Investigation on extendable multiport DC–DC boost converter for hybrid renewable energy systems

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ABSTRACT

In this work, the integration of renewable hybrid energy (RHE) resources using extendable multiport DC–DC boost converter is investigated. Three renewable energy sources such as solar photovoltaic (PV) system, wind energy system and fuel cell (FC) are integrated into the grid via this converter and grid-tied inverter. The output voltage of the multiport DC–DC boost converter is controlled using adaptive neuro fuzzy inference system-based controller. The overall system model is developed and tested in the MATLAB simulation software and also implemented in real time. The overall system is tested for different operating conditions such as change in irradiance condition of the solar PV panel, change in wind speed condition of the wind turbine, change in hydrogen pressure conditions of the FC and sudden change in load conditions and corresponding results are measured and analysed. The efficiency of the proposed system is about 98.21%. Finally, experimental results of the proposed model are also presented to examine the suitability of the system.

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Three-input step-up DC–DC converter (TISUC); wind turbine (WT); photovoltaic (PV); fuel stack (FS); grid; renewable energy resources (RES)

Nomenclature

RHE Renewable Hybrid Energy
DC Direct Current
ANFIS Adaptive Neuro Fuzzy Inference System
TISUC Three-Input Step-up DC–DC Converter
WT Wind Turbine
FS Fuel Stack
MPPT Maximum Power Point Tracking
RES Renewable energy resources
TWH Terawatt Hour
FC Fuel Cell
VER Variable Energy Sources
AC Alternating Current
PMSG Permanent Magnet Synchronous Generator
PWM Pulse Width Modulation

1. Introduction

The need for electrical power is extremely important due to an increase in world population, residents and industries. Earlier time, the electrical energy is generated by means of fossil fuels. But fossil fuels always created the problem for the environment and also disturbed the ecological structure of the world. To overcome this problem, renewable source of energy and nuclear energy are vital alternative sources for fossil fuels.

Renewable energy resources (RES) are used in most countries due to their increasing usage in all applications. Till now, 34.6% of using renewable energy sources was installed in India. These resources are frequently employed since they are efficient and inexpensive, and also the overall amount of energy consumption is increasing daily. In 2018, India generated 1487 TWH of total electricity. However, every year, the demand for electricity rises by 12%. Even though renewable sources are not reliable, it is sustainable. So to be reliable, the proposed hybrid system provides excellent solution for future electricity demand. Both solar and wind power generation systems are best sources, which brings the CO₂ level down from the atmosphere.

In the future, dispersed energy systems would need interfacing unique varieties of power resources. Fuel cells (FC), wind turbines (WT) and photovoltaic (PV) systems may proceed as appropriate options for assuring the aforesaid issues concerning delivery of nearby electric power load for customers, gratitude toward their reduced current spending then and non-appearance of transmission losses. Separate power delivery as of those sources is not cost-effective because of small depending ability and excessive initial costs. Therefore, the above-mentioned inadequacies may be quite determined via combining those sources with linking them to the utility grid.
Interfacing renewable energy sources to the grid [1] are proposed for operators and policymakers to address. Variable energy sources (VER) are renewable energy sources that combine wind and solar to produce electricity. While the costs of solar and wind continue to fall dramatically and wind and solar are becoming cheaper than traditional sources of energy in many places, reliability issues related to greater penetration of VER are challenging to conventional networks.

The power produced through these renewable resources always varies with environmental conditions. Due to this, the voltage at output of the renewable energy sources also varies. DC link voltage should be maintaining at specified level when renewable energy sources are integrated with grid. In general, renewable energy sources can connect directly to a grid-tied inverter if the voltage across the renewable energy sources meets the needed voltage level for grid integration. When the voltage across renewable energy sources is low, it is impossible to integrate with the grid and a DC–DC boost converter is necessary to bring the low voltage to the desired level [2,3]. Conventional DC–DC boost converters have the problem of operating at high duty cycles to boost the voltage, putting a lot of stress on the power semiconductor devices used in the DC–DC boost converter, lowering overall efficiency and limiting voltage gain [4–7]. Literature relevant to the DC–DC boost converter is as follows.

To improve the converter’s efficiency, a wireless sensors-based CMOS switched-capacitor DC–DC converter was presented in [8]. Three different gain topologies were used to configure the CMOS converter. With a switching frequency of 12 Mega Hertz, the proposed scheme had an efficiency of around 85%.

