



**Kinhekar, N., Padhy, N. P., Li, F. and Gupta, H. O. (2016) Utility Oriented Demand Side Management Using Smart AC and Micro DC Grid Cooperative. IEEE Transactions on Power Systems, 31 (2). pp. 1151-1160. ISSN 0885-8950**

**Link to official URL (if available):**

<http://dx.doi.org/10.1109/TPWRS.2015.2409894>

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# Utility Oriented Demand Side Management Using Smart AC and Micro DC Grid Cooperative

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**Abstract--** DC microgrid provides a viable and more efficient option to cater for DC loads in the building space and, in particular, data centers. This paper investigates the opportunities associated for utilities to optimize industrial demand response for smart AC and DC microgrid environment thus facilitating distribution utility to reduce peak energy on the existing AC distribution system. A load shifting demand side management (DSM) technique is used to shift AC industrial loads in response to time of day (TOD) tariff. Hence, an attempt has been made to study the impact of DSM strategies with optimal shifting of AC devices in the presence of DC microgrid. Simulations are carried out on a practical distribution system having large industrial loads but it has been assumed that the AC distribution system has DC microgrid with renewables and battery storage systems (BSSs). DSM results for AC distribution grid are compared and analyzed with differing DC microgrid set ups, for example with and without battery storage. It has been observed that the DSM strategy with DC microgrid in the presence of solar renewables and battery storage can substantially reduce average energy cost for demand to response and peak load burden on AC distribution utilities.

**Index Terms--** AC/DC loads, battery storage, DC microgrid, demand side management, and renewable generations.

## I. NOMENCLATURE

*Parameters of Smart AC- Micro DC Grid System:*

$ACP_{ac}(t)$	Actual consumption of AC energy at time $t$ (kWh).
$Target_{ac}(t)$	Value of targeted AC energy at time $t$ (kWh).
$Forecast_{ac}(t)$	Forecasted AC energy at time $t$ (kWh).
$Connect_{ac}(t)$	Amount of AC energy connected at time $t$ during load shifting (kWh).
$Disconnect_{ac}(t)$	Amount of AC energy disconnected at time $t$ after load shifting (kWh).
$Y_{kit,ac}$	Number of AC devices of type $k$ that are shifted from time step $i$ to $t$ .
$Y_{ktq,ac}$	Number of AC devices of type $k$ that are delayed from time step $t$ to $q$ .
$P_{L,ac}(t)$	AC load power demand at time $t$ (kW).
$P_{G,ac}(t)$	Total AC power generation at time $t$ (kW).
$Charging_{bi}(t)$	Amount of battery charged energy at time $t$ (kWh).
$Discharging_{bi}(t)$	Amount of battery discharged energy at

	time $t$ (kWh).
$P_{bt,i,t}^c$	Charged power of battery $i$ during the time period $t$ (kW).
$P_{bt,i,t}^d$	Discharged power of battery $i$ during the time period $t$ (kW).
$bt_{num}$	Number of BSSs.
$P_{bt,i}^{c,max}$	Maximum charged power of the battery $i$ (kW).
$P_{bt,i}^{d,max}$	Maximum discharged power of the battery $i$ (kW).
$E(t)$	Total amount of stored energy in the battery bank at time $t$ (kWh).
$E_{min}$	Minimum stored energy in the battery bank (kWh).
$E_{max}$	Maximum stored energy in the battery bank (kWh).
$\Delta t$	Time duration of each interval.
$\eta_c$	Charging efficiency of BSS (%).
$\eta_d$	Discharging efficiency of BSS (%).
$K_{lf(dc/ac)}$	Loss factor representing losses taken place during DC to AC conversion.
$K_{lf(ac/dc)}$	Loss factor representing losses taken place during AC to DC conversion.
$P_{(ac/dc)Loss}(t)$	Power loss during AC to DC conversion (kW).
$P_{(dc/ac)Loss}(t)$	Power loss during DC to AC conversion (kW).
$P_{pv,i,t}$	Power output of solar PV generation system $i$ at the time period $t$ (kW).
$P_{pv,i}^{max}$	Maximum power output of solar PV generation system $i$ (kW).
$spv_{num}$	Number of solar PV generation systems.
$P_{L,dc}(t)$	DC load power demand at time $i$ (kW).

## II. INTRODUCTION

DSM adjusts electrical loads in customer's premises with respect to time and amount of their use, helping electric utility to decrease demand peak and thereby redistribute the load of the system. This aids to reduce the huge gap between peak demand and the available generation of energy during peak period. DSM is the management of loads on demand side that helps to flatten the overall load curve. Load shifting from peak to off-peak period is one of the most effective DSM strategy used to flatten the load curve [1]. DSM encourages active participation of customers in reducing the peak demand by shifting the load according to the generation. The

customers in return are rewarded in a way that they have to pay low electricity price [2]. Reducing the consumption of energy during peak hours and scheduling the demand to low peak hours is one of the major goals of DSM [3]-[10]. DSM can be divided in two categories as a direct load control (DLC) that permits utilities to control a part of customer's load directly with their consent and an indirect load control (IDLC), that permits customers to manage their consumption on their own as per the price signal sent by the utility [11], [12]. Thus shifting of customer's controllable loads in order to reduce system peak demand is an important aspect of DSM [13].

As a result of fast growth in semiconductor technology, share of DC loads has significantly increased due to extensive use of electronic devices. These DC loads are supplied by AC sources in the present distribution system. In a distribution system, loads are broadly classified into two categories, AC and DC loads. AC loads such as water heaters, washing machine, dryer etc. are controllable (i.e. shiftable) in nature. Hence, these controllable AC loads can be shifted from peak to off-peak hours by using a load shifting DSM technique to flatten the overall load curve of the system. But, DC loads such as electronics equipments, computers, routers etc. are not controllable. In existing electrical grid, these DC loads are usually supplied by AC sources, but with additional losses to the system operation. Increasing use of laptops, computers, smartphones, and other personal electronic devices including lightning load requires a huge quantity of DC power. The amount of energy lost in conversion from AC to DC; to feed these DC loads vary with different devices, but is generally 10-25% [14]. DC microgrid is currently resurging due to growth of renewable DC power sources that can be used to feed DC loads directly that avoids the conversion losses [15]. The development of DC microgrid based on solar PV sources, storage, grid connection and DC load handles real time load balancing in the microgrid [16].

