

Design and Implementation of Step-Up DC-DC Converter by Cascading Cockcroft Walton Voltage Multiplier for Hybrid System

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ABSTRACT- this paper presents the use of a stepupdc-dc converter by cascading cock croftwalton voltage multiplier for a hybrid system. The hybrid renewable energy system used is a combination of as olar panel and a fuel cell. the conventional method isto use a converter increase the voltage and further uses a transformer to increase the voltage level of the output. The proposed converter topology used is boost converter cascaded with an n-stage cockcroft-walton voltage multiplier. the number of stages of the voltage multiplier increases the output level of the stepupdc-dcconverter which drives the load. The converter-voltage multiplier module provides continuous conduction with the voltage stress on cascaded capacitor-diode and switches being reduced. The output voltage obtained can be used in highvoltage applications .the simulation of the entire topology for hybrid system was done using matlab software.

KEYWORDS- Cockcroft-Walton (CW) voltage multiplier, solar panel, fuel cell, step-up DC-DC converter.

I. INTRODUCTION

In the present scenario throughout the world, everyone is concerned with fossil fuel exhaustion and environmental problems caused by conventional power generation. Hence renewable energy sources are used among which solar panels and wind generators are the most used. The solar panel generally uses a power converter for connecting with the load. The efficiency of photovoltaic (PV) module is too low and output power depends on insolation level and temperature. Therefore the solar or PV panel is used along with a fuel cell (FC) system making it a hybrid renewable energy system. The hybrid

renewable energy system is a combination of two or more renewable energy system to obtain higher efficiency than from a single energy power source. The fuel cell used converts an oxidant and fuel into electricity through an electrochemical process. They produce very low emissions and have high operating efficiencies. The converter topology used is a step-up converter which is cascaded with a Cockcroft-Walton (CW) voltage multiplier which increases the voltage level.

II. HYBRID SOLAR PANEL/FUEL CELL SYSTEM

The block diagram of the hybrid solar and fuel cell system with the power converter is show in the Fig. 1. It consists of solar panel, a fuel cell, a boost converter topology, CW voltage multiplier, a pulse generator and load. The solar panel is used as the primary supply and fuel cell as the backup supply. The converter is used to boost up the input voltage from the hybrid solar panel/fuel cell system.

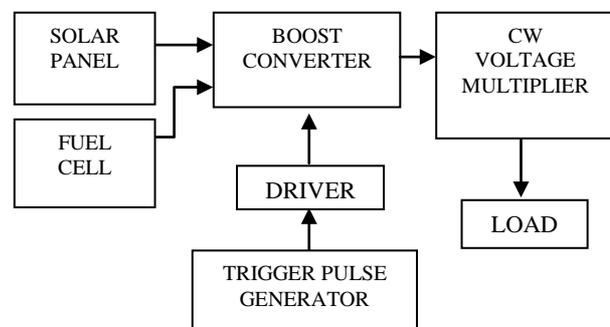


Fig. 1 Block diagram of the hybrid system

A. Solar Panel

The solar panel is a linked collection of PV modules, which is in turn made of multiple interconnected solar cells. The cells convert solar energy into electricity by photovoltaic effect. The power one PV module produces is enough to power a residential place. The collection of solar panels is a solar array. The solar array generally requires an inverter to convert DC power to AC power so it can be used to supply AC loads. The modules of the solar panel are connected in series to obtain the required voltage and the individual strings are connected in parallel to increase the current. The photons in sunlight that strike the panel are absorbed by semiconducting materials like silicon. The electrons present in the semiconductor material are knocked out from the atoms that cause an electric potential difference. Thus current starts to flow through the silicon to eliminate the potential and hence electricity is captured which is then supplied to the load. The equivalent circuit of solar cell is shown below as in Fig. 2.

