Isolated Microgrid for Rural Electrification

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***Abstract*—The electrification of remote areas has become a major concern for many developing and underdeveloped nations, especially in areas where fuel is expensive to deliver and the connection of electrical transmission lines is expensive and difficult to connect. This paper proposes an isolated microgrid for rural electrification, with the use of a standalone photovoltaic (PV) renewable energy system. Off-grid renewable energy technologies satisfy the demands of the consumer directly and avoid the need for distribution or transmission network upgrades. The system used for the microgrid consists of the PV system and a battery storage that serves as a backup. The load will be supplied from both the PV array and a battery bank. A boost converter is utilized to increase the voltage supplied by the PV to charge the batteries and supply the load. An inverter will be connected to a step up transformer. The inverter converts the direct current (DC) produced by the converter and battery storage units to alternating current (AC). The AC output will be used to supply the household loads. The simulations will be completed in PSIM software based on the designed system.**

Keywords-battery bank; converter; photovoltaic; renewable energy

I. Introduction

The rural electrification project has become a global concern in the areas where fuel is expensive to deliver and the connection of electrical transmission lines is expensive [1]. The high demand for energy and the urgent need for environmental protection required environmentally friendly and cost effective power system [2]. The use of renewable energy sources will reduce carbon emissions and greenhouse gases, and enhance the quality of life of the rural dwellers that are living in remote areas. There are many environmentally friendly and sustainable energy sources such as wind, solar, biomass and tidal. Solar energy stands out as the cleanest form of renewable energy and it is also available in abundance [3]. The energy production from renewable energy sources is increasing each year, most countries are aiming to achieve greater than 15% renewable energy production by 2020 [2]. One of the major drawbacks of using solar and wind is the failure to ensure consistent power supply, due to the intermittent and fluctuation characteristics of these resources [2]. Solar energy is produced in a parabolic shape during the day and no energy supply at night, while wind energy is seasonal and stochastic in nature.

A microgrid is an energy network made up of renewable energy sources (RES) and storage devices [4]. Microgrids can be operated locally at the substation. The energy produced can be feed to the national grid or consumed in an off-grid power system. In the near future, the power distribution system can be seen as the interconnection of several microgrids, which can generate power locally, consume and also store the energy produced [5]. A microgrid with photovoltaic (PV) panels and battery storage unit can be used to mitigate and solve real operational issues [4]. The widely used renewable energy source across the globe is the solar PV. The reason for that is because there is abundant solar power and cheap operational costs.

Standalone PV systems are mainly used in microgrids or off-grid households. The PV system consists of PV panels connected in series or parallel or both (Array), DC/DC converter, a battery storage unit and an inverter (when supplying AC loads). The inverter is not required when supply DC loads. A battery storage unit is required to store energy during the day and supply the loads at night in the absence of solar energy. The battery bank stabilizes the system by storing excess power produced, during periods when the load is drawing less power.

This paper presents an isolated microgrid system. The microgrid consists of a photovoltaic system. A PV system will be used. The system will also have a battery bank for energy storage. The reason for using a standalone solar PV system is because of the location of the rural area and the fact that South Africa has heat temperatures as compared to windy temperatures and regions. This system will be used to electrify houses in a rural area. The power generated will be for general use only. The battery storage will supply power at night when the power produced by the PV is not available.

The load will be supplied from both the PV array and a battery bank. An inverter will be connected on the output side of the PV system to convert direct current (DC) to alternating current (AC). During peak demands, the battery bank will be used to supply power to the loads. After the load demands are met and there is excess power, this power will be used to charge the battery bank. The paper has five sections which are section II literature review, section III mathematical modeling of the solar PV system, section IV microgrid design and section V is the conclusion.

II. LITERATURE REVIEW

Due to the increase in energy demands and population growth, conventional energy sources are incapable of meeting the required energy demand [3]. There is a huge difference between energy demand and energy supply and this has led to a serious global energy crisis. Standalone microgrid with green technologies can be used to address the electricity needs in rural communities [6]. Off-grid renewable energy technologies satisfy the demands of the consumer directly and avoid the need for distribution or transmission network upgrades.

