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An approach to operate high-powered legacy electrical appliances on small scale solar PV systems

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ABSTRACT

Due to high cost, solar Photovoltaic (PV) systems are not an attractive option for places where energy buyback programs are not available. Mostly because small scale PV systems are incapable of operating legacy high-powered electrical devices such as room air conditioners, induction motors and other compressor-based devices on renewable energy. This is because these devices show either capacitive or inductive behavior which results in a high transient power during their startup cycle, not accommodable by small-scale PV systems. Solutions to solve this problem such as Variable Frequency Drives (VFDs) are expensive and restrictive in their applicability.

In this paper, we propose an approach to operate high-powered legacy electrical appliances on small-scale solar PV. Our proposed method involves a real-time algorithm which detects the onset of a transient and shifts the appliances from PV to the utility during the transient duration. Upon reaching back to a stable state after the transient, the device is shifted back to PV. We have evaluated our transient detection algorithm on a two publically available datasets as well as on a specifically designed testbed system. Our evaluations show that for most common high-powered devices, the transients are detected fast enough to shift the load from PV to the grid and vice versa.

1. Introduction

Distributed generation (DG) is a cornerstone of the future smart grid. To encourage more and more DG sources, many countries like Germany, USA, Japan, Italy, etc. have energy buyback programs. These buyback programs are implemented as net metering or feed-in tariffs [1,2]. But at a few places, the feed-in tariff rates are not that attractive to the general public. Consequently, many building owners consider the payback period too long to invest in rooftop PV [3].

There is another interesting problem in the distribution systems in some developing countries. Many places in developing countries already have installed grid-tied meters. Energy generated as DG can be put back to the grid. However, this two-way energy flow cannot be used for net metering because the meters are configured to charge in both cases of energy coming in and going out from the meter to the grid. Therefore, if one installs a grid-tied PV system and that system puts the energy back to the grid. Instead of getting incentives, the meter owner has to pay for putting the energy back to the grid together with the energy that he uses from the grid. This is an interesting scenario, but historically this type of metering was deliberately designed to stop the theft of energy. But since there are a myriad number of consumers already having such meters, and it is very difficult to change the meters in a short time.

On top of that, there are still many places where energy buyback programs are not available. Even when energy buyback programs are available, the capacity of the grid to have multiple energy suppliers is limited. Some work approximates this number to be 20% [4] of the total 1–5 kW connections connected to the grid. Since buildings consume around 37% of the energy worldwide [5], it is important that these buildings can be retrofitted with alternate options to use PV if energy buyback programs are not attractive, limited or even non-existent.

To this end, we present an approach to detect the transient of the devices. By detecting the transients, we can operate heavy loads on a small scale Solar-PV. For this purpose, our proposed approach adds another low-cost layer to the solar PV system.

To summarize, we have implemented a variation of Hyper

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Ellipsoidal Clustering algorithm as in Ref. [6] to detect the transient of high-powered electrical devices. After detecting the transient, we use a variation of Smart Energy Switching Platform (SESP) proposed in Ref. [7] to shift the load from PV to the grid. Usually, for heavy loads, the transients are observed during the startup of the load and normal cycles of the appliance. Our system also implements the zero crossing circuit to prevent any extra transients because of switching between Solar-PV and main grid.

The rest of the paper is organized as follows: Section 2 discusses the related work. Section 3 outlines the motivation and problem statement. Section 4 discuss our approach in detecting transients. Section 5 describes the hardware changes needed to implement transient detection. Section 6 provides evaluation of our approach. Finally, Section 7 concludes the paper with a future outlook.

2. Related work

Inverters of Maximum Power Point Tracking (MPPT) type are normally used with grid-tied PV systems. These inverters work best when the grid is stable, and energy buyback option is available. MPPT inverters work under a given voltage bound. If the grid is not stable, the voltage fluctuations may damage the inverter. Moreover, if the energy buyback program is not available, then MPPT inverter may not be able to help in maximally utilizing the PV output. This is because most of the MPPT inverters are not designed to integrate the power from both PV and grid at the same time. What happens is that if the load of the whole building is under PV output, then it will use PV to power the building. However, when the load is more than the PV output, the whole load is shifted to the grid. Only the high-end MPPT inverter with enough battery storage can combine the voltage from the grid and PV. But in the case of an unstable grid with voltage fluctuations, this combination is not possible [8].

In Ref. [9], modeling of domestic appliances having higher transients such as refrigerators and freezers has been done using price signal control strategy which leads to variable tariffs to the overall reduction of operation costs of these type of appliances. In Ref. [10], a real-time scheduling technique using dynamic programming is proposed for a residential energy storage system. It lengthens the battery life as well, but it cannot provide the solution of heavy transient devices.

At the level of electrical devices, multiple solutions have been proposed in the literature to handle the problem of transients. Two major approaches are Variable Frequency Drives (VFDs) and Internet of Things (IoT) architecture.

Mostly electro-mechanical drive systems use variable frequency drives (VFD) are. VFD is a type of variable-speed drive which is used to control AC motor speed and torque by changing motor input frequency and voltage. Usually, VFDs are used in compressor-based devices. However, VFDs have been utilized to solve the problem of transients in PV systems in some recent efforts [11]. In this effort, a combo of VFD is designed with an inverter and a DC bus. The VFD controls the flow of energy to the grid using a DC bus. This solution is elegant, but it has a price tag of minimum $150 per device.

