Design of a Solar PV–Battery System for EV Charging

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Abstract. South Africa's EV market is growing faster than its charging infrastructure can keep up. Load-shedding and an already strained national grid make grid-tied charging stations unreliable, which is what motivated this work. This paper describes the design and simulation of an off-grid solar PV system that uses a backup battery bank to charge electric vehicles independently of the grid. To make the simulation meaningful, the EV itself was modelled as a battery with a state of charge rather than as a simple load. This allowed realistic charge and discharge cycles to be tested under varying solar conditions. The system brings together a PV array using Kyocera Solar KC200GT modules, an MPPT controller to extract maximum available power, a boost converter, and DC-DC converters that handle the interconnection between the storage battery and the EV battery. The entire system was built and simulated in MATLAB. The results showed that the storage battery and EV battery both behaved as expected through charge and discharge cycles, and the system managed energy flow between them without significant losses. While this is a simulation study and further hardware validation would be needed, the findings suggest that off-grid solar charging is technically feasible and worth serious consideration as South Africa looks for practical ways to scale its EV infrastructure without waiting on grid improvements.

1 Introduction

As the adoption of electric vehicles (EVs) in South Africa continues to grow, there is an urgent need to develop sustainable charging solutions that can meet the expanding energy use and reducing energy efficiency. Growing energy use and decreasing energy efficiency. reducing environmental impact [1, 2]. The transition from internal combustion engine (ICE) vehicles to environmental impacts of polluting cars. Polluting cars cause negative environmental effects, which is the driver behind EV growth. Due to the effects of ICE vehicles, which are key players in carbon dioxide (CO_2) CO emissions and urban air pollution [3]. South Africa's dependence on the fossil fuel energy resource, coal. generation further brings into focus the need for Switching to a renewable energy source for EVs charging. The nation has problems with increasing energy charges and the uncertainties of energy supplies, the importance of developing alternative energy solutions [4].

A photovoltaic system, sometimes called a PV system, uses photovoltaic cells to convert sunlight into energy directly. These cells are constructed from semiconductor materials, such as silicon, which use the photovoltaic effect to produce energy when exposed to sunshine. PV systems usually consist of solar panels or modules, which are made up of several PV cells joined together. These panels can be incorporated into building materials, erected on rooftops, or put on structures in the ground [5-7].

Other researchers have looked into the usage of solar PV for EV systems. Priyanshu Singla presented the design and simulation of a 4-kW solar power-based hybrid EV charging station. The authors utilized a three-stage charging strategy that integrates solar power, battery energy storage, and grid electricity to ensure a continuous power supply for electric vehicles (EVs). The simulation was conducted using MATLAB, where the system's components, including the MPPT (Maximum Power Point Tracking) controller, battery bank, and grid-tied inverter, were modelled to analyse performance under various conditions [8].

Smail Chtita, focuses on an improved power balance control strategy for off-grid photovoltaic systems. The authors developed a model of the entire system based on a linear PV array model and implemented a digital anti-windup control strategy to manage the charging of batteries effectively. MATLAB/SIMULINK was employed for simulations to demonstrate the performance of the proposed control strategy under different atmospheric conditions, achieving high efficiency and low steady-state power oscillations [9]. Alper Kerem, designed a solar-powered off-grid EV charging station that includes PV panels, a boost converter, and a bidirectional converter. The system was simulated to analyse the charging process of EV batteries and backup batteries under various operational scenarios. The simulation was performed using MATLAB, where the charging system's components were modelled to evaluate their performance in different cases, such as when the EV battery is charged directly from the PV panels or from the backup battery storage [10].

A major challenge facing the adoption of electric vehicles (EVs) in South Africa is the limited availability of reliable charging infrastructure, particularly in remote

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grid-constrained regions affected by persistent unstable electricity supply. Although several studies have investigated solar-powered EV charging systems, most existing designs are developed for stable grid-connected environments and are not specifically tailored to the operational realities of developing economies such as South Africa. This study therefore carries out a study on off-grid EV charging architecture designed for decentralized deployment in regions where grid reliability remains a major limitation. The proposed system combines a solar PV array, battery storage, MPPT control, and DC–DC converter topology. In addition, the work presents a low-cost modular design methodology that can be adapted for small-scale charging stations and scalable community-based EV charging applications. Unlike conventional simulation studies that model EV charging as a static load, the EV in this work is represented using a battery state-of-charge model to achieve more realistic charge–discharge behaviour under varying solar irradiance conditions. Furthermore, the prototype implementation presented in this paper should be regarded as a scaled-down design intended for conceptual and functional validation of system operation rather than direct full-scale performance validation. Consequently, the simulation and prototype results are compared qualitatively to demonstrate consistency in charging behaviour and system response, while acknowledging that differences in scale, thermal effects, converter losses, and hardware non-idealities prevent direct equivalence between the simulated and experimental systems. This clarification positions the study as an important preliminary step toward the development of practical decentralized renewable-energy-powered EV charging infrastructure suitable for South African operating conditions.

