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Design and Analysis of a Four-Port DC to DC Converter for a Hybrid Energy System

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Abstract - *A four-port DC-DC converter has been developed for integrating a hybrid energy from renewable sources system into an AC microgrid. This converter is particularly suitable for AC microgrid applications that require system-level power management. It boasts a straightforward design, making it effective for interfacing sources with varying voltage and current characteristics. The converter is created to connect a battery bank, a PV panel, a wind turbine, and an inverter, and a load. One of its key features is achieving zero voltage switching in steady-state conditions. To test its robustness, the converter is subjected to various scenarios simulating transient changes in the energy sources. The entire system is modelled and tested using MATLAB/Simulink software and hardware implementation. Results from simulations and hardware that the converter can efficiently manage the process of filling and emptying the battery based on its state of charge. Additionally, it ensures that the DC-link voltage remains stable and maximum power from PV panel and Wind turbine is obtained by MPPT algorithm.*

Key Words: four-port dc to dc converter, AC micro grid, Wind turbine, PV panel, battery, zero voltage switching.

1.INTRODUCTION

The world's population is rapidly increasing, leading to greater energy demands. This growth, along with industrialization and urbanization, has significantly boosted energy consumption [1]. Fossil fuels are scarce resources. Resources, not only face depletion but also contribute heavily to environmental issues such as air pollution and climate change [2]. To address these problems and because of the limitations utilizing fossil fuels, the world's energy focus is shifting towards renewable alternatives [4].

Price fluctuations for petroleum and natural gas have decreased the allure of using these fossil fuels as the main source of energy, igniting interest in more reliable and sustainable alternatives. Due to its purity, environmental friendliness, renewability, and capacity to produce alternative energy, wind and solar energy have grown in popularity [5]. Distributed power generation is replacing massive centralized power generation as distributed renewable energy resources (RESs) such as photovoltaic (PV) arrays and wind turbines are increasingly integrated into the grid [3]. However, because renewable energy is sporadic, batteries and additional energy-storing apparatuses are frequently utilized as a buffer against weather-related power generation fluctuations [6].

A viable method for planning and directing the application of distributed energy resources (DER) is the development of microgrids. There are various benefits to linking DERs to a microgrid preceding the main grid. First, considering solar and wind power may complement each other, using different sources of energy can reduce the uncertainty associated with renewable energy sources [1]. Second, compared to isolated energy from renewable sources systems, power management inside a microgrid offers a more dependable power generation profile.

Power converters are required for control the microgrid's power flow as well as the energy sources. They either provide the microgrid with inadequate power or absorb excess power produced by RESs [7]. Numerous energy sources can be integrated into the grid in two primary ways: either by utilizing numerous converters (one for each source) or by employing an integrated converter, also called a multiport converter with interface capability of multiple sources. The latter approach is better since it does not require board-to-board interactions and provides a more compact structure and higher power density with shared components and centralized control [8].

The majority of extant multiport converters that connect a source of energy, battery, and load (also known as a DC-link) have three ports. Several multiport DC-DC converters many architectural styles have been created, including interleaved buck-boost and boost topologies, dual active bridges, complete bridges, Z-source converters, three-phase structures, and LLC resonating designs [9]. However, these converters cannot link to more than three different sources without adding an additional port. Furthermore, most three-port converters are difficult to expand for four-port applications, with only a few four-port architectures possible without installing too many components. Furthermore, in most reversible three-port converters, only the battery has a reversible port, which can only be loaded by the RES [2]. Multiport converters handle diverse sources of energy such as solar cells, wind turbines, and batteries, offering a compact, cost-effective, and highly efficient solution [10].

