Journal of Mines, Metals and Fuels, *73(4): 1043-1052; 2025. DOI: 10.18311/jmmf/2025/48097*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Performance-Based Analysis of Quad Port Power Converter for Electric Vehicle Applications

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Abstract

A multiport power electronic converter is used to transform electrical power into several ports or interfaces. Several input and output ports allow multiport converter to connect to various power sources and loads. Depending on its design and use, this device regulates many power flows, including Direct Current (DC) to DC, Alternating Current (AC) to DC, DC to AC and AC to AC conversions. Multiport converters are typically utilised in smart grid applications, electric vehicles and renewable energy systems. One of the significant advantages of multiport converters is their ability to perform power flow control and energy balancing among different ports. They contribute to achieving higher efficiency, better power quality, and enhanced grid stability in various renewable energy and electric power applications. In this paper, a renewable energy system with solar panels, a battery and an AC source has been utilised in a multiport converter, which can regulate the power management between these sources and the electrical grid, optimising energy utilisation and system stability. The three input ports are equipped with any of the sources, and one port is for output, so the name four port converter model whose DC voltage is used for Electric Vehicle (EV) application. The DC/DC Converter can control and adjust the DC output voltage and current so that it is either higher or lower than the DC input voltage and current. The simulation has been done in MATLAB, and the results are validated.

Major Findings: *The four-port converter model whose DC voltage is used for EV applications gets its name from its configuration: the three input ports are equipped with any of the sources, and one port is for output. If all input sources can produce energy, then all three sub-converters will be turned on at the same time to meet the load requirement.*

Keywords: Electrical Power, Multi-Port Converter, Power Electronics, Power Quality, Renewable Energy

1.0 Introduction

The proposed DC/DC multi-input converter for Hybrid Electric Vehicles (HEVs) offers significant advantages over traditional converters in terms of productivity gains. It is designed to harness power from multiple sources, such as wind power, Photovoltaic (PV) panels, and Energy Storage Systems (ESS) to recharge batteries, improve efficiency and reduce fuel consumption in HEVs. Importantly, the converter is capable of providing the load with the necessary quantity of power even when one or two input sources are unavailable[1].

The system also includes an energy management strategy that is integrated into the control method,

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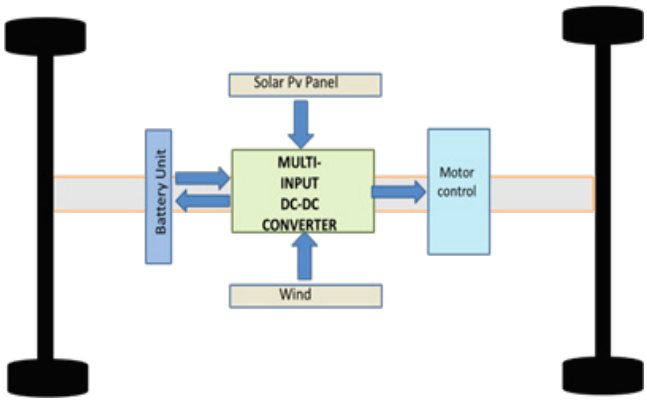


Figure 1. Proposed block diagram of multiport converter.

ensuring optimal utilisation of the available energy sources[2]. This strategy helps in effectively managing and distributing the power from different input sources to meet the vehicle's energy demands.

Furthermore, the proposed converter prototypical has been implemented. Also, it has been rigorously tested to authenticate the analytical findings and performance expectations. The testing process helps to prove the functionality and efficiency of the converter in real-world conditions, ensuring that it meets the requirements for use in HEVs[3].

The 3-input single output DC/DC converter is a pioneering design that leverages the unique characteristics of each input source to maximise efficiency and energy utilisation in Hybrid Electric Vehicles (HEVs). The unidirectional power flow from the solar PV panel and wind power source ensures that the energy generated from these sources is efficiently harnessed and transferred to the converter. Meanwhile, the bidirectional power flow capability of the battery unit allows for seamless energy transfer, enabling the system to effectively manage and balance power distribution based on real-time energy demands and availability[4].

