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BIDIRECTIONAL ISOLATED DC-DC CONVERTER FOR FUEL CELLS AND SUPERCAPACITORS HYBRID SYSTEM

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Abstract: In future, electrical power systems for electrical vehicles may employ hybrid energy sources, such as fuel cells and super capacitors. The fuel cells (FCs) and super capacitors (SCs) as an environmentally renewable energy system has been applied in many such fields, as hybrid electric vehicle and uninterruptible power supply (UPS) systems. The available power generated from a fuel cell (FC) may not be sufficient to meet sustained load demands, mainly during peak demand or transient conditions. During these conditions, supercapacitor (SC) bank can supply a large amount of power. The combined use of FC and SC has the potential for better energy efficiency, reducing the cost of FC technology, and improved fuel usage. Here, a bidirectional isolated dc–dc converter for fuel cells and the supercapacitor hybrid energy system is being controlled by phase-shift angle and duty cycle method. The dc-dc converter acts as a multiport device. The converter has three modes of operation (1) Boost mode (2) SC power mode (3) SC recharge mode. All switches are controlled by phase shifted PWM signals with a variable duty cycle. Zero voltage switching (ZVS) is achieved by the parasitic capacitance of the switches. For the simulation, MATLAB/Simulink is used. Here the operation principle of the proposed converter is being described and the waveforms for various stages of operation are analyzed.

Keywords: Bidirectional dc–dc converter, fuel cell, supercapacitor.

I. INTRODUCTION

In recent years, development of the clean power sources and electricity has become an important topic to protect the environment and overcome the energy crisis of the world [1]. Fuel cells (FC) are electrochemical devices which convert the chemical energy of the hydrogen into electric power directly, with consequent high conversion efficiency and possibility to obtain the extended range with the combustible feed from the outside [2]. Based on these advantages, fuel cell can be a promising substitute to the conventional fossil energy. But one of the main disadvantages of the fuel cell is its slow dynamics that is limited by the hydrogen and air delivery system. Thus, energy storage units, such as supercapacitors (SCs), are required as the auxiliary power sources for smoothing output power in the warming-up stage of the fuel cells [3], [4]. So hybrid power conversion systems with fuel cells and other energy sources are used in the many industrial systems such as uninterruptible power supply (UPS) (Fig 1). This converter has several advantages as compared to converters that employ battery as the source.

The bidirectional isolated dc-dc converter proposed here is a multiport device that includes a fuel cell and supercapacitor is analyzed and designed. The control of the three phase inverter is done using two methods; Phase shift and duty cycle control [5], [6]. Phase shift control is used to control the required power transferred by the converter and variable duty cycle control is to increase the efficiency. These methods control the bidirectional power flow flexibly. It minimizes the number of switches and their associated gate driver components by using two high-frequency transformers with a full-bridge circuit on the primary side. The voltage doubler circuit is placed on the secondary side. The input current ripple can be limited by the current-fed input that is favorable for fuel cells. The parasitic capacitance of the switches resonates with the inductor of the transformer for zero voltage switching [8]. In this converter there are 3 modes of operation: Boost mode, SC power mode, SC recharge mode.In the boost mode, the power is delivered simultaneously from the FCs and SCs to the dc voltage bus.In the SC power mode, only the SCs are connected and they provide the required load power. When the dc bus charges the SCs, the power flow direction is reversed that means the energy is transferred from the high voltage side to the low voltage side, and thereby the converter is operated under the SC recharge mode. A fuel-cell bank as the main input power source is connected to the

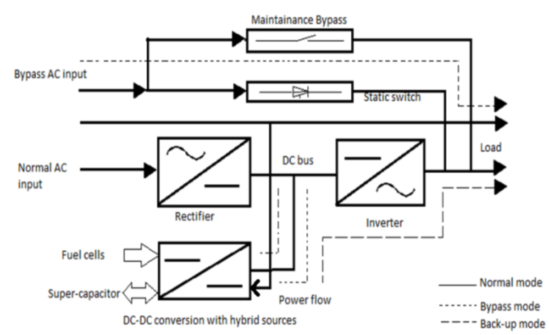

Fig 1: Block diagram of a dual conversion UPS system based on FC & SC

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boost half bridge circuit which can limit the input current ripple, and SC bank as the auxiliary power source can deliver power to the load through the full-bridge circuit. The proposed converter can draw power from these two different dc sources individually [9],[10] and simultaneously.The bidirectional flow of power can be controlled by the phase-shift angle δ which is between S1 and S5, and the power delivered can be varied by varying the duty cycle of S3 and S4 [11].

