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Predictive source management for low power domestic direct current grids

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ABSTRACT

The decrease in the price of solar photo voltaic (PV) panels has led to the widespread adoption of the solar power as a renewable energy source, not only at the grid level but also on the roof tops of the residential buildings. The solar PV panels produce direct current (DC) and can be readily used to drive DC powered loads or charge batteries. Direct powering of the loads from the solar panels is hindered by the highly variant nature of solar power generation which depends on a number of external as well as internal factors. The paper proposes a prediction based direct connection between PV panel and DC loads, only when the panel will be able to supply the required power to the load. The loads have been categorized based on how they need to be powered and their priority levels. The data specific to the rooftop was collected over two years using which the prediction of the panel output was carried out. Combining the load categorization and the power prediction a smart management system was designed which was able to decide on how the loads need to be powered and hence were connected to the appropriate source.

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1. INTRODUCTION

The demand for adoption of renewable energy sources have been constantly rising. Solar and wind are most widely adopted renewable energy sources across the globe. The cost of solar panels was one of the biggest hindrances in widespread adoption of solar panels around a decade back, but with the rise in demand and the increased production, the cost of power generation from solar panels has seen a decrease by 81% in the past decade [1]. One of the biggest advantages of the photo voltaic (PV) panels is that the generation of power using panels need not always be done at a remote location as is the case with the traditional fossil fuel-based generation. The PV panels can be installed on the rooftops of buildings and the power can be generated from the same. Many governments across globe have been providing incentives to end users, to encourage the use of roof top solar generation, for example government of India has been encouraging the installation of solar PV on roof tops with schemes introduced in banks to provide loans of up to Rs 10 Lakh to individual households. The National Solar Mission, India, has a target of achieving 40 MW of rooftop PV generation by the end of 2022 [2].

The power generated from the rooftop solar panels can be fed to the grid, such systems are called grid connected systems as depicted in the Figure 1. These systems have been studied widely for their benefits, challenges and drawbacks in various locations [3]–[7]. A 50 KW rooftop grid tied system was studied in [8] and the number of years it takes for such a PV system to return the amount invested upon it was derived. The authors note that without considerable government subsidy installation of rooftop PV for resedential users might not appear lucrative enough and might not get adopted in widespread. The grid tied systems have two major disadvantages, one is the requirement to ensure that the power from PV is inverted and made to be in synchronization with the grid power. This leads to the need of additional hardware, which leads to increase in the overall losses as well as the cost of the installation. Another disadvantage of grid tied systems is that the power fed to the grid will under go transmission and distribution losses as part of the grid transmission. The impact of the grid tied PV systems was analyzed in [9], bringing out the advantages and the disadvantages of the grid tied PV systems. Rosyad *et al.* [10] how profitable rooftop installations can be for the end user if he acts as a prosumer and feeds the energy back to the grid.

The second way of utilizing the power of the solar PV panel is to charge a secondary storage device like a battery from the power generated by the panels as shown in the Figure 2. The stored power in the battery can be used to power the loads. This method has also been widely studied [11]–[14]. Selection of the optimal battery for a given rooftop PV generation has been discussed in detail in [15]. An artificial intelligence (AI) based controller for the energy management of systems which have both grids tied systems as well as energy storage has been discussed in [16]. The use of rooftop PV for a specific application of charging the EV was explored in [17]. Making the rooftop PV more lucrative to end users has always been challenging, a method for this is presented in [18], by providing information about the investment and power production using PV through an application for the end users. Alboali *et al.* [19] explore incentives like tax deductions and feed in tariffs to make the roof top installations more attractive to the end users. Various roof top configurations have been discussed in [20] and comparison was made to identify the beneficial configuration for the end users. But the major drawback in using the battery based configuration is the use of alternating current (AC) grid in all the resedntial buildings. The power generated by the solar panels is direct current (DC) in nature which gets stored in the battery and again gets inverted to AC to power the domestic grid. The AC power then gets converted to DC at the loads. The multiple levels of conversion, leads to reduction in efficiency of the overall system.

