Design of off-grid solar photovoltaic system using DC-DC topologies for BIUST classrooms

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Abstract. The project is to Design and Develop an OFF-GRID solar photovoltaic System using DC-DC Topologies for BIUST classrooms light loads (lighting, projector, and computer). Narrowing this topic, focus is on harvesting solar energy using photovoltaic cells then boost the power using a DC-DC boost converter. This project consists of different subsystems, which are combined to have the solar system for classrooms light loads. These are Photovoltaic Solar Array, Maximum Power Point Tracking (MPPT), DC-DC boost converter and battery bank stores energy to be used when the sunrays are not efficient to supply the load. Lastly a DC-to-AC inverter is designed. The system is design is based on performed calculation to size each component to keep the system efficiency high. According to simulation of different DC-DC converters using Simulink, boost was the best converter to use looking at the output characteristics desired. Results from Proteus software simulation of the final circuit correspond with expectation from literature review. Furthermore, PVsyst software has been used to do the mathematical analysis of the designed model showing an estimated payback period of 2.6years whereas the output power for PVsyst model is 11.9 kW which the system produces given the design parameters calculated.

Keywords: DC-DC boost converter, Maximum power point tracking, Solar Photovoltaic system

1. Introduction

The existing power generation used in Botswana pollutes the air hence the need of pollution free power energy generation to conserve the environment. Photovoltaic solar generation, wind turbine generation and hydroelectric generation are the renewable energy sources used to counter this pollution problem [1]. For Botswana, hydroelectric generation is not suitable since there are extraordinarily little perennial water sources. In addition, it is not ideal to use wind turbine generation since the wind cycles here cannot be much efficient. Solar is the most preferable as it is based on sunlight striking solar PV modules [2] which is readily available country wide. The minimum irradiance in Botswana is in July at 4.15kWh/m2 [1]. Implementing solar PV system either grid connected, or off-grid will require a lot of capital to have large battery banks. Batteries will also have a short life span when charged directly from the solar panels because the voltage supplied by the solar varies randomly. Therefore, application of the correct converters will help in transforming the voltage from one level to the other, stepping up or down depending on the application. Stepping up voltage will reduce battery size needed.
When conducting a study of PV Interface for MPPT [3] compares the buck and boost DC-DC converters. The paper has done the Non-ideal Conditions of Photovoltaic Power Generation Comparison, Non-ideal Conditions of PPGC, System Structure Comparison, Control Variables of MPPT Comparison, Component Comparison and the Modelling Comparison of buck and that of the boost Dc-to-Dc converter topologies with regard to the Photovoltaic Interface of MPPT. The comparisons margin has been slight [3] but in conclusion, he proposes the boost converter as it has been of higher strength than the buck converter as it has better dynamic response and cheaper implementations. The gap identified is the way the researchers implement their design they do not combine boost and MPPT which when combined can yield better results in terms of efficiency and cost.

This paper is aimed at designing an efficient solar PV system for BIUST classroom buildings’ essential loads. A way to counter these is by application of DC-DC Converters and MPPT Constant Voltage control algorithm in the solar PV system[3]. Furthermore, the MPPT will be quite handy when regulating the voltage to avoid damaging the battery bank. One critical determinant of the regulation is battery size. Therefore, the paper shows analysis of simulated various DC-DC topologies for solar PV application. This deals with study of their, performance, efficiency and cost and conclude on the most optimum for application in the country especially for BIUST’s design. A complete solar PV system will be designed with the DC-DC converter, DC-AC inverter and sized for use in this project based on design calculations. This requires sizing the load of the lights and power consumption by all light loads which will subsequently help size the whole system. Available DC-DC systems include but not limited to buck, boost, buck-boost, fly back, SEPIC and CUK DC-DC converters[4].

2. Problem Statement
It has been realized that power outages interrupt learning in BIUST especially that the classes have no backup power supply. BIUST classroom blocks are used every day in the academic year and a solar PV system will minimize the electric consumption costs that the classrooms have been adding to the institution’s expenses and reduce carbon footprint. As an essential part of the institution, the classrooms always need to be electrified so that they are readily available. Thus, leading to the question, is it possible and convenient to design and attain a cost-effective off grid photovoltaic solar system for the BIUST classrooms.