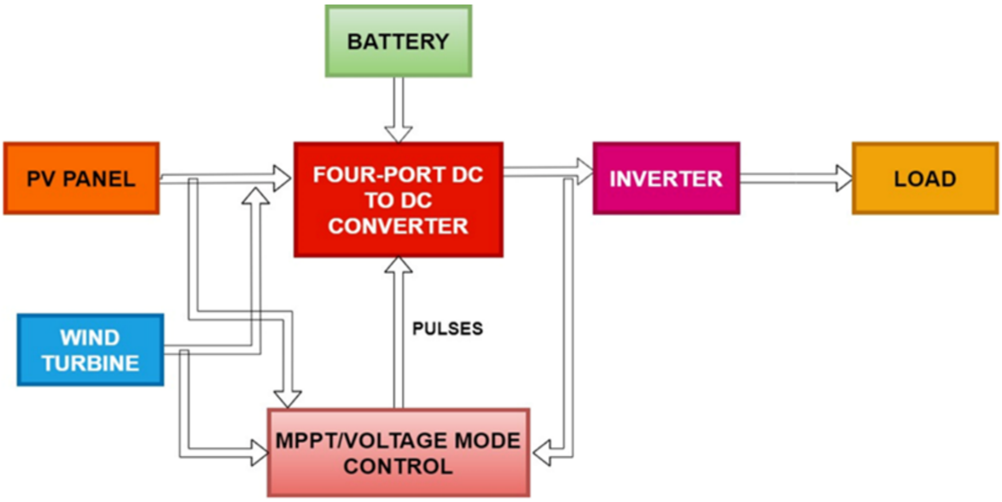

Fig-1: Schematic figure of the model

Compared to three-port converters, there has been fewer studies on four-port bidirectional converters. Many studies have focused on designing four-port bidirectional converters to link storage. However, in most existing four-port converters, the bidirectional port was specifically designed for the battery, meaning the battery gets power through the RES and fed to the DC link. This high-frequency charge/discharge cycle reduces battery life. The lack of a reversible port at the DC-Link prevents the energy in the microgrid from being stored in the battery, resulting in a 'use or waste' issue when the microgrid works in island mode. As a result, these four-port converters are appropriate for stand-alone applications such as satellites, electric vehicles, solar battery systems, and hybrid sources of renewable energy systems [1]. To incorporate renewable energy sources into AC load applications, bidirectional power converters are essential. They enable seamless energy flows in the two directions, while MPPT ensures maximum energy capture from PV and turbine sources [6].

2.Modelling of PV and Wind Turbine

The process of simulating a PV (photovoltaic) array and a wind turbine include determining how each would function under various operational and meteorological scenarios. This aids in our comprehension of their energy production capacity, efficiency, and the variables influencing their effectiveness. It is similar to forecasting how well wind turbines and solar panels would perform in actual conditions so that we can make better plans for using renewable energy.

2.1 Modelling of PV Array

To understand how a solar cell works, think of it as a type of diode. When light, in the form of photons with the right energy, hits the cell, it generates pairs of electrons and holes. These electrons and holes are separated by an electric field at the junction of the diode, and this separation creates a potential that drives the electrons and holes around an external circuit, generating electric current. However, not all the current generated makes it to the circuit due to losses. These losses come from the cell's series resistance, which causes power loss as current flows through it, and shunt resistance, which allows some current to leak away instead of going through the circuit. Additionally, some current leaks back across the p-n junction. These factors can be represented in an equivalent circuit for the solar cell, which includes a photocurrent source, a diode, series resistance, and shunt resistance.

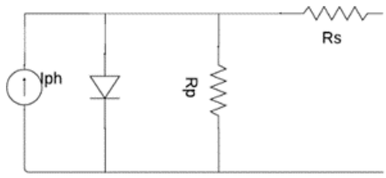

Fig 2- Standard equivalent circuit of a PV cell

$$I_L = I_{ph}[\frac{qv_d}{Ak_eT}) - 1] - \frac{v_d}{R_sh} \quad (1)$$

$$I_{ph} = I_{sc} + K_1(T_c - T_{ref)})G \quad (2)$$

$$I_sI_{Rs}\,[\frac{T_c}{T_{ref)}}]^3\, exp[q^E B(\frac{1}{T_{(ref)}} - \frac{1}{T_c})\, k_B A] \quad (3)$$

$$I_{Rs} = \frac{I_{sc}}{\left(\frac{qVc}{N_sKAT_c}\right) - 1]} \quad (4)$$

$$I_D = N_pI_s[e^{\left(\frac{v}{N_S}\right)+\frac{\frac{I_{Rs}}{N_S}}{NV_TC}-1}] \quad (5)$$

