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Original Article

A Novel Home Energy Management Algorithm Based on User Demand Analysis in Vietnam: A Case Study

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Abstract *- Smart Grid is one of the most critical challenges in Vietnam. An effective management system of residence power consumption is an integral part of the smart grid, and significantly reducing power consumption in peak hours is a great challenge. However, the solutions of Electricity of Vietnam Corporation do not compose an analysis of user demand in order to make it more effective. This article proposes a novel algorithm for effective management of home energy, taking into account the user demand analysis. This paper refers to two issues: firstly, a study of user demand for home devices is given. Then, a novel algorithm is proposed to optimize the operation schedules of home appliances based on two criteria: economic electricity bill and reduced power consumption under a pre-defined threshold.*

Keywords *- Smart home, Smart meter, User demand, Home energy management, Power consumption.*

1. Introduction

In recent years, the demand for electricity from households as well as manufacturing enterprises has been increasing. According to statistics, in Europe, more than 37% of energy is consumed by buildings, including apartment buildings and commercial centers; industries only consume 28% of energy, and the delivery industry transportation is 32% [1, 2].

In Vietnam, people's lives are improving day by day, and the need for family comfort is increasing. That is one of the reasons for the sudden increase in electricity consumption in the current population. In addition, industrialization and modernization have made our country's industries increasingly free from manual labour, replaced by machines. The problem with the change is that electricity consumption has increased significantly in the industry.

Meanwhile, the exploitation and use of new energy sources such as solar energy, wind energy, or nuclear energy are still in a small-scale research and experimental phase. As a result, power supply and distribution systems are increasingly incapable of meeting rising demand. One of the consequences of this is the overload during peak hours, especially during the hot season.

A lot of research has been conducted to develop intelligent energy management solutions for home appliances [3-7]. These studies focused on finding optimal operating schedules for home appliances based on user demand response. Meanwhile, other analyses were performed to build smart home energy management with the presence of renewable energy [8-13]. Integrating renewable energy into the home power system required modifying the operational schedules to balance the user's needs and the availability of uncertain power sources from renewables. Furthermore, electric prices are considered a constraint during the optimization of operating profiles of home appliances with renewable sources [14-18]. This is a significant requirement to urge shifting the appliance's operation for financial purposes. As a result, home devices were planned to operate at the time, resulting in lower electricity bills but not meeting users' demands.

On the other hand, other literature focused on home user's habits to propose flexible operational schedules for home appliances [19-22]. Demand response analysis of users is a crucial constraint to developing an appropriate Home Energy Management (HEM) response algorithm. However, these works solely depended on the single primary constraint, either fixed electric prices or users' demands to optimize the home appliances' operational schedules.

Multiple electric tariff rates within a day were not considered while performing the user's demand analysis. The fact is that electric companies use flexible electric tariffs as a measure to regulate consumers' demands for power system stability purposes. Thus, this is not a practical approach in utilizing a primary constraint optimization of HEM in Vietnam as the 3-price tariff of electricity is currently used.

One of the urgent solutions presented is the problem of leveling the load in electricity use between peak times and off-peak times to avoid system overload. It is the Electricity of Vietnam Corporation (EVN) policy to charge different electricity costs at different hours to encourage consumers to save energy, especially during peak hours. However, that solution has not yet shown the effectiveness of load leveling without the coordination with the user needs analysis problem.

This article introduces a HEM suggestion that combines the problem of analyzing the demand for using electrical energy and the 3-price tariff power meter, which will help to solve the load-leveling problem better while assisting consumers in saving energy costs. On that basis, the paper presented includes the following sections: Analysis of the electricity demand of a household is presented in section 2. Section 3 introduces a novel algorithm to save electricity by means of leveling the load between peak and off-peak hours, according to the objective function, which is to keep energy costs and limit power consumption at each time within the permitted threshold. Several simulation results are presented and discussed in section 4. Finally, conclusions and development directions are discussed in section 5.