3. Methodology

3.1. DC-DC converter simulation
DC-DC converter topologies are found in different classes categorized as isolated and non-isolated. Isolated converters consist of transformers that transform input voltage to a greater or smaller voltage quantities as per requirement [5]. These transformers are usually placed right after the converter’s Ac stage which is then followed by the rectification process. Isolated converters include Fly back transformer and Forward Transformer converters. Non-isolated converters are those that are not electrically separated with the use of a transformer thus meaning there is an electrical connection between the input and output voltage. This non-isolated converter group consists of Boost, buck-boost, and buck converters [5]. Quantitative comparison is carried out from literature reviewed evaluates how they vary in terms of number of parts, output power, ripples, and cost [6]. DC-DC converters use electrical components such as transistors, inductor, switches, transformers and capacitances to smoothen the output voltages when the input current and voltage is altered. Therefore, the output voltage remains the same even though the input voltage changes [6].

Buck, boost and buck-boost converters are further compared in Simulink simulation to observe output voltage with respect to input voltage and they are configured as in figure 1. That represents the configuration of boost converter. The converters are mainly controlled by Pulse Width Modulation through the control MOSFET acting as a high frequency switch with low switching losses, also requiring simple drive circuitry [7] An integrated DC-DC converter module output is connected in
series for a photovoltaic panel, where the Fly-back converter’s capacitor is connected to the output [8] [2]. The method is efficient compared to the conventional DC-DC converters as it enhances energy conversion and reduce the converters energy level. The 3 main converters are made up of an inductor, a diode, a capacitor and a transistor (which is used in place of a switch). These are needed to successfully increase voltage and the inductor volt-balance law states that the output voltage with regards to the input voltage. Solar PV is represented by a battery cell and a resistor used as load. These simulations in MATLAB are only for deciding which converter to use.

![Boost converter in Simulink](image)

**Figure 1.** Boost converter in Simulink

3.1.1. **Buck converter simulation.** The buck converter as simulated in MATLAB Simulink. 48V is input to the converter and feedback is taken at the load side into the comparator. It is then compared to the reference Voltage and the error is amplified by 100. This error is integrated with the Pulse from Pulse Width Modulator and once again compared to the reference voltage. The output is displayed and used in controlling the MOSFET Gate.

3.1.2. **Boost converter simulation.** The boost converter has a voltage limitation with the max duty cycles. However, Boost converter can be improved by making it an interlaced boost converter [9] [10]. The duty cycle is calculated from the equation (1) as

\[ V_{out} = \frac{V_{in}}{(1-nD)} \]  

Where D is the Duty cycle, \( V_{in} \) and \( V_{out} \) are input voltage and output voltage, respectively. By making D the subject of the formular, duty cycle is obtained. If duty cycle provides a non-zero value, then it means that the inductor current is either evolving positively or negatively and lastly that the inductor will be in a transient state. This converter has a higher efficiency of about 80 percent and performs best at a lower input ripple current. Although the converter gives out a higher output result from its input, the converter has no isolation and again gives out an output with higher ripples than its input. Also, the boost converter requires a load to be connected to the output capacitor so that the output voltage stays regulated and not damage the circuit components. Boost is more useful where it is
needed to track maximum power [2]. It is configured in MATLAB as figure 1. The same parameters used for buck converter have been used for consistency.

3.1.3. Buck-Boost converter simulation. Buck-Boost converter topology has also been simulated with the same controls, input and output voltages as the buck and boost topologies. This is to have a fair comparison of the converters.

3.2. Circuit design

The circuit is in Proteus as in figure 2. The main components that will be designed here are the DC-DC converter, the MPPT charge controller and the inverter. MPPT charge controller is simulated on Proteus with the rest of the circuit with rated components using Constant Voltage algorithm. This will be to analyze the algorithm and determine its efficiency in the converter, the MPPT charge controller and the inverter. A block diagram of the whole system is as shown in figure 3. The system is such that solar PV array, which is represented as solar panel of 48V, will be the sole power generator by converting the solar energy to electrical DC power supply. Through the MPPT, the battery (storage) is charged. The charge controller will allow the battery to charge when its voltage is less than the set minimum voltage. When the battery is fully charged, the charge controller will detect that the voltage of the battery is at the set maximum then it stops the charging process.

