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Smart Home Energy Management Algorithm Considering Renewables Energies and Storage Resources

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Abstract—The efficient use of the incorporation of photovoltaic generation (PV) and solar panel with the Home Energy Management System (HEMS) can play a significant role in improving grid stability and economic benefit of the consumers.

To reduce the peak load and electricity bill, was proposed a smart appliances control algorithm for the smart home energy management system (SHEMS) with integration of the renewable energy sources (RES) and energy storage system (ESS).

The proposed algorithm decreases the peak load and electricity bill by shifting starting times of shifted appliances from peak to off-peak periods.

Therefore, an energy storage system (ESS) and backup battery storage system (BBSS) is also considered for stable and reliable power system operation. The aims of this is to reduce energy usages and monetary cost with an efficient home energy management scheme (HEMS).

In this paper, a cost efficient power-sharing technique is developed which works based on priorities of appliances operating time.

Keywords— Smart home, HEMS; RESs; PV, ESS

I. Introduction

To reduce energy consumption and carbon emission, several works had proposed various energy management systems [1, 2] for smart grids [3]. The main purpose of EMS are to reduce the energy consumption, peak load, and electricity cost is based on shifting the power demand from peak to off-peak hours. In [4], the authors investigated the cost minimization problem in which the electrical appliances allow different levels of delay tolerance. The minimization of energy cost and the maximization of user comfort are the typical optimization problems in recent smart homes [5, 6]. Electricity consumers can manipulate on energy consumption to minimize the peak demand while reducing electricity bills [7, 8]. To decrease electricity lost it is important to maintain energy scheduling algorithm for electrical appliances based the price of the respective time slot.

To fulfil the increasing electricity demand with minimal emissions of greenhouse gases scientists have worked a generation of energy: renewable energy resources (RESs). Integration of RESs into the grid enhance the stability and reliability of power system. A Smart grid has different kinds of operational and operate with smart pieces like smart meters (SM), smart appliances (SA), renewable energy sources, electric energy storage resources etc. The main aspect of SG is the control of power production, transmission and distribution through advanced information and communication technologies (ICTs).

The key factors that make SG superior over traditional grids are: two-way communication advanced metering infrastructure (AMI) and information management units (IMUs). They introduce intelligence, automation and real-time control to power system. The two-way communication in SG not only keeps the end-users well informed about the varying electricity prices, maintenance schedules of the distribution network.

The SG integrate RESs and ESSs and SGs involves the residential and commercial users into demand-side management (DSM).The main objectives of different DSM and DR strategies in SG are the reduction of the electricity cost and minimization of energy consumption in peak hours. To achieve these objectives numerous of algorithms for an efficient HEMS have been proposed, such as integer linear programing (MILP) [9] etc.

In this context, we present HEMS, which integrate RES and ESS in SG system.

The remaining of this paper is organized as follows: section 2 presents the studied system description and modeling. The proposed home energy management strategy is illustrated in section 3. Finally, section 4 elaborates the conclusion of this paper.

II. Proposed system model

A. Architecture

This work investigates design of smart grids that targets the reduction of electricity cost for consumers and energy management- make electric grid operation. A Smart Home (SM) equipped with a smart meter along with the energy management controller (EMC), for a reliable bi-directional power and information flow between SG and SH. Each consumer has multiple electricity consuming smart appliances with different power ratings and length of operational time (LOT) and is equipped with their own distributable energy generation system (EGS), i.e., micro grid. The micro grid consist of the wind turbine (WT) and solar panel-photo voltaic (PV). The PV and WT produce a quantity of energy depending on weather condition, which does not always match the load demand. There are two possible scenarios: energy production is insufficient or there is surplus energy generation. These distributed energy generation system are intermittent in nature, therefore, to fulfill the load requirements of costumers, energy storage system (ESS) is also installed i.e., batteries. Energy storage and the main grid allow for the buffering of insufficient or excess power generation. The battery and grid can restore the production/consumption balance by supplying the lack of energy or by absorbing excess energy. In each SH, the consumers puts various parameters of all appliances in EMC. EMC is then responsible for the ON/OFF status of all appliances. The proposed optimization model is presented in figure 1.