2. Methodology

2.1. User Behavior Analysis

In order to propose a solution to save home energy consumption, information about the user demand for electrical appliances in the house and their use duration is needed. Therefore, the input signal of the home energy management system is the user demand based on their comfort preference, denoted user profile. From this profile, user demand habits of electrical appliances categorized as ON/OFF states can be learned and used for a sufficient period of time. Focus on the study of home energy management; it is assumed to receive external signals based on some custom residential appliances that consume high power, such as water heaters, dishwashers, air conditioners, clothes dryers, and charging devices. A user profile is given in Table 1.

Table 1. Habits of using electrical appliances

Devices	Priority	User Habits and Comfort Preference
Water Heater	1	Water Temperature: 40-50^{o}C
Air Conditioner	2	Room Temperature: 25-28^{o}C
Dishwasher	3	Finish at 23h Job Duration: 30 Minutes
Clothes Dryer	4	Finish before Midnight Job Duration: 90 Minutes
Charging	5	Full Charged by 8 a.m. Minimum Charge Time: 150 Minutes

As indicated in Table 1, the user chooses the water heater as the most preferred appliance, and the air conditioner, dishwasher, clothes dryer, and charging device are consequently selected in that order. User well-being is shown in the 3rd column of the table. With a water heater, the user's desired water temperature is 35-40^{o}C. The room temperature is 26-29^{o}C. The dishwasher needs to be finished before 23 hours, and the washing time is 30 minutes. For tumble dryers, it is required that the clothes are dried by noon, and the minimum drying time is 90 minutes. As for electric vehicle charging equipment, it needs to be recharged before 8 a.m., and the minimum recharge time must be 150 minutes.

Based on the analysis of user demands on electrical devices, operation and state models for these devices can be built at each time. The details of user habit modeling are presented in the next section.

2.2. Electric Devices' Operation Modeling

The operation model of electrical devices is built as logic functions with two values of 1 and 0, respectively, ON and OFF states. It is the input data for the energy-saving algorithm presented in the following subsection.

2.2.1. Water Heater (H) Operation Model

The hot water is pre-defined as a desired temperature range. If the temperature value is less than the desired minimum threshold (T_{min}), the water boiling machine is switched on, corresponding to the ON state. After the hot water reaches the required value (T_{max}), the water heater stops working, corresponding to the OFF state.

While the water warmness is within the necessary temperature values ($T_{min} < T < T_{max}$), the water heater remains in the state of the previous period. In this way, the following equation is used to simulate the operation of the water heater:

$$S_{H,n} = \begin{cases} 0 & T_{H,n} > T_{max} \\ 1 & T_{H,n} > T_{min} \\ S_{H,n-1} & T_{min} < T_{H,n} < T_{max} \end{cases} \quad (1)$$

Where:

$T_{H,n}$: Hot water temperature in the time interval n;

$S_{H,n}$: Water heater state in the time interval n.

2.2.2. Air Conditioner (AC) Operation Model

The room's hotness is initially pre-defined, within the desired temperature threshold according to the user's comfort preference. Similar to the above case, the problem is controlled by the ON/OFF controller mechanism. When the air hotness is larger than the desired value, the air conditioning machine is turned ON.

When the room temperature is less than the required temperature range, the air conditioner switches to the OFF state. While the room temperature is within the set temperature range, the state of the air conditioner remains the same as in the previous period. The operation model is as follows:

$$S_{AC,n} = \begin{cases} 0 & T_{AC,n} > T_{max} \\ 1 & T_{AC,n} > T_{min} \\ S_{room,n-1} & T_{min} < T_{AC,n} < T_{max} \end{cases} \quad (2)$$

Where:
$T_{AC,n}$: Room heat in the time period n;
$S_{H,n}$: Air conditioner state in the time period n.

2.2.3. Dishwasher Operation Model

Dishwasher is used every day in the evening after dinner. The user comfort preference is expressed as the job duration and the completion time. The state model of this electrical device is shown in the following equation:

$$S_{D,n} = \begin{cases} 0 & CT_n \geq CT_{max} \\ 1 & CT_n < CT_{max} \end{cases} \quad (3)$$

Where:
CT_n: Job duration or time to complete the job (e.g., accumulated ON time);
$S_{D,n}$: Dishwasher state within the time interval n.