II. PROPOSED CONVERTER

A bidirectional isolated dc–dc converter (Fig 2) that is being controlled by phase shift and duty cycle control to control the energy flow and improve the converter dynamic behavior and stability is proposed here. The phase-shift angle and duty cycle method used here minimizes the number of switches and their gate driver components by

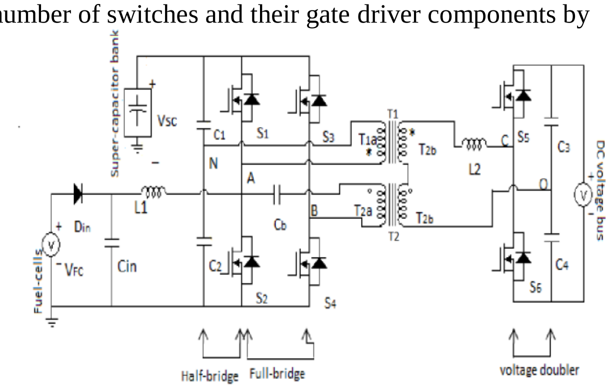


Fig 2: Proposed hybrid bidirectional dc-dc converter topology

using two high-frequency transformers that combine a half-bridge circuit and a full-bridge circuit together on the primary side. The voltage doubler is present on the secondary side. The current-fed input can limit the input current ripple that is favorable for fuel cells. The parasitic capacitance of the switches resonate with the inductor of the transformer for the purpose of zero voltage switching .Also, phase-shift and duty cycle modulation method is utilized to control the bidirectional power flow flexibly.BHB structure is on the primary side of the transformer T_1.This is associated with the switches S_1 and S_2 that are operated at 50% duty cycle. The SC bank as an auxiliary energy source is connected to the variable low voltage (LV) dc bus across the dividing capacitors, C_1 and C_2. Bidirectional operation can be realized between the SC bank and the high-voltage (HV) dc bus. Switches S_3 and S_4 are controlled by the duty cycle to reduce the current stress and ac RMS value when input voltage V_{FC} or V_{SC} are variable over a wide range. The transformers T_1 and T_2 with independent primary windings as well as series-connected secondary windings are employed to realize galvanic isolation and boost a low input voltage to the HV dc bus. A dc blocking capacitor C_b is added in series with the primary winding of T_2 to avoid transformer saturation caused by asymmetrical operation in full-bridge circuit. The voltage doubler circuit utilized on the secondary side is to increase voltage conversion ratio further. The inductor L_2 on the secondary side is utilized as a power delivering interface element between the LV side and the HV side. According to the direction of power flow, the proposed converter has three operation modes that can be defined as :1. Boost mode 2. SC power mode & 3. SC recharge mode. In the boost mode, the power is delivered from the FCs and SCs to the dc voltage bus. In the SC power mode, only the SCs are connected to provide the required load power. When the dc bus charges the SCs, the power flow direction is reversed which means the energy is transferred from the HV side to the LV side, and thereby the converter is operated under the SC recharge mode.

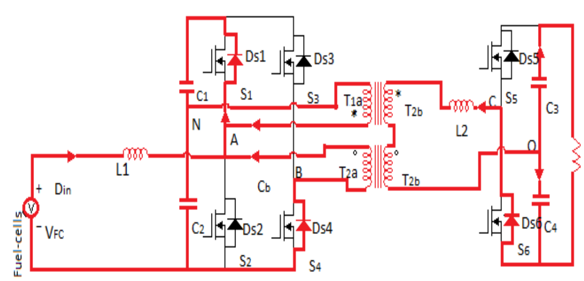
A. Boost mode

Boost mode is represented by the stages shown from Fig 3. In the boost mode n_1 and n_2 are the turn ratios of the transformers. The current flowing in each power switch on the primary side is presented. To analyze the operation principles, the following assumptions are given.(i)The switches are ideal with antiparallel body diodes and parasitic capacitors.(ii)Inductance L_1 is large enough to be treated as a current source.(iii)The output voltage is controlled as a constant.(iv)The leakage inductance of the transformers, parasitic inductance, and extra inductance can be combined together as L_2 on the secondary side. The half switching cycle can be divided into eight stages.