By integrating both unidirectional and bidirectional power flow capabilities, the converter optimises the use of available power sources, thereby increasing the total effectiveness of the system. This innovative scheme not only boosts productivity gains but also subsidises reducing fuel consumption and greenhouse gas emissions in HEVs[5,6]. Additionally, the higher gain achieved by this multi-input converter compared to traditional systems underscores its potential to significantly improve the performance and sustainability of HEV[7]. Artificial intelligence techniques now in use for Proportional Integral Derivative (PID) controller tuning frequently concentrate on single optimisation factors, ignoring possible performance benefits that could be attained by taking into account several objectives. Moreover, popular swarm-based PID optimisation techniques usually randomly initialise the population with no restrictions on input parameters, making them vulnerable to irregular, erratic, and less-than-ideal outcomes in open-ended search settings

Figure 1 shows the proposed block diagram of the four-port converter. Among these ports, three ports will act as inputs and one port as an output port.

The implementation of this advanced converter model, along with its rigorous testing, underscores its readiness for practical deployment in real-world HEV applications. The comprehensive testing process ensures that the converter meets the rigorous requirements for efficiency, reliability and safety in demanding operating conditions.

Challenges in implementing a Quad-Port Power Converter (QPPC) in Electric Vehicles (EVs) are complex control and power flow management can be addressed by implementing advanced control algorithms, Increased circuit complexity and component count can be reduced by use of integrated magnetics and soft-switching techniques, thermal management and heat dissipation can be reduced by heat sinks and bidirectional power flow stability can be reduced by adaptive control algorithms.

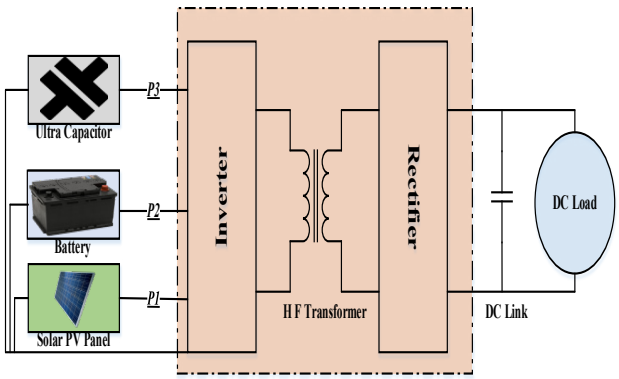


Figure 2. Outline of an isolated multi-port DC/DC converter.

As illustrated in Figure 2, an isolated multiport DC to DC-converter will be made for applications seeking both galvanic isolation and high voltage conversion gain.

A 3 port DC to DC converter with isolation was projected[8], although synchronous rectification switches could potentially be used to boost system efficacy. Better isolated bi-directional fly-back DC/DC converter[9] is provided; it has one separate control signal but includes the advantages of both the bi-directional and three port converters at lower price and size. Utilising control methods built on small signal designs, Reference[10,11] established an isolated three-port DC to DC-converter with synchronised rectification changes to boost the effectiveness of the system.

This work proposes the control design and modelling of a multiport isolated DC-to-DC converter. It features a high step-up conversion gain to provide DC load power and a battery port, ensuring the DC load constantly gets the required power. Figure 2 shows the outline of an isolated multiport DC-to-DC converter, wherein the ultra-capacitor, battery, and solar panel serve as input sources.

The hard-switching operation and inability to charge ESS from the output are two issues with the traditional TPC that are addressed in this research by proposing a novel soft-switched bidirectional multi-port DC-DC converter. A bidirectional power flow route is built into the TPC converter to enable ESS charging from the output. Additionally, to increase efficiency, a soft-switching cell with the fewest possible switches is added to the converter, ensuring that all switches in all operating modes have soft-switching conditions. The converter has a single magnetic core and performs all power conversions in a single stage thanks to the connected inducers in the soft-switching cell. Switching and conduction losses are thereby decreased. A quad-port converter allows seamless power exchange between four energy sources (e.g., battery, supercapacitor, renewable source, and load), dynamically optimising energy flow.