2.2.4. Operation Model of Clothes Dryer

With this model, the job duration time is initially set according to user preference, which is shown on the machine. The clothes dryer is switched ON, and the accumulated ON time is recorded. When this value reaches the pre-defined limit, it is turned OFF. The following equation is obtained:

$$S_{CD,n} = \begin{cases} 0 & CT_n \geq CT_{max} \\ 1 & CT_n < CT_{max} \end{cases} \quad (4)$$

Where:
CT_n: Accumulated ON time of clothes dryer;
CT_{max}: Time is required to complete the job.

2.2.5. Operation Model of Charging Devices

The requirements for this device are shown by the time it takes to charge an electric motorbike thoroughly before 8 a.m., and the minimum time for setting should not be less than 150 minutes. With this constraint, the device can work at any time of the day to recharge. Therefore, these devices can be OFF at peak hours to reduce power consumption and electricity costs. The operation model of this device is presented below:

$$S_{CV,n} = \begin{cases} 0 & SOC_n \geq SOC_{max} \\ 1 & SOC_n < SOC_{max} \end{cases} \quad (5)$$

Where:
SOC_n: Battery status of charge at time period n (%);
SOC_{max}: Maximum battery status of charge (%);
$S_{CV,n}$: Status of device at time interval n.

3. Energy Management Algorithm

3.1. Energy Management Criteria

From the EVN's point of view, power consumption increases dramatically during peak hours, which may have some bad consequences for electricity transmission. So, it is essential to propose some high threshold of power to reduce overloads during peak periods.

From the customer's point of view, the modernity of a smart home with the use of a large number of electrical devices gives the user more comfort but also dramatically increases power consumption and, therefore, increases electricity costs. Thus, energy management solutions that minimize electricity costs while optimizing power consumption during peak hours are attractive nowadays.

To realize the goal of optimal energy management, different objective functions are proposed to satisfy different requirements for saving energy. Specifically, in this paper, a new solution is proposed that combines the smart meter system and the regulation of the operation of unnecessary devices.

The objective function is to minimize the electricity cost consumed by the 3-tariff power meter. The regulation of home devices is given to limit the total power consumption in an apartment, which is always less than a threshold value. The details of this suggestion are presented below.

3.1.1. Reduce the Electricity Cost

The objective function for this criterion is given by:

$$J = min \sum_{t=1}^{m} E_{load}(t) * C(t) \quad (6)$$

Where m is the number of electrical devices used in the algorithm.

In this paper, it is assumed that electricity price is calculated according to different tariff rates in different time intervals of the day. To illustrate this objective function, a 3-price tariff applied to voltage levels below 6kV (for business households) is chosen with the following prices:

- Normal price: 2.320 VND / kWh
- Low price: 1.412 VND / kWh
- High price: 3.991 VND / kWh

According to this price list, if some devices are not essential to operate in the peak-hour period, they can switch the execution time to another period with the normal or low price. This regulation time can not only save a maximum cost of 2.579 VND/kWh but also decrease the high-power consumption during the peak-hours period. To implement this criterion, the lowest electricity price list is first determined, corresponding to the activation time of appropriate devices.

Then, for devices that are not critical to activate at that time, they are changed to the ON time according to the lowest cost without affecting the user preference.

3.1.2. Limit the Power Consumption

This criterion is used to limit power consumption through a threshold value (P_{th}) in order to keep the balance between consumption and electricity production on the home scale and the grid scale. This criterion is implemented based on the priority of electrical home devices.

In detail, at each time interval, if an unbalanced power occurs, the management algorithm will turn OFF devices with the lowest priority (the highest number in the second column of Table 1) to keep the power consumption from exceeding an experimental threshold value. For example, when the water heater is ON, and the power is exceeded, the algorithm will check the devices with lower priority to switch off to reduce the total energy. The contents of these two criteria are discussed in detail in the following sections.