$$I_L = N_pI_{ph} - N_pI_s[exp\left(\frac{qVc}{N_sKAT_c}\right) - 1] \quad (6)$$

$$V_T = k_B\frac{T_{OPT}}{q} \quad (7)$$

$$I_{SH} = \frac{I_{Rs} + V}{R_sh} \quad (8)$$

$$P=VI \quad (9)$$

2.2 Modelling of Wind Turbine

Renewable energy from wind is harnessed by a wind engine, which converts it into mechanical power, and then a generator converts that mechanical power into electrical energy. Essentially, the kinetic vitality derived from the air flowing through a given area is transformed into mechanical energy. The formula for the electricity generated by the windmill is:

$$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda, \beta)$$

ρ represents the air density, which typically ranges from 1.1 to 1.3 kg/m^3.A is the area swept out by the turbine blades, measured in square meters (m^2).V is the wind speed, measured in meters per second (m/s).Pm is the wind power, measured in watts (W) or joules per second (J/s).Cp is the power coefficient, that is a measure of how efficiently the wind energy is transformed into mechanical power. This coefficient depends about the point of speed ratio (λ) and the pitch angle (β).

The schematic block structure of a grid-connected system for transferring wind energy using PMSG is shown below fig 3. It consists of three main components: the wind turbine, PMSG, and a rectifier. The wind generator holds onto the kinetic vitality derived from the wind and converts it into rotational mechanical energy. Permanent Magnet Synchronous Generator (PMSG) takes the mechanical vitality derived from the wind engine and converts it into electrical power. Rectifier/Converter is the component changes the AC output from the PMSG into DC electricity, which is then used to energized the inverter.

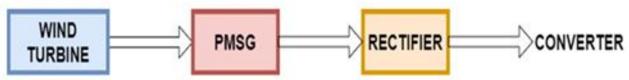

Fig-3. The schematic block structure for WECS connected to Converter

3. WORKING AND OPERATION OF THE CONVERTER

Figure 1 illustrates a two-stage grid-connected system that integrates multiple energy sources. The sources of energy are linked to a four-port DC-DC converter, where Ports 1 and 2 are linked to a wind turbine generator (WTG) and a photovoltaic (PV) panel, respectively, and Port 3 is linked to a battery. The output from this four-port DC-DC converter is then fed into a DC-AC converter, which regulates the DC voltage and converts it to AC. In this the PV panel and wind turbine is providing power which is provided to the load and charges the battery. The converter operates in boost mode when the Power is generated derived from renewable resources charges the battery and provided to dc grid. The P&O algorithm is utilized to maximize PV power extraction panel and wind turbine so that the panel directly powers the arrangement and when the irradiation reduces and the panel power generation is reduced, the battery starts providing the grid with the control is transferred to voltage mode control from MPPT. When both PV and Wind turbine is unavailable, then the battery starts to discharge and provides supply to the grid . This mode allows the converter to function in buck mode and charges the battery. When battery Soc is reduced below the limit, the battery starts to charge energy derived from renewable sources such as PV and Wind turbine source

3.1 The proposed converter is evaluated under the following conditions:

Event 1: When energy derived from renewable sources, the DC-link (pDC) is less than 0, mode allows the converter to function in buck mode, and the battery charges by absorbing energy derived from DC-link (Mode 1).When the energy generated from the renewable(pRES) is greater than zero, Mode two becomes in motion.

Event 2: When the electricity that is renewably generated (pRES) is greater than the power required through the DC-link (pDC), and pDC is greater than 0, there is abundance of green energy. The battery charges to absorb this excess energy, activating modes two and three.

Event 3: When power required through the DC link(pDC) exceeds the electricity that is renewably generated (pRES), the electricity that is renewable is insufficient to power the DC-link's load. The power source(battery) provides the additional power needed, activating modes four and three.

Event 4: When there is no renewable energy available (pRES = 0) and power required through the DC-link (pDC) is greater than 0, the energy source (battery)supplies all power to the DC-link, activating only Mode 4.

