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Design and modelling of high gain DC-DC converters for fuel cell hybrid electric vehicles

D Elangovan, V Karthigeyan, B Subhanu, M Ashwin and G Arunkumar

School of Electrical Engineering, VIT University, Vellore - 632014, Tamil Nadu, India

E-mail : elangovan.devaraj@vit.ac.in

Abstract. Transportation (Diesel and petrol internal combustion engine vehicles) approximately contributes to 25.5% of total CO₂ emission. Thus diesel and petrol engine vehicles are the most dominant contributors of CO₂ emission which leads global warming which causes climate change. The problem of CO₂ emission and global warming can be reduced by focusing on renewable energy vehicles. Out of the available renewable energy sources fuel cell is the only source which has reasonable efficiency and can be used in vehicles. But the main disadvantage of fuel cell is its slow response time. So energy storage systems like batteries and super capacitors are used in parallel with the fuel cell. Fuel cell is used during steady state vehicle operation while during transient conditions like starting, acceleration and braking batteries and super capacitors can supply or absorb energy. In this paper a unidirectional fuel cell DC-DC converter and bidirectional energy storage system DC-DC converter is proposed, which can interface dc sources at different voltage levels to the dc bus and also it can independently control the power flow from each energy source to the dc bus and vice versa. The proposed converters are designed and simulated using PSIM version 9.1.1 and gate pulse pattern, input and output voltage waveforms of the converters for steady state operation are studied.

1. Introduction

India as of 2009 was the third largest contributor of CO₂ in the world. As of 2010 25.5% CO₂ emission is by transport sector and it is standing second after electricity generation sector which contributes to 35.5% [1]. Now the need to switch to alternative energy comes in as a solution to the rise in CO₂ emission. The alternatives that we see today is electric vehicles. These electric vehicles need an electric power source to supply power the motor which runs the vehicle. This power source can be a battery but battery needs to be charged after it is discharged completely. This means that battery powered electric vehicles will have a limited driving range after which the batteries needs to be charged. Fuel Cell is a better substitute for batteries in this context. Hydrogen is given as input to fuel cell which has platinum which separates hydrogen into H⁺ and e⁻. These electrons flow through load. This electron flow is called current. Fuel cell can generate electric current as long as hydrogen is supplied. Hydrogen can also be stored like petrol and diesel in cylinders and can thus can provide on board battery charging. This would extend the driving range of electric vehicles. Fuel Cell (FC) is suitable solution for transportation vehicle applications because of their compactness and they use hydrogen which is alternative fuel as it does not emit CO₂ at the point of use. Among the various types of fuel cell technologies available, the proton exchange membrane fuel cell (PEMFC) is good for transportation vehicles applications as PEMFC has high power density and it operates at relatively low temperatures. A single FC system in a vehicle is not sufficient to satisfy the dynamically varying motor power demands. Fuel cell provide good efficiency and performance during steady-state



operation, but the response time of fuel cells during transient conditions (starting) and sudden high power demands (acceleration) is very unsatisfactory, so to overcome this challenge, the FC system should be connected with energy storage elements such as battery and super capacitor (SC), which should have good steady state and transient response to meet the total power requirement of the vehicle both in steady state and transient conditions.

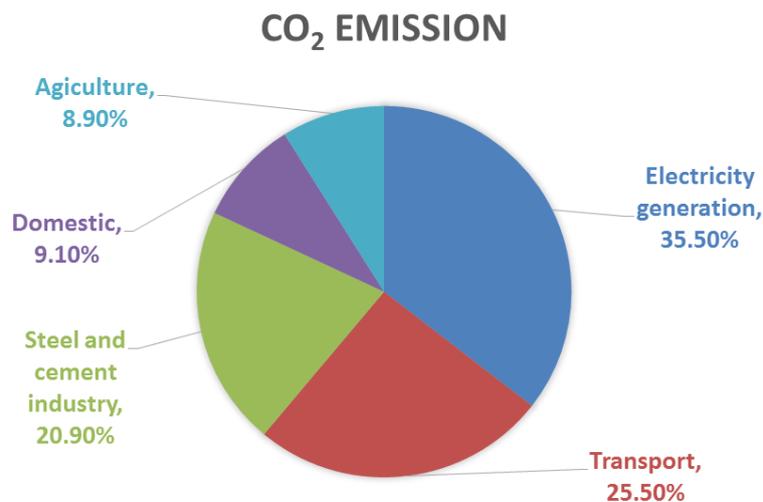


Figure 1. CO₂ emission scenario in India

2. Fuel cell hybrid vehicle powertrain

The below Figure 2 represents the general setup of a fuel cell hybrid electric vehicle power train with proposed converter topology [2], [3], [4] and [5]. Fuel cell is connected to the DC bus through a unidirectional converter and energy storage systems are connected to the DC bus through a bidirectional energy storage systems converter. A three phase inverter connects the traction motor to the DC bus. The traction motor is connected to the wheel through a differential. Thus when the motor rotates the vehicle moves.