There are seven sections in the paper. Section 2 describes the suggested converter and its modes of operation. Section 3 presents Modelling and Control. Section 4 discusses the results and hardware. Advantages, Disadvantages and Applications are provided in section 5, the Conclusion is stated in section 6, and section 7 presents the future work from this manuscript.

2.0 Proposed Multi Port DC To DC Converter: Its Analysis, Modeling, and Control

2.1 Circuit and Topology

The proposed converter topology and circuit diagram are shown in Figure 3

S1, S2, S3 and S4 are MOSFET switches used for switching purposes.

Vpv, battery and ultra-capacitor act as input sources, and Vout acts as an output source.

D1 to D5 are diodes, and Rlis is the limiting resistance.

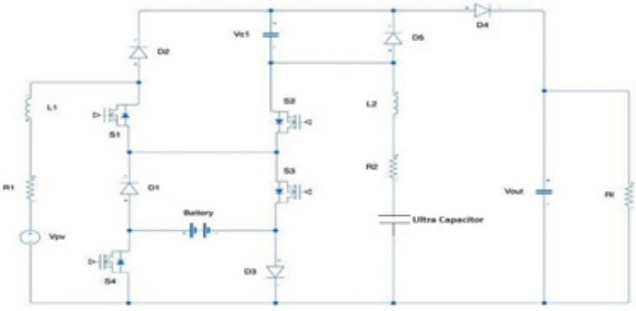


Figure 3. Circuit diagram of four/ multiport converter.

2.2 Circuit Operation Principles

In the projected three-input DC to DC boost converter, the structure consists of basically two boost converters, with an additional capacitor substituted in one of the converters, in addition to an energy-storage battery. This configuration is specifically designed to be suitable for hybrid systems, where multiple power sources need to be efficiently managed. The power management and control part of the system examines the converter's behaviour in relation to managing the sources. The two independent power sources, vPV (solar PV) and ultra-capacitor have their outputs based on their respective characteristics. L1 and L2 represent inductances of the input filters of the PV panel and ultra-capacitor, respectively. By connecting L1 and L2 in series with the input sources, the PV and ultra-capacitor are effectively transformed into current sources. r1 and r2 are the equivalent resistances of vPV and vUC

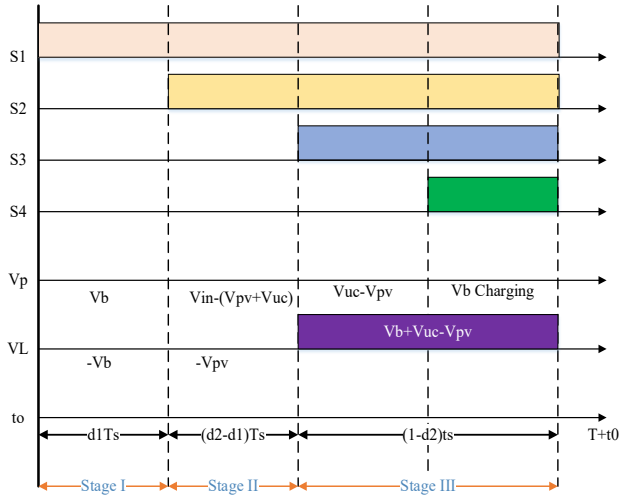


Figure 4. Basic waveforms of the proposed converter.

power. RL Load represents the corresponding resistance of the loads associated with the DC bus.

The power switches S1, S2, S3, and S4, along with diodes D1, D2, D3, and D4, are utilised to establish different modes of operation within the converter. C1, Capacitor is incorporated to raise the output gain, while output capacitor Co acts as an output voltage filter.