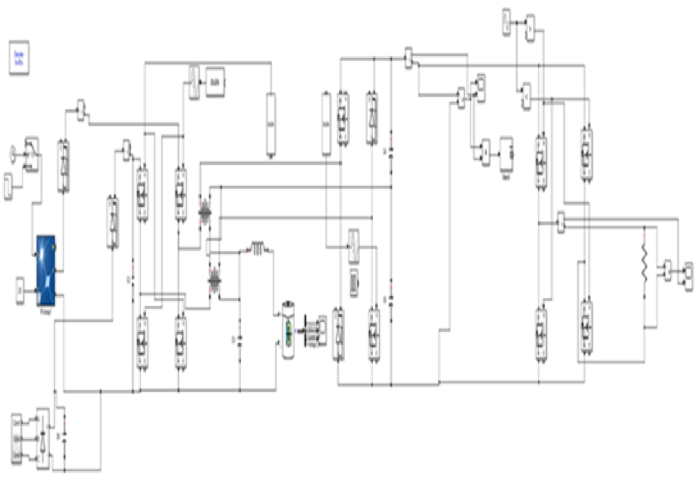

Fig-4 Simulation Circuit of the recommended four port dc-dc converter System

3.2 The control strategy of the intended converter

In this, the duty ratio (d) is generated using current control loop for which the reference current is generated using dc bus voltage control loop. The generated duty ratio is provided to delay angle generation this is employed based on the availability of renewable sources and ac grid. The Perturb and Observe algorithm is employed in for mppt to take out maximum power.

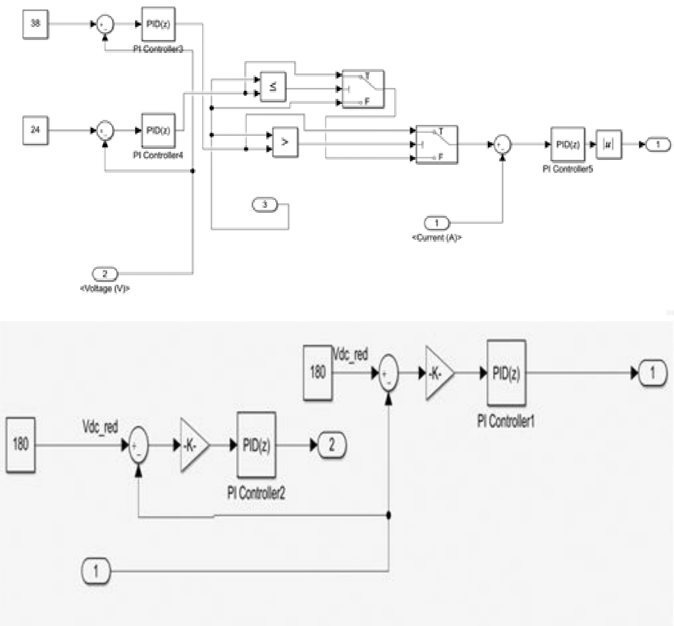

Fig-5 Controlling Mechanism for Planned System

4. Block Diagram of Hardware Prototype model

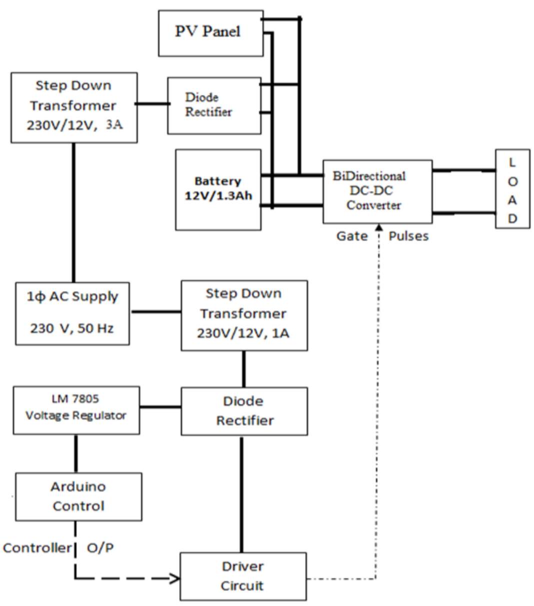

Fig-6 Block Diagram of Proposed Hardware model.

