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A Collaborative Approach to Operate High Powered Devices on Small-scale PV systems

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Abstract

The world needs renewable energy for the long-term future. One of the most promising renewable energy solar PV is ideal for buildings and rooftop. However, the uptake of solar PV in developing countries is rather slow. Mostly because it is expensive but also because heavy electrical appliances cannot be operated on small scale PV systems. In this paper, we present an approach to operate high powered devices on small-scale PV systems. In our approach, we have designed a platform called Smart Energy Switching Platform (SESP). A software layer on top of SESP allows the devices to follow a collaborative scheme where high power devices are moved to an on-state if enough power is available. With this approach, multiple high powered devices with transients can be operated with a smaller PV system. We have evaluated our approach using many simulation scenarios and has presented a case study to describe the working of the system.

Keywords: solar PV optimization;home area network;home energy management;simulation;

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1. Introduction

Fossil fuel resources are depleting. Therefore, in the coming years, renewable energy resources will be needed on a greater scale to fulfill the energy requirements of the world. However, the renewable energy such as solar PV is still an expensive affair in the developing countries. Also, due to its limited capability to run heavy electrical devices such as air conditioners, solar PVs are not commonly in buildings as an energy source. To run this type of electrical devices the PV system has to be designed in a such a way that it can sustain the maximum power needed by them. The maximum power required by heavy electrical devices depends on their type. For air conditioners or other cooling devices such as refrigerators and deep freezers the maximum instantaneous power is determined by short transients. These short transients may occur for only a few seconds but require multiple times more power than the stable power requirement of a given appliance. Moreover, if multiple electrical appliances need to run using PV, then the cost of PV increases further.

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To us, the acceptability of PV systems would enhance if heavy duty electrical devices can operate on PV systems on buildings. However, the traditional PV architectures cannot readily run heavy electrical appliances on PV. Therefore, in this paper, we describe a newly proposed design of PV called Smart Energy Switching Platform (SESP). Using this platform we develop algorithms that would help us in operating heavy electrical devices on PV.

In the rest of the paper, we first describe the hardware architecture Smart Energy Switching Platform (SESP). This will be followed by a description of an algorithm that helps us manage heavy duty electrical devices on PV. This is followed by some case studies of the proposed solution. Finally, we conclude the paper with some future work.

2. Smart Energy Switching Platform (SESP)

Most of the rooftop solar PV installations use Hybrid PV systems. Hybrid solar PV systems tie the energy coming from PV and grid at the main electricity distribution point of the building. 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 utilize the solar PV energy locally maximally. For this purpose, we proposed 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. Please 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. Every single device is connected with SESP individually via Smart Switches. These 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 problem.

The architecture of SESP is shown Fig.1. SESP consists of two main components: 1) Smart Switch(es) and 2) Central Coordinator (CC). There is only one CC in an installation that connects multiple Smart Switches with itself. 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.

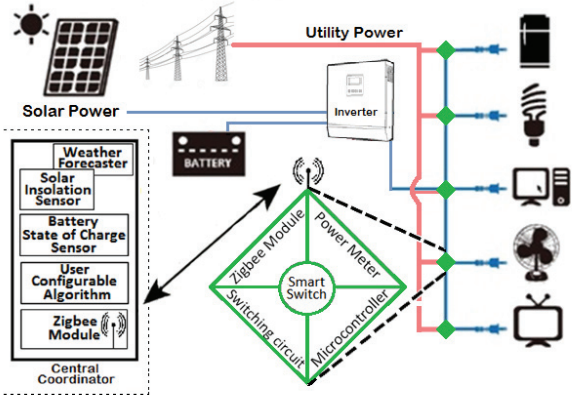


Fig. 1: Smart Energy Switching Platform. (Diamond symbols are Smart Switches where energy from solar and energy from the grid is coupled)

2.1. Smart Switch and Home Area Network

Smart switches are the change-over point that selects which energy(whether PV or grid) should be used to power-up the cluster/device. A smart switch consists of four main components: 1) Zigbee Module 2) Switching Circuit 3)

Power Meter and 4) Microcontroller. Fig. 2 and Fig. 3 shows the block diagram and whole package of the Smart Switch respectively.