The arrangement operates to produce a smooth current with the least amount of electric current ripple attainable, using Continuous Conduct Mode (CCM). This mode of operation confirms that the converter operates efficiently and effectively, providing stable output power while minimising fluctuations and ripple in the current.

Figure 4 displays the proposed converter's steady-state waveforms. Within a cycle of constant frequency switching, it comprises four basic converter stages. The duty cycles d1 and d2, which must be present to drive the switches S1 and S2, respectively, provide two independent control signals. Both the gate drive signal of switch S1 and the actual gate drive signal of switch S3 ought to trigger switch S2. When the positive voltage is supplied to the transformer's primary side, S4 will switch on; contrary, a negative voltage will turn on S3.

2.3 Steady State Analysis

Assuming the converter is lossless, the voltage balance Equation[12,13] within the converter can be utilised to determine the forward voltage conversion ratio once the converter is working in CCM[14,15.]

By carefully selecting inductor values above the intermittent conduction mode (DCM) restriction, the Equation for balanced volts for each second is,

$$V_b = V_{pv}(1-d_1) + \frac{V_{uc}}{n}(1-d_2) \quad (1)$$

Where Vb and Vpv are the battery and photovoltaic voltages for the two input ports, the battery and the PV module, respectively, and Vo is the output port voltage.

The forward voltage conversion ratio can be written in the following manner based on the second balance equation over the output inductor:

$$\frac{V_{out}}{V_{pv}} = \frac{n * d_2(1-d_1)}{d_2 - d_1 + d_2 d_1} \quad (2)$$

2.4 Modelling and Control

The system small signal model analysis for the Multiple Input Multiple Output (MIMO) converter can be performed using the standard circuit process in several operation modes[14,15].

2.4.1 State Space Average Model

Stage I involves turning on switch S1, which activates the battery[16].

Switches S2, S3, and S4 are turned on in stage II, while switch S3 is switched on in stage III.

Stage IV includes switching on switch S4, which maintains the battery charged[17,18]

The state equations in this stage are presented in Equation (3)

$$\left\{\begin{array}{c} \frac{d_{vc1}}{dt} = \frac{1}{C_1} iC_1 = \frac{1}{C_1}(i_{pv}) \\ \frac{d_{vc2}}{dt} = \frac{1}{C_2} iC_2 = \frac{1}{C_2}\left[\frac{V_b - V_{dc}}{C_2} n i_L\right] \\ \frac{d_{iL2}}{dt} = \frac{1}{L_2}[V_b - i_L L_2] \end{array}\right\} \quad (3)$$

Here, i_{pv} signifies the current of the solar PV module, and RL signifies resistance of load.

$$\frac{d_{vc1}}{dt} = \frac{1}{C_1} iC_1 = \frac{1}{C_1}(i_{pv} - i_L)$$

$$\frac{d_{vc2}}{dt} = \frac{1}{C_2} iC_2 = \frac{1}{C_2}\left[\frac{V_b - V_{dc}}{C_2} i_L\right]$$

$$\frac{d_{iL2}}{dt} = \frac{1}{L_2}\left[V_{c1} + i_{c1}C_1 + \frac{V_c}{n} + i_c C_0 - V_b - V_{in} - V_{uc}\right] \quad (4)$$

3.0 Modelling and Control

The simulation of the 4-port converter is shown in Figure 5.

3.1 Simulation of Four-Port Converter

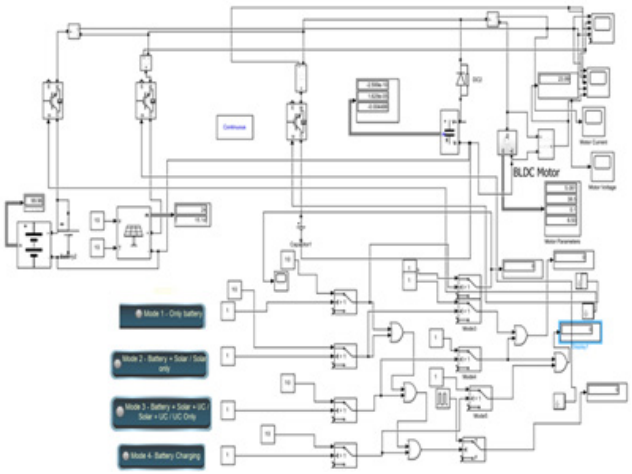


Figure 5. Simulation of four port converter.