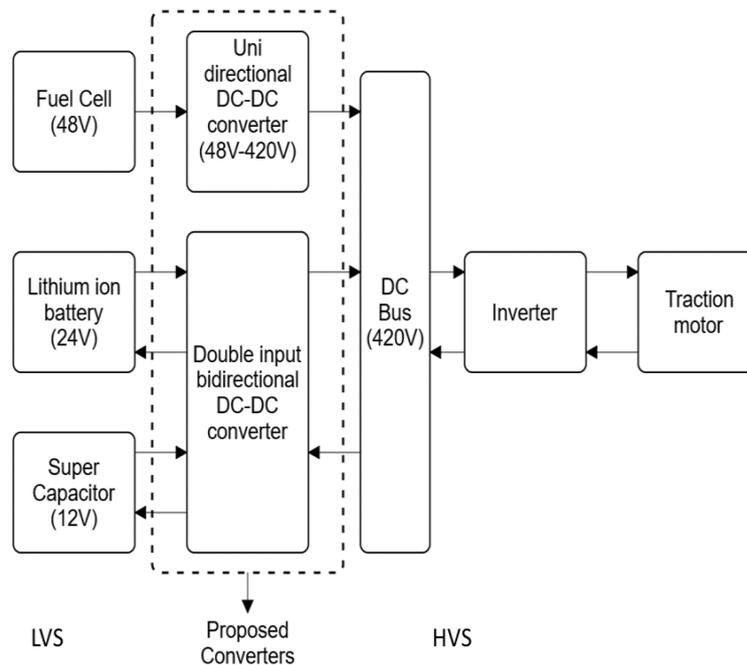


Figure 2. Powertrain structure of a fuel cell hybrid electric vehicle

3. Proposed converters

The operating modes, design and simulation of unidirectional fuel cell boost converter and bidirectional energy storage system converter are explained below

3.1. Unidirectional Fuel cell DC-DC converter

Output voltage of the fuel cell is 48 V and to connect it to 420 V DC it has to be stepped up, this job of stepping up the voltage from 48 V to 420 V is done by boost converter as show in the below Figure 3.

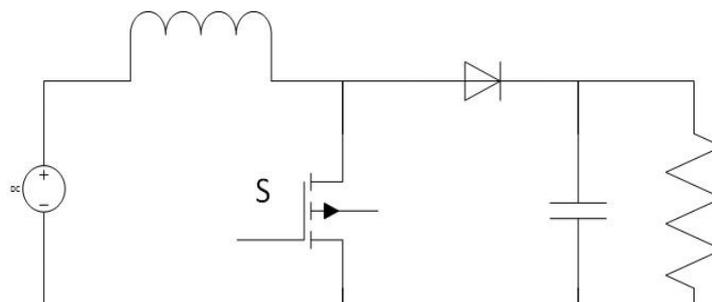


Figure 3. Unidirectional FC converter

3.1.1. Modes of operation

The unidirectional converter works in two modes as described below

Mode1: When switch is turned on as shown in Figure 4 the inductor is connected to the source and it starts to charge. Capacitor which was charged in the previous mode supplies power to the load.

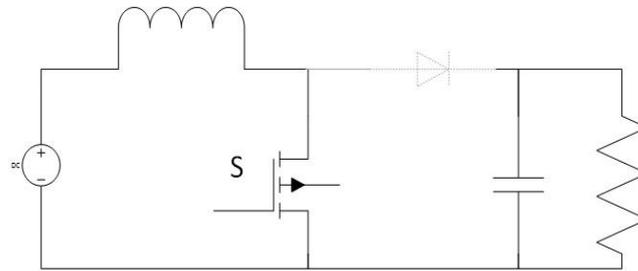


Figure 4. Mode1-Switch is turned on

Mode2: when switch is turned off as shown in Figure 5 inductor starts to discharge. Now source is connected to the load through the inductor.