Another problem with the use of VFDs and similar solutions is that not all of the legacy devices can be shifted to VFDs because of their hardware restrictions. In a case of VFDs the device needs to be redesigned for making it compatible with a particular solution. In comparison, the method proposed in this paper acts as a black box/extra layer to the traditional household devices. It indicates the feasibility of the proposed system to be compatible with legacy device [1] of any model. In order to point out the feasibility of the proposed system, it can be seen from Ref. [12] that in Pakistan, 3.8% new air-conditioners are bought every year. Some of them are replacements of the legacy air-conditioners. With this rate, it is expected to take decades before all the legacy air-conditioners are replaced with newer technologies. Although the number of legacy devices is decreasing this large number necessitates the solution to run these devices on small-scale renewable energy systems. Hence, the closest solution to this problem, VFDs, is applicable in limited scenarios.

Internet of Things (IoT) is also used for handling the transient spikes problem where devices form an ad-hoc mesh network and can communicate (through messages) to each other of an upcoming spike. As a result, multiple devices do not start at the same time [13] and PV output limit will not be breachable. However, since transient spikes come for a very short duration, communication delays and packet loss due to network congestions can miss these spikes. In addition to this, some over-provisioning of solar PV system is still needed in the system to accommodate the transient spikes of even a single device.

Other than VFDs and IoT, solutions to the problem of transients are the usage of better optimization and scheduling techniques like linear and dynamic programming. Such optimizations usually help in better management of available solar PV energy but have not been used to solve the transient problem completely [14,15].

To summarize, the state-of-the-art solutions to handle transients are either expensive or inefficient. Furthermore, except in VFDs, all the other solutions require some form of extra PV energy or batteries to accommodate transients spikes which result in high cost of solar PV system.

3. Motivation and problem statement

One of the reasons why PV systems are not attractive to many consumers is that many conventional devices are not able to operate on a smaller PV system because of their capacitive and inductive behavior. This is due to the higher transient power that these devices require in their startup cycle. All inductive and capacitive devices have transients [16]. While the normal energy consumption of many such devices is well within the range of the PV systems, yet these devices could not be operated on PV systems because of short interval transients or spikes. An example is given in Table 1 to understand this behavior.

It can be observed that the energy spike of an air-conditioner is almost 200% of its normal energy consumption and lasts for few seconds only as shown in Fig. 1. Consequently, if one has to operate an air conditioner using solar energy, the system has to be designed for maximum energy spike of the air-conditioner which significantly adds to the upfront and maintenance cost of the whole PV system. To us, this increased investment is a major factor that hinders the adoption of solar energy in developing countries. Moreover, one may over-design the PV system to accommodate one such device but even if we have sufficient energy in the PV to cater for one transient it is possible at times when multiple devices are in their transient state and may cause the whole energy system of the building to trip. For this reason, adding more capacity or adding more batteries to the PV system is not a feasible solution to the problem of transients spikes.

Furthermore, if one adds extra capacity to the PV system, the excess capacity remains underutilized for the most part. For example, Fig. 2 is the usage graph of a building with 4 kWh, which shows the mismatch between energy harvesting and energy consumption [17]. Only one traditional room air conditioner of around 1.8 kW can be operated on this system. Apparently, other devices could also be operated on this PV system, but the transient spikes of one room air conditioner make it difficult for other devices to operate on this system properly. Though, overall building is only able to consume around 40% of the energy that is generated

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[1] Device and Appliance are used interchangeably in this paper.

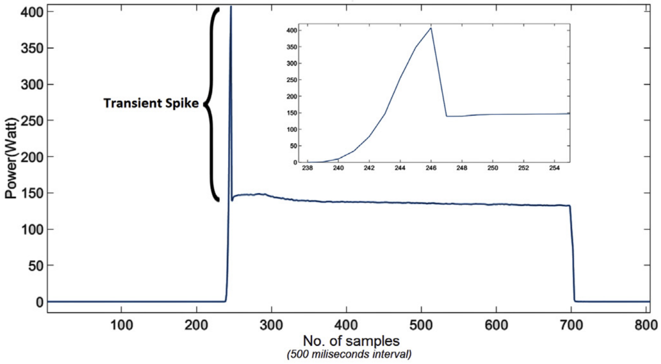
Table 1
Appliances power consumption.

Appliance	Stable Power (Watts)	Transient Power (Watts)	Transient Time (ms)
Refrigerator	150	350	2900
Washer	250	1150	1200
AC	1800	3200	3800

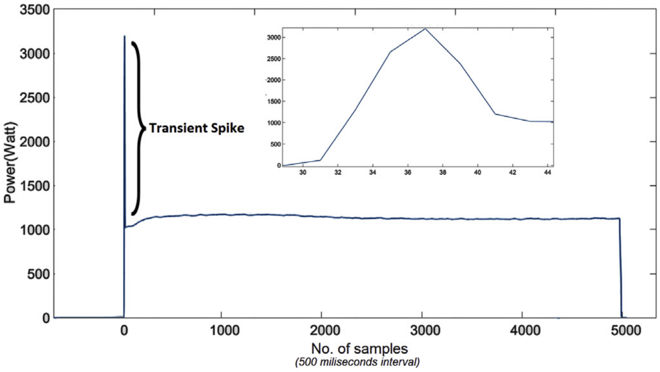
through PV.