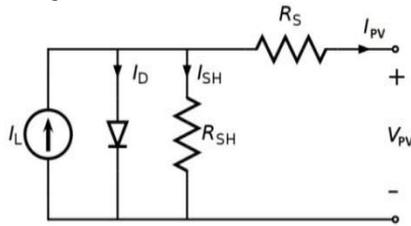


Fig. 2 Equivalent circuit of a PV cell

Applying KCL to equivalent circuit,

$$I_L - I_D - \frac{V_D}{R_{SH}} - I_{PV} = 0 \tag{1}$$

Applying KVL to equivalent circuit,

$$V_{PVcell} = V_D - R_S I_{PV} \tag{2}$$

The PN-junction diode characteristics is given by,

$$I_D = I_0 (e^{\frac{V_D}{V_T}} - 1) \tag{3}$$

B. Fuel Cell

The fuel cell used is a Proton Exchange Membrane (PEM) fuel cell that consists of an electrolyte which is a small, thin, and light permeable polymeric membrane. The reaction is catalysed using platinum electrodes are used on both sides of the membrane. The hydrogen molecules are supplied at the anode which splits the molecules into electrons and hydrogen protons. The protons pass through the polymeric membrane to the cathode while the electrons are passed round an external circuit to produce electricity. Oxygen is supplied to the cathode which combines with hydrogen to produce water. Hydrogen molecules are supplied to fuel cell directly or from natural gas, methanol or petroleum. Each electrode assembly has two electrodes of anode and cathode with a layer of catalyst which is thin. The desired amount of electrical power can be obtained by combining individual fuel cells

to form a fuel cell stack. The output voltage of a single fuel cell is given by the equation,

$$V_{fc} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \tag{4}$$

- V_{fc} - fuel cell voltage (V)
- E_{Nernst} - Nernst voltage (V)
- V_{act} - actual voltage (V)
- V_{ohm} - ohmic voltage drop (V)
- V_{conc} -concentration voltage (V)

The Nernst voltage of the fuel cell is,

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.31 \times 10^{-5} * T \left[\ln p_{H_2} + \frac{1}{2} \ln p_{O_2} \right] \tag{5}$$

- T - temperature (K)
- p_{H_2} - partial pressure of the Hydrogen (atm)
- p_{O_2} - partial pressure of the oxygen (atm)

The activation potential having anode & cathode is given by,

$$V_{act} = -[\epsilon_1 + \epsilon_2 T + \epsilon_3 T \ln CO_2 + \epsilon_4 \ln I_{stack}] \tag{6}$$

- I_{stack} - fuel cell operating current (A)
- ϵ_i - parametric co-efficient for each cell model (i=1, 2, 3,4)

$$CO_2 = \frac{p_{O_2}^{-498}}{5.08 \times 10^6 * e^{T+273.15}} \tag{7}$$

The ohmic voltage drop or loss is provided by the following equation,

$$V_{ohmic} = I_{stack} (R_m + R_c) \tag{8}$$

- R_m - resistance to transfer of protons through membrane
- R_c - resistance of the membrane to electron flow

The voltage drop due to mass transport or the concentration voltage is given as

$$V_{conc} = -B \cdot \ln \left(1 - \frac{J}{J_{max}} \right) \tag{9}$$

- B - parametric coefficient depending on the fuel cell
- J - actual current density of the fuel cell (A/m²)
- J_{max} - maximum current density of the fuel Cell (A/m²)

III. CONVERTER TOPOLOGY FOR HYBRID SYSTEM

The converter circuit consists of the step-up converter topology by which two switches are connected in series having an inductor in between the two switches. The converter also has a capacitor connected in parallel to the switches. The converter circuit output is then given to a CW voltage multiplier which is made of n-stages. The CW voltage multiplier converts AC or DC voltage from a lower level to a higher DC level. The output voltage of CW voltage multiplier depends on the number of stages

and voltage across the even capacitors. The advantage is that it is easy to insulate, requires low cost components and the voltage gain is proportional to the number of cascaded stages. It also utilises the output from any stage. The converter topology consists of nine stages. Hence there are 18 capacitors and 18 diodes. Each stage consists of two diodes and two capacitors respectively. The relationship between the supply voltage of the converter and capacitor voltage of CW voltage multiplier converter is given by

