Power Consumption Management and Control for Peak Load Reduction in Smart Grids Using UPFC

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Abstract—**Smart Grid is a new term dealing with intelligent, auto-balancing and self-monitoring power grids with minimal human intervention. Implementing this technology brings about reliability, high efficiency and economic benefits for the network. Moreover, through the control and management of power consumption, consumers will enjoy the benefits of cost reduction during the expensive peak time. This paper proposes a management model for optimized consumption reduction which decreases losses, generation costs and overload in transmission lines during the peak time. Although the peak generation cost is reduced, the cost of costumer's changes must be paid too, hence these changes are applied in such a way that the benefits for both parties will be maximal. By finding the best buses for power reduction and also the amount of the reduction, the maximum efficiency is reached with least changes. So, the Smart Grid will be able to compensate the costs of the customer's changes by adjusting tariffs or other economic plans.**

Keywords- Smart Grids, Comsumption Managment, UPFC, Overload, Losses, Peak Reduction

I. INTRODUCTION

Smart Grid is an intelligent, auto-balancing and self-monitoring power grid which accepts any source of energy and transforms it into a customer's end use (heat, light, warm water, etc.). Maximum usage of renewable energy sources and minimum negative environmental effects of power systems can be gained in Smart Grids. Smart grids have the ability to sense overloaded lines and reroute the power to reduce the overloads and prevent a potential outage situation. Real-time communication between the customer and the utility allows Smart Grids to optimize customer's energy usage based on price preferences [1-6].

The excessive increase in demand of energy in power systems may lead to the increase in generation and transmission costs, power losses, overload in transmission lines and fuel consumption. Also, power generation in peak hours is more costly. All of these reasons will lead utilities to reduce the peak demand.

The technologies employed in Smart Grids with the ability of controlling customer's power consumption, can be used to reduce the demand of energy and increase the efficiency.

The power industry points out that the demand-response load management program for reducing the consumption in peak time brings about many benefits for the utility and the customer. Consumers that defer peak time energy usage to a later hour reduce their peak time consumption and help the utilities to decrease the cost of generating expensive peak power.

Using Smart Grids is a key tool for achieving load-demand management by communicating peak prices to the consumers and integrating smart appliances and smart building controls with the objective of peak reduction. On the other hand, the utility determines the level of power reduction for each bus, and thus could be able to decrease the generation costs in power plants, and reduce power transmission losses and transmission lines overloads by using Flexible AC Transmission Systems (FACTS) devices [7-9]. The smart selection of appropriate buses for power reduction and also the amount of this reduction are very important in achieving the selected objectives.

In this paper, a power consumption management model is introduced to control the peak load reduction in a Smart Grid using the Unified Power Flow Controller (UPFC). In section II, the proposed model is illustrated. Section III describes the UPFC placement process. Section IV investigates the peak load reduction management model. Section V presents the simulation and the results. And finally, in section VI conclusions are presented.

II. THE PROPOSED MODEL

Power systems are composed of three main sections, i.e. Generation, Transmission, and Distribution. In traditional systems, communication between these three sections is minimal and using the information from all of them to optimize the overall system is extremely limited, if not impossible. Because of new developments in communication technologies and also the developments in consumption management systems, power systems can now be operated more efficiently. In the past, utilities were not able to apply much control over consumers, because they were considered solely as "Customers". In modern power grids, known as Smart Grids, power consumers are not only considered as customers, they are economic partners in the energy markets too. Any reduction in huge power generation and transmission costs creates significant benefits for both parties. The sources of these benefits include, but are not limited to, the reduction in power losses and the improvement of operation conditions which can reduce damages to the utilities. Therefore, with appropriate consumption management, a win-win situation can be created for both utilities and consumers.

A power system, by application of power control using load and generation information, is capable of reducing some of the problems facing it, such as high transmission and distribution losses, changes in bus voltage (over- or under-voltage), etc. Also, the power control in transmission system can provide high efficiency for the network through the reduction of losses, improved loadability and improved voltage profile.

FACTS devices are among the control tools which can have a significant effect on the power flow in different directions. These devices are of various types and are based on power electronic switches, advanced control theory and microcomputers and provide control for interconnected networks. One of the most important types of FACTS devices is the UPFC. The UPFC can be modeled in two ways: coupled model and decoupled model. Due to the need to modification of Jacobian matrix, the first model is complicated, while the second model can be easily integrated into load flow algorithms without modification or simplification of Jacobian matrix [10]. This model is shown in Fig. 1.