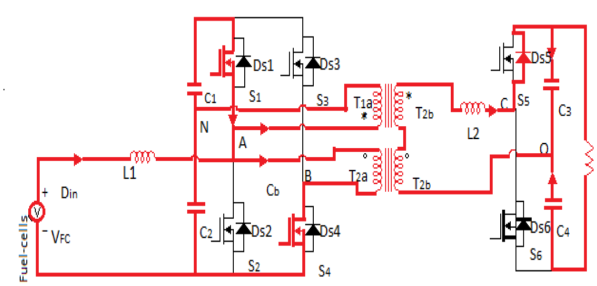
1) Stage 1: The voltage across L_2 is VT1b + $_{VT2b}$ – V_{CO}. S_1, S_4, and S_6 are gated, so $V_{T1b} = n_1V_{FC}$, $V_{T2b} = 2n_2V_{FC}$, and V_{CO}=−Vo/2.i_{L2} will increase linearly. Because $i_{T\,1a}$ +$i_{T\,2a}$ are negative and iL1 is positive, the current flows through D_{S1}.

2) Stage 2 :The value of $i_{T\,1a}$ + $i_{T\,2a}$ starts to be positive, and S_4 conducts to carry the current, but S_4 may conduct until the value of I_{L1} < $_{iT1a}$ + $i_{T\,2a}$.

3) Stage 3 : S_6 is turned off. The inductor L_2 starts to



(a)



(c)

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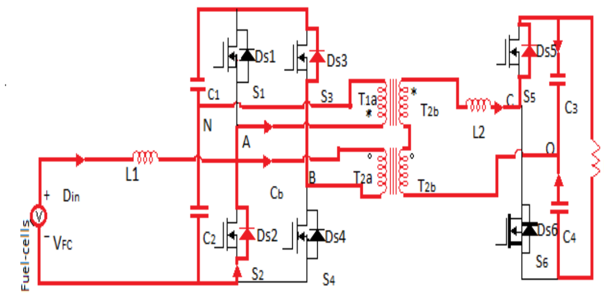


(e)

resonate with the stray capacitors C_{S5} and C_{S6}. When the voltage across C_{S5} reduces to zero, the body diode of S_5 conducts, so the voltage $V_{CO} = Vo/2$.

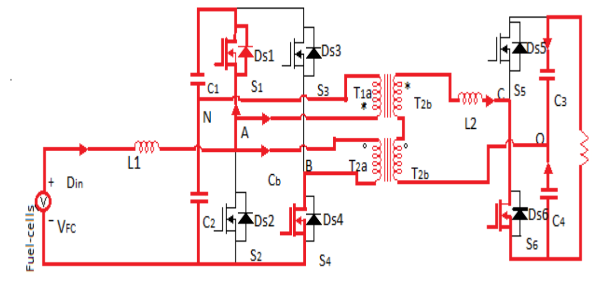
4) Stage 4 : S_5 is turned on under ZVS.

5) Stage 5: S_4 is turned off. L_2 begins to resonate with the stray capacitors C_{S3} and C_{S4} .When voltage across S_3 reduces to zero, D_{S3} is, forward biased.V_{T2b}=0.Hence,V_{L2} =V_{T1b}–$V_{CO.}$