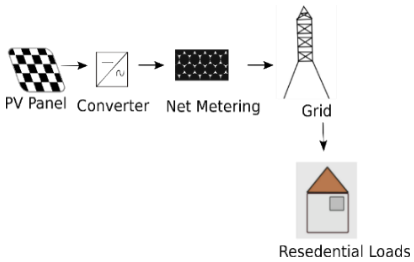

Figure 1. PV panel feeding power to grid

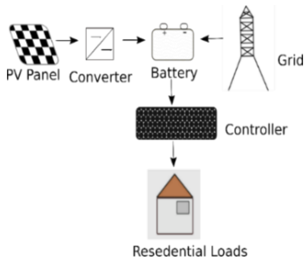

Figure 2. PV panel storing power in a battery

The presence of DC loads in the resedential buildings have grown considerably in the past decade. According to Garbesi *et al.* [21] most of the appliances used in residential buildings today can be replaced by an equvivalent DC load. Glasgo *et al.* [22] have done a detailed analysis regarding the amount of savings that can be achieved by using a DC grid for domestic buildings. The paper clearly indicates that based on the loads choosen to be powered using DC power the amount of savings can vary but overall a domestic building with a DC grid powering the DC loads is more efficient than the traditional AC grid. Various oppurtunities for use of DC in domestic buildings and the challenges faced have been analyzed. The report also lists out the various advantages a DC grid will have over an AC grid for DC loads [23].

The use of solar PV for domestic use and the various ways to optimize its use has been under extensive study in the recent past [24]–[27]. The studies cover various configurations and management systems to make the solar PV advantageous for the domestic use, but not many studies the benefits that might be derived by direct connection between load and the PV panels. To implement DC grids using the PV panels would involve multiple voltage conversions for maintaining the required voltage values at various points. The losses and other disadvantages of converter circuits have been covered under various studies [28]–[31] but none of the studies work on reducing the number of conversions required in a system, which is what is being proposed in this paper. The output power of the PV panels is not always constant and is dependent on various factors, which is a major drawback in direct connection between the PV panel and DC loads. The paper proposes a DC grid as shown in Figure 3, allowing the panels to power the loads directly based on the PV output predictions. The system will predict the approximate amount of power PV panels can generate in the near future based on which the power source for the DC loads can be decided. The loads are also configured based on whether the user wants to power them directly from solar or not. The user can also assign a priority to the loads to decide which loads should be preferably connected to the PV panels. The system will dynamically decide, based on the predictions and configurations, the appropriate power source for the load. The paper derives the approximate savings in power that can be achieved by considering a sample set of loads, giving an idea of actual savings which can be achieved on practical implementation.

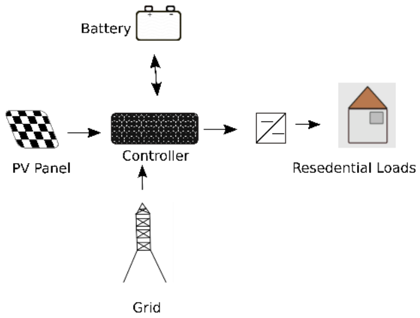

Figure 3. Proposed DC grid

2. METHOD

The power generated by the PV panels being DC in nature can be used to directly power the loads which operate on DC. But the intermittent nature of the solar power generation makes the direct connection unreliable. To be able to ensure that the loads can be powered by the solar panel directly as much as possible we need to be able to predict when the solar panel will be able to generate the power required by the load and only when the panel is able to genreate the required power, the panel should be connected to the load directly. In a resedential building loads present are of different ratings each having its own current and voltage requirements which need to be considered before establishing a direct connection between the panel and the loads. The Figure 4 indicates the overall block diagram of the proposed system.

