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DC-DC BIDIRECTIONAL ISOLATED CONVERTER FOR FUEL CELLS AND SUPER-CAPACITORS HYBRID SYSTEM

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***Abstract*— Future electrical power system in uninterruptible power supply (UPS) or electrical vehicle (EV) may employ hybrid energy sources, such as fuel cells and super-capacitors. It will be necessary to efficiently draw the energy from these two sources as well as recharge the energy storage elements by the DC bus. In this paper, a bidirectional isolated DC-DC converter controlled by phase-shift and duty cycle for the fuel cell hybrid energy system is analysed and designed. The proposed topology minimizes the number of switches and their associated gate driver components by using two high frequency transformers which combine a half-bridge circuit and a full-bridge circuit together on the primary side. The voltage doubler circuit is employed on the secondary side. The current-fed input can limit the input current ripple that is favourable for fuel cells. The parasitic capacitance of the switches is used for zero voltage switching (ZVS). The converter operates in three modes, such as Boost mode, Super capacitor power mode, Super capacitor recharge mode based on the flow of power from either of the source to the load and vice versa.**

***Index Terms*—Bidirectional dc-dc converter, current-fed, fuel cell, phase-shit, super-capacitor, boost half bridge.**

I. INTRODUCTION

The hybrid system based on fuel cells (FCs) and super-capacitors (SCs) as an environmentally renewable energy system has been applied in many fields, such as hybrid electric vehicle (HEV), uninterruptible power supply (UPS) and so on [1]. An extended-run time battery-less double-conversion UPS system powered by FCs and SCs can be taken as a valid example.

Comparing to diesel generators and batteries, fuel cells are electrochemical devices which convert the chemical potential of the hydrogen into electric power directly with consequent high conversion efficiency, so it has the possibility to obtain the extended runtime range with the combustible feed from the outside. But one of the main weak points of the fuel cell is its slow dynamics because of the limited speed of hydrogen delivery system and the chemical reaction in the membranes with a slow time constant [2]. Hence, during the warming-up stage or load transient, super-capacitors [3], [4] are utilized as the auxiliary power source for smoothing the output power. In addition, the fuel cell output voltage is varied widely, almost 2:1, depending on the load condition, and the terminal voltage of the super-capacitor bank is also variable during charging and discharging periods. Thus, it is very important for the conversion system to be capable of harvesting power from these two different power sources efficiently in widely input voltage range and load conditions.

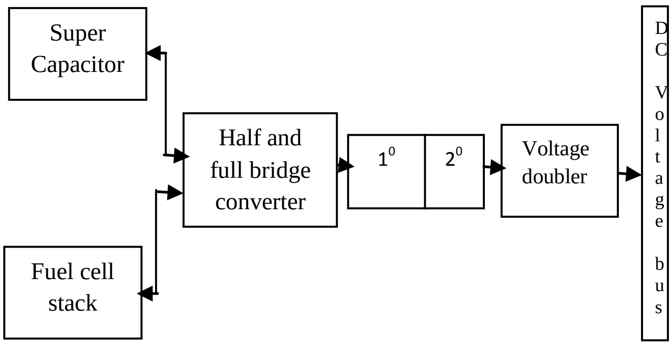

Figure. 1. Block diagram of proposed converter.

In recent years, many configurations of a hybrid DC power conversion system relating to FCs and SCs have been proposed. Based on the boost-half-bridge (BHB) circuit, and the hybrid full-bridge structure, a novel hybrid bidirectional DC-DC converter was derived and presented in. In this paper, characteristics of the proposed converter in [5] will be analyzed in depth. As shown in Fig. 2, a fuel cell bank as the main input power source is connected to the BHB circuit which can limit the input current ripple; a super-capacitor bank as the auxiliary power source can deliver power to the load through the full-

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bridge circuit. The proposed converter can draw power from these two different DC sources individually and simultaneously.

II. OPERATION PRINCIPLES OF THE HYBRID DC CONVERTER

As shown in Fig. 2, a BHB structure locates on the primary side of the transformer T_1 and it associates with the switches S_1 and S_2 operating at 50% duty cycle. The super-capacitor bank 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 super-capacitor 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 high voltage 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.

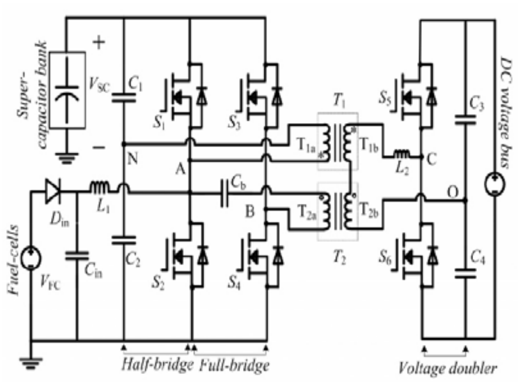

Figure. 2. The proposed hybrid bidirectional DC-DC converter topology.