$$V_c = \frac{V_s}{1-\delta_1} = \frac{V_s}{\delta_2} \quad (10)$$

The change in inductor current and capacitor voltage of converter are given by

$$\Delta I_L = 10\% I_o \quad (11)$$

$$\Delta V_c = 1\% V_c \quad (12)$$

The inductance (L) and capacitor(C) of the converter are given by

$$L = \frac{V_s \delta_1}{f \Delta I_L} \quad (13)$$

$$C = \frac{I_o \delta_1}{f \Delta V_c} \quad (14)$$

The time period of the converter is given as

$$T = \frac{1}{f} \quad (15)$$

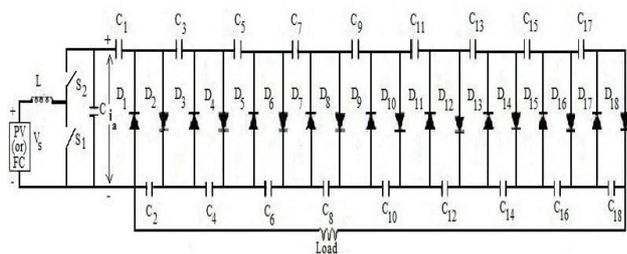


Fig. 3Nine-stage CW voltage multiplier cascaded with step-up converter

The output voltage and output current of CW voltage multiplier are given as

$$V_o = nV_c \quad (16)$$

$$I_o = \frac{V_o}{R} \quad (17)$$

The change in capacitor voltage of CW voltage multiplier is given by

$$\Delta V_c = 10\% V_c \quad (18)$$

The capacitor of the CW voltage multiplier is given by

$$C = \frac{2nI_o}{f \Delta V_c} \quad (19)$$

A. Operating Principle

The operating principle of the converter topology depends on the terminal current i_a which is a pulsating form current. The switches are given gate pulse by trigger

pulse generator through a drive circuit. The modes of operation are as follows:

Mode-I: S_1 and S_2 are turned OFF and diodes (D_1 to D_{18}) do not conduct. The inductor is charged by input DC from the hybrid system, hence the odd numbered capacitors ($C_1, C_3, C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17}) float while even numbered

Capacitors ($C_2, C_4, C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18}) supply the load.

S_1 and S_2 are turned ON and the current i_a is positive for modes II to X. The inductor is discharged and input source transfers energy to the CW voltage multiplier through the even numbered diodes.

Mode-II: D_{18} is turned ON, at the same time the other diodes do not conduct hence $C_2, C_4, C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} gets charged while $C_1, C_3, C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} are all discharged by i_a .

Mode-III: D_{16} is turned ON hence $C_2, C_4, C_6, C_8, C_{10}, C_{12}, C_{14}$ and C_{16} gets charged while $C_1, C_3, C_5, C_7, C_9, C_{11}, C_{13}$ and C_{15} are discharged by i_a . Hence C_{18} supplies the load while C_{17} floats.

Mode-IV: D_{14} is turned ON hence $C_2, C_4, C_6, C_8, C_{10}, C_{12}$ and C_{14} gets charged while $C_1, C_3, C_5, C_7, C_9, C_{11}$ and C_{13} are discharged by i_a . Hence C_{16} and C_{18} supply the load while C_{15} and C_{17} floats.

Mode-V: D_{12} is turned ON hence $C_2, C_4, C_6, C_8, C_{10}$ and C_{12} gets charged while C_1, C_3, C_5, C_7, C_9 and C_{11} are discharged by i_a . Hence C_{14}, C_{16} and C_{18} supply the load while C_{13}, C_{15} and C_{17} float.

Mode-VI: D_{10} is turned ON hence C_2, C_4, C_6, C_8 and C_{10} gets charged while C_1, C_3, C_5, C_7 and C_9 are discharged by i_a . Hence C_{12}, C_{14}, C_{16} and C_{18} supply the load while C_{11}, C_{13}, C_{15} and C_{17} float.

