Performance Analysis and Implementation of Buck-Boost Converter for Electric Vehicle Applications

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Abstract: ***With the rising integration of renewable energy systems, particularly solar photovoltaics (PV), efficient energy conversion and storage systems have become crucial to maintaining power quality and reliability. This paper presents the design and implementation of a solar energy conversion model utilizing a Maximum Power Point Tracking (MPPT) controller to optimize solar PV output. The model converts the solar-generated DC power into AC using an inverter, followed by a reconversion to DC for battery storage. A bidirectional converter along with a buck-boost converter regulates the power flow between the battery and the load, ensuring stable energy management. The system is designed to dynamically manage power flow between the load and storage, enhancing performance under various operating conditions. Real-time simulation results, developed and tested in MATLAB/SIMULINK, demonstrate the effectiveness of the proposed system in maintaining efficient power flow, ensuring battery life optimization, and managing load demand with minimal losses. Additionally, the design is implemented on hardware using the DSPACE controller, which facilitates real-time control and validation of the system. The hardware testing further validates the robustness of the system in balancing load fluctuations, providing a comprehensive solution for solar energy-based power systems.***

Keywords: dSPACE, Bidirectional DC-DC converter, MPPT, Electric Vehicle, Battery Management System, Buck-Boost.

1. Introduction

The batteries in Electric Vehicles (EVs) or Hybrid Electric Vehicles (HEVs) usually operate at several hundred volts and provide a significant amount of current. Lithium-ion batteries are vastly used in electric vehicles due to their high performance and compact designs. This batteries are reliable for zero emissions and their adaptation in electric vehicle due to their design and compatibility [1]. Electric Vehicles can also be integrated with renewable energy sources as a source of alternative to fossil fuel vehicles, which makes it highly adaptive to environment and sustainability [2,3]. Along with this, various other components are required in the circuit to complete the overall functionality and high efficiency of the vehicle. This can be achieved through high performance converters, near to lossless traction motors, stable DC grid inputs, and proper channels to gain outputs from the vehicle [4]. The various components inside these vehicles have different requirements for current input and voltage levels. These components generally run on lower voltages. For instance, the infotainment system, interior lighting, power windows, and other electronic accessories are designed to operate at 12V or 48V. Additionally, safety systems like airbags and backup cameras, as well as convenience features like seat heaters and USB charging ports, also rely on these lower voltage levels to function properly. To address this change of specifications, power electronic converters such as DC-DC converters can be employed for power transfer within the vehicle [5]. This DC-DC converter can step down the battery voltage to power up the auxiliary systems inside the vehicle, and it is also capable of stepping up the voltage to feed back to the battery, particularly during the regenerative braking. DC-DC converters can be unidirectional, or bidirectional, which is based on the direction of power flow. A bidirectional DC-DC converter is one of the best fits, when designing an electric vehicle powertrain, due to its efficiency, robustness, and its architectural design to fit in the circuit. The bidirectional DC-DC converter allows the EV to charge from the grid, and discharge energy back to the grid. This V2G operation helps stabilize the grid and facilitates V2L operation [6].

Switches play a major role in these converters, and selecting the perfect converter improves the overall working and efficiency. IGBTs are a perfect choice to look on, when working with DC-DC converters, as this switches are a perfect match to choose between MOSFETs and BJTs [7]. They offer high input impedance, almost equal to that of a MOSFET, and fast switching equivalent to the BJTs.

Practical applications for input DC can be directly through the grids, or other sources such as solar, or fuels can be used to power up the load and battery. Solar PV can be configured with an incremental MPPT controller to draw maximum voltage from the solar PV modules [8]. MPPT controllers function as A DC-DC converter, which takes direct current input from the solar modules and convert it to a different DC voltage and current which matches with the specifications required. MPPT controllers usually have a large functional time under standard environmental conditions and can extract maximum available power from the solar PV modules. They can easily adapt to use with any type of battery. Without a controller, there is a slight risk of battery being over charged, hence MPPTs optimizes the solar PVs to extract maximum possible power for desired requirements. However, addition of MPPT with a secondary battery source provides an added

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advantage of continuous power supply to load and peripherals, hence obtaining a smooth functioning of the vehicle [9-12].

Section 2 covers the working analysis of buck boost converter, along with its important derivations and calculations involving the power transfer along the circuit. Section 3 further discusses on the simulation and hardware functioning of the circuit, along with necessary protocols and controllers used in the circuit, to achieve the desired output by further addition of solar PV as an input. Section 4 mentions about the results obtained through the simulation of the converter and the comparing the hardware results for verifying the circuit accuracy in gaining the desired output. Section 5 further draws the conclusions obtained from the circuit.

2. Working Analysis of Buck Boost Converter

The power requirement for the battery and load is different, and can be met with the use of a typical converter, which can boost up the voltage for charging the battery, or boost down the voltage, when powering up the load, depending on the specific requirements. Converter design can be chosen such that it can easily meet the requirements, can easily step up and down the voltage, and can be implemented in a single circuit. One such topology is depicted in the figure 1.