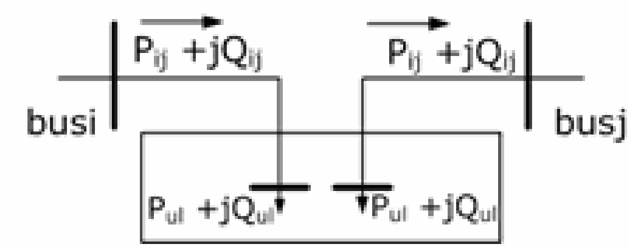

Fig. 1. UPFC's decoupled model

In this paper, using the existing control capabilities in Smart Grids, a management model is defined and its effects on utilities and customers are analyzed. The sample intelligent network is shown in Fig. 2.

This network has the following five sections: Generation, Transmission, Distribution, Customer Energy Services and Energy Management System (EMS). The energy management system is responsible for coordination of the subsystems. Through communicating with all subsystems, EMS is in charge of optimization and control of the network's various parameters.

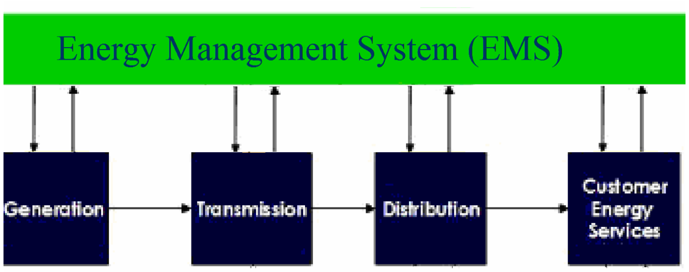

Fig. 2. Sample intelligent network

The energy management system has a significant role in this model. Its tasks are described as follows:

a. Load Forecasting

To have a clear picture of the network status, the amount of power consumption must be first determined. In fact, this forecast determines the optimal operational boundaries for the controlled devices and makes a quick network's response to the changes.

b. Optimization of FACTS Devices' Parameters

Using load forecasting, a general operation point can be determined for control devices according to the desired objectives. This general operation point is not absolutely optimal, because it is found using offline data. It gets closer to the global optimum with the increase of the accuracy of the load forecasting.

c. Online Control of FACTS Devices' Parameters

During the power control period, if the forecasted load is different than the actual load (a difference which is usually small), an online optimization will be performed to control these parameters and increase the efficiency of the system.

d. Customers' Energy Consumption Management

This management includes decreasing or increasing customers' energy consumption in order to achieve optimal operating conditions and also an improvement in the system efficiency. This is not an obligatory action enforced by the utility and is done with the customer's cooperation and consent, and its benefits are shared by both sides. Some of the available management tools, which are applied using customers' communication terminals, include: Tariff settings, short term and fast incentive programs, and similar approaches. This management system establishes a two-way communication between the customer and the utility and finds the optimal buses for consumption reduction and the amount of reduction during the peak time and offers its economic plan and proposition to the customers. Besides this, and through setting the parameters of FACTS devices, the management system controls the overload on transmission lines and reduces the power losses. To achieve this aim, the objective functions must be defined first, and then the optimal response must be determined using search (optimization) algorithms.

In this paper, the optimal placement of UPFC is done first, and then by using the results, the management model is implemented.

III. UPFC PLACEMENT

a. Problem Formulation

The placement of UPFC means finding the installation place and the optimized operational parameters of it. This problem must be solved by considering some objectives and constraints.

b. Objective Functions

Four objective functions are considered in this problem.

1. *Reduction in investment costs:*

UPFC installation cost can be modeled as follows:

$$I_C = C \times S \times 1000 \tag{1}$$

Where, I_C is the overall UPFC(s) installation cost (\$), C is the UPFC(s) installation cost (\$/KVA) and, S is the range of utilization (%).

As it is mentioned in [11],

$$C_{UPFC} = 0.0003s^2 - 0.2691s + 188.22 \tag{2}$$

Where, C_{UPFC} is the cost function of the UPFC (\$/KVA) and, s is the operating range of UPFC in KVA.

2. *Reduction in generation costs:*

$$Costgen = aP_g^{\ 2} + bP_g + c \tag{3}$$

Where, $Costgen$ is the generation cost, P_g is the amount of generation and, a, b and c are fuel constants.