3.2 Working

The given block diagram shown is the basics for the DC/DC buck and boost multiport converter's MATLAB/SIMULINK model. Since they might contain ultra-capacitors, batteries, and solar panels. In the present case, three supply sources are considered: an ultra-capacitor (Vuc), a storage battery (Vb), and a solar panel (Vpv). Every source operates at maximum efficiency in a particular area. The study and simulation of every mode of operation that the no insulated converter with three inputs and one output can operate. Considering the battery voltage (Vb) is 21 V and the solar panel voltage (Vpv) is 36 V. It aims to provide a constant voltage to the vehicle control device's DC bus. We take into account that in this operating mode, a resistor and the source indicating the Battery Vb are connected in parallel. These converters can provide bidirectional current flow to it is the bidirectional DC/DC buck and boost multiport converter. In this operation, there are four ideal Metal Oxide Semiconductor Field Effect Semiconductor (MOSFET)/Switches SW1, SW2, SW3 and SW4, are used to regulate the flow of current through the circuit. Each working mode of the converter is studied for its stability.

During charging conditions, switches SW1, SW2, and SW4 are operational, while switch SW3 is Inactive. When the switch is closed, current flows through the circuit, and the converter can step up or down the voltage level as needed. When the switch is open, the circuit is broken. Thus, no current flows through the converter.

3.2.1 Operation of Mode Multiport Converter

Mode 1: Only Battery

Mode 2: Battery + Solar or Solar only

Mode 3: Battery + Solar+ Ultra-capacitor or Solar + UC or Ultra-capacitor only

Mode 4: Battery Charging

This model can run according to the existing system. A total of four modes were considered. For each different mode, two MOSFETs are operated at a time in the whole circuit to control the MOSFET as per the chosen mode for an operation; there are three push buttons.

Mode 1: In this entire simulation run. by default, while running the simulation, conversion from mode 1 to mode 2 can be done by pushing the mode 1 button, then the value of the constant block changed from 1 to 2. As soon as the value became 2 and the condition for the mode 2 Switch was satisfied, the Boolean gate value of this switch became 1; then the mode 2 switch was operated, triggering MOSFET SW1 of the circuit, enabling the model to work only on battery mode.

Mode 2: The operating Mode 2 works similarly to Mode 1 with the help of a push button switch, which can be operated when MOSFET SW4 is switched on. This causes the model to work on Battery + Solar or Solar only.

Mode 3: Ultra-capacitor performs a similar role for the battery in this working mode. It can be operated when MOSFET SW2 is on the circuit, causing the model to work on Battery + Solar+ Ultracapacitor or Solar + UC or Ultra-capacitor only.

Mode 4: In this operating Mode, MOSFET SW3 is constant in the whole circuit.

Thus, the findings show that the DC-to-DC buck and boost multiport converter works well in the bidirectional mode. This suggests it can operate as a buck and boost multiport converter. The input side battery will supply the power that is required to load once it is fully charged.

A quad-port power converter that meets the demanding requirements of modern electric vehicles, ensuring efficient Power Flow Control, Voltage Regulation and Conversion Ratios, Efficiency, Thermal Management System Integration and Modularity power management and contributing to the overall performance and reliability of the EV system.

4.0 Results

While a switched-mode DC/DC converter converts by continually retaining the input energy and then discharging it to the output at an adjustable voltage, a linear DC/DC converter creates and maintains a given output voltage utilising a resistive voltage drop.

The DC output voltage and current can be adjusted and measured by a DC/DC converter. DC output voltage and current may vary from DC input voltage and current in either direction.

