$ and $P_{\min new} = 40\,\text{kW}$, as may be also noticed from Figure 15, so that the ratio value is $P_{\max new} / P_{\min new} = 2$.

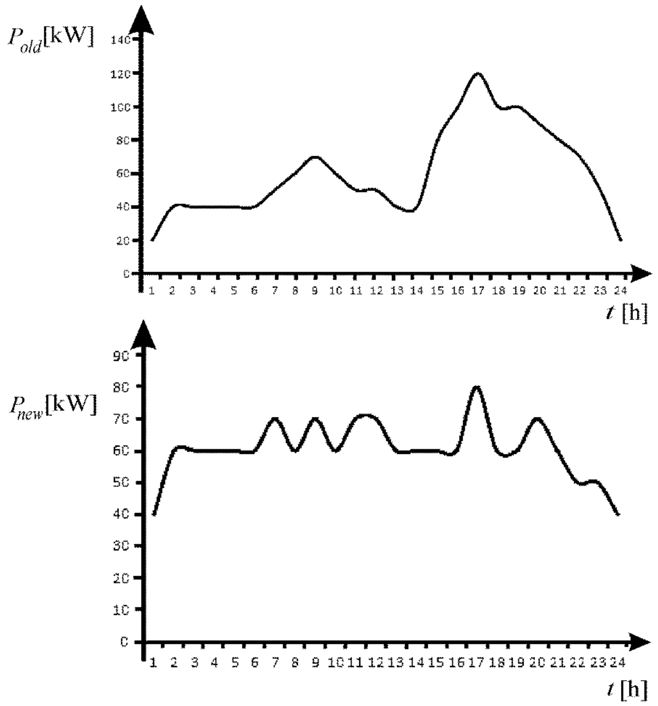

Figure 12. Old Daily Load Curve P_{old} and New Daily Load Curve P_{new}

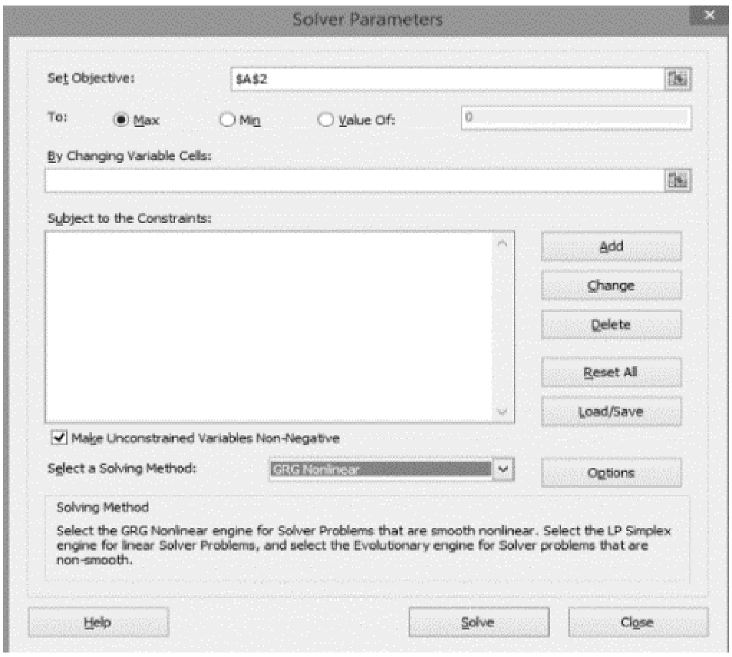

Figure 13. MS Excel Solver Tool

Table 1. Loads Time Schedule Before and After the Applied DSM Techniques

Time interval	P_{old}	Load 1 old demand time	Load 2 old demand time	Load 2 old demand time	Load 1 new demand time	Load 2 new demand time	Load 3 new demand time	P_{new}
1	20	0	0	0	1	0	0	40
2	40	0	0	0	1	0	0	60
3	40	0	0	0	1	0	0	60
4	40	0	0	0	0	1	0	60
5	40	0	0	0	0	1	0	60
6	40	0	0	0	0	1	0	60
7	50	0	0	0	0	1	0	70
8	60	0	0	0	0	0	0	60
9	70	0	0	0	0	0	0	70
10	60	0	0	0	0	0	0	60
11	50	0	0	0	0	0	1	70
12	50	0	0	0	0	0	1	70
13	40	0	0	0	0	0	1	60
14	40	0	0	0	0	0	1	60
15	80	1	0	0	0	0	0	60
16	100	1	1	0	0	0	0	60
17	120	1	1	0	0	0	0	80
18	100	1	1	0	0	0	0	60
19	100	0	1	1	0	0	0	60
20	90	0	0	1	0	0	0	70
21	80	0	0	1	0	0	0	60
22	70	0	0	1	0	0	0	50
23	50	0	0	0	0	0	0	50
24	20	0	0	0	1	0	0	40

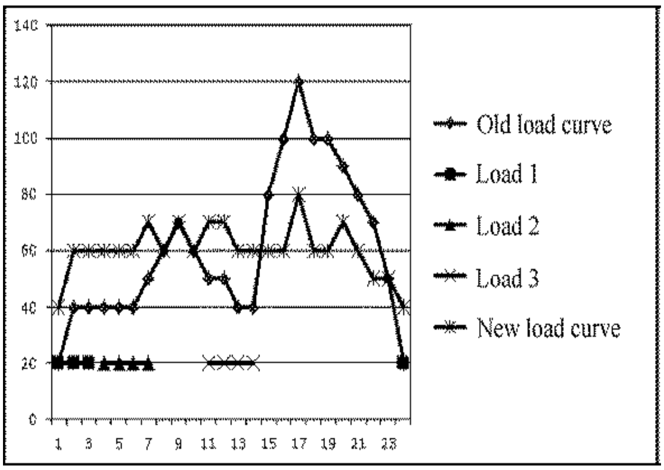