3. *Loss reduction:*

$$CostP_{Loss} = C_{Loss} \sum_i \sum_j (P_{ij} - P_{ji}) \tag{4}$$

Where, $CostP_{Loss}$ is the losses cost (\$), P_{ij} is the power injection from bus i to bus j, P_{ji} is the power injection from bus j to bus i and, C_{Loss} is the losses cost (\$/KW).

4. *Reduction of lines overload:*

$$CostOvl = C_{OVL} \prod_{Line} OVL \tag{5}$$

$$OVL = \begin{cases} 1 & P_{ij} \le P_{ij}^{\ opt} \\ \exp(a(1 - \dfrac{P_{ij}}{P_{ij}^{\ opt}})) & P_{ij} \succ P_{ij}^{\ opt} \end{cases} \tag{6}$$

Where, $CostOvl$ is the cost of overload, C_{OVL} is the cost of overload for each line, P_{ij}^{opt} is the optimum amount of power injection by system condition considerations and, a is a number between [0,1].

c. Constraints

1. *UPFC constraints:*

$$n_{UPFC} = 2 \tag{7}$$

$$-150MVar \le Q_{UPFC} \le 150MVar \tag{8}$$

$$0 \le P_{UPFC} \le 600MW \tag{9}$$

Where, n_{UPFC} is the maximum number of UPFCs which can be installed and, P_{UPFC} and Q_{UPFC} are active and reactive powers of UPFC, respectively.

2. *Generators constraints:*

$$P_{gi}^{\ \min} \prec P_{gi} \prec P_{gi}^{\ \max} \tag{10}$$

$$P_{gi} - \{P_{gi}^{\ 1}, P_{gi}^{\ 2}, \ldots\} \tag{11}$$

Where, P_{gi} is the active power generated by i[th] generator, $P_{gi}^{\ \min}$ and $P_{gi}^{\ \max}$ are the generation boundaries of i[th] generator and, $P_{gi}^{\ j}$ is the j[th] inaccessible output of i[th] generator.

3. *Load flow constraints:*

As any regular load flow program, some constrains are considered here, such as acceptable voltage boundary for each bus.

d. Optimization Method

A genetic algorithm is used in this paper to solve the UPFC placement problem. Each feasible solution is coded as a chromosome. Each chromosome consists of the output of each generator in the network, UPFCs active and reactive power output and the place of installation of each UPFC. All of the genetic operators such as mutation, crossover and migration are used in this optimization.

For evaluation of each solution in the optimization process and finding the best solution, a fitness function is defined as follows:

$$Fitness_i = d\cos tgen_i + I_{C_i} - d\cos tloss_i - d\cos tovl_i \tag{12}$$

Where, $Fitness_i$ is the i[th] solution fitness function evaluation, and:

$$d\cos tgen = \cos tgen2 - \cos tgen1 \quad (13)$$

$$d\cos tloss = \cos tloss2 - \cos tloss1 \quad (14)$$

$$d\cos tovl = \cos tovl2 - \cos tovl1 \quad (15)$$

Where, $\cos tgen2$ and $\cos tgen1$ are the generating cost after and before placement, respectively, $\cos tloss2$ and $\cos tloss1$ are the losses cost after and before placement, respectively and, $\cos tovl2$ and $\cos tovl1$ are the overload cost after and before placement, respectively.

IV. Peak Load Reduction Management Model

a. Problem Formulation

The costs of generation and transmission of power at peak hours are more than other times. Also, because of supplying the peak load by non-efficient generation units, the air pollutions and fuel consumption are more, too. The overload condition usually happens in peak hours and losses are more in these hours. All of these issues cause extra costs to the utilities. The Smart Grid can be used here to reduce the costs by load management in peak hours. This also follows costumer benefits.

After UPFC placement, the Smart Grid analyzes the load forecasting data through EMS and the present condition of the network, and introduces the selected buses for load reduction and other management strategies such as new setting of UPFC parameters and new consumption tariffs. Actually, the output of EMS is the new strategy of consumption.

b. Objective Functions

Reduction of generation costs, power losses, overloads in transmission systems, and increasing the benefits of selected customers can be among the objectives of the EMS. Three objective functions are considered in this problem.

1. *Reduction of extra costs due to selling power in peak period:*

In order to simplify the model, the fuel cost is considered as the generation cost and the electricity tariffs have been established with the same idea. In general, the real cost equation can be placed in the following objective function:

$$Costdv = \begin{cases} 0 & P_g \prec P_{dv} \\ \sum Costgen - Tariff \times P_D & P_g \geq P_{dv} \end{cases} \quad (16)$$

$$Costgen = aP_g^{\ 2} + bP_g + c \quad (17)$$

Where, *Costdv*, is the difference between costs and income of selling energy in peak hours, *Costgen*, is the generation cost, *Tariff*, is the tariff of selling electricity, P_D is the power demand and P_{dv}, is the amount of power at which the generation cost and the selling income are equal. Also, *a*, *b* and *c* are fuel constants.

