Solar Powered DC Systems for Domestic Electrification & Rural Application

A Project Report Submitted

to

the Planning & Convergence Department, Government of Odisha

By

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(Prof. N C Sahoo) (Dr. S Mohapatro)

Principal Investigator Co-Principal Investigator

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Executive Summary of the Project:

Project Title: Solar Powered DC Systems for Domestic Electrification & Rural Application	**Project Sanction Letter:** [(4463)/{Innov-5/2014(Pt)}]/P, Bhubaneswar Date: 13th April 2015
Starting Date of Project: 12th Aug 2015	**Approved Date of Completion:** 11th February 2017 30th November 2017 (with Extension)
Principal Investigator: Dr. Nirod Chandra Sahoo School of Electrical Sciences, IIT Bhubaneswar **Co-Principal Investigator:** Dr. Sankarsan Mohapatro School of Electrical Sciences, IIT Bhubaneswar	**Collaborator:** Odisha Renewable Energy Development Agency (OREDA), Bhubaneswar

Objectives of the Project:

Objectives	Status
Design and evaluation of an integrated PV based home electrification system without and with battery energy (2hrs), to meet the energy demands during day time for different loads such as fan, TV, and light for three house-load models: M-I (< 500W) , M-II (< 750 W) and M-III (< 1000 W)	Completed
Design and evaluation of an integrated PV based home electrification system using battery energy (1 day), to meet the energy demands during day and night time for different loads such as fan, TV, computer, mixer, and light	Completed
Design and evaluation of MPPT controller and battery charging controller	Completed
Evaluation and analysis of the energy saving as well as losses of PV based DC system in comparison to traditional PV powered AC system	Completed
Design of an optimum system considering all the system constraints such as technical feasibility and economic aspects for three house models M-I, M-II, and M-III	Completed

Technical/Scientific Achievements from the Project:

1. M Tech Thesis in Power System Engineering: 'Solar powered dc system for domestic electrification and rural application' by Ajit Kumar Sahu, 2016.
2. N. C. Sahoo, S. Mohapatro, A. K. Sahu and B. S. Mohapatro, "Loss and cost evaluation of typical DC distribution for residential house," IEEE International Conference on Power and Energy (PECon), pp. 668-673. (2016) https://doi.org/10.1109/PECON.2016.7951644.
3. N. C. Sahoo, S. Mohapatro, "Feasibility of Solar PV-Powered DC System for Residential Electrification—A Comparative Study," Proceedings of Symposium on Power Electronic and Renewable Energy Systems Control (PERESC 2020), vol. 616, pp. 171-183, Springer, Singapore. (2021) https://doi.org/10.1007/978-981-16-1978-6_15.

1. Introduction

Renewable energy resources have the potential to provide long-lasting solutions to the energy problems faced by a nation. From greenhouse gas emissions to poverty, renewable energy resources can foster an economy and help the environment. Renewable energies are widely perceived as a promising technology for electricity generation in remote locations in developing countries [1]**.** One of the viable solutions to today's energy problems is the use of renewable energy in an off-grid, autonomous home, which is powered by direct current, rather than alternating current coming from a power line which probably cannot be found nearby [1,6]. Using renewable energy can help the environment and foster the economy.

Why use DC power over AC power? To put it shortly, it is a sensible method for this application. It makes more sense to use DC power in rural areas since most places are geographically close and not as spread out like urban areas [8]. Since most renewable energy sources typically generate DC power, it is more viable to directly utilize this power in a standalone house nearby, eliminating the costs of large, expensive equipment such as inverters, AC-DC rectifiers and AC-DC converters inside appliances. Ultimately, this would eliminate the need for large transmission lines and substations for distribution of AC power, which are unheard of in many villages. Also12V/24V DC appliances are relatively cheaper compared to AC appliances because they do not require buck AC-DC converters to step down 230V AC from the wall outlet to the 12V DC required by the appliances [3].

There are many advantages by using DC power for short distance transmission [12]. DC systems do not introduce a reactance in the line, thus reduce the amount of losses in the line; power calculations and system analysis are simpler because there is no complex power–only a real component. Frequency is zero in DC systems, thus no frequency variation to monitor, and network connection does not require synchronization or balance of system. There is no susceptance in the line of a DC system, thus the effects of charging current are negligible. Only two conductors are required in a DC system, rather than three/four for an AC system, thus reducing cost of copper wire [8]. DC systems do not experience inductance, resulting in a smaller voltage drop than in AC systems for the same load; hence, DC systems have a better voltage regulation. DC systems do not experience the skin effect; therefore, the entire cross-sectional area of the line conductor can be utilized [15].

AC systems require more insulation in the transmission lines than DC systems because of greater potential stress for the same working voltage [6]; therefore, DC systems are less expensive in that aspect. The presence of capacitance in AC systems leads to greater power loss due to the charging/discharging of capacitance. As long as DC systems are able to efficiently transform voltages to other levels, DC transmission systems can be more efficient and stable as well as easier to monitor and analyze, as opposed to AC systems [8].

1.1 Background

Towards the end of the 19th century, the battle of the currents between Thomas Alva Edison and George Westinghouse took place. Edison worked with direct current (DC) systems and Westinghouse with alternating current (AC) systems. Everybody knows who won the fight. But is AC still the only right choice for the 21st century? When the battle began, the cities were illuminated by gas or arc light powered by dc dynamos. The arc light was produced between two carbon tips and gave a glaring light with an open flame and noxious fumes, and the tips needed to be periodically renewed. The arc light was suitable for streets and large indoor places like train stations and factories.

Edison saw a possibility to replace the arc lighting with incandescent lamps. The problem of finding a suitable filament was solved when Edison with some ideas from Joseph Swan made the carbonized cotton filament burn for more than 13 hours. Edison and his team developed dc dynamos with constant voltage output, meters, lamp sockets, switching equipment and fuses. The first incandescent lighting system with a central dc generating station was demonstrated at Holborn Viaduct in London, England, in January 1882. The more known Pearl Street Station in New York began in September 1882. The success resulted in many systems installed in cities across the continent. Edison's lighting systems had some drawbacks. They were operated with low-voltage dc, 100 V or 110 V, which resulted in small isolated systems to reduce the losses. A bigger system would have resulted in a large amount of copper.

In 1881, the first AC system was demonstrated in London by Lucien Gaulard and John Gibbs. Westinghouse took the ideas back with him to the U.S. and William Stanley improved the design. In 1886, the Westinghouse Electric Company had designed an equipment for AC lighting system. In 1887, Nikola Tesla filed for seven U.S. patents in the field of polyphase ac motors, power transmission, generators, transformers and lighting. Westinghouse purchased these patents, and employed Tesla to develop the ac system. In 1891, Westinghouse made history by setting up a 13-mile long transmission line. And many more could follow.

At that time an ac system was a proper choice. The loads were mainly incandescent lamps and machines, and the possibility to transform the voltage from one level to another made ac suitable for transmitting electric power over long distances. Also ac machines could be made more robust with less maintenance compared with dc machines.

1.1.1 DC House Project Overview

Considering the above background, the present project on "DC House" is aimed at investigating the economic viability of DC household electrification. The model design of the DC House must consider several variables. The purpose of the DC House is accordingly to develop a low-cost method of generating DC power and providing it to small village homes in rural areas where the conventional AC power supply is not easily available or affordable[7]. The hardware needed for the DC system must be affordable and feasible. Therefore, the specific components of the DC House must be chosen so as to appropriately accommodate the energy demand of the house while considering their circumstances. Ultimately, the DC House has the potential to improve the lifestyles of many unprivileged villages. The basic model design of the DC House is shown in Figure 1, which illustrates the DC power generation through photovoltaic module with battery integration [1, 5].For the sake of comparison, the layout of a PV-integrated AC house is shown in Figure 2.

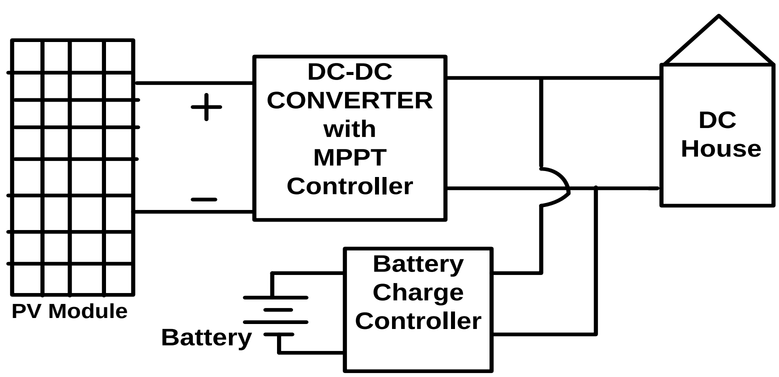

Figure 1: PV-integrated DC House layout diagram

1.1.2 AC Vs. DC Distribution System

We presently enjoy a predominantly ac electrical distribution system, the engineering basis for which was designed over 100 years ago. While ac distribution systems have served us well, we should periodically pause to assess what opportunities we have accepted or been denied by the overwhelming predominance of ac electrical power distribution systems. What opportunities could be obtained by engineering dc distribution into at least portions of our present system? What advantages of the present ac distribution system should be recognized and protected? According to a simple predictive model formulated, the premise of residential dc distribution will incur unfavorable total conversion efficiency compared to the existing the ac distribution. However, if a residence is supplied by a PV array or another dc generator, the total conversion efficiency within a residential dc distribution system could be similar to, or even better than, that for ac distribution.

1.1.2.1 Advantages of AC distribution system

1.1.2.1.1 Voltage Transformation

Perhaps the greatest benefit available to ac systems is the ease with which ac voltage can be elevated for distribution over distance and again lowered, if necessary, near the load. DC voltage conversion technology is improving, but dc voltage conversion might never be so simple, and has not yet reached the place where dc converters can routinely compete with transformers for high-voltage distribution. The exception is HVDC transmission, which rectifies and inverts to and from high voltage dc at only a limited number of remote substations.

1.1.2.1.2 Circuit Breaker Protection

Circuit protection is more mature for ac distribution systems than for dc systems; so it might be impossible to make a fair comparison. AC circuit protection schemes benefit from periodic zero voltage crossings, at which times the circuit breakers have an improved likelihood to extinguish fault current arc. But this limitation may not be so severe for protection of low-voltage dc circuits.

1.1.2.1.3 Voltage Stability

Voltage stability is an issue for both ac and dc distribution systems and becomes even more challenging where ac and dc are mixed. The advantage of an AC system is that the stable voltage can be controlled independently from real power through the management of reactive power. In a dc system, voltage drops are direct consequences of real power flow over a conductor’s length.

This being said, there is an interesting interplay between ac systems and power electronic conversion equipment. Active power supplies can manage power factor at their terminals and could inject reactive power into an AC system to help control ac system voltage.

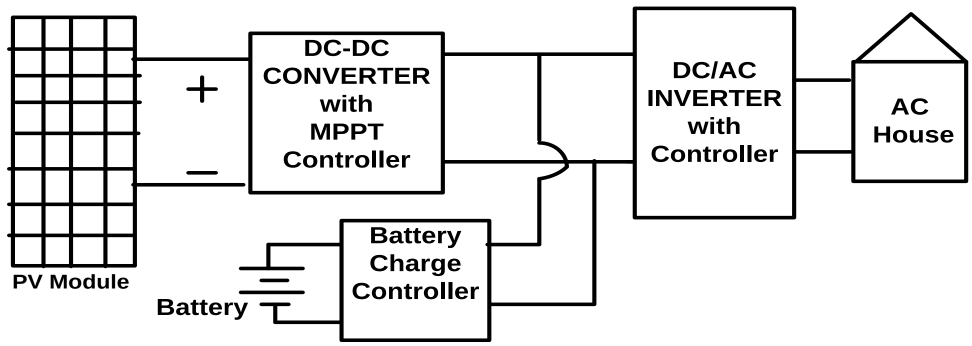

Figure 2: PV-integrated AC house layout diagram

1.1.2.2 Advantages of DC Distribution System

1.1.2.2.1 Incorporation of Renewable Energy Resources

DC renewable energy resources could be much more readily incorporated into a premise dc bus. Doing so would eliminate conversions, each of which saves between 2.5 % and 10 % of the developed energy.

1.1.2.2.2 Reliable and Uninterruptible Supply

Our growing desire for reliable information technologies requires uninterruptible power supplies. Each such supply must provide dc bus battery storage, which can continue to supply an application with power during unplanned ac outages.

1.1.2.2.3 Voltage Stability

We are reminded that dc distribution system components will not alleviate and might exacerbate our voltage stability calculations and challenges, especially if dc and ac distribution will coexist, as they must. Nonetheless, active input stages of power supplies might not only assure good power factor, they might also inject reactive power into their ac supplies to help control voltage and provide voltage stability.

1.1.2.2.4 Fluorescent Lighting and Electronics

Fluorescent lighting electronic ballasts are well served by dc power. Our movement away from less-efficient incandescent lighting toward lighting technologies like compact fluorescent fixtures (and eventually solid-state lighting) could accompany dc distribution. Doing so would save and consolidate at least one conversion step that is presently performed at each lighting fixture. A similar argument can be made for home electronic devices, all of which require dc power and must rectify ac power supplied to them.

1.1.2.2.5 Variable-speed Drives

Variable-speed drives, both in generation and loads, help match the input and output power. The result can be improved efficiency, improved personal comfort, or both. Variable speed control is more easily obtained from a dc source.

1.1.2.2.6 Power Quality

While power electronics are frequently viewed as a cause of poor power quality, power electronic converters can meet most power quality standards placed on an ac system and could even improve ac power quality. The first stages of dc power supplies should always perform power factor correction. Good design practices and filtering also assure acceptable harmonic power quality. The opportunity arises from using power electronic conversion for not only preventing poor power quality, but also for improving power quality.

1.1.2.2.7 50-Hz Health Concerns

Potential health concerns from human exposure to 50-Hz distribution could drive us toward increased use of dc distribution systems.

1.1.3 Power Transfer in DC Network

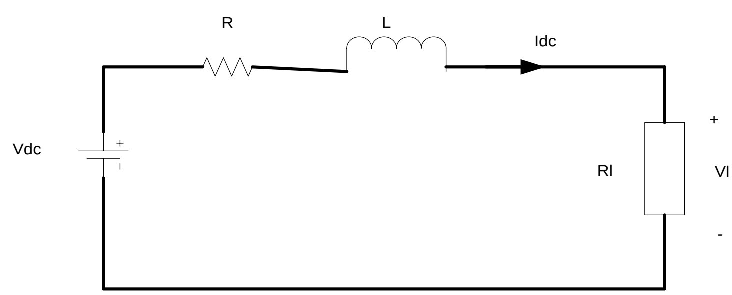

Figure 3: DC circuit

where R=conductor resistance, L=conductor inductance, Vdc=source voltage, VL=load voltage, and Rl=load resistance.

For the DC circuit shown in Fig. 3 current, voltages, and power loss are calculated. It can be shown mathematically that power and voltage losses increase with rising load power as well as with decreasing system voltage. The current increases if the same power is transported at a lower voltage. Due to this current increase, the voltage and power losses in the conductors will increase, illustrating that the voltage losses and power losses will be considerably larger in a very low voltage system. In addition to the problem of voltage losses, another problem in networks will arise in DC low voltage circuits due to the limitation of short circuit currents.

From the above Fig 3, the followings are calculated:

$$
\begin{aligned}
P_l &= \frac{V_l^2}{R_l} \\
V_l &= I_{dc}.R_l \\
V_{l,dc} &= V_{dc} - V_l = I_{dc}.R \\
P_{l,dc} &= P_{dc} - P_l = I_{dc}{}^2.\mathrm{R} = (\frac{V_l}{R_l})^2.R
\end{aligned}
\tag{1}
$$

Thus it can be seen that the voltage drop and power loss are directly proportional to conductor resistance. But the resistance of the conductor depends upon the thickness and length of the wire.

1.2 The DC Distribution System

This section presents the design of DC low-voltage distribution system. The design of DC low-voltage grid must fulfil the following requirements:

1. Transport of DC electrical energy from the source to the user with minimum energy losses.
2. DC electrical installation must be safe for the user.
3. Voltage quality of the supplied energy should guarantee proper functioning of the household appliances connected to the DC grid.
4. The cost of the entire DC electrical installation must be comparable to the cost of an AC installation.
5. Control of the electricity supply to the appliances must be simple.
6. The DC low-voltage network must be easy to install and maintain.

Following the description of the design, the calculations are performed to determine the behavior of the DC grid under rated operation conditions and in fault situations. These calculations will be used to check whether all requirements are fulfilled or not.

1.2.1 Safety requirements for DC low-voltage installation

The electrical installation of the DC low-voltage house will have to meet the requirements in NEN 1010 ’Safety requirements for low-voltage installations’. The most important information and requirements in NEN 1010 in direct relation to the design of conductor size (diameter) in the DC low-voltage installation are: (i) highest tolerable temperature of conductors, (ii) permissible voltage drop, (iii) expected electromechanical forces caused by short circuits, (iv) other mechanical forces to which conductors may be exposed, and (v) maximum impedance for the short circuit protection.

Also the following facts should be taken into consideration:

- Voltages below 24 V DC are, under normal circumstances, touch-safe and systems with a nominal voltage below 24 V DC do not need special measures to protect against direct and indirect touch.
- The conductors must be protected against over-currents and short circuits.
- The voltage losses in conductors should not cause malfunctioning of household appliances. (For 220 V AC installations, the maximum allowed voltage drop is 5% of the nominal voltage).

1.2.2 Components of DC distribution system

The DC low-voltage distribution system will in general contain the same elements as in an AC distribution system. This subsection discusses the most important components of the DC house and describes their suitability for use in a DC system. Important requirements for a particular component as laid down in NEN 1010 will also be highlighted.

1.2.2.1 Conductors

There will be no insuperable problems on using wires for DC. Special attention must be paid to the insulation of the conductors to prevent arcs and corrosion. Standard insulation of wires as used in AC installations should be sufficient to prevent these problems. If thick wires are required in the DC low-voltage system, problems concerning the maximum number of conductors in conduits may arise.

1.2.2.2 Switches

Switching DC circuits gives problems because of the absence of zero-crossings. For AC, the natural zero-crossings make extinguishing arcs very simple; for DC, special measures must be taken to extinguish the arc. The DC ratings of standard AC switches are unavailable for most switches, although one manufacturer gives 24 V, 10 A as the DC rating for a standard AC switch. A very low system voltage will facilitate DC switching; higher system voltages will make it more difficult to extinguish arcs. Because of this problem, switches for DC will be considerably larger and more expensive than AC switches if the same system voltage (220 V) is used.

However the solid state switch, does not give the problem of arcing. But this switch must still be able to dissipate the energy which is released with the interruption of the DC current. A disadvantage of the solid state switch is that the voltage drop across the conducting device. More research is required into switches for DC systems in domestic dwellings and especially the use of AC switchgear in DC networks.

1.2.2.3 Contacts and joints

For making contacts and joints in DC systems, problems may arise due to corrosion. Special attention must be paid to contacts and joints in humid areas; moisture free enclosures may be necessary. If a system has large currents, then a low contact resistance is required in order to prevent overheating of contacts and joints. If the wire diameter is considerably larger than the standard 2.5 mm^2 for AC house installations, it will not be possible to use standard equipment for making joints.

1.2.2.4 Outlets and plugs

Outlets and plugs should be rated for the system voltage and the maximum load current. Plugs may not fit in outlets of other voltages. Outlets may not be accessible by plugs of other voltages. This implies that different types of plugs and outlets are needed for the DC low-voltage house. Other types of plugs and outlets are available; so this will not give rise to any problems. Available outlets and plugs for DC are rated for 10 A, 24V.

2 Study of Different Loads and Simulation of DC House Model

At present in India, the electricity distribution is by AC. This could be the reason for which almost all home appliance are operated mainly with AC. However, many appliances run with DC internally. In India, there are not many manufacturing industries for DC appliances. At present few start-up companies are manufacturing limited DC appliances with less efficiency and at a higher price. However, it is expected that, if the big industries start manufacturing these appliances, then the price will come down drastically. As DC home appliances are not commonly used, this needs to be studied.

2.1 Model Houses: M-I, M-II and M-III

Three different house models were designed by taking into consideration the total load of the house and named as M-I (<500 W), M-II (<750 W) and M-III (<1000 W). The house model sizes are chosen considering a normal rural family.

2.1.1 M-I (< 500 W) house model

M-I model has 9 LED bulbs, 3 fans, a television and a mixer. The total load is under 500 W. Fig. 4 shows the schematic of the house model consisting of a bed room, a dining room, a drawing hall, kitchen and toilet for a lower middle class family with load consumption of about 500 W. Different load arrangement for the M-I house model is considered as per normal living style. The loads are so chosen such that the ultimate end-effect of the loading device will be the same in case of AC and DC, such as lumens in case of light, rpm in case of fan etc. It is seen that the total load in case of DC equipment for M-I is around 343 W, however in case of AC it became 490 W. The dimensions of the model house are 20 ft ×20 ft. The prototype developed in the laboratory is shown in Fig. 5.

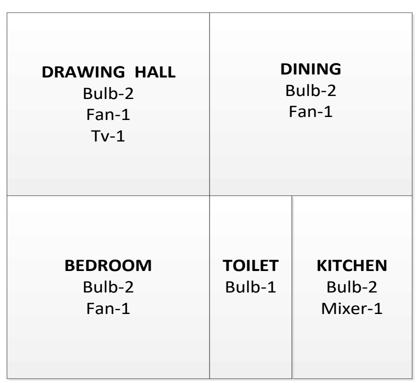

Figure 4: House model M-I with total load less than 500 W

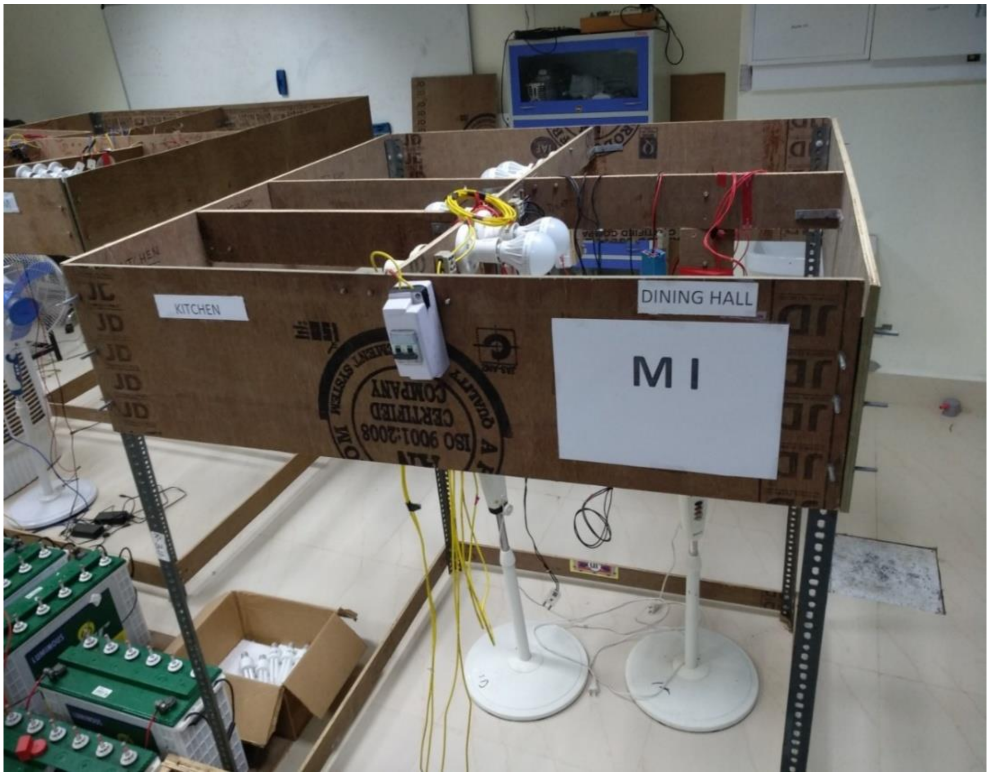

Figure 5: Prototype of house model M-I

2.1.2 M-II (< 750 W) house model

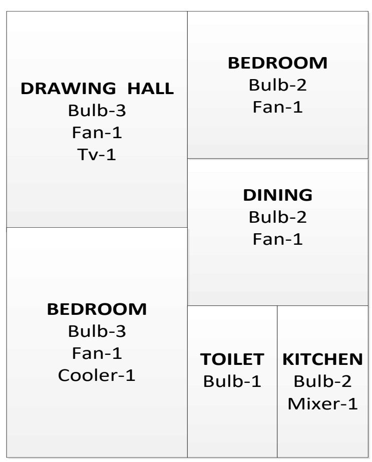

Figure 6: House model M-II with total load less than 750 W

M-II model has 13 LED bulbs, 4 fans, a television, a cooler and a mixer. The total load demand is under 750 W. Fig. 6 shows the schematic of the house model consisting of two bed rooms, one dining, a drawing hall, one kitchen and toilet for a middle class family. Different load arrangement for the M-II house model is considered as per normal living style. The load are so chosen such that the ultimate end-effect of the loading device will be the same in case of AC and DC, such as lumens in case of light, rpm in case of fan and cooler etc. It is seen that the total load in case of DC equipment for M-II is around 466 W, however in case of AC it became 720 W. The dimensions of the house model are20 ft ×30 ft. The prototype developed in the laboratory is shown in Fig. 7.

