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A Simple and Effective Strategy to Prevent Power Transformer Overloading

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Abstract

This paper presents a novel strategy to prevent overloading of distribution transformers. The strategy is based on a developed algorithm for home energy management (HEM) system. The algorithm is mainly aimed to prevent the complete power outage of an area that may occur due to transformer overloading. The task can be accomplished by a supervised reduction in power consumption of the customers supplied through the overloaded transformer without tripping the transformer, since the complete disconnection of service is considered undesirable by the customers. The proposed algorithm is intended to minimize the number of switched-off appliances to lessen their impact on the customer's comfort level. The strategy is simple and effective in terms of cost and performance. MATLAB/Simulink was used to simulate the system and to validate the proposed strategy. The simulation results show the effectiveness of the strategy to avoid transformer overloading and thus preventing power outage.

Keywords: Distribution transformer protection; HEM system; Interruptible appliances; Overloading prevention; Power outage.

1. Introduction

One of the most challenging problems that power distribution systems are facing is the overloading of distribution transformers, especially in high population density areas, which results in a complete power outage of the areas supplied through the overloaded transformers.

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The main general objectives of transformer overload prevention systems can be summarized as [1]:

- Protecting the distribution system from line lockout in case of a transformer failure.
- Isolating the faulted transformer from the rest of the grid to minimize the number of customers affected.
- Protecting the distribution transformer from overheating and thus expanding the lifespan of the transformer.
- Allowing a rapid restoration of service in case of transformer isolation.

Many different protection techniques have been proposed in the literature [2-8]. These techniques differ in their complexity and cost. Most of these techniques are based on differential protection of power transformer. In [8], A modified differential protection approach with current and voltage ratios scheme is proposed to overcome the possibility of mal-operation that occurs in the percentage differential protection scheme.

The differential protection methods, in general, protect power transformer by isolating it from the system to reduce damage. This action, in effect, results in service discontinuity to the customers connected to the isolated transformer, which is considered undesirable by customers.

A survey of power transformer protection techniques is done in [9]. Reference [10] reviews the development history of power system protection and introduces the concept of integrated wide area protection and control of power system. In fact, this system may not be feasible to be implemented in developing countries due to the lack of the required infrastructure and the difficulty to build it in these countries in the near future.

The conventional protection systems such as fuses and circuit breakers may protect the distribution systems in cost effective ways but they achieve this by isolating an entire area from the rest of the grid. This in fact will result in a complete power outage of the isolated area for some time before service is restored.

In [11], the authors proposed a microcontroller-based protection system for distribution transformer. The scheme is aimed to protect the transformer by tripping the load in case of overloading. This scheme, like the conventional schemes, will also result in complete service disconnection to all the customers supplied through the overloaded transformer, which is considered undesirable by the customers. The other drawback of this scheme and all the schemes that depend on complete load disconnection in case of transformer overloading is that the control system would not be able to measure the load current (which is the indicator of overloading) when it is being disconnected. Consequently, the relay or breaker may either oscillate until the overload is released or keep disconnected for a certain period of time.

In [12], a fault identification system is proposed to protect power transformer using differential relay mechanism with GSM communication module controlled by Arduino microcontroller. This method may help in identifying the fault but not preventing the occurrence of it, which is usually caused by transformer overloading. The method will also result in service discontinuity to the customers connected to the faulty transformer.

To address the above mentioned problems, a smartly and fairly forced reduction in power consumption should be considered in case of transformer overloading. In this paper, a novel method is proposed to protect distribution transformer without disconnecting entire area from the rest of grid. The method is feasible to be implemented in developing countries and it is based on a simple and effective algorithm to reduce power consumption of the customers supplied through the overloaded transformer.

2. Problem statement

Transformers are critical parts in power distribution systems.

Overloading of a transformer can result in quick aging of it.

The thermal aging can cause insulation of windings to become brittle and with the time it will crack, results in an internal transformer fault.

Once transformers fail, they usually need a long time to be replaced.Conventional protection methods such as fuses and circuit breakers isolate the overloaded transformer from the rest of grid.

This affects the continuity of service to all the customers connected to that transformer. However, complete loss of power is not accepted by customers.

Transformer overloading is usually caused by the increase in power consumption of some of the customers connected to that transformer.