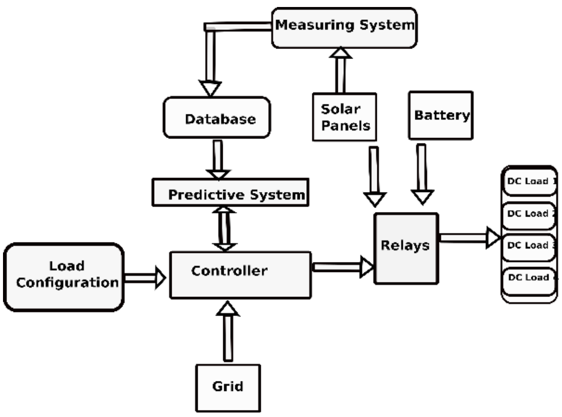

Figure 4. Block diagram of the proposed system

The data of power that the panel has genreated in the past will be required to develop a predicive system, which will be able to provide the approximate power that panels will be able to generate in the future. The power generated by the solar panels is mainly dependent on the solar irradiance and the temprature. The irradiance specific to a geographical location is available from a number of resources, but in the case of rooftop systems the generic irradiance data might not be accurate as there might be other structures present around the roof which might affect the amount of irradiance that will actually fall on the PV panels. To make sure that the panels power generation is recorded specific to the rooftop for which the system was being designed, the data of the power generated by the panel was recorded over a period of two years by installing a data logging system on the roof along with a panel. The recorded data, open circuit voltage, short circuit current, temperature, weather conditions at the location, recoded at the interval of every 5 minutes, was stored in a database and the same would act as the input data for the predictive system.

2.1. Predictive system

The application of machine learning in various applications related to electric grid has seen a steep rise in the recent past [32], [33]. The availability of data, technologies to store the data, techniques and programming languges to make the analysis and prediction easy have been the major factors fuelling the growth. The data of the source power recorded using the data measurement system is continously updated in a database. Regression based random forest algorithm [34] was implemented to utilize this data, analyze the same and provide predictions for the power which can be generated in the near future by the panels at the given rooftop. Every load connected to the predictive systems is associated with a load configuration data, consisting of the parameters listed in Table 1. The load configuration allows the controller to decide when it is appropriate to connect the load directly to solar panel and when should it be connected to the battery. Whenever the prediction of the current and voltage for the PV panel is less than the rated voltage and current for a load, it is not connected to the PV panel, but gets powered from the battery. The user can also decide which load should never be powered from the PV panel by setting the option of direct solar power to “1”. These could be loads which either require a huge amount of power, which panels might fail to supply or loads which user always wants to be driven by battery only.

Table 1. Parameters used for load configuration

Sl no.	Parameter name
1	Max current
2	Max voltage
3	Min current
4	Min voltage
5	Load priority
6	Direct solar power
7	Rate current
8	Rated voltage
9	Priority

To ensure that the loads are powered with the required voltage and current always, a switching circuit is provided for each load. Every load has connections to two battery sources, through switches, one acting as the main battery and the other as the auxiliary battery. The batteries and load are connected to the PV panel through switches as shown in the Figure 5. The switches in turn are controlled by the controller to decide how the load will be powered and how the power of the PV panel will be used. The logic for the switching circuit, for a single load, is provided in the Table 2. It can be noted that load is either powered by the panel or one of the batteries, which will be decided based on the PV panel predicted output as well as instantneous output. If none of the loads are not powered from the panel because the panel is not producing enough power for any of the loads to be powered, then the power genreated from the panels is used to charge the auxiliary batteries. At any given point of time the battery with higher amount of charge acts as the main battery and the other acts as the auxillary battery.