2.1.1. *Zigbee Module*

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

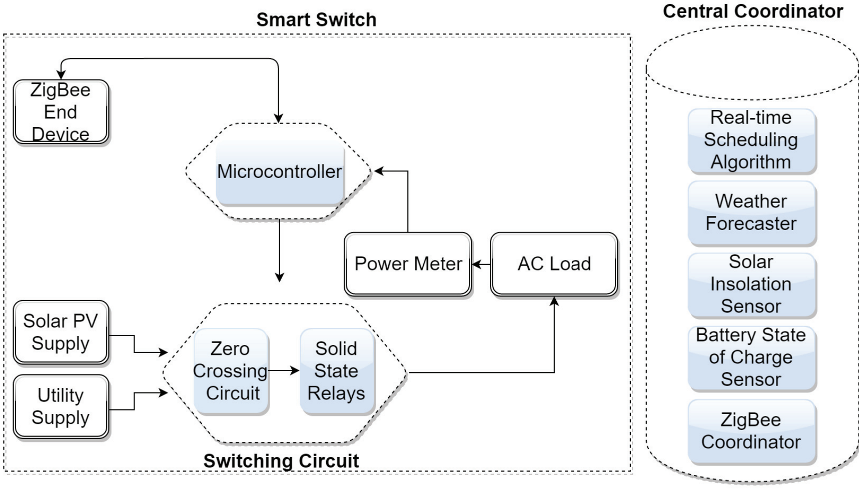
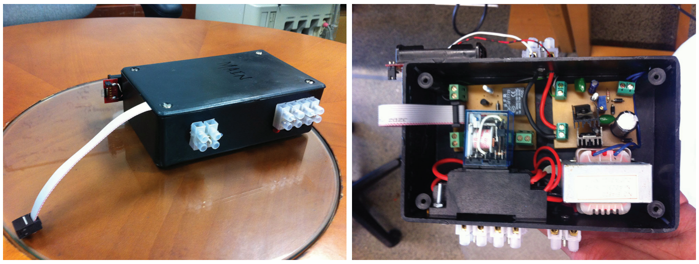


Fig. 2: Smart Switch Block Diagram



(a) Smart Switch Package (b) Smart Switch Circuitry

Fig. 3: Smart Switch

2.1.2. *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 [1]. 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 [2].

2.1.3. 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.

2.1.4. 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 integrate 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 [3].

2.2. Central Coordinator

Energy measurements of all devices with the help of Smart Switches using Zigbee modules, real-time information of solar PV production and state of charge (SOC) of batteries are communicated to the Central Coordinator. 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 [4]. 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 [5]. Additionally, CC also has a solar insolation sensor that provides information about the solar energy generation potential at a given time of the 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.

3. SESP Operation

Assuming, all of the clusters are powered by utility supply(grid) 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 minimum buffer of energy in the batteries to meet any random shortfall of solar energy production for a brief time period.

A practical implementation of SESP is shown in Fig. 4. It can be observed that on a sunny day, how clusters are adjusted automatically on real-time basis in a building with six clusters of varying profiles, for example. In Fig. 4, 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 are 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 exactly 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. To summarize, the SESP is able to 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 [4].