3.2. Energy Management Algorithm

The algorithm of saving electricity costs and limiting power consumption is given by the strategy of ON/OFF control of electrical home devices satisfying the determined objective functions. The proposed process begins by collecting data, which contain conditions and consumption power of all devices, using the importance and schedule of appliances, together with the Power Limit (P_{th}) and its associated duration. The overall algorithm is given in Figure 1. The algorithm checks for the comfort level of all appliances for the decision of appliance status. Then, the energy management decision procedure is as shown in Figure 2. The process is as follows:

Step 1: Divide a day into several time intervals, let's say N cycles. At each cycle, the 2 following steps are processed accordingly.

Step 2: Calculate energy consumption for electrical devices, corresponding to the time consumed until the end of each test cycle or the time to execute the job if that time is less than the test cycle. Then, calculate the electricity costs to pay for the above power consumption. For electrical devices that do not require a start time of an abbey, the algorithm calculates the lowest price through the above objective function. The ON time of devices will be updated according to the lowest cost.

At this step, the total power consumption of all ON home appliances with the lowest cost is compared to an acceptable value. Thus, the total power consumption threshold is assured as the low-cost period always falls into the off-peak period. However, in several cases, the ON devices priorities are equal, and the total power consumption needs to be supplemented to ensure electricity safety. This is done in the following step.

Step 3: Limit power consumption at each time. In this step, the algorithm will update information, including states of devices, the total power consumed by devices, the priority order of devices, and user profiles with each device, such as water temperature, room temperature, and actual start time of devices (updated in step 2). Then, the algorithm checks the total power consumption. In case of unbalanced power of grid-scale or user scale, some devices that are not strictly activated at that time (with low priority) will be OFF.

For example, at 12:45, a peak hour, the two devices, hot water, and air conditioner, are working together, causing an overload of the total power. According to Table 1, the air conditioner with a higher priority order will be OFF, and the algorithm recalculates the total power consumption until the condition $P_{total} \leq P_{threshold}$ is satisfied. Devices that are OFF at the test time will be restarted at the next time cycle when the condition $P_{total} < P_{threshold}$ is met.