The following assumptions are made about the converter's operation,
1) The circuit operates in a steady state.
2) The inductor current is continuous.
3) The capacitor is large enough to maintain a constant output voltage.
4) The switch remails closed for time *DT* and open for *(1-D) *T.*
5) All components are ideal.

When the switch is closed (ON), the converter operates in boost mode, where the supply voltage V_{s1} is applied directly across the inductor L. The current i_{L1} begins to increase, storing energy in the magnetic field of the inductor. The diode is reverse-biased due to the direction of current i_d, so no current flows through the capacitor or the load in this phase. The voltage across the inductor V_{L1} is V_{s1}, and i_{L1} builds up linearly. This phase is important because energy is stored in the inductor for use during the next phase.

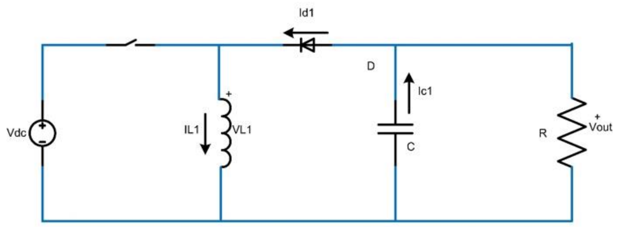

Figure 1: Converter Topology

As shown in figure 2, the input power source, which can be a DC voltage powered by a solar PV, supplies the load. The voltages and currents across various devices in the circuit can then be calculated as,

The voltage across the inductor is given by:

$$V_{L1} = V_{S1} = L\frac{di_{L1}}{dt} \quad (1)$$

$$\frac{di_{L1}}{dt} = \frac{V_{s1}}{L} \quad (2)$$

The rate of change of the inductor current is constant, which results in a linearly increasing inductor current. The preceding equation can be expressed as,

$$\frac{\Delta i_{L1}}{\Delta t} = \frac{\Delta i_{l1}}{DT} = \frac{V_{s1}}{L} \quad (3)$$

Solving for Δi_{L1} when the switch is closed gives

$$(\Delta i_{L1})_{closed} = \frac{V_{s1}DT}{L} \quad (4)$$

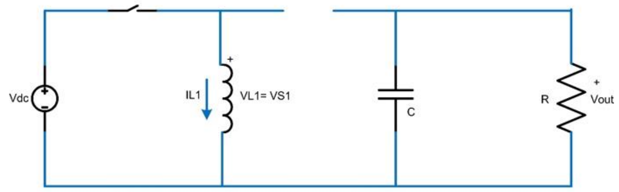

Figure 2: Closed Switch Analysis of the converter

When the switch is opened (OFF), it operates in buck mode, where the current i_{L1} through the inductor cannot change instantaneously, so the inductor maintains the current flow. The inductor acts as a source and reverses its polarity, now forward biasing the diode. The stored energy in the inductor is released, and current i_{d1} flows through the diode, charging the capacitor C , and supplying power to the load resistor. The voltage across the inductor V_{L1} is V_{out}, and current i_{L1} decreases.

The energy stored in the inductor is transferred to the load. The output voltage V_{out} can be either higher or lower than the input voltage, depending on the switch's duty cycle. The inductor current continues to decrease until the next cycle when the switch turns ON again.

Figure 3 shows the disconnected power supply, which is when the load is operated on stored energy inside the inductor.

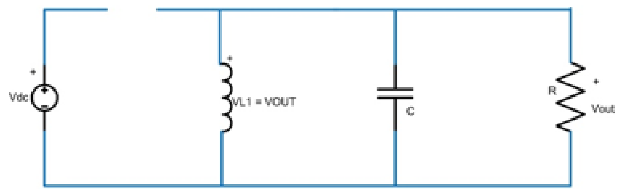

Figure 3: Open Switch Analysis of the converter

When switch 1 is open, the current through the inductor cannot change instantly. This causes the diode to become forward-biased, allowing current to flow into the resistor and capacitor. In this condition, the voltage across the inductor is,

$$V_{L1} = V_{\text{out}} = L\frac{di_{L1}}{dt} \quad (5)$$

$$\frac{di_{L1}}{dt} = \frac{V_{\text{out}}}{L} \quad (6)$$

The rate of change of inductor current is constant, and hence the change in the current is,

$$\frac{\Delta i_{L1}}{\Delta t} = \frac{\Delta i_{l1}}{(1-D)T} = \frac{V_{out}}{L} \tag{7}$$

Solving for Δi_{L1},

$$(\Delta i_{L1})_{open} = \frac{V_{out}(1-D)T}{L} \tag{8}$$

For steady- state operation, the net change in inductor current mut be zero over one period using equation (4) and (8).

$$(\Delta i_{L1})_{closed} + (\Delta i_{L1})_{open} = 0 \tag{9}$$

$$\frac{V_{s1}DT}{L} + \frac{V_{out}(1-D)T}{L} = 0 \tag{10}$$

Solving for V_{out},

$$V_{out} = -V_{s1}\left(\frac{D}{1-D}\right) \tag{11}$$

The duty ratio required for specified input and output voltage can be expressed as,

$$D = \frac{|V_{out}|}{V_{s1} + |V_{out}|} \tag{12}$$

The average inductor voltage is zero for periodic operation, resulting in,

$$V_{L1} = V_{S1}D + V_{out}(1-D) = 0 \tag{13}$$

The buck-boost converter's output voltage can be either less than or greater than the input voltage, depending on the switch's duty cycle. When D>0.5, the output voltage exceeds the input, and when D<0.5, the output voltage is lower than the input. This dual capability allows it to function as both a buck and a boost converter. In a buck-boost converter, the source is never directly connected to the load. Instead, energy is stored in the inductor while the switch is closed and transferred to the load when the switch is open. For this reason, the buck-boost converter is also known as an indirect converter.