2. *Reduction of losses:*

$$CostP_{Loss} = C_{Loss} \sum_i \sum_j (P_{ij} - P_{ji}) \quad (18)$$

Where, $CostP_{Loss}$ is the total cost of losses, P_{ij} is the power flows from bus *i* into bus *j*, P_{ji} is the power flows from bus *j* into bus *i*, and C_{Loss}, is the cost of losses in \$/KW.

3. *Management of lines' transmitted power:*

$$CostOvl = C_{OVL} \prod_{Line} OVL \quad (19)$$

$$OVL = \begin{cases} 1 & P_{ij} \leq P_{ij}^{\max} \\ \exp(a(1 - \frac{P_{ij}}{P_{ij}^{\max}})) & P_{ij} \succ P_{ij}^{\max} \end{cases} \quad (20)$$

Where, OVL is the loadability factor, $CostOvl$ is the cost of overload, C_{OVL} is the cost of overload for each line, $P_{ij}^{\max}$ is the maximum power injection allowed by system condition considerations and, a is a number between [0,1].

c. Constraints

1. *UPFC's Constraints:*

$$S_{UPFC} \leq S_{UPFC}^{design} \quad (21)$$

Where, $S_{UPFC} = P_{UPFC} + j\,Q_{UPFC}$ is the output power of UPFC, and S_{UPFC}^{design}, is the output boundary of UPFC calculated in placement analysis.

2. Load flow constraints:

As any regular load flow program, some constrains are considered here, such as acceptable voltage boundary for each bus.

3. Load management constraints:

The level of co-operation between the consumers and the utility depends on several conditions. Usually, because of consumption necessities, the power can not be reduced below a certain level. This minimum level should be considered as a constraint in calculations. The level of co-operation is determined experimentally.

$$P_i^{dec} \leq P_i^{\max} \tag{22}$$

Where, P_i^{dec} is the reduction of load for bus i and $P_i^{\max}$ is the maximum amount of contribution for the customer connected to the bus.

d. Optimization Method

Each feasible solution is coded as a chromosome. Each chromosome consists of the nominated buses for load changing, the amount of each change, and UPFCs parameters. All of the genetic operators such as mutation, crossover and migration are used in this optimization.

In this paper, a combination of fuzzy approach and GA is used. This combination will eliminate errors in normalizing the objectives. Linear Fuzzy membership functions are used for fuzzification of loadability factor and transmission costs [13]. Fig. 3 shows a sample linear membership function.

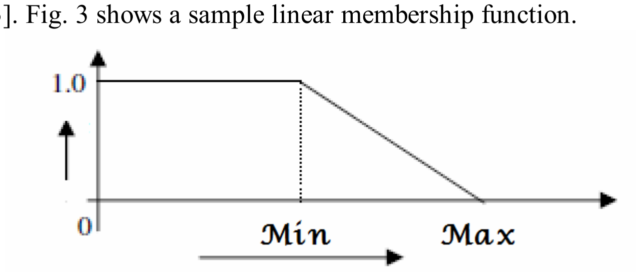

Fig. 4. Sample membership function

1. Utility cost reduction membership function:

This membership function consists of three parts: Low price energy selling cost, losses cost, and maximum customers benefit.

$$G_1 = \cos tdv + \cos tploss + cuincome(p_{dec}) \tag{23}$$

Where, *costdv* is the low price energy selling cost, *costploss* is losses cost, *cuincme* is customers refund for each MW reduction in its consumption, and p_{dec} is the amount of consumption reduction for each consumer. The cost of network in its current situation is considered as maximum of this function and the minimum is assumed to be zero.

2. Lines' loadability membership function:

$$G_2 = \prod_{Line} Ovl \tag{24}$$

3. Fuzzy evaluation:

$$Fit(G) = a\mu_1(G_1) + b\mu_2(G_2) \tag{25}$$

Where, *Fit(G)* is the fuzzy evaluation for all of the objectives, and *a* and *b* are the coefficient of each objective effect on overall evaluation function.

$$a, b \geq 0 \tag{26}$$

$$a + b = 1 \tag{27}$$

V. SIMULATION AND RESULTS

To examine its applicability, the model is applied on a case study. For this purpose, the 39-bus New England network is used. This network has 46 transmission lines and 19 consumption buses [14]. Fig. 4 shows the schematic of this network. Based on the existing data, the customer cooperation during the peak hours is considered as 40% of its load [5]. Table I, shows the network lines data.