2 Solar batteries

Solar battery systems, typically classified as deep-cycle electrochemical energy storage devices, are widely used in photovoltaic (PV) systems to store the direct current (DC) electrical energy generated by solar modules for later utilization. Unlike conventional starter batteries, deep-cycle batteries are designed to sustain repeated charge–discharge cycles while delivering a relatively stable output over extended periods. Various battery technologies, as shown in Figure 1, are used in solar energy systems, including lead–acid, lithium-ion, nickel-based, and flow batteries, which differ primarily in their electrode materials, electrolyte composition, energy density, cycle life, and thermal characteristics [11]. The comparison of these batteries is shown in Table 1.

The electrochemical processes occurring at the anode and cathode electrodes determine the energy storage capability and operational performance of the battery. Key performance parameters used to evaluate solar battery systems include battery capacity, energy efficiency, and depth of discharge (DoD).

The energy storage capacity of a battery defines the total amount of electrical energy that can be stored and delivered under specified operating conditions. It is commonly expressed in ampere-hours (Ah) or watt-hours (Wh) depending on the application. The theoretical stored energy in a battery can be expressed as $E = V \times I \times t$. Where E represents the stored energy (Wh), V is the battery terminal voltage (V), I is the current (A), and t is the discharge time (h). In practical systems, the available energy is also influenced by factors such as internal resistance, temperature, and state of charge (SOC). For battery packs used in EV or PV applications, the total energy capacity can also be expressed as $E_{bat} = V_{nom} \times C_{Ah}$. Where V_{nom} is the nominal battery voltage and C_{Ah} is the rated battery capacity in ampere-hours.

Another important performance metric is battery energy efficiency, which depicts the ratio of the useful output energy delivered during discharge to the energy supplied during charging. This parameter reflects internal energy losses caused by electrochemical reactions, resistive losses, and thermal effects within the battery. The round-trip efficiency of a battery system is therefore expressed in equation 1.

$$\eta_{bat} = \frac{E_{out}}{E_{in}} \times 100\% \quad (1)$$

where E_{out} is the energy delivered during discharge and E_{in} is the energy supplied during the charging process. Modern lithium-ion batteries typically exhibit efficiencies above 90–95%, whereas conventional lead–acid batteries may have efficiencies ranging from 70–85% depending on operating conditions.

Depth of Discharge (DoD) is the ratio of the amount of capacity that is being used compared to the nominal capacity of the battery and is an important indicator of battery utilization and lifespan. If the discharge is too high, it can cause batteries to degrade more quickly and shorten their cycle life. DoD can be mathematically expressed as equation 2.

$$DoD = \frac{C_{discharged}}{C_{rated}} \times 100\% \quad (2)$$

where $C_{discharged}$ represents the extracted capacity and C_{rated} denotes the rated battery capacity. The complementary parameter, known as the State of Charge (SOC), is defined as $SOC = 100\% - DoD$.

Proper management of DoD and SOC is essential in PV–battery systems and EV charging infrastructures to ensure optimal energy utilization, extended battery lifetime, and reliable system performance.

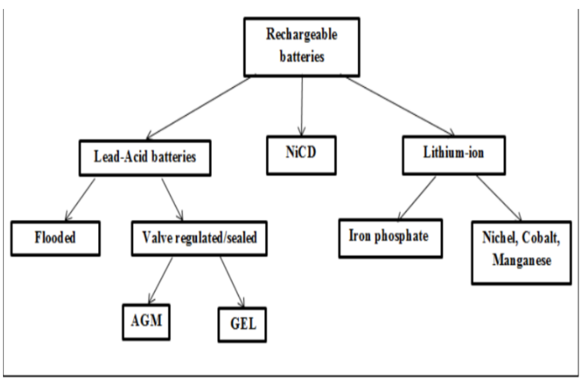

Fig. 1. Different types of solar batteries

Table 1. comparison of different batteries

	Lead-acid battery	Jel battery	AGM battery	Lithium battery
Maintenance	Need	No need	No need	No need
Depth of discharge	50%	75%	50%	80%
Lifespan	3-5 years	6-8 years	6-8 years	20 years
Cost				
Charge temperature	-0℃ to 50 ℃	-20℃ to 50℃	0 ℃to 50℃	0℃ to 45 ℃
Discharge temperature	-30℃ to 70 ℃	-40℃ to 60℃	-20 ℃to 60℃	-20 ℃to 60℃
Storage temperature	-20℃ to 60℃	-40℃ to 60 ℃	-20℃ to 60℃	-20 ℃to 60℃
Energy density	30W.h/kg	40W.h/kg	50W.h/kg	50-260W.h/kg