![Designed circuit in Proteus](image1)

**Figure 2.** Designed circuit in Proteus

![Block Diagram](image2)

**Figure 3.** Block Diagram
Simultaneously, power from the solar panel will be transferred to the DC-DC converter via the charge controller. Furthermore, the MPPT algorithm is the one that provides duty cycle that is used in switching the DC-DC converter. The MPPT will also maximize the utilization of power developed from the solar panels, which varies deepening more on the solar intensity. It does this by comparing the voltage levels. When power drops below the required level, at the dc end side, it varies the voltage from the battery to compensate the low supply. Similarly, it will vary when the solar panels start providing sufficient power again and it reduced the power supply from the battery. This is the Maximum Power Point Tracking process using Constant Voltage Method. An amplifier is connected across a voltage divider such that the difference in voltage can be detected and the deviation from set 48V will be amplified. The differential operational amplifier EL2120CN is implemented with a gain of 20, where the input to the non-inverting terminal is kept constant at 9 percent (+/-2.4v) of the likely regarded voltage output. The input to the inverting terminal is received from the voltage divider of the boost converter.

Between the converter and the load, an inverter circuit is designed as in figure 4. The inverter is made of a center tapped transformer that feeds the center pin from the regulated MPPT controlled 24V output. The other two primary feeds are for the transistors such that when one side is on the other is off. The switching is at 50Hz frequency controlled by pulse generator at the gates with current limiting resistor of 100Ohms. The switching causes alternating current hence a DC-AC inverter. A 47uF capacitor is connected in parallel to the transformer to correct the power factor. Inductors are connected to make the load inductive.

DC-DC converter regulates the voltage supplied before its conversion to Ac and passed to the load. This converter is dependent on the Duty Cycle developed by the MPPT algorithm. DC-AC inverter is for converting from DC to AC at least with 95 percent efficiency[9]. The loads here are of AC rating of 220V, therefore output voltage of the DC-AC converter is 220V.

3.3. Design calculations
Design of system components require that system parameters should be set and calculated taking into consideration the load, efficiencies, power and voltage ratings. This is done by calculating the load taking into consideration the parameters set in table 1.
Table 1. System Parameter

| Constant System Parameters | Value          |
|----------------------------|---------------|
| Battery efficiency         | 0.80          |
| Depth of Depletion         | 0.60          |
| Inverter efficiency        | 0.95          |
| System efficiency          | 0.97          |
| Inductive load?            | YES           |
| Residential load?          | 0             |
| Panel voltage(v)           | 48            |
| Day(6hr)                   | 6             |
| Night(3hr)                 | 3             |
| Panel ratings(w)           | 335           |
| Battery voltage(v)         | 24            |
| Battery voltage(ah)        | 180           |

The load is of Light devices using AC 230V. To find the load, assumptions are made that we refer to the Phillips Fluorescent lamps Manual for bulbs with cool daylight, Master Ecotone brand. Maintained illuminance is assumed at 300 lux. The table 2 Shows load of the system and the total required Wh rated for all the load taking into consideration the system parameters in table 1. Table 1 further shows the arrangement of batteries and solar panels as determined from the calculations and as they are used in simulation with PVsyst.

Table 2. Load, Inverter, Battery and Panel Sizing

| LOAD TYPE      | No. of LOAD | LOADC AP. (W) | DEMAND POWER (W) | DAY TIME (Wh)REQ. (6h) | BACKUP TIME REQUIRED (3h) |
|----------------|-------------|---------------|------------------|------------------------|----------------------------|
| LED LIGHT BULB | 144         | 10            | 1440             | 8640                   | 4320                       |
| PROJECTER      | 12          | 282           | 3384             | 20304                  | 10152                      |
| COMPUTR        | 12          | 65            | 780              | 4680                   | 2340                       |
| TOTAL          | 168         | 357           | 5604             | 33624                  | 16812                      |

TOTAL DAY TIME (Wh) REQUIRED 33624
TOTAL BACKUP (Wh) REQUIRED 36868
TOTAL Wh REQUIRED 34663
TOTAL W REQUIRED 1444
INVERTER SIZING (W) 11208
INVERTER SIZE (kW) 12

PANEL SIZING 29,27
APPROXIMATE NUM. OF PANELS SERIES 1
PARALLEL 30
BATTERY SIZING(Ah) 1536
APPROXIMATE BATTERY SIZE (Ah) 1600
SERIES 1
PARALLEL 9
3.3.1. Battery Storage. When there is sunlight ray, power absorbed will be used to charge the battery until it is fully charged and supply the load. When the voltage drops from the output of the converter and it is not enough to supply the load then the battery will discharge to the load.