Generally, grid-tied inverters were utilized to connect several renewable energy sources to the grid using independent DC–DC converters [9]. This technique necessitated independent control for each DC–DC converter, and as a result of the control scheme, an instability problem in the hybrid renewable energy system can arise. References [10,11] presented a single-stage DC–AC converter with multiple input energy sources. Similar issues arise as a result of this type of organization as well. To tackle this, a multiporter converter model for integrating hybrid renewable energy sources into the grid has been proposed [12–15].

Several-port converters like those seen in [16–21] are useful for integrating multiple power sources with varying energy capacities to get a controlled output voltage. The issue with that setup is that, in order to avoid power coupling, only one power source is authorized to transmit power into the load at a time. In [22], a bidirectional multi-input port converter for merging battery and FC sources for electric vehicle applications was presented. This converter is typically incompatible with a variety of renewable energy sources. According to the findings of this literature review, a high voltage gain DC–DC multi-input port converter is required for the effective integration of hybrid renewable energy sources into the grid, as well as an effective voltage controller for the high voltage gain DC–DC multi-input converter to maintain the power flow between various RES. The goal of this project is to fill these research gaps. Based on these research gaps, the objectives of this work are given as:

1. For hybrid renewable energy sources such as solar PV, wind energy and FC systems, the design and development of an extendable multi-input step-up converter are presented in this work.
2. In this work, an adaptive neuro fuzzy inference system (ANFIS)-based DC link voltage controller is presented to keep the DC link voltage at a set level for the improved operation of hybrid renewable energy sources.

The following is a breakdown of the paper’s structure:

Section 2 describes the overall system of the proposed three-input step-up DC–DC boost converters fed hybrid renewable energy system, Section 3 describes the simulation results and their discussions of the system’s performances, Section 4 describes the proposed system’s real-time implementation and Section 5 concludes with some remarks.

2. Multiport DC–DC boost converter for hybrid renewable energy systems

The general block diagram of the Multiport DC–DC boost converter for Hybrid renewable energy systems is shown in Figure 1(a). A three-input step-up converter is included in the proposed system, which is fed from a hybrid energy system such as solar PV, FCs, or wind energy.

The maximum power point tracking (MPPT) controller measures and processes the voltage and current of PV panels. The duty cycle is generated by the MPPT controller and processed by the pulse width modulation (PWM) generator. To extract the peak power out of the solar PV panel, the PWM generator sends a pulse to the S1 switch of the three-input port step-up converter. The MPPT controller measures and processes the FC voltage and current. The duty cycle is generated by the MPPT controller and processed by the PWM generator. To extract the peak power out of the FC, the PWM generator sends a pulse to the S2 switch of the three-input port step-up converter. The MPPT controller measures and processes the voltage and current of the wind generator rectifier. The duty cycle is generated by the MPPT controller and processed by the PWM generator. To extract the maximal power from the WT, the pulse from the PWM generator is sent to the S3 switch of the three-input port step-up converter.
The overall block diagram of the Grid integration of Multiport DC–DC boost converter for Hybrid renewable energy systems is shown in Figure 1(b). The output of the three-input port DC–DC step-up converter is connected to the DC–AC inverter input. The DC–AC converter’s output is connected to the grid via a harmonic filter. For the DC–AC inverter, the D-Q control technique is used. The grid voltage is processed via phase locked loop for generating phase sequence ($\theta$). The DC–AC converter’s DC link voltage ($V_{dc}$) was measured and compared to a reference voltage ($V_{dcref}$). The ANFIS processes the error voltage, and the ANFIS controller provides direct axis reference current ($I_d^*$) for the next stage. The inverse park transformation converts direct and quadrature axis reference current ($I_d^*$ and $I_q^*$) to reference alpha and beta current ($I_a^*$ and $I_b^*$). By using the clarketransformation, the actual grid current ($i_u, i_v, i_w$) is turned into alpha and beta current ($I_a$ and $I_b$). The reference and actual alpha and beta current are compared and processed via PR controller. The PR controller generates the controlled voltage signal ($u_a^*$ and $u_b^*$). This control signal is processed using space vector modulation to generate pulses for the DC–AC inverter, and it regulates power flow from renewable energy sources to load and grid, as well as grid to load, based on renewable energy sources’ power availability.

