Design of a Low Voltage DC Mini-grid for Isolated Healthcare Centres

Vishnu Dhinakaran, K. Akash, Rakshaa Viswanathan, A. Rakesh Kumar* and S. Arul Daniel

National Institute of Technology, Trichy, Tamil Nadu, India
E-mail: vishnudhinakaran27@gmail.com; akashgkr2001@gmail.com; rakshaa2000@gmail.com; arakesh@nitt.edu; daniel@nitt.edu
**Corresponding Author*

Received 24 May 2021; Accepted 05 August 2021;
Publication 15 October 2021

Abstract

Primary healthcare centres are essential to any inhabited place in the world. A lack of electrical power from the grid should not be a reason for people in remote rural areas to miss out on basic healthcare. In developing countries like India, rural healthcare centres usually have intermittent or no grid supply and run on diesel generator-based electricity or other conventional sources, if at all there are such centres established. This, however, contributes to environmental degradation and is also expensive to maintain, considering fluctuating fuel prices. To turn the dependence on renewable energy sources like photovoltaics would pave the way to sustainable energy production and utilization, which costs less in the long run. This research work aims at designing an islanded low voltage DC solar mini-grid that will provide enough power to sustain a primary healthcare centre that has less to no access to the national grid. Previous works in this context tend to rely on varying extents of intermittent supply from the national grid, which may not be the reality in most Indian rural areas. Additionally, an unreliable source of power

Distributed Generation & Alternative Energy Journal, Vol. 37_2, 255–280.
doi: 10.13052/dgaej2156-3306.3729

from the grid which is also difficult to predict would make sensitive and important loads less accessible.

Keywords: LVDC, solar PV system, islanded mini-grid, single point of failure, rural electrification.

1 Introduction

In a rapidly progressing world, energy demands are increasing exponentially day by day. The demand for electrical energy in developing countries like India is expected to go up to 2785 TWh in 2030, whereas the demand was as low as 949 TWh in 2015 [1]. This increasing demand can't be met with conventional methods alone for several reasons. The conventional electricity production methods have a high dependency on fossil fuels like coal, which is estimated to be fully depleted by the year 2112, and coal would be the only fossil fuel left beyond the year 2042 [2, 3]. This fear, along with concerns about the environmental impacts of burning fossil fuels has paved the way for Renewable Energy Sources (RES) to contribute to powering the electric grid across several nations around the globe.

There have been several studies on the different possible methods to extract power from RES and convert it into a deliverable form for consumers [4]. The most common form of delivering electrical energy to consumers is through a national grid which gives consumers and industries electrical energy of varied voltages in AC form. But with increased usage of power electronic devices, the amount of power quality disturbances has significantly increased in the grid, thus reducing the reliability of the grid for critical loads and reducing the lifetime of components like transformers in the grid, along with other consumers [5–7]. These problems faced by transmission and distribution can be resolved to a great extent by using DC power, which not only improves the lifetime of components in the grid but also reduces power losses during transmission to a noticeable extent [8, 9]. The possibility of shifting entirely to DC power and the availability of DC appliances of various kinds, ranging from LED lights to refrigerators, commercially available for reasonable rates, is an encouragement for such systems to be established [10, 11].

With improvements in both RES micro, nano, and mini-grids and DC distribution networks, it is important to look deep into the methods employed to extract the maximum power from these undepletable sources of energy, while also ensuring a reliable and continuous supply of power [12–14]. Power from PV arrays are reliable, but not continuous since the output from these cells depends on the solar irradiation, which is absent during the night. To ensure supply of power during these hours of the day, these systems are tied to the national grid so that the grid provides power whenever the PV arrays fail to supply adequate electricity [15].

However, in places with critical loads which need a continuous power supply of good quality, grids put forth the challenge of occasional power outages, due to natural occurrences like lightning or periodic repairs. The power requirements during such outages are generally met with diesel generators, but with increasing fuel prices and consciousness about its environmental impacts, Li-ion batteries are a promising technology that has been used worldwide [16, 17]. In rural areas of several developing countries, however, access to the grid might not be possible, and for such places, islanded mini-grids powered entirely by RES will prove to be resourceful. In tropical countries like India, solar energy is one of the most easily harnessable types of RES [18]. However, the UN, in one of its reports in 2018 talked about the developments in off-grid mini-systems and calls it "too slow to be on track to meet the global energy targets for 2030" [19].

Islanded PV systems are mostly backed up with battery banks to provide power during the darker hours of the day. These backup batteries are all the more essential in places with critical loads that require constant electricity, like hospitals and primary health care centres. Properly sized batteries have shown to be more stable by reducing power outages in off-grid PV systems [20]. Additionally, there are loads that are possibly sensitive to faults in systems and sudden voltage drops, which are generally overcome with extensive protective pieces of equipment like circuit breakers, fuses, grounding, power electronic devices to improve power quality, protective relays, and measurement devices [21].

It is common to perceive PV systems are expensive setups, but it has been found that mini-solar systems are, in fact, cheaper in comparison to pico-hydro systems [22]. Additionally, while mini-hydro systems are dependent on the availability of resources like water bodies, solar mini-systems are versatile with respect to the location it can be set up in. Apart from the comparatively low cost of setup, renewable energy systems have received a lot of support from several governments, and this support continues to increase. Thus, with any positive change in government policies, like subsidies, the economic feasibility of these mini-systems will increase [23]. Leaving the cost of setting up aside, rooftop PV systems have also shown promise in the long run by having impressive payback periods in rural areas of India [24].

Having an islanded source of electric power has the benefit of not having to depend on the national grid, but also does not require one to pay for the power they consume, since there are no tariffs. Grid-connected RES systems generally call for complex tariff methods, which become obsolete while adopting off-grid systems [25]. In some places, hybrid solar mini-systems are used, like solar-hydro, solar-wind, and solar-diesel. These hybrid systems, however, seem to have poorer cost-effectiveness and higher LCOE (Levelized Cost of Energy) as opposed to complete PV systems [26]. The overall efficiency of the system can be further increased by using load devices with better efficiency. It is possible to bring down the power consumption of a system by multi-fold by simply using similar DC devices with better efficiency [27]. Some studies have shown that it is also possible to power an entire home with just 25 watts in a small solar power system if the appliances used are super-efficient [28]. The term mini-grid in particular is specifically chosen from the guidelines for such systems set by IRENA in their recent article on mini-grids and their types, and this design in made as an off-grid system [29].