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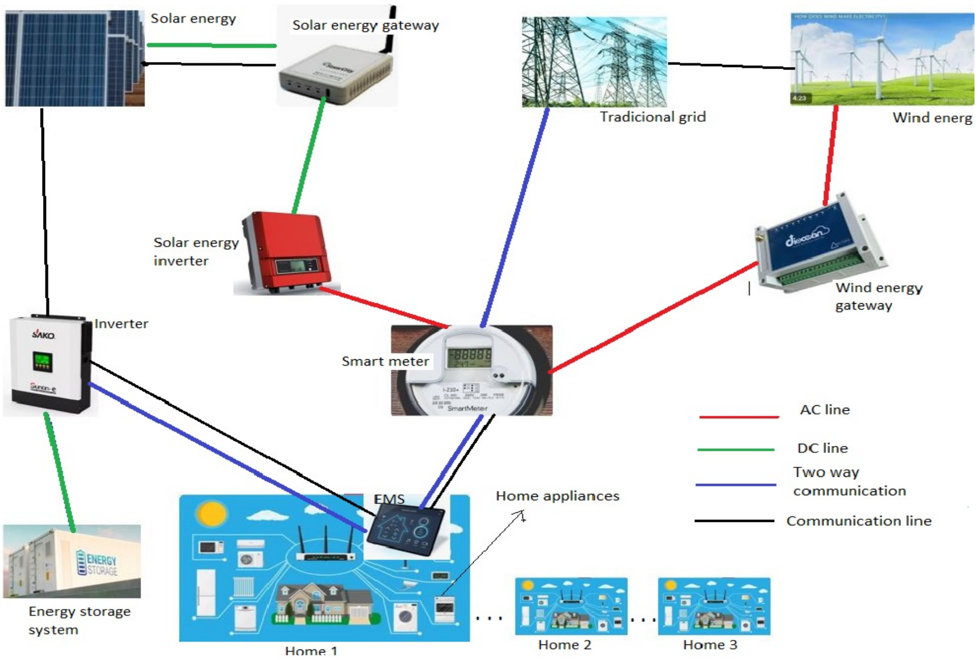


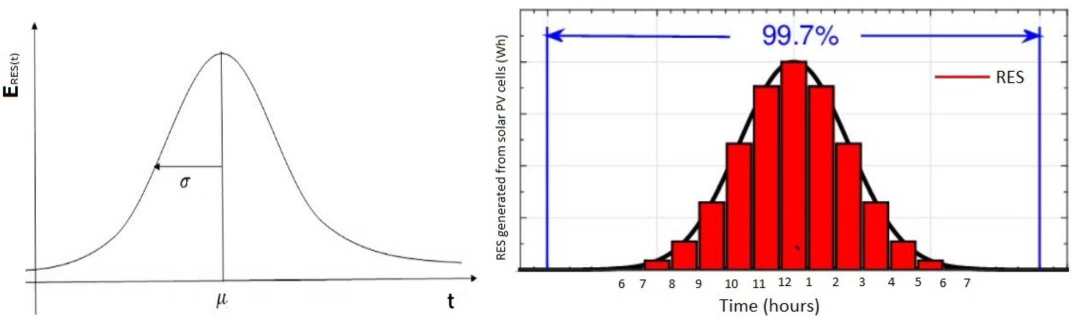
Figure 1. Proposed system model

B. RES Model

Photovoltaic (PH) cells and wind turbines can be used as local power generators, also known as distributed RES. These RESs can be used for the local energy generation, as well as for charging the batteries in BSUs. The generated energy, denoted by E_{RES} can be calculated by Gaussian function (1) as follows:

$$E_{RES}(t,\mu,\sigma) = \frac{1}{\sigma\pi\sqrt{2}} e^{\frac{(t-\mu)^2}{2\pi^2}} \quad (1)$$

Where t is time, µ - mean value and σ - is the standard deviation.



a) *b)*

Figure 2. a) Gaussian function representing the approximate PV cells energy generation (Wh) [10].

b) RES Generated energy E_{RES}.