DC microgrid is used to feed DC loads locally in the presence of battery storage. If residential, commercial and/or industrial AC and DC loads are identified, DC loads will be fed directly by DC microgrid and AC loads will be fed by AC distribution grid as well as by storage devices in DC microgrid. To reduce peak demand, the controllable AC loads can be shifted using load shifting DSM technique. In addition to load shifting, if BSSs are used to mitigate the system peak then this may certainly help to improve the flatness of load curve and can realize cost savings to customers by appropriately scheduling their power consumption to off peak hours [17]. Usually BSSs are used to discharge power during peak load conditions and to charge during off-peak load conditions of distribution system [18] and to cope up with the fluctuations in the power generated by large PV systems [19]-[21].

In this paper, DC sources are assumed to be localized generations near the load center. During off-peak condition, storage devices in DC microgrid are charged and can be used at the time of peak load conditions in DC microgrid and also help to reduce peaks on AC distribution grid; if necessary.

Formation of DC microgrid within present distribution system to feed DC loads and the use of load shifting technique to shift AC loads together can be helpful to improve DSM performance. Load shifting DSM programs reported in existing literature are used for AC distribution system [22]-[24]. But, the performance of DSM program in the presence of DC microgrid is yet to be thoroughly investigated. The DSM problems when the customers are equipped with energy storage devices are discussed in [25]. An optimal energy storage control strategy for grid-connected microgrids is presented in [26]. But, in this paper, we exploit the benefits of DC microgrid to improve the performance of existing load shifting DSM program with the help of battery storage. Also DSM solutions have been proposed for overall distribution system in the presence of DC microgrid with battery storage.

There have been several good works reported in the literature to solve energy and reserve scheduling problem in a smart distribution system considering distributed energy resources (DER) and demand response (DR) using stochastic optimization [27]-[31]. Several methods have been proposed to solve optimal in-home load scheduling problem: particle swarm optimization method [32] and game theory [33]. An optimal load scheduling problem for demand response in home energy management system is solved by genetic algorithm (GA) [34]. The formulation for above stated optimization problems is nonlinear in nature, so we anticipate that the load scheduling of industrial loads can be easily solved by GA. Hence, in this paper an attempt has been made to solve the load shifting DSM problem for industrial loads optimally by GA. However, the results obtained by GA have been validated by comparing with the results obtained in General Algebraic Modelling System (GAMS) software [35] using Mixed-Integer Non Linear Programming (MINLP) solver.

A load shifting DSM strategy in the presence of DC microgrid with battery storage is proposed to shift controllable AC devices of industrial customers at different hours of the day as per time of day (TOD) tariff and the results are compared with the load shifting DSM strategy only for AC distribution grid without DC microgrid. Data center loads are considered as typical DC loads to supply using DC microgrid [36], [37]. Half hourly forecasted AC and DC load data, TOD tariff and solar energy purchase cost data are given as inputs to the DSM program. Different kinds of shiftable AC loads from industrial customers are identified. Around 160 controllable AC loads from 6 different types of industrial customers are available for load shifting. Only 12% of the total connected AC load is made available for control from industrial area. DC loads from data center and IT company such as servers, telecommunications equipments, computers, routers, storage devices etc. are considered as nonshiftable/noncurtailable loads.

The rest of the paper is organized as: Section III provides the proposed DSM methodology along with problem formulation and proposed algorithm in brief. Section IV briefs about simulation data. Results of simulation along with discussion are presented in Section V. Finally, conclusions are

provided in Section VI.

### III. PROPOSED DSM METHODOLOGY

A load scheduling DSM strategy is proposed to shift all controllable AC loads of industrial customers at different hours of the day while DC loads continued to receive power from DC microgrid so as to reduce peak demand of the overall distribution system. DSM technique's objective could be maximizing the use of renewable DC sources, minimizing the power taken from existing AC distribution grid, and reducing the system peak load demand. Indian power system is in developing state where there is an energy deficit in peak power served. Hence, in this paper, industrial AC loads are considered for scheduling as per TOD tariff so that consumption of power will be reduced during peak load period. It is an energy scheduling approach based on fixed TOD tariff. This fixed TOD tariff is issued by the State Electricity Regulatory Commissions having discussion with the distribution utilities. These are declared to customers in advance by the utility so that they can extract its benefits by running their loads to low TOD tariff. Most of the industrial AC loads of the system under study are running in shifts. It is quite possible to schedule the loads during low energy cost period. Hence, the aim of the proposed optimization technique is to bring the final load curve as close as possible to the pre-defined target load curve of the system. The target load curve is defined as inversely proportional to the TOD tariff.

#### A. Problem Formulation

The DSM strategy proposed here works on the principle of shifting the connection moment of each shiftable AC device to bring the desired load curve closer to the target load curve of the system. Mathematical formulation of the load shifting DSM technique for the AC distribution grid is given as [23], [24]:

$$\text{Minimize } \sum_{t=1}^N (ACP_{ac}(t) - Target_{ac}(t))^2 \quad (1)$$

where  $N$  is the number of time steps in half hourly block. The  $ACP_{ac}(t)$  can be expressed as follows:

$$\begin{aligned} ACP_{ac}(t) = & Forecast_{ac}(t) + Connect_{ac}(t) - Disconnect_{ac}(t) \\ & + (1 + K_{lf}(ac/dc)) \cdot Charging_{bt}(t) \\ & - (1 - K_{lf}(dc/ac)) \cdot Discharging_{bt}(t) \end{aligned} \quad (2)$$

The  $Connect_{ac}(t)$  has two components [23]. Both components deal with the increment in the loads because of shifting of their connection instants. The first increment in the load at time  $t$  is because of device connection instants shifted to time  $t$ , whereas, the second increment in the load is because of device connection instants which are planned to be connected for the time steps that precede  $t$  and whose load consumption duration overlaps time period  $t$ .

The  $Connect_{ac}(t)$  can be expressed as follows [23]:

$$Connect_{ac}(t) = \sum_{i=1}^{t-1} \sum_{k=1}^D Y_{kit,ac} P_{1k} \times \Delta t$$

$$+ \sum_{l=1}^{j-1} \sum_{i=1}^{t-1} \sum_{k=1}^D Y_{ki(t-1),ac} P_{(1+l)k} \times \Delta t \quad (3)$$

where  $D$  denotes the number of device types which are controllable.  $P_{1k}$  and  $P_{(1+l)k}$  are the power consumptions at time steps 1 and  $(1+l)$  respectively for device type  $k$ , and  $j$  is the total consumption period for  $k$  type of device.