2 Reliability of Islanded PV Mini-Systems

The key issue presented by islanded nano and mini-grids as opposed to national grids connected to the utility is the problem of continuous power supply. Especially with autonomous systems with requirements of higher tier of service (Refer Figure 1), bad weather is a major concern that causes power outages. Something as simple as a cloudy week in august can cause the system to be forced to go without power for days on end. Even in non-monsoon months, off-grid PV mini-systems have been observed to have two power outages per week on an average [30].

Hence, improving the reliability of these mini-grids has become one of the major hurdles faced by those designing them. Measuring reliability, however, requires parameters to check. These parameters that are essential to a PV system can broadly be classified into four parts, namely Institutional, Environmental, Economic, and Socio-cultural [31]. Institutional parameters include durability of the physical system, decentralization, and openness to participate, expert know-how, and adaptability. This is entirely dependent on the technological advancements made in the energy sector. With advancements made in the field of power electronics, for example, the reliability of systems dependent on renewable energy and energy storage

Figure 1 Types of mini-grids according IRENA guidelines [29].

systems is increasing [32]. This, combined with energy forecasting methods like day-ahead and intra-day operational planning of energy dispatching on various levels make stand-alone systems increasingly attractive to a variety of energy markets [33]. The environmental parameter mainly deals with the impact the system has on its surroundings. Economic parameters consist of cost-effectiveness, funding to build the system, and contribution to the income of users. Socio-cultural parameters comprise accessibility and social acceptance.

The project deals with the modelling of an islanded Low Voltage (LV) DC PV mini-grid for a remote healthcare centre based on an existing one in a rural area of South India. This, however, has advantages that are similar to Solar Home Systems (SHS) in many ways. These off-grid systems have very low to no transmission and connection costs while providing a reliable power supply. On a socio-cultural aspect, these systems also empower the inhabitants by giving them an opportunity to be self-sustainable. Above all, these systems have a much lower negative impact on the environment due to the complete adoption of RES [34].

3 Investigation of Configuration

The block diagram of the proposed configuration can be given as shown in Figure 2. The block diagram shows the four major components of the proposed configuration, namely the loads, the interconnected distribution system, the PV Arrays, and the battery banks. Both the PV arrays and the battery banks are designed and sized based on the load requirements as shown in Table 1.

3.1 Loads

Any electrical system is designed and sized based on the load requirement of the system in question, thus it is intuitive to study the characteristics of the load before ideating the system. The aim of this work is to design a DC mini-grid topology for a primary health care centre that has unreliable or no power supply from the national grid. For the purpose of modelling the centre's load requirements, the electrical loads in a health care centre in Thuvakudi, Tiruchirappalli, India was taken as reference. It was found that the electrical loads in the centre can be broadly classified into three categories, which are lighting/fan loads, refrigerator loads, and electronic loads.

Electronic loads include the chargers for electronic gadgets like laptops, battery-operated medical testing equipment and printers. The electrical loads are modelled in the simulation as variable resistances based on the load consumption shown in Table 1. The peak power consumption curve for a day for each type (and total) of loads are as shown in Figures 3 to 6.

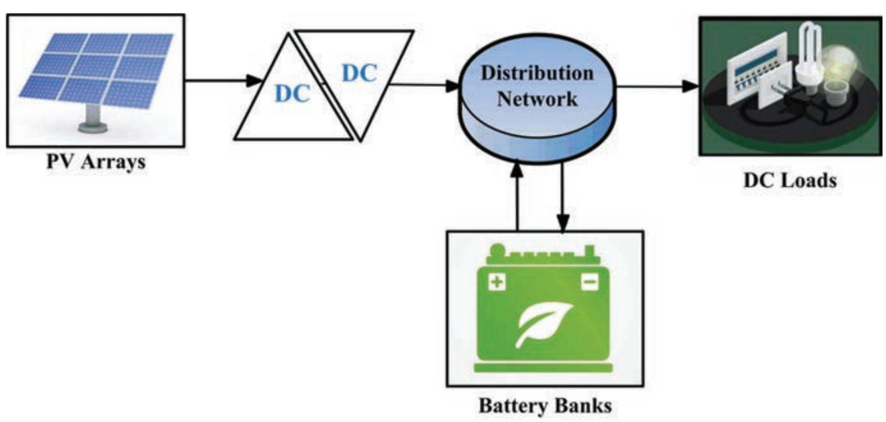

Figure 2 Basic diagram of suggested topology.

Table 1 Load analysis

S.no	Load	Voltage Rating (V)	Power Rating (W)	Current Rating (A)	No. of Devices	Usage in Hours	Power Consumption (W)	Energy Consumption (kWh)
1	Lights	12	36	3	10	13	360	5.04
2	Fans	12	24	2	10	13	240	3.36
3	Refrigerator	12	120	10	2	4	40	0.96
4	Laptop Charger	12	90	7.5	2	5	180	0.90
5	Charger for testing equipment	12	24	2	4	4	96	0.384
6	Printer	12	20	2.67	1	1	20	0.02

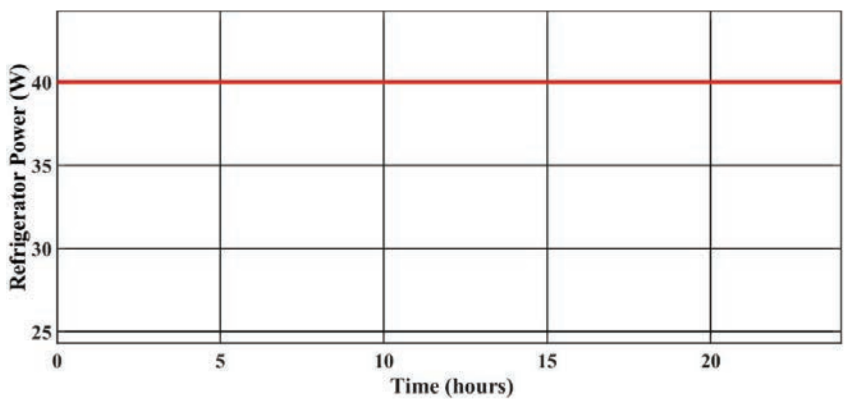

Figure 3 Refrigerator power (W).