A microgrid is a small-medium scale localized power system that can operate in parallel or autonomous from the national grid and is capable of supplying power in multiple loads to consumers. Microgrid system can be built either at customer facility or at a location that is part of a local distribution substation thereby eliminating the need for system upgrades. Microgrid system provides many benefits to the customers, including improved system reliability by providing power during utility outages. There are also benefits such as resolving overload problems on the national grid by removing loads from the electric power system (EPS) by allowing a part of the power system to operate in the island mode [7]. A microgrid system plays a significant role in the compensation of reactive power as well as suppressing the voltage fluctuation and flickers in the system [8].

There are various configurations for microgrid systems based on the load connected. The connection configuration of the microgrid system is based on the consumer loads and the distributed generation systems used. The PV systems are easy to install, require little maintenance owing to no moving parts, and can be installed at various locations. The seasonal adjustments of solar PVs in either single or dual axis tracking can increase the power generation by approximately 4 % in summer and winter and up to 29 % with the application of dual axis tracking [9]. The PV system is expensive compared to the wind system [9]. Wind energy systems are only cheaper when operated at a large scale, drawback they require expertise to operate and maintain them.

To enhance the energy efficiency and stability of the renewable energy system one or more renewable energy systems must be used in hybrid form. Hybridization of renewable energy sources is an important way to increase utilization and efficiency of traditional power system. Energy systems are integrated through sources to increase the energy utilization factor and smooth the variability of primary energy input [10], [11]. Hybrid power systems connect two or more energy systems that when integrated they can overcome the limitations inherent in either. Hybrid systems improved the overall system limitations in terms of efficiency, reliability, and emissions [8]. Hybridization involves renewable energy sources like wind and solar photovoltaic (PV) and battery storage. The application of green technologies such as PV and wind systems increases the reliability of a variable renewable generation system, in this case, wind is utilized as a backup when the power output of the PV is low [11]. Hybrid system is an essential part of smart-grid that provides relatively uninterrupted power supply at a lower cost of energy, and operates independently or in conjunction with the utility grid [12]. Hybridization of green technologies will reduce the capacity of battery system and the operation and maintenance costs of the system as compared to using diesel generator in a standalone power system [4].

The drawback of using a hybrid system is a function of the location of the site and the amount of power required by the consumer. In other areas, there are low wind projections and hence the installation of a wind system will not yield profit and will be costly to operate and maintain. The battery is a device that contains an electric cell or a series of cells capable of storing energy that can be converted into electrical energy. Electricity is produced by a chemical reaction on the battery [13], [14].

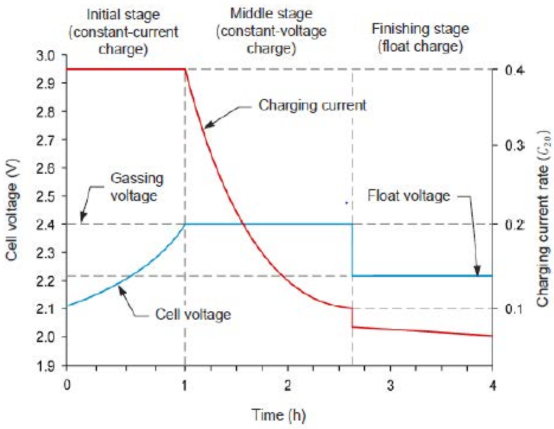


Figure 1. Constant voltage charging curve [15]

Battery charging starts with a constant current until a certain voltage is reached (gassing voltage) as shown in Fig. 1. Battery charging will continue at a constant voltage equal to gassing voltage until the charging current decreases to a value of about 0.1C20 [15]. Once the current has decreased the voltage will also decrease to float voltage to complete and maintain the battery charge. The life-limiting factors of batteries depend on the rate of charge or discharge, overcharge, high depth of discharge and load patterns [6]. Off-grid communities require backup power for a PV standalone system to function efficiently due to electricity generation systems that are stochastic in nature.