3 Electric vehicles

Electric vehicle – vehicles that are powered by an electric motor rather than the traditional internal combustion engine (ICE). EVs work by transforming the stored electrical energy within their battery into mechanical energy, which the motor uses to drive them. The motor can also act as a generator in deceleration/braking mode, recovering the energy by the process of regenerative braking, which can then be stored in the battery for later use [12].

3.1 Benefits of EVs

Electric vehicles (EVs) have a number of technical benefits over traditional internal combustion engine (ICE) vehicles, including environmental sustainability. EVs remove the need for tailpipe emissions, which helps the reduction of local air pollutants and helps to lower greenhouse gas emissions. Overall emissions from EVs are lower than the emissions from conventional cars even if they are powered from an electricity grid that relies on fossil fuels. As such, EVs contribute to the global push towards decarbonizing transport and moving towards cleaner fuels. From an operation point of view, EVs are more energy efficient and have lower lifecycle operating costs over an ICE vehicle. The more streamlined electromechanical design of EVs has fewer moving parts result in less mechanical wear, maintenance, and system complexity. Further, the price of electricity is generally more predictable and competitive than that of liquid fuels, making electricity-powered vehicles more cost-effective to operate. Additionally, EVs can connect with electrical networks, expanding the potential for the integration of renewable energy sources like solar and wind, which help achieve sustainable and decentralized energy systems. When it comes to performance and handling, EV powertrains offer instant torque application and enhanced dynamic performance, leading to superior acceleration and a smooth driving experience. Battery packs are strategically located in the vehicle structure to reduce the center-of-gravity, which improves vehicle stability, handling and safety. Moreover, EVs can be charged from various stations, including residential, workplace, and public charging stations, and have a range of advanced control options like remote monitoring and thermal management systems that enhance vehicle performance, operational efficiency, and convenience [13].

3.2 EV charging mode

The charging modes for electric vehicles (EVs) refer to the electrical connection and the power capacity required to transfer energy from the electricity grid into the EV battery. Slow charging, also known as Level 1 or low-power Level 2 AC charging, generally is in the range of 2.3 kW – 7.4 kW, depending on the supply voltage and current rating in residential applications. For instance, a regular electrical outlet can deliver around 2.3 kW (230 V / 10 A), and dedicated wall-mounted AC chargers can provide up to 7.4 kW (230 V / 32 A). The relatively low powers mean that charging times are in the range of 6 to 12 hours depending on the battery size of the EV and the charging power. This charging is common with overnight parking in residences, as the battery has more time to recharge. Fast AC charging is typically on a power level of 7.4kW to 22kW, and uses single-phase or three-phase AC power feeds. Three-phase, AC 400-V and 32-A chargers can provide charging at about 22 kW, which is much faster than slow charging. These charging systems use the built-in charger that is present in the vehicle to rectify the AC current into DC current and store it in the battery. Public and semi-public charging stations, including commercial areas, parking lots at workplaces, transportation hubs and public parking lots, are often equipped with fast AC charging infrastructure. DC fast charging systems are used where charging power is needed for more than just a small amount, with the AC–DC conversion taking place in the charging station, not inside the vehicle. The most common fast chargers are now 50 kW to 350 kW, which depends on the type of charger and the vehicle compatibility. They are designed to work with standardized connectors like CHAdeMO, CCS (Combined Charging System) or GB/T, which allow for rapid charging and shorten charging times. They are usually installed at strategic places in urban areas, highways and service stations, to assist long-distance travel and quick energy replenishment [14].

3.3 Mathematical modelling of PV cell

The single-diode model is the most widely used PV cell model because it provides a good balance between modelling simplicity and accuracy. In this model, a series resistance $R_s$accounts for internal ohmic losses, while a shunt resistance R_{sh}represents leakage current effects within the practical solar cell, as illustrated in Figure 2.

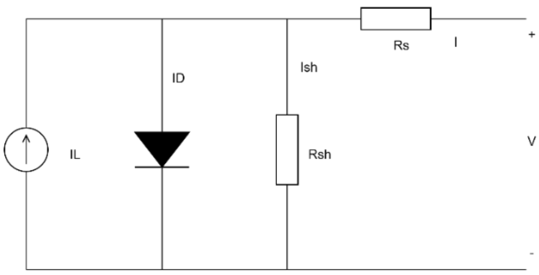

Fig. 2. Practical PV cell equivalent circuit.