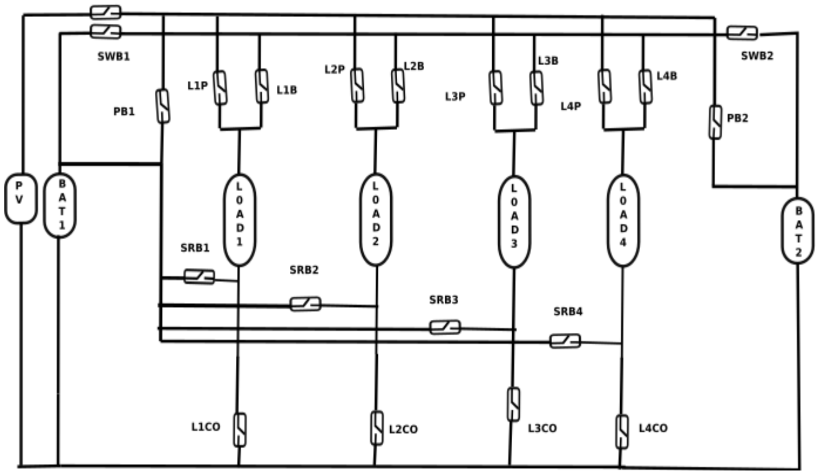

Figure 5. Switching circuit

Table 2. Switch states and resulting connections

SWP	SWB1	PB1	L1P	L1B	SRB1	L1CO	Load	Battery
ON	OFF	ON	ON	OFF	OFF	ON	PV-load	PV-BAT1
ON	ON	OFF	OFF	ON	OFF	OFF	Bat1-load	NC
OFF	OFF	OFF	ON	ON	OFF	OFF	PV-load	NC
ON	OFF	ON	OFF	OFF	OFF	OFF	PV-BAT1	NC

2.2. Controller

The controller will be the intelligence of the whole system taking the inputs from the predictive system, the load configuration details and the current load usage. The logic used by the controller to decide the source to be connected to the loads is depicte d in the Figure 6. The loads being considered are only the loads which are in the ON state at the given time.

The power from the PV panels is routed to all the loads through a seperate DC bus and the power from the batteries is routed using a seperate bus. Each load has the option of being connected to either of these busses, based on how they will be powered. The battries, one of which will be acting as the main battery delivers power into the bus and the second battery which acts as the auxillary battery accepts power from the PV bus, in case PV bus is able to supply. The Figure 7 depicts the complete diagram of system depicting the loads and the bus connections needed. The controller along with the switching circuit makes the connection between the loads and the busses based on which source needs to be used to power the loads. Next section provides the details of the system implemented to test the proposed idea.

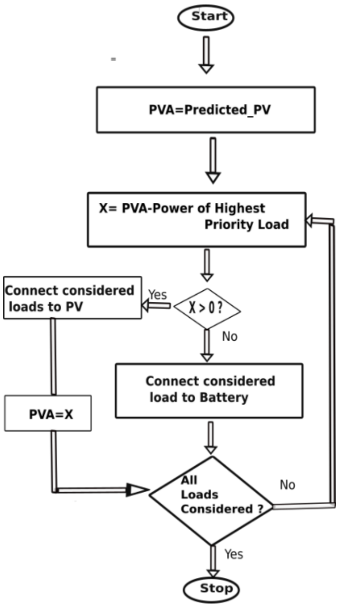

Figure 6. Algorithm flow

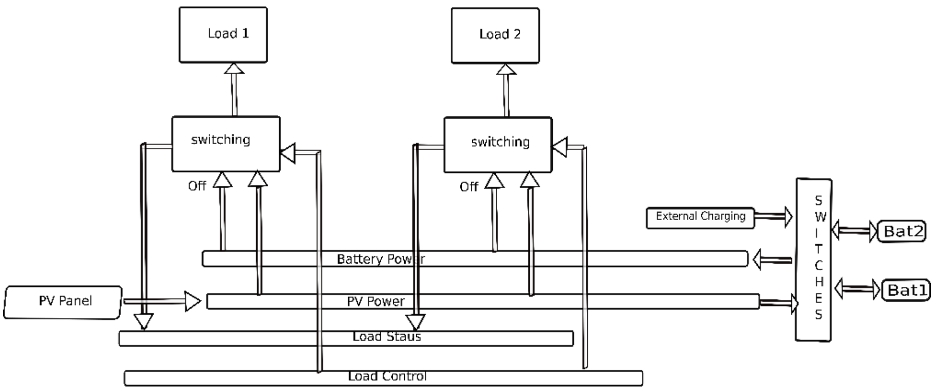

Figure 7. Complete system for 2 loads

3. IMPLEMENTATION

A 100 W solar panel with the maximum current Imp of 5.5 A and maximum voltage of Vmp-of 18 V was installed on the roof top. The panel was connected to a recording system to collect the data regarding the power being generated. Two 6 Ah batteries were used along with the panel, which were the main and auxiliary battery. The main battey was the source when the solar panel was not able to supply the power needed by the loads. The batteries were chosen considering the ratings of the loads being connected to the prototype.