III. MATHEMATICAL MODELING OF A SOLAR PV SYSTEM

Mathematical modeling is utilized in this work to simulate the behavior of the PV module [16]. In this modeling technique, a PV cell is depicted by a current source connected in parallel with a diode. This circuit also includes two resistors R_s (series resistance) and R_{sh} (Parallel resistance) as shown in Fig. 2.

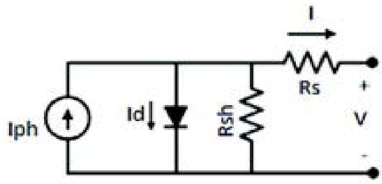


Figure 2. Equivalent model of a PV Cell [16]

The basic characteristics of the PV module such as P-V and I-V) can be utilized to derive the basic equations of the panel, before mathematical modeling of the system [16].

Input Power (Pin):

$$P_{in} = V_d \times I_{ph} \quad (1)$$

Diode current (I_d):

$$I_d = I_{sat}\left(e^{\frac{V}{V_t}} - 1\right) \quad (2)$$

Output current (I):

$$I = I_{ph} - I_d - \frac{R_s I + V}{R_{sh}} \quad (3)$$

Open circuit voltage (V_{OC}):

$$\text{VOC} = \text{V} = \frac{nkt}{q} in\left(\frac{I_{ph}}{I_d} + 1\right) \quad (4)$$

Short circuit current (I_{SC}):

$$I_{SC} = I_{ph}(V = 0) \quad (5)$$

where I_{ph} is the light generated photo-current of PV model, I_{sat} is the diode saturation current, V_t is the thermal voltage of solar cell, n id the diode ideality, k is the Boltzmann's constant, T is the operating temperature and q is the charge of an electron. Rs is the internal loss due to current flow and Rsh is the loss due to manufacturing defects [16].

Solar PV output power is dependent on two inputs temperature and irradiance. The solar irradiance on a surface varies depending on the orientation of the surface of the panel. The solar PV surface will obtain irradiance from the sun through the beam, diffuse and reflective irradiance. The beam irradiance is given by:

$$I_B = Ae^{-km} \quad (6)$$

where A is the apparent extraterrestrial flux, k is the optical depth and m is the air mass ratio.

The direct irradiation collected by the collector is given by:

$$I_{BC} = I_B \cos\theta \quad (7)$$

Where

$$\cos\theta = \cos\beta_N \cos(\theta_s - \theta_c)\sin\theta_t + \sin\beta_N \cos\theta_t \quad (8)$$

where θ_s and θ_c are the azimuth angles relative to the southern direction to the sun and nominal to the collector respectively. θ_t is the tilt angle of the collector.

The accuracy of the diffuse radiation is limited and affected by the precipitation of moister in the clouds and reflection of the radiation throughout the atmosphere. The diffuse irradiation is given by:

$$I_{DC} = CI_B\left(\frac{1 + \cos\theta_t}{2}\right) \quad (9)$$

where C is the sky diffuse factor

The reflected radiation on the surface of the collector is given by:

$$I_{RC} = \rho_r I_B(\sin\beta_N + C)\left(\frac{1 - \cos\theta_t}{2}\right) \quad (10)$$

where ρ_r is the ground reflectance.

The total radiation on the surface of the collector is expressed as follows:

$$I_C = I_{BC} + I_{DC} + I_{RC} \quad (11)$$

The total electrical power of a PV panel is dependent on the cell technology and the size of the panel.

IV. MICROGRID SYSTEM DESIGN

Based on Fig. 3, South Africa is a country that has high annual heat temperatures. Based on this heat patterns installation of solar microgrid power plants will produce cheap, clean and reliable power supply to the communities. Houses in rural areas do not have a lot of electrical appliances as they mostly dependent on natural resources for energy (e.g. wood to make fire). Table I shows a list of appliances that are typically used in the study.