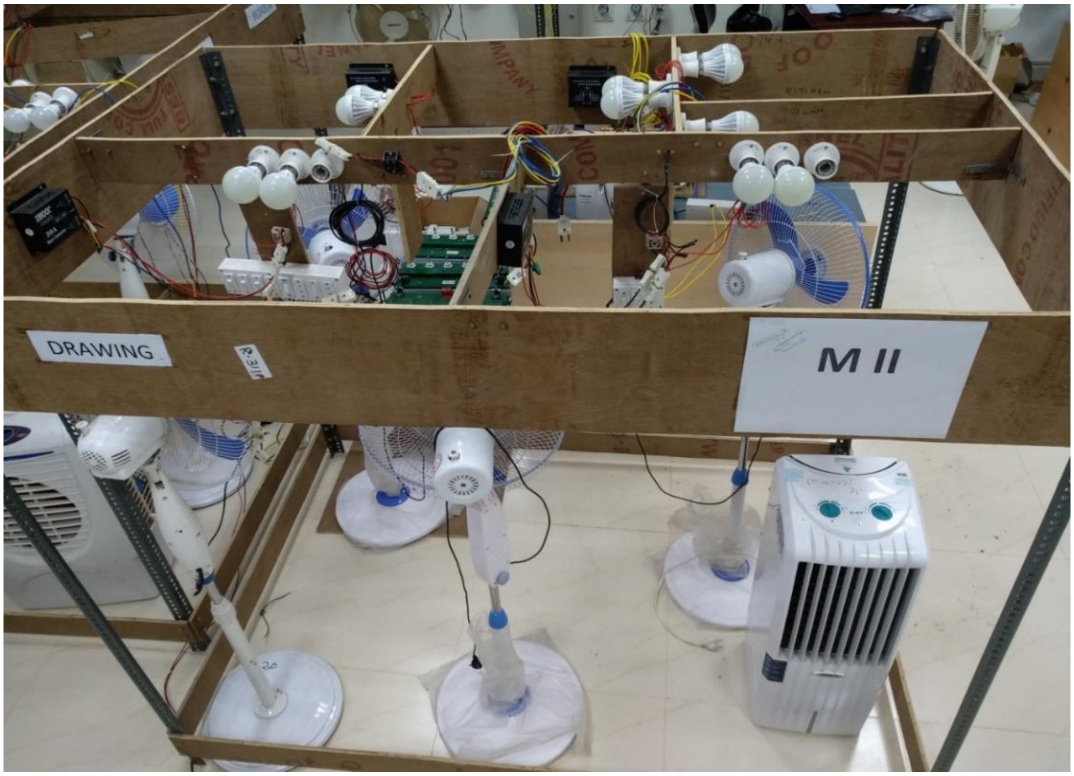

Figure 7: Prototype of house model M-II

2.1.3 M-III (< 1000 W) house model

M-III model has 17 LED bulbs, 4 fans, a television, a cooler, a laptop and a mixer. The total load demand is under 1000 W. Fig. 8 shows the schematic of the house model consisting of one bed room, one bed room with attached toilet, one dining, one drawing hall, one kitchen and toilet for an upper middle class family. Different load arrangement for the M-III house model is considered as per normal living style. The load are so chosen such that the ultimate end-effects of the loading devices will be the same in case of AC and DC, such as lumens in case of light, rpm in case of fan and cooler etc. It is seen that the total load in case of DC equipment for M-III is around 554 W, however in case of AC it became 840 W. The dimensions of the house model are 30 ft ×30 ft. The prototype developed in the laboratory is shown in Fig. 9.

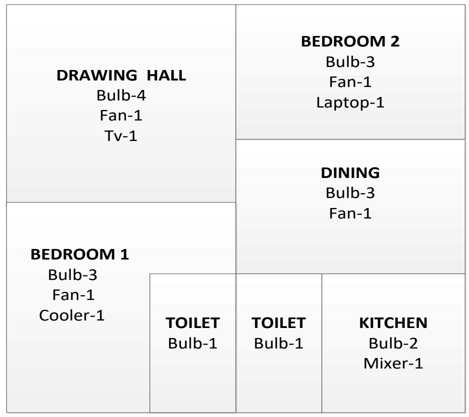

Figure 8: House model M-III with load less than 1000 W

Figure 9: Prototype of house model M-III

2.2 Different Loads and Equipment for Model Houses M-I, M-II and M-III

To visualize the conditions of a practical house, as mentioned in Section 2.1, different house models are considered. For all the house models, different loads are considered such as fan, light, mixer, cooler and laptop etc. For comparison, both AC and DC load types are considered for all the house models (PV powered AC electrification and PV powered DC electrification).

2.2.1 Selection of DC Voltage Level

As per the available literature (mentioned in references), the typical voltage levels used for DC distribution are 12 V, 24 V and 48 V. Depending on the level of voltage, the size of conductor will vary with current for a fixed load. Hence, it is obvious that, with high level of DC distribution voltage, the current will be low and accordingly the cross-sectional area of conductor will be low for a fixed load. However, with decrease in cross-sectional area, the resistance of the conductor will increase. Thus the I^2R loss and IR drop will not be very much significant in case of these three DC voltage level such as 12 V, 24 V and 48 V. In India at present, there are limited number of manufacturers for DC operated home appliances. Almost all the DC home appliances manufactured in India at present are operated with 12 V DC. Use of 48 V DC will lead to decrease in line losses, however the conversion loss will be present in DC-DC converter for converting 48 V DC to 12 V DC, as most of the appliances are of 12 V DC rating. Use of 12 V DC will lead to increase in line losses and conductor of higher diameter is required. Moreover, the conductor will carry high amount of current for full load, which is not desirable. With 12 V DC distribution, when the load will be fed from battery because of high discharge current the size of the battery will be higher. After having a tradeoff between availability of home appliances with different levels of DC voltage, line losses, line drop and discharge rate of battery, 24 V DC has been chosen as the distribution voltage for this project.

2.2.2 Basis of Choice for DC/AC Loads

It has been observed from the survey that the power ratings of commercially available similar DC type load and AC type load are not identical. Thus while selecting power ratings of DC/AC type loads, the end-effects of different loads are considered. The end-effects are assessed in terms of the lumen output of light, rpm of fan with same blade dimensions, wind speed output with same area covered by cooler and torque rating of mixer etc. Due to unavailability of different types of DC loads, here in this project, little variation in end-effects are considered, i.e., in case of TV, same screen size is considered.

Tables 1 to 3 provide details of various loads connected in different model houses. It is observed that while comparing the end-effects of some of the home appliances, DC appliances consume less power compared to the AC counterpart.

Table 1: Details of load for M-I house model with both AC and DC system

Load	Quantity	DC Load			AC Load		
		Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)	Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)
LED Bulb	9	7	4-6	63	15	12-14	135
Fan	3	35	27-33	105	60	50-55	180
Television	1	25	23-25	25	25	23-25	25
Mixer	1	150	120-125	150	150	120-125	150
			Total	343		**Total**	490

Table 2: Details of load for M-II house model with both AC and DC system

Load	Quantity	DC Load			AC Load		
		Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)	Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)
LED Bulb	13	7	4-6	63	15	12-14	195
Fan	4	35	27-33	140	60	50-55	240
Television	1	25	23-25	25	25	23-25	25
Mixer	1	150	120-125	150	150	120-125	150
Cooler	1	60	55-58	58	110	98-103	110
			Total	436		**Total**	570

Table 3: Details of load for M-III house model with both AC and DC system

Load	Quantity	DC Load			AC Load		
		Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)	Rating (W)	Power Under Running Condition (W)	Total Rated Power (W)
LED Bulb	17	7	4-6	119	15	12-14	255
Fan	4	35	27-33	140	60	50-55	240
Television	1	25	23-25	25	25	23-25	25
Mixer	1	150	120-125	150	150	120-125	150
Cooler	1	60	55-58	60	110	98-103	110
Laptop	1	60	56-59	60	60	56-59	60
			Total	554		**Total**	840

2.2.3 Technical Details of the Equipment and Accessories used

The equipment used for the project are mainly home appliances, solar panel, converters, inverters, batteries and conductors. Instead of buying separate equipment for different tests, the same equipment are used with little modifications. The technical details of all components are given in Table 4.

Table 4: Technical details of the equipment and accessories

Sl No	Item Type	Area (mm^2)	Make	Specification
1	Copper Conductor	0.5	Finolex	4A
		1	Finolex	13A
		1.5	Finolex	18A
		2.5	Finolex	24A
		4	Finolex	32A
		6	Finolex	41A
2	DC LED Bulb		Citylight	7W,12V,700 lux
3	AC LED Bulb		Crompton	7,230V ,700 lux
4	CFL		Anchor	15,230V,700 lux
5	DC Fan		Vikram	35W,12V,350 rpm
6	AC Fan		Orient	60W,230V, 350 rpm
7	Television		Rajivihan	25W,12/230V
8	DC Cooler		Rajivihan	60W,12V
9	AC Cooler		Sympomny	110W,230V
10	DC Motor		Unite Motor	150W,24V
11	Mixer		Panasonic	150W,230V
12	Laptop		HP	60W,19V/230V
13	Switch		Anchor	6A, 230 V
14	Switch		Anchor	15A, 230 V
15	Plug		Anchor	5A, 230 V
16	Holder		Anchor	6A, 230 V
17	Plug		Anchor	5A, 230 V
18	MCB		Havells	32A, 230 V
19	Battery		Luminous	12 VDC, 100 AH, Tubular
20	Inverter		Luminous	1.6 kVA, 230 V, 50 Hz
21	Charge Controller		Systeller	12/24V OUTPUT 48V, 40 A INPUT
22	Buck Converter		Xincol	24 VDC TO 12 VDC, 10 A
23	AC-DC Convertewr		Xincol	230 TO 12V, 15 A
24	Solar Panel		Tata Power Solar	300 W, V_{mpp}: 36.6 V, I_{mpp}: 8.2 A V_{oc}: 44.8 V, I_{sc}: 8.71 A

2.2.4 Design of Conductor for AC and DC Type House Wiring

In this project, different types of wiring configurations are used as one of the objective of this project is to provide optimal design for house wiring. The resistance of the wire will be lower as the diameter increases and the diameter of the conductor depends on the amount of current flowing. However, standard conductor sizes need to be taken, even if the current carrying capability is higher than the actual current.

2.2.5 Installation Design of AC and DC Type House Wiring

For all the three model houses, the wiring configuration is chosen so that the length of wire with high current carrying capacity is less and the total length is optimum. This is simply done by finding out the shortest path by observation/inspection of structure of the model. Fig. 10 shows the house wiring of M-II model house with AC distribution and Fig. 11 shows the house wiring of M-II model house with DC distribution. In a similar way, the wiring for the remaining model houses M-I and M-III were designed and tested.

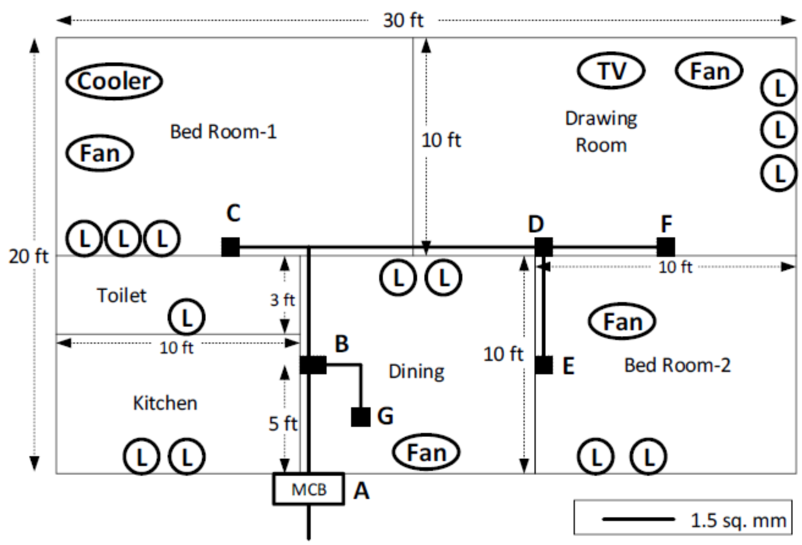

Figure 10: House wiring of conventional AC distribution system for M-II model house

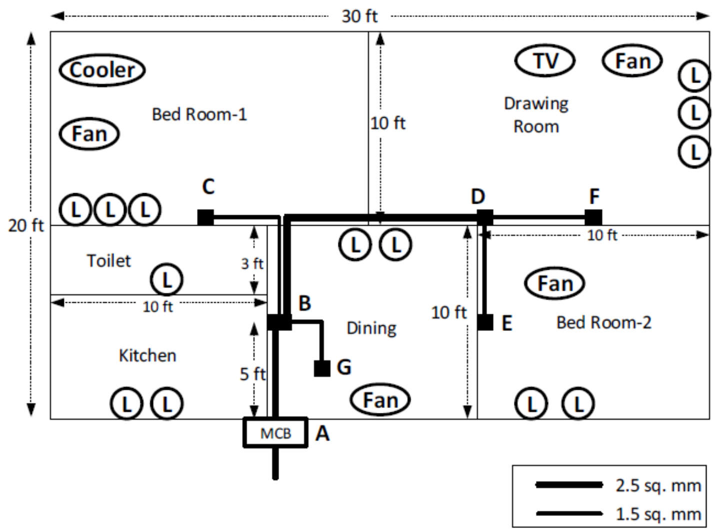

Figure 11: House wiring of DC distribution system for M-II model house

2.2.6 Experiment Design Details of the System

In this project, the studies have been conducted for three combinations of wirings and loads for all the three model houses with typical wiring designs (AC/DC) and load types (AC/DC). They are: AC wiring-AC load, DC wiring-DC load and AC wiring-DC load. In all the cases, the energy source is from the PV panels with battery backup. The focus is on loss calculation along with the associated cost.

2.2.6.1 AC Wiring-AC Load (ACW-ACL)

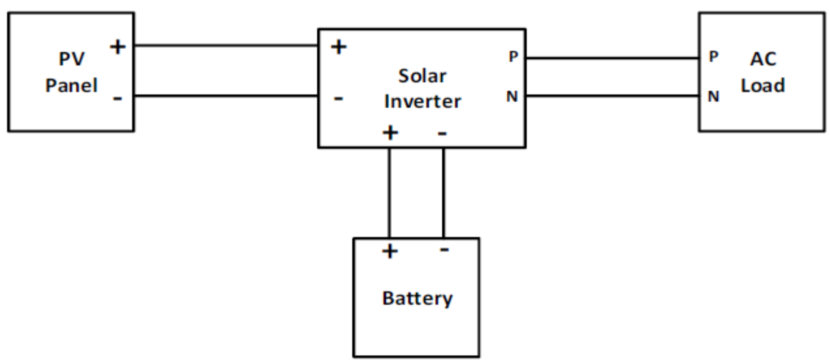

Figure 12: House wiring of AC distribution system with AC load for model house

This is the conventional existing system with AC wiring and AC loads. Fig.12 shows the configuration of house load connected to the PV panel. In this case, an inverter is used to supply the AC load. However, the inverter is using solar DC output as input for supplying power to the house models. The output of the inverter is regular 1 Phase, 230 V, 50 Hz ac. The wiring of the different house models have been designed according to the loads connected. The wire size of each section has been chosen depending on the amount of current flowing through it. The loads connected in the house are of regular AC type loads.

2.2.6.2 AC Wiring-DC Load (ACW-DCL)

Fig.13 shows the configuration of house loads connected to the PV panel. In this case, an inverter is used to supply the model house. However, the inverter is using solar DC output as input for supplying power to the house models. The output of the inverter is regular 1 Phase, 230 V, 50 Hz ac. The wiring of the different house models have been designed according to the DC loads connected by considering the voltage level of 230 V. The wire size of each section has been chosen depending on the amount of current flowing through it. The loads connected in the house are of regular DC type loads. This type of configuration is considered to evaluate the condition for the existing houses with AC distribution, where the loads are replaced by DC loads.

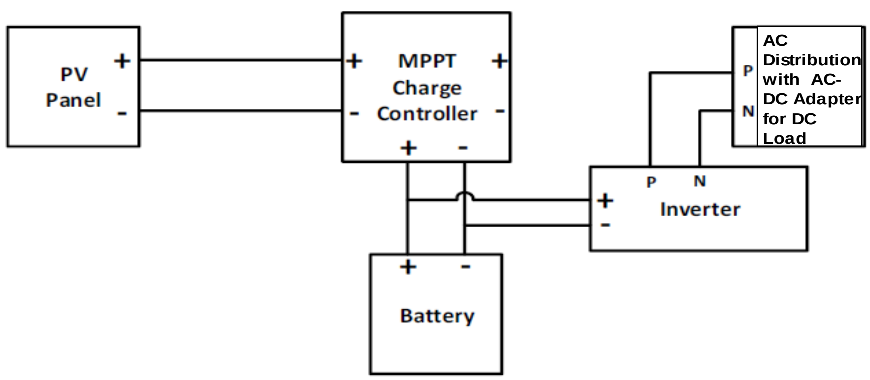

Figure 13: House wiring of AC distribution system with DC load for model house

2.2.6.3 DC Wiring-DC Load (DCW-DCL)

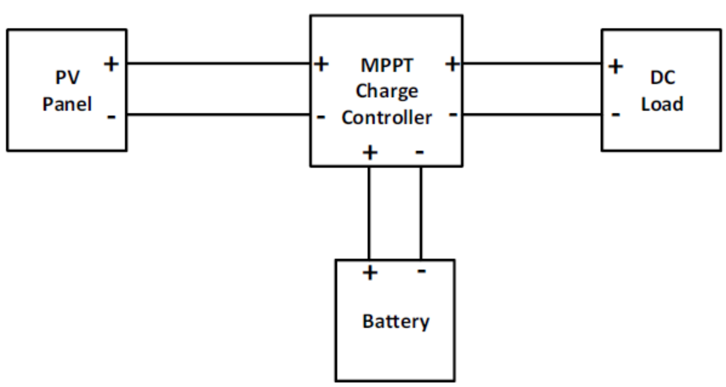

Figure 14: House wiring of DC distribution system with DC load for model house

Fig.14 shows the configuration of house loads connected to the PV panel. In this case, a charge controller is used and the DC power supplies the DC load. The output of the charge controller is 24 V DC. The wiring of the different house models are designed according to the DC loads connected. The wire size of each section has been chosen depending on the amount of current flowing through it. The loads connected in the house are of regular DC type loads.

2.2.7 Battery Sizing

In this project for all supply-load configurations and all test conditions, 200 Ah, 400 Ah and 600 Ah batteries are used for M-I, M-II and M-III house models, respectively. Here we have considered the DC distribution voltage level as 24 V DC; hence, for battery backup, two 12 V batteries are connected in series to obtain the required distribution voltage. However, for battery sizing, the total battery power required is computed as per 12 V DC, not as 24 V DC for easy understanding.

Table 5: Battery sizing for M-I, M-II and M-III house models with ACW-ACL configuration

House Model	Type of Backup Requirement	Total Load (W)	Total Energy (Wh)	Computed Capacity for 12 V Battery (Ah)*	Battery Capacity Considering UF (Ah)**	Battery Capacity Considering Discharge Factor (Ah)***	Used Battery Capacity (Ah)
M-I	2 Hr Full Load Backup	320	640	53.33	66.67	133.33	200
	6 Hr Backup	320	1920	160.00	200.00	400.00	
	12 Hr Backup	320	3840	320.00	400.00	800.00	
	As per daily Load Schedule	148	1776	148.00	185.00	231.25	
M-II	2 Hr Backup	532	1064	88.67	110.83	221.67	400
	6 Hr Backup	532	3192	266.00	332.50	665.00	
	12 Hr Backup	532	6384	532.00	665.00	1330.00	
	As per daily Load Schedule	215	2580	215.00	268.75	335.94	
M-III	2 Hr Backup	660	1320	110.00	137.50	275.00	600
	6 Hr Backup	660	3960	330.00	412.50	825.00	
	12 Hr Backup	660	7920	660.00	825.00	1650.00	
	As per daily Load Schedule	242	2904	242.00	302.50	378.13	

Table 6: Battery sizing for M-I, M-II and M-III house models with ACW-DCL configuration

House Model	Type of Backup Requirement	Total Load (W)	Total Energy (Wh)	Computed Capacity for 12 V Battery (Ah)*	Battery Capacity Considering UF (Ah)**	Battery Capacity Considering Discharge Factor (Ah)***	Used Battery Capacity (Ah)
M-I	2 Hr Full Load Backup	187	374	31.17	38.96	77.92	200
	6 Hr Backup	187	1122	93.50	116.88	233.75	
	12 Hr Backup	187	2244	187.00	233.75	467.50	
	As per daily Load Schedule	85	1020	85.00	106.25	132.81	
M-II	2 Hr Backup	310	620	51.67	64.58	129.17	400
	6 Hr Backup	310	1860	155.00	193.75	387.50	
	12 Hr Backup	310	3720	310.00	387.50	775.00	
	As per daily Load Schedule	139	1668	139.00	173.75	217.19	
M-III	2 Hr Backup	396	792	66.00	82.50	165.00	600
	6 Hr Backup	396	2376	198.00	247.50	495.00	
	12 Hr Backup	396	4752	396.00	495.00	990.00	
	As per daily Load Schedule	146	1752	146.00	182.50	228.13	

Table 7: Battery sizing for M-I, M-II and M-III house models with DCW-DCL configuration

House Model	Type of Backup Requirement	Total Load (W)	Total Energy (Wh)	Computed Capacity for 12 V Battery (Ah)*	Battery Capacity Considering UF (Ah)**	Battery Capacity Considering Discharge Factor (Ah)***	Used Battery Capacity (Ah)
M-I	2 Hr Full Load Backup	187	374	31.17	38.96	77.92	200
	6 Hr Backup	187	1122	93.50	116.88	233.75	
	12 Hr Backup	187	2244	187.00	233.75	467.50	
	As per daily Load Schedule	85	1020	85.00	106.25	132.81	
M-II	2 Hr Backup	310	620	51.67	64.58	129.17	400
	6 Hr Backup	310	1860	155.00	193.75	387.50	
	12 Hr Backup	310	3720	310.00	387.50	775.00	
	As per daily Load Schedule	139	1668	139.00	173.75	217.19	
M-III	2 Hr Backup	396	792	66.00	82.50	165.00	600
	6 Hr Backup	396	2376	198.00	247.50	495.00	
	12 Hr Backup	396	4752	396.00	495.00	990.00	
	As per daily Load Schedule	146	1752	146.00	182.50	228.13	

* Load current with 12 V battery = Total Wh/12

** Battery Capacity by considering utilization efficiency of 80% = Computed capacity/0.8

***Required Battery Capacity can be calculated by considering the discharge rate between 50% to 80%: Computed Battery Capacity/Discharge Rate

For the case of full load backup for 2 Hr, 6 Hr and 12 Hr, the discharge rate is considered as 0.5; however for the daily scheduled load case, the discharge rate is considered as 0.8. For battery sizing calculation for all configurations, utilization efficiency of battery is considered as 80% (considering the safe SoC level). Thus, the utilization factor (UF) is 0.8. For low voltage distribution and with full load operation with the battery, the battery size should be properly chosen because of high rate of discharge. Hence, for high discharge current, a factor ranging from 50-80% is considered. For daily scheduled load operation, the amount of current drawn from the battery is not so high; hence the discharge factor is considered as 80%. Tables 5-7 show the battery sizing calculation for all house models with different configurations.