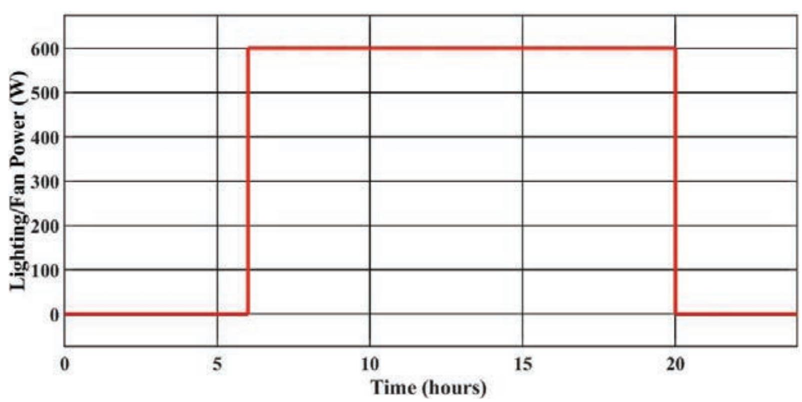

Figure 4 Lighting/fan load power (W).

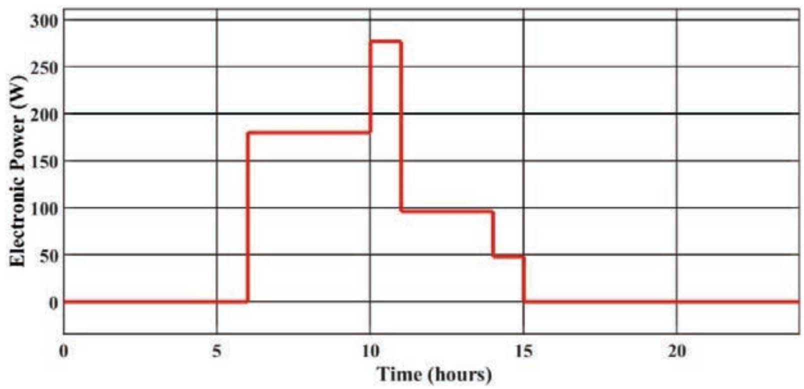

Figure 5 Electronic load power (W).

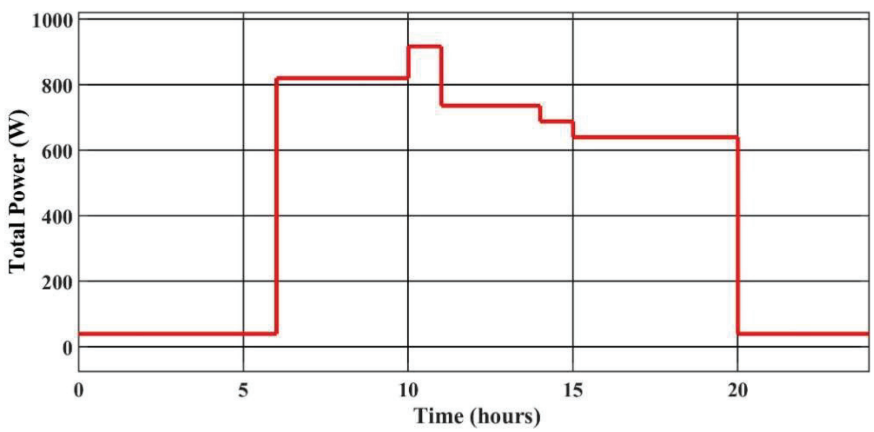

Figure 6 Total power profile (W).

3.2 PV Arrays

The PV arrays act as the primary power source for the islanded mini-grid. Each PV array block consists of two subsystems, consisting of a PV array and MPPT based DC-DC converter.

Each of the arrays has 7 PV modules connected in parallel. The ratings of each module are given in Table 2.

The irradiance data has been taken from the database of the US National Renewable Energy Laboratory (NREL) for the Trichy region [35]. The data has been taken for a span of one year and the average irradiation for each hour has been considered to simulate the system. This is considered as the average

Table 2 PV module parameters

Parameter	Rated Value
Rated Power per array (W)	250
Open Circuit Voltage, Voc (V)	37.2
Short Circuit Current, Isc (A)	8.96
Voltage at maximum power point, Vmp (V)	30.8
Current at maximum power point, Imp (A)	8.12
Cells per module	60

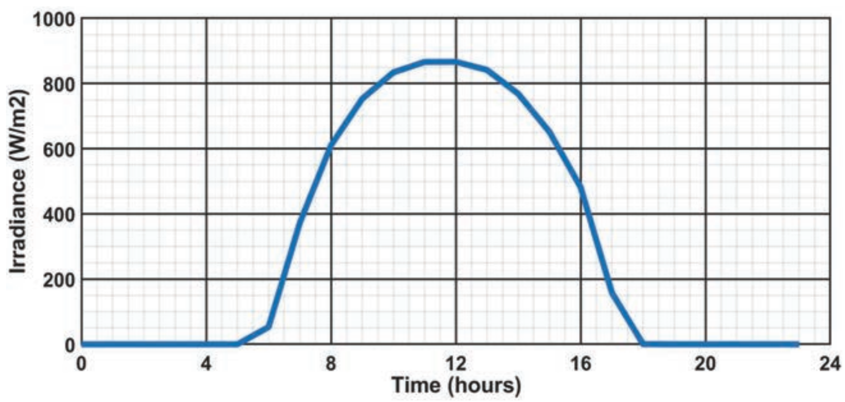

Figure 7 Average total solar irradiation in Trichy, India (Annual).

throughout the year since the change in weather due to seasons is considered negligible in this region. The annual average irradiation data was provided in Figure 7.

This irradiance data was fed to the solar panels and the simulations were carried out in the MATLAB Simulink platform.

3.3 MPPT DC-DC Controller

DC-DC converters are the electronic circuits responsible for converting one level of DC voltage to another. The reason for employing a DC-DC converter is that, though the PV panel provides a DC output, the output voltage varies based on the irradiance level, and the loads connected; and the batteries will demand a supply of constant DC voltage. The batteries are especially very sensitive to variations in voltage and overcharging them can damage the batteries, and hence the whole system. Every DC-DC converter typically

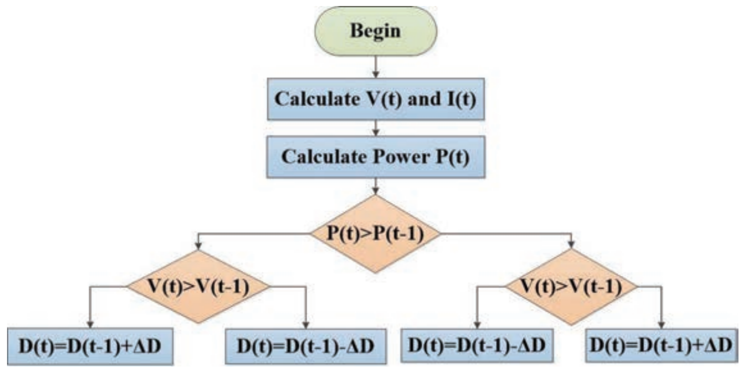

Figure 8 P&O algorithm for MPPT controller.

consists of a switch, the duty cycle of which governs the operation of the DC-DC converter irrespective of its topology. In this model, the loads demand a constant DC voltage supply of 12 V. The batteries are also at a safe and operable voltage when the voltage in the distribution system is close to 12 V.

