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Home Energy Management: Appliance Scheduling in Residential Microgrid

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Abstract—*With development of micro grid, residents have the chance to schedule their power usage in home by themselves for purpose of reducing electricity expense and alleviating power peak to average ratio (PAR). In this paper a home energy management system is built to determine optimal day ahead scheduling of household appliances based on set of sequential uninterruptible energy phases (SSUEP). The household contains shift able and essential appliances. These appliances are modeled according to SSUEP. The houses also contain Battery energy storage system (BESS) and Photovoltaic system (PV). Furthermore using shift able appliance flexibility consumer can be involved in demand response strategies to minimize the costs. For this purpose, a mixed integer linear programming framework based modeling of home energy management system is provided. Also impact of SSUEP based model on the day ahead energy management of micro grid is studied.*

Index Terms—micro grid, peak to average ratio, set of sequential uninterruptible energy phases, battery energy storage system, photovoltaic system and electric vehicles.

1. INTRODUCTION

Recently using the smart grid facilities and capabilities, the concept of micro grid has been introduced and developed as a way to achieve integration of the renewable energy, improving the demand side management and taking full advantage of energy storage systems. As low voltage distribution grid the micro grid is defined as set of loads, distributed energy resources and energy storage units. This micro grid, if properly managed can supply power demand of a district. Moreover consumers can reduce costs of supplying power demand on coordinated basis. This is feasible using demand side management.

Demand side management involves all plans taken by utility companies to manage the energy consumption of household loads. Therefore it is important to have accurate and appropriate model of these loads.

Due to fluctuations and unsteady power generation of the renewable resources in various weather conditions, energy storage systems have also been considered in smart grids. BESS store the energy for household purposes.

This paper aims at using an accurate SSUEP model in day-ahead management of a residential micro grid. The residential micro grid includes shift able and essential appliances, renewable energy resources, BESS.

Shifting the usage of power by consumers from peak to off peak period is one of the function of demand response strategies and thereby reducing the stress on transmission lines and distribution transformers. Due to less intensive requirements on grid results in enhancement in power delivery capability of grid and reduction in need of massive investment in grid. The utilization of demand response strategies can be considered mature for industrial consumers but this is new concept for residential households which contribute to nearly 40% energy consumption in the world.

In [1] household appliances have been modeled as fixed power demand loads. In [2] simple models of appliances are considered. In [3] appliances are assumed to consume constant power in given time slot. Ref [4] considers the L_1 regularization technique for planning the on off states of house hold appliances using auxiliary binary variables. Ref [5] uses bottom up approach for residential load modeling. It allows construction of the relative load shape area starting from knowledge of socioeconomic and demographic characteristics and load profiles of individual household appliances. Total load profile is formed by combining load profiles of individual appliances.

In [6] household appliances are categorized into deferrable/non deferrable and interruptible/non interruptible appliances. Ref. [7] classified various appliances in different sets considering their different energy consumption and operation characteristics and, provides mathematical models for it. In [8] real time pricing scheme is proposed so that PAR ratio could be reduced by demand response management in smart system. In this household appliances are categorized in in three categories. The first category A_u includes appliances which consumes a fixed amount of energy per unit time during fixed period of time. Second category B_u class appliances are those whose power demand in specific duration is determined by consumer's quality of usage. Third category C_u denotes appliances which have specific working period and modeled by fixed total power demand for certain operating durations. In [9] Reinforcement learning based appliance scheduling framework for residential customers is presented. In [10] describes electrical load management in smart homes via evolutionary techniques.

The paper is organized as follows. Section I represents the introduction. Section II describes the micro grid structure and modeling of appliances and BESS. Section III describes formulation of mixed integer linear programming (MILP) problem. Section IV represents the result. Section V contains conclusion followed by references.

2. PROBLEM DESCRIPTION

In this section residential micro grid model is explained. The operation of household appliances is described and modeling of BESS is also described.

3. MICROGRID MODEL

The residential micro grid model includes households. Each household includes set of shift able appliances and essential appliances, PV system, BES, and smart meter for exchanging information with micro grid. The power demand information of all appliances in the home is collected by smart meters and communication networks.