The  $Disconnect_{ac}(t)$  has two components [23]. Both components deal with the reduction in the loads because of delay in their connection time. The first delay is because of failure to connect the load at a pre-decided time step  $t$ , whereas, the second delay is because of failure to connect the load at time steps that precede  $t$ . The  $Disconnect_{ac}(t)$  can be expressed as follows:

$$\begin{aligned} Disconnect_{ac}(t) = & \sum_{q=t+1}^{t+m} \sum_{k=1}^D Y_{ktq,ac} P_{1k} \times \Delta t \\ & + \sum_{l=1}^{j-1} \sum_{q=t+1}^{t+m} \sum_{k=1}^D Y_{k(t-1)q,ac} P_{(1+l)k} \times \Delta t \end{aligned} \quad (4)$$

where  $m$  is the maximum allowable delay.

The  $Charging_{bt}(t)$  which is the amount of battery charged and the  $Discharging_{bt}(t)$  which is the amount of battery discharged at time  $t$  during off-peak and peak load conditions in AC distribution grid respectively are given by the following equations:

$$Charging_{bt}(t) = \sum_{i=1}^{btum} P_{bt,i,t}^c \times \Delta t \quad (5)$$

$$Discharging_{bt}(t) = \sum_{i=1}^{btum} P_{bt,i,t}^d \times \Delta t \quad (6)$$

The above minimization objective function (as in Eq. 1) is subject to the following set of constraints [23]:

Numbers of AC devices that are shifted are always positive.

$$Y_{kit,ac} > 0 \quad \forall i, j, k. \quad (7)$$

The total number of controllable devices at a particular time step must be less than or equal to the total number of available devices at that time step. A constraint related to this can be formulated as:

$$\sum_{t=1}^N Y_{kit,ac} \leq Controllable(i) \quad (8)$$

where  $Controllable(i)$  is the total number of AC devices of type  $k$  available for control at time step  $i$ .

A device can only be connected forward not backward, which can be expressed as:

$$Y_{kit,ac} = 0 \quad \forall i > t. \quad (9)$$

A constraint is imposed on the maximum permissible time delay for all devices according to the agreement between utility and consumer to limit the available number of time steps to be shifted, which can be given as:

$$Y_{kit,ac} = 0 \quad \forall (t-i) > m. \quad (10)$$

The battery storage systems must satisfy the following constraints [38]:

$$0 \leq P_{bt,i,t}^c \leq P_{bt,i}^{c,max} \quad i=1, \dots, btum \quad (11)$$

$$0 \leq P_{bt,i,t}^d \leq P_{bt,i}^{d,\max} \quad i=1,\dots,bt\text{num} \quad (12)$$

The charging and discharging equations which represents state of charge of BSSs are given as [38]:

$$\text{Charge: } E(t+1) = E(t) + \Delta t \cdot \sum_{i=1}^{bt\text{num}} P_{bt,i,t}^c \cdot \eta_c \quad (13)$$

$$\text{Discharge: } E(t+1) = E(t) - \Delta t \cdot \sum_{i=1}^{bt\text{num}} P_{bt,i,t}^d / \eta_d \quad (14)$$

where  $E(t)$  which is the total energy stored in the battery bank at time  $t$ , which is subjected to:

$$E_{\min} \leq E(t) \leq E_{\max} \quad (15)$$

The solar PV generation systems should satisfy the following constraint [21]:

$$0 \leq P_{pv,i,t} \leq P_{pv,i}^{\max} \quad i=1,\dots,spv\text{num} \quad (16)$$

The power balancing equation for entire distribution system including DC microgrid is given as:

$$P_{L,dc}(t) + P_{L,ac}(t) + \sum_{i=1}^{bt\text{num}} P_{bt,i,t}^c + P_{(ac/dc)Loss}(t) = \sum_{i=1}^{spv\text{num}} P_{pv,i,t} + \sum_{i=1}^{bt\text{num}} P_{bt,i,t}^d - P_{(dc/ac)Loss}(t) + P_{G,ac}(t) \quad (17)$$

### B. Proposed Algorithm

The DSM algorithm should provide enough flexibility to manage more controllable devices and battery energy storage systems of diversified nature. The developed algorithm should be capable of addressing complex nature of the controllable devices in terms of load patterns and duration. Thus minimization problem is of complex nature as it involves large number of controllable AC loads and battery storages. Different types of loads and consumption pattern of each load needs to be considered. The traditional mathematical algorithms such as linear and dynamic programming are commonly used in this field but cannot handle these complexities adequately [39]-[41]. The proposed problem formulation is of non-linear, mixed integer and non-convex nature. Hence to solve such problem evolutionary computational techniques are required [42], [43]. One of the evolutionary computational techniques is GA. GA provides many benefits in achieving optimal solution of complex mathematical problems. Hence, an evolutionary genetic algorithm has been proposed in this paper.

A cost function for overall distribution system is chosen such that final load curve as close as possible to the target load curve can be achieved, which is given as in (1). The first step to apply GA, a random value of 64 chromosomes, representing initial population is considered [44]. An integer array is constructed to represent each chromosome. Each array has a length  $N_t$  given as [22]:

$$N_t = \left( (48-m) \times m + \sum_{n=1}^{m-1} n \right) \times k \quad (18)$$

where  $N_t$  is the maximum number of possible time steps and  $k$  is the number of various kinds of devices. Then cost of each

chromosome is estimated with constraints given as in (7) to (12) and (15), (16). The chromosomes are ranked from lowest cost to highest cost. Top 50% chromosomes in a given generation are kept for mating and the rest are discarded. Uniform crossover method is used for mating and mutation rate of 0.04 is used. Thus new population of chromosomes is produced from the existing population. This process is iterated until the stipulated numbers of generations (i.e., 500) are reached.

The step by step algorithm for DSM controller is given as: Step 1)-Input data from distribution utility such as forecasted AC and DC loads, TOD tariffs, forecasted DC renewable prices including battery installation and annual maintenance cost and the number of BSS available in the system. Step 2)-Input data from industrial customers such as consumption pattern and duration of devices and types of devices. Step 3)-Preparation of target load curves for AC and DC loads based on their respective price structures. Step 4)-Provide data given in steps 1, 2, and 3 as input to GA. Step 5)-Output of GA gives information to consumers in the form of desired load curve with device shifting instructions.

In order to validate the proposed algorithm, the same problem formulation has been implemented in GAMS using MINLP solver on a PC with Intel core 2 duo 2.6 GHz processor and 2GB of RAM.

### C. Proposed Architecture

Fig. 1 depicts the working structure of the proposed DSM scheme using DC microgrid.