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The total daily energy generated from RESs must be positive and daily basis is:

$00 \leq E_{RES} \leq E_{\text{RES(max)}}$, where, $E_{\text{RES(max)}}$ is the maximum available RES, generated energy. If in my time interval, the RESs generated energy exceeds the end-user demand E_D, i.e.

$E_{RES} > E_D$

The energy can be used for charging the batteries and EV batteries for later use or during peak hours or can sold back to the grid.

C. Energy Storage Devices: Battery

The energy stored in the battery depend on their capacity and their state of charge devices, the output power is limited. The SOC is the ratio between the energy contained in the battery and its maximum capacity. There are three parameters that should be taken into account; the rated charging power, plug-in time and state of charge (SOC) battery. The SOC of a battery is assumed to vary between 20% and 100%.The time it takes to fully charge a battery depends on rated charging power, plug-in time and the battery SOC. In this article, battery is assumed to be plugged in when its battery SOC reaches 20% and the battery can be used when $SOC_{B,t} \geq 20\%$. The switch status of B ($S_{B,t}$) at time intervals can be calculated by the following equation:

$$S_{B,t} = \begin{cases} 0, & SOC_{B,t} = 100\% \\ 1, & SOC_{B,t} < 100\% \\ S_{B,t-1}, & 20\% \leq SOC_{B,t} \leq 100\% \end{cases} \quad (2)$$

Where, $S_{B,t}$ is the device status, $S_{B,t} = 0$, means that the appliance is switched off, $S_{B,t} = 1$, means the appliance is switched on and $SOC_{B,t}$ is the SOC battery in the time interval.

The battery power consumption is in kW, and $P_{B,t}$ at a given time interval can be calculated by:

$P_{B,t} = P_B * S_{B,t}$

Where, P_B is the amount of rated battery power in kW.

D. The Peak To Average Ratio (PAR)

The peak to average ratio can be minimized, using EMA, in favor of both the grid and consumer for maintaining demand-supply balance. PAR is the ratio of the peak consumption of the SH and the average consumption of the SH in every interval of time, and can be calculated by the equation:

$$\mu = \frac{E_{max}}{\frac{1}{T}\sum_{n=1}^{T} E_T} \quad (3)$$

E. ESS Constraints

To ensure maximum life span (maximum cycles) for the battery, minimum SOC should be defined. On the one hand, the upper limit of the SOC of batteries is defined to 1. On the other hand, batteries have a SOC_{min} set by the manufacturer, indicating that this SOC_{min} level enable batteries to operate.

SOC_s for the ESS battery is limited by a lower limit.

F. User's Comfort in Terms of Waiting Time (τ)

Presents interval of time when appliance is switches on, and due to the scheduling limitations of the system has to wait to start its operation. As previous have defined the earliest starting time τ_1 and the latest ending time τ_2 of an appliance and τ describes the time interval when an appliance performs its execution. This is presented in figure 3.

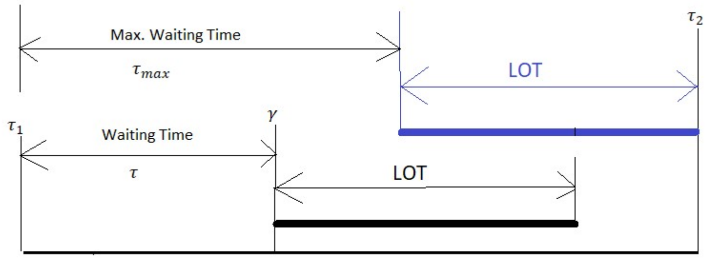

Figure 3. Starting time, ending time, LOT and waiting time

In this work, we consider 24h for implementation, 1h for each time slot expressed as:

T={t_1, t_2, ………..t_{24}}. Every appliance is connected with the Internet and capable of communication with the energy management controller (EMC). EMC is also connected with the Internet via WiFi, which shifts the appliances operation according to the scheduling algorithm. As shown in figure 3 the maximum consumer waiting time could be up to τ_{max}.