2.2.8 Conductor Loss

Tables 8 to 10 show the conductor loss calculation for all the house models with different configurations.

Table 8: Estimation of conductor loss with ACW-ACL, ACW-DCL and DCW-DCL configurations for M-I house model

Item	**Type**	**ACW-ACL**			**ACW-DCL**			**DCW-DCL**		
		Resistance (Ohm)	**Current (A)**	**Loss (W)**	**Resistance (Ohm)**	**Current (A)**	**Loss (W)**	**Resistance (Ohm)**	**Current (A)**	**Loss (W)**
Branch 1	Conductor	0.068	1.41	0.135	0.102	0.85	0.074	0.0408	6.5	1.724
Branch 2	Conductor	0.051	0.575	0.017	0.0766	0.3	0.007	0.051	2.12	0.229
Branch 3	Conductor	0.051	0.49	0.012	0.0766	0.21	0.003	0.051	2.68	0.366
Branch 4	Conductor	0.051	0.384	0.008	0.0766	0.33	0.008	0.051	1.68	0.144
Drawing Room	Bulb	0.058	0.12	0.0008	0.058	0.06	0.0002	0.058	0.29	0.005
Bed Room	Bulb	0.058	0.12	0.0008	0.058	0.06	0.0002	0.058	0.29	0.005
Dining Room	Bulb	0.048	0.12	0.0006	0.048	0.06	0.0001	0.048	0.29	0.004
Kitchen	Bulb	0.077	0.12	0.0011	0.077	0.06	0.0002	0.077	0.29	0.006
Toilet	Bulb	0.0905	0.06	0.0003	0.0905	0.03	0.0027	0.0905	0.14	0.002
Total				**0.1756**			**0.0954**			**2.485**

Table 9: Estimation of conductor loss with ACW-ACL, ACW-DCL and DCW-DCL configurations in M-II house model

Item	Type	ACW-ACL			ACW-DCL			DCW-DCL		
		Resistance (Ohm)	Current (A)	Loss (W)	Resistance (Ohm)	Current (A)	Loss (W)	Resistance (Ohm)	Current (A)	Loss (W)
Branch 1	Conductor	0.068	2.43	0.402	0.102	1.38	0.194	0.0408	10.89	4.839
Branch 2	Conductor	0.051	0.575	0.017	0.065	0.3	0.006	0.051	2.12	0.229
Branch 3	Conductor	0.034	0.91	0.028	0.051	0.52	0.014	0.034	4.25	0.614
Branch 4	Conductor	0.068	0.94	0.060	0.102	0.55	0.031	0.0408	4.52	0.834
Branch 5	Conductor	0.051	0.56	0.016	0.065	0.36	0.008	0.051	2.83	0.408
Branch 6	Conductor	0.051	0.38	0.007	0.065	0.19	0.002	0.051	1.68	0.144
Drawing Room	Bulb	0.058	0.19	0.002	0.058	0.09	0.0004	0.058	0.43	0.011
Bed Room	Bulb	0.058	0.19	0.002	0.058	0.09	0.0004	0.058	0.43	0.011
Bed Room	Bulb	0.058	0.12	0.0008	0.058	0.06	0.0002	0.058	0.29	0.005
Dining Room	Bulb	0.048	0.12	0.0006	0.048	0.06	0.0001	0.048	0.29	0.004
Kitchen	Bulb	0.077	0.12	0.001	0.077	0.06	0.0002	0.077	0.29	0.006
Toilet	Bulb	0.091	0.06	0.0003	0.0905	0.03	0.0001	0.0905	0.14	0.002
Total				**0.5367**			**0.2564**			**7.106**

It can be seen from the tables that the conductor loss for DC is high compared to the AC wiring system. It is due to the flow of high amount of current in DC system causing higher I^2R loss. However in case of AC, the current level is low with lower loss.

Table 10: Estimation of conductor loss with ACW-ACL, ACW-DCL and DCW-DCL configurations in M-III house model

Item	Type	ACW-ACL			ACW-DCL			DCW-DCL		
		Resistance (Ohm)	Current (A)	Loss (W)	Resistance (Ohm)	Current (A)	Loss (W)	Resistance (Ohm)	Current (A)	Loss (W)
Branch 1	Conductor	0.102	2.96	0.895	0.1534	1.8	0.497	0.0614	15.15	14.093
Branch 2	Conductor	0.068	0.63	0.027	0.102	0.34	0.012	0.068	2.47	0.415
Branch 3	Conductor	0.085	0.98	0.082	0.128	0.55	0.039	0.0852	4.79	1.955
Branch 4	Conductor	0.068	1.34	0.122	0.102	0.91	0.084	0.068	7.88	4.222
Branch 5	Conductor	0.051	0.62	0.020	0.0766	0.32	0.008	0.051	3.25	0.539
Branch 6	Conductor	0.068	0.72	0.035	0.102	0.52	0.028	0.068	4.63	1.458
Drawing Room	Bulb	0.058	0.24	0.003	0.058	0.12	0.0008	0.058	0.58	0.020
Bed Room	Bulb	0.058	0.18	0.002	0.058	0.09	0.0004	0.058	0.43	0.011
	Bulb	0.256	0.06	0.001	0.256	0.03	0.0002	0.256	0.14	0.005
Bed Room	Bulb	0.058	0.18	0.002	0.058	0.09	0.0004	0.058	0.43	0.011
Dining Room	Bulb	0.048	0.18	0.002	0.048	0.09	0.0004	0.048	0.43	0.009
Kitchen	Bulb	0.077	0.12	0.001	0.077	0.06	0.0003	0.077	0.29	0.006
Toilet	Bulb	0.091	0.06	0.0003	0.0905	0.03	0.003	0.0905	0.14	0.002
Total				**1.192**			**0.6735**			**22.744**

2.3 Study of different loads for DC house model

In order to select the loads needed for the DC house, it is important to consider the needs of the people living there, humanitarian goals of the DC house project and weigh them against the constraints that an isolated generation system provides. First, the limitations of our generation system should be accurately defined, and then a strategy is developed to select the loads that can meet the constraints. The following subsections highlight these issues.

2.3.1 LED Lighting

The DC House model needs to have a source of light for night hours. The most efficient form of lighting is through the use Light Emitting Diodes (LEDs). LED bulb is more efficient than Compact Fluorescent Lamp (CFL) and incandescent light bulbs. Required number of LEDs are used to light up the DC houses. However, the lumens emitted by these LED bulbs must be appropriate for the size of the model. A Simulink circuit model of seven LEDs is shown in Fig. 15.

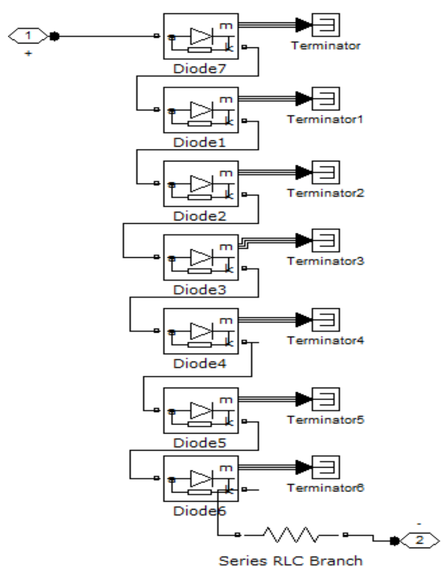

Figure 15: Simulink model of a LED circuit

In Fig. 15, the source voltage is 24 V, the forward voltage drop of each LED is 3.2 V, and the resistor value is 9 Ω. These assumptions would result in a branch current of:

$$I = \frac{24 - 7 \times 3.2}{9} = 177mA \tag{2}$$

The power dissipated by each LED and the resistor are determined as:

$$P_{resistor} = I^2 R = .177^2 \times 9 = 0.281W \quad (3)$$

$$P_{led} = 7 \times 3.2 \times 0.1777 = 4W \quad (4)$$

Then the efficiency of the string can be calculated by determining the amount of power dissipated by the LEDs compared to the amount of power dissipated by the entire string with "*n*" being the number of LEDs in the string. The efficiency (η) is determined as:

$$Efficiency_{led} = \frac{n * P_{led}}{n * P_{led} + P_{resistor}} \quad (5)$$

It indicates that the efficiency increases with the number of LEDs as there will always be power loss with the current limiting resistor, and this should be there to limit the current through the string thereby protecting the LEDs from damage. It is possible however to increase the number of LEDs per string, which would make the power wasted by the resistor less significant (which will always stay almost the same regardless of the number of LEDs in the circuit). The tradeoff associated with increasing the number of LEDs is the increasing requirement of source voltage.

2.3.2 Ceiling Fan

The table top/wall mount fan uses a simple permanent magnet DC motor. Its maximum power requirement (as stated in previous sections) is approximately 45-50 W. The Simulink model must accurately represent the transient and steady state characteristics of DC motor. The transient characteristics is more involved than that of the steady state operation which does not need to account for transient reactance in the motor windings. A generalized dc fan of the same order of magnitude in terms of power consumption is modeled as in Fig. 16 with an acceptable fan speed of 450-500 rpm. The torque for the motor is calculated using the rated electrical power of the fan.

$$P = T\omega \quad and \quad \mathrm{T} = \frac{P}{\omega} = \frac{50}{2\pi \times 500} = 0.16Nm \quad (6)$$

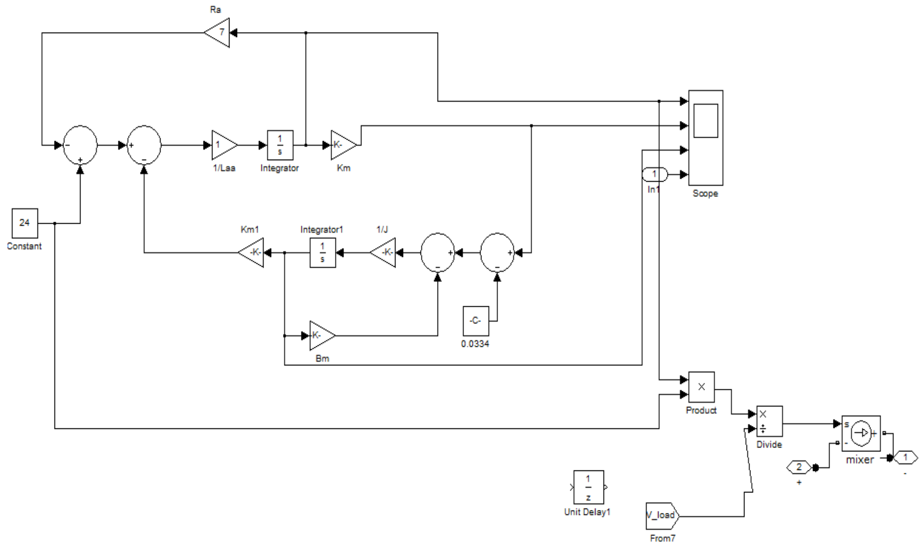

Figure 16: Simulink model of dc fan

2.3.3 Television (TV)

Generally the internal circuit of most of the televisions require DC power. It is obtained internally by converting 230 V AC to the required DC level. Thus unnecessary losses occur in the internal circuit. This can be avoided by operating the TV using DC source. Generally, the DC-operated televisions consumes 60-70 W. So, for simulation of a DC television, one can simply put an equivalent resistor whose value can be calculated as:

$$R_{television} = \frac{V_{load}^{\ 2}}{P_{television}} = \frac{24^2}{70} = 8.23\Omega \tag{7}$$

2.3.4 Mixer

Mixer is a simple DC motor like ceiling fan, but with higher capacity. The mixer consumes a power of 200-250 W. Depending on the rating of the motor, the torque also varies. Normally the speed of the motor lies between 15000-20000 rpm. For simulation of mixer, one can use the basic DC motor model with the required load torque is given as:

$$P = T\omega \;\; and \quad \mathrm{T} = \frac{P}{\omega} = \frac{200}{2\pi \times 20000} = 0.0016Nm \tag{8}$$

2.4 Simulation of M-I house model

The Simulink simulation model for M-I DC house and some typical results are discussed below.

2.4.1 Simulink Schematic of M-I house model

The Simulink schematic of the full M-I DC house connected with all loads is shown in Fig. 17. Figs. 18-22 show the detailed Simulink models for the dining room, drawing room, bed room, kitchen and toilet, respectively.

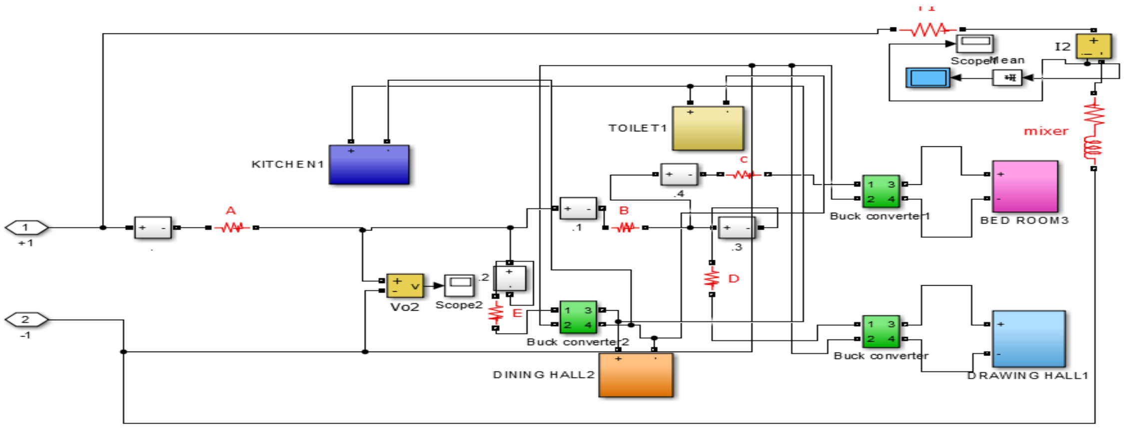

Figure 17: Simulink schematic of M-I DC house model

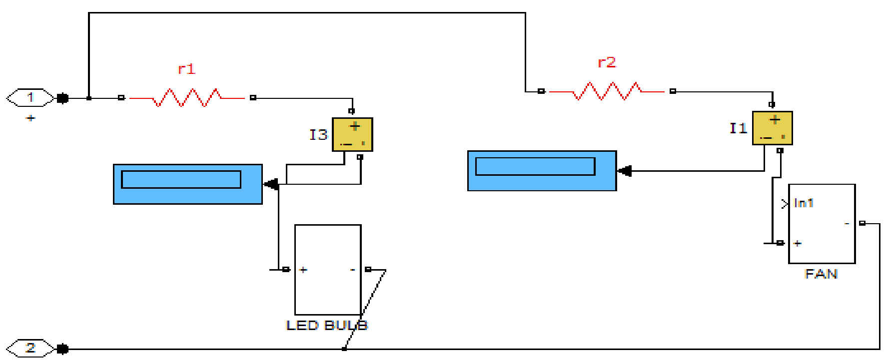

Figure 18: Simulink schematic of dining room in M-I house model

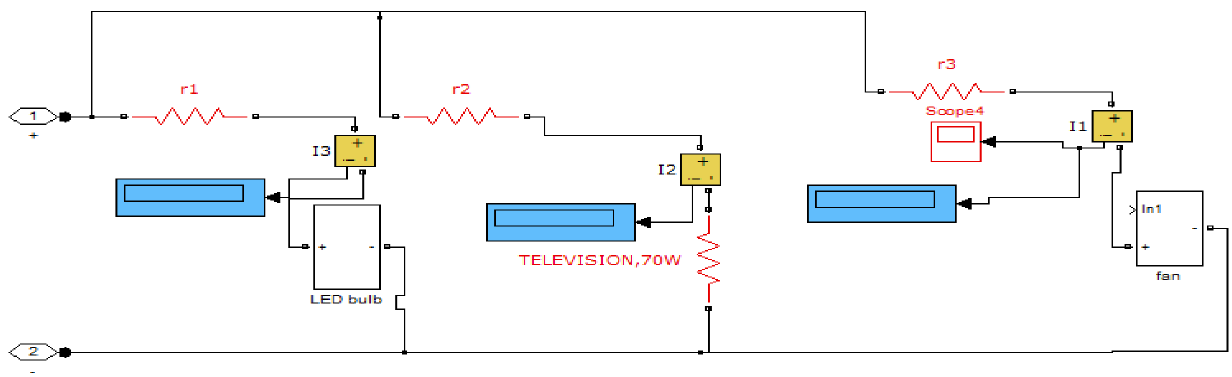

Figure 19: Simulink schematic of drawing room in M-I house model

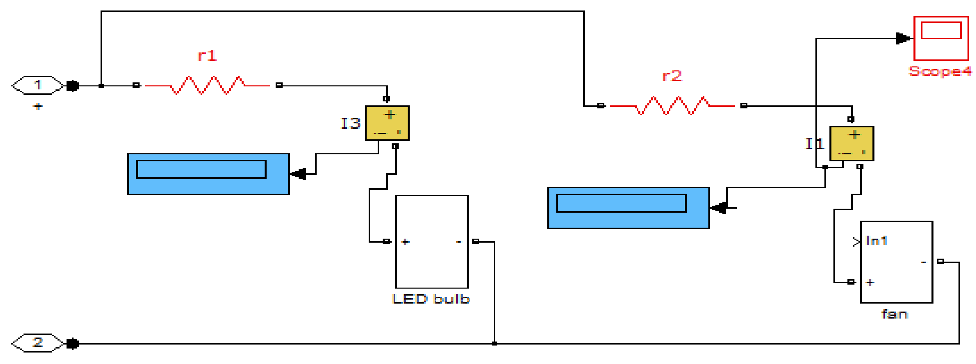

Figure 20: Simulink schematic of bed room in M-I house model

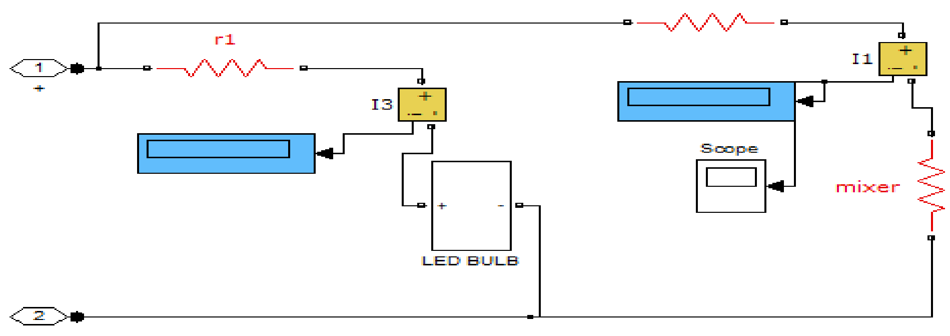

Figure 21: Simulink schematic of kitchen in M-I house model

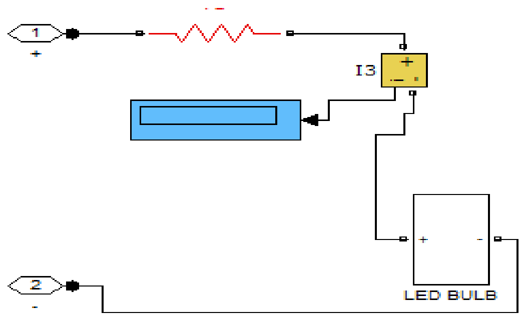

Figure 22: Simulink schematic of toilet in M-I house model

2.4.2 Simulation results of M-I house model

The simulation results for different loads are discussed below.

2.1.2.1 When All Loads Are Connected

When all the loads for M-1 model are connected, the current drawn by each type load and their voltage profiles are shown below.