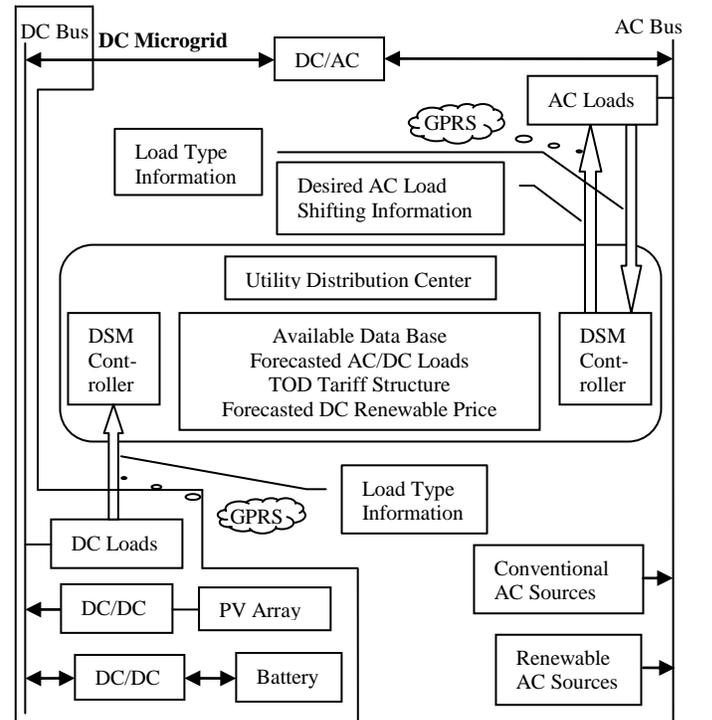


Fig. 1. The architecture of proposed DSM work using DC microgrid.

The proposed DSM architecture consists of three major components such as distribution utility, industrial loads and

AC/DC grid tied with smart networks that operate in a hybrid mode. The proposed architecture is quite common for urban distribution utilities all over the world but can certainly improve the energy crises of developing country like India. There have been several good papers in the literature stating the hybrid AC/DC systems with AC and DC sources/loads that are considered to be the most possible future distribution structures with widespread acceptance under the smart grids environment [45]-[47].

The TOD tariffs, forecasted DC renewable prices, forecasted half hourly AC and DC loads, and device energy consumption pattern information is available with the data base maintained by the distribution utility. This information is processed in the central processing unit. The proposed step by step DSM algorithm is used to generate the desired load curve of tomorrow. The device shifting pattern is obtained from the generated curve. This pattern will be communicated to smart meters placed at the industrial customer's premises using General Packet Radio Service (GPRS) technology by the distribution utility. Then the control signals will be transmitted to the industrial loads to perform action by DSM controller using ZigBee technology. Inbuilt sensors and actuators are used for automatic ON or OFF of the devices after receiving the control signals in real time. The communication infrastructure for the proposed DSM strategy between the distribution utility and various industrial loads is as shown in Fig. 2.

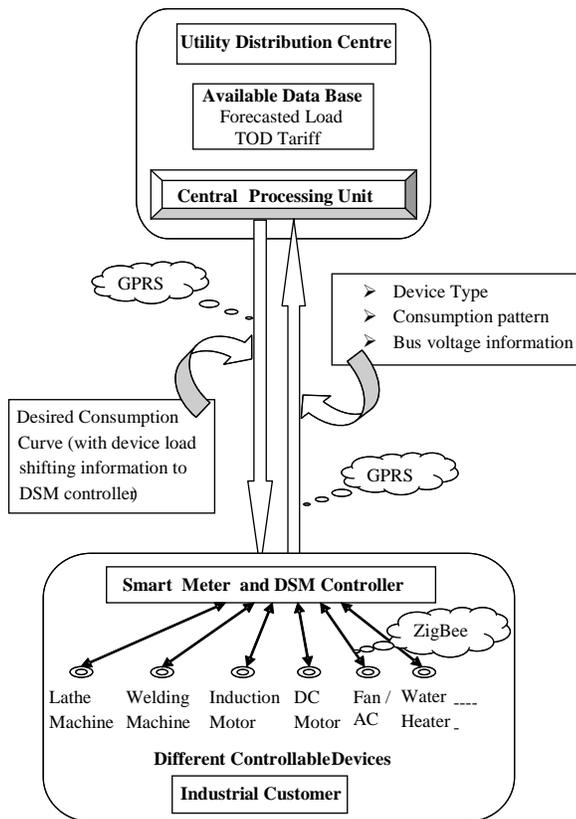


Fig. 2. The communication infrastructure between distribution utility and industrial customer.

#### IV. DETAILS OF DATA SIMULATION

The usefulness of the proposed technique is illustrated by carrying out simulations on a practical distribution system containing industrial loads of utility in western region of India. The system considered for simulation is from Mumbai, the capital city of Maharashtra state in India. The approximate population and spread over area of the city is 12.5 million and 437.5 km<sup>2</sup> respectively. The whole system has a residential customer base of approximately 0.35 million and 50,000 high tension (HT) and low tension (LT) and commercial and industrial customers in Mumbai city. The proposed load shifting technique was applied to a modified 15-bus, 11kV practical ring distribution system for industrial loads only. System consists of 4 main feeders, 8 distribution lines, and 20 distribution transformers. The industrial loads are placed at bus number 10 to 15. The loads for assumed DC microgrid are placed at bus number 13, 14, and 15. The modified distribution network diagram for the practical system is shown in Fig. 3.

The measured half hourly AC load consumption data of industrial customers for a day (48 half hours) recorded by Automatic Meter Reading (AMR) system has been used as forecasted AC load for simulation. A half hourly TOD tariffs has been taken to generate the target AC load consumption curve. DC microgrid is likely to come up in India. Hence, to do the analysis on DC microgrid, a load survey was carried out for a group of industrial customers to know the percentage of DC loads available with customers. Different types of customers namely; air catering company, IT company, data centre, large commercial offices, and manufacturing unit are