Power and Current Calculations

The output power and source power can be denoted as,

$$P_{out} = \frac{{V_1}^2}{R_1} \tag{14}$$

$$P_{S1} = V_{s1}I_{s1} \tag{15}$$

$$\frac{V_{out}^2}{R_1} = V_{s1}I_{s1} \tag{16}$$

Average source current is related to average inductor current by,

$$I_{s1} = I_{L1}D \tag{17}$$

resulting in,

$$\frac{V_{out}^2}{R_1} = V_{s1}I_{s1}D \tag{18}$$

Substituting for V_{out} using Equation (11) and for solving I_{L1}, we get,

$$I_L 1 = \frac{V_{out}^2}{V_{s1}R_1D} = \frac{P_{out}}{V_{s1}D} = \frac{V_{s1}D}{R_1(1-D)^2} \tag{19}$$

Maximum and Minimum inductor current are determined using equation (4) and (19).

$$I_{max} = I_{L1} + \frac{\Delta i_{L1}}{2} = \frac{V_{s1}D}{R_1(1-D)^2} + \frac{V_{s1}DT}{2L} \tag{20}$$

$$I_{min} = I_{L1} - \frac{\Delta i_{L1}}{2} = \frac{V_{s1}D}{R_1(1-D)^2} - \frac{V_sDT}{2L} \tag{21}$$

For continuous current , the inductor current must remain positive . To determine the boundary between continuous and discontinuous current, I_{min} is set to zero in Equation (21) , resulting in,

$$(Lf)_{min} = \frac{(1-D)^2R_1}{2} \tag{22}$$

$$L_{min} = \frac{(1-D)^2R_1}{2f} \tag{23}$$

As the switch is closed, the inductor current rises, as the source charges up the inductor, and when the switch is open, it disconnects the power source, hence leads to inductor discharging its energy, and drop in the current. This can be explained in the figure 4.

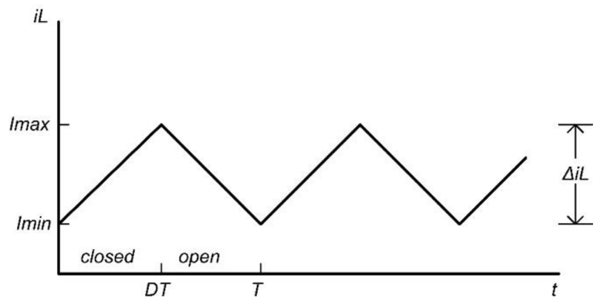

Figure 4: Inductor Current Behavior in Buck Boost Converter

The average inductor current can then be calculated as $\frac{I_{max}+I_{min}}{2}$. Similarly, the voltage across the inductor depicts a square waveform as in figure 5, which is due to the polarity of source and capacitor appearing across the inductor, when the switch is closed and open respectively.

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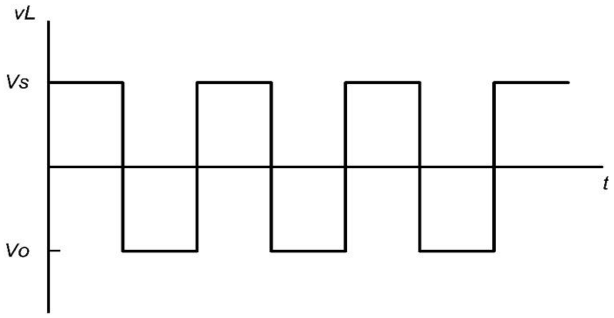

Figure 5: Inductor Voltage Behavior in Buck Boost Converter

The diode current behavior in the circuit is shown in the figure 6.

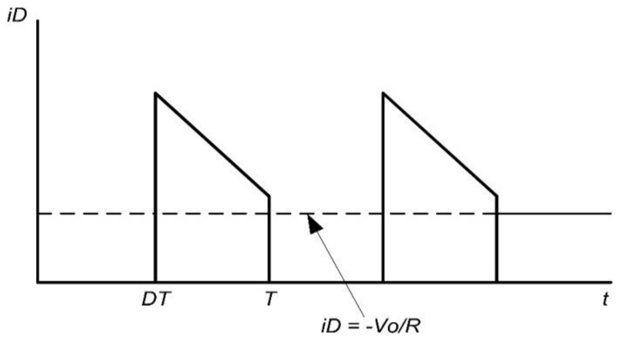

Figure 6: Diode Current in Buck Boost Converter

Similarly, capacitor current is shown in the figure 7. The output voltage ripple can be calculated as shown in the equation 24, followed by equation 25 and equation 26.