2.1. Wind turbine (WT)

Figure 2 depicts the WECS investigated in this study. The working of the WECS is defined by the following system parameters such as wind speed ($v_w$), diode bridge output voltage ($V_{dc}$) and mechanical speed ($\omega_m$).

In Figure 2, the power $P_T(v_w, \omega_m)$ reflects the power captured by the WT after friction losses are taken into account. The permanent magnet synchronous generator (PMSG) absorbs some of this power, while the balance adjusts the shaft speed ($P_I$). $P_{em}(\omega_m, V_{dc})$ is the electromagnetic power that enters the PMSG. The electromagnetic power $P_{em}(\omega_m, V_{dc})$ is separated into the resistive losses induced by the PMSG and the line, $P_R(\omega_m, V_{dc})$, and the diode bridge output power, $P_0(\omega_m, V_{dc})$, while ignoring the machine’s magnetic losses and the bridge’s diode losses. Finally, the converter receives the majority of the power $P_0(\omega_m, V_{dc})$ [20].

2.2. PV array

The equivalent circuit diagram of PV cell is exposed in Figure 3.

A solar cell is generally made up of a power supply and an inverted diode connected in parallel. It uses series and parallel resistors to represent series and parallel connections, respectively. A disruption in the direction of electron migration from the n to p junction causes series resistance, while leakage currents cause parallel resistance [13].

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Figure 1. (a) Multiport DC–DC boost converter for Hybrid renewable energy systems and (b) grid integration of Multiport DC–DC boost converter for hybrid renewable energy systems.

Figure 2. Equivalent circuit diagram of PMSG-based wind energy system.
The PV current at the output end is represented in the following equation:

\[ I = I_{\text{acc}} - I_d \]  

(1)

\[ I_d = I_0 \left( e^{\frac{qV_d}{kT}} - 1 \right) \]  

(2)

where the reciprocal of the diode current saturation is denoted by \( I_0 \), the current of short circuit in PV panel is denoted by \( I_{\text{acc}} \), the current through the diode is denoted by \( I_d \), electron charge is denoted by \( q \), voltage across of the diode is denoted by \( V_d \), Boltzmann constant (1.38 × 10^{-19} J/K) denoted by \( k \) and the temperature at junction is denoted by \( T \) in degree kelvin (K).

By solving Equations (1) and (2)

\[ I = I_{\text{acc}} - I_0 \left( e^{\frac{qV_d}{kT}} - 1 \right) \]  

(3)

By proper estimates,

\[ I = I_{\text{acc}} - I_0 \left( e^{\left( \frac{q(V + I_R) + qV_d}{nkT} \right)} - 1 \right) \]  

(4)

where PV cell current is denoted by \( I \), PV cell voltage is denoted by \( V \) and diode ideality factor is denoted by \( n \).

2.3. FC stack design

The equivalent circuit diagram of the fuel stack (FS) is displayed in Figure 4.

Water vapour anode pressure is considered to be 50% of saturated vapour pressure, whereas water cathode pressure is assumed to be 100%. The product is in the liquid phase and the FC runs at 100°C. The basic model signifies a specific gasoline mobile stack working on insignificant circumstances of temperature and strain. Based on the polarization curve obtained from the producer data sheet, the parameters of the equal circuit may be modified. A diode is used to prevent negative current from flowing into the stack. A FC stack generates a DC output with a low voltage and high current [15].
2.4. Design of three-input port step-up converter for hybrid energy system

Figure 5 depicts the proposed three-input port step-up converter for a hybrid energy system. The three-input sources are controlled by the power semiconductor switches S1, S2 and S3. Inductors and capacitors operated as converter filtering components, while diodes were utilized to freewheel the current during the off state of the power semiconductor switch [23].

The three-input port step-up converter’s steady-state output voltage across the load “R” is provided by

\[ V_O = \sum_{j=1}^{3} \frac{V_j}{1 - d_j} \]  

where three-input step-up converter output voltage is denoted by \( V_O \), each input port voltage is denoted by \( V_j \) and power semiconductor switch S1, S2 and S3 operating duty cycle is denoted by \( d_j \).

2.4.1. Modes of operation of the three-input step-up converter

There should be some overlapping time between the ON states of the power switches for normal converter operation. The switching signals of the input cell switches that are charging the even-numbered capacitors are interleaved with 180° phase shift with the switching signals of the input cell switches, which are charging the odd-numbered capacitors.