Therefore, if one finds a way to handle the spikes of the capacitive and inductive devices, these devices could be operated on smaller PV systems. It will not only reduce the upfront and maintenance cost, but also the consumers may be able to use multiple electrical devices having higher transient spikes at the same time on a smaller solar PV system.

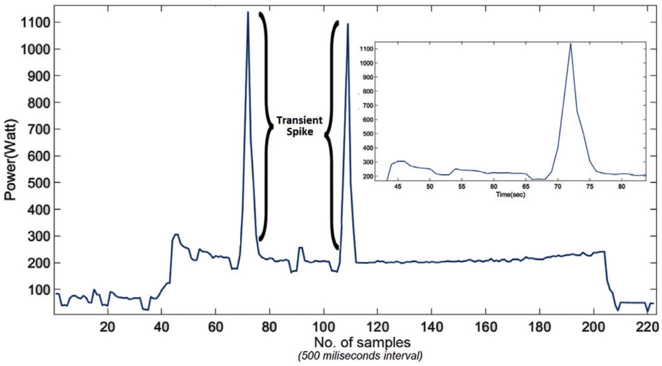
One way to solve this problem is that at places where the electrical grid (utility supply) is available, the devices could be shifted from PV to utility supply when a transient approaches. However, with the current Solar PV system models, this is difficult. Because the PV and utility supply are connected at the inverter-level at one central distribution point. The individual devices get the energy from the inverter. Thus, devices cannot be controlled fast enough to make the switch between PV and utility supply.



(a) Refrigerator



(b) Air Conditioner



(c) Clothes Washer

Fig. 1. Transients in different type of appliances.

4. Transient detection using Smart Switch and Outlier Detection Algorithm

As described in the earlier sections, electrical devices especially ones with capacitive and inductive characteristics have transients in their energy profile [16]. These transients make some of these devices inoperable on small PV systems [11]. For this purpose, Smart Switch is instrumented to detect the instantaneous state of devices and make a selection between PV and grid to accommodate transient spikes. Further details of Smart Switch is discussed in the next section. To this end, a transient detection algorithm is implemented in the Smart Switch. This algorithm is named as Outlier Detection Algorithm (ODA) as shown in Algorithm 1. ODA is a modified version of more commonly known Incremental Hyper Ellipsoid Algorithm (HEA) [6]. It processes the energy readings coming from power meter of a device at a rate of 20 samples per seconds and detects any transients in the power profile of the device. Note that this power meter is a part of the Smart Switch.

As transients could come at any moment during the device's operation. Therefore, it is not possible to forecast and model the occurrence of the transients using simulations. Moreover, transients occur in a very short period. Therefore, we have to devise a mechanism that detects transients and switch the power source to utility supply before the transient crosses a threshold to avoid the tripping of PV system.

In the Hyper Ellipsoidal Algorithm (HEA), the statistical trend of the data is observed to detect the deviation of the data from the normal trend. The reason for using HEA is that not every little deviation is an outlier that should cause the energy source to be changed-over. Instead, we need to look at the statistically significant change that may indicate the start of a transient. Another reason for using HEA is that it is a general purpose algorithm. Indeed we would not like to design a separate algorithm for each type of device. The algorithm works in the following way:

Let $P_N = p_1, p_2, \ldots, p_N$ be the first N values of power stored in an array of readings stored locally in the microcontroller of the Smart Switch. The word array of readings here is used to follow the jargon of the Data Mining community that specializes in clustering algorithms.

'N' in this case is the size of the array. So when the local smart switch is first turned ON, 'N' values are added to the array at the onset of this algorithm. The array mean/average (m_N) and

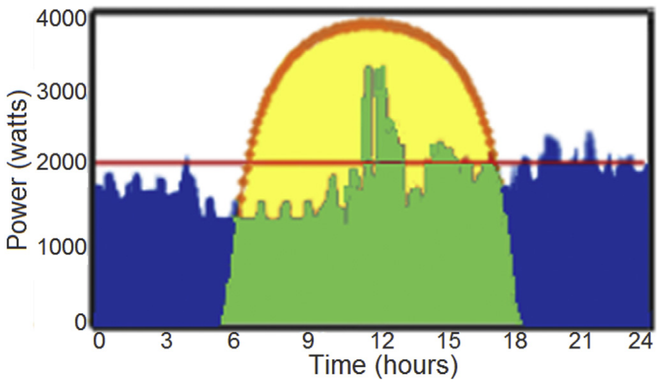


Fig. 2. Average utilization of a typical solar PV system without buyback program w.r.t energy harvesting over one day.

covariance (S_N) of the data coming from the load profiles of each array are then calculated using the equation given below:

$$m_N = \frac{1}{N}\sum_{i=1}^{n} p_i \tag{1}$$

$$S_N = \frac{1}{N-1}\sum_{i=1}^{n}(p_i - m_N)(p_i - m_N)^T \tag{2}$$

To define the boundary of the array, Mahalanobis Distance [6] is used. Mahalanobis Distance (e_N) determines the boundary of the array and is defined as follows:

$$e_N = (p_n - m_N)^T S_N^{-1}(p_n - m_N) \tag{3}$$

The incoming data point is considered an outlier if it satisfies the following equation:

$$(p_n - m_N)^T S_N^{-}(p_n - m_N) > t^2 \tag{4}$$

From the equation, it can be observed that the Mahalanobis distance of the new incoming power value should be less than t^2 for a data point to be considered a normal value. ‘t’ is dependent upon the normal distribution of the data. If the normal data follows a chi-squared distribution, then the boundary of $t^2 = ((X_d^2)_p)^{-1}$ captures 98% of the data [6].