$$|Q| = \left(\frac{V_{out}}{R_1}\right) DT = C\Delta V_{out} \tag{24}$$

Solving for V_{out},

$$\Delta V_{out} = \frac{V_{out} R_1 T}{R_1 C} = \frac{V_{out} D}{R_1 C f} \tag{25}$$

or

$$\frac{\Delta V_{out}}{V_o ut} = \frac{D}{R_1 C f} \tag{26}$$

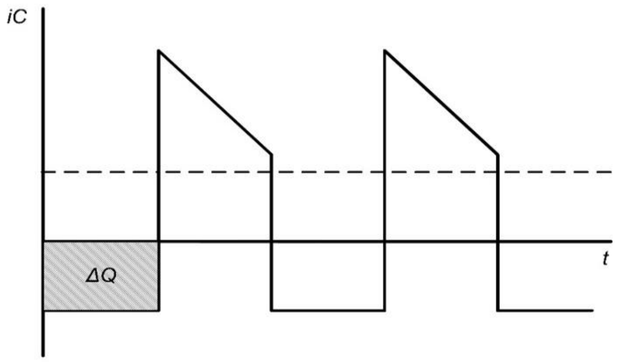

Figure 7: Capacitor Current in Buck Boost Converter

3. Simulation Topology

This MATLAB simulation models a battery management system (BMS) that regulates the charging and discharging of a battery. It uses control loops (specifically Proportional-Integral or PI controllers) to regulate both voltage and current. The system is designed to ensure that the battery operates safely and efficiently, delivering the desired power to a load while managing its state of charge (SOC). Detailed explanation of how the different parts of the system work together.

The battery is modeled as a power source connected to a load, represented by a resistor and capacitor combination. The load simulates a real-world device or system that draws power from the battery. Two MOSFETs act as switches, controlling the direction of current flow, either **charging** or **discharging** the battery. These switches are essential in selecting the correct mode of operation (charging or discharging).An **inductor** is placed in the circuit, indicating that the battery might be connected to a DC-DC converter, which smooths out the current flow between the load and the battery. This setup is typical in efficient power conversion systems.

The voltage control loop on the left-hand side controls the voltage across the load This is important to ensure the load receives stable power. The target or reference voltage (e.g., 48V) is compared with the actual voltage measured across the load. The difference (error) is fed into a PI controller, which calculates the necessary adjustment to maintain the desired voltage. The output of this voltage control loop is the reference discharge current. This is the current that should flow from the battery during discharging to meet the load's demand. This reference current is then fed into the current control loop to ensure the actual current matches this value.

The **current control loop** takes the reference current and compares it with the actual current flowing from the battery. The PI controller in this loop calculates the required adjustment in the current to match the reference value. The output of the current controller is then sent to a switching signal block, which adjusts the MOSFETs to control the actual current flowing through the battery circuit. This loop ensures that the current flowing into or out of the battery remains within safe limits and aligns with the demands set by the voltage control loop (in discharging mode).

In charging mode, the system aims to control the battery voltage to ensure safe and efficient charging. A reference voltage (25.98 V) is compared with the actual battery voltage. The error between the two is fed into another PI controller. This controller outputs the reference charge current. This is the amount of current the system should allow into the battery during charging. The reference current is then passed to the same current control loop, ensuring that the current fed into the battery aligns with the desired charging current.

Switching Logic for Charge/Discharge:

- The system incorporates switching logic to toggle between charging and discharging modes based on the battery's state and the reference values.
- When the reference charge current (`IB_ref_charge`) is negative (e.g., -22 A), the system recognizes that the battery should be charging.
- When the reference discharge current (`IB_ref_dis`) is positive (e.g., 16.2 A), the system recognizes that the battery should be discharging.

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- Logic blocks like "NOT" and comparators are used to ensure that the correct MOSFET switches (`s_P` and `s_N`) are activated for charging or discharging.
- This ensures that current flows in the right direction, depending on whether the battery is charging or powering the load.

Battery Feedback and Monitoring:
The battery model outputs three key values:

- SOC (State of Charge): This indicates how much charge is left in the battery.
- Current (`IB`): The current flowing into or out of the battery.
- Voltage (`VB`): The voltage of the battery.

These values are continuously fed back into the control system to adjust the operation dynamically, ensuring that the battery operates within safe limits and delivers the required power.

The system compares the desired load voltage with the actual voltage and adjusts the discharge current to match. A current control loop ensures the actual current aligns with this discharge current by managing the MOSFET switches. This allows the battery to supply stable voltage and current to the load as needed.

The system compares the desired battery voltage with the actual battery voltage and adjusts the charging current accordingly. A current control loop ensures that the charging current remains within safe limits. As the battery charges, the system monitors its state of charge (SOC) and adjusts the current flow as needed.

The voltage control loop regulates the power delivered to the load, ensuring stable operation. The current control loop ensures that the battery charges or discharges safely and efficiently, adjusting the actual current to match the desired reference. Switching logic determines whether the battery is in charge or discharge mode, using MOSFETs to control current flow. Feedback from the battery allows the system to dynamically adjust its operation, optimizing the battery's performance. This design ensures that the battery is managed efficiently, maintaining safe operation and delivering stable power to the connected load.