According to Figure 5, the first and third inputs charge the odd-numbered capacitors, and their switches (S1 and S3) have the same switching pattern, while the second input charges the even-numbered capacitors, and the second input switching signal has a 180° phase shift with the S1 and S2 switching signals. The duty cycles of the switches are assumed to be equal for presenting the operating modes of the proposed converter.

Figure 6(a) depicts the gating signal for the switches S1, S2 and S3. The converter operation in different mode such as mode 1, mode 2 and mode 3 is shown in Figure 6(b–d).

**Mode 1**: All of the power switches S1, S2 and S3 are turned on in this mode (see Figure 6(b)). The input voltages charge the three inductors L1, L2 and L3, and their currents rise linearly. All the diodes are biased reversely, and also, they are not conducting; therefore, the voltage of all the capacitors except the output capacitor remains constant. The output load is supplied by the output capacitor in this mode 1.

**Mode 2**: The primary and second switches S1 and S2 are both on in this mode, but the third switch S3 is off. Diodes D2, D4 and D5 are forward biased and diodes D1 and D3 are reverse biased. The third inductor L3’s current charges the even-numbered capacitors C2, C4 while discharging the odd-numbered capacitors C1, C3, C5. The load is supplied by the output capacitor C.

**Mode 3**: Power switches S1 and S2 are turned off, while power switch S3 is turned on. Diodes D2, D4 and D5 are reverse biased and the diodes D1 and D3 are forward biased. The current flowing through the primary and secondary inductors L1 and L2 is used to charge the odd-numbered capacitors C1, C3, C5 and discharge the even-numbered capacitors C2, C4. The load and output capacitors are supplied by the ultimate input inductor L3.

2.4.2. Design of inductor and capacitor

The average current of the inductors can be expressed as

\[ i_{L1,avg} = \frac{M}{1 - d_1} I_{out} \]  
\[ i_{L2,avg} = \frac{M}{1 - d_2} I_{out} \]
\[ i_{L,3,\text{avg}} = \frac{M}{1 - d_3} I_{out} \]  

(8)

where \( I_{out} \) is the average output current and \( M \) is the voltage gain of the converter.

The boost cell inductor of a three-input step-up converter is designed similarly to that of a standard boost converter. The inductors are designed for continuous conduction mode functioning of the converter (CCM). For the CCM process of converter, the minimum rate of inductors can be computed as follows:

\[ L_{1,\text{min}} = \frac{(1 - d_1)d_3 V_1}{2M I_{out,sw}} \]  

(9)

\[ L_{2,\text{min}} = \frac{(1 - d_2)d_2 V_2}{2M I_{out,sw}} \]  

(10)

\[ L_{3,\text{min}} = \frac{(1 - d_3)d_3 V_3}{2M I_{out,sw}} \]  

(11)
### Table 1. Simulation parameters of three-input sources.

| Parameter | Value |
|-----------|-------|
| WT        | Wind speed 12 m/s |
|           | Generator type PMSG |
|           | Rated power 576 watts |
|           | Output voltage 48 V |
|           | Output current 12 A |
| PV panel  | Irradiance 1000 W/m² |
|           | Temperature 25°C |
|           | Number of cells $12 \times 12 = 144$ |
|           | Short circuit current (Isc) 5.33 A |
|           | Open circuit voltage (Voc) 86.7 V |
|           | Voltage at maximum power point (Vmpp) 82 V |
|           | Maximum power (Pmpp) 410 watts |
| FC        | Number of cells 65 |
|           | Output voltage 48 V |
|           | Output current 14.1 A |
|           | Output power 676 W |

where $f_{sw}$ is the switching frequency of the converter and $V_1$, $V_2$, and $V_3$ are the input voltage of each port of the converter.

The capacitor value for three-input step-up converters is given as follows:

$$C_{1,\text{min}} = C_{2,\text{min}} = C_{3,\text{min}} = \frac{\lambda V_o}{f_{sw}R_{L,\text{min}}V_{PP,\text{max}}}(12)$$

The maximum ripple voltage is denoted by $V_{PP,\text{max}}$, and the converter’s minimum load resistance is denoted $R_{L,\text{min}}$. The $\lambda$ value should be between 1 and 3 to account for the effect of output voltage ripple caused by the capacitors’ effective series resistance.