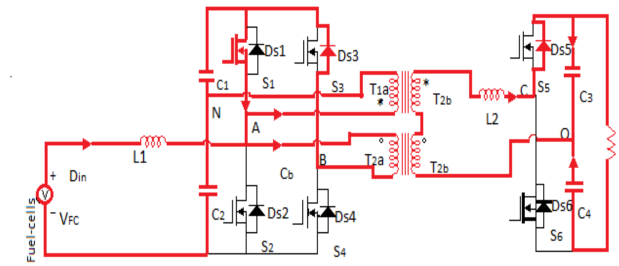
6) Stage 6: S_1 is turned off.L_2 begins to resonate with the stray capacitors C_{S1} and C_{S2} .C_{S1} is charged from 0 V, and C_{S2} is discharged from $2V_{FC}$. The rate of change on voltage depends on the magnitude $i_{T1a}+i_{T2a}-I_{L1}$ .At t_5,V_{CS2} attempts to overshoot negative rail and then D_{S2} is forward biased. Then, S_2 can be turned on under ZVS.

7) Stage 7 :At this stage,$V_{T1b}=-n_1V_{FC}$,$V_{T\ 2b}=-2n_2V_{FC}$, and V_{CO} = Vo /2.The primary current decays. Until $i_{L\ 1>}\ i_{T\ 1a} + i_{T\ 2a}$, the current starts to flow through the switch S_2.

8) Stage 8:Both i_{T1a} and i_{T2a} are to be negative, makes S_3 and S_5 conduct.After this cycle, the second half cycle starts.



(b)



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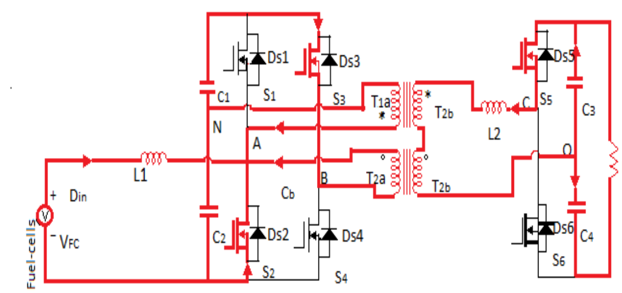

(f)

Fig 3: Operating stages: (a) Stage 1, (b) Stage 2, (c) Stage 4, (d) Stage 5, (e) Stage 7, and (f) Stage 8.

B. SC power mode

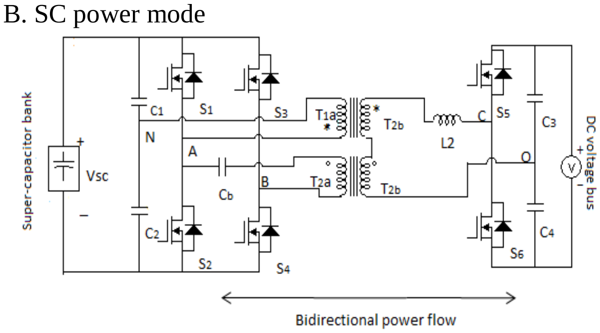

Fig 4: Converter in SC power mode and SC recharge mode

For a short period of utility power failure in UPS system or during the fuel-cell warming-up stage, the converter will be operated under the SC power mode and the power flows from SC bank to the dc voltage bus. The converter diagram is shown in Fig 4. The typical waveforms will be similar with those in the boost mode.

C. SC recharge mode

The SC recharge mode is also shown by Fig 4. Here the power flows from the HV side to the LV side which means the SC will be charged by the HV dc bus. Here, the power flow direction is reversed so the gate drive signal of *S*5 is leading to that of *S*1.

III. CONTROL STRATEGY

The control here is mainly done by phase shift control and duty cycle control method. Phase shift control method is used for controlling the bidirectional power flow, that is, to determine the direction of power flow in the converter. The gate drive signal between S_5 and S_1 will be varied to determine the specified direction. If the gate drive signal of S_1 is leading to that of S_5, then the power flow will be from low voltage side to high voltage side. That is during boost mode and SC power mode. If the gate drive signal of S_5 is leading to that of S_1, then the power flow will be from high

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voltage side to low voltage side. That is, during SC recharge mode.