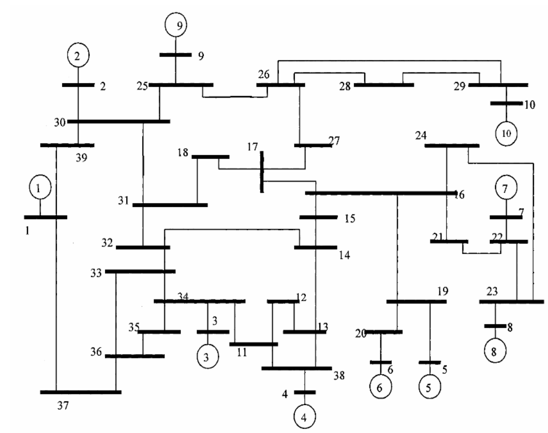

Fig. 5. The 39-bus New England network

a. UPFC Placement Results

It is necessary to run the optimum power flow before UPFC placement process. All the generators are assumed to be the same, and for achieving better results, generation cost function is assumed to have three portions for different load conditions. The relationship between cost and generation is given as a linear function.

$$Costgen = \begin{cases} 5P_g + 1000 & P_g \leq 200\ MW \\ 8P_g + 400 & 200\ MW \prec P_g \prec 450\ MW \\ 24.13P_g - 6859 & P_g \geq 450\ MW \end{cases} \tag{28}$$

TABLE I
NETWORK LINES DATA

Bus Number		Resistance	Reactance	Charging/2
From	To			
30	39	0.0035	0.0411	0.3494
1	39	0.0010	0.0250	0.3750
30	31	0.0013	0.0151	0.1286
30	25	0.0070	0.0086	0.0730
31	32	0.0013	0.0213	0.1107
31	18	0.0011	0.0133	0.1068
32	33	0.0008	0.0128	0.0671
32	14	0.0008	0.0129	0.0691
33	34	0.0002	0.0026	0.0217
33	36	0.0008	0.0112	0.0738
34	35	0.0006	0.0092	0.0565
34	11	0.0007	0.0082	0.0695
35	36	0.0004	0.0046	0.0039
36	37	0.0023	0.0363	0.1902
1	37	0.0010	0.0250	0.6000
38	11	0.0004	0.0043	0.0365
38	13	0.0004	0.0043	0.0365
13	14	0.0009	0.0101	0.0862
14	15	0.0018	0.0217	0.0183
15	16	0.0009	0.0094	0.0086
16	17	0.0007	0.0089	0.0671
16	19	0.0016	0.0195	0.1520
16	21	0.0008	0.0135	0.1274
16	24	0.0003	0.0059	0.0340
17	18	0.0007	0.0082	0.0660
17	27	0.0013	0.0173	0.1608
21	22	0.0008	0.0135	0.1274
22	23	0.0006	0.0096	0.0923
23	24	0.0022	0.0350	0.1805
25	26	0.0032	0.0323	0.2565
26	27	0.0014	0.0147	0.1198
26	28	0.0043	0.0474	0.3901
26	29	0.0057	0.0625	0.5145
28	29	0.0014	0.0151	0.1245
11	12	0.0016	0.0435	0.0000
13	12	0.0016	0.0435	0.0000
4	38	0.0000	0.0200	0.0000
5	19	0.0007	0.0142	0.0000
6	20	0.0009	0.0180	0.0000
7	22	0.0000	0.0143	0.0000
8	23	0.0005	0.0272	0.0000
9	25	0.0006	0.0232	0.0000
2	30	0.0000	0.0181	0.0000
10	29	0.0008	0.0156	0.0000
20	19	0.0007	0.0138	0.0000
3	34	0.0000	0.0250	0.0000

By using this function, the amount of generation for each generator will be as shown in Table II.

TABLE II
GENERATORS OUTPUT BEFORE UPFC PLACEMENT

Gen. No.	1	2	3	4	5	6	7	8	9	10
Output(MW)	1218	451	971	450	450	459	683	450	450	573

Under this conditions, the power loss and OVL of the network in peak hours are 31 MW and 5.86, respectively. It is assumed that the optimum current for each line of the network is 75% of its nominal current. The network's active and reactive load data are given in Tables III and IV, respectively.