Therefore, instead of completely disconnecting electricity to all customers (even the low-use ones), the customers who exceed their predefined threshold value should be forced to reduce their consumption below the threshold.

This method will prevent transformer overloading and thus prolonging its lifespan in addition to avoiding complete power outage of the area supplied through it.

3. The proposed scheme

3.1. System structure

The proposed scheme is based on involving a central power monitor at the secondary side of distribution transformer. The monitor measures the total current drawn from the transformer. In case of transformer overloading, the monitor sends warning signals to each consumer supplied through that transformer. The infrastructure of the proposed scheme is illustrated in Figure 1. In the customer side, a home energy management (HEM) unit is installed at each customer's home which collects warning signals (from the central power monitor), the customer’s total current, and the instantaneous values of currents drawn by the interruptible appliances in building. The interruptible appliances can be specified, any time, by customer. This will give customers the freedom to select their interruptible appliances by plugging them to the mains through a current sensing module. Wi-Fi technology can be used for the communication between current sensing modules and

HEM unit. It should be confirmed here that not all appliances are interruptible. Thus, not each appliance at customer's home needs current sensor or communication system. The number of interruptible appliances at customer's home is limited according to the customer's predefined threshold, and they are identified by the customer himself according to his/her own needs.

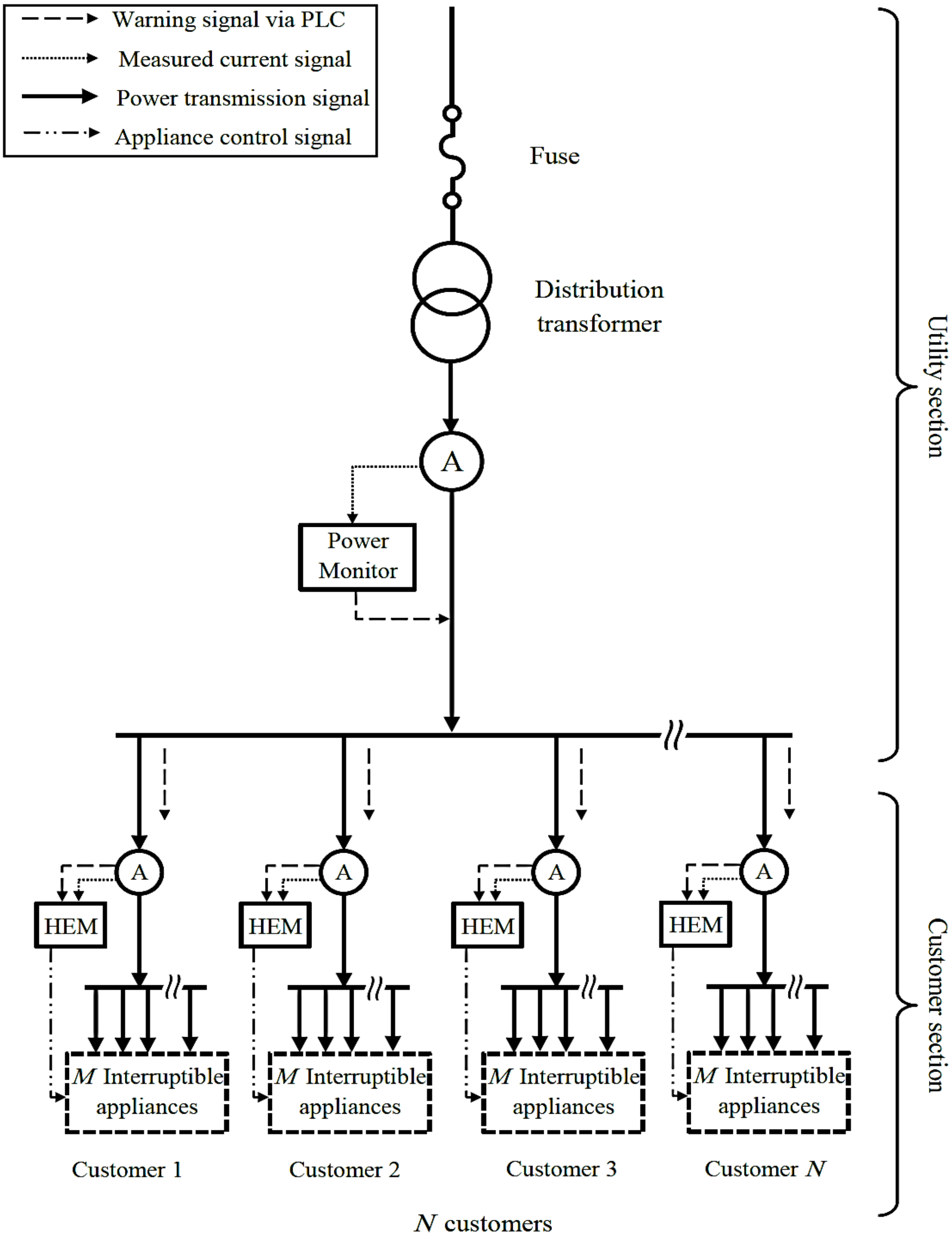

Figure 1: The proposed infrastructure

The threshold for each customer depends essentially on the size of distribution transformer and the number of customers served by that transformer.

Once the HEM unit receives a warning signal, it will compare the instantaneous value of total current with the predefined current threshold. If it exceeds the threshold, the HEM unit will send switching signals to the minimum number of interruptible appliances according to the proposed algorithm explained in the following subsection.

It should be noted here that only nonessential loads will be usually connected to the HEM unit. A nonessential load is any load that can be deferred for a period of time with little to no effect on comfort level or interruption of a process. In most situations, the interruptible appliances are appliances that have some sort of thermal storage such as water heaters, air conditioners or freezers. Thus, the proposed system will not significantly degrade the customer's comfort level. In contrast, reducing load by turning off some nonessential appliances for short amounts of time is more acceptable than complete outage of the area in case of transformer overloading.