3.3.2. Battery Sizing. For a Battery supply of 36.868 kW, the following requirements are to be met.
Depth of Depletion=60% and V= 24 V
Number of batteries required is given by equation 2.

\[
Battery_{size} = \frac{Backup\_requirement}{System\_voltage} \tag{2}
\]

Substitute into Equation (2).

\[
Battery_{size} = \frac{36868}{24} = 1600 Ah
\]

\[
Battery_{parallel} = \frac{Battery_{size}}{Battery\_rating} \tag{3}
\]

Substitute into Equation (3) to find the number of battery arrangement in parallel.

\[
Battery_{parallel} = \frac{1600}{180} = 9
\]

\[
Battery_{series} = \frac{System\_voltage}{Battery\_rating} \tag{4}
\]

Using the Equation (4), number of batteries in series is 1. The number of days of autonomy is approximated to be 1 day.

3.3.3. Duty Cycle. The Boost duty cycle Equation (5):

\[
D = 1 - \frac{V_{in}}{V_{out}} \tag{5}
\]

\[
D = 1 - \frac{24}{48} = 0.5
\]

Switching Frequency. For a switching time of 1µs, the switching frequency is calculated as in Equation (6):

\[
F_s = \frac{Minimum\_Duty\_Cycle}{Minimum\_on\_time} \tag{6}
\]

\[
F_s = \frac{0.5}{10^{-6}} = 500 kHz
\]
Inductor Value. The inductor value is calculated as in Equation (7):

\[
L_{\text{min}} = \frac{D - (1 - D)^2}{2F_s} \\
= \frac{0.5(1 - 0.5)^2}{2(500 \times 10^3)} \\
= 125\,nH
\]

3.3.4. Capacitor Value. The capacitor calculation is as in Equation (8):

\[
C = \frac{D}{F_sRV_R} \\
= \frac{0.5}{(500 \times 10^3) \times 16.67 \times 0.000125} \\
= 480\,\mu F
\]

3.3.5. Amplifier. Equation (9) gives the gain of the voltage error whereas Equation (10).

\[
V_{in} = V1 - V2 \\
V_{in} = 2.4 - 2.15659 \\
V_{in} = 0.24341V \\
Gain = \frac{V_{out}}{V_{in}} \\
Gain = 20.5 \\
R_f = \frac{V_{out}}{V_{in}} (-R_{in}) \\
R_f = \frac{5}{0.24341} (-1k) \\
= 20.54\,kOhms
\]

3.3.6. 555 timer in astable state. Equation (11) used for switching time is manipulated to find the capacitor C2.

\[
\text{Switching time} = 0.693(R_1 + 2R_2)(C_2) \\
1\mu s = 0.693(100)C_2 \\
C_2 = 14nF
\]
3.3.7. Solar Panel Sizing. The minimum irradiance in July is at 4.15kWh/m²[4]. One panel can produce 335W at full sunlight; panel of 1.6m*1m gives an output power of 300W and dc voltage of 48V. It consists of 60 cells.

3.3.8. Inverter Sizing. Since the

\[
\text{Inverter \_ output \_ power} = \text{Demand \_ power} \times 2
\]

Using Equation(12), the inverter size is calculated to be:11.9 kW. A highly efficient and fast transient boost converter using adaptive constant voltage control, assume efficiency of 95%.