TABLE III
ACTIVE LOAD FOR EACH BUS (MW)

Bus 1	Bus 3	Bus 12	Bus 15	Bus 16	Bus 18	Bus 20	Bus 21	Bus 23	Bus 24
1104	9.2	8.5	320	329.4	158	628	274	274.5	308.6
Bus 25	Bus 26	Bus 27	Bus 28	Bus 29	Bus 31	Bus 32	Bus 35	Bus 36	
224	139	281	206	283.5	322	500	233.8	522	

TABLE IV
REACTIVE LOAD FOR EACH BUS (MVAR)

Bus 1	Bus 3	Bus 12	Bus 15	Bus 16	Bus 18	Bus 20	Bus 21	Bus 23	Bus 24
250	4.6	88	32.3	32.3	300	103	115	84.6	92.2
Bus 25	Bus 26	Bus 27	Bus 28	Bus 29	Bus 31	Bus 32	Bus 35	Bus 36	
47.2	17	75.5	27.6	26.9	2.4	184	84	176	

By running the MATLAB program written for this purpose, the optimum place for UPFCs are lines 11 (between buses 34 and 35, and the shunt branch of the UPFC will be connected to bus 34) and 16 (between buses 38 and 11, and the shunt branch of the UPFC will be connected to bus 38). The result of UPFC placement and the output of generators after UPFC placement are given in Tables V and VI, respectively. In allocated UPFCs' parameters, "Active Power" is the active power that is transferred from Bus-i to Bus-j and "Reactive power" is the injected reactive power at both buses in UPFC.

TABLE V
ALLOCATED UPFCS' PARAMETERS

Place of Installation (Line)	Active Power (MW)	Reactive power at Bus-j (MVar)	Reactive power at Bus-i (MVar)
11	390	150	150
16	180	150	150

TABLE VI
GENERATORS OUTPUT AFTER UPFC PLACEMENT

Gen. No.	1	2	3	4	5	6	7	8	9	10
Output(MW)	1154	526	809	525	510	520	570	517	517	506

After the placement, the power loss and OVL of the network in peak hours are 30.71 MW and 1, respectively.

b. Peak Load Reduction Management Results

First, it is assumed that the UPFCs allocated in the placement process are installed in the network. The loads are considered to be 30% more than Tables III and IV.

Initially, the evaluation of solutions for each objective is done separately. The initial state of the system is chosen as the maximum loss of income and the worst overload is considered to be OVL=1.5. In the best situation, there is no loss of income for the utility and its value is set equal to zero. On the other hand, the best loadability factor for the system in normal state is OVL =1. The solutions in which the lines' power is out of emergency limit will be removed from the assessment process. After the simulation program is run, the Fuzzy results will be attained. Tables VII and VIII show the calculated parameters of UPFCs and the amount of load reduction in each bus, after the management model is applied, respectively.

TABLE VII

ALLOCATED UPFCS' PARAMETERS AFTER PEAK LOAD MANAGEMENT

Place of Installation (Line)	Active Power (MW)	Reactive power at Bus-j (MVar)	Reactive power at Bus-i (MVar)
11	200	10	0
16	160	150	0

TABLE VIII

ACTIVE LOAD REDUCTION FOR EACH BUS (MW)

Bus 1	Bus 3	Bus 12	Bus 15	Bus 16	Bus 18	Bus 20	Bus 21	Bus 23	Bus 24
353	3.6	0.68	51.2	26	13	200	0	0	99
Bus 25	Bus 26	Bus 27	Bus 28	Bus 29	Bus 31	Bus 32	Bus 35	Bus 36	
90	22	22	16	45	77	40	37	208	

By implementation of this management model, the peak load is reduced by 1307 MW, the power losses are reduced from 27.22 MW to 22.25 MW, and OVL reduces from 1.68 to 1.12.

VI. CONCLUSIONS

The reduction of power consumption at peak hours not only reduces the utility's cost of generation and operation, but also can bring about considerable benefits for the customers who co-operate with the utility towards realizing the Smart Grid. Smart Grids using communication with consumers play a significant role in this context. In the model proposed in this paper, a number of buses in a Smart Grid are selected for power reduction and the amount of changes in the power consumption is determined for each of them to reduce the peak demand. This load management model maximizes the efficiency with minimal changes in consumption. The simulation results prove the effectiveness of this method.

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VIII. BIOGRAPHIES

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