The DC-DC converter employed in the system makes use of the maximum power point tracking method, which will account for maximum power extraction under all conditions. Among the different types of algorithms for maximum power point tracking, the algorithm employed in the model is the Perturb and Observe method (P&O method) [36]. This is one of the most commonly used MPPT algorithms due to its ease of implementation.

In the Perturb and Observe method, the controller adjusts the voltage in small proportions depending on the power delivered by the PV array. The voltage is adjusted slowly in such a way that the power extracted from the array stays at the maximum possible point for given irradiation. This algorithm is otherwise commonly known as the hill-climbing method since the voltage of the array depends on the changes in the power delivered by the array. The power increases below the maximum power point and decreases beyond it, giving it a hill-like appearance. The flow chart for the perturb and observe method was provided in Figure 8. In the simulation, the MPPT function block was coded based on the flowchart, and the output was pulse width modulated to provide the duty cycle for the switch.

3.4 Battery Banks

The system suggested is an islanded mini-grid and thus needs a reliable backup energy source at times when the PV array does not provide any

Table 3 Battery parameters

Battery Parameter	Rated Value
Nominal Voltage (V)	11.2
Rated capacity (Ah)	400
Initial state of charge	65%

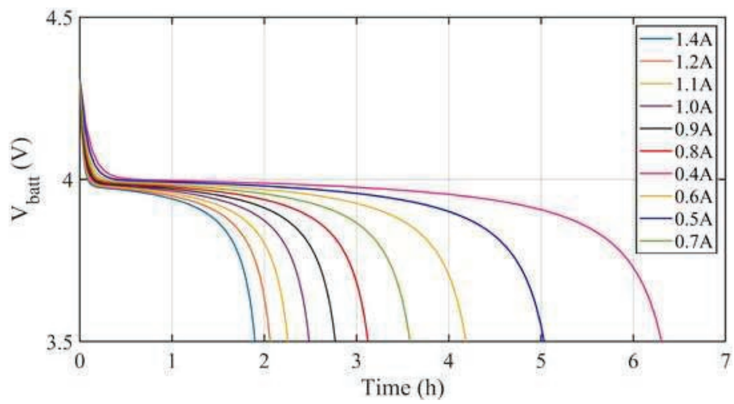

Figure 9 Li-ion battery characteristics.

electrical power. A Li-ion battery bank of appropriate amperage can ensure that the loads are continuously energized, even when the PV arrays give no power output. The battery banks discharge during the part of the day when the PV arrays have no output and charge themselves when there is sufficient power output from the arrays. The rating of the battery banks is as shown in Table 3. To achieve 400Ah, 4 Li-ion batteries of 100Ah each can be stringed together in parallel combination.

Figure 9 shows the characteristics of a typical 4 V Li-ion battery, and using the study made in Lozito et al [37]. Other commercially available versions of Li-ion batteries also follow similar curves, albeit with a shifted scale. It was deduced that the voltage of a Li-ion remains almost constant until a knee point which arrives when the SoC of the battery drops below 20%, but to increase the longevity of the battery, it is best to always keep the SoC above 50%.

3.5 Interconnected Distribution System

The PV arrays, loads, and the battery banks have been connected in an interconnected distribution system topology, which is known to have high

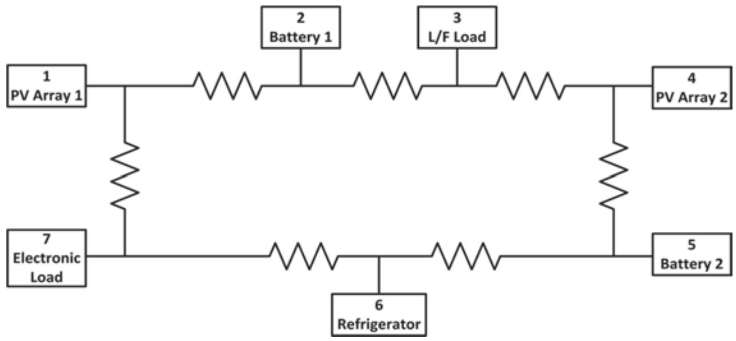

Figure 10 Interconnected distribution system.

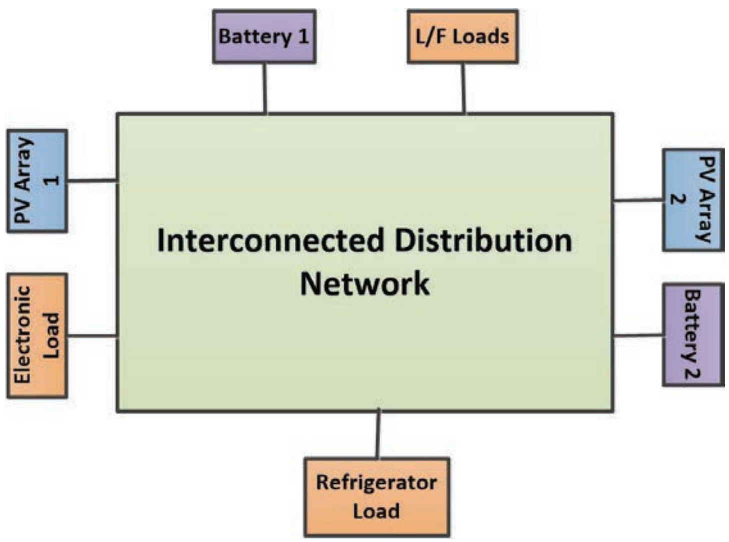

Figure 11 Overall simulation block diagram.

reliability and efficiency among all the prevalent distribution topologies, along with a high fault tolerance due to reduced possibility for Single Points of Failure (SPOF). Figure 10 shows the block diagram for the distribution system employed here.