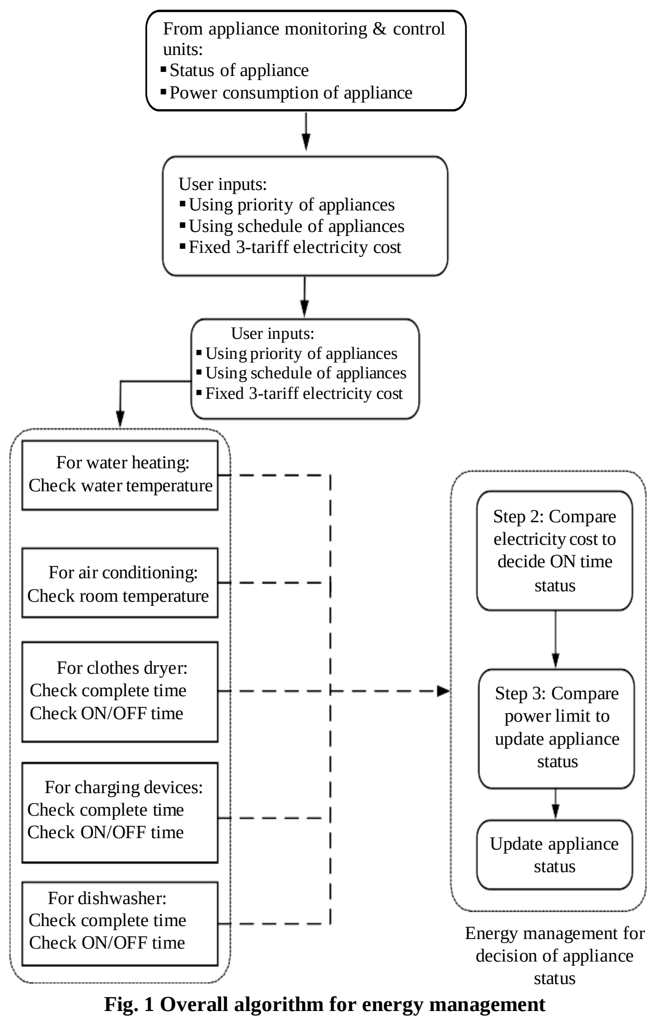

Fig. 1 Overall algorithm for energy management

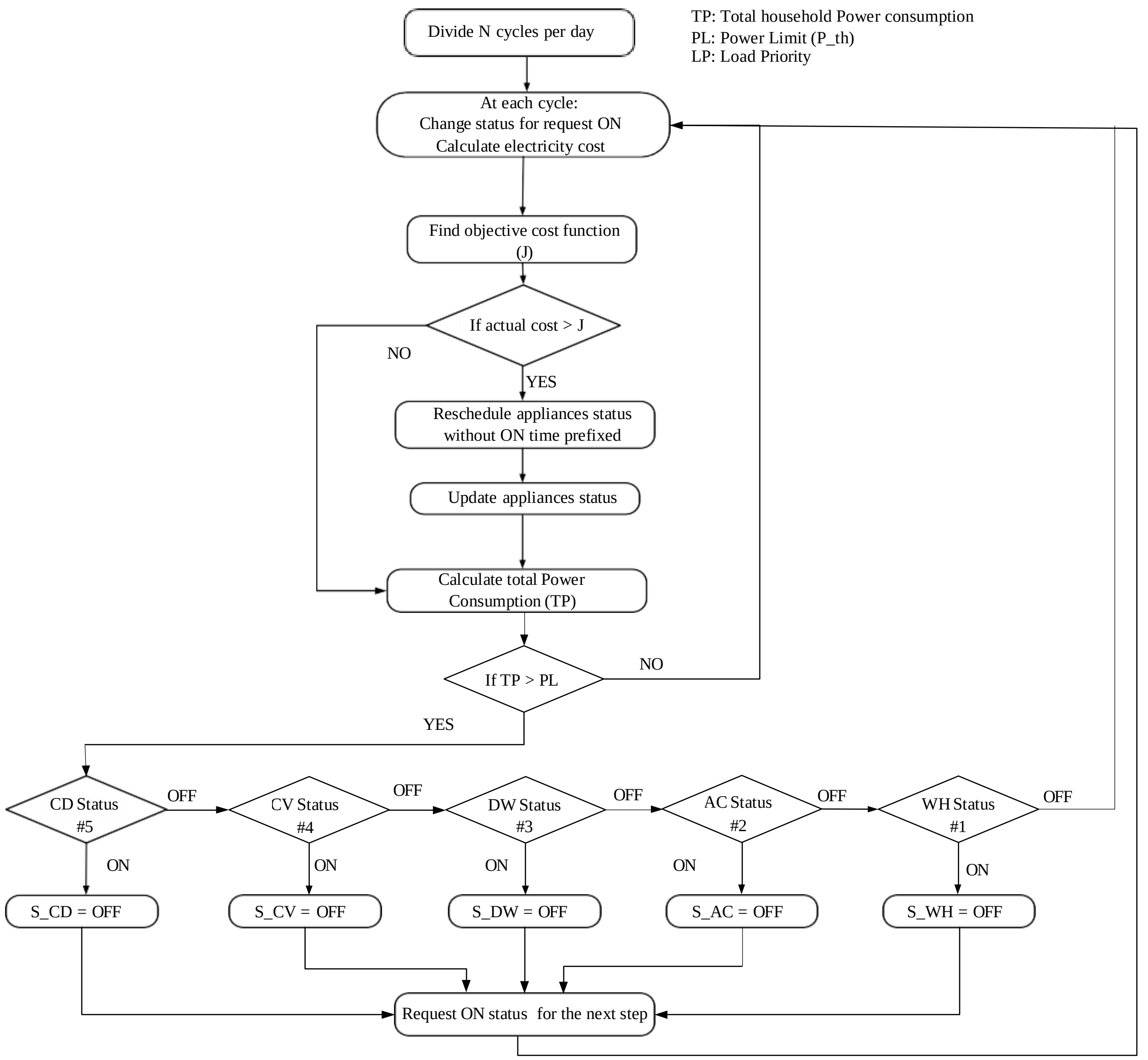

Fig. 2 Decision making process for home energy management

4. Results and Discussion

To evaluate the results of the energy management algorithm corresponding to the criteria of reducing the electricity cost and reducing the total power consumption load within the usage permission, the model of electrical appliances in the house is described by the simulation model in Matlab/Simulink.