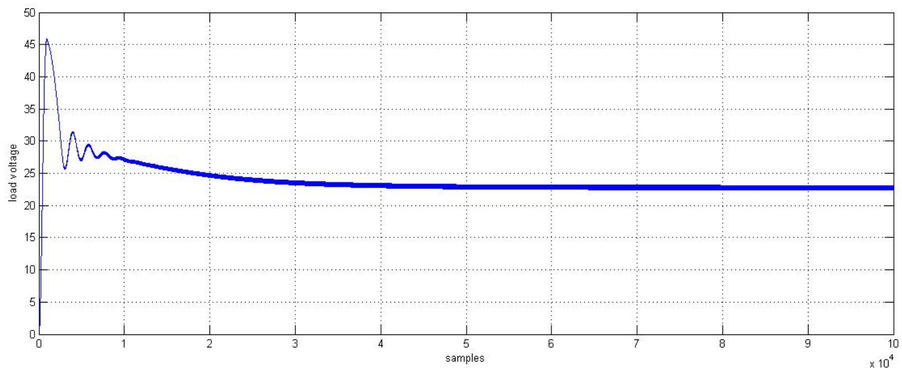

Figure 23: Total load voltage

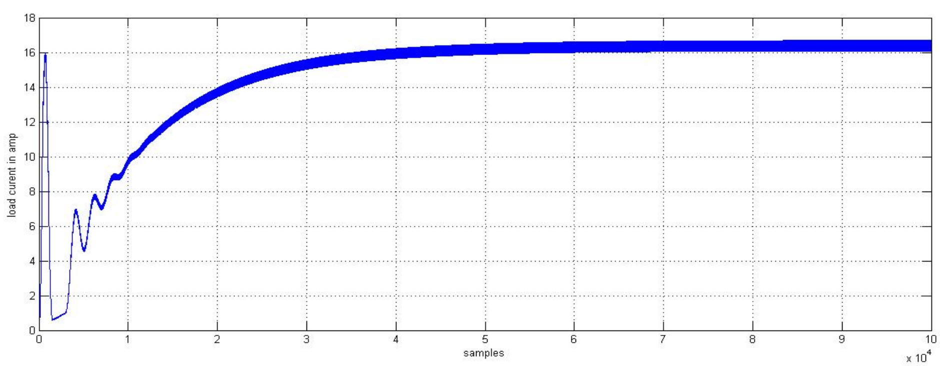

Figure 24: Total load current

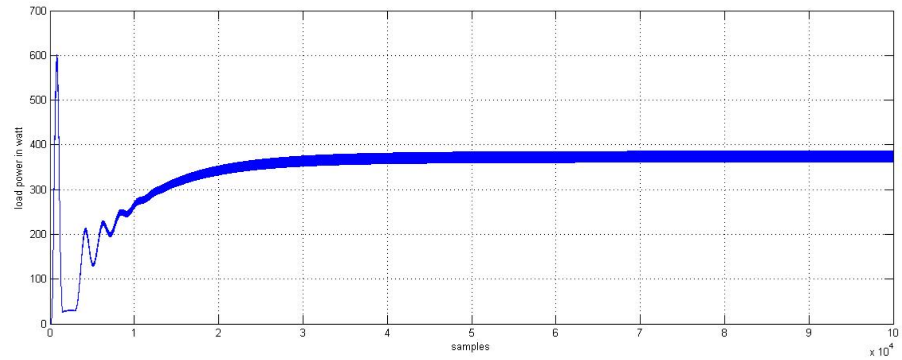

Figure 25: Total load power for M-I house model

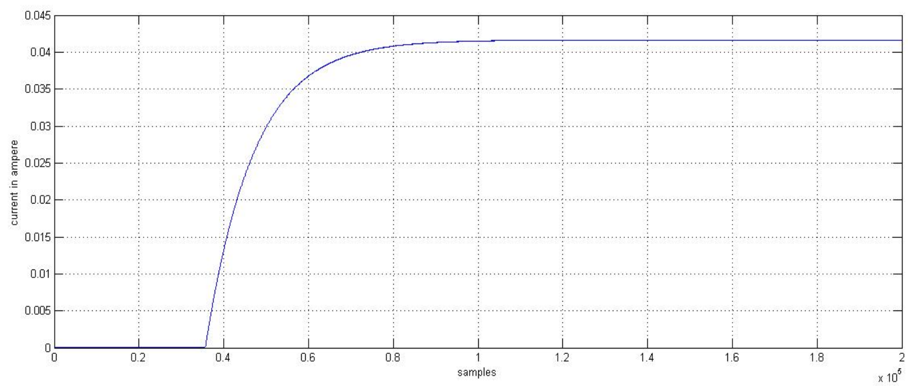

Figure 26: Current drawn by LED bulb

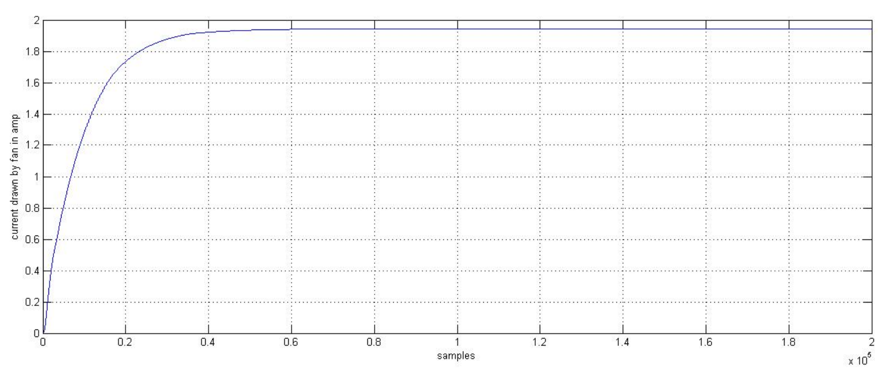

Figure 27: Current drawn by fan

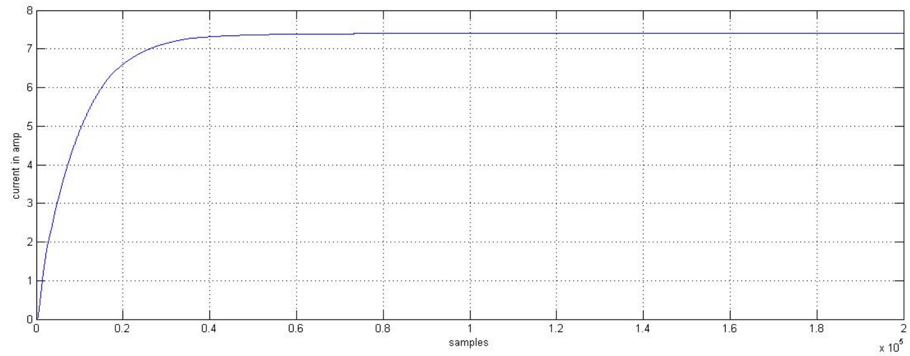

Figure 28: Current drawn by mixer

2.4.2.2 Performance during load switching

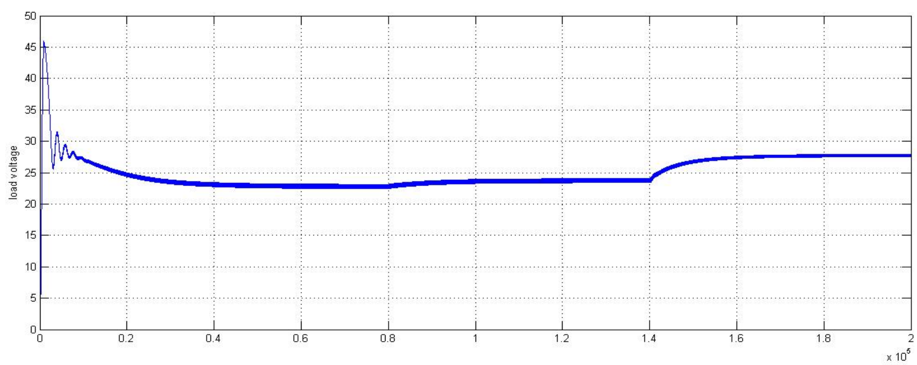

Figure 29: Total load voltage

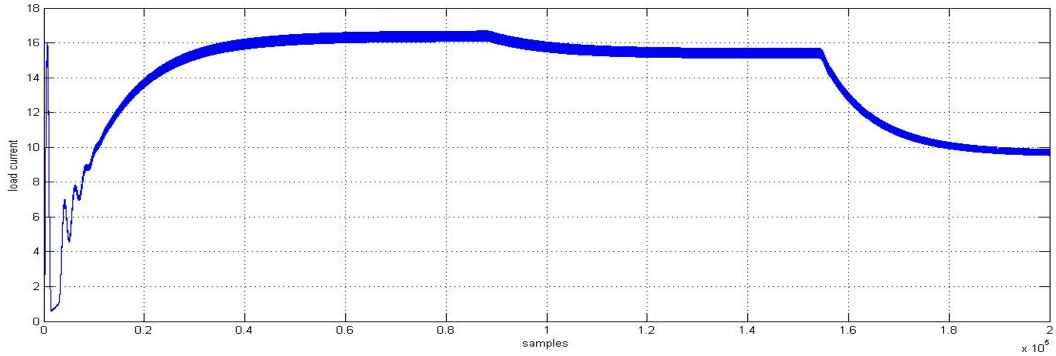

Figure 30: Total load current

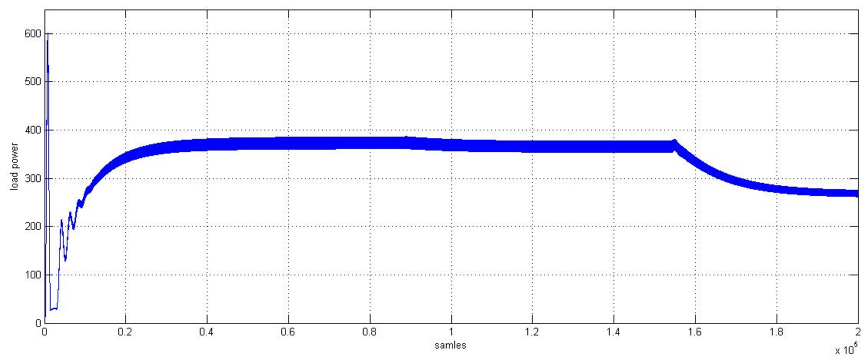

Figure 31: Total load power

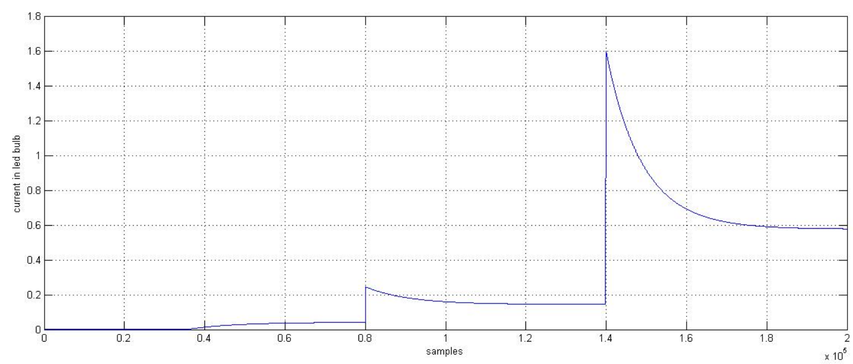

Figure 32: Current drawn by LED bulb

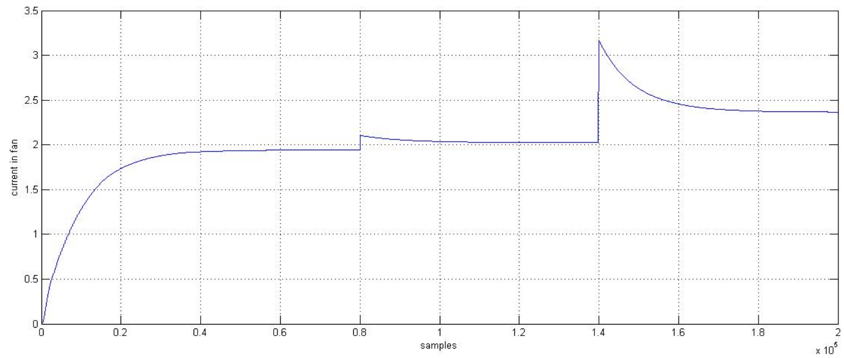

Figure 33: Current drawn by fan

3. Design and evaluation of an integrated PV based home electrification system, without and with battery energy (2hrs), to meet the energy demands during day time for different loads such as Fan, TV, and Light

In this project, an integrated PV-based home electrification system is realized. For all the model houses, experimental data have been collected, without and with battery energy (for 2 hours), for PV powered AC load and PV powered DC load. During measurement, all the loads are switched ON.

Loss (W) = Battery Power (W) – Total Load Power (W) ⟹ Only with Battery

Loss (W) = Solar Power (W) + Battery Power (W) – Total Load Power (W) ⟹ With PV and Battery

3.1 M-I house model (< 500 W)

Basically the M-I model house is tested for two hour of back up with full load. Battery capacity used for this test is of 200 Ah. Intermittently the mixer is switched on for 5 minutes in every 15 minutes interval. Tables 11 and 12 show the average battery power drawn for the total load without solar energy for two hours for AC and DC loads, respectively. The battery power and load power are calculated as average quantities accordingly. It is observed that, with ACW-ACL system, there is a loss of around 60 W compared to 5 W in the case of DCW-DCL. Difference in loss is mainly due to the presence of inverter in case of ACW-ACL system instead of charge controller in case of DCW-DCL system.

Table 11: AC load of M-I running without solar input (2 hours) for ACW-ACL

	Battery Voltage (V)	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Total Load Power (W)**	**Loss (W)**
End of 1 hour	24.24	15.6	378.144	213	1.5	319.5	58.644
End of 2 hour	23.86	16.1	384.146	213	1.5	319.5	64.646

Table 12: DC load of M-I running without solar input (2 hours) for DCW-DCL

	Battery Voltage (V)	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Total Load Power (W)**	**Loss (W)**
End of 1 hour	24.86	6.98	173.5228	24.08	6.98	168.218	5.3048
End of 2 hour	24.68	7.04	173.7472	23.9	7.04	168.3968	5.3504

The power shared by the PV source and battery for the total load of M-I for two hours with AC and DC loads are depicted in Tables 13 and 14, respectively. The test conditions are same as in the case without solar power. Here also, intermittently the mixer was switched on for 5 minutes in consecutive 15 minutes interval. However, the time of test was during the morning when the solar power is gradually increasing. The battery power and load power were calculated as average quantities accordingly (on hourly basis). The difference in loss is also observed between AC and DC loads.

Table 13: AC load of M-I running with solar input (2 hours) for ACW-ACL

PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Load Power (W)	Loss (W)
24.6	1.82	44.77	24.24	13.75	333.36	213	1.5	319.5	58.64
25.2	6.94	174.88	24.86	8.47	210.75	214	1.5	321	64.64

Table 14: DC load of M-I running with solar input (2 hours) for DCW-DCL

PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Load Power (W)	Loss (W)
27.7	1.62	44.87	27.76	5.36	148.79	26.98	6.98	188.32	5.34
27.9	5.37	149.82	27.68	1.67	46.22	26.9	7.04	189.37	6.67

3.2 M-II house model (< 750 W)

Similar tests are conducted on M-II house model for two hour of back up with full load. Tables 15 and 16 show the average battery power drawn for the total load of M-II without solar energy for two hours for AC and DC load, respectively. The battery capacity used for this test is of 400 Ah. It is observed that, when the M II model is experimented with ACW-ACL system, there is a loss of around 90 W compared to 10 W in the case of DCW-DCL system. The difference in loss is mainly due to the presence of inverter in case of ACW-ACL system instead of charge controller with DCW-DCL system.

Table 15: AC load of M-II running without solar input (2 hours) for ACW-ACL

	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Total Load Power (W)	Loss (W)
End of 1 hour	24.12	25.8	622.296	213.1	2.5	532.75	89.546
End of 2 hour	23.81	26.4	628.584	213	2.5	532.5	96.084

Table 16: DC load of M-II running without solar input (2 hours) for DCW-DCL

	Battery Voltage (V)	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Total Load Power (W)**	**Loss (W)**
End of 1 hour	24.67	11.71	288.8857	23.8	11.71	278.698	10.1877
End of 2 hour	24.53	11.76	288.4728	23.7	11.76	278.712	9.7608

The average power shared by the PV source and battery for the total load of M-II for two hours with AC and DC loads are given in Tables 17 and 18, respectively. The test conditions are same as in the case without solar power. However, the time of test was during the morning when the solar power is gradually increasing. The difference in loss is also observed between ACW-ACL and DCW-DCL system. It is observed that the loss in the case of ACW-ACL system is around 90 W and in case of DCW-DCL system, it is around 8 W.

Table 17: AC load of M-II running with solar input (2 hours) for ACW-ACL

PV Voltage (V)	**PV Current (A)**	**PV Power (W)**	**Battery Voltage (V)**	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Load Power (W)**	**Loss (W)**
24.6	2.43	59.778	24.24	23.7229	575.042	213	2.56	545.28	89.54
25.4	9.05	229.87	25.12	16.4029	412.04	214	2.55	545.7	96.21

Table 18: DC load of M-II running with solar input (2 hours) for DCW-DCL

PV Voltage (V)	**PV Current (A)**	**PV Power (W)**	**Battery Voltage (V)**	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Load Power (W)**	**Loss (W)**
27.51	1.78	48.9678	27.47	9.93	272.777	26.84	11.71	314.296	7.448
27.62	6.33	174.8346	27.55	5.43	149.597	26.92	11.76	316.579	7.851

3.3 M-III house model (< 1000 W)

Similar tests are conducted on M-II house model for two hour of back up with full load. The battery powers drawn for the total load of M-III without solar energy for two hours for AC and DC load are given in Tables 19 and 20, respectively. The battery capacity used for the above test is of 600 Ah. There is a loss of around 110 W in ACW-ACL system compared to 15 W in the case of DCW-DCL system for the M-III house model. The difference in loss is mainly due to presence of inverter in case of ACW-ACL system instead of charge controller in case of DCW-DCL system.

Table 19: AC load of M-III running without solar input (2 hours) for ACW-ACL

	Battery Voltage (V)	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Total Load Power (W)**	**Loss (W)**
End of 1 hour	24.12	31.9	769.428	213	3.1	660.3	109.128
End of 2 hour	23.83	32.5	774.475	213	3.1	660.3	114.175

Table 20: DC load of M-III running without solar input (2 hours) for DCW-DCL

	Battery Voltage (V)	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Total Load Power (W)**	**Loss (W)**
End of 1 hour	24.32	15.41	374.7712	23.32	15.41	359.3612	15.41
End of 2 hour	24.19	15.5	374.945	23.19	15.5	359.445	15.5

The measurements are also recorded for the average power shared by the PV source and battery for the total load of M-III for two hours with AC and DC load and are given in Tables 21 and 22, respectively. The time of test was during the morning when the solar power is gradually increasing. It is observed that the loss in the case of ACW-ACL system is around 110 W and in case of DCW-DCL system, it is roughly 11 W.

Table 21: AC load of M-III running with solar input (2 hours) for ACW-ACL

PV Voltage (V)	**PV Current (A)**	**PV Power (W)**	**Battery Voltage (V)**	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Load Power (W)**	**Loss (W)**
24.3	2.13	51.759	23.87	30.2447	721.941	213	3.12	664.56	109.14
24.92	7.14	177.9288	24.46	24.9555	610.411	214	3.15	674.1	114.24

Table 22: DC load of M-III running with solar input (2 hours) for DCW-DCL

PV Voltage (V)	**PV Current (A)**	**PV Power (W)**	**Battery Voltage (V)**	**Battery Current (A)**	**Battery Power (W)**	**Inverter Output Voltage (V)**	**Inverter Output Current (A)**	**Load Power (W)**	**Loss (W)**
27.51	2.14	58.8714	27.01	13.27	358.423	26.41	15.41	406.978	10.31
27.82	7.02	195.2964	27.47	8.54	234.594	26.82	15.56	417.319	12.57

4. Design and evaluation of an integrated PV based home electrification system using battery energy (1 day), to meet the energy demands during day and night time for different loads such as fan, TV, Laptop, Mixer, and Lights etc.

All the three model houses (M-I, M-II and M-III) are tested based on some typical daily load profile. Total losses were calculated as:

Loss (W) = Solar Power (W) + Battery Power (W) – Total Load Power (W) ⟹ With PV and Battery

4.1 M-I house model (< 500 W)

The M-I house model has been tested for a daily load schedule given in Table 23 (a typical loading pattern of different rooms is considered).

Table 23: Typical considered load schedule for M-I house model for complete one day

	Load	**6:00 AM**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5:00 AM**
Drawing Room	Light	■	■								■	■	■	■	■	■	■	■							
	Fan	■	■	■	■	■					■	■		■	■	■	■	■							
	Television	■	■								■	■		■	■	■	■	■							
Bed Room	Light	■	■	■					■	■					■	■									
	Fan	■	■	■					■	■					■	■	■	■	■	■	■	■	■	■	■
Dining Room	Light	■	■	■	■					■	■						■		■	■	■	■	■	■	■
	Fan			■	■			■		■	■			■			■								
Kitchen	Light		■	■	■	■	■			■	■			■		■	■	■							
	Mixer			■																					
Toilet	Light		■										■												

The house model M-I was tested for one complete day with solar PV and battery backup (capacity = 200 Ah). The power measurements are taken for three different configurations, i.e., ACW-ACL, ACW-DCL and DCW-DCL. For battery power, a negative sign represents the power drawn by battery in a charging mode. Table 24 shows the sharing of PV and battery power. It is seen that the loss varies from 33 W during off-peak hours to around 45 W during peak hours for ACW-ACL configuration. The loss includes inverter and conductor losses; the loss is mainly due to the inverter.

Table 24: Sharing of PV power and battery power for a given load power for M-I during complete day with ACW-ACL configuration

Time	Drawing room			Bedroom		Dining room		Kitchen		Toilet	Load Power (W)	PV Power (W)	Battery Power (W)	Loss (W)
	Light (W)	Fan (W)	TV (W)	Light (W)	Fan (W)	Light (W)	Fan (W)	Light (W)	Mixer (W)	Light (W)				
6 hrs	29	58	25	29	58	29					228	40	230	42
7	29	58	25	29	58	29		29		14.5	271.5	170	144.5	43
8		58		29	58	29	58	29	45		306	230	121	45
9		58				29	58	29			174	360	-150	36
10		58						29			87	328	-209	32
11								29			29	560	-499	32
12							58				58	625	-533	34
13				29	58						87	700	-579	34
14				29	58	29	58	29			203	695	-455	37
15	29	58	25			29	58	29			228	450	-183	39
16	29	58	25								112	350	-204	34
17	29										29	180	-119	32
18	29	58	25				58	29			199	34	201	36
19	29	58	25	29	58					14.5	213.5	12	241.5	40
20	29	58	25	29	58			29			228	0	273	45
21	29	58	25		58	29	58	29			286	0	332	46
22	29	58	25		58			29			199	0	236	37
23					58	29					87	0	120	33
24					58	29					87	0	120	33
1					58	29					87	0	120	33
2					58	29					87	0	120	33
3					58	29					87	0	120	33
4					58	29					87	0	120	33
5 hrs					58	29					87	0	120	33

The house model M-I has been tested with DC load and electric wiring as per AC calculations, i.e., for supply voltage of 230 V. Table 25 shows the power sharing between PV and battery for one day with defined DC load schedule. Near the DC loads, adapters are used for conversion from AC to DC.

This study is done to explore the possibility of using the existing wirings in house and replacing all AC loads by DC loads. Because of less load in case of DC loading, the inverter loss (including conductor loss) also comes down by small amount.

Table 25: Sharing of PV and battery power for a given load power for M-I during complete day with ACW-DCL configuration

	Drawing room			**Bedroom**		**Dining room**		**Kitchen**		**Toilet**	**Load Power (W)**	**PV Power (W)**	**Battery Power (W)**	**Loss (W)**
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**				
6 hrs	14	33.5	25	14	33.5	14					134	65	112	43
7	14	33.5	25	14	33.5	14		14		7	155	185	16	46
8		33.5		14	33.5	14	33.5	14	40		178	272	45	49
9		33.5				14	33.5	14			95	347	216	36
10		33.5						14			47.5	450	-366	36.5
11								14			14	522	-476	32
12							33.5				33.5	612	-547	31.5
13				14	33.5						47.5	650	-568	34.5
14				14	33.5	14	33.5	14			109	540	-395	36
15	14	33.5	25			14	33.5	14			134	430	-259	37
16	14	33.5	25								72.5	280	-178	29.5
17	14										14	148	-112	22
18	14	33.5	25				33.5	14			120	48	106	34
19	14	33.5	25	14	33.5					7	127	0	159	32
20	14	33.5	25	14	33.5			14			134	0	166	32
21	14	33.5	25		33.5	14	33.5	14			167.5	0	203	35.5
22	14	33.5	25		33.5			14			120	0	152	32
23					33.5	14					47.5	0	80	32.5
24					33.5	14					47.5	0	80	32.5
1					33.5	14					47.5	0	80	32.5
2					33.5	14					47.5	0	80	32.5
3					33.5	14					47.5	0	80	32.5
4					33.5	14					47.5	0	80	32.5
5 hrs					33.5	14					47.5	0	80	32.5

Table 26 shows the power sharing between PV and battery for M-I during one day with DC loads with electrical wiring done as per the current calculated using 24 V DC distribution. It is found that the loss is in the range of 2 to 3 W. The power from the PV and battery is supplied directly to the M-I house model.