3.6 Overall Simulation Topology

The interconnected topology of the mini-system has been simulated on the MATLAB Simulink platform. The various blocks for the same are as shown in Figures 11 and 12. The PV array block in Figure 12 shows one PV

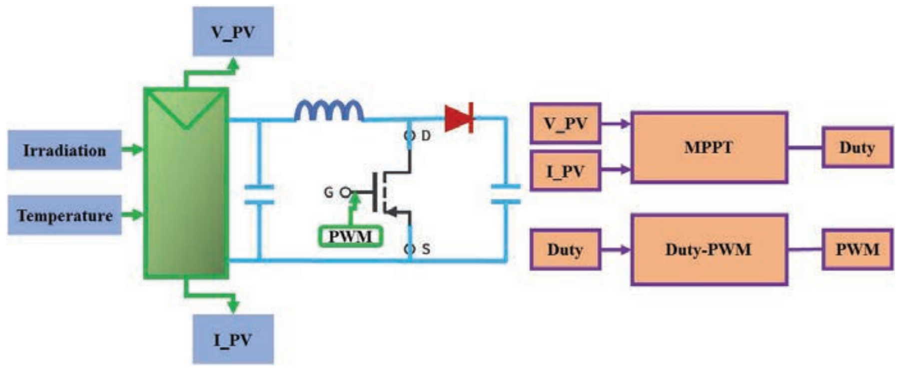

Figure 12 PV array block.

panel block which has 11 PV modules of the ratings in table 2 connected in parallel.

4 Simulation and Analysis of Configuration

The model was simulated for a period of 24 seconds in the MATLAB Simulink platform and the necessary data were extrapolated to 24 hours with a multiplication factor of 3600. Here, 0 denotes midnight and one second in the simulation corresponds to an hour for the real model.

4.1 Load Characteristics Analysis

4.1.1 Refrigerator load

The refrigerator load is of critical nature because of containing vaccines and drugs that need to be stored at low temperatures and hence would be required to run throughout the year. The said load is modelled as a time-invariant load which draws a steady current of 2.67 amperes all through the day. This is an approximated linear figure assuming that the compressor of the refrigerator runs for about 4 hours in a day, and the total energy is divided equally throughout the day. Figure 13 shows the adjusted load characteristics plot for the refrigerator.

4.1.2 Lighting/fan loads

The lighting and fan loads are assumed to be at its constant peak usage from 6 AM to 8 PM. It is also assumed to drop to zero (no usage) during the rest of the time in a given day. For the designed system, the peak load is close to 50

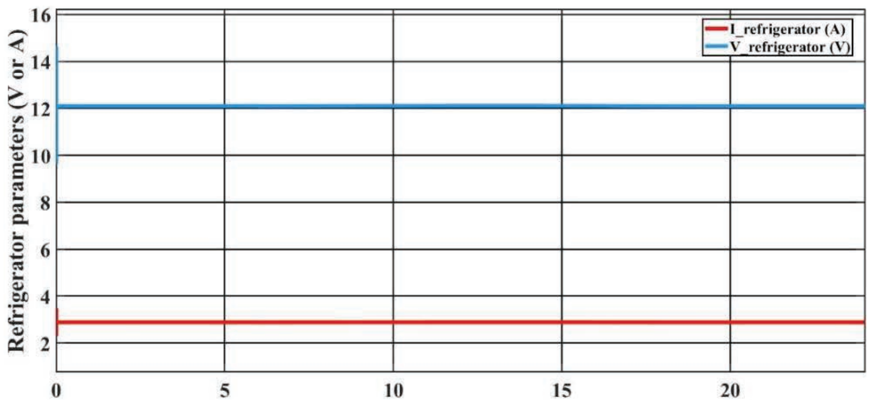

Figure 13 Refrigerator parameters.

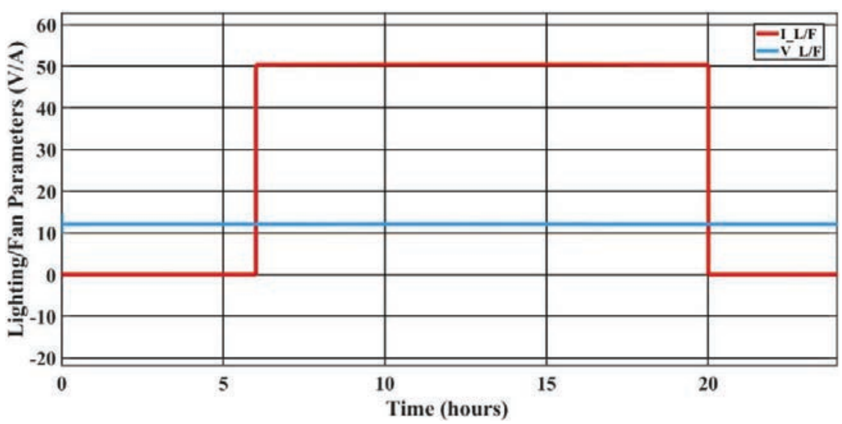

Figure 14 Lighting/fan parameters.

amperes. Figure 14 shows the load characteristics curve for the lighting and fan loads.

4.1.3 Electronic loads

The electronic loads are diverse in nature, ranging from printers to charging devices, and are hence distributed unevenly throughout the day. A current of 15 amperes flows from 6 AM to 10 AM. The load peaks between 10 AM to 11 AM with a current of about 23 amperes, stays at 8 amperes from 11 AM to 2 PM, then changing to a low 4 amperes between 2 and 3 PM before dropping to zero at other times. Figure 15 shows the load characteristics curve for electronic loads.

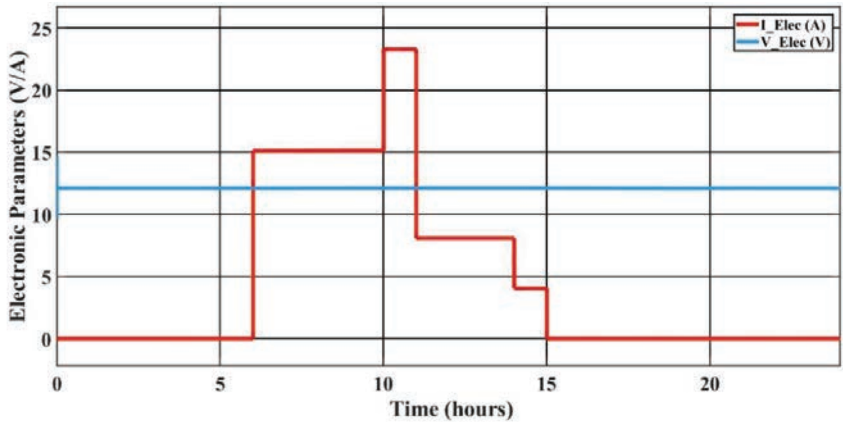

Figure 15 Electronic load parameters.