Using Kirchhoff's Current Law (KCL), the load current of the photovoltaic (PV) cell can be expressed as the difference between the photo-generated current, diode current, and shunt current, as shown in Equation (3):

$$I = I_{ph} - I_d - I_{sh} \quad (3)$$

The diode current is shown in Equation (4) and the current that flows through the shunt resistor is shown in Equation (5). The solar irradiance related to the light-generated current is proportional to the light-generated current as described in Equation (6), K_I in Equation (6) is the temperature coefficient of the short circuit current and I_{sc} is the short circuit current at STC (standard test conditions).

$$I_d = I_o\left(e^{\frac{q(V+IR_S)}{AkT_C}} - 1\right) \quad (4)$$

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad (5)$$

$$I_{ph} = [I_{sc} + K_I(T_c - T_r)]\frac{G}{G_{STC}} \quad (6)$$

Substituting Equations (4), (5) and (6) into Equation (3) gives the output current of the PV cell in equation (7):

$$I = I_{ph} - I_o\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (7)$$

The open-circuit voltage of the PV cell is given by (8):

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_o} + 1\right) \quad (8)$$

3.4 Boost converter

The DC–DC boost converter shown in Figure 3 operates as a voltage step-up device that interfaces the photovoltaic (PV) source with the battery and the electric vehicle (EV) charging load. The converter increases the PV output voltage to the required level for charging the battery while simultaneously supplying power to the EV charger. The duty cycle of the MOSFET switch in the converter is regulated by a Maximum Power Point Tracking (MPPT) controller, which ensures optimal energy extraction from the PV array and improves the overall system efficiency.
The relationship between the input and output voltage of the boost converter as a function of the duty cycle is shown in equation (9):

$$\frac{V_o}{V_i} = \frac{T_s}{t_{off}} = \frac{1}{1 - D} \quad (9)$$

where:
T_s= switching period, V_o= average output voltage, V_i= input voltage from the PV array, and D= duty cycle of the switching device.
The design equations for the inductor and capacitor values required for boost converter modelling are given in Equations (10) and (11), respectively.

$$L = \frac{V_{in}}{D \times f_{sw} \times I_L} \quad (10)$$

$$C = \frac{I_{out}}{f_{sw} \times \Delta V_{out}} \quad (11)$$

where:
I_L= inductor (load) current and f_{sw}= switching frequency, I_{out}= output current, ΔV_{out}= allowable output voltage ripple.

These design parameters ensure stable operation of the boost converter and maintain the desired voltage level required for efficient battery charging and EV load supply.

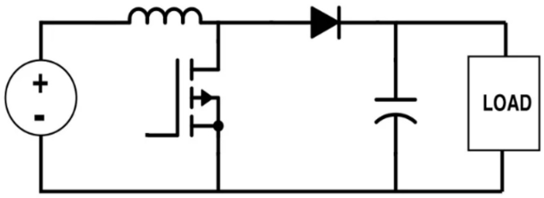

Fig. 3. Schematic diagram of a boost converter available at LINK

4 Results

4.1 PV system modelled on MATLAB/SIMULINK

Fig. 4 display the MATLAB/Simulink implementation of the photovoltaic (PV) power conversion system integrated with a Maximum Power Point Tracking (MPPT) controller and a DC–DC boost converter. The PV module receives solar irradiance (G) and temperature (T) as inputs, which determine the generated voltage and current of the PV array. These electrical parameters are measured and fed into the MPPT controller, where the instantaneous power of the PV system is calculated to determine the optimal duty cycle required for maximum power extraction. The generated duty cycle controls the MOSFET switching device within the boost converter.

The converter (inductor, diode, switch and output capacitance) converts the PV voltage to a higher-level DC voltage required for subsequent use like charging batteries or supplying EV loads. Such a configuration will result in effective energy capture from the PV source with constant output voltage and better system performance at different environmental conditions. The Perturb and Observe (P&O) (MPPT) (Figure 5) technique was used in this study due to its simple implementation, low computational requirement, and suitability for standalone solar PV applications. The current–voltage (I–V) and power–voltage (P–V) characteristics of the PV array at different temperatures is shown in Figure 6. The curves represent the operating

 https://doi.org/10.1051/e3sconf/202672904005

characteristics of the output current, output voltage and output power of the system with a marked out point of the maximum power point. This figure shows the output power of the PV system as a function of time, as shown in Figure 7. The result demonstrates that the system remains stable around 4 kW, which confirms the successful MPPT and stable power generation.