The voltage doubler circuit utilized on the secondary side is to increase voltage conversion ratio further. According to the direction of power flow, the proposed converter has three operation modes which can be defined as: boost mode, super-capacitor power mode and super-capacitor recharge mode. In the boost mode, the power is delivered from the fuel cells and super-capacitors to the DC voltage bus. In the super-capacitor power mode, only the super-capacitors are connected to provide the required load power. When the DC bus charges the super-capacitors, 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 super-capacitor recharge mode.

A. *Boost Mode*

In the boost mode, the timing diagram and typical waveforms are shown in Fig. 3, where 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, but the voltage and current resonant slopes during the switching transitions are not shown here for simplicity. To analyze the operation principles clearly, the following assumptions are given: (1) All the switches are ideal with anti-parallel body diodes and parasitic capacitors; (2) The inductance L_1 is large enough to be treated as a current source; (3) The output voltage is controlled well as a constant; (4) The leakage inductance of the transformers, parasitic inductance and extra inductance can be lumped together as L_2 on the secondary side. The half switching cycle can be divided into eight intervals and their timing diagram and typical waveforms are shown in the figure 3.

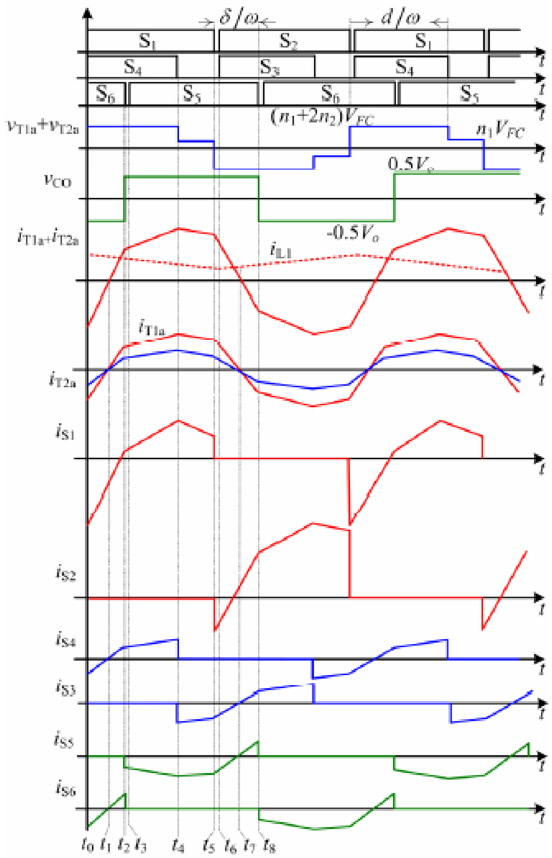

Figure. 3. Timing diagram and typical waveforms in the boost mode.

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The power delivered by this converter can be calculated, as follows:

$$P_o = \begin{cases} \dfrac{V_L V_H \left(2\pi\delta - 4\delta^2 + 2\delta d + \pi d - d^2\right)}{2\pi\omega L_2} & (0 \le |\delta| \le d) \\ \dfrac{V_L V_H \left(2\pi\delta - 2\delta^2 - 2|\delta| d + \pi d + d^2\right)}{2\pi\omega L_2} & (d \le |\delta| \le 0.5\pi) \end{cases} \quad (1)$$

where δ is the phase-shift angle; ω is the switching angular frequency; $V_L = n_1 V_{FC}$ and $V_H = V_O/2$, respectively; the duty cycle d is defined as:

$$d = 2\pi \cdot \frac{T_{on\,S3}}{T_s} = 2\pi \cdot \frac{T_{on\,S4}}{T_s}$$

It can be seen that when duty cycle control is utilised together with the phase shift control, at same input and output voltages the average power delivered is increased, because the duty cycle control can limit the required reactive power. But with the duty cycle reducing, the output power increasing is not significant. When the phase shift angle is larger than 0.6, the delivered angle power is decreased, because in fact the duty cycle reduces the average voltage across the secondary windings. The ZVS condition can be deduced on the precondition that the anti parallel diode of the switch must conduct before the switch is triggered.