3.2. The mathematical model

The HEM unit communicates with *M* interruptible appliances to read their currents (in ampere) and in the same time, it controls their operation at warning events. A simple and fast algorithm is proposed in this work. The algorithm is based on generating ($2^M - 1$) decimal integer numbers (from 1 to $2^M - 1$) and then converting those numbers into *M*-bit binary numbers. Each binary number will be considered as a column vector of 1s and 0s of length *M* (which represents ON/OFF switching signals). The obtained column vectors are combined into a single switching matrix *S* of size $M \times (2^M - 1)$ as in (1).

$$S = \begin{bmatrix} 1 & 0 & 1 & \dots & 1 \\ 0 & 1 & 1 & \dots & 1 \\ 0 & 0 & 0 & \dots & 1 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix}_{M \times (2^M - 1)} \qquad (1)$$

This matrix represents all the possible combinations of switching the *M* interruptible appliances ON or OFF.

A row vector *A* of *M* elements those represent the amperes drawn by each appliance is created as in (2).

$$A = [a_1 \quad a_2 \quad \cdots \quad a_M] \qquad (2)$$

A is then multiplied by the switching matrix *S* . This is accomplished by taking the dot product of *A* with each of the columns of *S*. The result is a row vector *I* of $2^M - 1$ elements that represent all possible values of current that can be drawn with all possible different combinations of interruptible appliances.

$$I = AS = [a_1 \quad a_2 \quad \cdots \quad a_M] \begin{bmatrix} 1 & 0 & 1 & \dots & 1 \\ 0 & 1 & 1 & \dots & 1 \\ 0 & 0 & 0 & \dots & 1 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix} = [\, i_1 \quad i_2 \quad \cdots \quad i_{(2^M - 1)}] \qquad (3)$$

Each element of the resulting vector I will be compared with the amount of current to be cut down by the customer (I_{CD}). I_{CD} is the difference between the total current (I_t) consumed by a customer and his predefined threshold (I_{th}). The element with the closest value to I_{CD}, provided that it is not less than I_{CD} (to guarantee that the saved amperes are not less than I_{CD}), will be selected. The index of the selected element will be determined in order to find the combination of ON/OFF switches that can realize the target current reduction. This can be accomplished by simply subtracting I_{CD} from each element of vector I to get the vector E as in (4).

$$E = I - I_{CD} \qquad (4)$$

The index of the minimum non-negative element of E will be selected in order to determine the corresponding column in the matrix S which represents the required switching signals to achieve the target load reduction.