In this a single-phase AC supply of 230V, 50Hz is provided to step down transformer of voltage ratio 230/12 V, 1A, 50Hz so that it can be converted to DC voltage and regulated. The diode rectifier is used to convert the 12V ac to 12V dc voltage. The rectified dc voltage is provided to 5V and 12V Voltage regulator. The 5V regulated voltage is provided to Arduino micro controller which generates the pulses according to the control strategy. The 12V regulated dc supply is provided to driver circuit so that it can able to drive the Power Electronic switches of the proposed converter as per the gate pulses generated from the controller.

4.1 Hardware Model

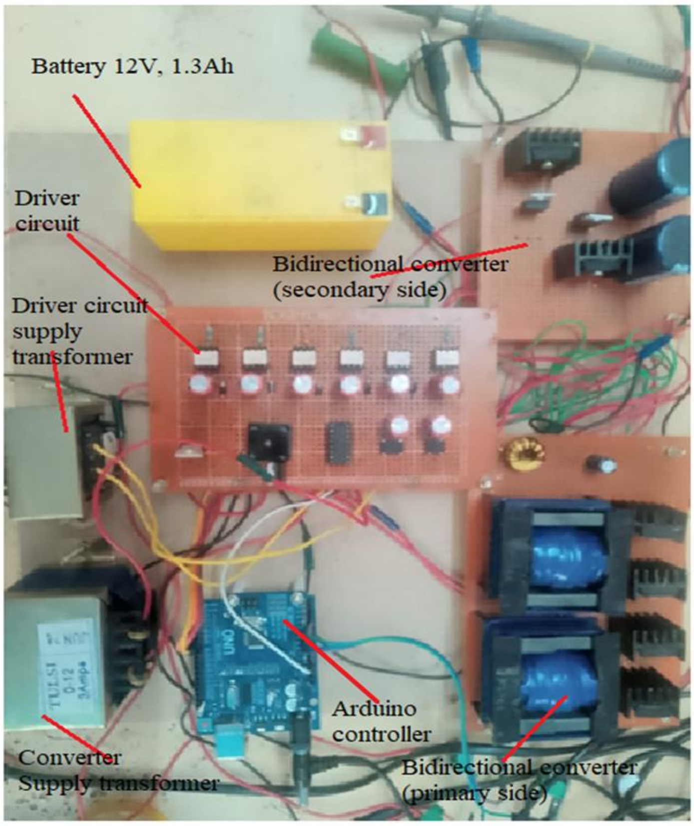

Fig-7 Hardware Circuit of the Proposed System

In this, 12V transformer voltage is subjected to diode rectifier to get dc voltage which is connected as a source to the proposed converter which will boost the voltage to 48V at load side. A12V, 1.3Ah battery is also connected which will act as load and gets charged when primary supply is available and starts to discharge when the primary supply is cut off.

The pulses for the switches are generated by the Arduino controller which will send the gate signal to the switches through driver circuit.

The rectified voltage is provided to the Arduino and driver circuit gets the V_{cc} supply. The Arduino generates gate pulse for proposed converter switches.

5.RESULTS AND ANALYSIS

The above fig 4 shows the simulation circuit of the intended system. In this, the PV panel and Wind turbine source is connected to the system until t=1.5s and disconnected at 1.5s. The PV provides power to the load from 0 s to 1s with 1000W/m2 irradiation and 400W/m2 from t=1s to 1.5s where it is disconnected. The battery was initially charged with PV and as PV is disconnected at t=1.5s, the battery starts to discharge and supplies the load. The MPPT control will provide pulses to the converter and then as PV is disconnected, the stand-alone control will provide pulses to the converter from t=0.1.5s to 2s. The voltage with PV generating power with different irradiation levels and with battery charging and discharging modes. In this, effectiveness of the converter with battery charging condition is 92.6%, and during battery discharging mode, the effectiveness of the converter is 93.2% for the load power of 2KW.