4.2 Battery Characteristics Analysis

The batteries taken provide a constant voltage of 12 V to the designed loads. However, the current and State-of-Charge (SOC) of the batteries change with variation in load used. The power output from the PV arrays go to zero by 4 PM on an average, and hence it is best that the batteries are fully charged at the time. For this condition, and to aid in healthy charging and discharging the initial battery; SOC is chosen at 65%, assuming the initial condition is taken at midnight. This system design does not let the SOC of the battery banks go below 50% at any time of the day to ensure maximum lifetime of the battery banks, and a considerable amount of reserve. Figures 16 and 17 shows the battery 1 and battery 2 characteristics respectively.

The topology suggested can theoretically work for long periods with no additional power source apart from the PV arrays and battery on most days of the year. Unfortunately, it is not possible to foresee bad weather or sudden damage to equipment. Therefore, it is important to account for enough Loss of Energy Expectation (LOEE) and Loss of Load Expectation (LOLE) to increase the reliability of the system and reduce the risks of damaging sensitive loads and loads of medical and economic importance like the refrigerators storing the vaccines. This additional safety measure is more important than normal in places like health care centres, where almost all loads are sensitive.

One of the most common reasons for complete system failure is the existence of Single Points of Failures (SPOF). SPOFs are parts of any system that, if failed, result in the failure of the entire system, regardless of the

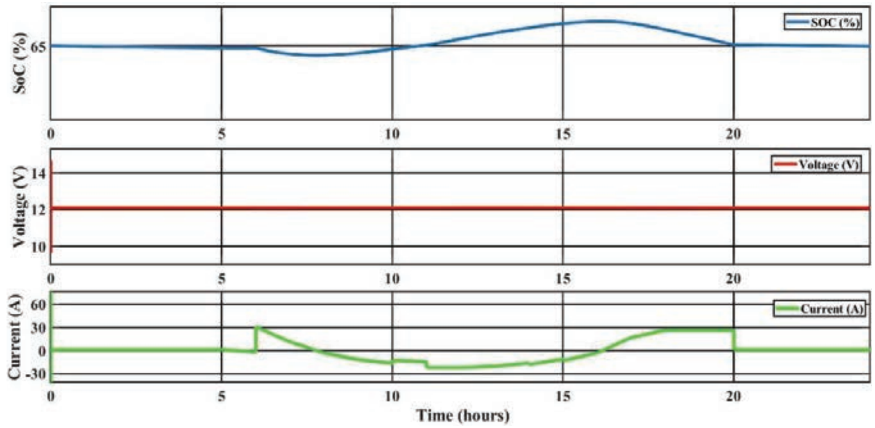

Figure 16 Battery 1 characteristics.

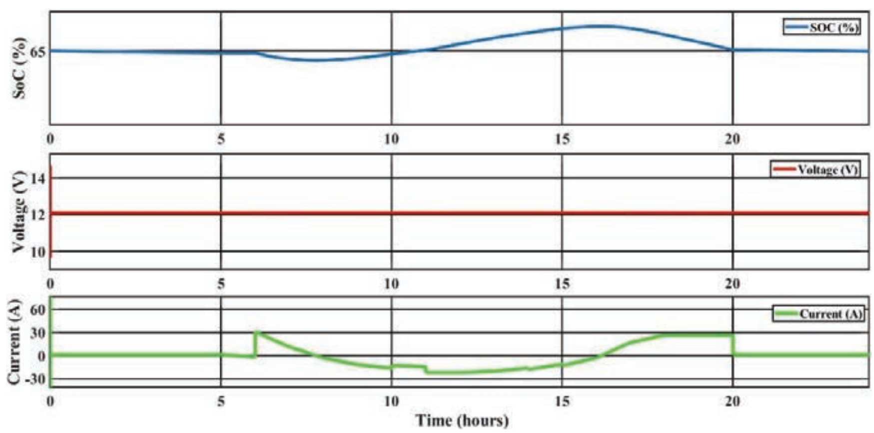

Figure 17 Battery 2 characteristics.

working condition of other parts. In a stand-alone mini-grid such as this model, an SPOF is extremely risky. With no backup power from the grid, the batteries and PV arrays are the only sources of electrical power to all the loads.

This is the reason that this model suggests dividing each of the sources in two parts. In this case, in the event of failure of one of the sources, three of the others remain to keep the loads in working condition, albeit for a limited time. But this provides enough time to rectify the fault in the part that failed without any compromise. Since there are no SPOFs in this system, the fault tolerance of the suggested model is adequately high.

Table 4 Sustainability of system

Number of PV Arrays	Number of Battery Banks	Is the Model Working in Normal Conditions?	Is the Model Working in Compromised Load Operation?
2	2	Yes	Yes
1	2	Yes	Yes
2	1	Yes	Yes
1	1	No	Yes
0	2	No	Yes
0	1	No	No
2	0	No	No
1	0	No	No
0	0	No	No

The table below depicts the theoretical possibility of whether the system can or cannot sustain one full day, i.e., 24 hours without damage to the loads and without allowing the SOC of either battery banks drop below 20%. This is done in two parts: normal operation of loads and compromised operation. Compromised loads is a consideration made with maintaining all essential loads as such and reducing the usage of non-essential loads to 25% of normal usage. It is to be noted that in conditions where even one element does not function, the battery bank(s) is considered to begin discharging from an SOC of 65%.

Table 4 shows that the suggested topology can sustain faults to a good degree and for long enough without any impact on its loads. However, in case both the battery banks fail in an unfortunate event, the design does not accommodate for the PV array directly supplying power to the loads, even during the day. However, this problem can easily be overcome by using a cascading voltage control loop to the boost converter.

5 Conclusion

With the increased concentration on renewable energy resources and solar energy becoming one of the most promising sources of renewable energy, there has been an increased focus on designing both centralized as well as decentralized solar power plants. Taking into account the inaccessibility to grids in rural remote areas of several developing countries and increased complexity in the transmission lines to enhance power quality, decentralized systems can play a prominent role in electrifying remote and rural areas. The increased usage of power electronic devices which are employed for converting DC energy to AC energy in case of conventional solar power plants have an impact on the power quality of the grid by introducing harmonics and voltage unbalances, which require additional complex pieces of equipment to neutralize like STATCOMs and UPFCs.