Input: - Vector $a(1),\ a(2),\ \cdots,\ a(M)$ of currents drawn by each interruptible appliance

- Total current I_t received from the ammeter.

Output: Switching signals vector $b_o(1),\ b_o(2),\ \cdots,\ b_o(M)$

Initialization: set

$$b_o = [b_o(1),\ b_o(2),\ \cdots,\ b_o(M)] = 0$$

% computation of the amount of current to be cut down by the customer

$$I_{CD} = I_t - I_{th}$$

for $k = 1, 2, \ldots, 2^M - 1$ **do**

% conversion of k from decimal to M-bit binary number

% conversion of the binary number into a column vector of M elements of 1s and 0s

end for

% insertion of all the $2^M - 1$ columns into a matrix of size $M \times (2^M - 1)$

% computation of vector I which represents all the possible variations of current consumption for the interruptible appliances

$$I = [a(1)\quad a(2)\quad \cdots\quad a(M)] \begin{bmatrix} 1 & 0 & 1 & \ldots & 1 \\ 0 & 1 & 1 & \ldots & 1 \\ 0 & 0 & 0 & \ldots & 1 \\ \vdots & \vdots & \vdots & \ldots & \vdots \\ 0 & 0 & 0 & \ldots & 1 \end{bmatrix} = [\,i(1)\quad i(2)\quad \cdots\quad i(2^M - 1)]$$

% computation of the differences between each element of vector I and the value of I_{CD}

$$E = I - I_{CD}$$

% finding the minimum non-negative element of E

$$\min(E) = \min[e(1)\quad e(2)\quad \cdots\quad e(2^M - 1)] \quad ,\forall\, I \geq I_{CD}$$

% getting the index of the minimum element to find the corresponding vector of switching signals

Final solution: $b_o(1),\ b_o(2),\ \cdots,\ b_o(M)$

Figure 2: Pseudo code of the proposed HEM unit algorithm

The proposed algorithm is intended to minimize the number of switched-off appliances to lessen their impact on the customer's comfort level. The proposed algorithm is further clarified in the pseudo code shown in Figure 2.

4. Methods

MATLAB®/Simulink® was used to carry out the simulation experiments and analysis.

A single-phase power grid model was entirely built using the building blocks of Simulink environment.

For convenience, only four customers were considered in the simulation.

Each customer's house contained two types of appliances: interruptible and uninterruptible appliances. Only four of the appliances were assumed as interruptible and the rest as uninterruptible appliances.

The uninterruptible appliances were aggregated into a single load for convenience.

Therefore, only twenty different load profiles were considered and randomly generated for the four customers. Every five profiles were adopted for one customer (four of them were for the interruptible appliances and the fifth one was for the aggregated uninterruptible appliances).

Each profile is a vector of 24 samples of 1's and 0's.

These samples indicates the operation status of the appliance (i.e. ON or OFF).

The vector was then multiplied by the nominal power consumption of the appliance.

The pseudo code of the proposed home energy management (HEM) algorithm was firstly developed and then converted into MATLAB programming language to be included in "MATLAB Function" block that can be found in User-defined library.

This block was then added to each customer's house as a HEM unit.

The phasor simulation method was utilized in this research in order to make the simulation of a whole day very fast.

In other words, the simulation of the overall power grid for 24 hours (86400 seconds) was executed in several minutes rather than hours in contrast with the time-domain simulation method.

The system was firstly simulated without the proposed HEM unit and then with the HEM unit involved.

The results of both simulation experiments were compared to validate the proposed technique and to show its effectiveness to prevent transformer overloading.

5. Results and discussion

The overall Simulink power distribution system model is shown in Figure 3.

The customers are connected to a common distribution transformer.

The central power monitor reads the total current drawn from the transformer through the ammeter and sends warnings to the HEM unit of each customer in case of overloading.

For convenience, only four appliances are considered as interruptible and the others (aggregated in a single block) as uninterruptible, as shown in Figure 4.

Each appliance has its own load profile and each one of the four customers has different load profile as illustrated in Figures 5–8.

The Simulink model of one of the appliances is shown in Figure 9.