### Table 2. Simulation parameters for three-input step-up converter and grid-tied inverter.

| Parameters                              | Values |
|----------------------------------------|--------|
| Rated power                            | 2000 watts |
| Inductors (L1, L2, and L3)             | 1 mH   |
| Duty cycles of the switches            | 0.6    |
| Capacitors (C1, C2, C3)                | 10 mF  |
| Switching frequency ($f_{sw}$)         | 10 kHz |
| Output voltage                         | 515 V  |
| Output current                         | 3.89 A |
| Grid-tied inverter                     |        |
| Grid voltage                           | 400 V  |
| Grid frequency                         | 50 Hz  |
| Filter inductor (L11)                  | 1000 mH|
| Filter inductor (L22)                  | 500 mH |
| Filter capacitor (C11)                 | 100 mF |
| Switching frequency                    | 10 kHz |
| PR controller proportional gain        | 8.500  |
| PR controller integral gain            | 100    |
| PR controller harmonic filter gain      | 986.8  |

2.5. **ANFIS-based DC link voltage control**

Neural networks are a family of intelligent algorithms with which they can be used to predict, classify and control time series and also for identification purposes. In those studies, it is more important to minimize the error value and thereby increase efficiency. Figure 7 shows the ANFIS structure for the DC link voltage control. The ANFIS controller receives two inputs, such as error voltage $e(k)$ and rate of change of error voltage $\Delta e(k)$, and based on these inputs and fuzzy rules created by means of the neural network, the ANFIS controller provides reference direct axis current ($I_{d,\ast}$) to the grid inverter control. ANFIS input is described as follows:

$$e(k) = V_{dc}(\text{ref}) - V_{dc}(13)$$

![Simulink model of the three-input port step-up converter for hybrid energy with grid integration.](image)
\[
\Delta e(k) = e(k) - e(k-1) \tag{14}
\]

In ANFIS architecture, if-then rules are based on the first-order Sugeno model are considered.

Rule 1: If \((e(k)_{1} \text{ is } A_{1}) \text{ and } (\Delta e(k)_{1} \text{ is } B_{1})\) then \(Y_{1} = s_{1}e(k)_{1} + t_{1}\Delta e(k)_{1} + r_{1}\)

Rule 2: If \((e(k)_{2} \text{ is } A_{2}) \text{ and } (\Delta e(k)_{2} \text{ is } B_{2})\) then \(Y_{2} = s_{2}e(k)_{2} + t_{2}\Delta e(k)_{2} + r_{2}\)

where \(A_{i}\) and \(B_{i}\) denote the input fuzzy sets. The output is denoted as \(Y_{i}\).

3. Simulation results and discussions

The three-input step-up converter for grid integration in a hybrid renewable energy system is simulated with MATLAB software, and the findings are reported in this part. The proposed system is made up of three sources: a WT, a PV system and a FC cell, each of which produces a different voltage and power. Table 1 shows the modelling specifications for the wind system, PV system and FC stack cell.

The simulation specification of the three-input step-up converter and grid-tied inverter is shown in Table 2.

The overall Simulink model of the three-input port step-up converter for hybrid energy with grid integration is shown in Figure 8.

The torque supplied to the generator shaft is the output of the WT simulation model, with wind and generator speeds as inputs. The torque generated by a generator is determined by its power and speed. The integrated Sim Power System library was used to create the PMSG WT model. WT drives the rotor shaft and generates mechanical torque based on the generator and wind speed. The rectifier and the three-input port step-up converters are connected to the generator’s electrical output power (stator winding).
PV model is created and implemented to check the non-linear properties of the PV module output. This PV model receives two inputs i.e. solar irradiance and cell temperature, to give the output as voltage and current, and it is connected to the three-input port step-up converter. FS was constructed and implemented to check the non-linear nature of the FC output. This model receives one input i.e. fuel pressure and output of the FC model is voltage and current, and it is connected to the three-input port step-up converter.

MATLAB Simulink was used to create and construct the ANFIS controller model. A fuzzy logic method with a five-layer artificial neural network (ANN) structure is used in the proposed neuro-fuzzy controller. The ANFIS system employs neural network techniques to choose an appropriate rule base, which is accomplished by a backpropagation technique. DC link voltage maintained at reference dc voltage is based on ANFIS controller output. Figure 9(a,b) shows the error and rate of change of the error voltage membership function.