When these power electronic devices are used in micro, nano, and mini-grids, the injection of harmonics is much more pronounced. The power sector, with growing concerns about the power quality in distribution networks, has slowly started to adopt DC power generation, transmission, and distribution, each with their own benefits. Additionally, with the advent of highly efficient devices operating on DC power, the platform for standalone DC distribution systems, microgrids and mini-grids has been cemented. These DC systems can be powered by solar energy alone, or a hybrid mix, like solar and pico-hydro, giving consumers many viable options for the future.

The proposed islanded DC mini-grid topology functions smoothly for most of the scenarios of component failures in various levels of loading, making it a reliable and feasible for implementation for a health care centre, which has critical and essential loads like refrigerators. The DC-DC converter blocks working with the P&O algorithm of the MPPT method is connected to the PV arrays and extracts the maximum power from them in all conditions. The interconnected distribution topology accounts for maintaining the constant voltage profile throughout the system and increasing the overall fault tolerance. The proposed topology can be extended to any type of building, with suitable sizing of the PV arrays and the battery backup.

Additionally, two or more mini-grids of similar design can be interconnected with each other, with the increase in the reliability of the combined system. This can be helpful especially in rural areas, where several essential buildings can be powered through a common source or multiple common sources, to emulate an islanded microgrid. This topology can also be modified to accommodate domestic loads and loads in cottage industries, which can boost the employment and economy of a country significantly.

References

[1] The future of Indian electricity demand, Brookings India, October 2018. https://www.brookings.edu/wp-content/uploads/2018/10/The-future-of-Indian-electricity-demand.pdf (Accessed August 2020).

[2] N. Abas, A. Kalair, N. Khan, "Review of fossil fuels and future energy technologies", Futures, Volume 69, 2015, Pages 31–49, ISSN 0016-3287, https://doi.org/10.1016/j.futures.2015.03.003.

[3] Shahriar Shafiee, Erkan Topal, "When will fossil fuel reserves be diminished?", Energy Policy, Volume 37, Issue 1, 2009, Pages 181–189, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2008.08.016.

[4] S. R. Bull, "Renewable energy today and tomorrow," in Proceedings of the IEEE, vol. 89, no. 8, pp. 1216–1226, Aug. 2001, doi: 10.1109/5.940290.

[5] X. Liang, "Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources," in IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 855–866, March-April 2017, doi: 10.1109/TIA.2016.2626253.

[6] M. Singh, V. Khadkikar, A. Chandra and R. K. Varma, "Grid Interconnection of Renewable Energy Sources at the Distribution Level With Power-Quality Improvement Features," in IEEE Transactions on Power Delivery, vol. 26, no. 1, pp. 307–315, Jan. 2011, doi: 10.1109/TPWRD.2010.2081384.

[7] Sachin K. Jain, S.N. Singh, Harmonics estimation in emerging power system: "Key issues and challenges", Electric Power Systems Research, Volume 81, Issue 9, 2011, Pages 1754–1766, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2011.05.004.

[8] A. Agustoni, E. Borioli, M. Brenna, G. Simioli, E. Tironi and G. Ubezio, "LV DC distribution network with distributed energy resources: Analysis of possible structures," CIRED 2005 – 18th International Conference and Exhibition on Electricity Distribution, Turin, Italy, 2005, pp. 1–5, doi: 10.1049/cp:20051292.

[9] M. Saeedifard, M. Graovac, R. F. Dias and R. Iravani, "DC power systems: Challenges and opportunities," IEEE PES General Meeting, 2010, pp. 1–7, doi: 10.1109/PES.2010.5589736.

[10] U. Boeke and M. Wendt, "DC power grids for buildings," 2015 IEEE First International Conference on DC Microgrids (ICDCM), 2015, pp. 210–214, doi: 10.1109/ICDCM.2015.7152040.

[11] D. Salomonsson, L. Soder and A. Sannino, "Protection of Low-Voltage DC Microgrids," in IEEE Transactions on Power Delivery, vol. 24, no. 3, pp. 1045–1053, July 2009, doi: 10.1109/TPWRD.2009.2016622.

[12] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi and J. M. Guerrero, "DC Microgrid Protection: A Comprehensive Review," in

IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2019.2904588.

[13] H. Lotfi and A. Khodaei, "AC Versus DC Microgrid Planning," in IEEE Transactions on Smart Grid, vol. 8, no. 1, pp. 296–304, Jan. 2017, doi: 10.1109/TSG.2015.2457910.

[14] I. Tank and S. Mali, "Renewable based DC microgrid with energy management system," 2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES), 2015, pp. 1–5, doi: 10.1109/SPICES.2015.7091542.

[15] Hossein Lotfi, Amin Khodaei, "Hybrid AC/DC microgrid planning", Energy, Volume 118, 2017, Pages 37–46, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2016.12.015.

[16] Barun K. Das, Forhad Zaman, "Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection", Energy, Volume 169, 2019, Pages 263–276, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2018.12.014.

[17] Mala Ramesh & Rajeshwer Prasad Saini (2020) Effect of different batteries and diesel generator on the performance of a stand-alone hybrid renewable energy system, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, DOI: 10.1080/15567036.2020.1763520

[18] M.R. Sharma, R.S. Pal, "Interrelationships between total, direct, and diffuse solar radiation in the tropics", Solar Energy, Volume 9, Issue 4, 1965, Pages 183–192, ISSN 0038-092X, https://doi.org/10.1016/0038-092X(65)90045-9.

[19] UN. The Sustainable Development Goals Report; Technical Report; United Nations: New York, NY, USA, 2018.

[20] M. Hijjo, P. Bauer, F. Felgner and G. Frey, "Energy management systems for hospitals in Gaza-strip," 2015 IEEE Global Humanitarian Technology Conference (GHTC), Seattle, WA, 2015, pp. 18–25, doi: 10.1109/GHTC.2015.7343949.

[21] D. Salomonsson, L. Soder and A. Sannino, "Protection of Low-Voltage DC Microgrids," in IEEE Transactions on Power Delivery, vol. 24, no. 3, pp. 1045–1053, July 2009, doi: 10.1109/TPWRD.2009.2016622.

[22] P. Maher, N.P.A. Smith, A.A. Williams, Assessment of mini hydro as an option for off-grid electrification in Kenya, Renewable Energy, Volume 28, Issue 9, 2003, Pages 1357–1369, ISSN 0960-1481, https://doi.org/10.1016/S0960-1481(02)00216-1.