Gate Circuit: To power up the switches, the gate signal for the switches is shown in the figure. The switching frequency of the gate signal is 10kHz. At a time, only one switch operates and the other switch stays off, this is facilitated with the help of a NOT gate attached at the input of a gate signal which reverses and produces the output. This is shown in figure 8.

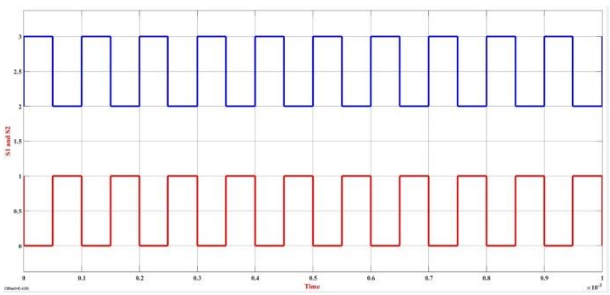

Figure 8: Gate Signals for Simulation

The gate signals for the switches are recorded from a hardware setup as is shown in figure 9. There are slight distortions in hardware counterpart, which is most likely due to noise introduced during the transient state.

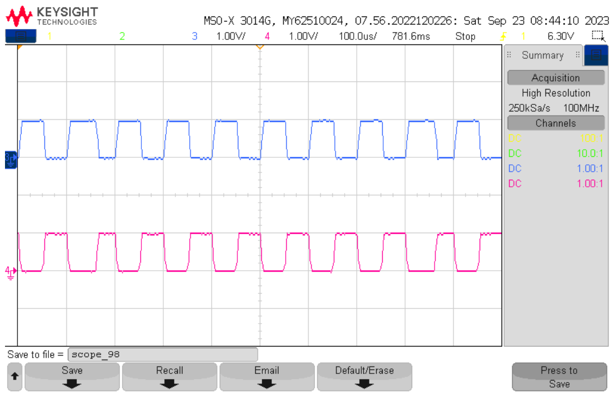

Figure 9: Gate Signals for hardware setup

The table 1 shows the technical specifications for the simulation, table 2 follows up with the battery specifications used in the simulation and table 3 covers the switch specifications used for simulation.

Table 1: Technical specifications

Input Voltage	Vin = 48V
Input Current	Iin = 0.694μA
Load	R = 6π
Resistor and Capacitor	R = 0.003 π , C =1000 µF
Resistor and Inductor	R = 0.05 π , L = 0.576 mH

Table 2: Battery Specifications

Nominal Voltage	24V
Rated Capacity	50 Ah
Initial %SOC	%SOC = 45%
State of Charge	% SOC = 44.96 %
Battery Voltage	V_b = 25.61 V
Battery Current	I_b = 16.88 A
Load Voltage	V_L = 47.93V
Load Current	I_L = 7.988 A
Reference Voltage	V_{ref} = 25.95 V
Reference Current	I_{ref} = 15.69 A
DC Source Power	P_{dc} = -55.32 µW
Battery Power	$P_{battery}$ = 409.4 W
Load Power	P_o = -382.8 W

Table 3: Switch Specifications

Internal Resistance	R_{on} = 0.004 Ω
Snubber Resistance	R_S = 10 µΩ
Switching Frequency	F_{SW} = 10 kHz

4. Results

4.1 SOC Estimations – Battery Discharging

As initial SOC of battery was set to 45.00541% and with the solar PV disconnected, the battery starts supplying power to the motor and its SOC falls from 45.00541%. The discharge takes place linearly and hence we can derive a function which represents the graph as in figure 8.

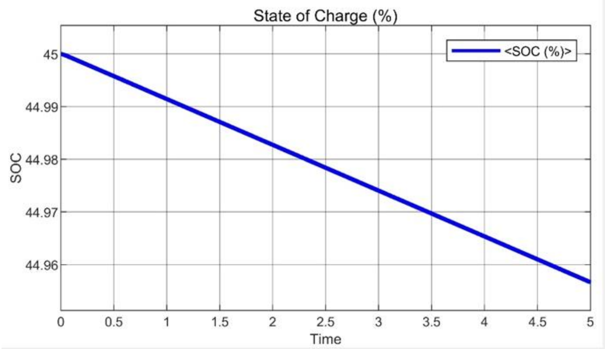

Figure 10: SOC for battery discharging

We can model the SOC as a linear function:

$$SOC_t = SOC_{t=0} + k.t \tag{27}$$

Where

1) $SOC_{t=0}$ is the initial SOC at the start.
2) SOC_t is the function representing SOC at time t seconds.
3) k is the decreasing slope of the function

After 5 time units, the SOC drops to 44.95128%, hence slope of the function can be calculated as:

$$k = \frac{\Delta SOC}{\Delta t} = \frac{45.0054 - 44.9512}{0-5} = -0.010826 \tag{28}$$

Hence, the function can be represented by substituting the values:

$$SOC_t = 45.00 - 0.0108t \tag{29}$$

$$t = \frac{45.0054}{0.010826} = 4157.1586 \; seconds \; 69.2859 \; minutes$$

$$= 1.1547 \; hours. \tag{30}$$

It will take 1.1 hours to completely discharge the battery and it discharges at a rate of 0.010826% per second.