The grid is connected to the load side. Initially, the total power generated by the three sources is sent to the three-input step-up DC-to-DC converter. Then, the output of converter is given to grid through inverter.

3.1. Results and discussion:

In this section, simulation results are discussed for the following operating conditions such as constant input parameter conditions with a constant load, sudden change in input parameter variations in a solar
Figure 11. (a) Voltage and current for sudden change in irradiance variations in solar PV system and (b) power and instantaneous voltage and current for sudden change in irradiance variations in solar PV system.

PV system, FC system and wind energy system with a sudden change in load variation conditions.

3.1.1. Constant input parameter conditions with constant load

In these conditions, irradiance and cell temperature of the PV panel are fixed at 1000 W/m² and 25°C, wind speed of the WT is fixed at 12 m/s, fuel pressure of the FC stack is fixed at 1 atm and load is fixed at 1500 W. The corresponding results are shown in Figure 10(a,b).

In these conditions, PV panel voltage and current maintain at 82 V and 4.95 A; wind generator rectifier voltage and current maintain at 44 V and 11.6 A; and FC voltage and current maintain at 47 V and 13.9 A, respectively. The power generated by the PV panel, wind generator rectifier and FC stack are 406, 510.4 and 653.3 W, respectively. Total power generation by the renewable sources is 1569 watts, and it satisfies the load demand power loss in the system and grid not supplying the power to the load.

3.1.2. Sudden change in irradiance variations in solar PV system

In these conditions, irradiance of the PV panel varied from 1000 to 500 W/m² at 1 s, and the temperature is fixed 25°C, wind speed of the WT is fixed at 12 m/s, fuel pressure of the FC stack is fixed at 1 atm and load is fixed at 1500 W. The corresponding results are shown in Figure 11(a,b).

In these conditions, PV panel voltage and current maintain at 80 V and 2.45 A; wind generator rectifier voltage and current maintain at 44 V and 11.6 A; and FC voltage and current maintain at 47 V and 13.9 A, respectively.
FC voltage and current maintain at 47 V and 13.9 A, respectively. The power generated by the PV panel, wind generator rectifier and FC stack are 196, 510.4 and 653.3 W, respectively. Total power generation by the renewable sources is 1359 watts and grid supplying 200 W power to satisfy the load demand and power loss in the system.

3.1.3. Sudden change in wind speed condition of the WT

In these conditions, irradiance and cell temperature of the PV panel are fixed at 1000 W/m² and 25°C, wind speed of the WT is varying from 12 to 9 m/s at 1 s, fuel pressure of the FC stack is fixed at 1 atm and load is fixed at 1500 W. The corresponding results are shown in Figure 12(a,b).

In these conditions, PV panel voltage and current maintain at 82 V and 4.95 A, wind generator rectifier voltage and current maintain at 44 V and 6.36 A and FC voltage and current maintain at 47 V and 13.9 A. The power generated by the PV panel, wind generator rectifier and FC stack are 406, 280 and 653.3 W, respectively. Total power generation by the renewable sources is 1339 watts and grid supplying 260 W power to satisfy the load demand and power loss in the system.

3.1.4. Sudden change in fuel pressure of the FC

In these conditions, irradiance and cell temperature of the PV panel is fixed at 1000 W/m² and 25°C, wind speed of the WT is fixed at 12 m/s, fuel pressure of the FC stack varied from 1 to 0.5 atm at 1 s, and load is...
fixed at 1500 W. The corresponding results are shown in Figure 13(a,b).

In these conditions, PV panel voltage and current maintain at 82 V and 4.95 A, wind generator rectifier voltage and current maintain at 44 V and 11.6 A, FC voltage and current maintain at 47 V and 6.19 A. The power generated by the PV panel, wind generator and FC stack are 406, 510.4 and 291 W, respectively. Total power generation by the renewable sources is 1207 watts and grid supplying 290 W power to satisfy the load demand and power loss in the system.

3.1.5. Sudden change in load conditions
In these conditions, irradiance and cell temperature of the PV panel is fixed at 1000 W/m² and 25°C, wind speed of the WT is fixed at 12 m/s, fuel pressure of the FC stack is fixed at 1 atm, and load demand is varied from 1500 to 1000 W. The corresponding results are shown in Figure 14(a,b).