Figure 6 shows the simulation results when a battery current is 40 A for 0.2 seconds, after which the solar PV will supply the current to the motor, and the machine will run on photovoltaics. It is seen that the output of the battery and PV will cater for the load current.

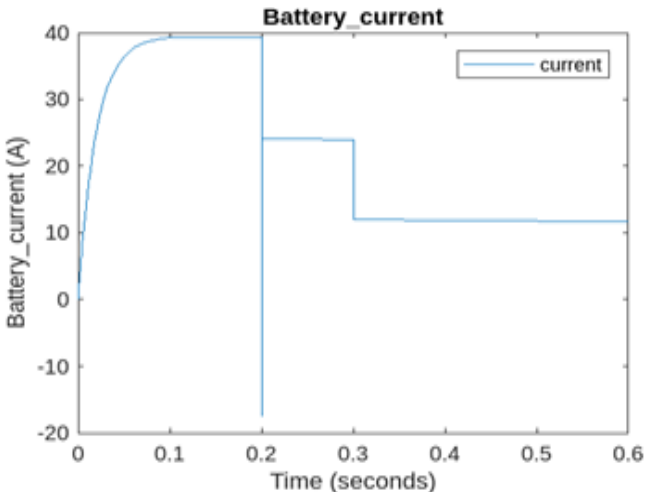


Figure 6. Simulation result when the battery is ON.

Figures 7 and 8 show the simulation results of solar current and ultra-capacitor current, both contributing to the work motor as per the required load condition. Initially, a Brushless Direct Current Motor (BLDC) motor runs on a battery. Once solar power is available,

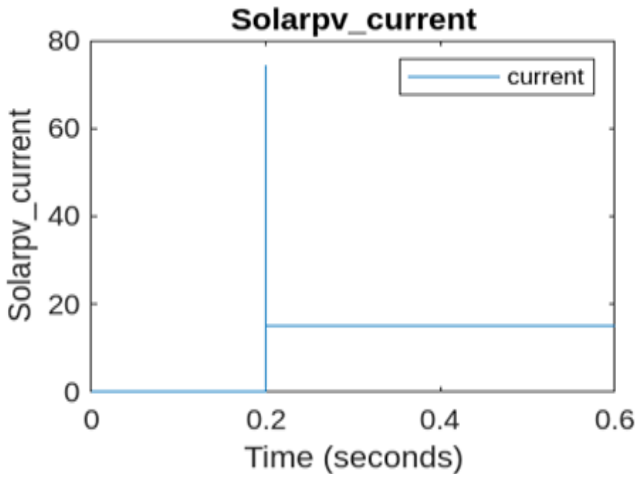


Figure 7. Simulation result when Solar PV is ON.

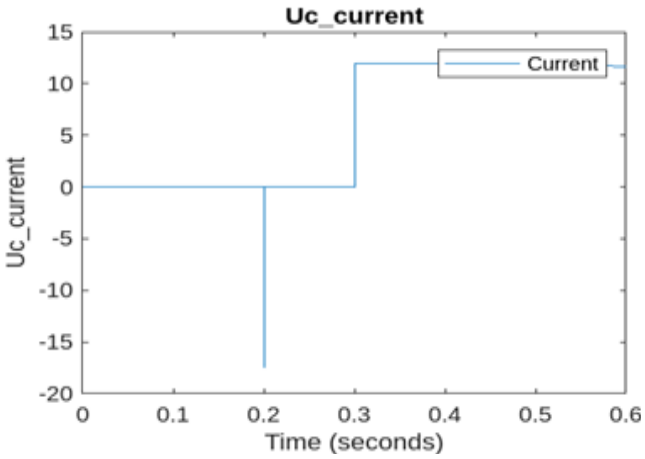


Figure 8. Simulation result when ultra-capacitor is ON.

it is shifted to a solar PV system, but it may be possible that PV output may decrease in such cases, the motor takes appropriate input from an ultra-capacitor. It stables at 10 A after 03 secs and gives constant output.