In duty cycle control method, the power flow can be varied by varying the duty cycle of S_3 and S_4.If the duty cycle of S_3 and S_4 is made to 35%,then the voltage across the transformer $V_{T1a}+V_{T2a}$ will be obtained as a stepped waveform. And If the duty cycle of S_3 and S_4 is made to 50%, then the voltage across the transformer $V_{T1a}+V_{T2a}$ will be obtained as a square waveform. Thus by varying the duty cycle, the voltage across transformer varies and results in a variation of RMS current across load side. So the power delivered can be varied. Thus phase-shift angle, and the duty cycle control increases conversion efficiency and thus can be used to control the converter and make the total power losses minimal.

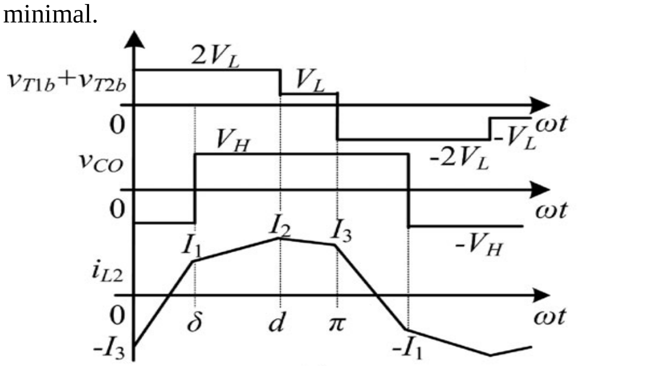

Fig 5: operating waveforms in boost mode when $0 \leq \delta \leq d$ [11]

From Fig 5, the output average power can be obtained as:

$$Po = \frac{\int_0^{\pi} (v_{T\,1b+T\,2b}\,(\omega t) \cdot i_{L2}\,(\omega t)) \cdot d\omega t}{\pi}$$

$$= \frac{V_H V_L\,(2\pi\delta - 4\delta^2 + 2\delta d + \pi d - d^2)}{2\pi\omega L_2}$$

Where, δ is the phase-shift angle and ω is the switching angular frequency. $V_L=n_1 V_{FC}$ and $V_H= Vo/2$. d is the duty cycle. When $d=\pi$, average power is given as,

$$Po = \frac{2 \cdot V_H V_L}{\pi\omega L_2}\,\delta\,(\pi - \delta)$$

The input inductance L_1 can be calculated as,

$$L1 = \frac{\pi V\mathrm{FC}}{\omega \cdot \Delta IL1}$$

$\Delta IL1$ is the ripple current of the input current.

$$L2 = \frac{2 \cdot V_H V_L}{\pi\omega Po}\,\delta\,(\pi - \delta)$$

Thus value of auxiliary inductance L_2 can be calculated.

Table 1: PARAMETER SPECIFICATIONS

PARAMETER	VALUE
Input voltage V_{FC}, V_{SC}	30-50 V_{DC}, 50-100 V_{DC}
Output power Po	1 KW
Output voltage Vo	400 V DC
Auxiliary inductor L_2	40 micro H
Input inductor L_1	20 micro H

IV. SIMULATION RESULTS

The simulation of the entire system is obtained by MATLAB/SIMULINK.The converter works with a variable input voltage 30–50 V and a constant output voltage 400 V. The duty cycles of *S*1 and *S*2 are kept at 50%. The bidirectional power flow can be controlled by the phase-shift angle δ which is between *S*1 and *S*5, and the duty cycle d of *S*3 and *S*4.