The system is firstly simulated without the proposed HEM unit (Figure 10) and then with the HEM unit involved (Figure 11). It can be noticed, in Figure 10, that the transformer is overloaded three times (at 7:00 AM, 5:00 PM and 7:00 PM) as indicated by the warning signals.

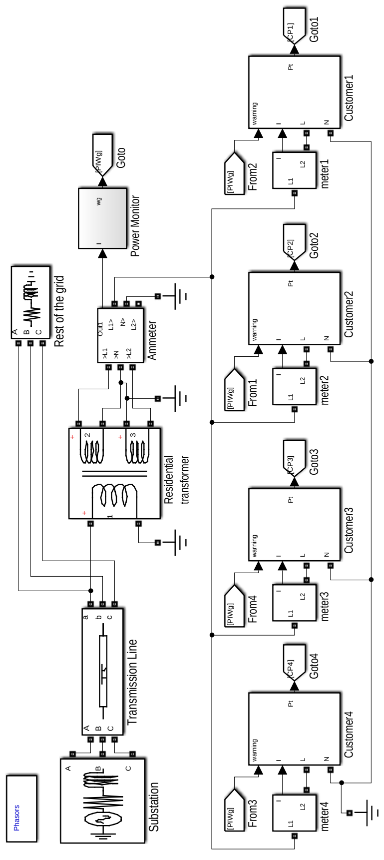

Figure 3: Simulink model of the proposed infrastructure

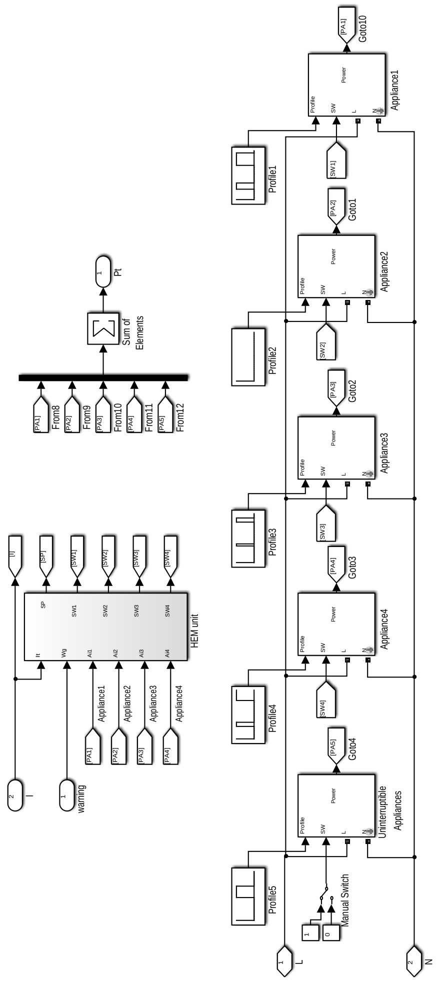

Figure 4: Simulink model of customer's house appliances with HEM unit

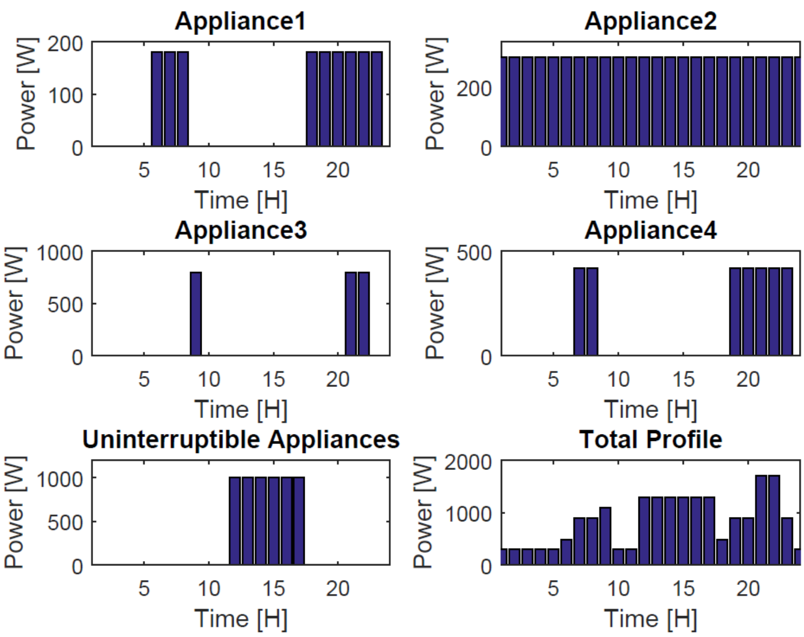

Figure 5: Power consumption data of customer 1