Figure 9 shows the simulation results of the BLDC motor current. Irrespective of input or supply, the motor runs at a constant speed and takes required from available sources at that instant. It shows the working current of the motor. A similar flow transpires in a voltage waveform. Figure 10 shows the simulation results of BLDC motor voltage. A steady 24 V DC voltage is obtained. As depicted in Figures 9 and 10, the output torque, speed and power of the motor will match with the required load torque.

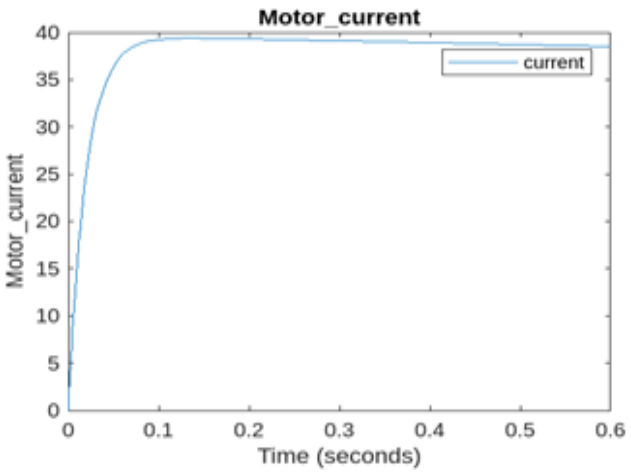


Figure 9. BLDC motor Current.

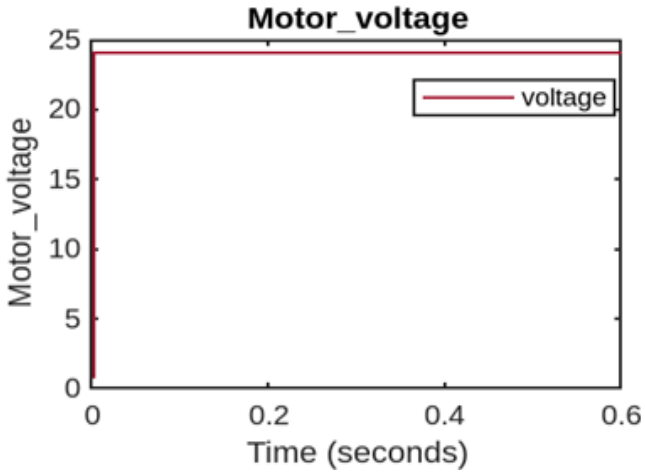


Figure 10. BLDC motor voltage.

Tables 1 and 2 show the PV array Parameters and Li-Ion Battery parameters, respectively, which are in the simulation.

Table 1. PV array parameters

PV Array Parameters	
Maximum Power	213.15 Watts
Cells per module	60
Open Circuit Voltage	36.3V
Short Circuit Current (Isc)	40 A
Voltage at the maximum power point	29 V
Current at the maximum power point	7.35 A

Table 2. Li-ion battery parameters

Lithium-Ion type Battery Parameters	
Nominal Voltage	21
Rated Capacity	1 Ah
Initial SOC	100%
Battery Response Time	ec

5.0 Hardware Diagram of Multiport Converter

In Figure 11, a hardware model in DC/DC buck and boost multiport is shown. In this model, three sources of AC supply, a storage battery and a solar panel have been considered.AC supply is 230V to 5V, battery (Vb) is 0V to 30V, and solar panel (Vpv) is 12V. The study simulates various modes of operation for a non-insulated converter with three inputs and one output. By prioritizing the solar panel, then the battery and then the AC supply, the supply management can be done. AC Supply is used for battery charging and also for relay for switching purposes of the sources.