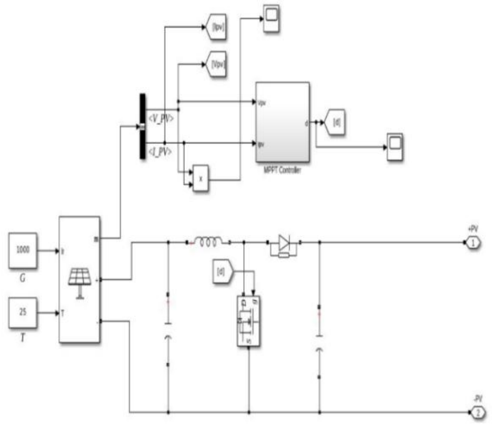

Fig. 4. PV System with MPPT

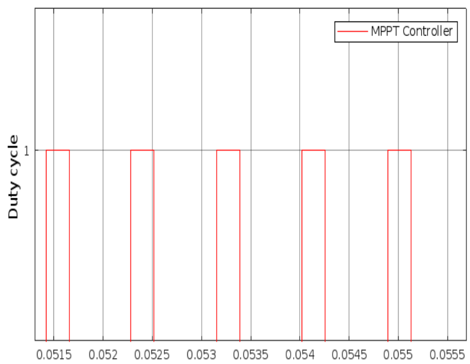

Fig. 5. Duty cycle

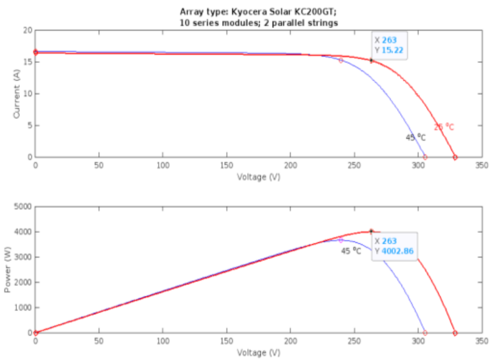

Fig. 6. I-V and P-V characteristics under varying temperatures from Kyocera Solar KC200GT.

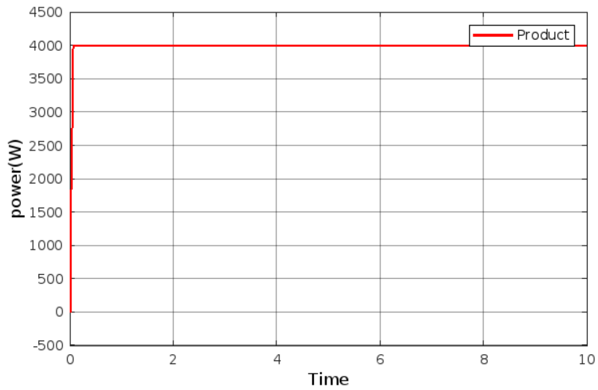

Fig. 7. The power produced by PV

4.2 Storage battery setup

The MATLAB/Simulink model of the Battery Energy Storage System (BESS) integrated with a bidirectional DC–DC converter and associated control unit is presented in Figure 8. The system comprises a bidirectional converter incorporating controlled semiconductor switching devices, an inductor, and passive filtering components to regulate bidirectional power flow between the DC bus and the battery pack. The converter interface is connected to the PV-side DC bus through the positive (+PV) and negative (−PV) terminals, enabling both charging and discharging operation depending on system energy demand and solar generation conditions. A closed-loop control scheme continuously monitors the battery current (I_{batt}), terminal voltage, and State of Charge (SOC), with the SOC signal being fed back into the controller for effective battery management. The measured battery current is compared with a reference current and processed through a proportional–integral (PI) controller, which generates pulse-width modulation (PWM) gating signals for the converter switching devices. Complementary switching operation ensures controlled energy transfer between the DC bus and the battery storage system, thereby maintaining stable charging conditions while preventing battery overcharging and excessive depth of discharge.

The results presented in Figure 9 illustrate the discharging mode of the storage battery under conditions of insufficient solar irradiance, where the PV array is unable to satisfy the load demand. The SOC profile exhibits a gradual decreasing trend over time, indicating battery energy depletion during discharge operation. The battery current and voltage initially increase at the start of operation and subsequently stabilize at approximately 400 A and 400 V, respectively, demonstrating stable converter performance and regulated power delivery throughout the discharge cycle.

The results shown in Figure 10 represent the charging mode of the storage battery. In this operating condition, the SOC profile increases progressively with time, indicating that surplus energy generated by the solar PV array is effectively utilized to charge the battery energy storage system.