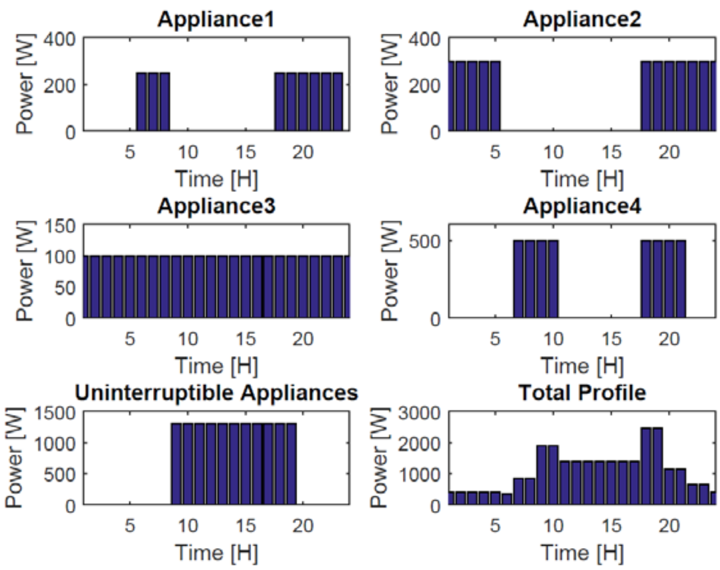

Figure 6: Power consumption data of customer 2

In Figure 11, when the proposed algorithm is involved, once the HEM units were triggered by the first warning signal they automatically forced the reduction of consumption for the customers who exceeded their predefined thresholds. Thus, no more warnings occurred subsequently. That means the transformer overloading is prevented by automatically reducing consumption of some customers who exceeded their threshold instead of tripping the transformer.