Table 26: Sharing of PV and battery power for a given load power of M-I during complete day with DCW-DCL configuration

	Drawing room			Bedroom		Dining room		Kitchen		Toilet	Load Power (W)	PV Power (W)	Battery Power (W)	Loss (W)
Time	Light (W)	Fan (W)	TV (W)	Light (W)	Fan (W)	Light (W)	Fan (W)	Light (W)	Mixer (W)	Time				
6 hrs	9.6	33.5	25	9.6	33.5	9.6					120.8	76	47	2.2
7	9.6	33.5	25	9.6	33.5	9.6		9.6		4.8	135.2	195	-56.8	3
8		33.5		9.6	33.5	9.6	33.5	9.6	40		169.3	230	-57.7	3
9		33.5				9.6	33.5	9.6			86.2	300	-211.8	2
10		33.5						9.6			43.1	426	-381.9	1
11								9.6			9.6	425	-414.4	1
12							33.5				33.5	300	-265.5	1
13				9.6	33.5						43.1	356	-311.9	1
14				9.6	33.5	9.6	33.5	9.6			95.8	235	-137.2	2
15	9.6	33.5	25			9.6	33.5	9.6	40		160.8	165	-1.2	3
16	9.6	33.5	25								68.1	80	-10.9	1
17	9.6										9.6	60	-49.4	1
18	9.6	33.5	25				33.5	9.6			111.2	18	96.2	3
19	9.6	33.5	25	9.6	33.5					4.8	116	0	119	3
20	9.6	33.5	25	9.6	33.5		33.5	9.6			154.3	0	157	2.7
21	9.6	33.5	25		33.5	9.6	33.5	9.6			154.3	0	156.8	2.5
22	9.6	33.5	25		33.5		33.5	9.6			144.7	0	147	2.3
23					33.5	9.6					43.1	0	44.2	1.1
24					33.5	9.6					43.1	0	44.1	1
1					33.5	9.6					43.1	0	44.3	1.2
2					33.5	9.6					43.1	0	44.3	1.2
3					33.5	9.6					43.1	0	44.2	1.1
4					33.5	9.6					43.1	0	44.2	1.1
5 hrs					33.5	9.6					43.1	0	44.2	1.1

4.2 M-II (< 750 W) house model

The M-II house model has been tested for a daily load schedule given in Table 27 (typical loading pattern of different rooms is considered).

Table 27: Typical considered load schedule of M-II house model for complete one day

	Load	6:00 AM	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5:00 AM
Drawing Room	Light	■	■											■	■	■	■	■							
	Fan	■	■	■	■	■					■	■		■	■	■	■	■							
	Television	■	■								■	■		■	■	■	■	■							
Bed Room 1	Light	■	■	■					■	■					■										
	Fan	■	■	■					■	■					■			■	■	■	■	■	■	■	■
	Cooler								■	■					■	■	■	■	■	■	■	■	■	■	■
Bed Room 2	Light			■				■	■				■		■			■							
	Fan	■	■	■				■	■				■		■			■	■	■	■	■	■	■	■
Dining Room	Light			■			■									■	■		■	■	■	■	■	■	■
	Fan			■			■		■							■	■								
Kitchen	Light		■						■							■									
	Mixer			■												■									
Toilet	Light		■												■										

The house model M-II was tested for one complete day with solar PV and battery backup (capacity = 400 Ah). The power measurements are taken for three different configurations, i.e., ACW-ACL, ACW-DCL and DCW-DCL. Table 28 shows the sharing of PV and battery power. It is seen that the loss varies from 35-50 W during off-peak hours to around 70 W during peak hours for ACW-ACL configuration. The loss includes inverter and conductor losses which is mainly due to the inverter.

Table 28: Sharing of PV and battery power for a given load power during complete day with ACW-ACL configuration

	Drawing room			**Bedroom 1**			**Bedroom 2**		**Dining room**		**Kitchen**		**Toilet**	**Load Power (W)**	**PV Power (W)**	**Battery Power (W)**	**Loss (W)**
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Cooler (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**				
6 hrs	43.5	58	25	43.5	58			58						286	78	261	53
7	43.5	58	25	43.5	58			58			29		14.5	329.5	189	209	68.5
8		58		43.5	58		29	58	29	58		45		378.5	325	125	71.5
9		58												58	458	-365	35
10		58												58	620	-526	36
11									29	58				87	735	-611	37
12							29	58						87	730	-606	37
13				43.5	58	100	29	58		58	29			375.5	690	-239	75.5
14				43.5	58	100								201.5	568	-317	49.5
15		58	25											83	380	-261	36
16		58	25											83	280	-161	36
17							29	58						87	139	16	36
18	43.5	58	25											126.5	39	130	42.5
19	43.5	58	25	43.5	58		29	58					14.5	329.5	0	397	67.5
20	43.5	58	25						29	58	29	45		287.5	0	341	53.5
21	43.5	58	25						29	58				213.5	0	262	48.5
22	43.5	58	25		58	100	29	58						371.5	0	443	71.5
23					58	100		58	29					245	0	296	51
24					58	100		58	29					245	0	297	52
1					58	100		58	29					245	0	296	51
2					58	100		58	29					245	0	297	52
3					58	100		58	29					245	0	297	52
4					58	100		58	29					245	0	297	52
5 hrs					58	100		58	29					245	35	262	52

The house model M-II has been tested with DC load and electric wiring as per AC calculations, i.e., for supply voltage of 230 V. Table 29 shows the power sharing between PV and battery for one day with defined DC load schedule. Thus converters are used for DC load to operate under AC distribution. The losses were reduced to 35-45 W, as compared to the previous case where AC loads were used. This could be due to reduced load in case of DC load. The inverter is lightly loaded compared to the previous case.

Table 29: Sharing of PV power, battery power for a given load power during complete day with ACW-DCL configuration

	Drawing room			**Bedroom 1**			**Bedroom 2**		**Dining room**		**Kitchen**		**Toilet**				
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Cooler (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**	**Load Power (W)**	**PV Power (W)**	**Battery Power (W)**	**Loss (W)**
6 hrs	21	33.5	25	21	33.5			33.5						167.5	86	125	43.5
7	21	33.5	25	21	33.5			33.5			14		7	233.5	148	134	48.5
8		33.5		21	33.5		14	33.5	14	33.5		45		228	350	-72	50
9		33.5												33.5	425	-358	33.5
10		33.5												33.5	598	-531	33.5
11								33.5	14	33.5				81	650	-533	36
12							14	33.5						47.5	700	-618	34.5
13				21	33.5	62	14			33.5	14			178	614	-392	44
14				21	33.5	62								116	499	-342	41
15		33.5	25											58.5	347	-253	35.5
16		33.5	25											58.5	212	-118	35.5
17							14	33.5						47.5	122	-42	32.5
18	21	33.5	25											79.5	23	93.5	37
19	21	33.5	25	21	33.5		14	33.5					7	188.5	0	234	45.5
20	21	33.5	25						14	33.5	14	45		186	0	230	44
21	21	33.5	25						14	33.5				127	0	169	42
22	21	33.5	25		33.5	62	14	33.5						222.5	0	268	45.5
23					33.5	62		33.5	14					143	0	184	41
24					33.5	62		33.5	14					143	0	185	42
1					33.5	62		33.5	14					143	0	184	41
2					33.5	62		33.5	14					143	0	185	42
3					33.5	62		33.5	14					143	0	186	43
4					33.5	62		33.5	14					143	0	185	42
5 hrs					33.5	62		33.5	14					143	18	167	42

Table 30 shows the power sharing between PV and battery with DC loads with electrical wiring for 24 V DC distribution. The PV power is distributed through the charge controller. The loss is about 2 W during off-peak load and about 5 W with peak load. During day time, the load is fed by PV source and the surplus power is used for charging of battery. During night time, the battery feeds the loads.

Table 30: Sharing of PV and battery power for a given load power during complete day with DCW-DCL configuration

	Drawing room			**Bedroom 1**			**Bedroom 2**		**Dining room**		**Kitchen**		**Toilet**	**Load Power (W)**	**PV Power (W)**	**Battery Power (W)**	**Loss (W)**
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Cooler (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**				
6 hrs	14.4	33.5	25	14.4	33.5	62		33.5						216.3	75	148	6.7
7	14.4	33.5	25	14.4	33.5	62		33.5			9.6		4.8	230.7	189	44.6	2.9
8		33.5		14.4	33.5	62	9.6	33.5	9.6	33.5		45		274.6	244	35.2	4.6
9		33.5												33.5	380	-345	1.5
10		33.5												33.5	478	-443.6	0.9
11									9.6	33.5				43.1	558	-513	1.9
12							9.6	33.5						43.1	600	-555.3	1.6
13				14.4	33.5	62	9.6	33.5		33.5	9.6			196.1	520	-320	3.9
14				14.4	33.5	62								110	340	-227	3
15		33.5	25											58.5	280	-220.6	0.9
16		33.5	25											58.5	150	-91	0.5
17							9.6	33.5						43.1	80	-36.5	0.4
18	14.4	33.5	25			62								135	25	113	3
19	14.4	33.5	25	14.4	33.5	62	9.6	33.5					4.8	230.7	0	234	3.3
20	14.4	33.5	25			62			9.6	33.5	9.6	45		232.9	0	238	5.1
21	14.4	33.5	25			62			9.6	33.5				173.5	0	177	3.5
22	14.4	33.5	25		33.5	62	9.6	33.5						211.5	0	215	3.5
23					33.5	62		33.5	9.6					138.6	0	141	2.4
24					33.5	62		33.5	9.6					138.6	0	141	2.4
1					33.5	62		33.5	9.6					138.6	0	141	2.4
2					33.5	62		33.5	9.6					138.6	0	141	2.4
3					33.5	62		33.5	9.6					138.6	0	141	2.4
4					33.5	62		33.5	9.6					138.6	0	141	2.4
5 hrs					33.5	62		33.5	9.6					138.6	0	141	2.4

4.3 M-III (< 1000 W) house model

The M-III house model has been tested for a daily load schedule given in Table 31 (typical loading pattern of different rooms is considered).

Table 31: Typical considered load schedule of M-III house model for complete one day.

	Load	6:00 AM	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5:00 AM
Drawing Room	Light	■	■											■	■	■	■	■							
	Fan	■	■	■	■	■						■	■	■	■	■	■	■							
	Television	■	■	■	■	■						■	■	■	■	■	■	■							
Bed Room 1	Light	■	■	■	■	■									■	■	■	■							
	Fan	■	■	■	■	■								■	■	■	■	■							
	Cooler																	■	■	■	■	■	■	■	■
	Toilet Light		■													■									
Bed Room 2	Light			■										■	■	■									
	Fan	■	■	■	■		■	■						■	■	■			■	■	■	■	■	■	■
	Laptop			■	■									■	■	■									
Dining Room	Light		■	■	■						■						■	■		■	■	■	■	■	■
	Fan		■	■	■						■					■	■								
Kitchen	Light		■	■					■	■			■			■	■								
	Mixer			■									■												
Toilet	Light		■													■									

The house model M-III was tested for one complete day with solar PV and battery backup (capacity = 600 Ah). The power measurements are taken for three different configurations, i.e., ACW-ACL, ACW-DCL and DCW-DCL. Table 32 shows the sharing of PV and battery power. It is seen that the loss varies from 45-55 W during off-peak hours to around 65-75 W during peak hours for ACW-ACL configuration. The loss includes inverter and conductor losses which is mainly due to the inverter.

The house model M-III has been tested with DC load and electric wiring as per AC calculations, i.e., for supply voltage of 230 V. Table 33 shows the power sharing between PV and battery for one day with defined DC load schedule. Thus converters are used for DC load to operate under AC distribution. The losses were reduced to 40-50 W, as compared to the previous case where AC loads were used. This could be due to reduced load in case of DC load. The inverter is lightly loaded compared to the previous case. This loss is mainly due to the inverter. The distribution wiring inside house is carrying current with respect to 230 V AC. For the DC loads, the adapters are being used at the load point.

Table 34 shows the power sharing between PV and battery with DC loads with electrical wiring for 24 V DC distribution. The PV power is distributed through the charge controller. The loss is about 5 W with peak load. During day time, the load is fed by PV source and the surplus power is used for charging of battery. During night time, the battery feeds the loads. The total load for the DC case is reduced as compared to AC load, keeping in mind the ultimate output of a load wherever possible, i.e., lumens from light, fan speed in rpm etc.

Table 32: Sharing of PV and battery power for a given load power during complete day with ACW-ACL configuration

	Drawing room			Bedroom - 1				Bedroom 2			Dining room		Kitchen		Toilet	Load Power (W)	PV Power (W)	Battery Power (W)	Loss (W)
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Cooler (W)**	**Toilet Light (W)**	**Light (W)**	**Fan (W)**	**Laptop (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**				
6hrs	58	58	25	43.5	58				58							300.5	75	289	63.5
7	58	58	25	43.5	58		14.5		58		43.5	58	29		14.5	460	175	361	76
8		58	25	43.5	58			43.5	58	58	43.5	58	29	45		519.5	288	311	79.5
9		58	25	43.5	58				58	58	43.5	58				402	425	49	72
10		58	25	43.5	58											184.5	570	-342	43.5
11									58							58	650	-556	36
12									58							58	700	-605	37
13													29			29	734	-672	33
14													29			29	690	-628	33
15											43.5	58				101.5	480	-341	37.5
16		58	25													83	347	-230	34
17		58	25										29	45		157	145	52	40
18	58	58	25		58			43.5	58	58						358.5	39	382	62.5
19	58	58	25	43.5	58			43.5	58	58						402	0	473	71
20	58	58	25	43.5	58		14.5	43.5	58	58			29		14.5	460	0	536	76
21	58	58	25	43.5	58						43.5	58	29			373	0	441	68
22	58	58	25	43.5	58	100					43.5	58				444	0	519	75
23						100			58							158	0	200	42
24						100			58		43.5					201.5	0	247	45.5
1						100			58		43.5					201.5	0	248	46.5
2						100			58		43.5					201.5	0	247	45.5
3						100			58		43.5					201.5	0	248	46.5
4						100			58		43.5					201.5	0	247	45.5
5hrs						100			58		43.5					201.5	15	248	46.5

Table 33: Sharing of PV and battery power for a given load power during complete day with ACW-DCL configuration

	Drawing room			**Bedroom - 1**				**Bedroom 2**			**Dining room**		**Kitchen**		**Toilet**				
Time	**Light (W)**	**Fan (W)**	**TV (W)**	**Light (W)**	**Fan (W)**	**Cooler (W)**	**Toilet Light (W)**	**Light (W)**	**Fan (W)**	**Laptop (W)**	**Light (W)**	**Fan (W)**	**Light (W)**	**Mixer (W)**	**Light (W)**	**Load Power (W)**	**PV Power (W)**	**Battery Power (W)**	**Loss (W)**
6hrs	28	33.5	25	21	33.5				33.5							174.5	64	156	45.5
7	28	33.5	25	21	33.5		7		33.5		21	33.5	14		7	257	180	131	54
8		33.5	25	21	33.5			21	33.5	58	21	33.5	14	45		339	348	48	57
9		33.5	25	21	33.5				33.5	58	21	33.5				259	488	-172	57
10		33.5	25	21	33.5											113	523	-372	38
11									33.5							33.55	625	-556	35.45
12									33.5							33.5	689	-620	35.5
13													14			14	575	-526	35
14													14			14	390	-332	44
15											21	33.5				58.5	280	-186	35.5
16		33.5	25													58.5	165	-73	33.5
17		33.5	25										14	45		117.5	12	144	38.5
18	28	33.5	25		33.5			21	33.5	58						232.5	0	290	57.5
19	28	33.5	25	21	33.5			21	33.5	58						253	0	302	49
20	28	33.5	25	21	33.5		7	21	33.5	58		33.5	14		7	315	0	376	61
21	28	33.5	25	21	33.5						21	33.5	14			209	0	264	55
22	28	33.5	25	21	33.5	62			33.5		21					224	0	277	53
23						62			33.5							95.5	0	136	40.5
24						62			33.5		21					116	0	157	41
1						62			33.5		21					116	0	157	41
2						62			33.5		21					116	0	159	43
3						62			33.5		21					116	0	159	43
4						62			33.5		21					116	0	160	44
5hrs						62			33.5		21					116	0	160	44

Table 34: Sharing of PV and battery power for a given load power during complete day with DCW-DCL configuration

	Drawing room			Bedroom - 1				Bedroom 2			Dining room		Kitchen		Toilet				
Time	Light (W)	Fan (W)	TV (W)	Light (W)	Fan (W)	Cooler (W)	Toilet Light (W)	Light (W)	Fan (W)	Laptop (W)	Light (W)	Fan (W)	Light (W)	Mixer (W)	Light (W)	Load Power (W)	PV Power (W)	Battery Power (W)	Loss (W)
6hrs	19	34	25	14	34				34							160	62	100	2
7	19	34	25	14	34				34		14		10		5	189	159	32.2	2.2
8		34	25	14	34		5	14	34	58	14	34	10	45		321	288	37.9	4.9
9		34	25	14	34				34	58	14	34				247	420	-169.7	3.3
10		34	25	14	34											107	553	-444.2	1.8
11									34							34	600	-566	0
12									34							34	610	-576	0
13													10			10	580	-569	1
14									34				10			38	420	-381	1
15											14	34				48	289	-239.6	1.4
16		34	25													59	146	-85.5	1.5
17		34	25										10	45		114	90	25.7	1.7
18	19	34	25		34			14	34	58						218	15	206	3
19	19	34	25	14	34			14	34	58			10			228	0	231.2	3.2
20	19	34	25	14	34		5	14	34	58		34	10		5	272	0	276.3	4.3
21	19	34	25	14	34						14	34				174	0	176.6	2.6
22	19	34	25	14	34	62		14			14					216	0	219.1	3.1
23						62			34							96	0	97.7	1.7
24						62			34		14					110	0	112	2
1						62			34		14					110	0	112	2
2						62			34		14					110	0	112	2
3						62			34		14					110	0	112	2
4						62			34		14					110	0	111.9	1.9
5hrs						62			34		14					110	0	112	2

5. Design and Evaluation of MPPT Controller and Battery Charging Controller

For construction of a DC house, many subsystems are used. The major components are: PV module, battery charging control circuit, MPPT algorithm (INC and P&O method), and DC-DC converters (adapters) etc. They are elaborately discussed below.

5.1. PV Module

The output of PV module depends on the insolation level of the sunlight falling on the PV module, environmental temperature and characteristics of PV module. Before calculating the hourly output of PV module, the average hourly insolation on horizontal surface should be converted to that on the PV module. Generally, Hay’s model is used for this purpose as discussed below. Fig. 34 shows the equivalent circuit of a PV cell. The practical characteristic equation of PV cell is a transcendental equation which has no analytic solution, and it cannot be directly used for calculating the output of the PV module. Assuming that maximum power point tracking (MPPT) is used and the PV module is always working at the maximum power point, the formulas for calculating the optimum operating point current and voltage under arbitrary conditions have the following forms.

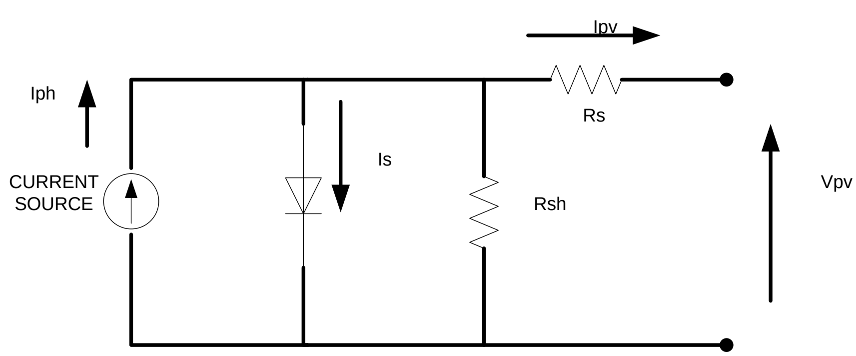

Figure 34 Equivalent circuit of PV module

For simulating a PV module, the following equations are used.

$$I_{pv} = I_{sc}\left\{1 - C_1\left(exp\left(\frac{V_{pv}-V}{C_2V_{oc}}\right) - 1\right)\right\} + VI \quad (9)$$

where

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) exp\left(\frac{-V_{mp}}{C_2 V_{oc}}\right) \quad (10)$$

$$C_2 = \frac{\frac{V_{mp}}{V_{oc}} - 1}{ln\left(1 - \frac{I_{mp}}{I_{sc}}\right)} \quad (11)$$

$$V_{pv} = V_{mp}\left[1 + 0.0539 ln\left(\frac{E_{tt}}{E_{st}}\right)\right] + B_0 T \quad (12)$$

$$V = V_{pv} - V_{mp} \quad (13)$$

$$T = T_{cell} - T_{st} \quad (14)$$

$$I = L_0\left(\frac{E_{tt}}{E_{st}}\right) VT + \left[\frac{E_{tt}}{E_{st}} - 1\right] I_{sc} \quad (15)$$

$$T_{cell} = T_A + 0.02.E_{tt} \quad (16)$$

For practical use, a certain number of PV modules need to be connected to meet user's demand on voltage and power. The operating voltage of system determines the number of series connected PV modules and the number of parallel connected PV modules strings determines the capacity of the PV array, so does the situation of battery bank. The hourly output voltage and power of PV array are:

$$V_{PVA} = N_{PVS}.V_{PV} \quad (17)$$

$$P_{PV} = N_{PVP}.N_{PVS}.V_{PV}.I_{PV} \quad (18)$$

where N_{PVS} is the number of series-connected PV modules and N_{PVP} is the number of parallel-connected PV modules.

5.2 MPPT Algorithm

Maximum power point tracking (MPPT) is a technique used commonly with the wind turbines and photovoltaic (PV) solar systems to maximize power extraction under all conditions. The principle applies generally to all variable power sources. The PV solar systems exist in many different configurations with regard to their connections with inverter systems, external grid, battery bank, or other electrical loads. Regardless of the ultimate destination of the solar power, the central problem addressed by MPPT is that the efficiency of power transfer from the solar cell depends on both the amount of sunlight falling on the solar panels and the electrical characteristics of the load. As the amount of sunlight varies, the load characteristic that gives the highest power transfer efficiency changes so that the efficiency of the system is optimized when the load characteristic changes to keep the power transfer at highest efficiency. This operating condition is called the maximum power point (MPP) and MPPT is the process of finding this point and keeping the load characteristic there. Electrical circuits can be designed to present arbitrary loads to the photovoltaic modules and then convert the voltage, current, or frequency to suit other devices or systems, and MPPT solves the problem of choosing the best load to be presented to the PV system in order to get the most usable power out. The solar cells have a complex *I-V* characteristics curve. It is the purpose of the MPPT system to sample the output of the PV system and to modulate the effective load resistance so as to obtain maximum power for any given environmental conditions.