4.2 Load Voltage and Current

The load voltage and load current characteristics as obtained from the simulation is shown in the figure 9. This load voltage is depicted by the red curve, which indicates that the load voltage starts around 42V and then increases rapidly stabilizing which suggests that system reaches a steady voltage after an initial transient response.

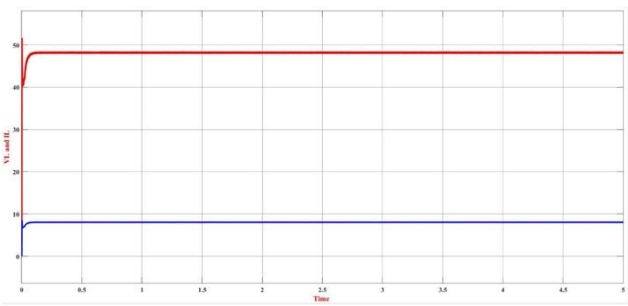

Figure 11: Load Voltage and Current in simulation

The load current is depicted by the blue curve, which follows similar characteristics and stabilizes rapidly with minimal oscillations.

Similar results are obtained in the hardware part, as depicted in figure 10. Hence, this verifies the operation for the load characteristics.

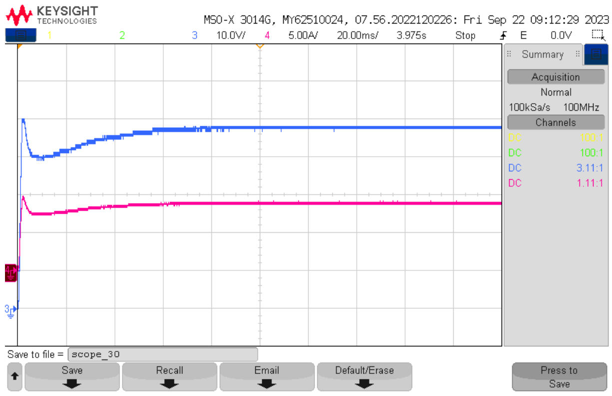

Figure 12: Load Voltage and Current in hardware setup

4.3 SOC Estimations – Battery Charging

As initial SOC is 44.9951%. Solar PV is connected as an input, hence it charges the battery and supplies power to the load as shown in the figure 11.

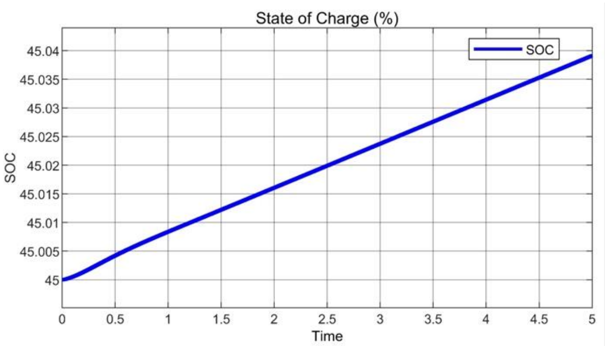

Figure 13: SOC for battery charging

The charging function is linear and hence we can represent it in a function.

$$SOC_t = SOC_{t=0} + k.t \tag{31}$$

Where,

1) $SOC_{t=0}$ is the initial SOC at the start.
2) SOC_t is the function representing SOC at time t seconds.
3) k is the increasing slope of the function

After 5 time units, the SOC rises to 45.0439, hence slope of the function can be calculated as:

$$k = \frac{\Delta SOC}{\Delta t} = \frac{45.0439 - 44.9951}{5-0} = 0.00976 \tag{32}$$

Hence, the function can be represented by substituting the values:

$$SOC_t = 44.9951 + 0.00976t \tag{33}$$

$$t = \frac{100 - 44.9951}{0.00976} = 5635.74 \; seconds = 93.92 \; minutes$$

$$= 1.5654 \; hours \qquad (34)$$

It will take 1.5 hours to charge the battery at a rate of 0.00976%.

4.4 Power Calculations – Connected Battery

The source, battery and load power during the operation is represented in the figure 12.

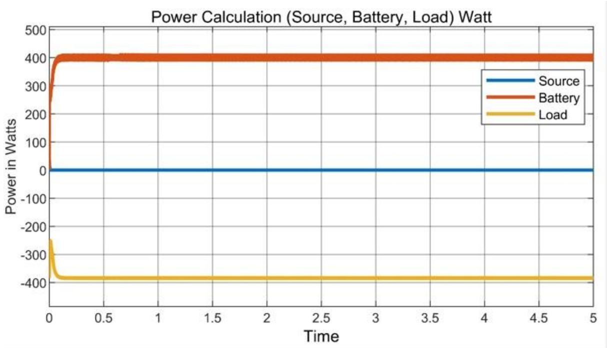

Figure 14: Power Calculations with battery discharging (Simulation)

The red line depicts the source power P_S which is constant 0, as the grid is disconnected during this phase of operation. The blue line depicts the power supplied by the battery and is steady through the operation. The green line depicts the power absorbed by the load, and hence it is negative in value. Comparing the simulation results with the hardware results yields similar accuracy as shown in figure 13.