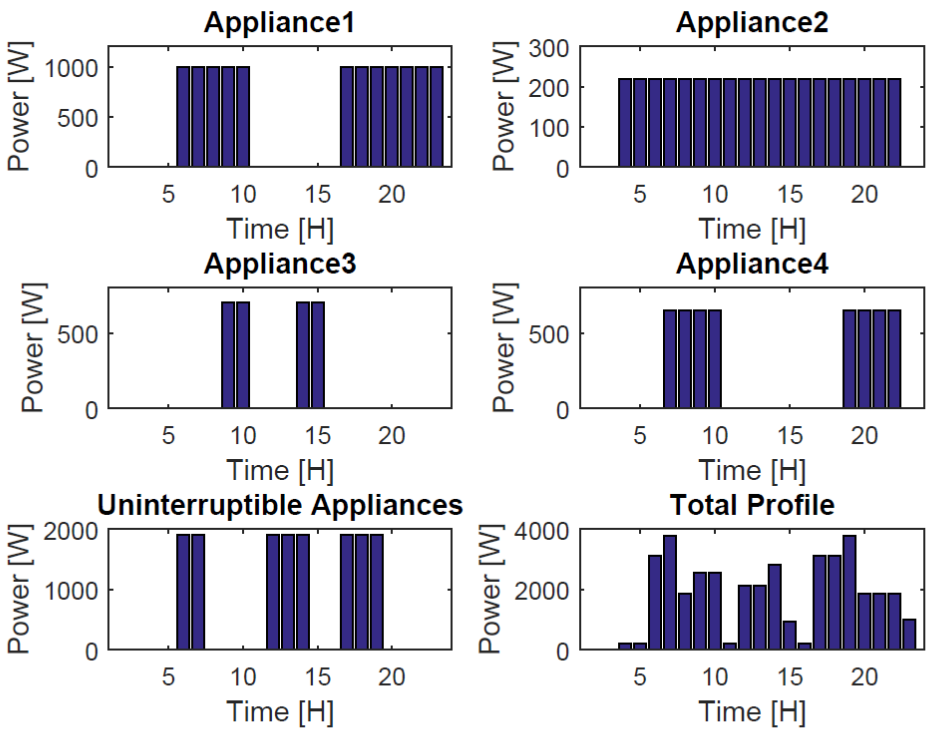

Figure 7: Power consumption data of customer 3

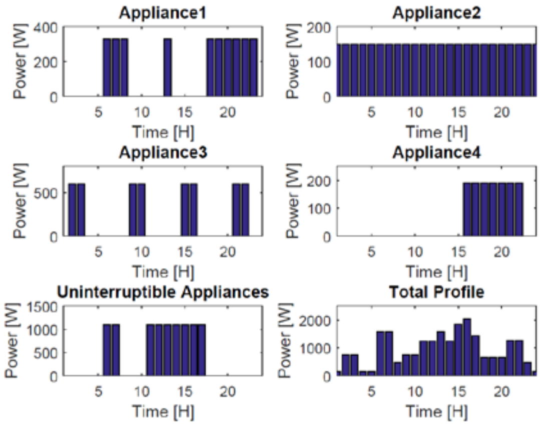

Figure 8: Power consumption data of customer 4

Although the load curves in Figures 10 and 11 are significantly fluctuating, which is uncommon, this case is considered to examine the robustness of the system in the worst case since the less fluctuating curves are more easier to follow and to respond to their variations. It should be confirmed here that the warning level must be less than the maximum ratings of the power transformer in order to give the system a sufficient time to act before the protective relay trips or the fuse might blow. Moreover, making power transformer operates below the overload region will increase its lifespan.

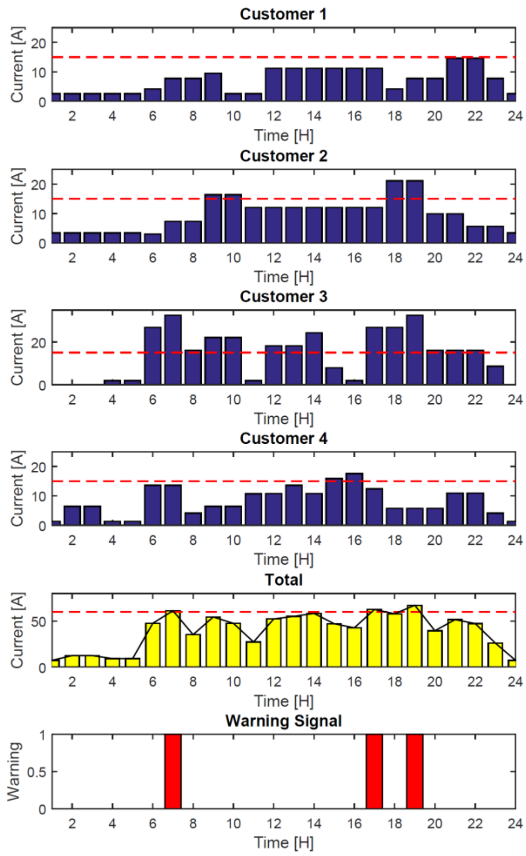

Figure 9: Transformer overloading continues when the proposed algorithm is not involved