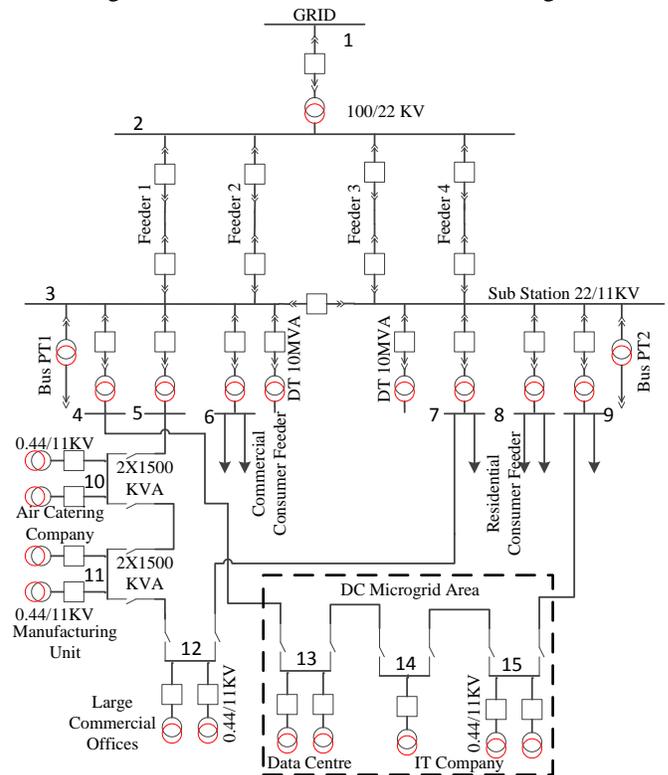


Fig. 3. The practical distribution system network diagram.

TABLE I  
CONTROLLABLE DEVICE DATA IN THE INDUSTRIAL AREA [23]

Device Type	Fan/AC	Induction Motor	Welding Machine	Water Heater	DC Motor	Lathe Machine	Total	
Half Hourly Consumption of Devices (kW)	1 <sup>st</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	2 <sup>nd</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	3 <sup>rd</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	4 <sup>th</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	5 <sup>th</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	6 <sup>th</sup> Half Hour	15	30	12.5	4.8	40	8.5	-
	7 <sup>th</sup> Half Hour	15	30	12.5	4.8	-	-	-
	8 <sup>th</sup> Half Hour	15	30	12.5	4.8	-	-	-
	9 <sup>th</sup> Half Hour	15	30	-	-	-	-	-
	10 <sup>th</sup> Half Hour	15	30	-	-	-	-	-
Number of Devices	19	20	36	34	18	27	154	

under the industrial category. Major loads in data centre and IT company such as servers, telecommunications equipments, computers, routers, data storage devices etc. are identified as DC loads. Hence, 50% of data centre and IT company load data supplied by the distribution utility is considered as DC load for simulation purpose.

DC microgrid is assumed to be a small integrated part within whole AC distribution system. DC loads present in DC microgrid are assumed to be supplied only by DC sources like PV arrays and BSS. Power generation using fuel cell is not commercially accepted in India and hence it is not considered for the analysis. When there is insufficient solar, the power is taken from AC bus and BSS. Total 10 numbers of BSSs of 100 kWh each are used for simulation. Charging and discharging efficiency of a BSS is considered to be 90% [48]. It is assumed that a BSS is charging from DC sources when ample generation is available or from the grid during off peak hours when TOD tariff is less. Discharging of BSS takes place through both DC microgrid and AC distribution system during emergency. Loss factor of 10% is considered for the losses taking place during DC to AC conversion while supplying power to AC distribution system.

Power taken from DC renewable sources is costlier than that of AC pool prices. Also the power drawn from BSS is costlier than that drawn from DC renewable as it involves one-time battery installation cost and time to time maintenance cost. It is assumed that sufficient sunlight is available for 10 hours from 7 a.m. in the morning to 5 p.m. in the evening during day time. Hence, PV array is the DC source available to feed DC loads during day time. DC renewable prices during day time are considered to be Rs. 6.5/kWh for 10 hours and Rs. 9.5/kWh for rest of the hours, as BSSs are assumed to be main source of power supply during night time. Though the power supplied by DC renewable is costlier, it is mandatory to purchase power from renewable generations under the green power obligations, renewable purchase obligations led down by the Maharashtra Electricity Regulatory Commission (MERC), India [49].

Forecasted half hourly AC and DC load data of industrial customers are shown in Fig. 4. The TOD tariff data and DC renewable prices are shown in Fig. 5. The maximum load demand of industrial customers for whole AC distribution grid and DC microgrid in this study are 6930 kW and 1467 kW

respectively. Maximum allowable delay of 6 hours is taken while carrying out the simulations. On a typical day, the control period is started from 9 a.m. of present day to 9 a.m. of next day as peak is generally started around 9<sup>th</sup> hr of the day for a given distribution area. The consumption patterns of the AC devices under control for the industrial customers are shown in Table I.

There are around 160 devices of AC distribution grid available for control. System under study is considered from commercial capital of India, where large number of IT offices, commercial offices, and data centers are situated.

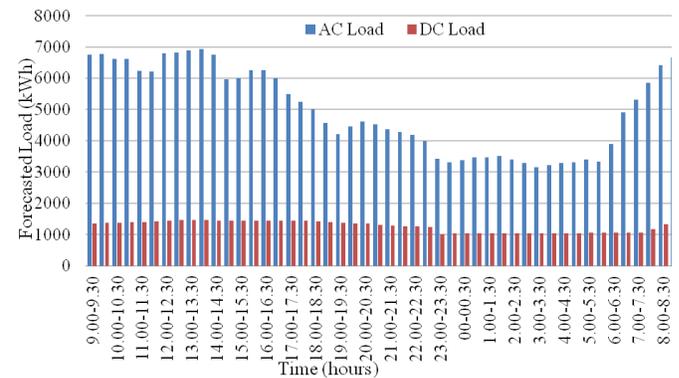


Fig. 4. Forecasted AC and DC load data for industrial customers.

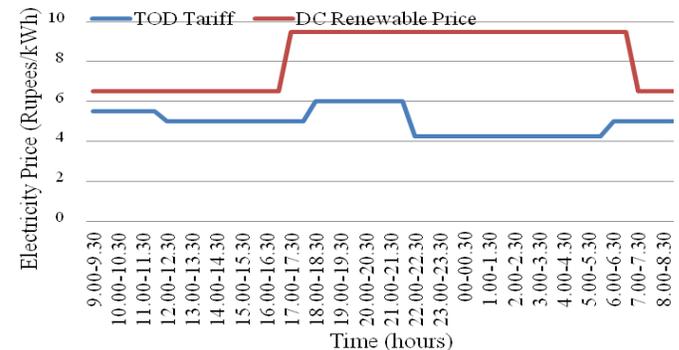


Fig. 5. TOD tariff data and DC renewable price data.

## V. RESULTS AND DISCUSSION

Two case studies are performed using proposed DSM technique. First one is performed by assuming whole AC distribution system without existence of DC microgrid.