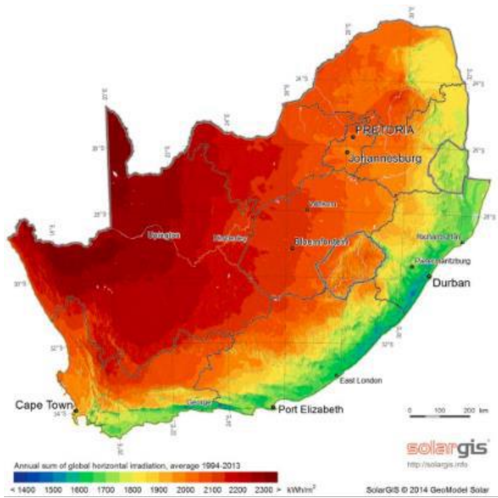


Figure 3. Solar irradiance of South Africa [17]

TABLE I. LOAD ESTIMATION

Load	Watt	Quantity	Hour/Day	Total watt
Compact florescent lamp	20	4	6	80
Refrigerator	400	1	12	400
TV	100	1	6	100
Total	-	-	-	580

The estimated house load is 600W. The solar PV model for this paper is based in the CENTSYS 250W. The PV module and the characteristics of the module are presented in Table II.

TABLE II. DATA OF 250 W CENTSYS MODULE

Maximum Power	250W
Open Circuit Voltage	37.8V
Tolerance	±3%
Short Circuit Current	8.7A
Maximum Power Voltage	31.5V
Maximum Power Current	7.94A
Module Efficiency	15.3%
Solar Cell Efficiency	17.2%
Series fuse rating	15A
Terminal box	IP65
Maximum system voltage	1000V DC
Operating temperature	-40°C to 85°C

The design of the solar PV microgrid was done in PSIM. PSIM is an electronic simulation software package that is designed use in power electronics and motor drive simulations. This software can also be used for any electronic circuits. The I-V and the maximum power curve of the PV will be simulated in PSIM after inputting all the parameters of the solar panel module.