To simulate practical loads in a resedential system, 4 DC loads were considered which emulated in their power consumption the real time loads as closely as possible. The configurations of the loads, which provided the load details, along with the priority and the direct solar connection option are listed in the Table 3. The random forest predictive algorithm was used for predicing the power generated by the panels. The algorithm was implemented on a raspberry pi using python and sci-kit libraries. The data collected from the measuring ciruit was provided as input to the algorithm. Data was split into 80% as training data and 20% was used as the data to test the performance of the algorithm. The training accuracy was obtained to be 92 % whereas the test accuracy was 85%, after fine tuning the parameters. The output from the model was a vector, which indicated the loads which can be connected to the PV panel and those which can not be connected. This output vector was taken as input by the controller which ensured the connection between the load and sources based on the same. The prototype developed is shown in Figure 8, with the raspberry pi as the main controller running the predictive algorithm. The relays act as the switches to create connections between the load and the sources.

Table 3. Load configuration parameters

Sl no	Parameter name	Load 1	Load 2	Load 3	Load 4
1	Max current	1	2	3	4
2	Max voltage	6	14	14	24
3	Min current	0.9	1.8	2.8	3.9
4	Min voltage	5.5	11.5	11.5	22.5
5	Load priority	2	1	3	4
6	Direct solar	1	1	1	0
7	Rated current	0.5	1	2	3
8	Rated voltage	5	12	12	24

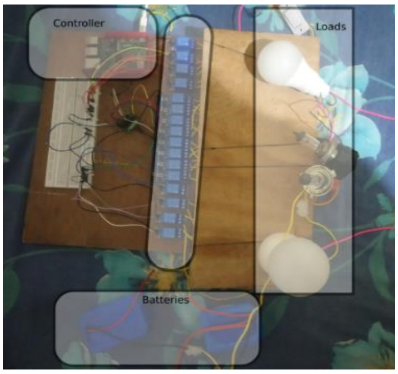

Figure 8. Hardware setup

4. OBSERVATIONS

The prototype developed was tested under three scenarios to ensure that the output of the PV panels can be used to drive loads at different times of the day as the output of the PV varies. The four scenarios considered were that of early morning, midmorning, afternoon, and evening. The observations and inferences drawn from them are detailed in next section.

4.1. Scenario 1: early morning

Early morning the solar irradiation is low and the power generated by the PV panels is not very high on an average the power generated form the panels was capable of powering only one load. Based on the prediction of PV generation as well as the current power generation, the algorithm creates a list of loads that could be powered from the panel. This was labeled as allow load. The controller compares the allow load values with the actual status of the loads, to decide which load needs to be connected to which source. Table 4 provides the status of the loads being considered at a certain time, along with the allow load values at that time. It can be inferred that at the given conditions only load 1 can be powered from PV panel, where as all other loads need to be powered from a battery. The Figure 9 shows the signal changes and the switch status for load 1 at time being considered. It can be noticed in the figure that the switch L1P, which connects PV panel to load 1 is high as long as allow load signal is high and the load 2 which is also in the ON state gets connected to the main battery through the switch L2B. The switches which connect the panels to loads directly, like the L1P for the load 1, are controlled such that the loads are disconnected from the panel and connected to the battery a few time units before the panel output is predicted to fall below the required limits for the load. This ensures that the source to the load is switched to a realiable option at all times. The power generated by PV during the period when it was used to power load 1 was more then what load 1 required and hence the extra power was used to charge the battery with lower SoC. The configuration of the switching circuit for load 1 and load 2 as shown in the Table 5. To power load 1 in the case of an AC grid it would have required 3 levels of voltage conversion per load. One from panel to battery then from battery to AC grid and finllay from AC to DC at the load.