5.2.1 Incremental Conductance (INC) Method:

The incremental conductance algorithm is based on the fact that the slope of the power vs. voltage characteristics of the PV module is zero at the MPP, positive (negative) on the left side of it and negative (positive) on the right, as can be seen in Fig. 35.

$$\frac{\partial I}{\partial V} = -\frac{I}{V} \quad \text{: At the MPP} \tag{19}$$

$$\frac{\partial I}{\partial V} > -\frac{I}{V} \quad \text{: On the left side of MPP} \tag{20}$$

$$\frac{\partial I}{\partial V} < -\frac{I}{V} \quad \text{On the right side of MPP} \tag{21}$$

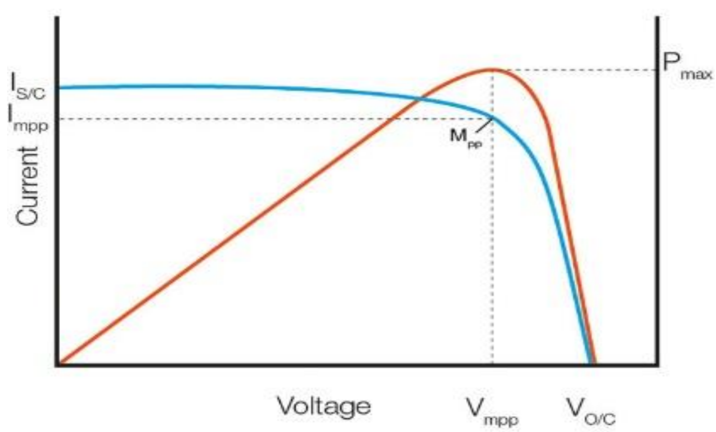

Figure 35: Typical *I-V* and *P-V* characteristics of a PV module

5.2.1.1 Simulink Model of INC MPPT Algorithm

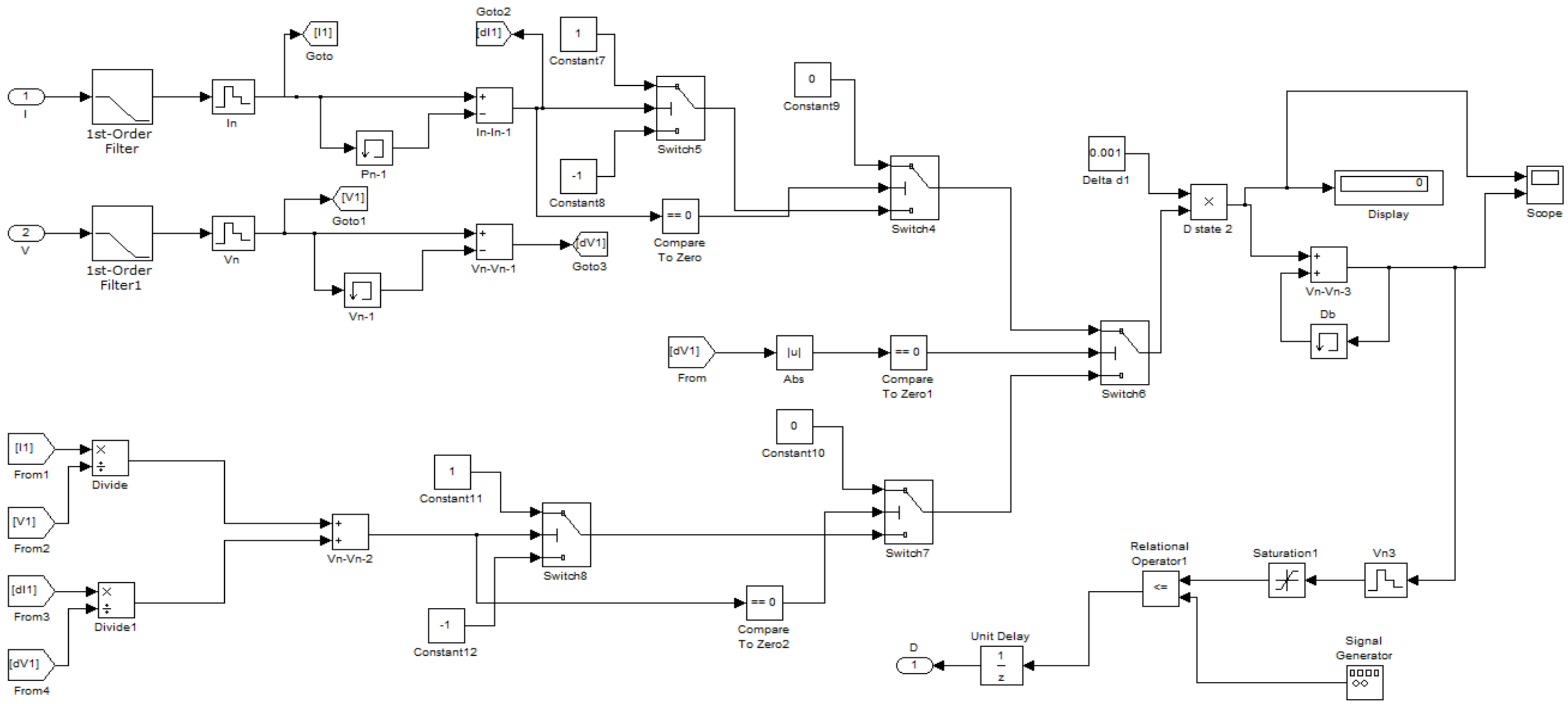

Figure 36: INC method simulation model

In the MPPT algorithm based on INC principle, the algorithm continuously evaluates the slope of the characteristics and adjusts its operating point towards the MPP. This algorithm is implemented in Simulink and the simulation model is shown in Fig. 36.

5.3 Battery Charge Controller

In this study, the development of a bidirectional power converter for standalone PV power generation system and system energy management is considered with a lithium-ion battery being used to regulate the power. The overall framework of the proposed system comprises a maximum power point tracking controller, bidirectional buck-boost converter, and lithium-ion battery. An energy management is done to increase the power utilization rate of the photovoltaic power generation system. Some measurement results are made to verify the feasibility of an air conditioner system with a photovoltaic power generation system and lithium-ion battery hybrid power supply.

5.4 Bidirectional Buck-Boost Converter

To facilitate power storage from standalone photovoltaic power generation systems during overproduction, it provides the stored power from an auxiliary source during electricity shortages. This study uses a bidirectional buck-boost converter as shown in Fig. 37 to manage the storage and supply of power between photovoltaic power generation systems and batteries. Due to the circuit structure of a bidirectional converter, it allows bidirectional power flows and two operation modes can be set for this converter depending on the direction of the power flow: boost and buck modes. The following section provides in-depth descriptions on the fundamental topology and component design of the proposed bidirectional buck-boost converter circuit.

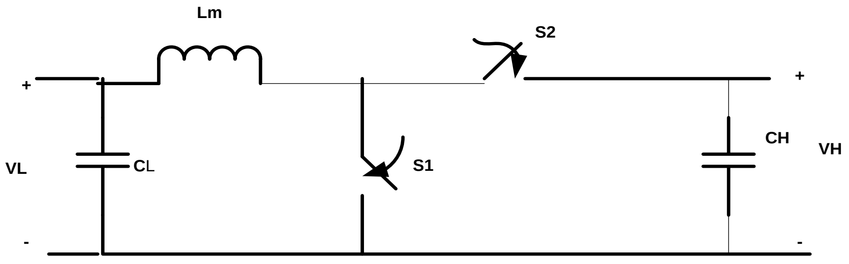

Figure 37: Bidirectional buck-boost converter circuit

5.4.1 Boost Mode

This converter circuit possess two operating modes depending on the switch status in the switch-mode power supply (SMPS): open and closed. Subsequently, in a single operation cycle, the converter's duty cycle D is defined as the ratio of the closed duration of the switch to period T.

$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} \tag{22}$$

where t_{on} and t_{off}, respectively, represent the closed and open durations of the switch in a cycle.

Closed switch S1 (0<t<DT)

When switch S1 on the low-voltage side of the converter is closed, switch S2 on the high-voltage side presents an opened state because of the complementary switching mechanism between the switches on the high-voltage and low-voltage sides. The equivalent circuit is shown in Fig. 38. In this mode, the inductor Lm and low-voltage supply V_L are connected in parallel. So

$$V_{Lm} = V_L = L_m \frac{di_{Lm}}{dt} \tag{23}$$

The rate of change in the inductor current i_{Lm} is constant. Therefore, the inductor current presents a linear increase when the switch is closed. The change of the inductor current can be expressed as

$$\frac{\Delta i_{Lm}}{\Delta t} = \frac{\Delta i_{Lm}}{DT} = \frac{V_L}{L_m} \tag{24}$$

From the above equation: $i_{Lm(on)} = \frac{V_L}{L_m} DT$ (25)

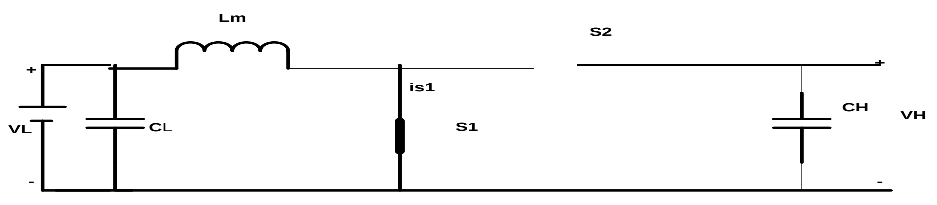

Figure 38: Equivalent circuit of the bidirectional buck-boost converter operating under boost mode when the switch S1 on the low-voltage side is closed

Open switch S1 (DT<t<T):

When switch S1 on the low-voltage side of the converter is in an open mode, switch S2 on the high-voltage side presents a closed state. The equivalent circuit for the converter is shown in Fig. 39. The inductor voltage V_{Lm} for this state can be expressed as:

$$V_{Lm} = V_L - V_H = L_m \frac{di_{Lm}}{dt} \tag{26}$$

and $$\frac{di_{Lm}}{dt} = \frac{V_L - V_H}{L_m} \tag{27}$$

When the switch S1 is open, the change of the inductor current i_{Lm} presents a linear decrease. Thus

$$\frac{\Delta i_{Lm}}{\Delta t} = \frac{\Delta i_{Lm}}{(1-\mathrm{D})\,\mathrm{T}} = \frac{V_L - V_H}{L_m} \tag{28}$$

From the above equation, we get: $$\Delta i_{Lm(off)} = \frac{V_L - V_H}{L}(1-D)T \tag{29}$$

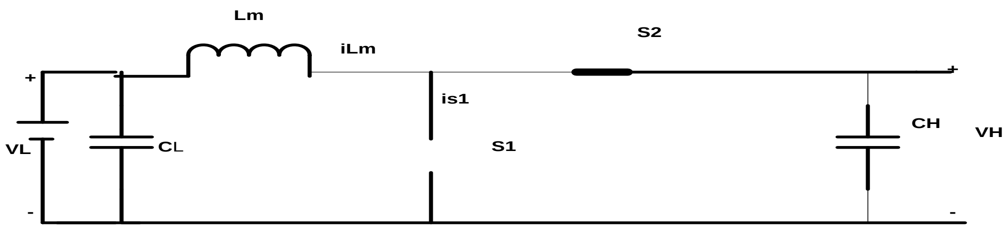

Figure 39: Equivalent circuit of bidirectional buck-boost converter operating under boost mode when the switch S1 on the low-voltage side is open

Under steady-state operation, the change of the converter's inductor current in a single cycle of operation must equal zero, that is,

$$i_{Lm(\mathrm{on})} + i_{Lm(\mathrm{off})} = 0 \tag{30}$$

Putting the values in above equation,

$$\frac{V_L}{L_m} DT + \frac{V_L - V_H}{L_m}(1-\mathrm{D})\,\mathrm{T} = 0 \tag{31}$$

By simplifying the above equation, $$V_H = \frac{1}{1-D} V_L \tag{32}$$

Capacitance and inductance design for the converter under boost mode:

a. The value of the capacitor is: $C_H = \dfrac{D}{R_H f(\dfrac{\Delta V_H}{V_H})}$ (33)

b. The value of the inductor is: $L_{m,\min} > \dfrac{D(1-D)^2 R_H}{2f}$ (34)

5.4.2 Buck mode

This section provides in-depth descriptions on the principles of operation and component designs of the bidirectional buck-boost converter operating under buck mode.

Closed switch S2 (0<t<DT):-

When switch S2 on the high-voltage side of the converter is closed, switch S1 on the low-voltage side presents an opened state because of the complementary mechanism between the signals controlling the switches on the low-voltage and high-voltage sides. Subsequently, the converter in this state becomes an equivalent circuit, as shown in Fig. 40. The voltage on both ends of inductor component Lm is:

$$V_{Lm} = V_H - V_L = L_m \frac{di_{Lm}}{dt} \tag{35}$$

Simplifying the above equation: $\dfrac{di_{Lm}}{dt} = \dfrac{V_H - V_L}{L_m}$ (36)

During this operation mode, the rate of change for the inductor current is positive, thus presenting a linear increase. When the switch is closed, the change of the inductor current in Eq. (23) is rewritten as

$$\frac{\Delta i_{Lm}}{\Delta t} = \frac{\Delta i_{Lm}}{DT} = \frac{V_H - V_L}{L_m} \tag{37}$$

So $i_{Lm(\text{on})} = \dfrac{V_H - V_L}{L_m}.\text{DT}$ (38)

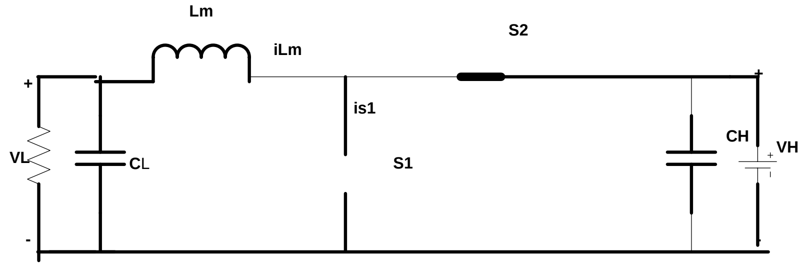

Figure 40: Equivalent circuit of the proposed bidirectional buck-boost converter operating under buck mode when the switch S2 on the high-voltage side is closed

Open switch S2 (DT<t<t):

When switch S2 on the high-voltage side of the converter is open, switch S1 on the low-voltage side presents a closed state. The equivalent circuit for the converter is shown in Fig. 41, and the voltage at both ends of the inductor can be expressed as

$$V_{Lm} = -V_L = L_m \frac{di_{Lm}}{dt} \tag{39}$$

Thus,
$$\frac{di_{Lm}}{dt} = \frac{-V_L}{L_m} \tag{40}$$

In this operation mode, the rate of change of the inductor current is a negative value, thus, presenting a linear decreased. When the switch is closed, the change in the inductor current in can be rewritten as

$$\frac{\Delta i_{Lm}}{\Delta t} = \frac{\Delta i_{Lm}}{(1-\mathrm{D})\,\mathrm{T}} = \frac{-V_L}{L_m} \tag{41}$$

From above equation:
$$i_{Lm(\mathrm{off})} = \frac{V_L}{L_m}(1-\mathrm{D})\,\mathrm{T} \tag{42}$$

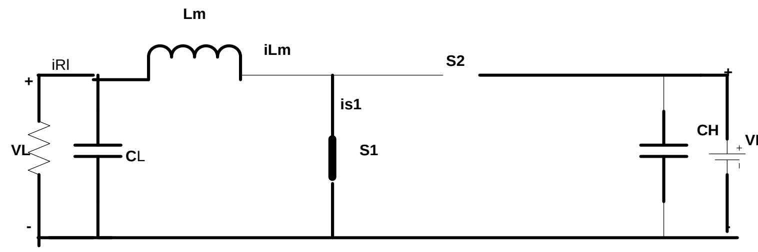

Figure 41: Equivalent circuit of the proposed bidirectional buck-boost converter is operated under buck mode when the switch S2 on the high-voltage side is open

Under steady-state:
$$i_{Lm(\mathrm{on})} + i_{Lm(\mathrm{off})} = 0 \tag{43}$$

Putting the values in this equation: $\frac{(V_H - V_L)}{L_m} DT - \frac{V_L}{L_m}(1-D)T = 0$ (44)

Simplify the above equation we get, $V_L = V_H . D$ (45)

Therefore, under this operation mode, the voltage V_L on the low-voltage side is smaller than the voltage V_H on the high-voltage side. The value of the capacitor and inductor in boost mode are given below.

The value of the capacitor is; $C_L = \frac{(1-D)}{8(\frac{V_L}{V_L}) L_m . f^2}$ (46)

The minimum value of the inductor is defined as: $L_{m\_min} = \frac{(1-D) R_L}{2f}$ (47)

To maintain the consistency of the inductor current flows for the bidirectional buck-boost converter when operating under boost and buck modes, can be further simplified as follows:

$$L_{m\_boost} = \frac{D(1-D)^2 V_H{}^2}{2 P_H f} \tag{48}$$

$$L_{m\_buck} = \frac{(1-D) V_L{}^2}{2 P_L f} \tag{49}$$

where $P_L = \frac{V_L{}^2}{R_L}$ and $P_H = \frac{V_H{}^2}{R_H}$. Assuming that the D value is increased from 0 to 1 in increments of 0.005, these values can then be substituted into function $D(1-D)^2 V_H{}^2$ and function $(1-D) V_L{}^2$. Furthermore, when D=1/3, function $D(1-D)^2 V_H{}^2$ achieves the maximum value solution, and this value is greater than $(1-D) V_L{}^2$ in any duty cycle, indicating that is under any duty cycle

$$\frac{D(1-D)^2 V_H{}^2}{2 P_H f} > \frac{(1-D) V_L{}^2}{2 P_L f} \tag{50}$$

When operating under boost or buck mode, the D value is substituted with 1/3 when designing the inductance value of the bidirectional buck-boost converter. Subsequently, the product is multiplied by 1.25. This process ensures that the inductor current can operate under CCM.

6. Evaluation and Analysis of the Energy Saving as well as Losses in PV Powered DC System in Comparison to Traditional PV Powered AC System (During Day Time with Continuous Loading)

6.1 Simulation of Solar Powered AC Electrification System

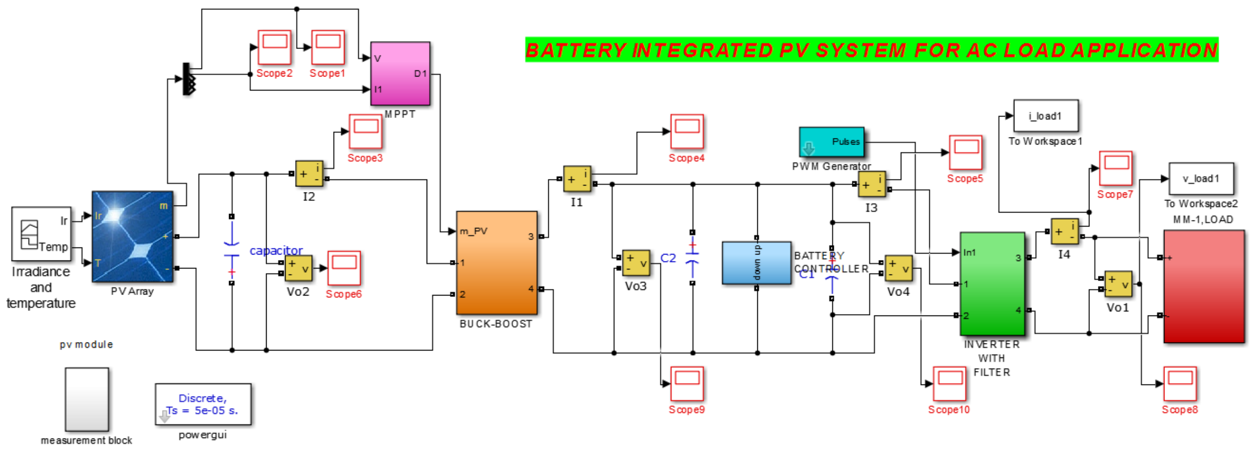

Figure 42: Simulink model for AC load/house connected to solar PV array

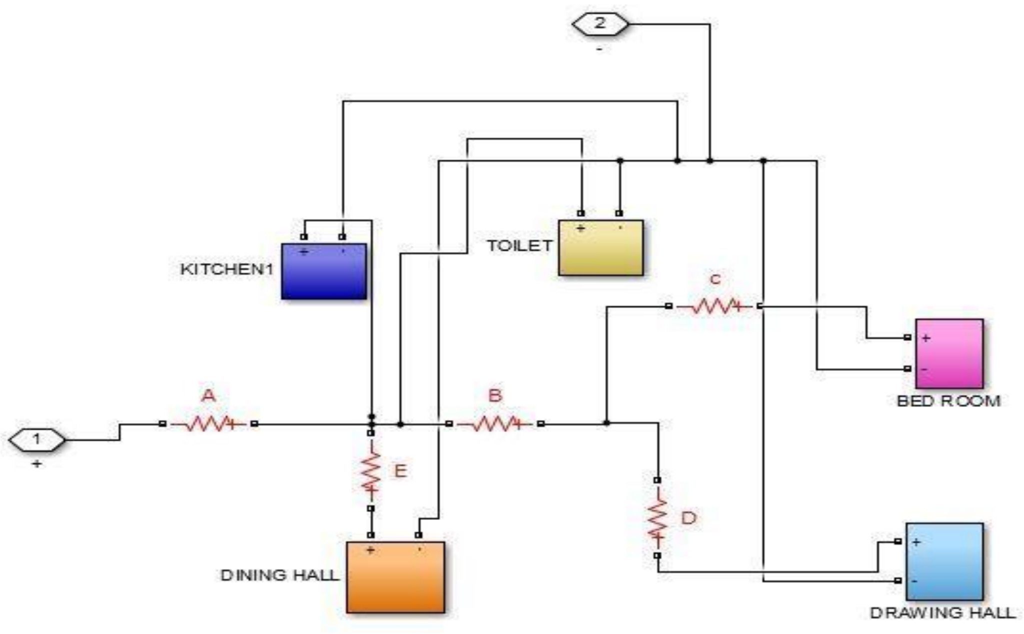

Figure 43: Simulink model of the AC house (M-I)

The simulation study of solar powered AC system is done using Simulink. Fig. 42 shows the complete simulation model and the detailed loads of the AC house (M-I) is shown in Fig. 43. The load current and voltage waveforms are shown in Figs. 44 and 45, respectively.

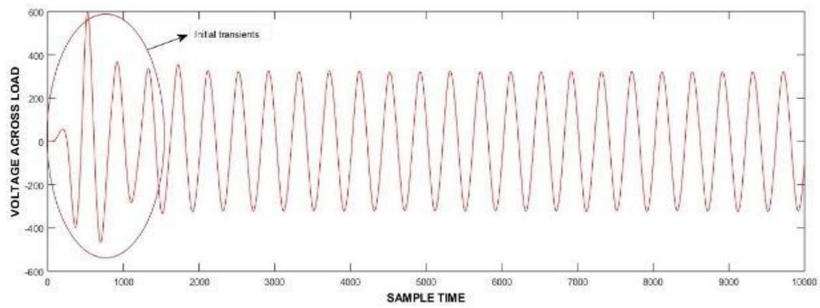

Figure 44: Load voltage waveform

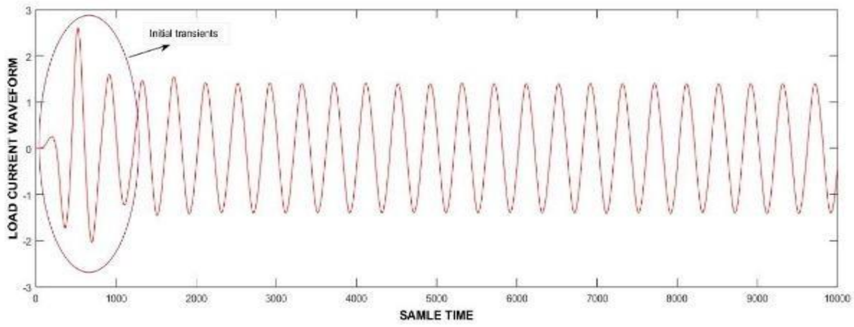

Figure 45: Load current waveform

6.2 Simulation of Solar Powered DC Electrification System

The Simulink simulation model for the PV powered DC house is shown in Fig. 46. Fig. 47 shows the Simulink model of the DC house model M-I (which includes DC-DC buck converter to step down the voltage from 24 V DC to 12 V DC for the loads that operates on 12 V supply). The load voltage waveform has some initial transients for some time as shown in Fig. 48.