LOT is defined by all appliances and according this the algorithm will have to start the appliances to complete its operation up to the final time τ_2. For example, if WM has a time span of 10h (from 8:00—18:00) and LOT=2h, this means that our proposed algorithm must start on from 8:00—18:00 to complete its operation of 2h, with a waiting time ranging from 0-8h.

G. Categorization of Appliances

We have considered a smart home with multiple home appliances. They are divided into three main categories/classes named shiftable, non-interruptible and base load appliances.

H. Shiftable Appliances

Shiftable appliances can be fully managed and these types of appliances can be shifted or interrupted

In any time slot keeping in view the minimization of PAR and electricity bill [11]. Shiftable appliances class includes the electrical car, vacuum cleaner, dish washer, washing machine, spin dryer, laptop, cooker hub, microwave oven [12]etc. The energy consumed by all shiftable appliances in the total time interval of 24h with 24 –time slots can be calculated by the following equation.

$$E_s = \sum_{a_s \in A_s}\left(\sum_{n=1}^{24}(\rho_{s,n} x X_{s,n} x \tau_s\right), \qquad \tau_1 < \tau_s < \tau_2 \tag{4}$$

Where a_s–presents each shiftable appliances,

A_s – is the set of shiftable appliances,

$\rho_{s,n}$ - is the power rating of shiftable appliances

$X_{s,n}$ –is ON(1) and OFF(0) states of the nth – shiftable appliances

$$X_{s,n} = \begin{cases} 1, & if\ a_s\ is\ ON \\ 0, & if\ a_s\ is\ OFF \end{cases}$$

τ_s – is the LOT for each shiftable appliances,

τ_1– is the earliest starting time and

τ_2–is the latest ending time of shiftable appliances and $\tau_1 < \tau_s < \tau_2$

I. Non-Intgerruptible Appliances

These are those regular appliances A_{ni} that cannot be shifted or interrupted while performing their operations. This type of appliances may not be interrupted when execution starts but shifted to any time slot before starting their execution. Non-interruptible appliances class includes the Washing machine, Dish washer and Spin dryer. This type of appliance may be scheduled between possible earliest starting and possible least ending time. Let $a_{ni} \in A_{ni}$ represent a single appliance from this category. The $\rho_{ni,n}$ presents the power rating of each appliances in this category. Then the total consumed electricity E_{ni} of all Non-interruptible appliances in the total time interval of 24h can be calculated by the following equation.

$$E_{ni} = \sum_{a_{ni} \in A_{ni}} (\sum_{n=1}^{24} (\rho_{ni,n} x X_{ni,n} x \tau_{ni}) \qquad \tau_1 < \tau_{ni} < \tau_2 \qquad (5)$$

Where,

a_{ni} – presents each Non-Interruptible appliances,

A_{ni} – is the set of Non-Interruptible appliances,

$\rho_{ni,n}$ - is the power rating of Non-Interruptible appliances

$X_{ni,n}$ – is the ON (1) and OFF (0) states of the n^{th} – Non-Interruptible appliances

$$X_{ni,n} = \begin{cases} 1, & if\ a_{ni}\ is\ ON \\ 0, & if\ a_{ni}\ is\ OFF \end{cases}$$

τ_{ni} – is the LOT for each Non-Interruptible appliances,

τ_1– is the earliest starting time and

τ_2– is the latest ending time of Non-Interruptible appliances and $\tau_1 < \tau_{ni} < \tau_2$