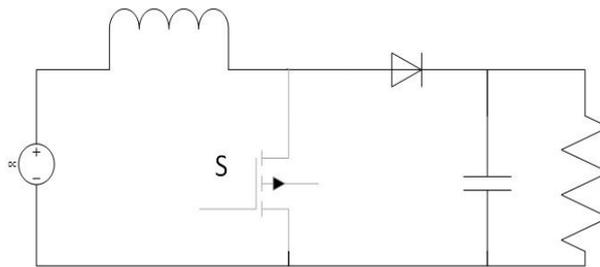


Figure 5. Mode2-Switch is turned off

3.1.2. Design of unidirectional converter

In this section the design procedure of the converter is explained. The design equations are presented to calculate the component ratings. V_s represents the source voltage, V_o represents the output voltage, f_s represents the switching frequency of the switches.

1. Duty cycle ratio (D) of the converter is given by

$$D = 1 - \frac{V_s}{V_o} \quad (1)$$

2. The value of the boost inductor, L is given by

$$L = \frac{V_s D}{\Delta i f_s} \quad (2)$$

Where Δi represents the peak to value of ripple in the inductor current and it is assumed as 10% of the inductor current

3. The value of the capacitor, C is given by

$$C = \frac{V_o D}{R f_s \Delta V} \quad (3)$$

Where ΔV represents the ripple in the output it is taken as 1% of the output voltage

3.1.3. Specification:

Table 1 represent the ratings of component and Table 2 represents the converter rating

Table 1. Components ratings

| S.No | Component specifications | Value |
|------|--------------------------|-----------|
| 1 | Input capacitor | 10 uF |
| 2 | Inductor | 156.75 uH |
| 3 | Output Capacitor | 6.526 uF |

Table 2. Converter ratings

| S. No | Converter specifications | Value |
|-------|--------------------------|----------------|
| 1 | Fuel cell voltage | 48 V |
| 2 | Output voltage | 420 V |
| 3 | Switching frequency | 100 kHz |
| 4 | Duty cycle | 0.88 |
| 5 | Load resistance | 135.6 Ω |

3.1.4. Model developed in PSIM:

The circuit model developed in PSIM is shown in Figure 6

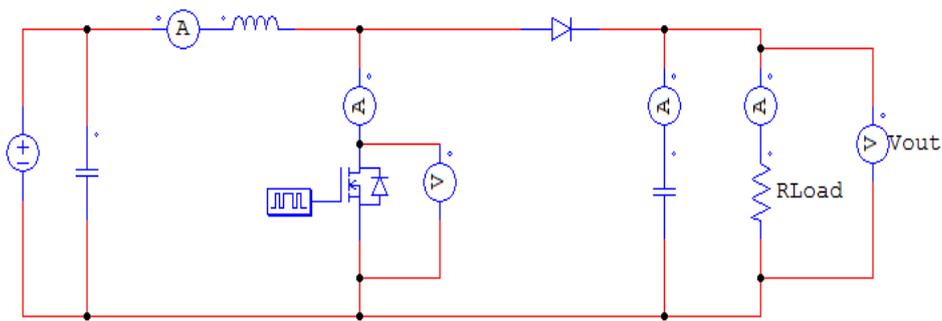


Figure 6: Simulation circuit model of unidirectional FC converter developed in PSIM

3.1.5. Simulation result:

Switching pulse pattern, Inductor current, Output current, Output voltage, Capacitor current waveforms of developed unidirectional converter are shown in the Figure 7