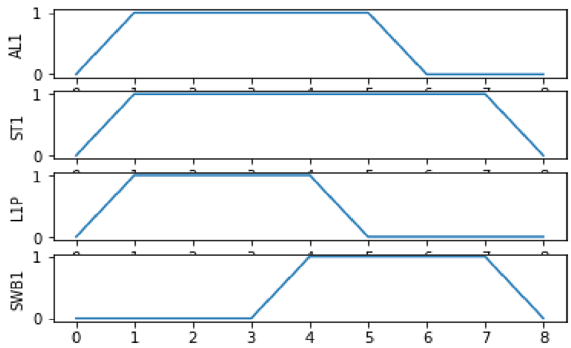

Figure 9. Signal changes in scenario 1

Table 4. Load status and loads allowed for PV connection in scenario 1

Load no	Status	Allow load
Load 1	ON	1
Load 2	ON	0
Load 3	OFF	0
Load 4	OFF	0
Total power required		14.5 W

Table 5. States of switches in switching circuit in scenario 1

Switch state	Switch name
ON	SWP
	L1P
	LICO
	PB1
	L2B
	L2CO
OFF	L1B
	L2P
	L3P
	L4P
	L3CO
	L4CO
	PB2
	SB2

In the case of a DC grid powered from battery, it would have required two voltage conversions per load, PV panel to battery, and battery to the load. When a load is connected to the panel directly, the load needs only one level of conversion, from the panel to the load. Table 6 lists the total number of conversions needed for the scenario 1, with two active loads.

Table 6. Conversions used in various connection in scenario 1

Power source	Conversions needed
AC grid	6
DC grid	4
DC grid direct conneciton	3

4.2. Scenario 2: mid morning

The power generation capacity of the panels increases reaching higher levels by the time of 10:00 AM to 11:00 AM. On an avergae day the panel was capable of driving atleast two loads by this time. Table 7 depicts the status of the loads on a sample day considered. The predicted power on a given day at the time being considered was 42 W, with 14 V, and 3 A current, whereas the load required 38.5 W. Based on the ratings of the loads any of the three loads 1, 2, and 3 could be connected to the panel individually. The algorithm decides the loads which will be powered by the panel based on the load priorities set in the configuration. Load 1 and load 2 have higher priority and after connecting these two loads the predicted current of the panel will not be enough to drive the load 3 and hence load 3 gets connected to the battery. The Figure 10 show the signal changes in the switching circuit when the loads get turned ON. It can be noted that L1P and L2P are high as long as allow load signal is high, ensuring that the power from the panel is used to drive the loads 1 and 2 when panel is generating enough power.

Table 7. Load status and loads allowed for PV configurations in scenario 2

Load no	Status	Allow load
Load 1	ON	1
Load 2	ON	1
Load 3	ON	1
Load 4	OFF	0
Total power required		38.5 W