The heat exchange process is a slow change process, so the authors considered that the process of water heating in the tank takes place for 1 hour and stops for 1 hour. The operation of the air conditioning system is similar: it operates for 1 hour and stops for 30 minutes. The ON/OFF operation of these two devices takes place continuously. To simulate the observation process of these two devices, by dividing a day into 48 periods, a power curve of each device is obtained as shown in Figure 3. The blue line illustrates the operation of the hot and cold-water system, the red line shows the operation of the air conditioning system. For other devices, which have limited usage time and limited start-up time, the process is simulated in such a way that it takes place at the beginning of the demand for use, as shown in Figure 4.

Figures 3 and 4 show that most of the electrical equipment has the desired execution time in peak-hour periods. As a consequence, the electricity cost of electrical equipment is significantly high. The total power consumption of all home appliances is shown in Figure 5, and the ranges of electricity costs to be paid for the appliances in a day are illustrated in Table 2. It is noted that in peak hours time, the total power consumption is relatively high, and the proposed energy management algorithm must reduce it. For devices that do not require continuous execution, as shown in Figure 4, they can shift the device initialization time to another time period with lower electricity costs and reduce total capacity consumption at peak times.

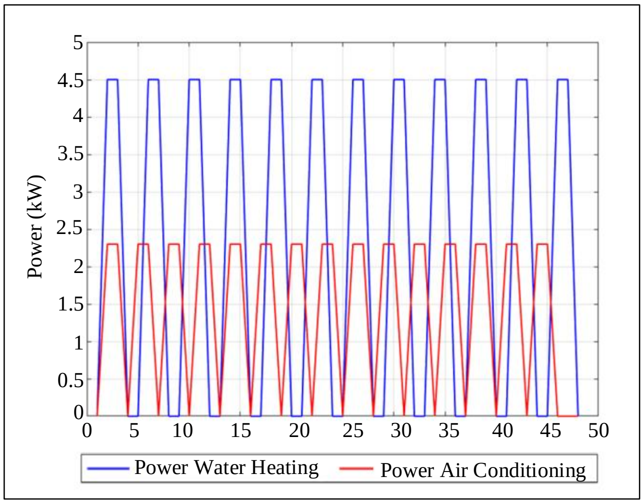

Fig. 3 Power consumption of water heating and air conditioning

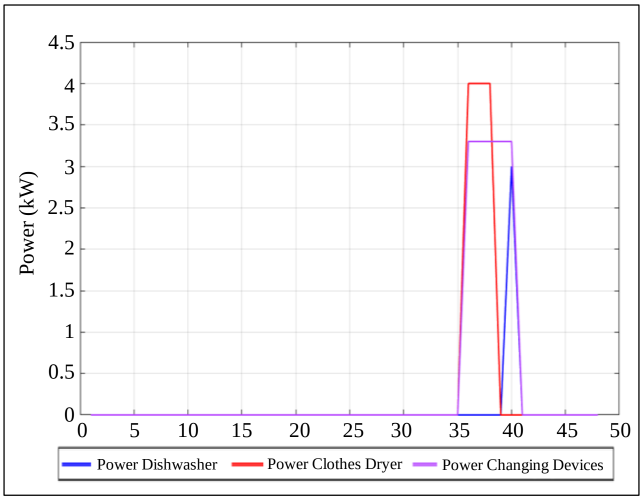

Fig. 4 Power consumption of home appliances

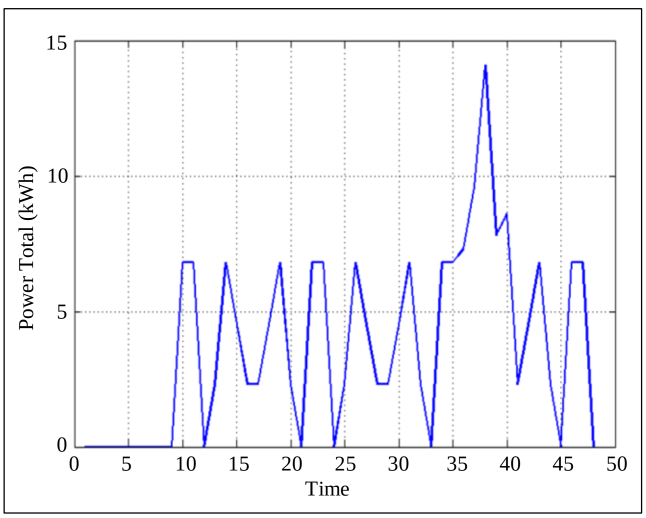

Fig. 5 Total power consumption within a day

For this purpose, it has proceeded to calculate the cost of power consumption if the device is activated at each time. The optimization of electricity costs will be done by finding the value of the objective function *J*:

$$J = min \sum_{t=1}^{m} E_{load}(t) * C(t)$$

For each device, its initialization time is considered, as required by Table 1, corresponding to the electricity costs to be paid for each possibility. Then, the total electricity cost of the chosen devices is calculated by:

$$J_k = \sum_{t=1}^{k} P(k) * Duration(k) * C(t)$$

Where:
$Duration(k)$: Execution time of the kth device;
P(k): Power consumption of the kth device;
C(t): Electricity cost for 1 hour.