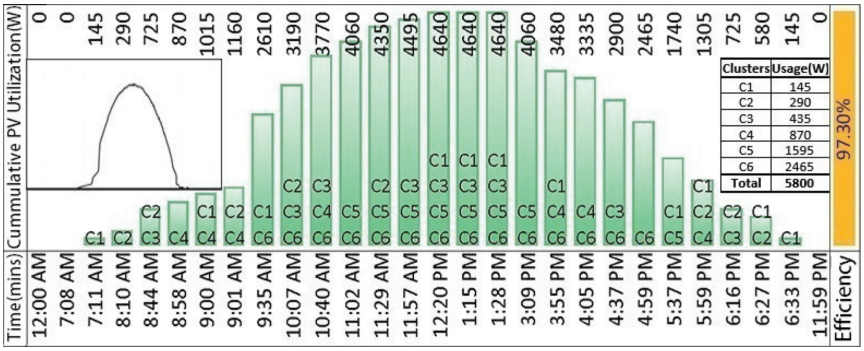
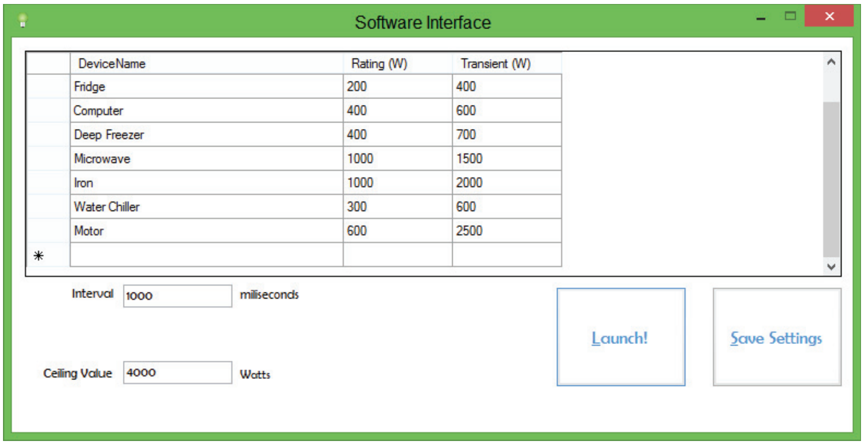


Fig. 4: PV utilization using SESP on a typical sunny day. Six clusters are used in this scenario.

4. Handling Transients using SESP

We have developed a simulation-based software system which can operate and schedule the devices in real-time based on their transient states. This system works in the following way:

First of all, the power ratings of every appliance are calculated along with transient power requirement. Both transient and stable power consumption for each device are entered in the system. The time interval of all transients should also be mentioned.



DeviceName	Rating (W)	Transient (W)
Fridge	200	400
Computer	400	600
Deep Freezer	400	700
Microwave	1000	1500
Iron	1000	2000
Water Chiller	300	600
Motor	600	2500

Interval 1000 milliseconds

Ceiling Value 4000 Watts

Fig. 5: Simulation Interface - Settings window

4.1. Algorithm to Handle Transients in SESP

The algorithm to handle high powered devices is given in Algorithm 1. This algorithm works at the Central Coordinator side. The input to this algorithm is the sorted list of power consumption of devices. This input has to be given once. Other inputs to the algorithm include the instantaneous power usage by devices as well as the power produced from the PV system.

This algorithm is monitoring that if a power consumption of device if more than the generated power of PV then it will be shifted to the utility. Whenever a device is turned on it is by default run on the utility so that its transient does not affect the PV system. However, if the PV system has enough power to handle the transient, then the device is turned on using the PV system. Once the transient finishes it is switched back to the PV if enough PV power is available at the given time. When multiple devices are in the system, then the algorithm makes sure that all of these devices do not turn on at the same time. It performs the turning on and off in a scheduled way so that the transients do not affect the PV system. Again if the PV has enough generated power to handle the transient, then it turns it on using PV otherwise use the utility power to turn the device on for the transient period.