Since the micro grid is connected to the smart grid and day-ahead prices of electricity and power demand is known, micro grid can act as power consumer or power supplier at certain hours of day. A significant amount of micro grid power demand is supplied by power generated from PV and/or bought from grid. The consumers can charge their BES when price is lower and discharge it during on peak period.

Since the consumers already know the day-ahead prices, they can avoid using shift able appliances during on peak periods and use them in off peak periods.

4. APPLIANCE MODEL

According to the consumer's quality of usage and operating characteristics, household appliances are classified in two categories. First category includes appliances which are programmable and shift able. Washing machine, dish washer and tumble dryers are examples of this category. The second category appliances are continuously on and their power demand should always be fulfilled. Air conditioners and refrigerators belong to this category. Operation of appliances can be modeled according to this categorization.

1. Shiftable appliance modelling

In the proposed methodology all the appliances of category are modeled by SSUEP. In this methodology an appliance operation process is divided into a set of sequential energy phases. An energy phase is an uninterruptible sub task of appliance operation which utilises a pre-specified amount of energy. In sequential energy phases a sub task is not started untill the active sub task is finished. All these energy phases are called power demand profile of appliances.

Inter phase delay is one of the capabilities of shift able appliances. Although all energy phases should be processed continuously for appliance, individual phase can be delayed for certain time durations. For example in washing machine once dewatering phase is done, washing phase can be delayed for certain time.

Some household appliances have to start working only after some other appliances. For example tumble dryer should be used only after washing machine. Another case is that consumers have some time preferences so that household appliances would work according to pre specified plan.

The purpose of proposed methodology is to find a set of power profiles with minimum costs such that essential constraints of household appliances are met.

2. SSUEP mathematical model

Binary decision variables are required to plan the operation of household appliances. The binary variable $X_{h,i,l}^{t}$ indicates whether a specific energy is being processed or not. If for appliance i the l^{th} energy phase is being processed within time slot t, then $X_{h,i,l}^{t}$= 1. The other two binary decision variables that are needed to explain the appliances operation mathe- matically are $Y_{h,i,l}^{t}$ and $M_{h,i,l}^{t}$.Variable $Y_{h,i,l}^{t}$=1 if l^{th} phase of appliance i within time slot t is already finished. Next decision variable $M_{h,i,l}^{t}$=1 if there is delay between the l-1 and l^{th} phase in time slot t.

The operational constraints of house hold appliances are as follows.

Energy phase duration: The energy phase duration is modeled by following constraint.

$$\sum_{t=1}^{T} X_{h,i,l}^{t} = PT_{i,l} \quad \forall\, h,i,l \tag{1}$$

Where $PT_{i,l}$ represents the energy required by phase l for appliance i.

Uninterruptible operation time slot: According to this constraint all the time slot of phase lare processed continuosly and uninterruptibly.

$$X_{h,i,l}^{t} \le 1 - Y_{h,i,l}^{t} \quad \forall\, h,i,l \tag{2}$$

$$X_{h,i,l}^{t-1} - X_{h,i,l}^{t} \le Y_{h,i,l}^{t} \quad \forall\, h,i,l,\ \forall t=2,3\ldots..T \tag{3}$$

$$Y_{h,i,l}^{t-1} \le Y_{h,i,l}^{t} \quad \forall\, h,i,l,\ \forall t=2,3\ldots..T \tag{4}$$

If in Eq (2) $Y_{h,i,l}^{t}$=1, then energy energy phase of of appliance i in home h is already finished within th etime slot t. so $X_{h,i,l}^{t}$ should be zero. According to eq(3), $Y_{h,i,l}^{t}$=1 provided that $X_{h,i,l}^{t}$ changes from 1 to 0 and acording to eq (3) $Y_{h,i,l}^{t}$ must remain equal to 1.