J. Base Load Appliances

Are those regular appliances A_b that cannot be shifted or interrupted while performing their operations. Generally, these appliances considered the main load of any household; these appliances also are non-shiftable and non-interruptible appliances. We consider interior lighting and refrigerators as base load appliances. Let $a_b \in A_b$ represent a single appliance from this category. The $\rho_{b,n}$ presents the power rating of each appliances in this category. Then the total consumed electricity E_b of all base load appliances in the total time interval of 24h can be calculated by the following equation.

$$E_b = \sum_{a_b \in A_b} (\sum_{n=1}^{24} (\rho_{b,n} x X_{b,n} x \tau_b) \qquad \tau_1 < \tau_b < \tau_2 \qquad (6)$$

Where,

a_b – presents each Base-Load appliances,

$\rho_{b,n}$ - is the power rating of Base-Load appliances

$X_{b,n}$ –is ON(1) and OFF(0) states of the n^{th} – Base-Load appliances

$$X_{b,n} = \begin{cases} 1, & if\ a_b\ is\ ON \\ 0, & if\ a_b\ is\ OFF \end{cases}$$

τ_b – is the LOT for each Base-Load appliances,

τ_1– is the earliest starting time and

τ_2– is the latest ending time of Base-Load appliances and $\tau_1 < \tau_b < \tau_2$

TABLE 1. PARAMETERS OF HOME APPLIANCES

Appliances Category	Appliance Name	Power Rating (KW/h)	Earliest Starting Time (h)	Ending Time (h)	Time span (τ_2- τ_1)(h)	LOT (h)
Shiftable appliances	Desktop	0.4	18	24	6	3.0
	Laptop	0.1	18	24	6	3.0
	Microwave	1.5	07	10	3	1.0
	Vacuum cleaner	1.6	09	17	8	1.0
	Electric vehicle	3.5	18	08	14	3.0
	Cooker oven	3.5	15	20	5	1.0
	Cooker hub	3.0	06	10	4	1.0
Non-interruptible appliances	Washing machine	2.2	09	12	3	2.0
		1.8	09	17	8	2.0
	Dish washer	2.5	13	18	5	1.0
	Spin dryer	2.5	13	18	5	1.0
Base-load appliances	Interior lighting	1.0	16	24	8	8.0
	Refrigerator	0.4	00	24	24	24.0

K. Energy Consumption Model

The total energy consumption of the house with the smart appliances is given by:

$$E_T=E_{ni}+E_s+E_b \quad (7)$$

Where E_{ni} - is the energy consumption of the non-Interruptible appliances, E_s – is the energy consumption of the shifted appliances and E_b is the energy consumption of the base load appliances.

The generated electricity from RES is stored in EES and the EV battery for future use. In ON-peak hours, the smart home use the electricity from the RES or ESS or EV battery and the excess of the electricity is stored back to the ESS. They use energy from the grid when needed, i.e., when their demand exceeds the RES, generated energy plus the ESS stored energy. Their energy consumption is calculated using the following equation:

$$E_c=E_T-\sum_{n=1}^{24}(E_{RES}\pm E_{ESS}) \quad (8)$$

Where

E_c – is the energy consumption of smart homes.

E_{RES} – is the energy generated in the SH,

E_{ESS} – is the energy stored in the SH.

If E_{ESS} is the positive, this means that RESs are discharging the batteries and providing energy to the load and if E_{ESS} is negative, this means that RES charging the battery.

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L. The Objective Of Energy Management Algorithm With RES And ESS

We consider the following objective for the proposed EMA with RES and ESS:

1. Minimization of the consumers electricity bill
2. Reducing of the average waiting time of appliances
3. Minimization of PAR
4. Integration of RES and ESS in the EMA.
5. With these objective can achieve the optimization of energy of all appliances, using different scheduling techniques. If V_T – is the maximum energy capacity in every time slot, then the consumer energy cost can be minimized. Total aggregated energy consumption of home appliances needed to keep within the maximum threshold limit of V_T. $E_T \leq V_T$.