Algorithm 1: Real-time Scheduling Algorithm

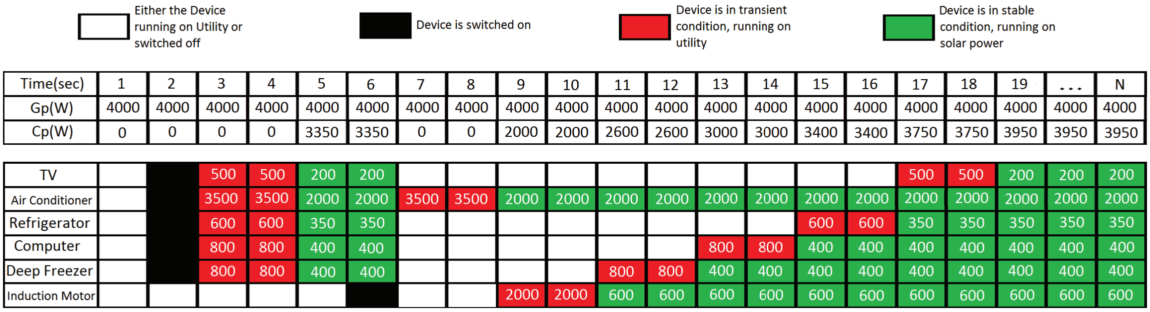
```
Data: Sorted list of devices including their power consumption
Result: Real-time scheduling of devices on the basis of their transient/high spikes times
Input: $G_p$=instantaneous generated power
        $C_p$=instantaneous cumulative consuming power of all devices
        $C_{p,i}$=instantaneous power consumption of each device $D_i$
initialization;
for $t \leftarrow 0$ to $n$ do                                         /* t = time */
    if ($C_{p,i}$ &$C_p$<$G_p$ ) then
        switch to solar;
    else if ($C_{p,i}$ <$G_p$||$C_p$>$G_p$) then
        all devices switch to utility;
        $D_1$ is turned on;
        run on utility until it gets stable;    /* stable means normal device power consumption */
        switch the $D_1$ to solar;
        .
        .
        .
        $D_N$ is turned on;
        run on utility until it gets stable;    /* stable means normal device power consumption */
        switch the $D_N$ to solar;
        Do until $C_P \geq G_P$;
    else if ($C_{p,i}$ >$G_p$) then
        remain on utility;
    else
        switch all devices to utility;                         /* default condition */
    end
end
```

5. Evaluation

To evaluate our proposed architecture we have developed a case study. This case study has a PV system that is capable of producing around 4KW peak power for a building. The six devices in the building with their normal power requirements as well as transients are TV (200, 500), Air conditioner (2000, 3500), Refrigerator (350, 600), computer (400, 800), deep freezer (400, 800) and induction motor (600, 2000).

5.1. Case Study

In this case study, a 4kW PV system is considered and ideally it is producing its peak power i.e. 4kW, although this number could be any number under 4kW depending on the time of the day as well as weather factors. The Fig. 6 shows the time quantum of 5 seconds for each column. In the first 5 seconds, no device is turned on in the system. In the second time quantum, five devices are requesting to turn on. Since the total transient power needed by these devices is less than the PV power the devices are not shifted to utility and are turned on using the PV power. In the third time quantum, the devices are actually turned on by SESP after ensuring that enough power is available to meet their demand.



☐ Either the Device running on Utility or switched off

⬛ Device is switched on

🟥 Device is in transient condition, running on utility

🟩 Device is in stable condition, running on solar power

Time(sec)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	...	N
Gp(W)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Cp(W)	0	0	0	0	3350	3350	0	0	2000	2000	2600	2600	3000	3000	3400	3400	3750	3750	3950	3950	3950

TV		⬛	500	500	200	200											500	500	200	200	200
Air Conditioner		⬛	3500	3500	2000	2000	3500	3500	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Refrigerator		⬛	600	600	350	350									600	600	350	350	350	350	350
Computer		⬛	800	800	400	400							800	800	400	400	400	400	400	400	400
Deep Freezer		⬛	800	800	400	400					800	800	400	400	400	400	400	400	400	400	400
Induction Motor						⬛			2000	2000	600	600	600	600	600	600	600	600	600	600	600

Fig. 6: Real-time Scheduling of Devices with respect to time quantum

It can be seen that, in the 4th and 5th time quantum, these devices stabilizes and by the 6th quantum all five devices are using normal power. However, in the sixth quantum, the induction motor is requesting to be turned on. Since the sum of the transient of an induction motor and the five devices is more than the required power there are two solutions possible. Either to shift the induction motor to a utility for the transient or turn off the five devices and use the PV power solely to turn-on the induction motor. The second option is needed in places where the grid is unreliable. Another reason for having this possibility is to use our proposed architecture in off-grid environments. The graphical representation of this case study is given in Fig. 7.