Sequential processing of energy phases : sequential processing of energy phases implies that before proceeding to next phase previous phase should be finished. It is given by eq(5) as follows.

$$X_{h,i,l}^{t} \leq Y_{h,i,l-1}^{t} \quad \square\ h,i,l,\ \square\ l=2,3\ldots..L \tag{5}$$

Inter phase delay duration: Once the specific phase is finished , next phase can start instantaneously or with some inter phase delay. This constraint is given by eq (6).

$$M_{h,i,l}^{t} = Y_{h,i,l-1}^{t} - X_{h,i,l}^{t} - Y_{h,i,l}^{t} \quad \square\ h,i,t,\ \square\ l \geq 2 \tag{7}$$

$$\sum_{t=1}^{t} M_{h,i,l}^{t} \leq PD_{i,l} \quad \square\ h,i,l \tag{8}$$

Where PD represent the specified inter phase delay.

Time preference: According to this constraint, user can control the working period of appliances within a desired time slot. It means appliances cannot work out of preference time.

$$X_{h,i,l}^{t} \leq UP_{i}^{t} \quad \square\ \text{i,l,t} \tag{9}$$

Where UP_{i}^{t} represent duration of time preference.

2. Modelling of essential appliances

As mentioned earlier, some appliances cannot be planned because they are directly affected by the consumers quality of usage.appliances like refrigerator or air conditioner have to be continuously operated according to their operational characteristics. The essential type appliances cannot be modeled using SSUEP because programming phase encounters some problems.

The air conditione model is represented as follows.

$$PP_{AC}^{t} = C_{AC}UP_{AC}^{t} \quad \square\ i = AC,\ \square\ t \tag{10}$$

Where C_{AC} represents elasticity component of air conditioner and UP_{AC}^{t} represents the time preference span in which operation of air conditioner is defined.

The refrigerator model is given as follows:

$$PP_{ref}^{t} = C_{ref}\, UP_{ref}^{t} \quad \square\ i=ref,\ \square\ t \neq \alpha \tag{11}$$

$$PP_{ref}^{t} = (C_{ref} + C_{def}) \quad \square\ i=ref,\ \square\ t = \alpha \tag{12}$$

Where C_{ref} and C_{def} represents elasticity component power of the refrigerator and power demand for defrost cycle.

BESS Model

The BESS model employed in this study is described by following equations.

$$0 \leq P_{BES,h,ch}^{t} \leq P_{BES,h,ch}^{max} \tag{13}$$

$$0 \leq P_{BES,h,dch}^{t} \leq P_{BES,h,dch}^{max} \tag{14}$$

Where $P_{BES,h,ch}^{t}$ represents amount of power charged in BESS and $P_{BES,h,dch}^{t}$ represents amount of power discharged from BESS.

Also $P_{BES,h,ch}^{max}$ and $P_{BES,h,dch}^{max}$ denotes the maximum charging and discharging rates respectively.

$$P_{BES,h,ch}^{t} \cdot P_{BES,h,dch}^{t} = 0 \tag{15}$$

The above equation controls the charging and discharging of BESS.

Regarding the charging and discharging rates, the BESS energy for each time slot depends on its energy from previous time slot and governed by following equation.

$$E_{BES,h}^{t} = E_{BES,h}^{t-1} + CE_{BES}.P_{BES,ch}^{t} - P_{BES,h,dch}^{t} \quad \square\ t \geq 2 \tag{16}$$

Where CE_{BES} denotes charging efficiency.

$$E_{BES}^{min} \leq E_{BES}^{t} \leq E_{BES}^{max} \tag{17}$$

Where E_{BES}^{min} and E_{BES}^{max} denotes the maximum and minimum BES capacities.

5. MATHEMATICAL FORMULATION

In this section, first of all, the objective function is introduced. Then balancing constraint and power transaction restriction is discussed. At last problem is formulated as MILP problem.

Objective function

The objective is to minimize the cost of supplying residential micro grid power demand which involves cost profit difference. The cost function involves cost of power bought from grid and maintenance and operational cost of BES. The profit function involves income from power generated through PV and BES which is sold to grid.

Objective function is modeled by following equation.

$$\sum_{t=1}^{T}\left(\sum_{h=1}^{H}\left(\lambda_{s}^{t}.\ \mathrm{P}_{S}^{t} - \lambda_{B}^{t}.P_{B}^{t} + A.\mathrm{P}_{BES,h}^{t} + B\right) + \sum_{v=1}^{V}\left(A.P_{EV,v}^{t} + B\right)\right) \tag{18}$$

The non-negative variables P_B^t and P_S^t denotes total power bought from grid and total power sold to it within time slot t. $\lambda_B^t$and λ_S^t represents the prices of power bought and sold in time slot t respectively. The BESS operational and maintenance costs are assumed as linear function of charging and discharging capacities. Coefficient A and B are positive.