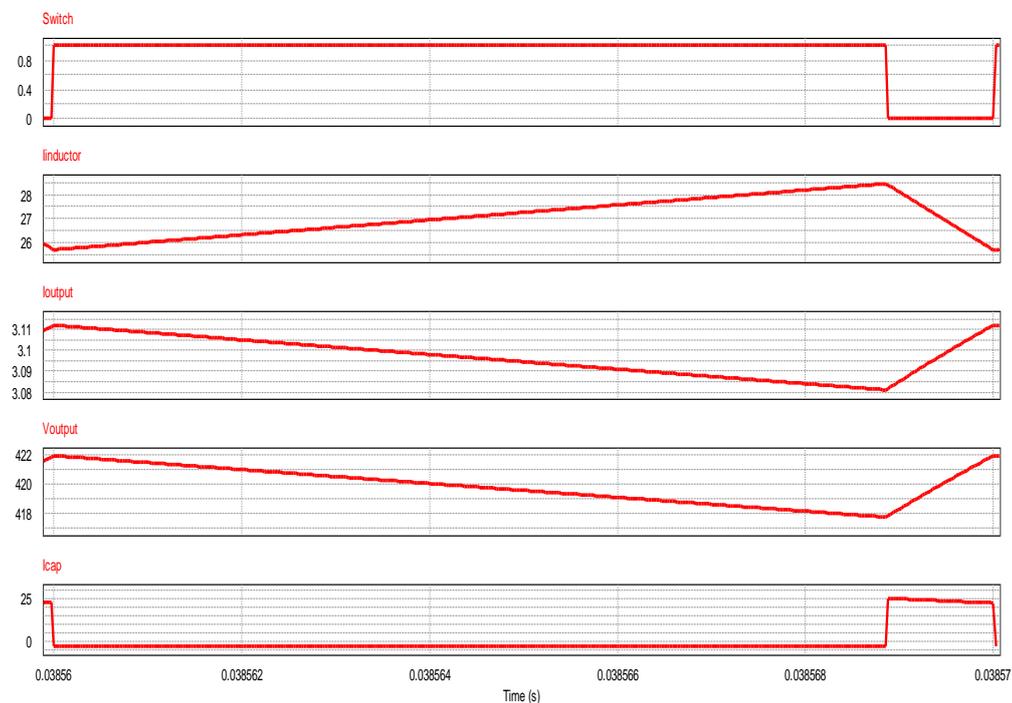


Figure 7. Switching pulse pattern, Inductor current, output current, output voltage and capacitor current of the unidirectional FC converter

3.2. Bidirectional Energy storage system (ESS) DC-DC converter:

Bidirectional DC-DC converter consists of two full-bridges on the low voltage side of the high frequency transformers and two half bridge doubler's on the high voltage side of the high frequency transformers as shown in Figure 8. The energy storage elements like batteries and super-capacitors are connected at each low voltage side of the high frequency transformer and a traction motor can be connected to high voltage side through a dc-ac inverter. In the proposed bidirectional ESS converter individual power sources are connected to the dc bus by means of a bi-directional boost/buck dc-dc converter. In boost mode the bidirectional converter energy is transferred from the power source to the dc bus. In buck mode the energy obtained during regenerative braking is used to charge the battery and the super capacitor.

The selected bidirectional converter topology gives u an option to connect power sources at different voltage levels to the DC bus. When a fuel cell electric vehicle is starting or accelerating, the bidirectional converter works in boost mode and keep the DC bus voltage at desired value, and power flows from the battery or super capacitor source to the traction motor load. When the vehicle is in regenerative braking mode, the bidirectional converter works in buck mode to charge the energy storage elements, and power flows from motor to the battery and super capacitor source [6], [7], [8] and [9].