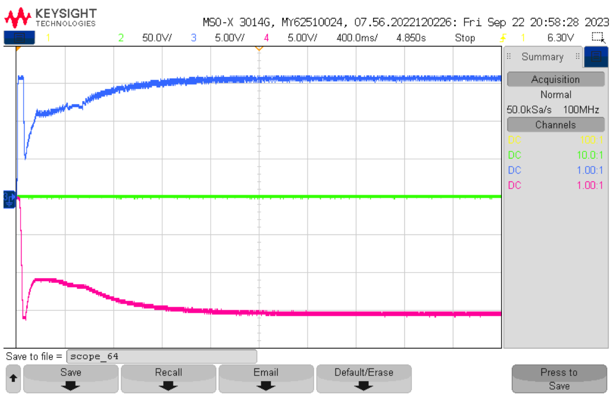

Figure 15: Power Calculations with battery discharging (Hardware setup)

The hardware results are shown in figure (number). Here the source is disconnected, and hence is depicted as green curve, at 0 Watts. The blue curve is the power supplied by the battery and pink curve is the power absorbed by the load. The system takes time to achieve steady state, as it has minimal oscillations at the start, but eventually stabilizes within 1.2 seconds of operation indicating a well developed system.

4.5 Power Calculations – Connected Supply

The blue line depicts the power calculations from the source as it gives a average power of 760W to the load and the battery. The orange line depicts the battery power which is negative as it absorbs the power from the source and is charging at a rate of 0.00976% per second as mentioned in section 5.3. The load is absorbing an average power of 383.7W as shown in figure 14.

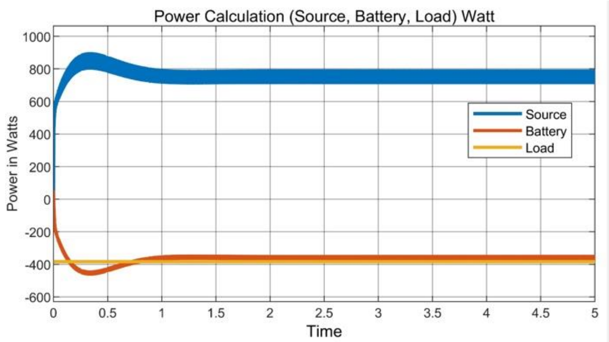

Figure 16: Power Calculations with source connected (Simulation)

4.6 Battery Voltage – Charging

The reference voltage is depicted by the orange curve as shown in the figure 17. It is set at 25.955 Volts, which indicates that charging system tries to maintain this voltage as a target value during the charging process.

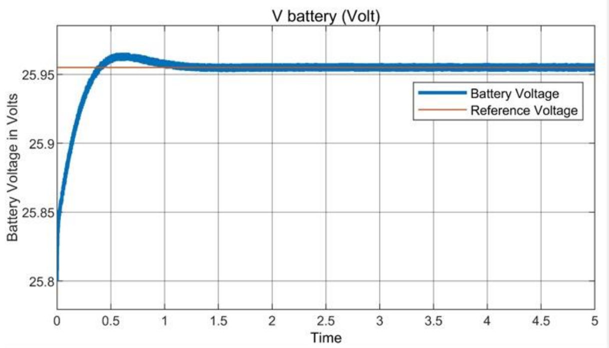

Figure 17: Battery Voltage during charging phase

The blue curve depicting the charging curve starts at 25.8 Volts and shows a surge, rising quickly to 25.97 volts and then oscillating at the reference voltage. This is due to the initial charging current being high as the battery tries to absorb energy rapidly which is common at lower SOCs.

The minimal difference between the battery and reference voltages after intial spike suggests efficient voltage regulations by charging system.

The charging process can be represented as a exponential function:

$$V_{battery}(t) = V_{final}\left(1 - e^{-\frac{t}{\tau}}\right) \qquad (35)$$

Where:
1) $V_{battery}(t)$ is the battery voltage at time t.
2) V_{final} is the final voltage, which can be equated to the reference voltage.
3) t is the time and τ is the time constant.

4.7 Battery Voltage - Discharging

The battery voltage starts around 25.75 Volts and rapidly decreases during the first 0.5 seconds before gradually stabilizing at 25.6 Volts. This sudden voltage drop is due to internal resistance and load current as shown in the figure 18.

The system tries to maintain the reference voltage and battery voltage to equal values, but the voltage difference is due to the loss of performance during the discharge process.

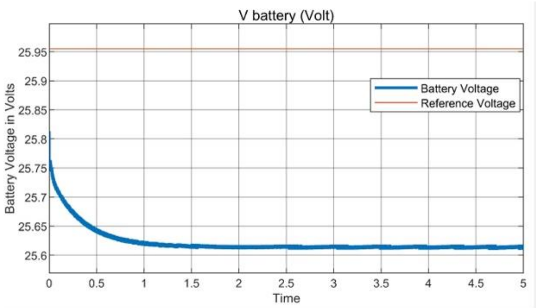

Figure 18: Battery Voltage during discharging phase

The battery discharge behavior can be modeled using the **RC discharge equation** similar to charging but in reverse. The voltage across the battery as it discharges follows an exponential decay pattern, described by:

$$V_{battery}(t) = V_{initial} \cdot e^{-\frac{t}{\tau}} \tag{36}$$

Where:
1) $V_{battery}(t)$ is the battery voltage at time t.
2) $V_{initial}$ is the initial voltage of battery.
3) t is the time and τ is the time constant.