Balancing constraint

This constraint ensures the demand- supply balance. It is given by following equation.

$$P_S^t + \sum_{h=1}^{H} P_{pv,h}^t + DE_{BES} \sum_{h=1}^{H} P_{BES,h,dch}^t + =$$
$$= P_B^t + \sum_{h=1}^{H} \left(\sum_{\substack{i=1, \\ i \neq AC,ref}}^{I} \sum_{l=1}^{L} \left(PP_{i,l}\, X_{h,i,l}^t \right) + PP_{Ref}^t + PP_{AC}^t \right)$$
$$+ \sum_{h=1}^{H} P_{BES,h,ch}^t \quad (19)$$

Where $PP_{i,l}$ represent power is allotted to l^{th} energy phase of the appliance *i*. P_{PV}^t denotes PV power generation for home h.

Power transaction limits

The power transaction between grid and micro grid is limited by following equations. If micro grid draws power from grid in a time slot then grid cannot be fed from micro grid in that time slot. The reverse case is also described by following equations. $P_{B(max)}^t$and $P_{S(max)}^t$ represent the power bought from grid and power sold to grid within time slot t.

$$P_S^t \leq P_{S(max)}^t . w^t \quad (20)$$

$$P_B^t \leq P_{B(max)}^t (1 - w^t) \quad (21)$$

$$w^t \in \{0, 1\} \quad (22)$$

Where, w^t represent binary variable.

Problem formulation

The proposed optimization framework to plan day-ahead energy management of a residential micro grid can be stated as follows.

Minimize objective function - (18)

Subject to constraints - (1) to (17) and (19) to (22)

RESULTS

In this paper a planned framework is considered for 24 hour which is divided into 96 time slots of 15 minutes. The residential micro grid involves 10 houses. Five shift able and four non shift able appliances are considered. The power demand of each appliance is given in Table 1 and Table 2. The price of electricity is given in Fig. 1.The price of sold and bought power is taken to be equal.

Each household is equipped with a PV of 3 KW. The BESS used is of 4KW. In order to utilize BESS optimally, the minimum and maximum energy of batteries is taken to be 30% and 80% respectively. The charging and discharging efficiency is taken as 0.9.the values of A and B is taken as 1.7 and 0.9 respectively.

TABLE 1: SHIFT ABLE APPLIANCE ENERGY

Appliances	Energy of phases(KW)					
	1	2	3	4	5	6
WM	2.1	2.1	0.25	0.24	0.15	0.1
TD	2.2	2.2	2.2	2.2	2.2	0.5
DW	2.3	2.1	2.04	2.02	0.02	0.02
EWH	1.8	1.8	1.74	1.74	1.78	0.02
EO	1.85	1.86	1.86	1.88	2.1	0.01

TABLE 2: NON-SHIFT ABLE APPLIANCE ENERGY

Appliances	Energy of phases(KW)					
	1	2	3	4	5	6
WM	2.1	2.1	0.25	0.24	0.15	0.1
TD	2.2	2.2	2.2	2.2	2.2	0.5
DW	2.3	2.1	2.04	2.02	0.02	0.02
EWH	1.8	1.8	1.74	1.74	1.78	0.02
EO	1.85	1.86	1.86	1.88	2.1	0.01