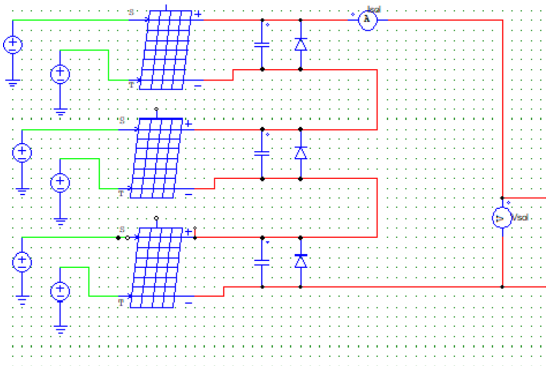


Figure 4. Solar PV array

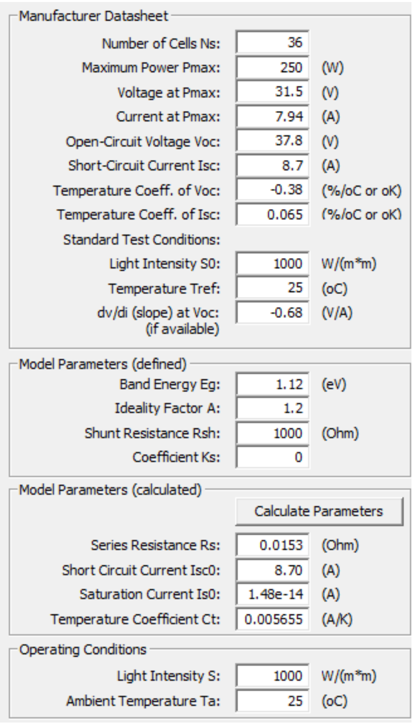
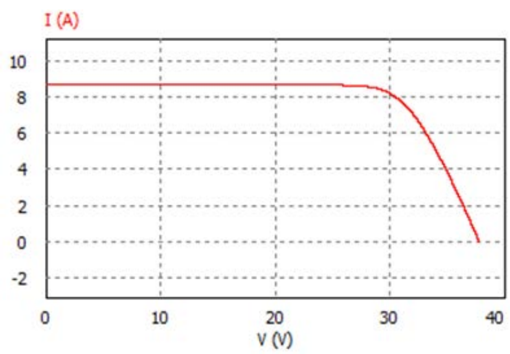
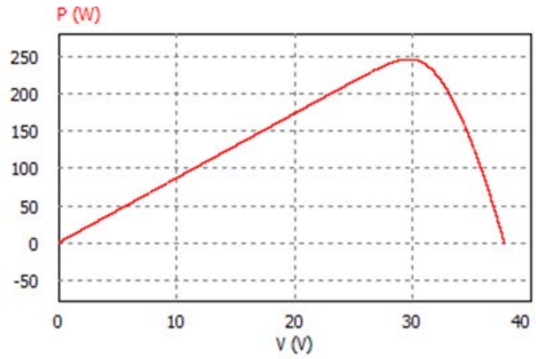


Figure 5. PV solar parameters in PSIM



(a)



(b)

Figure 6. (a-b) I-V and P-V curves from PSIM

Fig. 4 depicts the series connection of 3 solar PV modules. The PV physical model parameters are shown in Fig. 5. The characteristic information of the 250W CENTSYS was used to simulate the maximum I-V and P-V curves shown in Fig. 6.

A. Boost Converter

A boost converter is a DC-DC converter that is utilized to step up the input voltage (while stepping down the current) to supply the load. A boost converter is made up of a switch (MOSFET or IGBT), inductor, capacitor, and a diode. The capacitor and inductor are used as ripple voltage and current filters respectively. The DC input to a boost can be from many sources as well as batteries, DC from solar panels, fuels cells, and DC generators.

TABLE III. BOOST CONVETER DESIGN INFORMATION

Switching frequency	150kHz
Input current	7.94A
Input voltage	100V
Output Voltage	200V

The information given in Table III is the output values from the series solar system array.

$$D = 1 - \frac{V_{in}}{V_{out}} \tag{12}$$

D is the duty ratio of the converter. The voltage across the load can be stepped up by varying the duty ration D. The minimum output voltage (V_{out}) of the system will be obtained when D = 0.

$$I_{out} = (1 - D) I_{in} \tag{13}$$

$$R_{Load} = \frac{V_{out}}{I_{out}} \tag{14}$$

R_{Load} is the design resistive load of the converter. The inductive of the converter is obatined by:

$$L = \frac{D(1-D)R}{2f} \tag{15}$$

The capacitance of the converter is obtained by:

$$C = \frac{D}{2fR_{Load}} 33.1nF \tag{16}$$

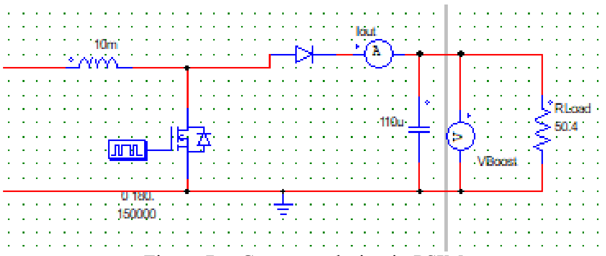


Figure 7. Converter design in PSIM

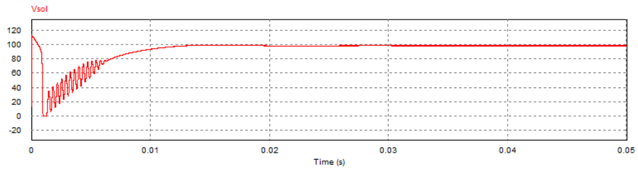


Figure 8. Boost converter input voltage graph

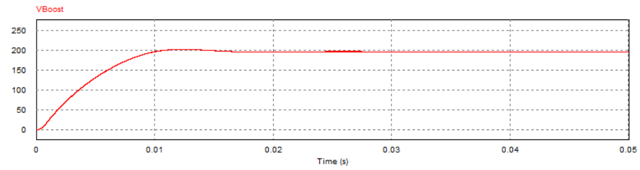


Figure 9. Boost converter output voltage

Fig. 7 shows the boost converter design in PSIM. The inductance and capacitor values were updated as shown above on Fig. 7. The L-C filter values were updated to get a smooth output for the current and voltage. . This converter was simulated with an input voltage of 100VDC as seen in Fig. 8 and the out but is 188VDC as shown in Fig. 9.

B. Battery Storage

The battery storage unit forms an important part in the microgrid system. PV solar systems only function for 12 hours during the day and the energy produced during the day must be stored in order to supply loads at night or during cloudy days. A typical flooded lead-acid cell is shown in Fig. 10. The batteries consist of one or more cells; each cell is made up of an electrolyte, positive electrode, separator and negative electrode [19]. The batteries are rated based on their ampere-hour capacity and nominal voltage. Lead acid cells are designed by the respective manufacturers in such a way to have alternating negative and positive plates, interconnected with multiple or single layers if separator material is used [19]. The service life of lead-acid can be maximized with a proper routine maintenance. Electrolyte topping must be performed regularly to compensate for water loss while charging. The maintenance intervals for these batteries are about 2 to 4 months.

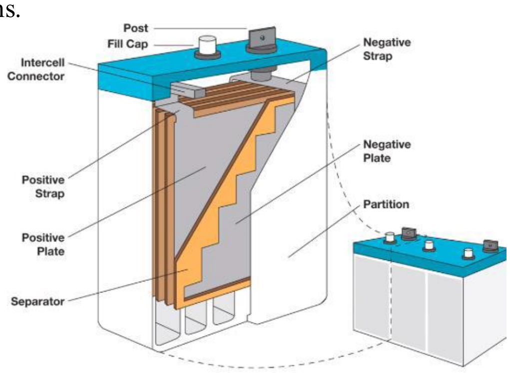


Figure 10. Lead acid battery [18]

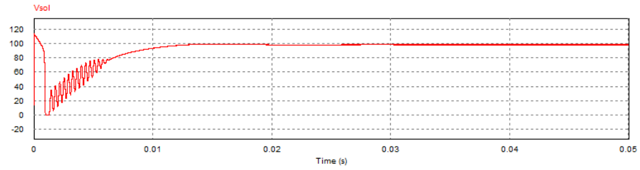


Figure 11. Solar PV output voltage for battery charge

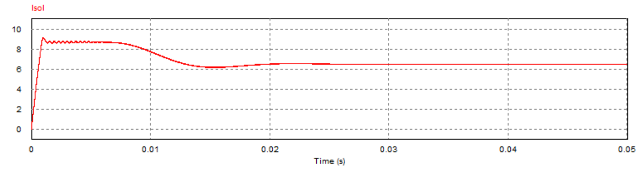


Figure 12. Solar PV output current for battery charge

Fig. 11 above shows the charging voltage of the batteries, a constant current is supplied to the cells until the battery voltage is constant. Fig. 12 shows the charging current of the batteries. The current will decrease and stay constant once the cell voltage is on float.

C. Inverter Design

The main power source of the microgrid is a solar panel that produces DC output. The household electrical loads require an alternating current (AC) to function. It is for this reason a bridge DC-AC inverter is required in the system before the load supply. The inverter is connected after the battery bank, both the PV and battery bank produce DC outputs that must be inverted to AC. The output of the inverter is a chopped AC voltage with zero DC components. Depending on the load supplied an LC low pass filter might be required on the output of the inverter to minimize the high-frequency harmonics.