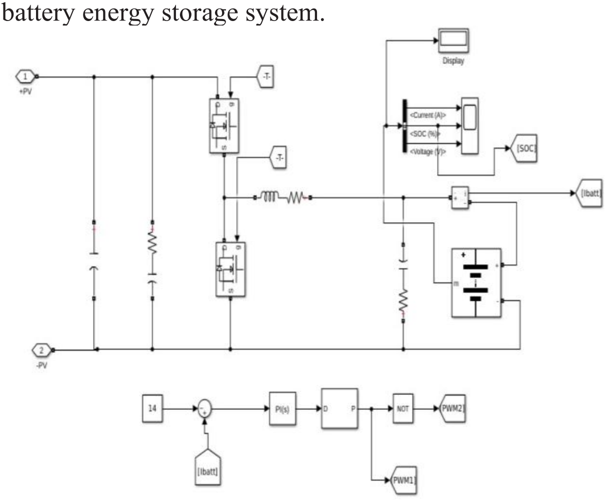

Fig. 8. Battery energy storage system with Buck-Boost bidirectional converter.

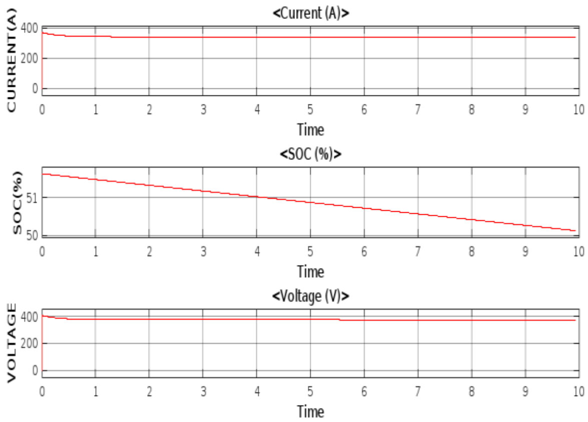

Fig. 9. A storage battery in discharging mode

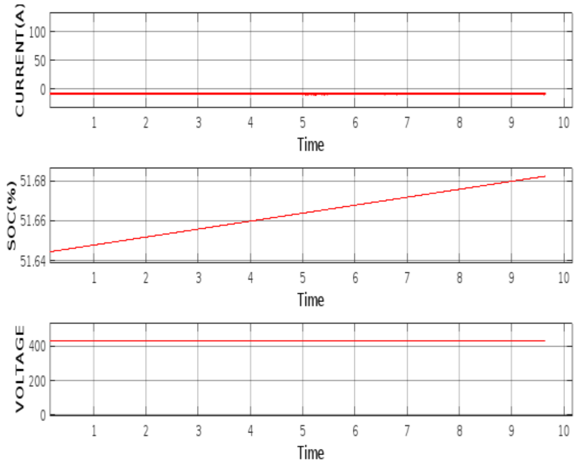

Fig. 10. A storage battery in charging mode

4.3 EV BATTERY

The MATLAB/Simulink simulation model of the integrated EV charging system with battery energy storage and control is shown in Figure 11. The model is composed of an EV controller which controls the charging process by providing the suitable control signals to the power electronic converter. The converter processes the power transfer from the DC source to the EV battery and consists of switching devices, inductor, and protective devices. All the important electric parameters like battery voltage, charging current and state of charge (SOC) are continuously monitored in the system. Such measured signals are fed back to the control unit for proper regulation of the charging current and voltage. The addition of filtering and protection components helps keep the system steady and avoids overcurrent and rippling. Overall, this configuration is proving to allow controlled and efficient charging of the EV battery and keeping the battery and its power electronics within safe operating limits.

4.4 Experimental Setup

The experimental setup for the solar PV powered EV charging system consists of two-stage power-conversion architecture which helps to bridge the voltage gap between solar source and vehicle. The first stage is a solar PV panel of 22V, and the second stage is a buck converter for the PV panel output to a stable 12V for the battery storage system. This intermediate storage is a buffer to be used as shown in the bread board implementation in Figure 12, and the lab calibration with multimeter to confirm the 20V to 12V step down ratio in Figure 13. This setup allows for efficient energy harvesting even in the worst case scenario of the solar module being at its peak voltage. The second stage is to convert the 12V intermediate storage to the 9V EV battery with a further buck converter. It is an environment controlled charging station for the electric vehicle chassis, where the final battery will always be charged with 9V power, even if the solar input is fluctuating. These components are integrated as illustrated in Figures 14 and 15 in which the complete system (solar panel, control circuitry, storage battery and prototype EV) is subjected to tests in the outdoor environment. Two multimeter were used to measure the voltages, the DC converter output voltage was 12.35V, and the EV battery was 5.97V. This two-stage buck conversion technique will be an effective and scalable solution for small-scale EV charging stations using conventional high voltage solar modules.