Mode-VII: D_8 is turned ON hence C_2, C_4, C_6 and C_8 gets charged while C_1, C_3, C_5 and C_7 are discharged by i_a . Hence $C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

Mode-VIII: D_6 is turned ON hence C_2, C_4 and C_6 gets charged while C_1, C_3 and C_5 are discharged by i_a . Hence $C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

Mode-IX: D_4 is turned ON hence C_2 and C_4 gets charged while C_1 and C_3 are discharged by i_a . Hence $C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

Mode-X: D_2 is turned ON hence C_2 gets charged while C_1 is discharged by i_a . Hence $C_4, C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_3, C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} floats.

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S_1 and S_2 are turned ON and the current i_a is negative for modes XI to XIX. The inductor is discharged and input source transfers energy to the CW voltage multiplier through the odd numbered diodes.

Mode-XI: D_{17} is turned ON while diodes (D_1 to D_{16} and D_{18}) do not conduct hence $C_2, C_4, C_6, C_8, C_{10}, C_{12}, C_{14}$ and C_{16} are all discharged while $C_1, C_3, C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} are all charged by i_a . Hence C_{18} supplies the load.

Mode-XII: D_{15} is turned ON hence $C_2, C_4, C_6, C_8, C_{10}, C_{12}$ and C_{14} are all discharged while $C_1, C_3, C_5, C_7, C_9, C_{11}, C_{13}$ and C_{15} are charged by i_a . Hence C_{16} and C_{18} supply the load while C_{17} floats.

Mode-XIII: D_{13} is turned ON hence $C_2, C_4, C_6, C_8, C_{10}$ and C_{12} gets discharged while $C_1, C_3, C_5, C_7, C_9, C_{11}$ and C_{13} are all charged by i_a . Hence C_{14}, C_{16} and C_{18} supply the load while C_{15} and C_{17} floats.

Mode-XIV: D_{11} is turned ON hence C_2, C_4, C_6, C_8 and C_{10} are all discharged while C_1, C_3, C_5, C_7, C_9 and C_{11} are all charged by i_a . Hence C_{12}, C_{14}, C_{16} and C_{18} supply the load while C_{13}, C_{15} and C_{17} float.

Mode-XV: D_9 is turned ON hence C_2, C_4, C_6 and C_8 are discharged while C_1, C_3, C_5, C_7 and C_9 are charged by i_a . Hence $C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while C_{11}, C_{13}, C_{15} and C_{17} float.

Mode-XVI: D_7 is turned ON hence C_2, C_4 and C_6 are all discharged while C_1, C_3, C_5 and C_7 are charged by i_a . Hence $C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

Mode-XVII: D_5 is turned ON hence C_2 and C_4 gets discharged while C_1, C_3 and C_5 are charged by i_a . Hence $C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

Mode-XVIII: D_3 is turned ON hence C_2 is discharged while C_1 and C_3 are charged by i_a . Hence $C_4, C_6, C_8, C_{10}, C_{12}, C_{14}, C_{16}$ and C_{18} supply the load while $C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} are floating.

Mode-XIX: D_1 is turned ON hence C_1 is charged by i_a . Hence all even capacitors supply the load while $C_3, C_5, C_7, C_9, C_{11}, C_{13}, C_{15}$ and C_{17} float.

TABLE I DESIGN VALUES FOR CONVERTER TOPOLOGY

Parameter	Value
Supply voltage (V_s)	12V
Switching frequency (f)	2000Hz
Output power (P_o)	1000W
Output voltage (V_o)	220V
Output current (I_o)	4.55A
Load resistance (R)	48.4 Ω
Time period (T)	0.5ms
Duty cycles (δ_1 & δ_2)	0.5

Inductor (L)	6.69mH
Capacitor (C)	258.26 μ F
Number of stages (n)	9
Capacitors (C_1 to C_{18})	16.78mF

IV. SIMULATED CONVERTER TOPOLOGY FOR HYBRID SYSTEM

The simulation of the converter for the hybrid system is done using MATLAB software. The solar panel is used as the primary supply. The simulated solar panel of converter topology is shown as in Fig. 4.