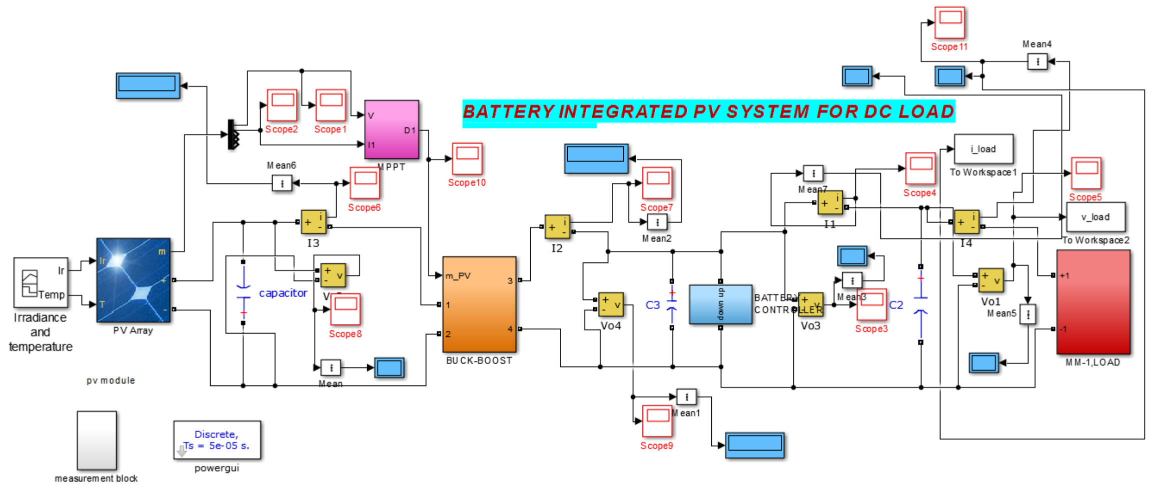

Figure 46: Simulink model for PV powered DC house

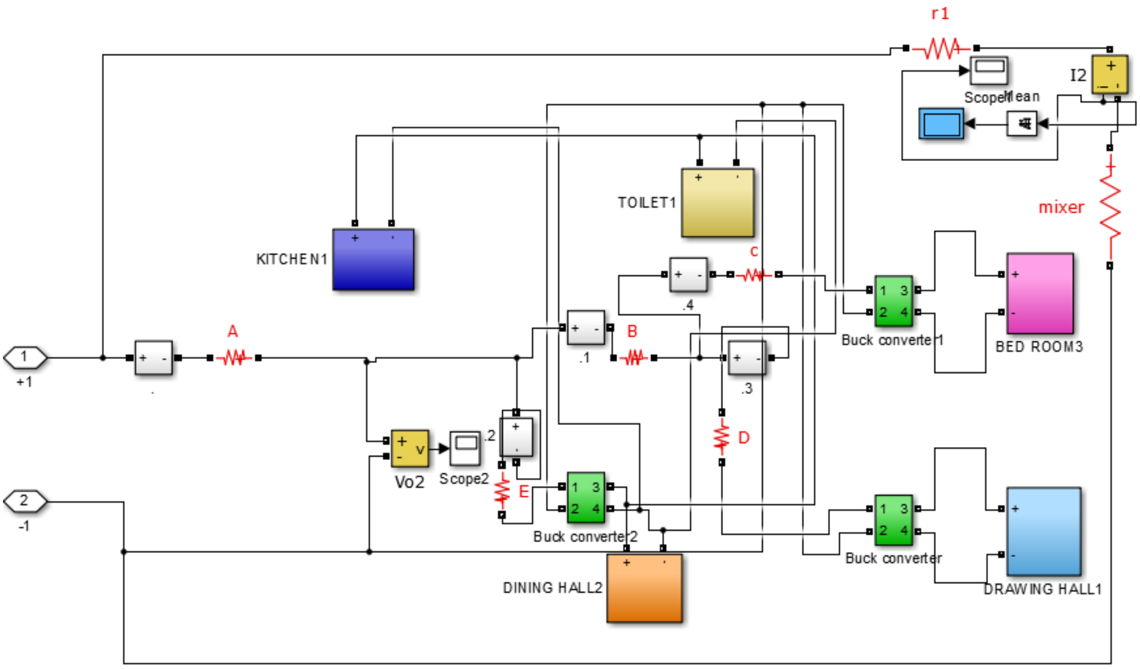

Figure 47: Complete load model for M-I

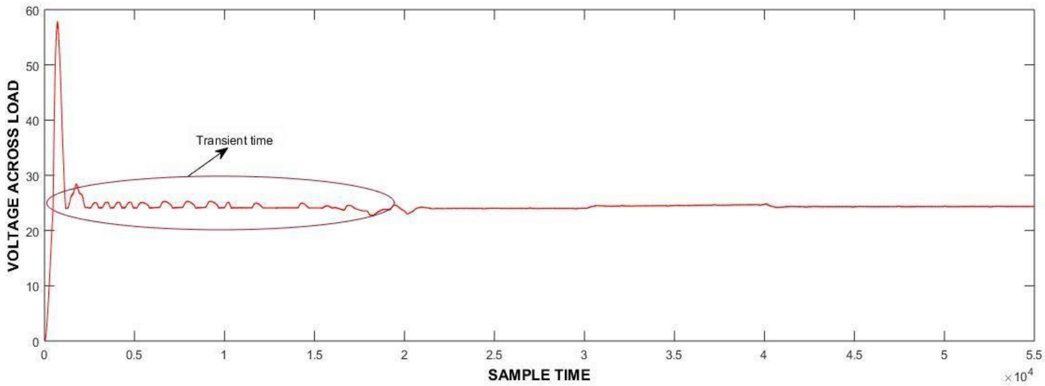

Figure 48: Load voltage waveform across M-I house model

6.3 Experimental Results

The experiments are conducted for ACW-ACL, ACW-DCL and DCW-DCL configurations for all the three model houses (M-I, M-II and M-III). The measurements are taken from 6 AM to 5 PM with PV power and battery power for continuous loading. Intermittently the mixer is switched on for 5 minutes in consecutive 15 minutes interval. The battery power and load power are calculated as average quantities accordingly. Loss is calculated as:

Loss = PV Power + Battery Power – Total Load Power

The total load power (inverter output power) includes the loading of the home appliances and the distribution conductor losses.

6.3.1 M-I, M-II, M-III house models with ACW-ACL configuration

Tables 35 to 37 show the sharing of battery power and solar power for M-I, M-II and M-III house models, respectively, with **full load** from 6 AM to 5 PM. Here the solar output is fed to the inverter. Thus the losses are mainly due to the inverter. The wiring configurations are as per the calculated current by considering supply voltage of 230 V AC. All the loads were operated with AC and their power ratings as defined earlier.

Table 35: Sharing of PV and battery power for full load of M-I during 6 AM to 5 PM with ACW-ACL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6:00 AM	24.6	1.82	44.77	24.24	13.75	333.3	213	1.5	319.5	58.57
7:00 AM	25.2	6.94	174.89	24.86	8.47	210.56	214	1.5	321	64.45
8:00 AM	25.5	11.76	299.88	25.1	3.65	91.62	212	1.5	318	73.5
9:00 AM	26.2	16.18	423.92	25.89	-1.54	-39.87	213	1.5	319.5	64.55
10:00 AM	27.1	18.45	500	26.52	-4.34	-115.1	213	1.5	319.5	65.4
11:00 AM	27.4	22.99	629.93	26.9	-9.28	-249.63	212	1.5	318	62.3
12Noon	27.6	23.55	649.98	27.2	-9.84	-267.65	212	1.5	318	64.33
1:00 PM	26.8	20.14	539.75	25.9	-6.06	-156.95	213	1.5	319.5	63.3
2:00 PM	26.1	18.39	479.98	25.8	-3.72	-95.98	213	1.5	319.5	64.5
3:00 PM	25.5	11.76	299.88	25.13	3.22	80.92	212	1.5	318	62.8
4:00 PM	25.1	4.78	119.98	24.6	10.74	264.2	213	1.5	319.5	64.68
5:00 PM	24.2	1.23	29.77	23.96	14.81	354.85	213	1.5	319.5	65.12

Table 36: Sharing of PV and battery power for full load of M-II during 6 AM to 5 PM with ACW-ACL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	24.6	2.43	59.78	24.24	23.72	574.97	213	2.56	545.28	89.47
7 AM	25.4	9.05	229.87	25.12	16.4	411.97	214	2.55	545.7	96.14
8 AM	26.01	12.68	329.81	25.45	12.93	329.07	212	2.56	542.72	116.16
9 AM	26.2	14.12	369.94	25.72	10.58	272.12	213	2.55	543.15	98.91
10 AM	27.1	17.71	479.94	26.82	6.03	161.72	213	2.56	545.28	96.38
11 AM	27.3	20.87	569.75	26.84	2.54	68.17	212	2.55	540.6	97.32
12Noon	27.61	21.73	599.97	26.83	1.44	38.64	212	2.56	542.72	95.89
1 PM	26.8	20.14	539.75	26.24	3.78	99.19	213	2.55	543.15	95.79
2 PM	25.92	17.36	449.97	25.63	7.54	193.25	213	2.56	545.28	97.94
3 PM	25.51	12.54	319.9	25.13	12.62	317.14	212	2.55	540.6	96.44
4 PM	25.1	4.78	119.98	24.67	21.1	520.54	213	2.56	545.28	95.24
5 PM	24.2	1.23	29.77	23.85	25.56	609.61	213	2.56	545.28	94.1

Table 37: Power sharing on full load in M-III (6 AM--5 PM) with ACW-ACL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	24.3	2.13	51.76	23.87	30.24	721.83	213	3.12	664.56	109.03
7 AM	24.92	7.14	177.93	24.46	24.95	610.28	214	3.15	674.1	114.11
8 AM	25.12	9.75	244.92	24.89	22.37	556.79	214	3.14	671.96	129.75
9 AM	25.97	14.55	377.86	25.01	16.44	411.16	213	3.15	670.95	118.07
10 AM	26.89	16.73	449.87	26.24	12.69	332.99	213	3.14	668.82	114.04
11 AM	27.12	20.64	559.76	26.89	8.37	225.07	212	3.14	665.68	119.15
12Noon	27.24	21.29	579.94	26.96	7.85	211.64	214	3.15	674.1	117.48
1 PM	26.78	18.14	485.79	26.42	11.32	299.07	213	3.14	668.82	116.04
2 PM	25.45	14.93	379.97	25.01	16.34	408.66	212	3.16	669.92	118.71
3 PM	25.18	12.98	326.84	24.68	18.45	455.35	212	3.15	667.8	114.39
4 PM	24.49	4.89	119.76	23.86	27.84	664.26	213	3.14	668.82	115.2
5 PM	24.12	1.32	31.84	23.56	32.06	755.33	213	3.16	673.08	114.09

6.3.2 M-I, M-II, M-III house models with ACW-DCL configuration

Tables 38 to 40 show the sharing of battery and solar power for M-I, M-II and M-III house models, respectively, with **full load** from 6 AM to 5 PM. The solar output is fed to the inverter. Thus the losses are mainly due to the inverter. The losses are less as the loads are operated with DC and the equivalent total load for DC is less compared to AC. Near the load, an adapter is used for operation of DC load. This experiment investigates the feasibility of replacing AC load with DC load keeping the existing wiring.

Table 38: Power sharing on full load in M-I from 6 AM to 5 PM with ACW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	24.6	0.81	19.93	24.24	8.72	211.37	213	0.88	187.44	43.86
7 AM	25.4	7.71	195.83	24.92	1.65	41.12	214	0.89	190.46	46.49
8 AM	25.5	10.98	279.99	25.1	-1.72	-43.17	212	0.88	186.56	50.26
9 AM	26.2	14.12	369.94	25.91	-5.2	-134.73	213	0.89	189.57	45.64
10 AM	27.1	17.7	479.67	26.83	-9.28	-248.98	213	0.88	187.44	43.25
11 AM	27.3	20.14	549.82	26.9	-11.7	-314.73	212	0.89	188.68	46.41
12Noon	27.4	20.8	569.92	26.83	-12.6	-338.06	212	0.88	186.56	45.3
1 PM	26.8	20.14	539.75	25.9	-11.73	-303.81	213	0.89	189.57	46.37
2 PM	26.1	17.8	464.58	25.8	-8.99	-231.94	213	0.88	187.44	45.2
3 PM	25.5	11.76	299.88	25.13	-2.63	-66.09	212	0.89	188.68	45.11
4 PM	25.1	4.78	119.98	24.6	4.62	113.65	213	0.88	187.44	46.19
5 PM	24.2	0.75	18.15	23.96	9.04	216.6	213	0.89	189.57	45.18

Table 39: Power sharing on full load of M-II from 6 AM to 5 PM with ACW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	24.24	1.82	44.12	24.12	13.37	322.48	213	1.46	310.98	55.62
7 AM	25.12	8.97	225.33	24.89	5.69	141.62	214	1.47	314.58	52.37
8 AM	25.84	12.53	323.78	25.48	1.84	46.88	214	1.46	312.44	58.22
9 AM	26.12	13.54	353.66	25.87	1.34	34.67	213	1.47	313.11	75.22
10 AM	27.31	18.26	498.68	27.94	-4.6	-128.52	213	1.47	313.11	57.05
11 AM	27.54	20.51	564.85	27.08	-7.34	-198.77	212	1.47	311.64	54.44
12Noon	27.78	22.45	623.66	27.12	-9.3	-252.22	214	1.46	312.44	59
1 PM	26.47	19.85	525.43	26.13	-6.04	-157.83	213	1.46	310.98	56.62
2 PM	25.32	16.51	418.03	25.06	-1.96	-49.12	212	1.47	311.64	57.27
3 PM	25.08	13.52	339.08	24.78	0.98	24.28	212	1.46	309.52	53.84
4 PM	24.32	3.58	87.07	23.95	11.7	280.22	213	1.47	313.11	54.18
5 PM	24.01	0.83	19.93	23.72	14.59	346.07	213	1.46	310.98	55.02

Table 40: Sharing of PV and battery power on full load of M-III from 6 AM to 5 PM with ACW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	24.51	2.77	67.89	24.01	16.51	396.41	213	1.86	396.18	68.12
7 AM	24.98	7.56	188.85	24.39	11.4	278.05	214	1.87	400.18	66.72
8 AM	25.23	10.58	266.93	24.79	9.39	232.78	214	1.87	400.18	99.53
9 AM	25.78	11.09	285.9	25.01	7.18	179.57	213	1.87	398.31	67.16
10 AM	26.91	17.46	469.85	26.36	-0.36	-9.49	213	1.86	396.18	64.18
11 AM	27.23	21.3	580	26.82	-4.34	-116.4	212	1.87	396.44	67.16
12Noon	27.54	22.51	619.93	26.94	-5.8	-156.25	214	1.86	398.04	65.64
1 PM	27.12	19.54	529.92	26.42	-2.55	-67.37	213	1.86	396.18	66.37
2 PM	25.78	14.54	374.84	25.07	3.41	85.49	212	1.87	396.44	63.89
3 PM	25.01	12.79	319.88	24.87	5.69	141.51	212	1.86	394.32	67.07
4 PM	24.31	4.52	109.88	23.97	14.7	352.36	213	1.86	396.18	66.06
5 PM	24.01	1.16	27.85	23.79	18.32	435.83	213	1.87	398.31	65.37

6.3.3 M-I, M-II, M-III house models with DCW-DCL configuration

Tables 41 to 43 show the sharing of battery and solar power for M-I, M-II and M-III house models, respectively, with **full load** from 6 AM to 5 PM. Here the solar output is fed to the charge controller. Thus the losses are mainly due to the charge controller. The wiring is done as per the calculated current for 24 V DC. All the loads were operated with DC and their power ratings are as reported in earlier sections. The losses are quite less compared to the cases where the loads are operated with AC or by the use of traditional PV powered AC.

Table 41: Sharing of PV and battery power for full load of M-I during 6 AM to 5 PM with DCW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	27.7	1.62	44.87	27.76	5.36	148.79	26.98	6.98	188.32	5.34
7 AM	27.9	5.37	149.82	27.68	1.67	46.23	26.9	7.04	189.38	6.67
8 AM	28.3	10.6	299.98	28.68	-3.78	-108.41	27.9	6.82	190.28	1.29
9 AM	29	12.58	364.82	28.68	-5.77	-165.48	27.79	6.81	189.25	10.09
10 AM	29.4	15.3	449.82	29.15	-8.58	-250.11	28.36	6.72	190.58	9.13
11 AM	30	19.2	576	29.02	-12.52	-363.33	28.23	6.68	188.58	24.09
12Noon	30.3	19.8	599.94	29.89	-13.12	-392.16	29.1	6.68	194.39	13.39
1 PM	29.2	17.1	499.32	28.75	-10.27	-295.26	27.96	6.83	190.97	13.09
2 PM	28.7	16.72	479.86	28.61	-9.9	-283.24	27.82	6.82	189.73	6.89
3 PM	28.3	10.6	299.98	28	-3.76	-105.28	27.75	6.84	189.81	4.89
4 PM	27.9	4.3	119.97	27.3	2.75	75.08	26.67	7.05	188.02	7.03
5 PM	27.5	1.09	29.98	27.14	6.03	163.65	26.59	7.12	189.32	4.31

Table 42: Sharing of PV and battery power for full load of M-II during 6 AM to 5 PM with DCW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	27.51	1.78	48.97	27.47	9.93	272.78	26.84	11.71	314.3	7.45
7 AM	27.62	6.33	174.83	27.55	5.43	149.6	26.92	11.76	316.58	7.85
8 AM	27.93	10.34	288.8	27.11	1.48	40.12	26.67	11.82	315.24	13.68
9 AM	28.07	11.75	329.82	27.56	-0.03	-0.83	26.92	11.72	315.5	13.49
10 AM	28.24	17.24	486.86	27.94	-5.6	-156.46	27.06	11.64	314.98	15.42
11 AM	28.39	20.42	579.72	27.99	-8.83	-247.15	27.12	11.59	314.32	18.25
12Noon	28.89	21.87	631.82	28.12	-10.31	-289.92	27.33	11.56	315.93	25.97
1 PM	28.12	18.49	519.94	27.64	-6.73	-186.02	26.99	11.76	317.4	16.52
2 PM	27.87	12.77	355.9	27.32	-0.93	-25.41	26.73	11.84	316.48	14.01
3 PM	27.67	10.87	300.77	27.01	1.08	29.17	26.38	11.95	315.24	14.7
4 PM	27.55	4.28	117.91	26.87	7.77	208.78	26.12	12.05	314.75	11.94
5 PM	27.42	1.16	31.81	26.48	11.3	299.22	25.78	12.46	321.22	9.81

Table 43: Sharing of PV and battery power for full load of M-III during 6 AM to 5 PM with DCW-DCL configuration

Hour	PV Voltage (V)	PV Current (A)	PV Power (W)	Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
6 AM	27.51	2.14	58.87	27.01	13.27	358.42	26.41	15.41	406.98	10.31
7 AM	27.82	7.02	195.3	27.47	8.54	234.59	26.82	15.56	417.32	12.57
8 AM	27.91	9.88	275.75	27.53	5.66	155.82	26.89	15.54	417.87	13.7
9 AM	28.02	11.77	329.8	27.61	3.82	105.47	26.94	15.59	419.99	15.28
10 AM	28.15	12.29	345.96	27.61	3.24	89.46	27.01	15.53	419.47	15.95
11 AM	28.31	19.42	549.78	27.72	-3.91	-108.39	27.05	15.51	419.55	21.84
12Noon	28.92	21.51	622.07	28.32	-6.04	-171.05	27.23	15.47	421.25	29.77
1 PM	28.29	19.12	540.9	27.77	-3.56	-98.86	27.16	15.56	422.61	19.43
2 PM	27.83	12.46	346.76	27.23	3.08	83.87	26.86	15.54	417.4	13.23
3 PM	27.47	10.19	279.92	26.98	5.38	145.15	26.34	15.57	410.11	14.96
4 PM	27.51	4.51	124.07	26.95	11.02	296.99	26.02	15.53	404.09	16.97
5 PM	27.45	1.31	35.96	26.85	14.24	382.34	25.76	15.55	400.57	17.73

7. Evaluation and analysis with full loading during night hours for all model houses

Experiments are conducted for ACW-ACL, ACW-DCL and DCW-DCL configurations on all model houses (M-I, M-II and M-III). This time the experiments are conducted during night time with only battery power for continuous loading. As before, the mixer is switched on for 5 minutes in consecutive 15 minutes interval. The battery power and load power are calculated as average quantities accordingly.

Losses were calculated as: Loss = Battery Power – Total Load Power

7.1 M-I (< 500 W) house model

Tables 44 to 46 show the battery power drawn for the full loading of M-I house model during night hours. Table 44 shows the hourly measurements during night hours in ACW-ACL configuration. The battery used is of 200 Ah capacity. With full load, it is able to provide power for about four hours without much dip in battery voltage. Table 45 shows the power backup during night hour in ACW-DCL configuration. Here, all the loads were of DC types. Hence the total load with DC is also reduced compared to AC. With same 200 Ah battery, it is able to provide 6 hour backup. Table 46 shows the power drawn from the battery with full load for the house model M-I with all the loads being of DC types in DCW-DCL configuration. As the total load is further reduced, the battery provides backup for 12 hours.

Table 44: Battery power drawn with full load of M-I during night for ACW-ACL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.24	15.6	378.14	213	1.5	319.5	58.64
23.86	16.1	384.14	213	1.5	319.5	64.64
23.44	19.2	450.04	213	1.7	362.1	87.94
23.05	16.7	384.93	213	1.5	319.5	65.43

Table 45: Battery power drawn with full load of M-I during night for ACW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.12	9.59	231.31	213	0.88	187.44	43.87
23.89	9.89	236.27	213	0.89	189.57	46.70
23.61	10.3	243.18	213	0.88	187.44	55.74
23.38	9.96	232.86	213	0.88	187.44	45.42
23.14	10.1	233.71	213	0.88	187.44	46.27
22.9	10.2	233.58	213	0.88	187.44	46.14

Table 46: Battery power drawn with full load of M-I during night for DCW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.86	6.98	173.52	24.08	6.98	168.21	5.30
24.68	7.04	173.74	23.9	7.04	168.39	5.35
24.49	7.1	173.87	23.71	7.1	168.48	5.39
24.28	7.18	174.33	23.39	7.18	168.37	5.95
24.15	7.26	175.32	23.36	7.26	169.73	5.59
24.02	7.25	174.14	23.23	7.25	168.92	5.22
23.89	7.05	168.42	23.1	7.05	161.93	6.48
23.75	7.37	175.03	22.96	7.37	168.77	6.26
23.61	7.44	175.65	22.82	7.44	169.85	5.80
23.46	7.42	174.07	22.75	7.42	168.8	5.27
23.3	7.45	173.58	22.67	7.45	168.89	4.69
23.14	7.48	173.08	22.59	7.48	168.9	4.18

7.2 M-II (< 750 W) house model

Tables 47 to 49 show the battery power drawn for the full loading of M-I house model during night hours. Table 47 shows the hourly measurements during night hours in ACW-ACL configuration. The battery used is of 400 Ah capacity. With full load it is able to provide power for about four hours without much dip in battery voltage. Table 48 shows the power backup during night hour in ACW-DCL configuration. Here, all the loads were of DC types. Hence the total load with DC is also reduced compared to AC. With the same 400 Ah battery, it is able to provide 6 hour backup. Table 49 shows the power drawn from the battery with full load for the house model M-II with all the loads being of DC types in DCW-DCL configuration. As the total load is further reduced, the battery provides backup for 12 hours.