Substituting the values in the equation results in:

$$V_{battery}(t) = 25.75e^{-\frac{t}{\tau}} \tag{37}$$

Hence, we have designed an effective charging and discharging model, which integrates a good renewable energy source and a controller, to power up a load and battery. The desired voltage levels are met with the help of a buck-boost converter, which operates in a bidirectional topology and fairly meets the power demands of the electric vehicle.

Similar results are obtained in case of hardware counterpart, as depicted in figure 19. Both, the battery voltage, and battery reference voltage, are approximately around 26 Volts, indicating that the system follows the reference voltage as indicated, and functions correctly.

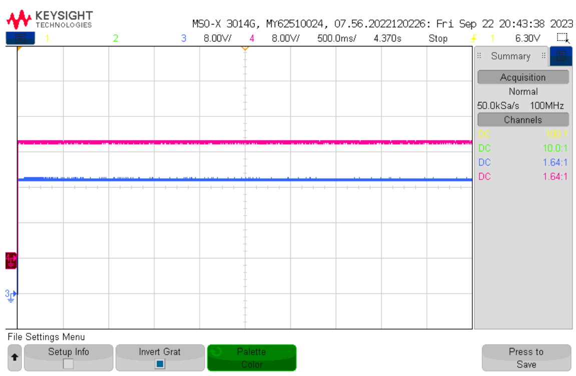

Figure 19: Battery Voltage during discharging phase in hardware setup

4.8 Battery Current: Discharging

The battery discharging current from simulation is shown in the figure 20. The battery reference current and discharging current is around 15.52 Amperes, and it gets to steady state with minimal oscillations.

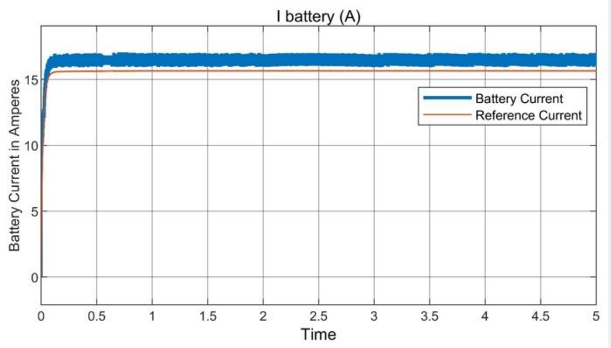

Figure 20: Battery Current during discharging in simulation

Figure 21 shows the battery discharging current to the load. The hardware results accurate matches to the simulation results and hence verifies the operation.

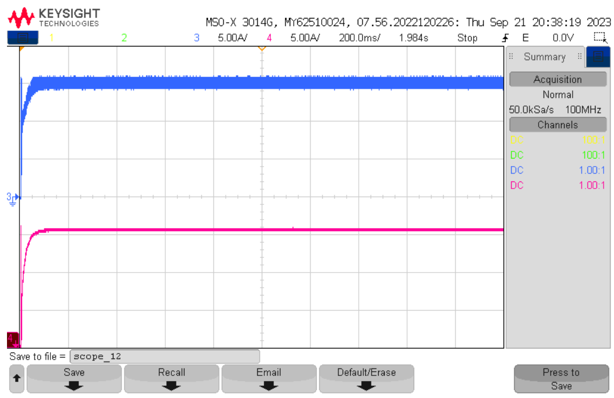

Figure 21: Battery current during discharging in hardware setup

5. Conclusion

In this study, we modeled the charging and discharging processes of a battery using linear functions and analyzed the performance of the system in both simulation and hardware setups. During the discharging phase, the battery SOC dropped linearly, and it was estimated that a full discharge from an initial SOC of 45.00541% would take approximately 1.1 hours at a discharge rate of 0.010826% per second. The charging phase showed similar linear behavior, with an SOC increase of 0.00976% per second, requiring about 1.5 hours to fully charge the battery from an initial SOC of 44.9951%. Both the load voltage and current exhibited steady-state behavior after an initial transient response, with minimal oscillations in both the simulation and hardware setups, confirming the accuracy of the system's performance.

Power calculations demonstrated that during the discharging process, the battery effectively supplied power to the load, while the source remained disconnected. The hardware results closely matched the simulation, reinforcing the validity of the model. The charging process, when the source was connected, showed that the battery absorbed power at the expected rate, while the load consumed a steady amount of power.

Finally, the battery voltage and current behaviors during both charging and discharging were modeled using exponential functions. The system maintained stable reference and battery voltage levels, further confirming the system's reliability. The hardware setup mirrored the simulation results closely, verifying the operation of the renewable energy-based system in real-time scenarios. The system, through the use of a bidirectional buck-boost converter, successfully managed both charging and discharging operations while ensuring stable voltage and current levels, meeting the power demands of the load effectively.

The results highlight the successful design and implementation of the system, providing reliable performance in both simulation and practical hardware testing.

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