3.4. Cost estimation

The cost and simulations have been generated from PVsyst for a projection of 20 years. These are done considering the system parameters in table 3.

| Table 3. System Parameters in PVsyst |
|-------------------------------------|
| Type of the system: Battery associated standalone system |
| PV Field Orientation | Tilt | 30° | azimuth | 0° |
| Orientation of the PV Panel | Tilted with 30° and Azimuth angle 3° |
| Photo Voltaic Module Details | Model CIGS-3350A1, Number of Modules = 30, Nominal Power=335 Wp, Total Nominal power = 10.05K Wp, |
| Battery | Battery module Li-Ion, 26V 180Ah | Technology | Lithium-ion, LFP |

The battery parameters in table 3 are also necessary with the daily constant consumption for estimation of the total system costs.

4. Results and discussion

Since the system uses battery storage, the solar energy is utilized for all the time that the sun is available even when the load is significantly low and the energy stored in the batteries [2]. This maximizes power tracking.

The Boost converter used with the solar PV has been able to boost supplied 48V (acting as the PV voltage) to maintain a constant voltage of 24V at the output battery which acts as the battery storage. This is at the aid of a constant voltage control MPPT algorithm. The algorithm is designed using a 555 timer and a non-inverting operational amplifier. The OP Amp with the reference voltage compares the output voltage and the error is amplified to control the timer, which in turn controls the switching of the MOSFET. When the switch is on, the inductor gets charged and the battery sustains provision of power to the load. When the switch is off, the inductor charges the battery bank and supplies the load with power.

The frequency of this signal is 50Hz such that the output of the inverter is at 50Hz. When one transistor gate is high the other is low such that the transistors conduct one after the other to help in
completing the AC wave form. Channel B is the output AC voltage with a Peak Voltage of 330V measured with the cursor of the oscilloscope. The RMS voltage is therefore 233V which is required for the light loads. The output waveform of the inverter is shown in figure.5.

![Figure 5. Output waveform after inverting to AC](image)

The calculated parameters have been used to model the solar PV system using PVsyst software to get the performance of the system. The results are a simulation of the 15th day of July with reference to GPS location of BIUST and estimates of weather conditions of this day. This is the day where the solar irradiation is expected to be at minimum this year.

Figure 6 shows the daily graph of the effective energy at the output of the array (average: 30.62) kWh/day with varying ambient temperature and sky model. The effective energy output of the array increases as the temperature rises to average operating temperature. At 1230Hrs the output energy of the array is at maximum as the sky model is at the highest clear state. As the output globe sky model drops, the effective output energy of the array drops too until 1530Hrs. From 1530Hrs the energy that will be used by the end user on this day is expected to be that of the battery storage alone.

Figure 7 displays simulation results of effective energy at the PVarray(30.62kWhr/day), Load (33.65kWhr/day) and the energy needed by the load (33.65kWhr/day). Since the energy demanded by the user is greater than that generated by the array. The battery has compensated the deficiency so the output power being equal to the one demanded by the load. It also shows the array nominal energy (4.65kWh/day) which is greater than the actual array virtual energy atMPP (42.50kWh/day) due to losses.

Cost of the system is based on the charge tariffs of Botswana Power Corporation of BWP 9.41/kWh. The cost of the system is estimated to have a payback period of 2.6 years having been financed with a loan of BWP101 800.09 with an interest of 14% and a subsidy of BWP20 000.00. This is a workable payback period. Plant operation costs include a monthly salary to operators of BWP5000.00.
Figure 6. Effective energy from array vs Irradiation in PVsyst

Figure 7. Energy distribution during the day
5. Conclusion
The objective of the project has been reached. This is to say a solar PV system that supplies BIUST classroom essential loads has been designed to the simulation stage. The system supplies an 11.9 kW load of lights with power. In the simulation, only up to the inverter has been designed. A boost converter topology has been found to be suitable and cheaper for implementation in the project. The Boost converter used with the solar PV has been able to boost supplied 48V to maintain constant voltage at the output battery. This is at the aid of a constant voltage control MPPT algorithm. The algorithm is designed using a 555 timer and a non-inverting operational amplifier. The OP Amp with the reference voltage compares the output voltage and the error is amplified to control the timer, which in turn controls the switching of the MOSFET successfully. Boost converter has been used, as it had been more advantageous and cheaper according to reviews in literature. Furthermore, the research brings about more knowledge on implementing DC-DC converter topologies for solar PV application. It has been challenging to implement the MPPT algorithm in sync with the converter.

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