After the array is complete, a new power value is added into the array in the following way. The incoming power value is first checked using (4) If the value is an outlier, then a weight is given to the current power value p_{n+1} and the previous value is replaced in the array. For the case that the value p_{n+1} is not an outlier, then following equations are used for updating the mean and inverse covariance of the array:

$$m_{n+1} = \frac{nm_n + p_{n+1}}{n+1} \tag{5}$$

$$S_{n+1}^{-1} = \frac{nS_n^{-1}}{n-1}[I - X] \tag{6}$$

where:

$$X = \frac{(p_{n+1} - m_n)(p_{n+1} - m_n)^T S_n^{-1}}{\frac{n^2-1}{n} + (p_{n+1} - m_n)^T S_n^{-1}(p_{n+1} - m_n)} \tag{7}$$

In doing so the power value p_1 is discarded from the stored values in the array and in general, p_i is replaced by p_{i+1} so that space in the array can be made.

Note that (5) and (6) help in getting an iterative elliptical boundary estimation as in Ref. [6]. It makes the algorithm faster compared to processing the mean and inverse covariance of the data again and again which is a time-consuming computation. Thus the algorithm is fast enough to detect any change in milliseconds.

Although the above algorithm is iterative, we need to add the capability to detect minor deviations which are false positive transients. This is needed so that a change in the load profile can also be detected keeping under consideration the previous trend of the load profile. This may be substantial for the devices which have a lot of fluctuations for which the overall mean remains the same, but millisecond level fluctuations may cause the array mean to fluctuate rapidly hence changing the outlier boundary. Giving weight λ to the previous values is one method that can be used in order to add tracking capability. For this purpose, we have used exponential moving average:

$$m_{n+1,\lambda} = \lambda * m_{n,\lambda} + (1-\lambda)p_{n+1} \tag{8}$$

The iterative formula for covariance after adding the forgetting factor lambda becomes:

$$S_{n+1,\lambda} = \frac{\lambda(n-1)}{n}S_{n,\lambda} + Y \tag{9}$$

where:

$$Y = \frac{\left(p_{n+1} - m_{n+1,\lambda}\right)\left(p_{n+1} - m_{n+1,\lambda}\right)^T}{n} \tag{10}$$

After integrating equation (8) into (9) and using matrix inverse lemma just like the one used in recursive least square (RLS) filtering equation, we come up with a formula to directly compute the inverse covariance using previous mean and inverse covariance value as shown below in (11):

$$S_{n+1,\lambda}^{-1} = \frac{nS_{n,\lambda}^{-1}}{\lambda(n-1)}[I - Z] \tag{11}$$

where:

$$Z = \frac{(p_{n+1} - m_n)(p_{n+1} - m_n)^T S_n^{-1}}{\frac{n-1}{n} + (p_{n+1} - m_n)^T S - 1_n (p_{n+1} - m_n)} \tag{12}$$

It should be noted here that all the above derivation is done so that the boundary of the hyper-ellipsoid e_n can be computed efficiently by keeping millisecond level changes in the load profile of a device. All of the equations mentioned above are used in Outlier Detection Algorithm (ODA).

Algorithm 1. *Outlier Detection Algorithm* (*ODA*)

```
Output: Detects the deviation of load profile of the device
while (1) do
    $e_N$ = Update Mahalanobis Distance();
    $m_N$ = Update Mean();
    $S_N^{-1}$ = Update Inverse Covariance();
    if ($e_N < t$) then                    /* t = boundary of cluster */
        outlier = 1;
    else
        outlier = 0;
    end
end
```

5. Integration with solar PV and home area network

In general, grid tied with battery backup or hybrid solar PV systems tie the energy coming from PV and grid at the main electricity distribution point of a building. As mentioned earlier in Section 1, this model of energy distribution works best when the grid is stable, and energy buyback programs are available. In the absence of the option of putting the energy back on the grid or when the feed-in tariff is not attractive, one would like the buildings to maximally utilize the solar PV energy locally. For this purpose, we use the Smart Energy Switching Platform (SESP) that takes the coupling of the solar power and energy from the grid at the device level for more fine-grained utilization of solar energy. Note that this coupling does not mean tie off both sources. This means, changing-over and selection of PV or grid energy at a given time to power the device. It should also be noted that switching between power sources may induce additional transients which are catered by using a zero-crossing circuit which will be explained later in the section. Each single device is connected with SESP individually via a Smart Switch. This separate change-overs of devices at finer level enables us to handle the transients in an efficient way without exhausting the available PV energy. These change-overs of both PV and grid energies are synchronized in such a way that the power requirements of devices are fulfilled during their startup cycle to cater the transient spikes problem.

The architecture of SESP is shown Fig. 3. SESP consists of two main components: 1) Smart Switch(es) and 2) Central Coordinator (CC). There is only one CC in an installation while multiple Smart Switches are connected to it. Using a Smart Switch (diamond shaped symbols) selected devices in the building are connected with two sources of energy i.e. solar PV and grid. Smart Switch is placed with a single electrical device or a cluster of devices to control the source of energy. For heavy electrical devices such as air conditioners or induction motors, a cluster will have one device only.