Second one is performed by assuming DC microgrid as an integrated part within AC distribution system. This DC microgrid is connected to rest of the AC distribution system at one point of connection using bidirectional converter (as shown in Fig. 1.). DSM results are compared for these two case studies to analyze the effect of existence of DC microgrid with battery storage on the DSM performance of AC distribution system.

#### A. Case Study 1 – DSM of AC Distribution System without DC Microgrid

In this case study the target load curve is produced as inverse to TOD tariff structure of industrial customers. Load scheduling DSM strategy is used to shift the controllable AC loads of industrial customers optimally to next low peak hours so that the desired load curve follows the target curve. Total number of devices given in Table I have been taken for simulation. The simulation result obtained for industrial customers is shown in Fig. 6 and tabulated in Table II. Peak load reduction of 12.92% is achieved without DC microgrid.

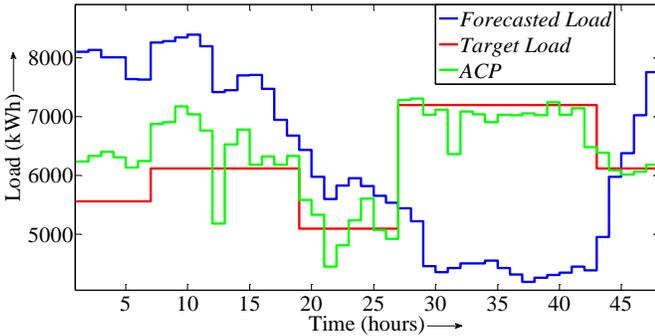


Fig. 6. DSM results of AC Distribution System without DC microgrid.

#### B. Case Study 2 – DSM of AC Distribution System with DC Microgrid and Battery Storage

In this case study, 50% of data centre and IT company load data provided by the distribution utility is considered as DC load and assumed to be supplied using DC microgrid. Hence, the amount of DC load considered is subtracted from the total load on AC distribution system. The remaining AC load is considered as the forecasted load for the simulation purpose to obtain DSM solutions with DC microgrid. The target load curve is produced as inverse to TOD tariff structure. Load scheduling DSM strategy is used to shift the controllable AC loads of industrial customers optimally to next off peak hours so that the desired load curve follows the target curve.

Simulation time required to converge the solution of proposed DSM algorithm is 3 hours. It is acceptable as the DSM strategy to be applied is performed 24 hours before its actual implementation. Fig. 7 shows the simulation result obtained for the case study.

Simulation results for the proposed DSM strategy with and without DC microgrid is summarized in Table II. DSM results are better when DC microgrid with battery storage is incorporated in present AC distribution system. Peak load reduction is increased to 19.65% from that of 12.92% because of DC microgrid with battery storage. It is observed that

during day time peak load condition, solar PV system helps to achieve higher peak reduction. Thus, there is significant reduction in peak load demand on AC distribution system when DC microgrid is incorporated within AC distribution system to feed DC loads separately.

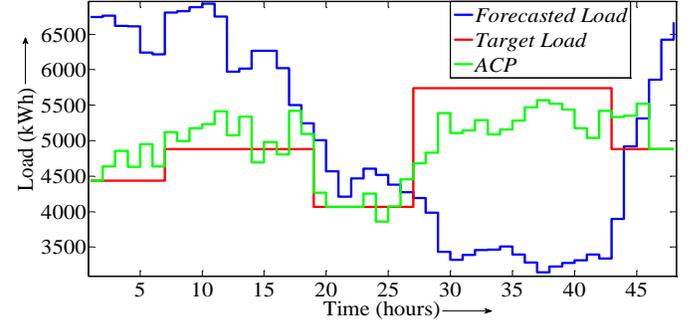


Fig. 7. DSM results of AC distribution system with DC microgrid.

TABLE II  
REDUCTION IN PEAK DEMAND

Type of System	AC Distribution System without DC Microgrid	AC Distribution System with DC Microgrid
Peak Load without DSM (kW)	8391	6930
Peak Load with DSM (kW)	GA	5568
	MINLP	5602
Peak Reduction (kW)	GA	1362
	MINLP	1328
Percentage Reduction (%)	GA	12.92
	MINLP	12.2

The above results are obtained by solving the load shifting DSM problem formulation using GA technique. In order to validate these results the same formulation has been implemented in GAMS using MINLP solver and have been compared with GA results as shown in Table II. The results obtained are satisfactory and close to that obtained by GA but the best results are obtained using GA tool mainly because of non linear and non-convex objectives. It has been observed that with increase number of devices GA perform better compared to commercial solver. These solvers do struggle with increase in number of devices and system size and can only provide a local optimum solution in the search space. Whereas if time limitation will not be given to GA; then it can provide the global optimum solution for any type of optimization problem.

The main purpose of study is to reduce the peak load burden on AC distribution system. When DC microgrid is integrated in present AC distribution system, DC loads are catered by renewable DC generations, reducing the peak load on existing AC grid. Peak load reduction and valley filling are the objectives of DSM program. DC microgrid helps to flatten the load curve by reducing the peak and filling the valley of forecasted load curve as shown in Fig. 8 below.

Though the DC microgrid helps in peak load reduction of overall distribution system but it's cost effectiveness needs to be analyzed. Cost of DC renewable purchase per kWh is higher as compared to TOD tariffs. Overall cost of electricity purchase for the period of 24 h with and without DC micro-

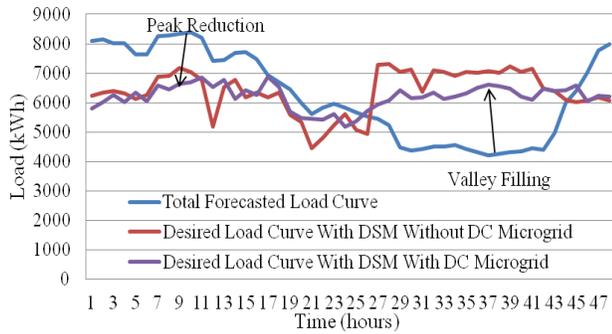


Fig. 8. Peak reduction and valley filling in presence of DC microgrid.

-grid is as shown in Table III. Percentage reduction in cost after DSM is higher in case of AC distribution system with DC microgrid as compared to cost reduction without DC microgrid. Half hourly electricity cost without DSM and DC microgrid is compared with the cost with DSM and DC microgrid as shown in Fig. 9. There is not much appreciable reduction in electricity purchase cost with DC microgrid, as cost of DC renewable purchase is higher. Also the savings due to AC to DC conversion losses, converter equipments cost, and carbon credits earned of renewable energy are ignored as it is not within the scope of this paper. But, it is observed that the power purchase from distribution system with load shifting DSM applied in presence of DC microgrid is cheaper during peak load hours while it is costlier during off-peak hours as compared to AC distribution system without DC microgrid since power purchase from battery source during night hours is costly. Hence, it is better to purchase power from solar PV during day time peak load hours while purchase power from AC grid during night off-peak hours instead from battery source to cater DC loads in the system. Thus, DSM using DC microgrid with battery storage is a promising solution to feed the loads at peak hours of the present distribution system.