Where E_T is the total energy demand of the consumer

III. Proposed Schemes

In the smart grid, every smart home is connected with a smart meter, and the smart meter is further connected with an EMC. The smart meter and EMC enable the mutual two-way communication between electricity consumers and the utility. It enable the consumer to perform load shifting from peak to off-peak hours for cost minimization. However, load shifting in off-peak hours may cause the generation of peaks in off-peak hours. This problem is considered as an optimization problem, However, our scheme take into consideration the minimizing of electricity cost and PAR reduction with minimum user waiting time simultaneously. Therefore, the main targets of our work are electricity cost and PAR reduction with minimum user waiting time.

A. Energy Management Algorithm Considering Renewable Energy And Storage Resources

The flowchart of the proposed energy management algorithm with RES is presented in figure 4. In order to ensure maximum efficiency, the energy of renewable sources is used firstly. Here we define the difference of total consumed energy and total renewable energy (from photovoltaic and wind turbine) as $P_T=Pc-(P_{PW}+P_{WT})$.

$P_C(t)$ represents the total load of currently working appliances in HEMS system at time t.

$P_g(t)$ represents the power supplied by the main grid at time t. $P_r(t)$ represents the generating power of the RES system at time t. P_i is the working power of the appliance *i*.

Here the strategy is to minimize the energy consumption from the grid. Such, the RES generating power has the highest use priority while the grid power has the lowest use priority.

$P_b(t)$ is the available output powers of the RES storage system at time *t.*

In first step, if the generating power $P_r(t)$ of RES system is enough for supporting the requested appliance and all other working appliances at time t, $(P_C(t)+P_i)$, the requested appliance can starts without using energy of storage battery and grid; otherwise the energy of the battery is checked.

If the generating power $P_r(t)$ plus the available power of the battery $P_b(t)$ is enough for supporting the requested appliance and all other working appliances at time t $(P_C(t)+P_i)$, the requested appliance can starts without using energy from the grid; otherwise the energy of the grid is required.

The starting time of the requested appliance is determined according to the type of the requested appliance. If the requested appliance is of non-interruptible load type and the power consumption $P_g(t)+P_i$ supplied by the main grid is less than threshold limit of P_t, the requested appliance can start.

When a shifted appliance request for starting at off-peak hours and power consumption, $P_g(t)+P_i$ is larger than threshold limit P_t, the starting of appliances may be shifted for time less than Length of Operational Time (LOT).