The solar-powered EV charging station prototype, with a solar PV array and intermediate Battery Energy Storage System (BESS), was assessed by conducting systematic voltage monitoring. The dynamic behaviour of the system was observed by taking measurements at 6 minute intervals during both charging and discharging. The charging rate of 12V BESS is shown to be gradual as seen in Figure 16, increasing from 11.1V to 11.32V after 60 minutes. This is a relatively low charging rate, around 0.22V/h, which is due to the fact that the voltage difference between the source and the battery rating are very small, thus this low voltage difference allows only small charging current to enter the charging system. At the same time, the charging curve was more distinct for the 9V EV battery in Figure 17, which increased from 6.6V to 7.32V in the 60-minute period, equating to a charging rate of 0.72V/h. The discharging phase for both 12V BESS and 9V EV battery (as shown in Figures 18 & 19) was very steep, however. The major reason for this quick go-fast is that the 4 electric motors driving the wheels in the EV are all consuming current at a high level. The high loads the motor drive system puts on the stored energy means it is being used up much faster than the charging system can replace it, revealing the importance of efficient power management and perhaps increased storage in order to sustain operation.

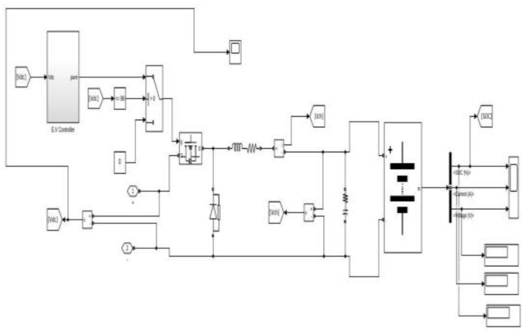

Fig. 11. EV Battery Setup on MATLAB/Simulink

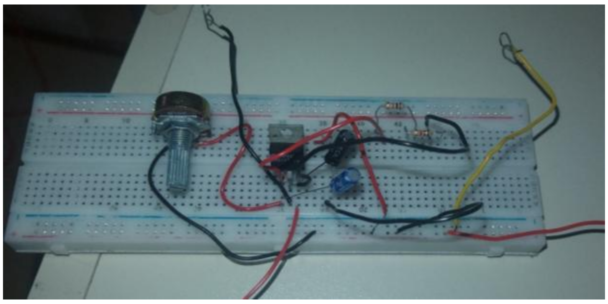

Fig. 12. DC converter of 12V to 9V before testing.

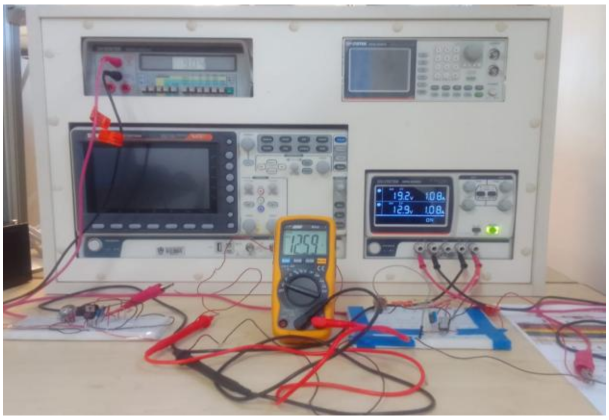

Fig. 13. DC converters for 18V to 12V and 12V to 9V after testing.

Fig. 14. Charging an EV battery with solar PV

Fig. 15. Multimeters displaying an input voltage for a DC converter and output voltage