TABLE III  
COMPARISON OF ELECTRICITY PURCHASE COST

Type of System	Cost without DSM (Rs.)	Cost with DSM (Rs.)	Cost Reduction (Rs.)	Percentage Reduction (%)
AC Distribution System without DC Microgrid	15,13,447	15,05,203	8,244.6	0.54
AC Distribution System with DC Microgrid	17,00,431	16,61,380	39,051	2.29

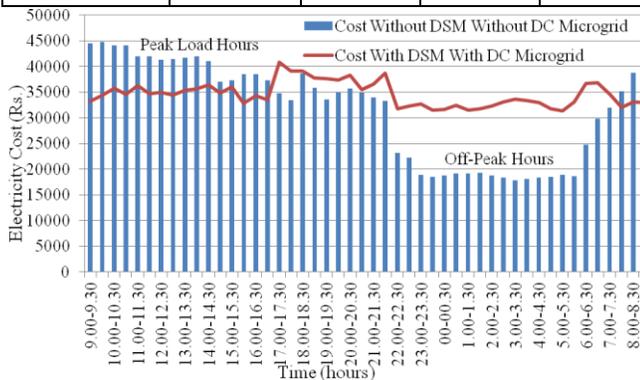


Fig. 9. Electricity cost comparison with and without DC microgrid.

The power taken from DC renewable is costlier than that of TOD tariffs as on today. But, growing concern due to green power obligations, technological advancements in the use of renewable and market competition of renewable power producers will definitely decrease the cost of future renewable purchase. Solar PV is the prime generation source considered for DC microgrid in this paper. India is amongst top 5 destinations worldwide for solar energy [50]. Government of India has launched the Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010 that targeting at solar capacity addition of 20 GW by 2022 and aimed at reducing the cost of solar power generation in the country [51]. In light of this, introduction of DC microgrid within existing AC distribution system to feed DC loads is the viable futuristic option. The authors plan to work in future on techno-economic feasibility study of introducing DC microgrid within present distribution system.

## VI. CONCLUSION

Recently DC microgrid has been appeared as a new paradigm that can improve the efficiency of overall power distribution system. DC microgrid is used to feed DC loads in the system directly by available DC renewable sources. In this study an attempt has been made to improve the DSM performance of practical AC distribution system by introducing synthetic DC microgrid with battery storage. Doing so, there is a peak load reduction of 19.65% for the AC distribution system with DC microgrid which is reasonably higher than the reduction in peak without DC microgrid. Hence, the amount of power drawn from AC mains can be reduced significantly. Thus the performance of DSM programs for AC distribution system has been investigated using DC microgrid. In the era of green power obligations, it will be always helpful to introduce DC microgrid and extract its benefits to improve DSM solutions. It is also found that DC microgrid for DSM is a viable solution even being expensive, mainly due to green power obligations, promotion for renewable energy and secures power supply.

## VII. ACKNOWLEDGMENT

The authors acknowledge the financial support from EPSRC (UK) and DST (India) HEAPD Project Grant under Smart Grid Initiatives. The first author acknowledges support by the Quality Improvement Programme (QIP) scheme of the All India Council for Technical Education (AICTE), Government of India. The authors gratefully acknowledge the guidance of Mr. Shekhar Khadilkar, Chief Manager - DSM cell from TATA Power Limited, Mumbai for his kind support.

## VIII. REFERENCES

- [1] C. W. Gellings, *Demand-side management: concepts and methods*. Liburn, GA: Fairmont, 1988.
- [2] P. Palensky and D. Dietrich, "Demand side management: demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Informat.*, vol. 7, no. 3, pp. 381-388, Aug. 2011.
- [3] F. Rahimi and A. Ipakchi, "Demand response as a market resource under the smart grid paradigm," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 82-88, Jun. 2010.