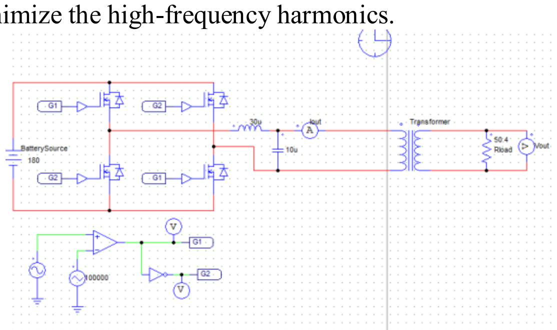


Figure 13. Inverter design PSIM

Fig. 13 shows the inverted design that was simulated in PSIM connected to a step up transformer with a resistive load. The resistive load was calculated in equation 14.

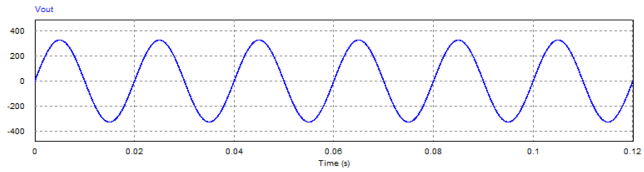


Figure 14. Inverter output voltage

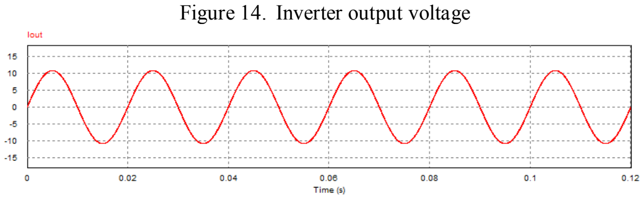


Figure 15. Inverter output current

The voltage and current output of the transformer are shown in Figures 14 and 15 respectively. The required 230VAC is achieved from the transformer output. The maximum output current of the microgrid for a single household is 3.8A. The output current produced is enough to run the loads. The root mean square (rms) values of the transformer outputs are supplied to the load to operate the household loads.

V. DISCUSSION OF RESULTS

The microgrid design was done using the PV system with a battery bank. The solar PV array was connected in series to get the required voltage and current. The DC-DC boost converter was used to boost the incoming supply from the solar panels. The input supply was stepped up to 230 VDC, some of the energy is used to charge the lead-acid battery bank while the other supplies the load. The flooded lead acid battery is utilized in the microgrid as an energy storage system. The battery storage unit will supply the loads at night and during cloudy days. An inverter is incorporated in the microgrid design to invert the DC input from the converter and the battery bank to AC for the household loads. The switching pulse of the inverter has a switching frequency of 50Hz, which is the operating frequency in South Africa. From all the simulation that was completed on PSIM, they microgrid is able to function and also supply the required voltage and current to the load.

A. Discussion of Improvements to Research

The power produced from the PV solar system is only available during sunny days. A hybrid system can be used on the microgrid to supply power when weather conditions are not good. A diesel generator can be incorporated into the system to supply energy when the solar panel is not operational. The diesel generator can be programmed to only function when the battery bank current reaches a low set limit. This function will make sure that the power stored in the batteries will be used up first before the use of the generator. The advantage of this is the saving of fuel costs. Maximum power point tracking (MPPT) can be utilized in the solar array to increase the efficiency of the PV panels. Temperature has an influence on the solar PV output voltage, while solar irradiance affects the output current of the PV. Including an MPPT system in the solar PV array will increase the system efficiency and performance. Lithium-ion batteries can be used as a storage unit. The efficiency of the lithium-ion battery is more than that of the lead-acid and also the cycle life is more.