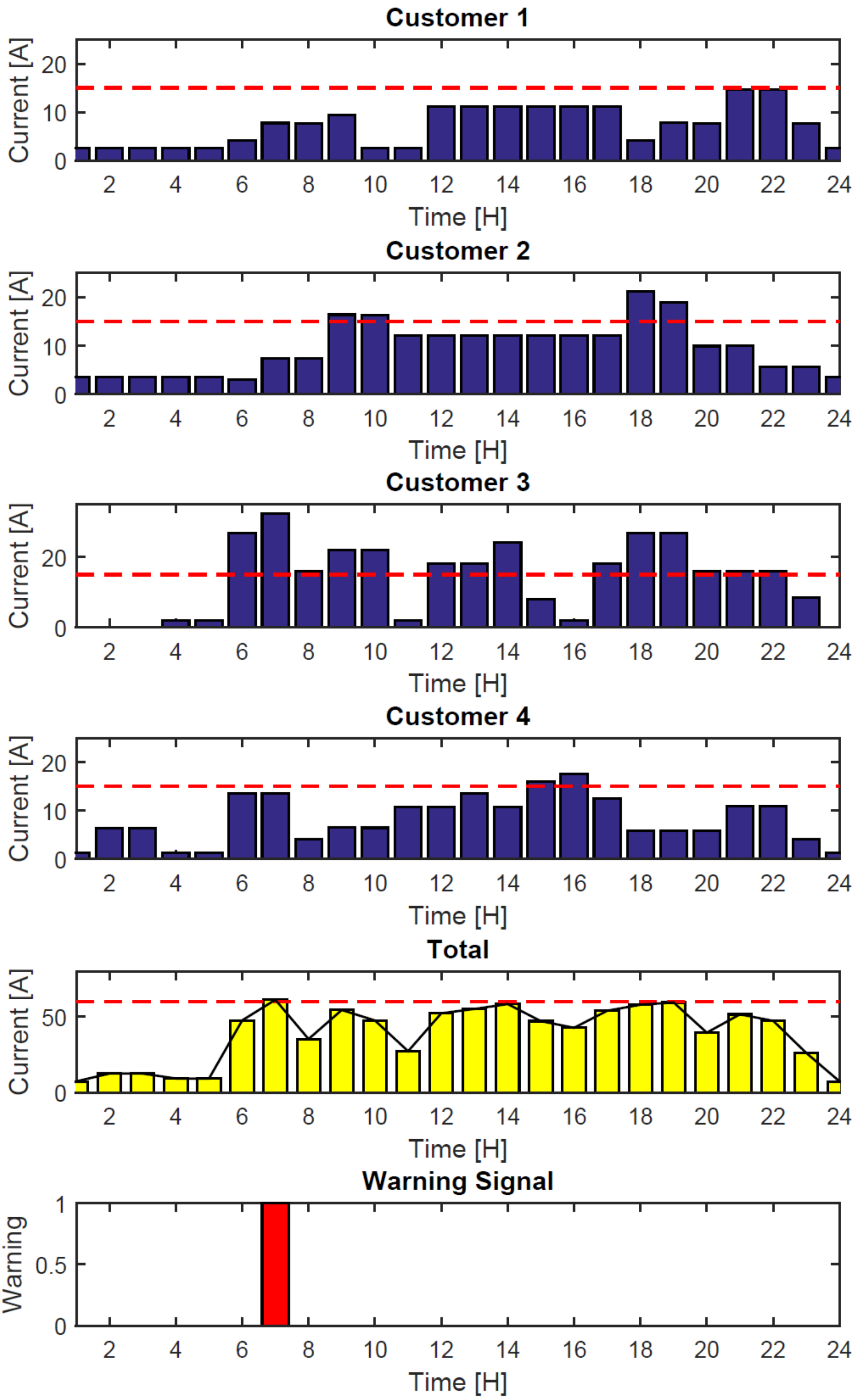

Figure 10: Transformer overloading is prevented when the proposed algorithm is involved

6. Limitations of the study

Although the simulation results have been satisfactory, the proposed strategy should have been experimentally implemented in a real-world power sub-grid to support the simulation results. Unfortunately, there were no available permission to utilize a real-world transformer even with a small number of customers. However, this can be considered in future work.

7. Conclusion

Many different protection strategies have been proposed in the literature. These strategies differ in their complexity and cost. However, most of these strategies focus on the protection of power transformer without taking the prevention of service discontinuity into consideration. Additionally, some of the strategies are not feasible to be implemented in most of developing countries.

A simple and effective strategy is proposed in this paper that can prevent transformer overloading and, in the same time, it avoids transformer tripping and consequently prevents power disconnection. Furthermore, the strategy can be implemented in developing countries at reasonable cost.

The simulation results show that once the total current drawn from the transformer reaches a threshold level, the power monitor sends warning signals to the customers and the HEM units switch off the minimum number of interruptible appliances that expected to reduce the consumption and stop the warning. This strategy protects the power transformer from being overloaded without isolating it from the rest of grid and thus prevents major power outage of an entire area. The experimental implementation of the proposed scheme can be considered in future work based on low-cost microcontrollers. Power line communication (PLC) technology can be utilized to send the warning signals over existing power cables.

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