J_k is a vector that presents the total power consumption cost of *k* devices within different time intervals. Then,

$$J_k min = min \sum_{t=1}^{k} P(k) * Duration(k) * C(t)$$

From the above equation, the time to activate device *k* can be chosen so that the total cost of the first *k* devices is minimal. Continue the process of finding $J_k min$ until all devices are exhausted:

$$J = min \sum_{t=1}^{m} E_{load}(t) * C(t) = J_m min$$

As a result, the lowest electricity costs to be paid for the operation of each specific device can be calculated in a day, as shown in Table 3.

Comparing the results of Tables 2 and 3, it is noted that the proposed suggestion can help to reduce the daily electricity cost by shifting the task operation time to periods of low tariff. This also partly reduces the total load power consumption during peak times.

Table 2. Electricity cost for each device

Devices	T_ON	Duration (h)	Cost (VND)
Water Heater	X	X	122.870
Air Conditioner	X	X	81.609
Dishwasher (D)	20h	0.5	5.986
Clothes Dryer (CD)	18h	1.5	15.964
Charging Device (CV)	18h	2.5	33.997

Table 3. Optimal electricity cost for each device

Devices	T_ON	Duration (h)	Min of Cost (VND)
Water Heater	X	X	122.870
Air Conditioner	X	X	81.609
Dishwasher (D)	22h30m	0.5	2.118
Clothes Dryer (CD)	22h30m	1.5	8.472
Charging Device (CV)	0h	2.5	11.649
	1h	2.5	11.649
	2h	2.5	11.649

To test the total power consumption with an allowable threshold, a day is divided into several intervals, for example, 48 periods of half an hour. At each test time (i.e., from 1:48), the total power consumption of all devices (Pt-total) is calculated and then compared to the allowed power threshold ($P_{threshold}$). If $P_{t\text{-}total} > P_{threshold}$, it is proposed to OFF operating devices in order from the least essential device until $P_{t\text{-}total} \leq P_{threshold}$, then stop the test.

As a result, the power diagram of the devices at the optimal times is shown in Figure 6. In consequence, the electricity cost to pay for the equipment is significantly reduced, as tabulated in Table 3. The difference between the two power curves in Figures 5 and 7 shows the effect of reduction of peak power consumption by shifting device activation time to other periods of the day.

Through an illustrative example with several devices and an analysis of user requirements, the proposed algorithm has come up with a solution to change the activation time of devices in order to save electricity costs. It also balances the power consumption reasonably but does not affect the consumer's life comfortably.