5.1. Smart Switch and home area network

As mentioned in earlier sections, Smart switches are the change-over point that selects which energy (whether PV or grid) should be used to power-up the device. A smart switch consists of four main components: 1) Zigbee Module 2) Switching Circuit 3) Power Meter and 4) Microcontroller. Fig. 4 shows the block diagram of the Smart Switch. In Fig. 4, the Outlier Detection Algorithm runs locally in the smart switch. The sampling rate of reading the power values is kept high for detecting the transients. The sampling rate and processing capability can be made much faster by using the state of the art processing unit.

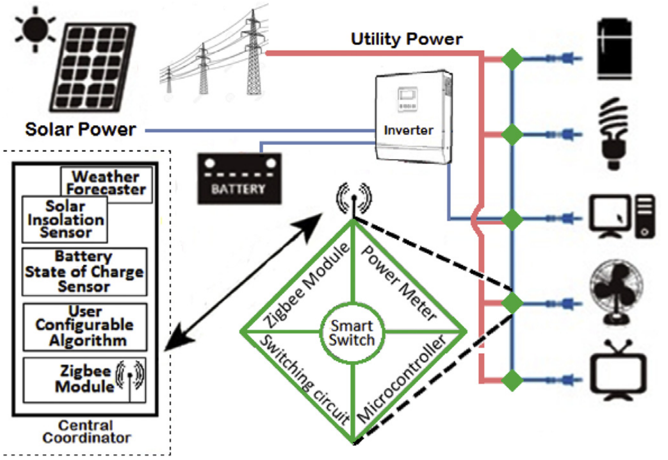


Fig. 3. Smart energy switching platform. (Diamond symbols are Smart Switches where energy from solar and energy from the grid is coupled).

The SESP is an added layer of the traditional hierarchy of the solar PV setup. The benefit is that we do not need to design the system according to a particular device as in a case of VFDs (for which the device has to be made for it to work on VFD implementation). The proposed platform acts as a black box between the solar PV and load. The only addition is that the proposed black box can switch between the main grid and solar PV. This can easily be integrated into the traditional proposed HAN for smart grids. The only addition is the processing unit for a faster sampling of the power readings. Note that these are not the readings from the smart meter instead this is a power meter associated with each smart switch. Switching power sources cause the power spikes which is solved by using the zero crossing circuit. Next, we describe the architecture and components of the Smart Switch and SESP.

5.1.1. Zigbee Module

All type of communication is done using Zigbee protocol. For this, we used CC2530ZDK kit [18]. It constantly communicates with the central coordinator node and receives signals back from it to decide whether the energy source of the cluster [2] should be shifted or not.

5.1.2. Switching circuit

Switching circuit is used to switch between the two power sources as well as to turn the device on/off. During switching, from solar PV to utility supply and vice versa, the circuit has to be designed while taking care of the zero crossing phenomenon. As we know that, we should take care of zero crossing when clipping the waveform as it could be problematic. In the absence of zero crossing circuit, the switching of sources may result in excess power consumption instead of controlling and limiting it [19]. As a result, instead of lower down the transient spike, it will be doubled. For this purpose, we have used zero-crossing solid-state relays in our switching circuit to avoid this problem [20].

5.1.3. Microcontroller

A sensitive microcontroller e.g. PIC 18F45 or ATMEGA 128 is used to process the energy value of the device as reported by the power meter of Smart Switch. Instantaneous power is measured by the power meter at 20 samples per second. However, the energy consumption information is communicated to the coordinator node after each second to minimize network load. An Outlier Detection Algorithm (ODA) has been programmed in this microcontroller for catering transient spikes. The explanation of this algorithm is defined in next section.

5.1.4. Power meter

To keep the cost of the power meter to as low as possible, we have designed the power meter using very basic components in our research lab and integrated it in Smart Switch. The power meter measures the instantaneous real power, RMS voltage and RMS current of the appliance with sufficient accuracy. More details of this power meter are discussed in Ref. [21].

5.2. Central coordinator

Energy measurements of all devices with the help of Smart Switches using Zigbee modules, real-time information of solar PV

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[2] The devices and clusters arrangement depends on the needs of the system. One cluster can have multiple low-power devices or a single high-power device.

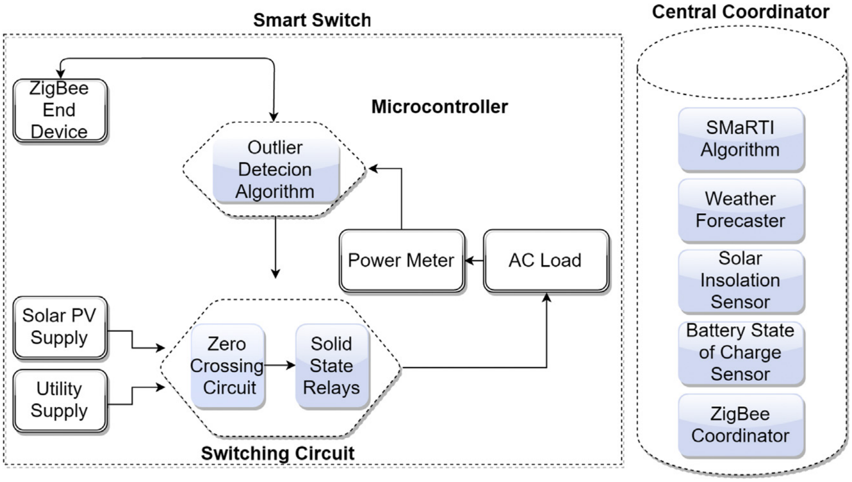


Fig. 4. Smart Switch block diagram.

production and state of charge (SOC) of batteries are communicated to the Central Coordinator (CC). All the information is processed with the help of an algorithm called SMaRTI to decide which power source (either PV or utility) should be selected by a specific cluster. More details on the SMaRTI is discussed in Ref. [7]. CC also has a weather forecaster that predicts the solar insolation of next few hours and next day and the using publicly available weather information [22]. Additionally, CC also has a solar insolation sensor that provides information about the solar energy generation potential at a given the time of day.