B. Super-capacitor Power Mode

For a short period of utility power failure in UPS system which can be handled by super-capacitors or during the fuel cell warming-up stage, the converter will be operated under the super-capacitor power mode and the power flows from super-capacitor bank to the DC voltage bus as shown in Fig. 6

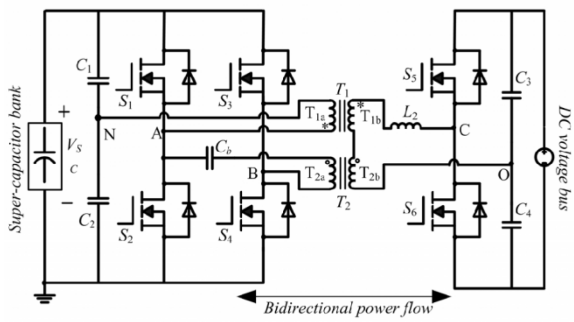

Figure. 4. Converter topology in capacitor power mode

The timing diagram and typical waveforms in this mode are illustrated in Fig. 7. It can be seen that the typical waveforms are similar with those in the boost mode, but because there is no i_{L1}, the current stresses of S_1 and S_2 are completely same.

The peak current can be expressed by

$$I_{S1,peak} = I_{S2,peak} = (n_1 + n_2) \cdot I_2$$

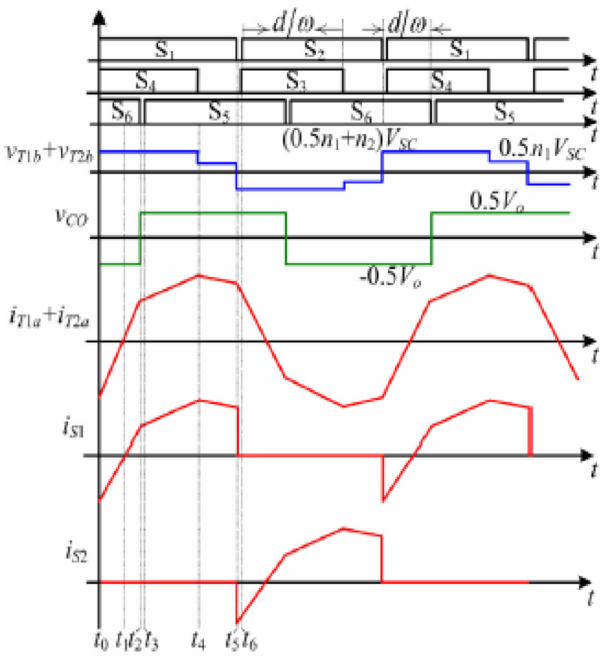

Figure.5.Timing diagram and typical waveforms under the super capacitor power mode

C. Super capacitor recharge mode

As shown in Fig. 4, in the super-capacitor recharge mode, the super-capacitor will be charged by the high voltage DC bus which means that the power flows from the HV side to the LV side. The timing diagram and typical waveforms are illustrated in Fig. 8, where the gate drive signal of S_5 is leading to that of S_1 due to the reversed power-flow direction

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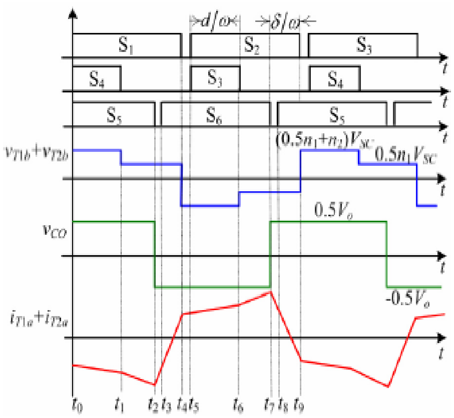

Figure.6. Timing diagram and typical waveforms under the super capacitor researching mode

III. SIMULATION MODEL AND RESULTS

The fuel cell is used as the primary source of this converter and hence it can be simulated using Simulink to produced a desired DC output voltage of around 50VDC. The normal batteries can store huge amount of charge in it, but the drawbacks of batteries are it take a sufficient amount of time to get it charged, and this is the reason why the batteries are replaced by fuel cells which can store huge amount of charge as well as the charging time is comparatively less than that of the batteries.While bringing out the expected output by simulating the converter circuit using Simulink/MATLAB, the cycle of the simulation development can be given as

1. Prepare the circuit diagram of the converter that need to be simulated.
2. Choose a new M-File in MATLAB and drag and drop the required electronic components from the Simulink library into the M-File.
3. Connect all the components, assign the values for the components of the Converter and choose the correct switching frequency.
4. Run the simulation by setting a proper run time and click on to the scope for obtaining the output of the circuit.
5. Compare the output obtained with the expected output as per the standards.

The results obtained when the proposed converter topology is simulated by using Matlab 7.0.5 can be shown as follows. The converter is simulated in two different modes of operation and the desired output voltage as well as the switching currents is obtained by placing scopes at proper locations in the simulation. The simulation results and the explanation of which in each modes of operation is explained below.