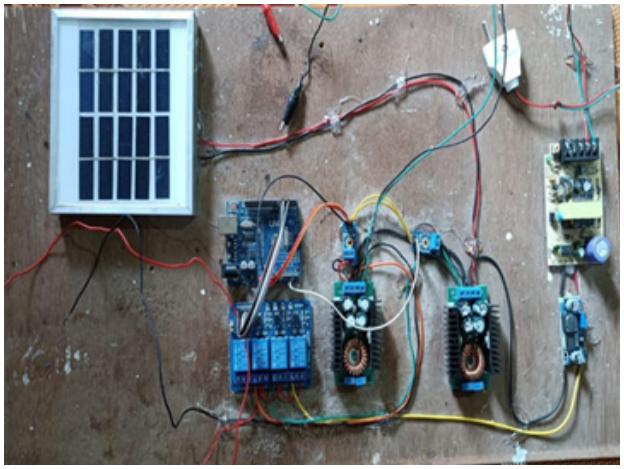


Figure 2. Hardware diagram of multiport DC/DC converter.

6. Advantages, Disadvantages and Applications

6.1 Advantages

a) Faster Charging: By combining power from multiple sources, multiport converters can

deliver higher charging power, reducing charging times significantly[19]. This is especially beneficial for electric vehicle owners who need to quickly recharge their vehicles.

b) Improved Range and Efficiency: Multiport converters are used in conjunction with energy storage systems in electric vehicles, allowing for efficient charging and discharging of the storage systems. This enhances the overall efficiency and range of the vehicle[20].

c) Integrating Renewable Energy: Multiport converters enable the integration of renewable energy sources into the charging process of electric vehicles. This reduces reliance on fossil fuel-based electricity generation and promotes the use of clean, renewable energy.

6.2 Disadvantages

a) Complexity: Multiport converters are more complex than single-port converters, which can make them more difficult to design and implement.

b) Cost: Multiport converters require more components and advanced control systems, which can increase their cost.

c) Efficiency: Multiport converters may not be as efficient as single-port converters due to the added complexity and increased number of components.

6.3 Applications

a) Renewable Energy Systems: Multiport converters can be used to link various energy sources, such as solar panels and AC turbines, in renewable energy systems and manage power flow between them[21].

b) Electric Vehicles: Multiport converters can be used in electric vehicles to interface with multiple sources[22]

c) Smart Grids: Multiport converters can be used in smart grids to interface with multiple energy sources and devices, such as generators, batteries, and loads, and manage power flow between them[23].

d) Industrial Automation: Multiport converters can be used in industrial automation to interface.

e) Telecommunications: Multiport converters can be used in telecommunications to interface with multiple energy sources and devices, such as batteries and power supplies, and manage power flow between the sources[24].

f) Medical Devices: Multiport converters can be used in medical devices to interface with multiple devices

7.0 Conclusion

- The DC/DC Converter can vary and regulate the DC output voltage and current to either be greater or lesser than the DC input voltage and current.
- A switched-mode DC/DC converter converts by periodically retaining the input energy and then discharging it to its output at another voltage.
- A linear DC/DC converter produces and controls an outcome voltage through a resistive voltage drop. It appears that based on what amount of energy sources and loads input the simulation made for a Multiple Input Single Output (MISO) multiport converter topology with three inputs and one output display that operating modes are chosen by the switching commands based on an appropriate strategy of energy management which will insure the load demand from the energy sources.
- To ensure the load demand, all three sub-converters are activated simultaneously if all input sources can generate energy. If energy devices are used, the extra power will be stored.

8.0 Future Plan

The plan of the DC/DC multiport converter aims to improve its efficiency, power density, integration with renewable energy sources, grid integration, and control as well as protection features. Also, by applying certain metaheuristic algorithms, the gains without an algorithm and with an algorithm can be compared for analysis. These advancements will contribute to the development of more efficient and reliable power conversion systems for various applications, including renewable energy integration, electric vehicles, and energy storage systems.

The converter will also have enhanced protection mechanisms to ensure safe and reliable operation under various operating conditions. One of the main goals is to enhance the overall efficacy of the converter. This can be achieved by reducing power losses during the conversion process. Research and development efforts will focus on improving the switching devices, optimising the control algorithms and minimising the conduction as well as switching losses.

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