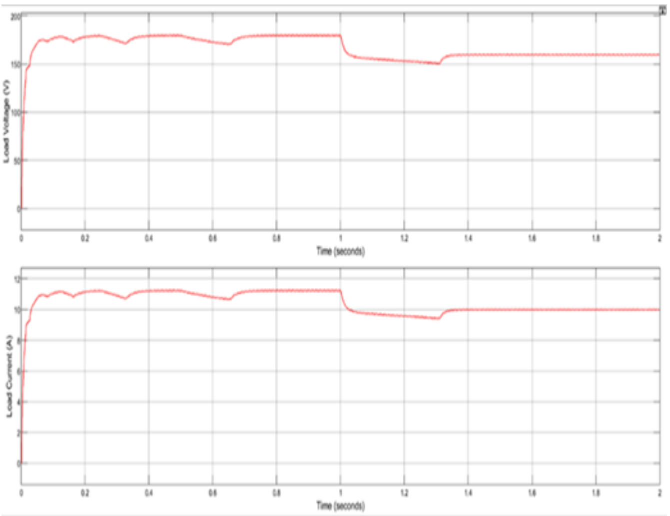

Fig-8 Load voltage and current waveform for different modes

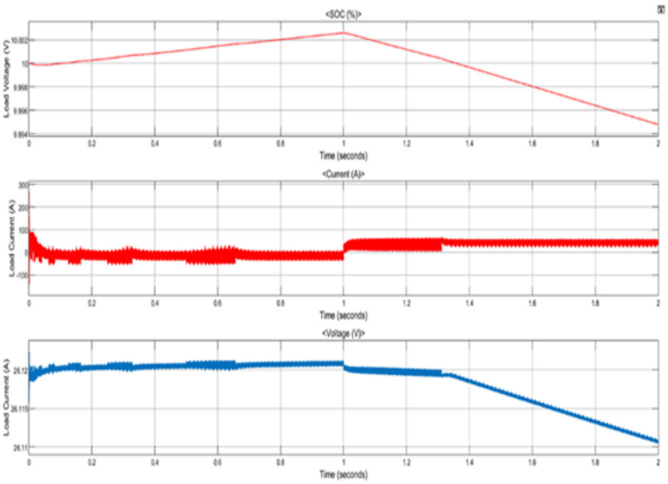

Fig-9 Battery Charging and Discharging

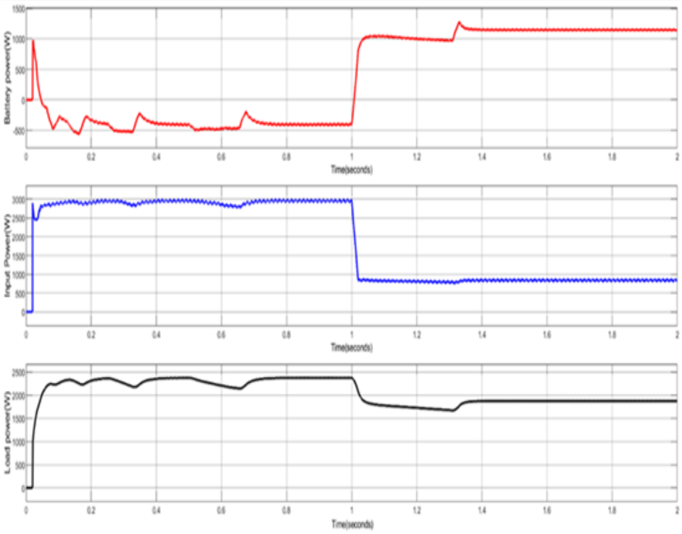

Fig-10 The power curves such as battery power, Input power and load power

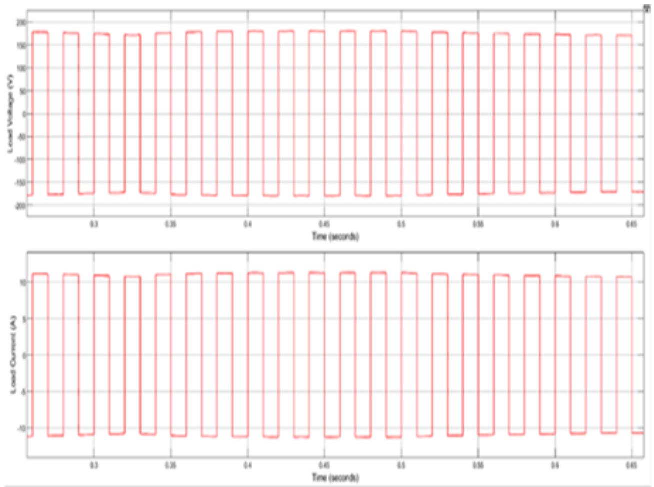

Fig-11 An H-Bridge inverter is linked to the dc bus, and its output voltage and current.