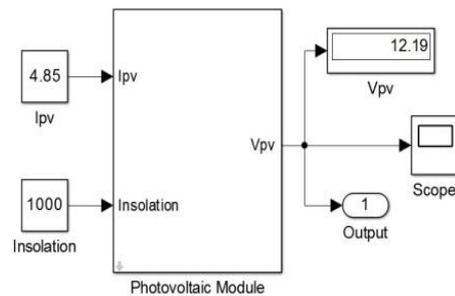


Fig. 4 Simulated solar panel of converter topology

The solar panel has a subsystem which contains the design equations based on the equivalent circuit of a solar cell.

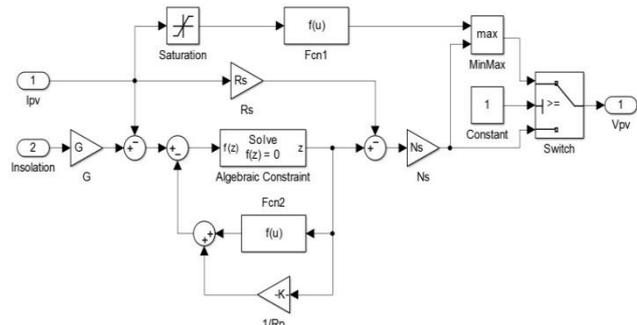


Fig. 5 Subsystem of the solar panel

The output waveforms and results obtained can be used so that it is easier to design the prototype model. The waveform of the output voltage of solar panel is shown below in Fig.6.

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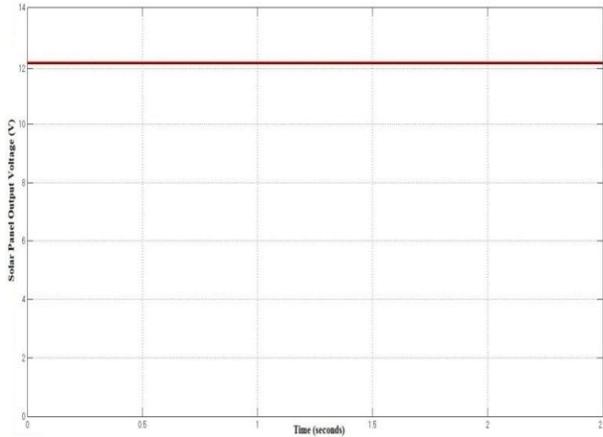
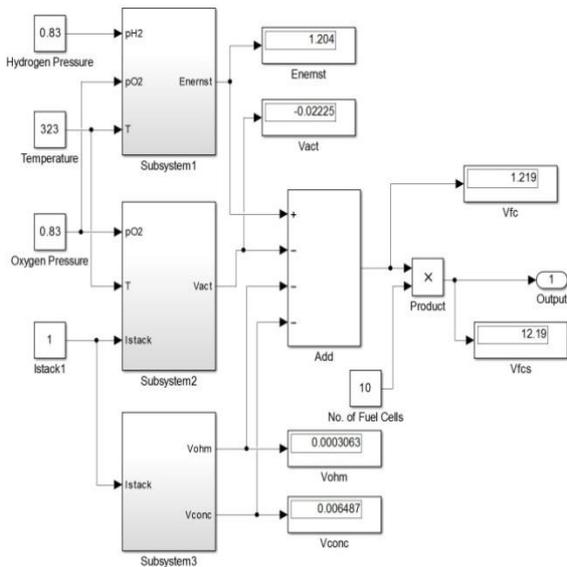


Fig. 6 Output voltage waveform of solar panel

The fuel cell is used as a back-up to the solar panel. The fuel cell and the solar panel are connected in parallel. Therefore only one will be used at a time. The simulated fuel cell is shown



below as in Fig. 7.