- [4] J. Medina, N. Muller, and I. Roytelman, "Demand response and distribution grid operations: opportunities and challenges," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 193-198, Sep. 2010.
- [5] H. Saele and O. S. Grande, "Demand response from household customers – experiences from a pilot study in Norway," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 102-109, Mar. 2011.
- [6] J. L. Mathieu, P. N. Price, S. Kiliccote, and M. A. Piette, "Quantifying changes in building electricity use, with the application to demand response," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 507-518, Sep. 2011.
- [7] C. Cecati, C. Citro, and P. Siano, "Combined operations of renewable energy systems and responsive demand in a smart grid," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 468-476, Oct. 2011.
- [8] A. J. Conejo, J. M. Morales, and L. Baringo, "Real-time demand response model," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 236-242, Dec. 2010.
- [9] A. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320-331, Dec. 2010.
- [10] P. Siano, "Demand response and smart grids-a survey," *Int. J. Renewable Sustainable Energy Rev.*, vol. 30, pp. 461-478, Oct. 2013.
- [11] J. Chen, F. N. Lee, A. M. Breipohl, and R. Adapa, "Scheduling direct load control to minimize system operational cost," *IEEE Trans. Power Syst.*, vol. 10, no. 4, pp. 1994-2001, Nov. 1995.
- [12] K. H. Ng and G. B. Sheble, "Direct load control-a profit-based load management using linear programming," *IEEE Trans. Power Syst.*, vol. 13, no. 2, pp. 688-694, May 1998.
- [13] Y. Tang, G. Zheng, and S. Zhang, "Optimal control approaches of pumping stations to achieve energy efficiency and load shifting," *Int. J. Elect. Power Energy Syst.*, vol. 55, pp. 572-580, 2014.
- [14] B. T. Patterson, "DC, come home: dc microgrids and the birth of the enernet," *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 60-69, Nov. 2012.
- [15] X. Liu, P. Wang, and P. C. Loh, "A hybrid ac/dc microgrid and its coordination control," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 278-286, Jun. 2011.
- [16] M. Sechilariu, B. C. Wang, and F. Locment, "Supervision control for optimal energy cost management in DC microgrid: design and simulation," *Int. J. Elect. Power Energy Syst.*, vol. 58, pp. 140-149, 2014.
- [17] C. O. Adika and L. Wang, "Smart charging and appliance scheduling approaches to demand side management," *Int. J. Elect. Power Energy Syst.*, vol. 57, pp. 232-240, 2014.
- [18] M. D. Anderson and D. S. Carr, "Battery energy storage technologies," *Proc. IEEE*, vol. 81, no. 3, pp. 475-479, Mar. 1993.
- [19] M. Bragard, N. Soltan, S. Thomas, and R. W. De Doncker, "The balance of renewable sources and user demands in grids: Power electronics for modular battery energy storage systems," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 3049-3056, Dec. 2010.
- [20] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez, and W. M. Grady, "Battery energy storage for enabling integration of distributed solar power generation," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 850-857, Jun. 2012.
- [21] J.-H. Teng, S.-W. Luan, D.-J. Lee, and Y.-Q. Huang, "Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable PV generation systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1425-1433, May 2013.
- [22] D. Huang and R. Billinton, "Effects of load sector demand side management applications in generating capacity adequacy assessment," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 335-343, Feb. 2012.
- [23] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244-1252, Sep. 2012.
- [24] N. Kinhekar, N. P. Padhy, and H. O. Gupta, "Multiobjective demand side management solutions for utilities with peak demand deficit," *Int. J. Elect. Power Energy Syst.*, vol. 55, pp. 612-619, Feb. 2014.
- [25] H. M. Soliman and A. L. Garcia, "Game-theoretic demand-side management with storage devices for the future smart grid," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1475-1485, May 2014.
- [26] P. Malysz, S. Sirospour, and A. Emadi, "An optimal energy storage control for grid-connected microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1785-1796, Jul. 2014.
- [27] A. Zakariazadeh, S. Jadid, and P. Siano, "Stochastic operational scheduling of smart distribution system considering wind generation and demand response programs," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 218-225, Jun. 2014.
- [28] A. Zakariazadeh, S. Jadid, and P. Siano, "Smart microgrid energy and reserve scheduling with demand response using stochastic optimization," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 523-533, Jul. 2014.
- [29] M. Mazidi, A. Zakariazadeh, S. Jadid, and P. Siano, "Integrated scheduling of renewable generation and demand response programs in a microgrid," *Int. J. Energy Conver. Manage.*, vol. 86, pp. 1118-1127, Jul. 2014.
- [30] A. Zakariazadeh, S. Jadid, and P. Siano, "Stochastic multi-objective operational planning of smart distribution systems considering demand response programs," *Int. J. Elect. Power Energy Syst.*, vol. 111, pp. 156-168, Mar. 2014.
- [31] A. Zakariazadeh, S. Jadid, and P. Siano, "Economic-environmental energy and reserve scheduling of smart distribution systems: A multiobjective mathematical programming approach," *Int. J. Energy Conver. Manage.*, vol. 78, pp. 151-164, Nov. 2013.
- [32] M.A.A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Coordinated scheduling of residential distributed energy resources to optimize smart home energy services," *IEEE Trans. Smart Grid*, vol. 1, pp. 134-143, Sep. 2010.
- [33] A. -H. Mohsenian-Rad, V. W.S Wong, J. Jatskevich, and R. Schober, "Optimal and autonomous incentive-based energy consumption scheduling algorithm for smart grid," in *Proc. IEEE Conf. Innov. Smart Grid Technol.*, Gaithersburg, MD, USA, 2010.
- [34] Z. Zhao, W. C. Lee, Y. Shin, and K. Song, "An optimal power scheduling method for demand response in home energy management system," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1391-1400, Sep. 2013.
- [35] A. Brooke, D. Kendrick, A. Meeraus, and R. Raman, *GAMS a User's Guide*. GAMS Development Corporation, Washington DC, 1998.
- [36] D. Salomonsson, L. Soder, and A. Sannino, "An adaptive control system for a DC microgrid for data centers," *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1910-1917, Nov. 2008.
- [37] D. J. Becker and B. J. Sonnenberg, "DC microgrids in buildings and data centers," in *Proc. IEEE Int. Tele. Energy Conf. (INTELEC)*, pp. 1-7, Oct. 2011.
- [38] S. X. Chen, H. B. Gooi, and M. Q. Wang, "Sizing of energy storage for microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 142-151, Mar. 2012.
- [39] Y. Y. Hsu and C. C. Su, "Dispatch of direct load control using dynamic programming," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 1056-1061, Aug. 1991.
- [40] K.-H. Ng and G. B. Sheble, "Direct load control – A profit based load management using linear programming," *IEEE Trans. Power Syst.*, vol. 13, no. 2, pp. 688-694, May. 1998.
- [41] C. N. Kurucz, D. Brandt, and S. Sim, "A linear programming model for reducing system peak through customer load control programs," *IEEE Trans. Power Syst.*, vol. 11, no. 4, pp. 1817-1824, Nov. 1996.
- [42] T. Back, D. Fogel, and Z. Michalewicz, *Handbook of evolutionary computation*. New York: IOP Publ. and Oxford Univ. Press, 1997.
- [43] K. Y. Lee and M. A. El-Sharkawi, *Modern heuristic optimization techniques: theory and applications to power systems*. Wiley.com, vol. 39, 2008.
- [44] R. L. Haupt and S. E. Haupt, *Practical Genetic Algorithms*. New Jersey: John Wiley and Sons, 2004.
- [45] Y. J. Reddy, Y. V. P. Kumar, K. P. Raju, and A. K. Ramesh, "Retrofitted hybrid power system design with renewable energy sources for buildings," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2174-2187, Dec. 2012.
- [46] N. Eghtedarpour and E. Farjah, "Power control and management in a hybrid AC/DC microgrid," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1494-1505, May 2014.
- [47] F. Nejathkhan and Y. W. Li, "Overview of power management strategies of hybrid AC/DC microgrid," *IEEE Trans. Power Electron.*, to be published.
- [48] K. Divya and J. Ostergaard, "Battery energy storage technology for power systems – an overview," *Electr. Power Syst. Res.*, vol. 79, no. 4, pp. 511-520, Mar. 2009.
- [49] Maharashtra Electricity Regulatory Commission Regulations (2010): Renewable purchase obligation, it's compliance and implementation of REC framework. [Online]. Available: <http://www.mercindia.org.in/Regulations.htm>

- [50] Government of India Ministry of New and Renewable Energy: Solar energy overview. [Online]. Available: <http://www.energyaccess.in/renewable-energy>
- [51] Government of India Ministry of New and Renewable Energy: JNN solar mission. [Online]. Available: <http://www.mnre.gov.in/solar-mission/jnsm/introduction-2/>

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