In CC the users may also set priorities for the required state of charge (SOC) of batteries, or priorities of devices running on clusters. Based on these priorities, CC tries to maximize the usage of solar energy amongst the device clusters.

5.3. SESP operation

Assume, all of the clusters are powered by grid supply in the start. The SESP works in the following manner: At sunrise, the system starts sensing the solar energy production. Central coordinator keeps a continuously updated and sorted list of energy usage information from all clusters. As soon as the solar energy production is enough to switch the least energy consuming cluster its energy source is shifted from utility supply to solar PV. The Central coordinator sends a control signal to a Smart Switch to change the source of energy for the cluster. Based on a user-defined time interval the central controller checks the solar energy production and tries to match with a combination of clusters to maximally utilize the solar energy and shifting the clusters from utility supply to PV. Also, the central controller stores a minimum buffer of energy in the batteries to meet any random shortfall of solar energy production for a brief period.

A practical implementation of SESP is shown in Fig. 5. It can be observed that on a sunny day, how clusters are adjusted automatically on a real-time basis in a building with six clusters of varying profiles, for example. In Fig. 5, one can note that as soon as the solar energy is available at sunrise, one or more clusters are shifted to solar energy. After a given time interval a new set of clusters is shifted to solar energy. This process continues until sunset. A reader should note here that from sunset to sunrise, all of the clusters are shifted to utility supply due to the absence of PV energy. The solar energy usage is almost the same as the solar insolation curve. Thus, at the end of the day, the efficiency of solar energy production in this particular building is more than 97% of the available solar insolation. A step by step description of how the algorithm works is given below.

Step 1: Initialize the system with all clusters running on Utility.

Step 2: While there is daylight, get the current Solar PV output (P_s).

Step 3: Get the current energy consumption of clusters.

Step 4: Select the combination from the clusters that minimizes $P_s - P_{cluster}$, where $P_{cluster}$ is the power needed for selected cluster. Note that the cluster selection is iterative by exhausting all the combinations of devices to form the cluster which gives minimum value of the difference between solar PV output and the i^{th} contender combination of devices to be shifted on solar PV unit.

Step 5: Wait for user-defined time and go to Step 2.

Step 6: When there is no daylight, transfer all the clusters to Utility again.

Next we compare the cost of ownership of SESP system with traditional PV and Utility. For this comparison, we assume a building which requires 0.16 million kWh of energy over ten years. The building requires energy mostly in daytime. Assuming average rate of $0.24 per kWh over ten years, the Utility energy would cost around $38,000. Traditional PV which consumes 70% of PV energy and 30% of Utility energy would cost around $37,000. This PV system is designed to provide 9 h of energy throughout the year. Therefore, the requirement of more battery banks and associated equipment; extra PV panels, has increased the price of the system significantly. Our system, SESP, for the same ten years would cost around $20,000. SESP consumes 90% PV energy and 10% Utility energy. Thus the cost of ownership over ten years has reduced by more than 40% in comparison to Utility or Traditional solar PV. The cost of ownership of SESP includes the capital, maintenance and running cost of the system for the whole time period.

To summarize, the SESP can bring the cost of the system down by about 42% even after adding the cost of Smart Switches and related electric wiring. Further, the payback period of a solar energy system is down from nine to seven years. This reduction in cost and payback period is possible by reducing the number of batteries required in the system which in turn reduces the maintenance cost of the system. Also, using SESP, one does not need expensive MPPT hybrid inverters and can use the PWM off-grid inverters which are available in half the price [7].

5.4. Switching energy sources

In this section, the calculations done by Outlier Detection Algorithm (ODA) are further processed. In this regard, we proposed another algorithm called Energy Switch Algorithm (ESA) given in

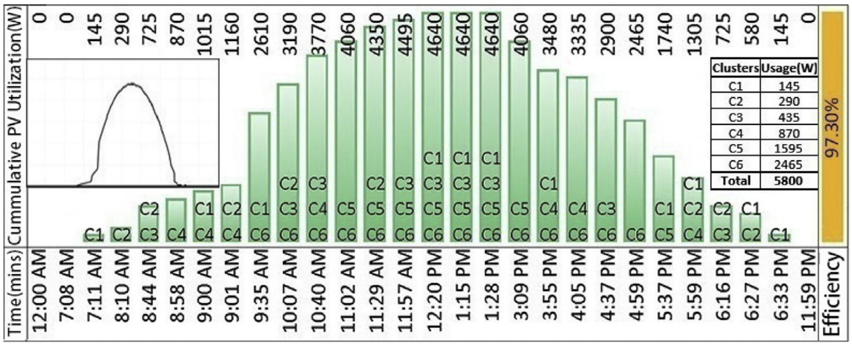


Fig. 5. PV utilization using SESP on a typical sunny day. Six clusters are used in this scenario.