Therefore, if the second option is used, the five devices are turned off for a brief period while the air-conditioner (AC) stabilizes. Once it stabilizes, the other five devices are turned on one by one starting from the one with the highest transient. If the total power exceeds the PV output the transient is shifted to the utility, but if the utility is not available this device will not be turned on until induction motor completes its job and is turned off.

The five devices will be turned on one after the another. Finally, at the 19th time quantum all devices are in their stable state and are being run on PV power. We are assuming that the transient of these devices will come only during the startup phase. However, this is seldom true in reality. Most devices with thermostats have compressors that turn on and off regularly. To handle such a scenario whenever a transient is imperative, the device will request SESP to go into a transient state. If SESP algorithm finds enough power it will give the signal to the device to turn on. However, if the transient requires more power than the device is either shifted to the utility or is started after turning off some of the other devices. The turning off of the device is something that a user can control such as TV so that there is no disturbance as much as possible in the quality of life of the user.

6. 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 are able to combine the voltage from the grid and PV. But in a case of an unstable grid with voltage fluctuations, this combination is not possible [6].

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.

Variable Frequency Drives (VFD) are mostly used in electro-mechanical drive systems. 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 [7]. In this effort, a combo of VFD is designed with an inverter and a

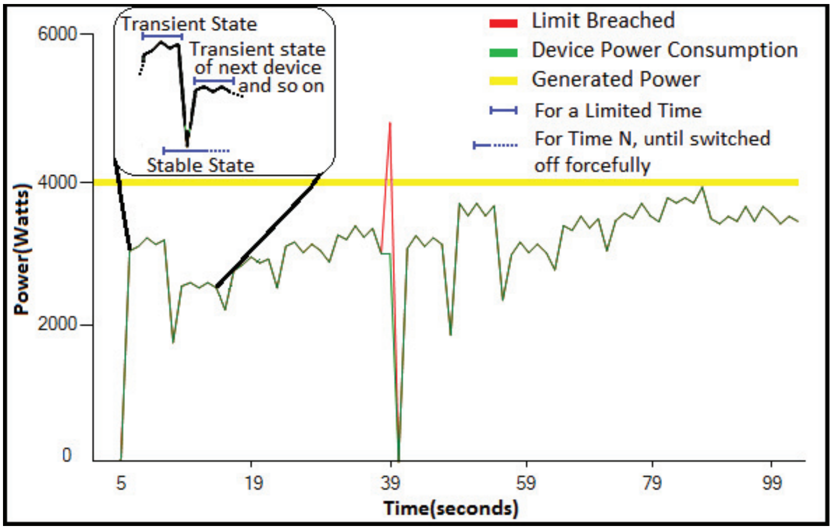


Fig. 7: Graphical representation of real-time scheduling of the devices. The zoomed-in view shows the transient stability of a single device followed by transient start of another device.

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. In addition to this, not all of the legacy devices can be shifted to VFDs because of their hardware restrictions. Therefore, Variable Frequency Drives (VFD) although is a solution, but can only be applicable to 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 [8] 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 [9,10]. High-resolution energy modeling is done in [11] and Simulator related to power consumption of several devices are designed in [12]. But both are unable to cater real-time high spikes of high power devices.

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.

7. Conclusion

The proposed solution has been shown to utilize the maximum output of the renewable energy system without overwhelming the system. To summarize, the over-provisioning of alternate power sources like solar or wind power systems can be avoided by using the collaborative approach mentioned in the paper. By using this approach, one can maximally utilize the solar PV energy.

The future work of this approach is to use this in the off-grid settings. Moreover, this work can be extended to use prioritizing of devices so that even more devices can be operated on small scale PV systems. Another future direction is to make this system work in multi-state modes where devices can go into any power state and utilize as much energy as available. Devices with Variable Frequency Drives (VFDs) are an ideal candidate for this sort of approach.

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