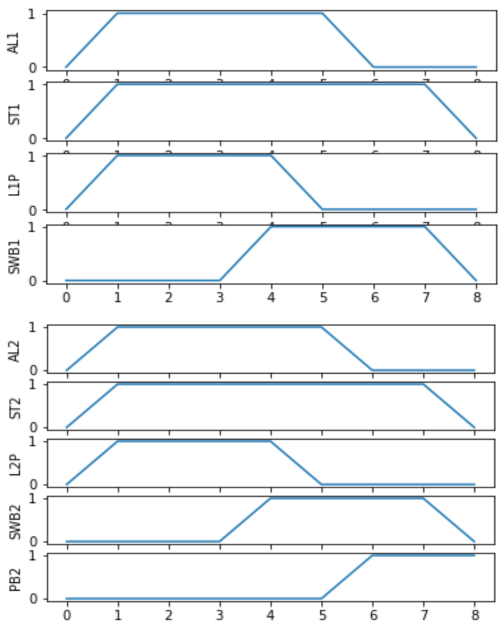

Figure 10. The state of signals in scenario 2

The L1P and L2P go low before allow load goes low based on the predictions by the algorithm, which ensures that the loads are connected to the battery before the PV output drops below the required values. We can also note that the switch PB1, meant to connect the panel to the battery, is turned ON when the loads get disconnected from the panel. Thus, utilizing the PV output to charge the battery. The switching table for the loads in use are presented in the Table 8 indicating the states of the swtiches for load 1 and load 2. If the same set of loads were to be used in an AC grid, each load would have required their individual convertions and along with the common convertions at battery taking the total 9 conversions for three loads. In a DC grid 6 convertions would be required. In the proposed model, we can do the same using only 4 convertions. The Table 9 lists the number of convertions in every configuration.

Table 8. Switching circuit status

Switch state	Switch name
ON	SWP
	L1P
	L2P
	L2CO
	PB1
	L3B
	L3C0
OFF	L1B
	L2B
	L3P
	L4P
	L3CO
	PB2
	SWB2

Table 9. Converters used in various configurations in scenario 2

Power source	Conversions needed
AC grid	9
DC grid	6
DC grid direct conneciton	4

4.3. Scenario 3: afternoon

When the PV array is generating its peak output, the current being generated is sufficient to drive any of the loads 1, 2, and 3 individually and thus all the corresponding allow load signals are high at this time. But the actual connections of the loads are decided based on the configurations set for the load. From the load configuration we can see that load 4 is mentioned not be connected to the solar PV. Thus with out connecting load 4, the power generated by the panel is sufficient to drive all the three loads with the excess current being used to charge the battery. The three switches L1P, L2P, and L3P connect the load to the panels directly, disconnecting it only when the ouput prediction is expected to fall below the required limit. In an AC grid to power 4 loads a total of 12 conversions would be needed, which would reduce to 8 in case of DC grid, and would further go down to 5 in the case of the proposed algorithm.

4.4. Projected savings

The proposed algorithm clearly indicates the reduction in the number of voltage conversions needed when allowing the loads to be connected directly to the PV panels. The standard buck converters available off the shelf have an approximate efficiency of 95%. The reduction in use of converters will lead to substantial savings over a period of time. The Table 10 calculates the approximate amount of savings that can be achieved for the 4 sample loads considered in the study. The number of conversions required for a load in AC grid has been compared with that of the proposed direct connection between loads and the panel. We noted above that the number of conversions per load reduces by 2 in the case of a direct connection between load and the panels. To calculate the total savings obtained in power, we will use the (1).

$$(Savings\ in\ WH/day) = (No. of\ Conversions) * (Loss\ in\ converter) * (Number\ of\ hours\ of\ direct\ connection) * (Number\ of\ loads) \quad (1)$$

Table 10. Projected savings for the considered sample loads

Parameter	Power	Average usage in daylight (hours)	Average direct connection (hours)	Power savings/day (WH)	Power savings/month (WH)	savings/year (WH)
Load 1	2.5	5	4	0.5	15	180
Load 2	12	4	2	1.2	36	432
Load 3	24	4	1	1.2	36	432
Load 4	72	4	0	0	0	0
	Total					1.044 KWH

The above calculation in just for 4 loads in a single house. In a practical setup the number of loads will be higher in number thus leading to higher savings. The same implementation when extended to multiple homes in a grid, will lead to a substantial reduction in the average demand from the grid.

5. CONCLUSION

The prevalance of DC loads in domestic use leads to the need of exploring the possibility of having a DC grid at the domestic level. This is possible only if the the DC power sources can ensure efficient and reliable driving of loads. The paper proposed a direct connection between the PV panel and the load, based on the prediction of power generation by the PV panels. It was noted that such a direct connection can lead to reduction in the usage of number of convertions in the system, hence reducing the losses and making the system more efficient. An efficient system would make the rooftop PV more beneficial for the end user, hence leading to increase in installations of the roof top PV panels. This in turn will reduce the power drawn from the grid and thus lead to reduction in use of fossil fuels, making way for a greener and cleaner environment.

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