[23] Saule Baurzhan, Glenn P. Jenkins, Off-grid solar PV: Is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries?, Renewable and Sustainable Energy Reviews, Volume 60, 2016, Pages 1405–1418, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.03.016.

[24] Mageshwari, S. & Daniel, S. Arul & Gounden, N.. (2017). Feasibility studies of rooftop photovoltaic (PV) systems for domestic consumers in rural India. International Journal of Energy and Statistics. 05. 1750005. 10.1142/S2335680417500053.

[25] Sini Numminen, Semee Yoon, Johannes Urpelainen, Peter Lund, An evaluation of dynamic electricity pricing for solar micro-grids in rural India, Energy Strategy Reviews, Volume 21, 2018, Pages 130–136, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2018.05.007.

[26] R.K. Akikur, R. Saidur, H.W. Ping, K.R. Ullah, Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review, Renewable and Sustainable Energy Reviews, Volume 27, 2013, Pages 738–752, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2013.06.043.

[27] Periyasamy Muthuvel, S. Arul Daniel, D.G. Yazhini, Retrofitting domestic appliances for PV powered DC Nano-grid and its impact on net zero energy homes in rural India, Engineering Science and Technology, an International Journal, Volume 19, Issue 4, 2016, Pages 1836–1844, ISSN 2215-0986, https://doi.org/10.1016/j.jestch.2016.09.019.

[28] Phadke A, Jacobson A, Park WY, Lee GR, Alstone P, Khare A. Powering a Home With Just 25 Watts of Solar PV: Super-efficient Appliances Can Enable Expanded Off-grid Energy Service Using Small Solar Power Systems. USA: Ernest Orlando Lawrence Berkeley National Laboratory; 2015.

[29] International Renewable Energy Agency (IRENA), December 2020, accessed July 2021, <https://www.irena.org/publications/2020/Dec/Quality-infrastructure-for-smart-mini-grids>

[30] Numminen, Sini, Lund, P., Yoon, Semee, Urpelainen, Johannes. (2018). Power availability and reliability of solar mini-grids in rural areas: A case study from northern India. Sustainable Energy Technologies and Assessments. 29. 147–154. 10.1016/j.seta.2018.08.005.

[31] Nauman Riyaz Maldar, Cheng Yee Ng, Lee Woen Ean, Elif Oguz, Ahmad Fitriadhy, Hooi Siang Kang, 2020. "A Comparative Study on the Performance of a Horizontal Axis Ocean Current Turbine Considering Deflector and Operating Depths," Sustainability, MDPI, Open Access

Journal, vol. 12(8), pages 1–22, April. <https://ideas.repec.org/a/gam/jsusta/v12y2020i8p3333-d347860.html>

[32] H. Wang, K. Ma and F. Blaabjerg, "Design for reliability of power electronic systems," IECON 2012 – 38th Annual Conference on IEEE Industrial Electronics Society, 2012, pp. 33–44, doi: 10.1109/IECON.2012.6388833.

[33] S. Peyghami, P. Palensky and F. Blaabjerg, "An Overview on the Reliability of Modern Power Electronic Based Power Systems," in IEEE Open Journal of Power Electronics, vol. 1, pp. 34–50, 2020, doi: 10.1109/OJPEL.2020.2973926.

[34] Narayan, Nishant, Vega, Victor, Qin, Zian, Popovic, Jelena, Bauer, Pavol, Zeman, Miro. (2020). The Long Road to Universal Electrification: A Critical Look at Present Pathways and Challenges. Energies. 13. 508. 10.3390/en13030508.

[35] NREL's PVWatts® Calculator [Online]. Available: http://pvwatts.nrel.gov/

[36] Salman, Salman, Ai, Xin, WU, Zhouyang. (2018). Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system. Protection and Control of Modern Power Systems. 3. 10.1186/s41601-

[37] Lozito, G.M.; Lucaferri, V.; Riganti Fulginei, F.; Salvini, A. Improvement of an Equivalent Circuit Model for Li-Ion Batteries Operating at Variable Discharge Conditions. *Electronics* 2020, *9*, 78. https://doi.org/10.3390/electronics9010078

Biographies

Vishnu Dhinakaran is an undergraduate student pursuing his bachelor's degree in electrical and electronics engineering from National Institute of

Technology (NIT-T). He is currently interested in topics related to power electronics, energy storage systems, control, optimisation and energy economics. He is also a writer and editor of the media house and magazine of NIT-T, and a writer for Tronicals, the biannual technical magazine of the annual national level symposium at NIT-T, where he was also the Joint Secretary for a year.

K. Akash is currently pursuing pre-final year in the bachelor's degree in Electrical and Electronics Engineering at National Institute of Technology, Tiruchirappalli (NIT-T). His areas of interest include power electronics and renewable energy systems.

Rakshaa Viswanathan is currently pursuing Bachelor of Technology in electrical and electronics engineering from the National Institute of Technology, Tiruchirappalli (Batch of 2018–2022). Her research interests include power electronics, deep learning, internet of things, and sensors.

A. Rakesh Kumar completed his Bachelors in Engineering with a honors in Electrical and Electronics Engineering from Anna University, Chennai, India in 2011 and Masters in Engineering in Power Electronics and Drives from Anna University, Chennai, India in 2013. He worked as Assistant Professor with the Department of EEE, Rajalakshmi Engineering College, Chennai, India from 2013 to 2015. He then went on to join for a full time PhD with the School of Electrical Engineering (SELECT), Vellore Institute of Technology (VIT) from 2015 to 2019. He was also serving as Teaching cum Research Assistant from 2015 to 2019 with the same. Currently, he is a Post-Doctoral Fellow with the Nano and Micro grid lab, Department of EEE, National Institute of Technology, Tiruchirappalli, India.

S. Arul Daniel completed his B.E. degree programme from the Government College of Technology, Coimbatore, in 1988 and M.E. degree in Power Systems from the Regional Engineering College, Tiruchirappalli in 1991. He pursued his PhD degree in Electrical Engineering at the Regional Engineering College, Tiruchirappalli between 1999 and 2003 & obtained the degree in 2003 from the Bharathidasan University. He is currently a Professor

(Higher Administrative Grade) in the Department of Electrical and Electronics Engineering at NIT Tiruchirappalli. He has also served as the Head of the Department and Dean (Academic). His research interests include distributed generators, microgrids, and power electronic interfaces for renewable energy systems.