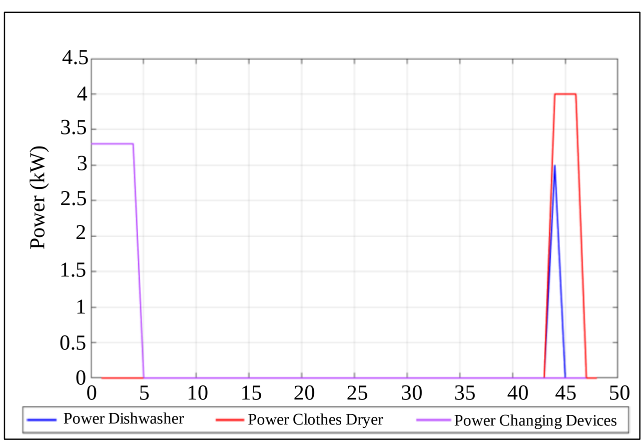

Fig. 6 Power of devices at optimal periods

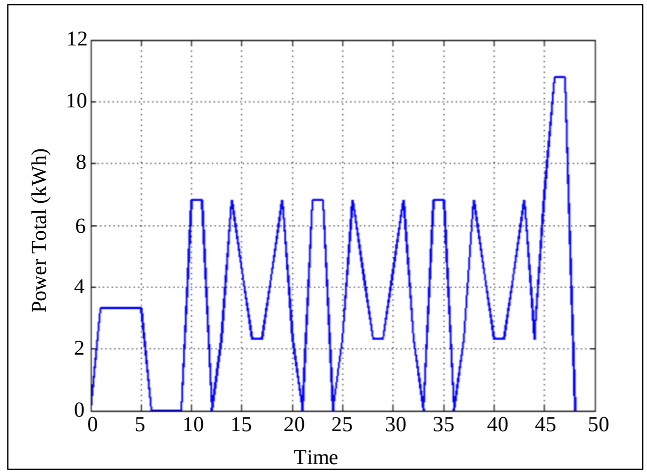

Fig. 7 Total daily power after implementing the power limit algorithm

The algorithm will be integrated into the proposed experimentation to remote measure the power consumption of home electrical devices, which is presented in Figure 8. Functions of each module:

- AC power source: AC loads for the measurement.
- Measurement module: includes current and voltage sensor modules and a microcontroller, which is used to measure the electrical parameters such as voltage, current, power, and energy.
- Isolation module: isolates the control circuit and loads; the main task of the block is to prevent interference in the electronic circuit to limit measurement errors.
- DC power module: realize the task of converting 220VAC to 5VDC power to supply microcontrollers, LCDs, and other modules.
- TTL converter module: converts the measurement signal into a communication signal in the microcontroller.
- Communication module (NodeMCU ESP 8266): receives data from the TTL converter block and decodes and sends measurement results to the HMI module.

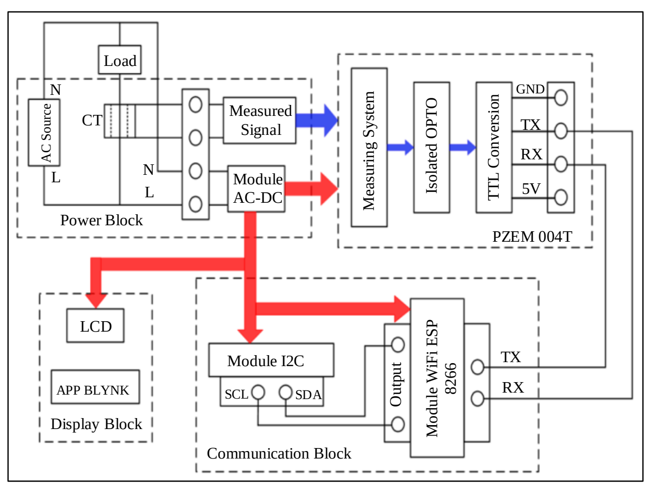

Fig. 8 Principle scheme of measurement system

5. Conclusion

The paper proposes a solution to the problem of effective energy management that is based on the analysis of user needs. The proposed algorithm consists of two parts: analyzing user needs in terms of activation time and implementation time for necessary electrical equipment in the house with different usage priorities, then exploiting the ability to shift the activation time of the devices according to 2 criteria: the lowest electricity cost and the power consumption does not exceed the allowed threshold. Simulation results have demonstrated the effectiveness of this intelligent energy management algorithm. For future work, the authors will apply this algorithm to smart home problems combined with intelligent grids in order to manage electrical energy on the grid most efficiently.

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