Fig. 7 Simulated fuel cell of converter topology

The first subsystem is the calculation of the Nernst voltage (E_{Nernst}). The simulated subsystem1 for calculating the Nernst voltage is shown in Fig. 8.

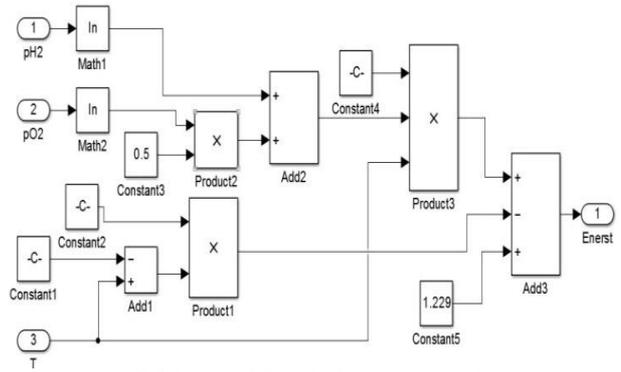


Fig. 8 Subsystem1 for calculating Nernst voltage

The second subsystem of the fuel cell is calculation of the actual voltage (V_{act}). The simulated subsystem for calculating the actual voltage is shown in Fig. 9.

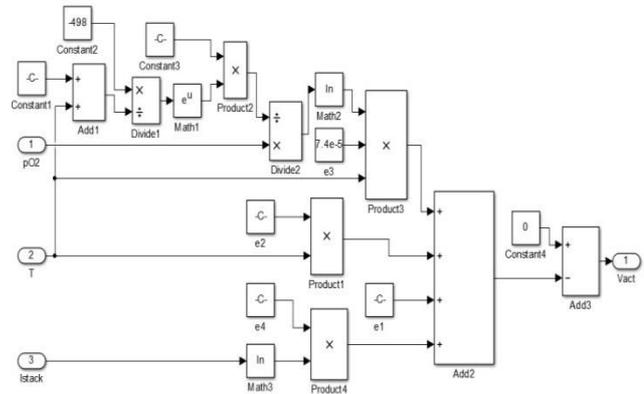


Fig. 9 Subsystem2 for calculating actual voltage The third subsystem of the fuel cell is for calculating the ohmic voltage drop (V_{ohmic}) and the concentration voltage (V_{conc}). The simulated subsystem is shown as in Fig. 10.

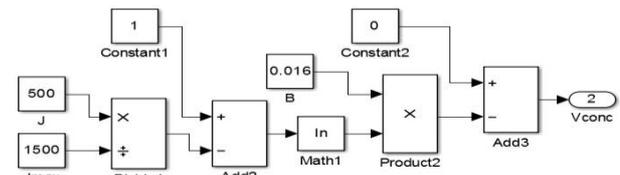
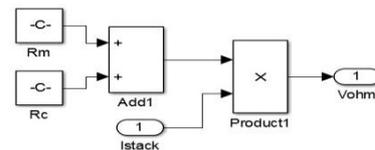


Fig. 10 Subsystem3 for calculating V_{ohmic} & V_{conc}

The simulated fuel cell has one output waveform which is the output voltage shown as in Fig.11.

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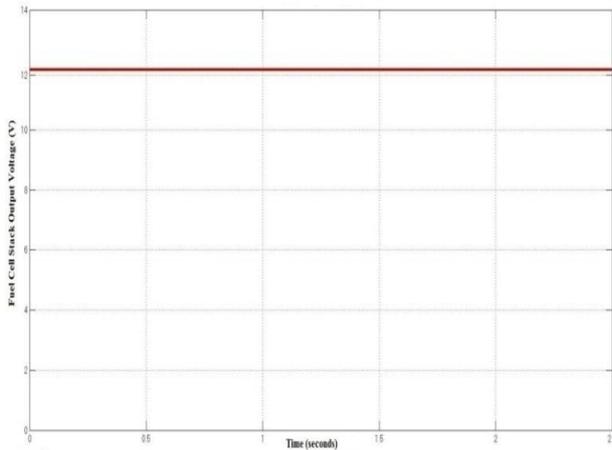


Fig. 11 Output voltage waveform of fuel cell

The simulated circuit consists of two output waveforms of the output voltage and output current. From the waveforms it can be observed that after a certain point the steady state is achieved. The simulated converter for the hybrid system is shown in Fig. 12.