Algorithm 2. This algorithm has direct control over the hardware of Smart Switch. In other words, the ESA is a bridge between ODA and the hardware of Smart Switch.

Here, the working of Energy Switching Algorithm is explained. Let's suppose, the system in its normal state and waiting for the signal of an outlier being detected. In doing so, if the required power need of a device is less than the generated power that solar PV, then the load is put on solar PV. If the load is beyond the generating power of PV, it will be put on the utility supply. Given that the load is getting power from solar PV at a specific time and if a transient is detected. As pointed out earlier that if the system may detect a change that may not be a transient. Then SESP, in this case, is still required to change-over to utility supply because one cannot be sure whether the change will lead to transient or the final state that can be catered by the power from solar PV system. The idea is to detect the transient at millisecond level granularity.

Algorithm 2. *Energy Switching Algorithm* (*ESA*) *with SESP*

```
Result: Switching of power between main utility and solar PV
while (1) do
    if $outlier == 1$ && $S_PV == 1$ then
        $S_{PV} = 0$                      /* $S_{PV}$ = Solar Output Switch */
        $U_S = 1$                         /* $U_S$ = Utility Supply Switch */
    else if $P_D < P_S$ then /* $P_D$ = Power required by device, $P_S$ = Power
    Generated by Solar                                                      */
        $S_{PV} = 1$
        $U_S = 0$
end
```

6. Evaluation

The applicability of our proposed approach is heavily dependent on three factors: The first one is the detection of outliers by the Outlier Detection Algorithm (ODA). The second one is the capability of the microcontroller to process the value fast enough to detect a spike in time. Finally, the third one is the time to be taken by the solid state relay to switch the power source once an outlier is detected.

6.1. Experimental setup

To evaluate the performance of our system, we have implemented a testbed to simulate the working of the conventional device. The test bed can be used to generate a waveform to depict the behavior of a transient load. Also, we have used two publicly available datasets to substantiate our results. In doing do we have also integrated a signal generator so that waveforms of small granularity can be generated? The primary use of this testbed is to generate real-time waveforms which also depict the transient behavior of a device. Note that we are going to show results for single unit air-conditioner, refrigerator, and clothes washer only on which we tested the ODA algorithm. We have evaluated our approach on these devices because these are the most common electrical appliances used in households especially in hot climates. Furthermore, these three devices are the main cause of the transients among the household devices due to which the solar PV system is over-designed and gets expensive.

6.2. Results using signal generator

Our goal is to evaluate if the Smart Switch which consists of the ODA, the microcontroller, and the solid state relay can make the switch between the two power sources at the onset of the transient. The evaluation setup consists of a pulse generator and an oscilloscope, which are connected to Smart Switch as a load. As it is discussed in Table 1, the transient time varies from 120 ms to 380 ms. We used a signal generator to generate a pulse having similar characteristics as of a transient. In our results, the transient pulse is detected within 60 ms by the microcontroller using the ODA. The solid-state relay takes another 200 ns to make the switch between the power sources [23]. Together from the detection of the transient to the change-over, it takes less than 60 ms. This means, for most of the devices which have low gradient transients such as air conditioner and refrigerator the changeover will take place in time to avoid the transient spike. In short, our system works for common legacy devices such as air-conditioners and refrigerators.

6.3. Results using energy datasets

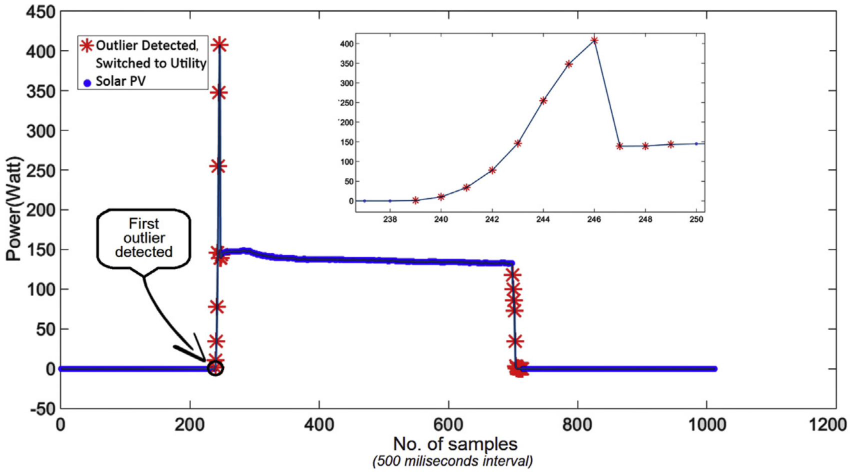
For evaluating our proposed Outlier Detection Algorithm (ODA), we have modified granularity of publicly available datasets [24–26]. We have multiple runs of ODA on three inductive devices namely air conditioner, refrigerator and clothes washer. The time granularity of the dataset is 500 ms for energy sampling. This time granularity is chosen to see the effectiveness of the algorithm in real settings. The results of the ODA are shown in Fig. 6. The straight horizontal line in the figure is the threshold value under which no switching should take place.

For the refrigerator in Fig. 6a the algorithm can detect the transient at around 239th sample of the refrigerator's operation. The circled star on the power profile is where the algorithm detected and reported a transient. After that, it continues to report the next few values as transients. This reporting of transients will continue until the values are back to stable power (switching power sources is one time). Note that this kind of transient detection cannot be performed by simple thresholding of power values because devices stabilize their energy values differently. To avoid this problem, the algorithm changed over the device to utility supply after detecting the first transient spike.