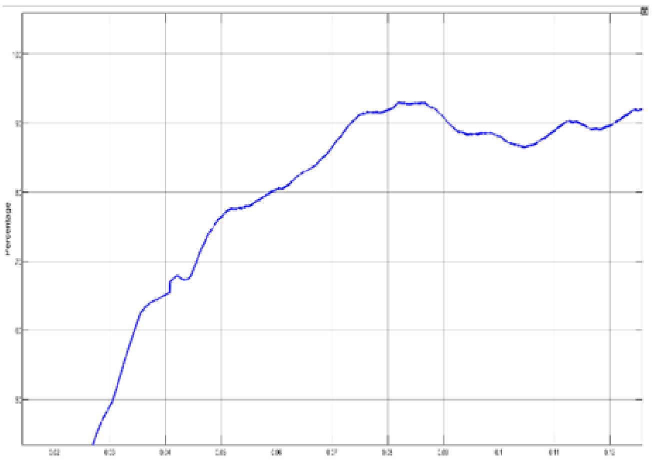

Fig-12 Efficiency Curve

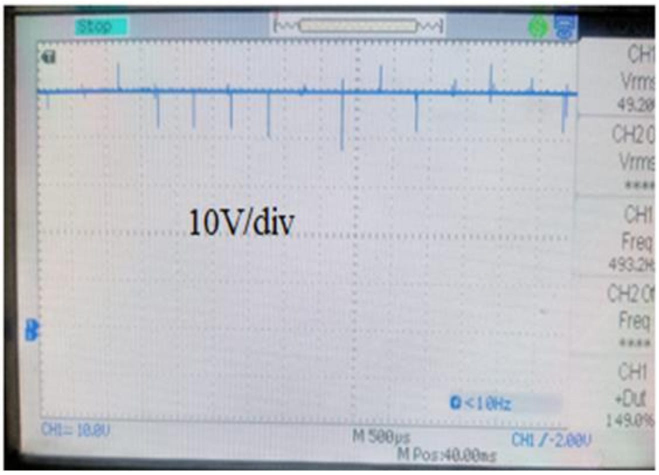

Fig-13 The load voltage across the R load

Fig-14 The load voltage along with battery voltage when battery is charging

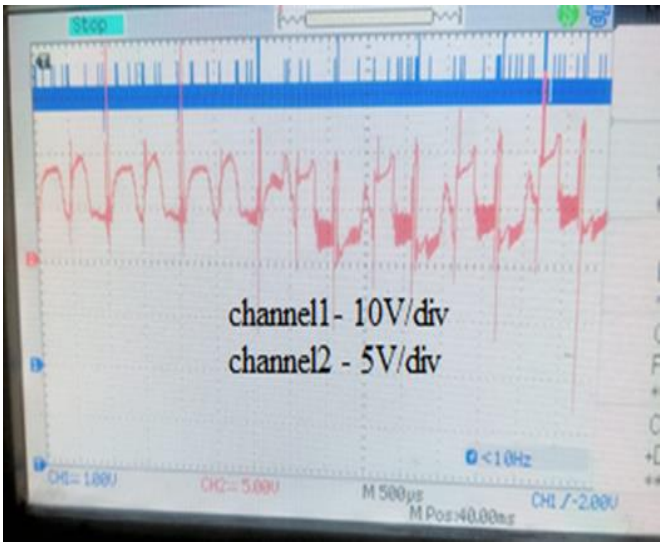

Fig-15 The load voltage along with battery voltage when battery is discharging

6. CONCLUSIONS

A brand-new DC-DC converter with four ports was developed for hybrid energy applications. This converter, based on a phase-shifting DC-DC converter, integrates various energy sources such as a photovoltaic (PV) panel, a wind turbine generator (WTG), and a battery. This model helped in creating several controllers to manage the DC-link voltage, battery voltage, and current. Simulation of converter effectively executes MPPT for both of PV panel and the WTG when solar and wind power are available. Additionally, it controls charging and discharging of batteries to maintain a steady DC-link voltage.

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