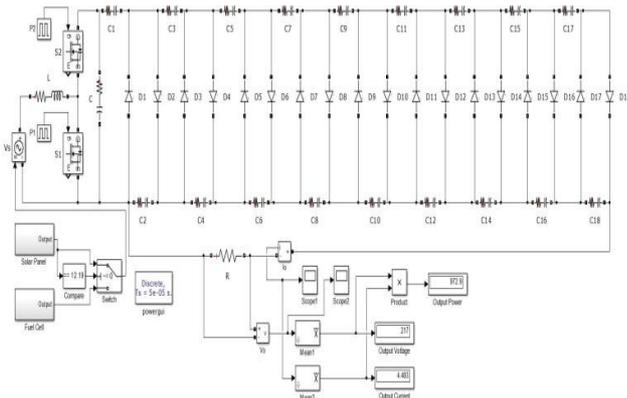


Fig. 12 Simulated circuit of converter cascaded with CW voltage multiplier

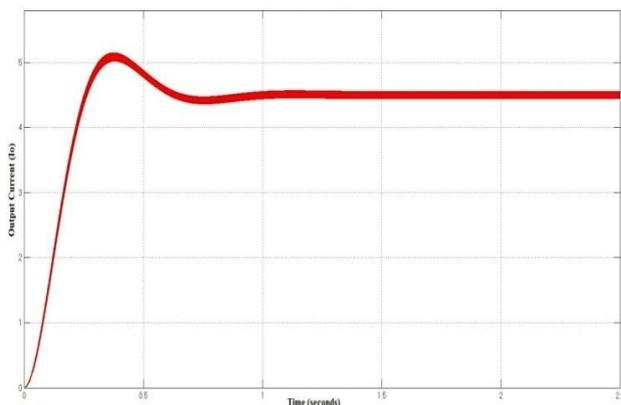


Fig. 13 Output current waveform of simulated converter circuit

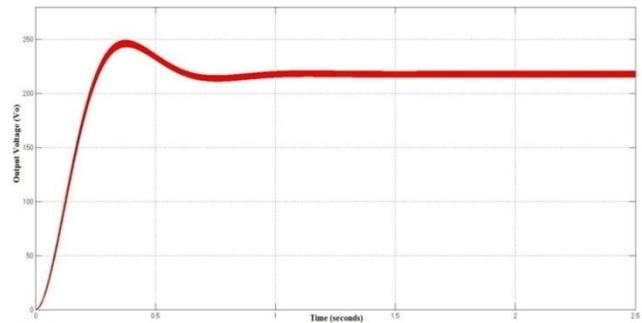


Fig. 14 Output voltage waveform of simulated converter circuit

TABLE II RESULTS OBTAINED FROM SIMULATION

Parameter	Value
Supply voltage (V_s)	12.19V
Output current (I_o)	4.483A
Output voltage (V_o)	217V
Output power (P_o)	972.9W

V. CONCLUSION

In this paper, the solar panel and fuel cell were designed and simulated initially using MATLAB software. The boost converter cascaded with Cockcroft-Walton voltage multiplier was designed and then integrated with the solar panel and fuel cell with solar panel as the primary source and fuel cell as the backup. Then the entire setup was simulated using MATLAB software. From the simulation results it was observed that, the proposed circuit for the hybrid system is suitable for high voltage applications. The boost converter for Cockcroft-Walton voltage multiplier depends on the capacitance value and number of stages of the voltage multiplier. In future work, for the same or any number of stages of the voltage multiplier used the voltage level can be improved by changing the capacitance value.

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