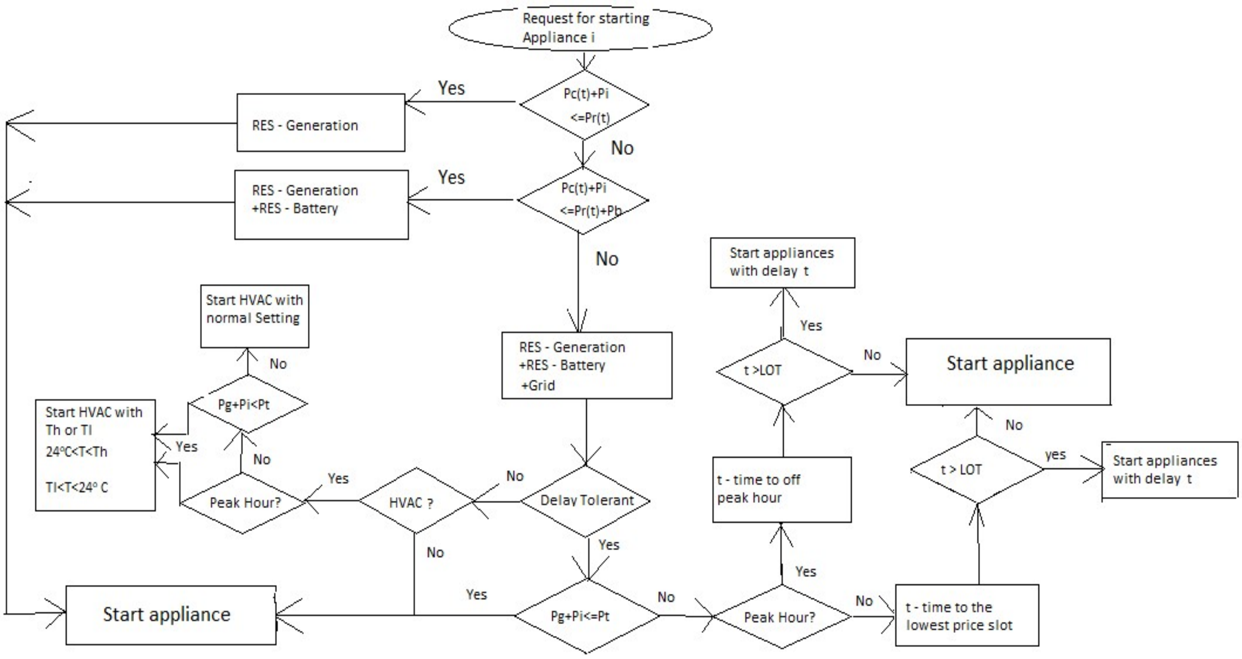

Figure 4. Flowchart of Energy management Strategy

When a shifted appliance request for starting at peak hours and power consumption $P_g(t)+P_i$ is larger than threshold limit P_t , and if t>LOT (t- time to off-peak hour) the starting of appliances may be shifted for time t_l=t-LOT, otherwise the appliance can start.

When a HVAC (Heating, Ventilation, and Air Conditioning) requests for turning on, the HVAC can turn on immediately. At peak hours, the HVAC is set to the highest target temperature T_h (for cooling) or in lowest temperature T_l (for heating), in order to reduce the working load. During the off-peak hours, if the power consumption $P_g(t)+P_i$ exceeds the power threshold P_t, the HVAC is set to the higher target temperature T_h (for cooling) $24^oC<T<=T_h$, or to the lowest target temperature T_l (for heating) $T_l <T<24^oC$, in order to provide power constraint.

IV. Conclusion and Future Work

This paper has presented an optimal algorithm and energy management scheme for a home integrating RES to avoid the peak load, and to reduce the electricity bill. Generation of renewable energy reduces the dependence of the grid. Therefore, the energy bill is reduced and the use of clean energy is empowered for sustainable development. The use of ESS presents a financial interest for homeowners, support the integration of RER and relieves the main grid during on-peak periods. The proposed scheme reduce the total electricity cost, reduce the PAR reduction factor and achieve a high comfort level of the end-user by minimizing the waiting time of home appliances.

The proposed smart appliance control algorithm significantly decreases the peak load and helps to reduce electric energy cost at home. In this paper, a theoretic detailed description of the algorithm for home energy management is done, where RES is connected.

The practical implementation of the algorithm will be realized in the future since it presents a very complex system, especially the architecture of the control system, which we have chosen for the implementation of the SHEM algorithm, is also described in this paper. We have closer values of cost reduction after the practical implementation of the algorithm.

The proposed SHEM algorithm effectively control and manage the appliance operation to keep the total household consumption below a specified demand limit. The proposed algorithm takes into account both load priority and customer preferences settings. SHEM algorithm is designed to keep the total household demand below the limit level, customers may need to sacrifice their comfort preferences (i.e., water temperature, room temperature exceeds the preferences setting).

This paper presents a new SHEMs algorithm for home to efficiently manage renewable energy, battery storage, and power grid, implemented in the description system architecture. Our control algorithm makes the decision based on the predicted future renewable energy generation and energy consumption.

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