Table 47: Battery power with full load of M-II during night for ACW-ACL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.12	25.8	622.29	213.1	2.5	532.75	89.54
23.81	26.4	628.58	213	2.5	532.5	96.08
23.47	30.1	706.44	213	2.77	590.01	116.43
23.15	27.92	646.34	213	2.57	547.41	98.93

Table 48: Battery power with full load of M-II during night for ACW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.55	14.94	366.77	213	1.46	310.98	55.79
24.36	15.01	365.64	213	1.47	313.11	52.53
24.18	15.29	369.71	213	1.46	310.98	58.73
23.9	16.21	387.41	213	1.46	310.98	76.43
23.85	15.44	368.24	213	1.46	310.98	57.26
23.65	15.59	368.70	213	1.46	310.98	57.72

Table 49: Battery power with full load of M-II during night for DCW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.67	11.71	288.88	23.8	11.71	278.698	10.18
24.53	11.76	288.47	23.7	11.76	278.712	9.76
24.36	13.6	331.29	23.55	13.6	320.28	11.01
24.22	11.91	288.46	23.42	11.91	278.9322	9.52
24.08	11.98	288.47	23.28	11.98	278.8944	9.58
23.93	12.05	288.35	23.14	12.05	278.837	9.51
23.76	12.13	288.20	22.99	12.13	278.8687	9.34
23.6	12.22	288.39	22.82	12.22	278.8604	9.53
23.44	12.31	288.54	22.66	12.31	278.9446	9.60
23.26	12.4	288.42	22.5	12.4	279	9.42
23.08	12.5	288.5	22.32	12.5	279	9.5
22.9	12.6	288.54	22.14	12.6	278.964	9.57

7.3 M-III (<1000 W) house model

Tables 50 to 52 show the battery power drawn for the full loading of M-I house model during night hours. Table 50 shows the hourly measurements during night hours in ACW-ACL configuration. The battery used is of 600 Ah capacity. With full load it is able to provide power for about four hours without much dip in battery voltage. Table 51 shows the power backup during night hour in ACW-DCL configuration. Here, all the loads were of DC types. Hence the total load with DC is also reduced compared to AC. With the same 600 Ah battery, it is able to provide 6 hour backup. Table 52 shows the power drawn from the battery with full load for the house model M-III with all the loads being of DC types in DCW-DCL configuration. As the total load is further reduced, the battery provides backup for 8 hours.

Table 50: Battery power with full load of M-III during night for ACW-ACL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.12	31.9	769.42	213	3.1	660.3	109.12
23.83	32.5	774.47	213	3.1	660.3	114.17
23.46	33.6	788.25	213	3.1	660.3	127.95
23.16	33.7	780.49	213	3.1	660.3	120.19

Table 51: Battery power with full load of M-III during night for ACW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.39	19.06	464.87	213	1.86	396.18	68.69
24.23	19.11	463.03	213	1.86	396.18	66.85
24.97	21.54	537.85	212	1.87	396.44	141.41
23.77	19.52	463.99	213	1.86	396.18	67.81
23.55	19.74	464.87	214	1.85	395.9	68.97
23.28	19.97	464.90	213	1.86	396.18	68.72

Table 52: Battery power with full load of M-III during night for DCW-DCL configuration

Battery Voltage (V)	Battery Current (A)	Battery Power (W)	Inverter Output Voltage (V)	Inverter Output Current (A)	Inverter Output Power (W)	Loss (W)
24.32	15.41	374.77	23.32	15.41	359.36	15.41
24.19	15.5	374.94	23.19	15.5	359.44	15.5
24.04	15.59	374.78	22.98	15.59	358.25	16.52
23.9	15.69	374.99	22.9	15.69	359.30	15.69
23.75	15.8	375.25	22.75	15.8	359.45	15.8
23.6	15.9	375.24	22.6	15.9	359.34	15.9
23.45	16	375.2	22.45	16	359.2	16
23.3	16.1	375.13	22.3	16.1	359.03	16.1

8. Cost Analysis:

In this project work cost analysis for all the three configuration has been done as mentioned in Tables 53 to Table 55, respectively. In this cost analysis, some of the user-based home appliances (such as laptop, mixer, cooler and television) are not considered. This cost analysis was done at the time of project execution. As per the analysis, the costs are more or less the same for all the configurations. However, with the increase in users for DC operated equipment over the coming years, the prices of the DC home appliances will come down resulting in substantial less cost for DCW-DCL configuration.

Table 53: Estimation of cost for ACW-ACL, ACW-DCL and DCW-DCL configurations for house model M-I with light, fan load and different converters/inverter

Item Type		**ACW-ACL Configuration**			**ACW-DCL Configuration**			**DCW-DCL Configuration**		
	Area (sqmm)	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**
Conductors	0.5	5	12	60	5	12	60	5	12	60
	1	9		0	9	18	162	9		0
	1.5	13	18	234	13		0	13	11	143
	2.5	20	5	100	20	5	100	20	6	120
	4	32		0	32		0	32	5	160
Bulb		130	9	1170	120	9	1080	120	9	1080
Fan		3000	3	9000	1400	3	4200	1400	3	4200
Switches (6A)		12	8	96	12	8	96	12	8	96
Switch (15 A)		50	1	50	50	1	50	50	1	50
Plug (5A)		20	4	80	20	4	80	20	4	80
Plug (15A)		50	1	50	50	1	50	50	1	50
Holder		25	9	225	25	9	225	25	9	225
Switch Board		45	4	180	45	4	180	45	4	180
MCB		500	1	500	500	1	500	500	1	500
Battery (100 Ah)		9000	2	18000	9000	2	18000	9000	2	18000
Inverter		9000	1	9000	9000	1	9000			0
Charge Controller				0			0	8000	1	8000
Buck Converter				0			0	1200	3	3600
AC-DC Converter				0	500	4	2000			0
				38745			**35783**			**36544**

Table 54: Estimation of cost with ACW-ACL, ACW-DCL and DCW-DCL configurations for house model M-II with light, fan load and different converters/inverter

Item Type		ACW-ACL Configuration			ACW-DCL Configuration			DCW-DCL Configuration		
	Area (sqmm)	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**
Conductors	0.5	5	18	90	5	18	90	5	18	90
	1	9		0	9	36	324	9		0
	1.5	13	36	468	13		0	13	11	143
	2.5	20		0	20	5	100	20	25	500
	4	32	5	160	32		0	32		0
	6	45		0	45		0	45	5	225
Bulb		130	13	1690	120	13	1560	120	13	1560
Fan		3000	4	12000	1400	4	5600	1400	4	5600
Switches (6A)		12	10	120	12	10	120	12	10	120
Switch (15 A)		50	1	50	50	1	50	50	1	50
Plug (5A)		20	6	120	20	6	120	20	6	120
Plug (15A)		25	13	325	25	13	325	25	13	325
Holder		50	1	50	50	1	50	50	1	50
Switch Board		45	4	180	45	4	180	45	4	180
MCB		500	1	500	500	1	500	500	1	500
Battery (100 Ah)		9000	4	36000	9000	4	36000	9000	4	36000
Inverter		9000	1	9000	9000	1	9000			0
Charge Controller				0			0	8000	1	8000
Buck Converter				0			0	1200	4	4800
AC-DC Converter					6	500	3000			0
				60753			**57019**			**58263**

It is noted that some of the loads like television, cooler, mixer and laptop are based on user interest. Hence, technical (loss) analysis is done including all the mentioned loads; however the cost analysis is done excluding these specific user interest based loads. Also the cost of solar PV panels is not included in the cost analysis as it is constant for all the three configurations. From the price comparison, it is observed that the prices of DC equipment are quite high compared to AC equipment. One of the main reasons would be the lack of number of major manufacturers. It is expected that once the big companies come forward to manufacture the DC appliances, the cost of DC appliances will go down. At present, the cost difference is small, but in future the difference will be significant. The M-I, M-II and M-III house models can be set up with an estimated cost of Rs. 36,000/, Rs. 57,000/- and Rs. 77,000/, respectively. The sizes of solar PV panels can be chosen as 600 W, 900 W and 1200 W for M-

I, M-II and M-III models looking at the weather conditions during the whole year. Hence the approximate cost towards solar PV panels would be Rs. 60,000/- , Rs. 90,000/- and Rs, 1,20,000/ for M-I, M-II and M-III house models, respectively.

Table 55: Estimation of cost for ACW-ACL, ACW-DCL and DCW-DCL configurations for house model M-III with light, fan load and different converters/inverter

Item Type		**ACW-ACL Configuration**			**ACW-DCL Configuration**			**DCW-DCL Configuration**		
	Area (sqmm)	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**	**Price (Rs.)**	**Quantity (mt / Nos.)**	**Total Price (Rs.)**
Conductors	0.5	5	70	350	5	70	350	5	70	350
	1	9		0	9	45	405	9		0
	1.5	13	45	585	13	5	65	13	28	364
	2.5	20	5	100	20		0	20	17	340
	4	32		0	32		0	32	5	160
	6	45		0	45		0	45	5	225
Bulb		130	17	2210	120	17	2040	120	17	2040
Fan		3000	4	12000	1400	4	5600	1400	4	5600
Switches (6A)		12	11	132	12	11	132	12	11	132
Switch (15 A)		50	1	50	50	1	50	50	1	50
Plug (5A)		20	7	140	20	7	140	20	7	140
Plug (15A)		25	17	425	25	17	425	25	17	425
Holder		50	1	50	50	1	50	50	1	50
Switch Board		45	5	225	45	5	225	45	5	225
MCB		500	1	500	500	1	500	500	1	500
Battery (100 Ah)		9000	6	54000	9000	6	54000	9000	6	54000
Inverter		9000	1	9000	9000	1	9000			0
Charge Controller				0			0	8000	1	8000
Buck Converter				0			0	1200	5	6000
AC-DC Converter				0	500	7	3500			0
				79767			**76482**			**78601**

9. Electrification of Kansapada Primary School, Near IIT Bhubaneswar, Argul

As a part of this project, solar DC power distribution has been implemented in a Primary School, near IIT Bhubaneswar at Kansapada and it has been inaugurated jointly by IIT Bhubaneswar and Planning & Convergence Department (Govt. of Odisha) officials.

9.1 DC Distribution Diagram of School

The school has one room for class room purpose, one room for kitchen cum dining for mid-day meal and one office room. Thus the light facility for all rooms, fan facility for class room and office room have been provided. As all the load appliances connected in the school are available with 12 V DC level, the distribution system voltage level is chosen to be 12 V DC. The DC distribution system diagram and its block diagram model is shown in Fig. 49. The various technical details of this school DC electrification system are given in the following sub-sections.

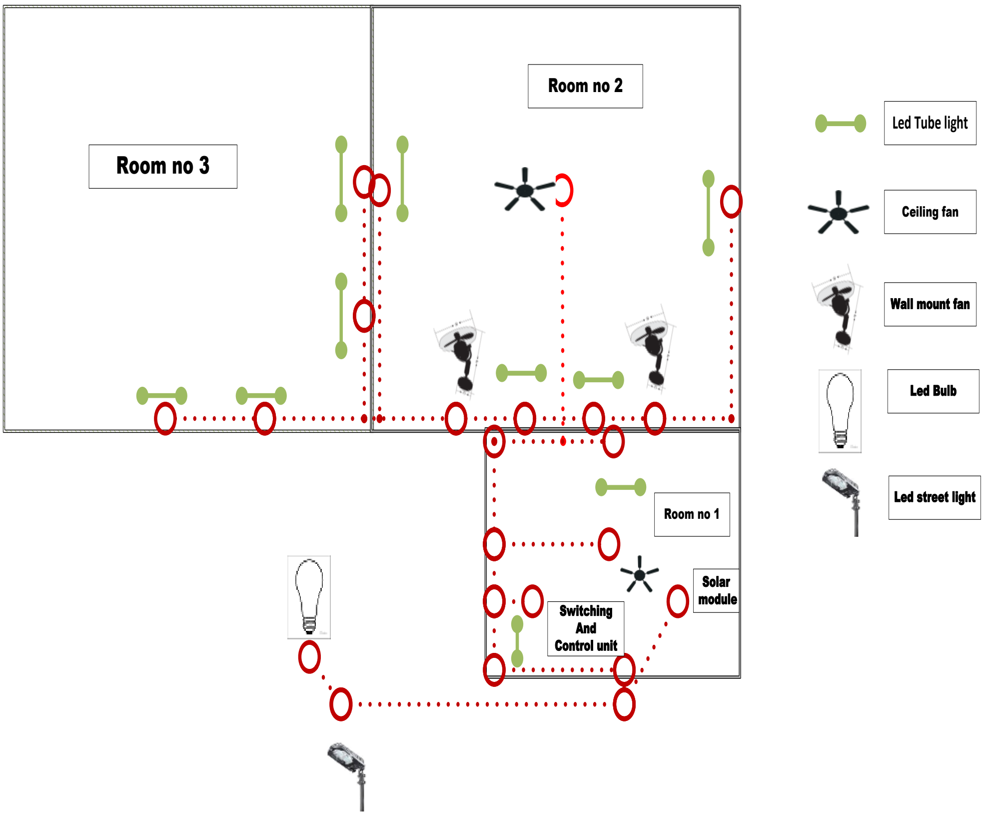

Figure 49: DC distribution diagram of primary school at Kansapada

9.1.1 Solar Power Based DC Distribution System Block Diagram

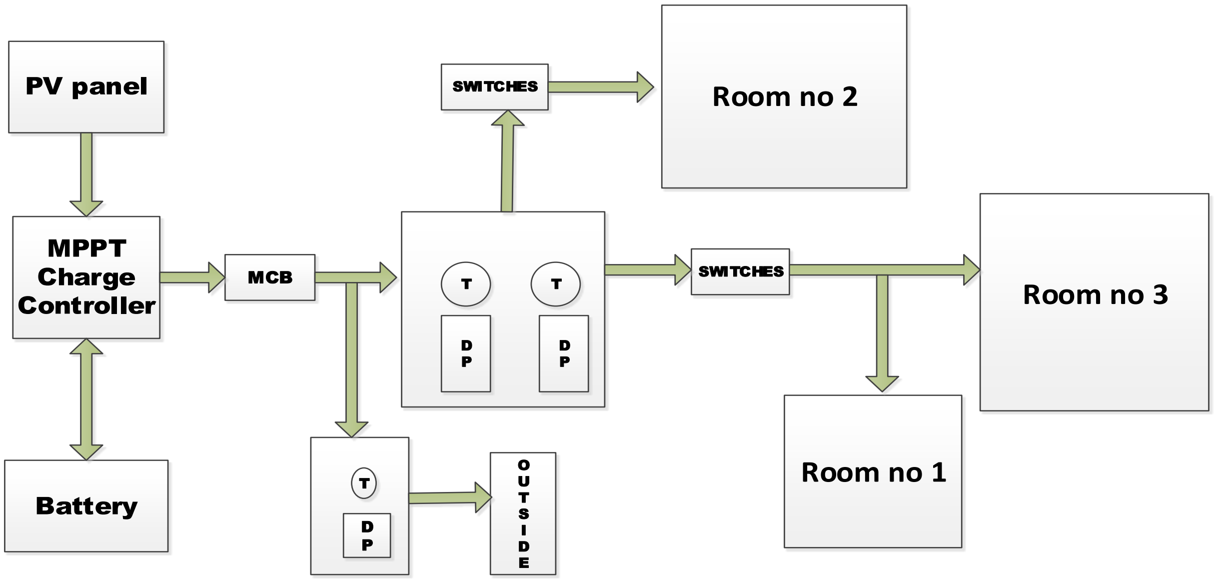

Figure 50: Block diagram of solar PV power DC house at Kansapada primary school

The overall block diagram model of the solar DC power distribution at the school is shown in Fig. 50.

9.1.2 Different loads (room wise)

Looking at the size of the room, number of lighting loads and fan have been decided. Table 56 gives these details. The rating of the load may vary up to +/- 20% with time.

Table 56: Different loads connected room wise in Kansapada School

Load	**Light load (W)**	**Fan load (W)**	**Total (W)**
Room 1 (Office Room)	(2*9)=18	24	42
Room 2 (Class Room)	(4*9)=36	(18*2)+24=60	96
Room 3 (Kitchen)	(4*9)=36	Nil	36
Outside	(18+7)=25	Nil	25
Grand Total	115	84	199

9.1.3 Specification and cost of equipment used in electrification of Kansapada School

The cost of the equipment used is given in Table 57. Looking at the technical competency of the school and involvement of school children, control for all the switches is given in office room only and it is tried to make the total distribution system timer-based. Thus three timers (one for office room, one for class room and kitchen and one for outside lighting) have been used. As per the timing given by the teachers of the school, the timers have been programmed such that the appliances will be switched on or switched off as per the set time. Fig. 51 shows some of the photographs taken during inauguration of the solar Dc power electrification at the Kansapada primary school.

Table 57: Costing of electrification of Kansapada School

Equipment	Specification	Quantity	Cost (Rs.)
Solar PV Panels	200 W, V_{oc} =22.5V , I_{sc} = 12A	3	40,000
MPPT Charge Controller	40A ,24/12 V(input-48V)	1	12,000
Battery	150Ah	1	18,000
Fan	12 VDC, 340 Rpm	2	7,000
Wall Mount Fan	12 VDC, 250 rpm	2	4,500
Tube Light	12 VDC, 900 lux	10	7,500
Street Light	12 VDC,1800 lux	1	2,200
Led bulb	12 VDC,700 lux	1	270
Timer	12 VDC, 20A	3	2,700
MCB	25 A, 32A	2	900
DP Switch	32 A	3	400
Switch	6 A	7	100
Conductor and Conduit Pipes	1.5 sqmm	As required	3,000
		Grand Total	**98,570**

Figure 51: Photographs taken during inauguration of solar powered DC electrification system at Kansapada Primary School

10. Items Delivered:

10.1 Power source for home and small business unit

As demonstrated in this project, the solar photovoltaic power based DC distribution will definitely be a viable solution for the small houses and business in the remotely rural areas. The feasibility of this solar DC distribution with DC loads has been tested at the laboratory level with three different segments of house loading (M-I, M-II and M-III depending on the amount of load power). The power source based on the solar PV has been tested with these house models for 2 Hr, 6 Hr, and 12 Hr backups. The above house models have also been evaluated with defined daily scheduled loads. All these house models are successfully tested in the laboratory. Further, the technology has also been implemented at Kansapada Primary School near Argul.

10.2 Cost analysis of (PV based) 24 V AC and DC system for home appliances

Due to unavailability of home appliances at 24 V AC, the cost analysis is done for the 230 V AC system. The cost analysis has been reported for three different configurations in the model houses (M-I, M-II and M-III based on room size and power requirements) with AC distribution wiring for AC load, AC distribution wiring for DC load and DC distribution wiring for DC load. All three model house are defined in terms of typical sizes and total load of the house. The M-I house model is chosen as size of 20 ft × 20 ft with a total load less than 500 W. M-II house model is chosen as 20 ft × 30 ft with a total load less than 750 W. The M-III house model is chosen as 30 ft × 30 ft with a total load less than 1000 W. It is noted that some of the loads like television, cooler, mixer and laptop are based on user interest. Hence, technical (loss) analysis is done including all the mentioned loads; however the cost analysis is done excluding these specific user interest based loads. Also the cost of solar PV panels is not included in the analysis as it is constant for all the three configurations. It is remarked that, based on the output of light in lumens and speed of fan, the DC and AC equipment can be chosen. From the price comparison, it is observed that the prices of DC equipment are quite high compared to AC equipment. One of the main reasons would be the lack of number of major manufacturers. It is expected that once the big companies come forward to manufacture the DC appliances, the cost of DC appliances will go down. At present, it can be concluded from the cost analysis that the DCW-DCL configuration is also fairly reasonable among all the three configurations. Of course, at present, the price difference is small, however in future the difference will be significant. The M-I house model can be set up with an estimated cost of about Rs. 36,000/, the M-II house model with about Rs. 57,000/- and M-III house model with Rs. 77,000/-. The size of solar PV panels can be chosen as 600 W for M-I, 900 W for M-II and 1200 W for M-III models looking at the weather conditions during the whole year. Hence the approximate cost towards solar PV panels would be Rs. 60,000/- for M-I, Rs. 90,000/- for M-II and Rs, 1,20,000/ for M-III house model.

10.3 Standardization for 24V DC system for all home appliances without adapter

In this project, the analysis has been done for 24 V DC system without using AC-DC adapter, because the distribution wiring for all the three house models are done according to the voltage level of 24 V DC for DCW-DL configuration. The DC voltage level for the distribution is chosen as 24 V. It has been verified and analyzed that all the three different house model for 2 Hr, 6 Hr, and 12 Hr backup. In addition, the house models with 24 V DC distribution are tested for typical daily schedule loads. The 24 V DC distribution can be standardized for the house distribution by having a tradeoff between size of conductor, size of battery, losses and availability of home appliances. At present availability of different home appliances at 24 V DC is also limited. Hence, once more manufacturers start manufacturing these home appliances in larger quantities, the cost can come down and the voltage level can be standardized again. As of now, there is no standard for the level of DC voltage for electrical distribution inside house.

10.4 Comparison of losses and performances of different equipment at 12V, 24V, and 48V

In India, at present, there are limited number of manufacturers for DC operated home appliances. Many DC home appliances, which are manufactured in India at present, are operated with 12 V DC. Use of 48 VDC will lead to decrease in line losses, however the conversion loss will be present in DC-DC converter for converting 48 V DC to 12 V DC, as most of the appliances are of 12 V DC rating. Use of 12 V DC will lead to more increase in line losses and conductors of higher diameters are required. Moreover, the conductors will carry high current for full load, which is not desirable. With 12 V DC distribution, when the load will be fed from battery, the size of the battery will be higher because of high discharge current. After having a tradeoff between the availability of home appliances with different level of DC voltage, line losses, line drop and discharge rate of battery, 24 V DC is chosen as the distribution voltage for this project. The losses are compared among the conventional solar powered 230 V AC system with AC load, solar powered 230 V AC system with DC load (using adapter) and solar powered DC system with DC load. It is observed that the conductor losses for DC system is little higher compared to the AC system. This is mainly due to the higher amount of current flowing through conductor. In AC system, the amount of current flowing through the conductor is quite low compared to DC system, hence the I^2R loss is lower. All the three house models are tested for the three configuration, i.e., ACW-ACL, ACW-DCL and DCW-DCL and the losses are compared as in Table.

10.5 Optimum design of system keeping in view of cable size, DC voltage levels, and battery

As per the literature available mentioned in references, the level of voltages used for DC distribution are 12 V, 24 V and 48 V. Depending on the level of voltage, the size of conductor will vary with current for a fixed load. Hence, it is obvious that with high level of DC distribution voltage, the current will be low and accordingly the cross-sectional area of conductor will be low for a fixed load. However, with decrease in cross-sectional area, the resistance of the conductor will increase. However the I^2R loss and IR drop will not be very much significant in case of these three DC voltage levels such as 12 V, 24 V and 48 V. In India at present, there are limited number of manufacturers for DC operated home appliances. However, with decrease in level of voltage, the amount of current flowing through the conductor or supplied by battery during night hour will lead to increase in size of battery because of high discharge rate. Hence with a tradeoff among all the possible options, 24 V DC can be chosen as DC voltage level for distribution. Also depending on the size of house model, i.e., equivalent to M-I, M-II and M-III, the conductor sizes can be chosen. The battery sizing will also depend on the loading of the houses. The details of battery sizing are provided in this report.

11. Conclusions

In this project, investigations on technical and economic feasibility of solar powered DC distribution system for home electrification have been carried out. Three model houses (with different structural models) with power requirements of 500 W, 750 W and 1000 W have been constructed in the Smart Grid and Hybrid Energy Systems laboratory of School of Electrical Sciences of IIT Bhubaneswar. Typical residential home appliances such as lights, fans, mixers and laptops have been considered. It has been observed that the solar DC distribution system is technically feasible. For detailed comparative analysis, three different electrical configurations, i.e., AC Wiring-AC Load, AC Wiring-DC Load and DC Wiring-DC Load, are examined experimentally for all the three model houses. It is observed that the power loss is minimum in case of DC Wiring-DC Load configuration. The experimental results reestablishes the feasibility of solar DC power distribution. The detailed cost analysis also gives a good indicator for field implementation of this technology. With more users for DC loads, the cost will definitely come down. For field demonstration of the technology, a primary school near IIT Bhubaneswar has been successfully electrified with solar DC power under this project. It is remarked that this technology will definitely gain momentum.

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