Figure 14. Load Shifting and Peak Clipping DSM Techniques Applied

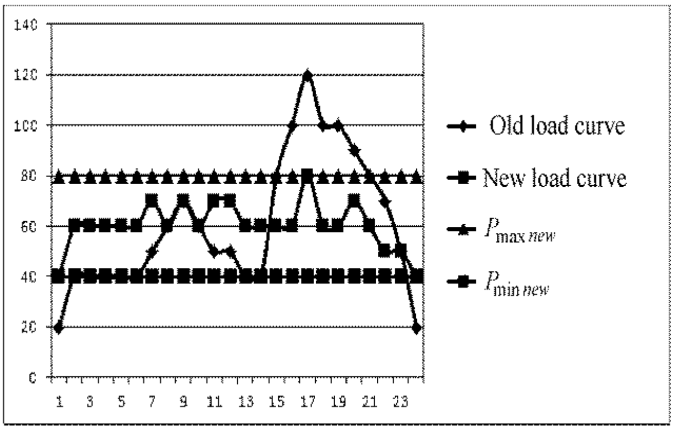

Figure 15. Load Shifting and Peak Clipping DSM Techniques Applied

In Table 2 are given the results for some important parameters, $P_{av} = \sum_{j=1}^{J} P_{(j)} t_{(j)} / \sum_{j=1}^{J} t_{(j)}$, $P_{\max}$, $LF = P_{av} / P_{\max}$, and savings per year in percentages, after the applied DSM techniques.

Table 2. Some Important Parameters Before and After the Applied DSM Techniques

Parameter	Before Applied DSM Techniques	After Applied DSM Techniques
$P_{\max}$ [kW]	120	80
Energy per year [kWh/year]	529250	529250
P_{av} [kW]	60,4167	60,4167
$LF=P_{\text{av}}/P_{\max}$	0,5035	0,7552
Demand Cost *LE*	10512	7008
Energy Cost/Year *LE*	81239,875	81239,875
Cost/Year *LE*	91751,875	88247,875
Cost/Month *LE*	7645,9896	7353,9896
End-user savings per year %	–	3,818995

Other optimization tools may be also used, such as LINGO [5], which is an optimization modeling software for linear, nonlinear and integer programming, suitable for this kind of problems solving.