TABLE 3 BATERRY ENERGY STORAGE SYSTEM SPECIFICATION

BATTERY CAPACITY (KWh)	4
MAX CHARGING RATE (Kw)	0.6
MAX DISCHARGING RATE (kw)	0.6

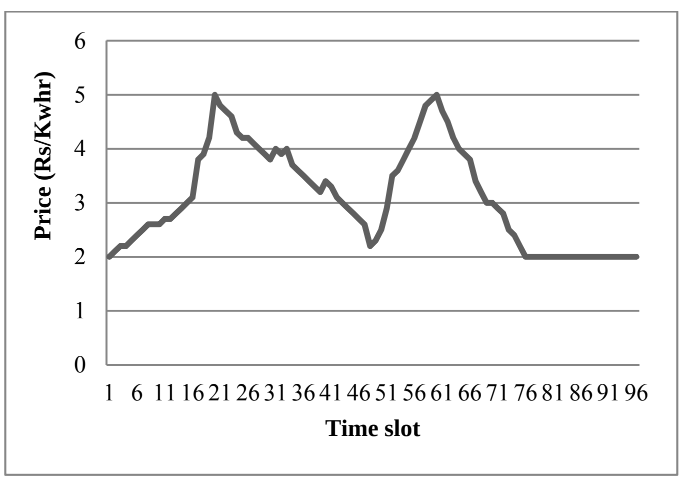

Fig.1 Variation of real time price with Time

The MILP optimization was run on a Corei5, 2.20 GHz laptop with a 4 GB RAM. The problem was simulated in the GAMS software and the Cplex12 was chosen as the solver.

In order to find the effects of the optimization framework, three scenarios are considered. The main purpose of these scenarios is to study the effects of the accurate SSUEP model on the day-ahead planning of the residential micro grid. These scenarios also investigate the start-time shifting capability of the shift able household appliances. Peak-to-Average Ratio (PAR) is taken as the comparison criterion. In order to calculate the PAR, the daily peak load is divided by the daily average load. In the scenario *A*, the start-time shifting of the shift able appliances are ignored and these appliances are operated regardless of the day-ahead prices and the on-peak period. In scenario B, the start-time shifting is considered and the shift able appliances are shifted to the lower-price periods based on the day-ahead prices. The day-ahead planning of the 4th home in the residential micro grid for the scenario A and B is considered for calculation. For the scenario A, shift able appliances like the dishwasher, washing machine, and the tumble dryer are used by the consumers for the time slots 32 to 50 during which the energy price is high. The peak load constitutes 4.88 kW which occurs in a high-price time slot (time slot 37). This is responsible for the increased energy costs.

For the scenario B, shifting the appliances' operating time to the lower-price hours, in addition to reducing the costs, results in lowering the on-peak load in the high-price hours or the on-peak period. With a four-hour delay, the start time of the washing machine is shifted from the time slot 40 to 56. With a three-hour delay, the tumble dryer is shifted from the time slot 47 to 62. Moreover, anticipating the start time of the dishwasher from the time slot 34 to 16 not only reduces the costs, but also makes it feasible to use the PV's power generation. However, shifting the shift able appliances of the scenario B, for the low-price hours of the time slot 57, leads to a peak load of 4.29 kW.

The total power demand curves of different scenarios for the day-ahead planning of the residential micro grid are shown in Fig. 2.

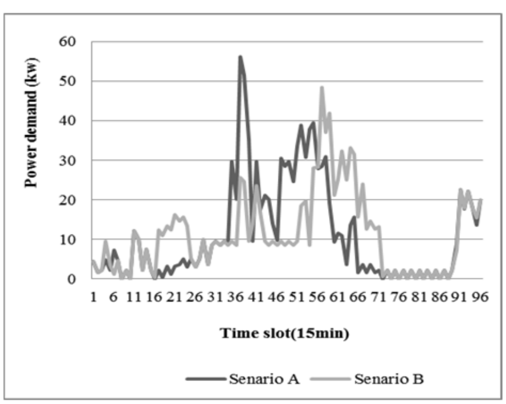

Fig.2 Power demand of different cases

TABLE 4

ECONOMIC RESULTS

CASES	COST (Rs)	Peak Power (KW)	PAR
CASE 1	2920.80	54.20	4.88
CASE 2	2468.90	46.42	4.29

6. CONCLUSION

In this paper, residential micro grid with shift able and essential loads is modeled as MILP optimization problem. The household are also equipped with EV, BES and PV. The effects of accurate SSUEP based model on day ahead energy management of residential micro grid is studied. The accurate SSUEP based model of household appliances makes it feasible to utilize the start time shifting and inter phase delay capabilities of shift able appliances. Different cases are taken under consideration. The results shows that, making use of flexibility of shift able loads results in reduction in cost and Peak to average ratio (PAR).

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