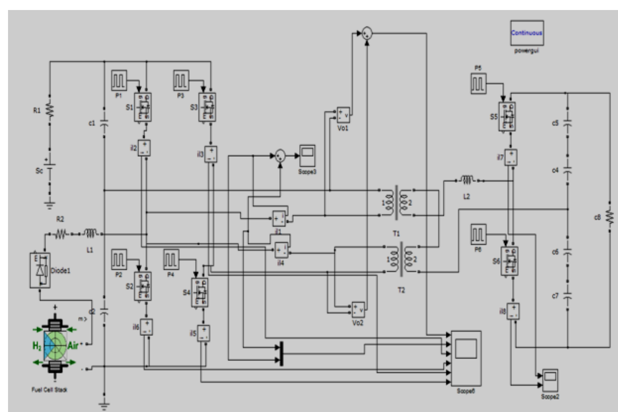

Fig 6. Simulink diagram of the proposed dc-dc converter

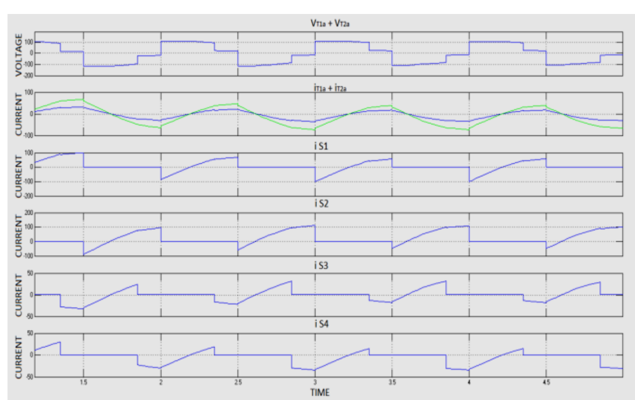

Fig 7: Voltage and current waveforms for boost mode

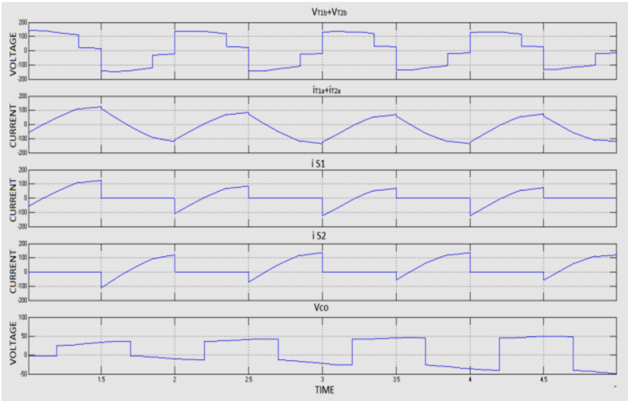

Fig8:Voltage and current waveforms for SC power mode

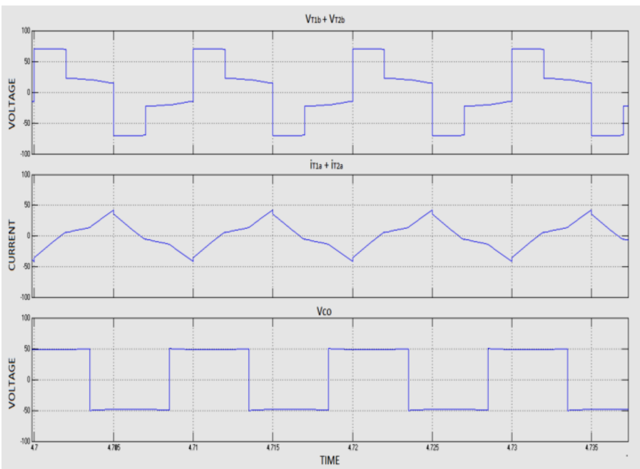

Fig 9: Voltage and current waveforms for SC recharge mode

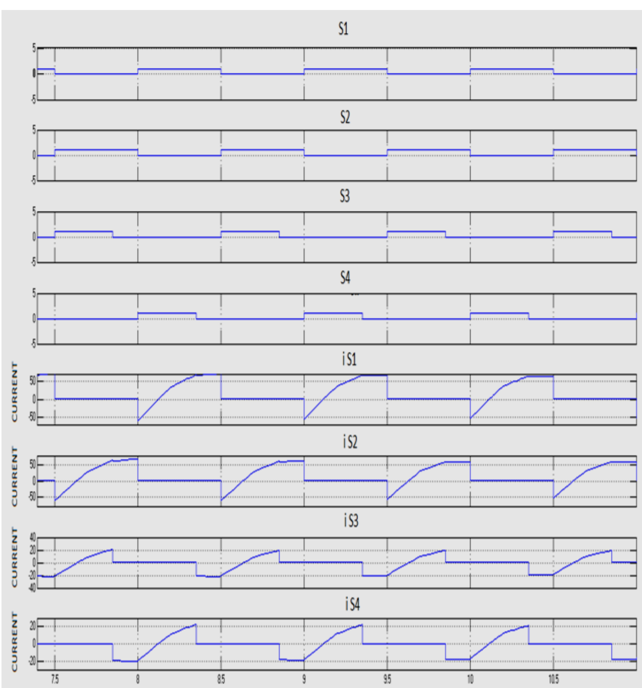

Fig 10 : Current across each switch during switching

Fig 6 shows the simulink diagram of the dc-dc converter for various modes of operation. Fig 7, Fig 8 & Fig 9 shows the voltage and current waveforms of the boost mode, SC power mode and SC recharge mode respectively.

Fig 10 shows the current waveforms across each switch. From this we can understand that the switching takes place when there is current across the switch i.e, when the voltage across the switch is zero. So zero voltage switching has been achieved.

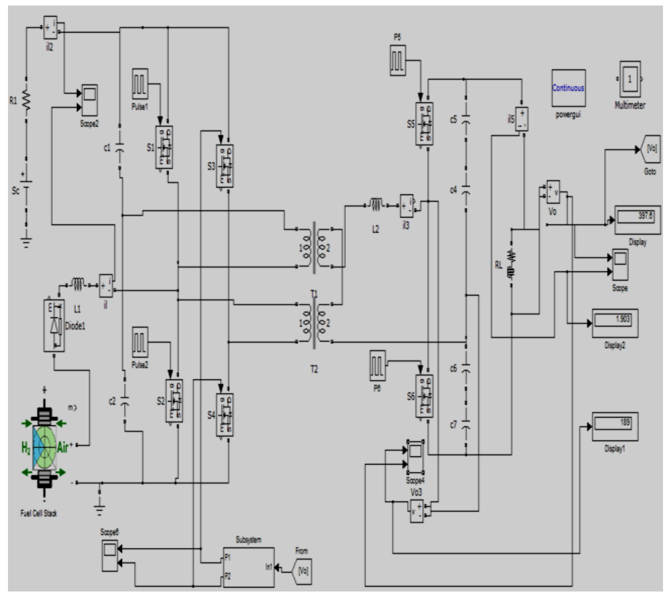

Fig 11: Simulink diagram of the proposed dc-dc converter for constant output voltage

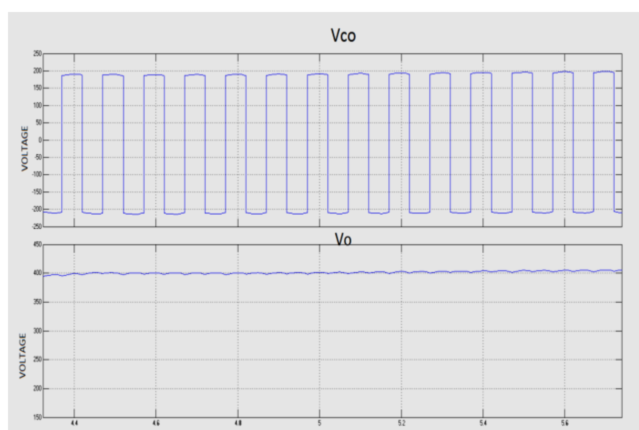

Fig 12: Input & output voltage waveform across voltage doubler circuit

Fig 11 shows the Simulink diagram of the proposed dc-dc converter for constant output voltage & Fig 12 shows the voltage obtained across the voltage doubler circuit. A constant voltage of 400V will be obtained.

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V. CONCLUSION

A novel hybrid bidirectional dc–dc converter using the phase shift and duty cycle control method has been proposed and studied. A regulated load voltage of 400 V has been achieved across the load. Zero voltage switching condition across each switches also been achieved. The converter has high conversion efficiency. The duty-cycle control can effectively eliminate the reactive power and increase the efficiency when input voltage is varied over a wide range. The proposed model can be used for different load profiles for different transients and short-time interruption. The lifetime of an FC system can be improved if combined FC system and UC bank is used instead of a stand-alone FC system or a hybrid FC and standby battery system.

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BIOGRAPHY

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