If among the rest of the loads still exist other controllable loads, e.g. four storage heaters having *P*=5kW, which have to work for four hours continuously in order to store the desired thermal energy, further optimal solution for the time schedule could be found. If the heaters may be turned on at any time and turned off four hours later, preferably during night hours having lower tariff, the possibility to change their demand time should be exploited. The optimal solution would be the following, as presented in Tables 3 and 4.

In Table 3 are given the results for $P_{av} = \sum_{j=1}^{J} P_{(j)} t_{(j)} / \sum_{j=1}^{J} t_{(j)}$, $P_{\max}$, $LF = P_{av} / P_{\max} = 0.8631$, and further savings per year are obtained after the applied DSM techniques.

Table 3. Some Important Parameters Before and After the Applied DSM Techniques

Parameter	Before Applied DSM Techniques	After Applied DSM Techniques
P_{max} [kW]	80	70
Energy per year [kWh/year]	529250	529250
P_{av} [kW]	60,4167	60,4167
$LF=P_{av}/P_{max}$	0,7552	0,8631

Table 4. Loads Time Schedule Before and After the Applied DSM Techniques

Time interval	P_{old}	Load 4 old demand time	Load 5 old demand time	Load 6 old demand time	Load 7 old demand time	Load 4 new demand time	Load 5 new demand time	Load 6 new demand time	Load 7 new demand time	P_{new}
1	40	0	0	0	0	0	0	1	1	50
2	60	0	0	0	0	0	0	0	0	60
3	60	0	0	0	0	0	0	0	0	60
4	60	0	0	0	0	0	0	0	0	60
5	60	0	0	0	0	0	0	0	0	60
6	60	0	0	0	0	0	0	0	0	60
7	70	0	0	1	1	0	1	0	0	65
8	60	0	0	1	1	0	1	0	0	55
9	70	0	0	1	1	0	1	1	0	70
10	60	0	0	1	1	0	1	1	0	60
11	70	0	0	0	0	0	0	1	0	65
12	70	0	0	0	0	0	0	1	0	65
13	60	0	0	0	0	0	0	0	0	60
14	60	0	0	0	0	0	0	0	0	60
15	60	0	0	0	0	0	0	0	0	60
16	60	0	0	0	0	0	0	0	0	60
17	80	1	1	0	0	0	0	0	0	70
18	60	1	1	0	0	0	0	0	0	50
19	60	1	1	0	0	0	0	0	0	50
20	70	1	1	0	0	0	0	0	0	60
21	60	0	0	0	0	0	0	0	0	60
22	50	0	0	0	0	0	0	1	1	60
23	50	0	0	0	0	0	0	1	1	60
24	40	0	0	0	0	0	0	1	1	50

After applying load shifting and peak clipping techniques, the new load curve and load time schedule as given in Table III are obtained. The maximum value from the old daily load curve is $P_{\max old} = 80\,\text{kW}$ and the minimum value is $P_{\min old} = 40\,\text{kW}$. Their ratio value was $P_{\max old} / P_{\min old} = 2$. After applying two of the DSM techniques, the obtained limiting values are $P_{\max new} = 70\,\text{kW}$ and $P_{\min new} = 50\,\text{kW}$, so that the ratio value is $P_{\max new} / P_{\min new} = 1.4$. Load factor is improved, so that $LF = P_{av} / P_{\max} = 0.8631$, and the load curve waveshape is optimized.

5. CONCLUSION

DSM techniques, such as valley filling, load shifting, peak clipping, energy conservation and load building, are described in this paper, so as optimization procedures for minimizing energy costs and maximizing load factor, thus improving load curves waveshapes and power quality. The corresponding objective functions and constraints for these DSM techniques are also presented.

Optimization is done in this paper for two simple cases, but the same procedure may be used for complex power system cases. Savings per year in percentages may be much greater, depending on power system specifications, number, type, controllability and demand of the loads. This is proved by two examples. MS Excel Solver tool is used to optimize the load curves for the given examples. For this case, load shifting and peak clipping techniques are used, so that load factor is increased for 50% after the first optimization procedure and then further after the second optimization procedure for 14%, so that is increased in total for about 70%.

The aims of DSM programs are fulfilled through their implementation and further improvements of the procedure with including various constraints.

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