VI. CONCLUSION

In this paper, an isolated microgrid for rural electrification was proposed. The solar PV system is used to power up a household in the rural community with only essential electric supplies. The PV system has an electric storage system that makes use of lead-acid battery. The output voltage of the PV module is stepped up with the application of the boost DC-DC converter. The output voltage and current of the converter are used to charge the batteries and also supply the load. An inverter is used to change the DC output of the converter and the battery bank to AC output. PSIM software was used for the simulation of the microgrid. Simulations are done for battery charging, the boost converter function and to illustrate the full function of the full bridge inverter.

REFERENCES

[1] T. Adefarati and R. C. Bansal, "Integration of renewable distributed generators into the distribution system: a review," *IET Renewable Power Generation,* vol. 10, no. 7, pp. 873-884, 2016.

[2] T. Adefarati and R. C. Bansal, "The impacts of PV-wind-diesel-electric storage hybrid system on the reliability of a power system," *Energy Procedia,* vol. 105, pp. 616-621, 2017.

[3] T. Adefarati and R.C. Bansal, "Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources," *Applied Energy,* vol. 206, pp. 911-933, 2017.

[4] C. Lupanga and R. C. Bansal, "A review of technical issues on the development of photovoltaic sysyems," *Renewable & Sustainable Energy Reviews, vol. 73, pp. 950-965, 2017.*

[5] T. Adefarati and R. C. Bansal, "Reliability assessment of distribution system with the integration of renewable distributed generation," *Applied Energy,* vol. 185, pp. 158-171, 2017.

[6] T. Adefarati, R. C. Bansal, and J. J. Justo, "Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area," *The Journal of Engineering,* vol. 2017, no. 13, pp. 740-744, 2017.

[7] T. Adefarati and R.C. Bansal, "Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources," *Applied Energy,* vol. 236, pp. 1089-1114, 2019.

[8] T. Adefarati, R. C. Bansal, and J. J. Justo, "Reliability and economic evaluation of a microgrid power system," *Energy Procedia,* vol. 142, pp. 43-48, 2017.

[9] H. Tazvinga, M. Thopil, P. B. Numbi, and T. Adefarati, "Distributed renewable energy technologies," in *Handbook of Distributed Generation*: Springer, 2017, pp. 3-67.

[10] R. C. Bansal and T. S. Bhatti, "Small signal analysis of isolated hybrid power systems: reactive power and frequency control analysis," Alpha science International, Oxford, UK, 2008.

[11] J. E. Paiva and A. S. Carvalho, "Controllable hybrid power system based on rewewable energy sources for mordern electrical grids," *Renewable Energy,* pp. 271-279, 2013.

[12] L. Gidwani, H. Tiwari, and R. C. Bansal, "Improving power quality of wind energy conversion system with unconventional power electronic interface", *Int. J. Electrical Power and Energy Systems,* vol. 44, pp. 445-453, 2013.

[13] M. S. Bin Kadiran, "Charging and discharge methods of lead acid battery," Available online: http://umpir.ump.edu.my/id/eprint/4519/1/cd6777_66.pdf, Accessed: July, 2019.

[14] T. Adefarati, N. B. Papy, M. Thopil, and H. Tazvinga, "Non-renewable distributed generation technologies: a review," in *Handbook of Distributed Generation*: Springer, 2017, pp. 69-105.

[15] Festo Didactic, "Battey Charging Methods," Available online: www.labvolt.com, Accessed: July 2019.

[16] A. Salman, A. Williams, H. Amjad, K. L. Bhatti, and M. Saad, "Simplified modeling of a PV panel by using PSIM and its comparison with laboratory test results", in Proc *IEEE Global Humanitarian Technology Conference (GHTC),* 2015 .

[17] "Energyblog," centre for renewable & sustainable energy studies, 21 November 2014, Available online: http://www.energy.org.za/news/158-new-solar-resource-maps-for-south-africa, Accessed: June, 2019.

[18] "Home Power," Home Powe, [Online]. Available: https://www.homepower.com/anatomy-flooded-lead-acid-cell, Accessed: June 2019.

[19] D. G. Vutetakis, "Batteries," in *the Avionics handbook*, CRC Press LLC, 2001.