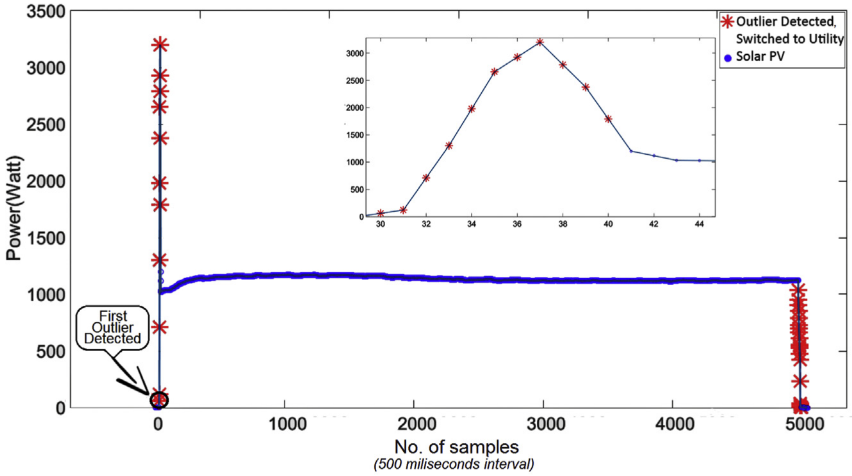
Solid state relays can perform this operation in less than 200 ns. Similarly, the algorithm again detects a transient at around 700th sample of power profile. However, this transient spike comes due to the tripping of the compressor of a device when the compressor of the refrigerator is turned off. As the power consumption of the device is being reduced. Thus, no switching will take place which is also mentioned Algorithm 1.

In Fig. 6b, an air conditioner's power measurement and all types of transients spikes are shown. Note that this is a non-inverter single unit legacy room air conditioner and draws around 200% of its normal energy in its transient phase. In this scenario, similar detection and changing-over will take place as in a refrigerator.

An interesting case of evaluating ODA is on energy usage of a Clothes Washer as shown in Fig. 7. In this case, the outliers are detected by ODA even before the real spike. To handle such situation we have calculated threshold value of power under which no changeover will take place even if an outlier is detected. The threshold value is calculated as a factor of the available PV energy. Thus, if the transient is detected under the threshold value, the changeover will not take place. However, if the transient is more than the threshold value, then the device will be shifted to the utility supply. One more thing to note is that the second transient traditional to legacy devices also detected by the ODA. For VFDs, the



(a) Refrigerator



(b) Air Conditioner

Fig. 6. Transient detection in inductive loads.

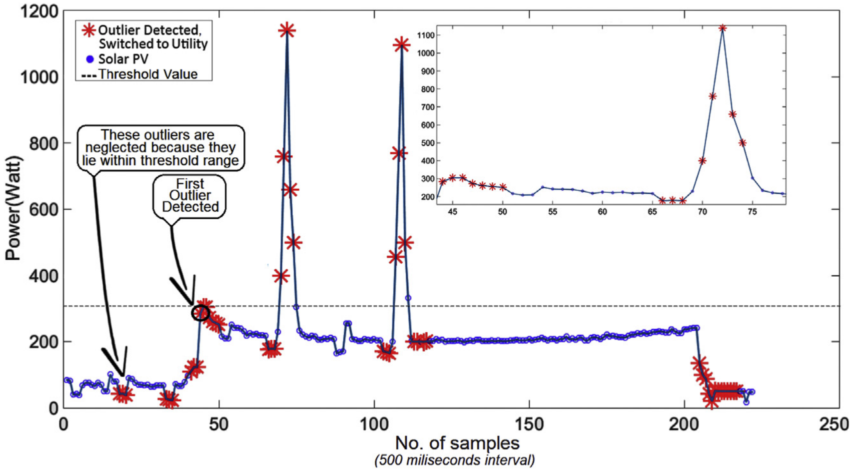


Fig. 7. Transient detection in a clothes washer using threshold value.

whole device needs to be redesigned and also the VFD used will be specific to that particular device whereas our approach can be treated as a black box to any legacy device just like an added stack/layer to a system.

7. Conclusion

In this paper, an alternate solution for PV usage at places with limited or non-existent energy buyback programs is presented to operate high-powered legacy appliances. Our proposed approach can maximize the solar energy output by decentralizing the PV energy and using Outlier Detection Algorithm to detect transients. This decentralization gives many advantages. One advantage is that the PV system is separate from the utility supply, but at a finer level. Thus, the PV system will efficiently use the maximum solar energy available. Moreover, the platform can also be configured according to the need of any building. A minimum battery bank is needed if the usage of the consumer is mostly during daytime.

With our method, electrical devices that otherwise needed over designed PV, can now be operated on PV with the minimum battery bank. Transient detection allows us to shift the transient load to the utility supply. The load consumes power from the main grid until it reaches back to stable state conditions after which the load is shifted back to solar PV with the help of the zero crossing circuit to prevent power spikes.

In future, we plan to extend the SESP to multiple buildings in the neighborhood as well, to form an energy co-op. In this way, even better PV utilization is expected. But more importantly, this will also provide us the possibility to run the devices having inductive and capacitive characteristics on PV, and even if the grid is not available.

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