A. *Boost Mode – simulation results*

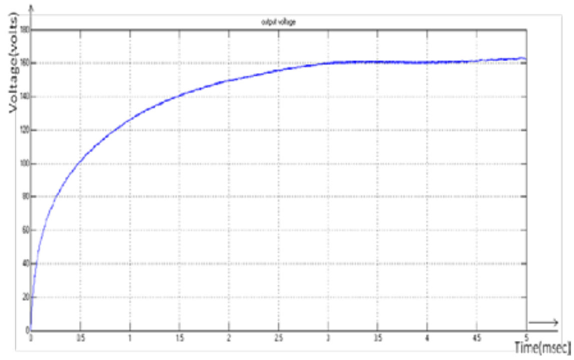

Figure. 7. Output Voltage of boost mode operation.

Various switching currents that arises in a boost power mode simulation can be shown as

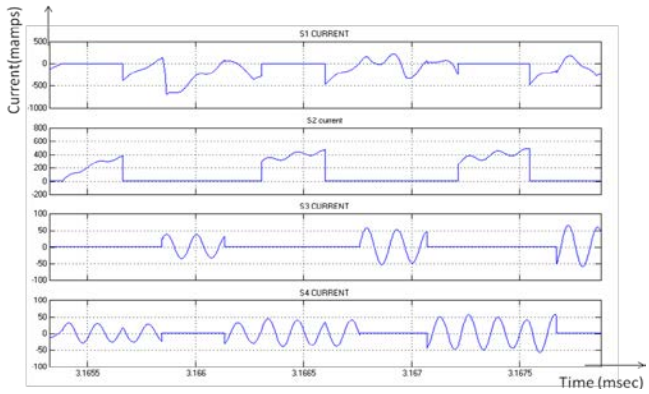

Figure. 8. Switching currents of boost mode of operation

This is the mode of operation in which the power is extracted from the primary voltage source (ie., Fuel cell), and hence in the proposed converter simulation in boost mode of operation, the input supply from the fuel cell stack will be boosted up and will be obtained across the load.

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Fig 7. shows the DC output voltage which is in its boosted form that is obtained across the load when the converter is simulated in boost mode of operation. It is seen that a satisfactory DC voltage is

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obtained across the load in this particular mode of operation.

Fig 8. shows the current waveforms obtained along the switches that are used in boost mode of operation. The waveform describes the variation of currents in the four switches that are used in proposed converter circuit.

B. Capacitor power mode – simulation results

The capacitive power mode is that mode of operation in which the power for the converter input is drawn exclusively from the super capacitor bank. This is the mode of operation in which the converter works when the fuel cell is in its warming up stage which is the time taken for the fuel cell to get charged up. Hence this mode of operation exists only for a short period of time which is dependent on the charging time of fuel cell stack that is been used as the primary power source.

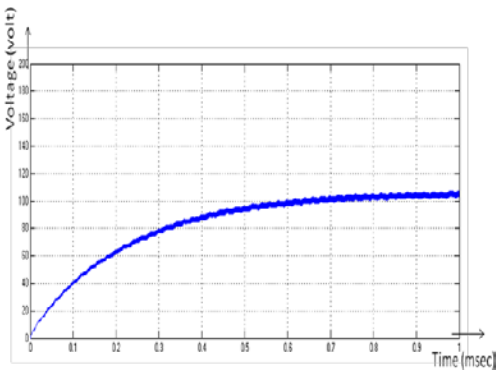

Figure. 9. Output Voltage of capacitor power mode operation.

Fig 9. shows the output voltage at the load when the circuit is simulated under super capacitor power mode. A satisfactory DC output is obtained as shown in the simulation of the circuit.

V. CONCLUSION

A novel hybrid bidirectional DC-DC converter consisting of a current-fed input port and a voltage-fed input port was proposed and studied. Using the outputs obtained in the simulation of the proposed converter circuit, the satisfactory working of the converter for the purpose it is intended for can be assured, and hence it is possible to rely upon the hardware model of the converter for the fuel cell and super capacitor hybrid system. So we can conclude that the proposed converter is a promising candidate circuit for the fuel cell and super-capacitor applications. Due to the limitation of present experiments, energy management strategies to control system power and achieve high overall efficiency of the proposed converter will be studied in future along with the realisation of the proposed converter in hardware.

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BIOGRAPY

P.Pugazhendiran was born in Tamilnadu, in 1979. Received his UG degree in Electrical and Electronics Engineering from Coimbatore Institute of Technology (CIT) in 2001 and PG degree from College of Engineering (CEG), Guindy, Anna university, Chennai in 2001.His research interests includes Power quality issues, Power Converters, Renewable energy sources, Electrical Drives. He Published More than 5 Engineering Books. Teaching Experience over a decade. He is currently working at I.F.E.T College of Engineering as Assistant Professor and head of the department. He is a life member of ISTE.

Mohammed Nisham was born on 1990 at Mahe, situated in Kerala, at present he is pursuing his bachelor's degree in Electrical and Electronics Engineering at IFET College of Engineering, Villupuram, and Tamil Nadu. His areas of interests are power electronics, Power quality issues and computer networks.