In these conditions, PV panel voltage and current maintain at 82 V and 4.95 A, wind generator rectifier voltage and current maintain at 44 V and 11.6 A, FC voltage and current maintain at 47 V and 13.9 A. The power generated by the PV panel, wind generator rectifier and FC stack are 406, 510.4 and 653.3 W, respectively. Total power generation by the renewable sources is 1569 watts and grid receiving power 500 W from renewable energy source and remaining power satisfy the load demand and power loss in the system.

3.1.6. Efficiency of the proposed system
Power efficiency is defined as the ratio of the output power to the input power. Figure 15 represents the efficiency comparison of the existing and the proposed
Figure 14. (a) Voltage and current for sudden change in load conditions and (b) power and instantaneous voltage and current for sudden change in load conditions.

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100\%$$

where $\eta$ is the efficiency in per cent (%), $P_{\text{in}}$ is the input power from sources (W) and $P_{\text{out}}$ is the output power in watts (W).

The input power from the three sources is 1569 W and the output power is 1541 W. Then, the efficiency of the proposed system is

$$\eta = \frac{1541}{1569} \times 100 \quad \eta = 98.21\%$$

Efficiencies of various converters used along with hybrid renewable energy grid-connected system are compared in Table 3 showing that the proposed converter for the hybrid system is efficient and is displayed using a bar graph. Table 3 shows the comparison between various converters.

From the above comparison on efficiencies of various DC–DC converters using hybrid inputs (three inputs), the proposed system operates with an efficiency of 98.21%.

| REF | Converters                                      | Efficiency |
|-----|------------------------------------------------|------------|
| [24] | Multiphase DC–DC converter                      | 85%        |
| [18] | Multi-input CBBVSI                              | 92.4%      |
| [8]  | Single input CBBVSI                             | 93%        |
| [23] | Two input step-up DC–DC converter              | 97%        |
|      | Proposed three-input step-up DC–DC converter    | 98.21%     |
4. Experimental verification

The real-time investigation of three-input port step-up converter for hybrid renewable energy with grid integration is discussed in the section. The experimental set-up for the proposed system is shown in Figure 16. PV emulator, WT emulator and FC emulator are acted as renewable energy sources, and the specification of the emulators is presented in Table 4. Specification for the three-input port step-up converter and grid-tied inverter are same as the simulation specification.

In this section, experimental results are discussed for the following operating conditions such as constant input parameter conditions with constant load. In these conditions, irradiance and cell temperature of the PV emulator is fixed at 1000 W/m² and 25°C, wind speed of the WT emulator is fixed at 12 m/s, fuel pressure of the FC emulator is fixed at 1 atm, and load is fixed at 1150 W. The corresponding results are shown in Figure 17. In these conditions, PV Emulator voltage and current are maintained at 80 V and 4.2 A, wind emulator voltage and current maintain at 48 V and 9.1 A, FC voltage and current maintain at 48 V and 11.5 A. The power generated by the PV panel, wind generator rectifier and FC stack are 336, 437 and 437 W, respectively. Total power generation by the renewable sources is 1210 watts, and it satisfies the load demand power loss in the system and grid not supplying the power to the load.

Experimental results for change irradiance from 1000 to 500 W/m² are shown in Figure 18.

In these conditions, PV Emulator voltage and current maintain at 80 V and 4.2 A during 1000 W/m², PV
5. Conclusion

A new extensible three-input step-up DC–DC converter is designed in this work to achieve better voltage gain. The suggested converter improves voltage by increasing the number of inputs, making it appropriate for a wide range of applications in hybrid energy systems, from low to high voltage/power (HESs). The overall system has been implemented in MATLAB software. The proposed system was tested in MATLAB with different operating conditions such as constant input parameter with constant load conditions, sudden change in irradiance of PV panel, sudden change in wind speed conditions of WT, sudden change in fuel pressure conditions of FC and sudden change in load.
conditions, resulting in the maintenance of power balance in all-operating conditions. In simulation, the proposed system converter efficiency is around 98.21% for the all-operating conditions. The proposed system has been investigated in real-time hardware experimentation. From these test results, the proposed converter can act as a high step-up multi-input converter for hybrid renewable energy applications.

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