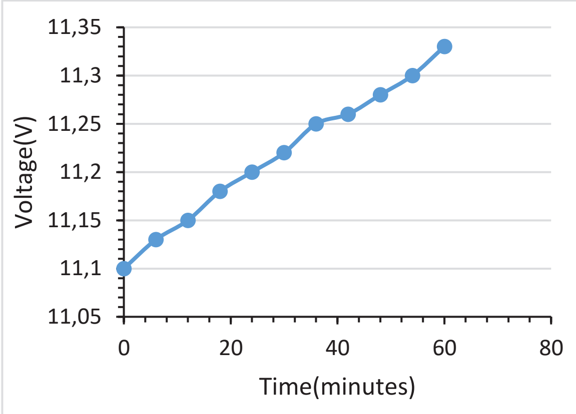

Fig. 16. A 12V battery charging

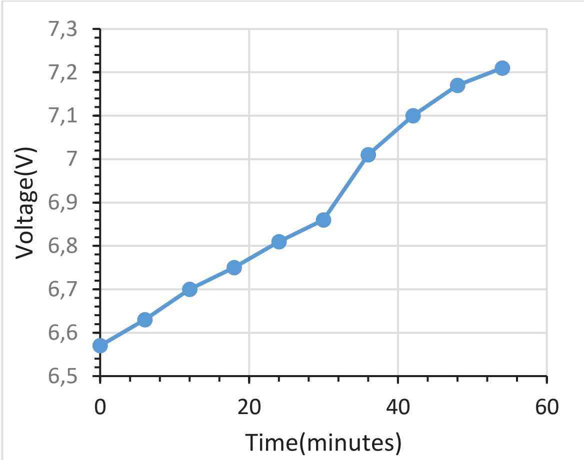

Fig. 17. A 9V battery charging

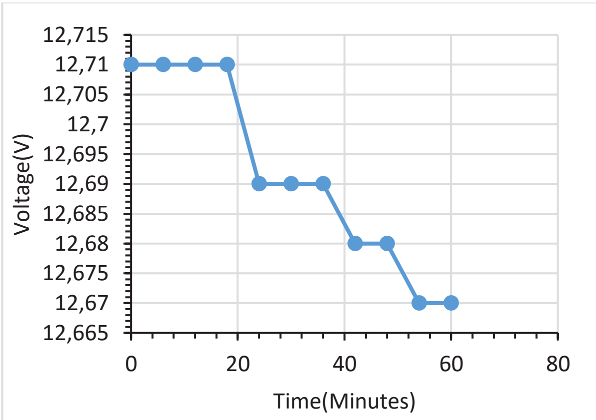

Fig. 18. A 12V battery discharging

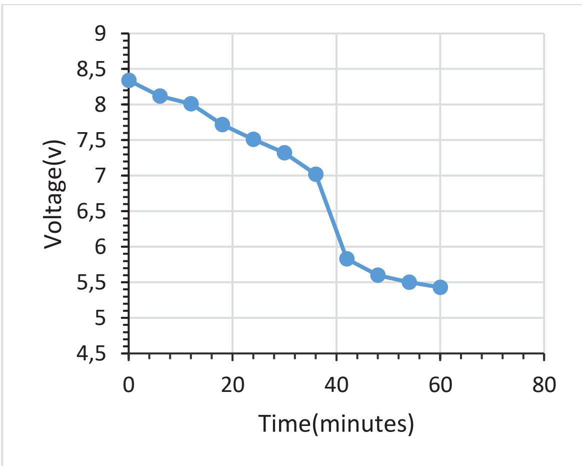

Fig. 19. A 9V EV battery discharging

5 Discussion

The comparative study between simulation and prototype results shows a consistent charging behaviour of the battery energy storage system. The battery voltage rises gradually when operating under MPPT in simulation, which suggests that the maximum power is extracted from the solar array and the power is well regulated by the boost converter. The prototype results show a similar trend with battery voltage continuously increasing during charging, which confirms the correctness of the system design. Any minor deviations noted on the prototype are considered to be due to practical non-idealities such as connection losses and thermal influences, which are not included in the simulation model. As a result of discharging, the voltage of the battery decreased as time went on, both in simulation and in the experiment, as expected due to the electrochemical discharging nature of the battery. In practice, however, factors such as internal resistance, temperature changes, and load changes make the prototype display a slightly higher voltage drop. The simulation assumes optimal operating conditions and higher theoretical efficiency, while the prototype demonstrates some practical challenges due to environmental fluctuations and hardware inefficiencies. In conclusion, the findings validate the system's reliability and highlight the importance of optimizing the system and thermal management in practical applications.

6 Conclusion

This study illustrates the technical feasibility of a solar PV driven EV charging system with BESS. The proposed system successfully harnesses solar energy to provide charging power to the EV battery and also integrates a backup battery, which guarantees continuous operation in case of insufficient solar irradiance. The battery energy storage system enables to maintain the stability of charge–discharge cycles and to ensure the continuity of the system under different solar generation conditions. The capability of the system is verified by the simulation analysis and prototype implementation which proves that the system is capable of providing a stable power supply and effective energy management between the PV array, battery storage system and EV load. The results show that the integrated system is capable to maintain charging processes despite fluctuations in solar energy sources availability. But some performance restrictions have been noticed in the prototype phase which is mainly due to connection losses, inefficiencies in the converter and thermal effects in the hardware components. The current constraints underscore the importance of optimizing the hardware, managing heat, and implementing more sophisticated energy management solutions to maximize system efficiency. The results confirm that charge battery powered EV charging infrastructure is a technically sound solution for off-grid and decentralized charging applications, and is a valuable contribution towards building sustainable transportation systems and integrating renewable energy into the grid, especially in remote or grid-constrained locations.

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