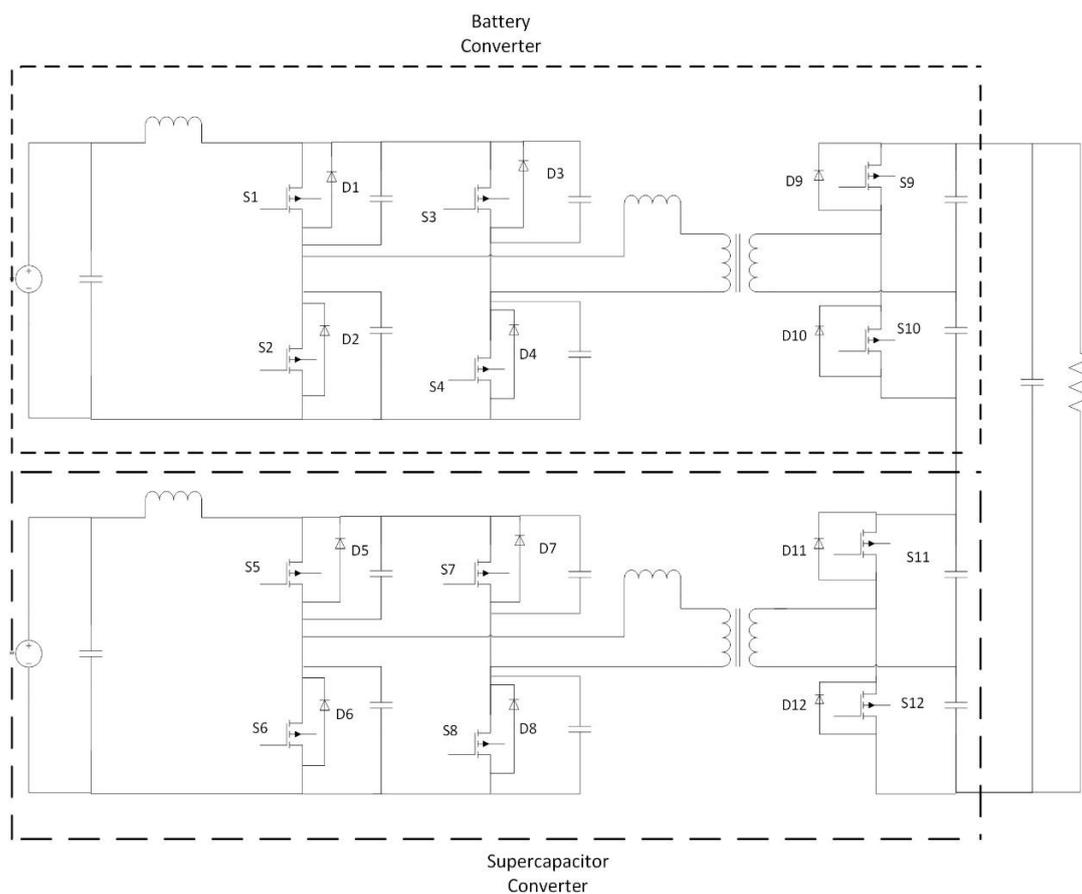


Figure 8. Bidirectional ESS converter

3.2.1 Boost mode of operation of the bidirectional converter:

Working of the super capacitor converter is explained for a cycle after which the waveforms are repetitive in nature. Working of the battery converter is similar to that of the super capacitor converter.

Model: As shown in Figure 9 switches S_5 , S_6 , S_7 , S_8 and body diode D_{12} are turned on. As all the four switches are turned on the boost inductor starts to get charged. Leakage inductor of the transformer also starts to get charged. Negative of the transformer leakage inductance voltage appears across the transformer primary. Transformed power at the transformer secondary is rectified and doubled by the diode D_{12} and doubler circuit capacitors and it is given to the load.

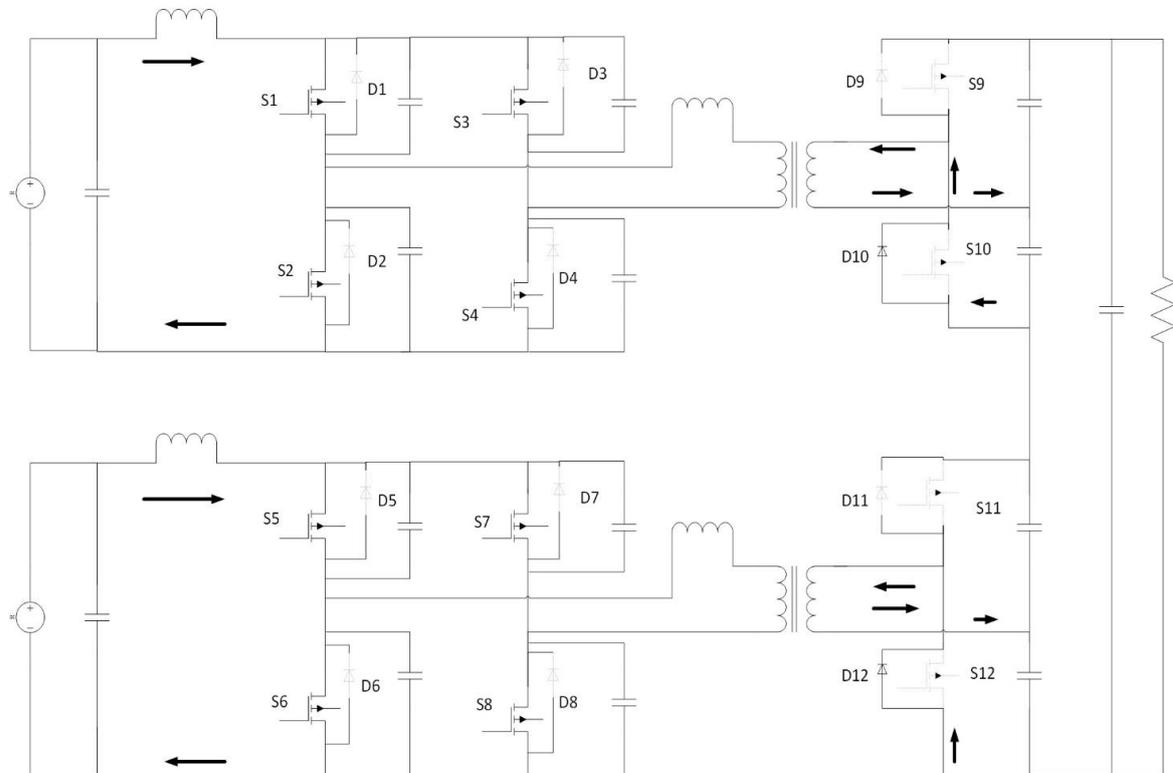


Figure 9. Mode 1 circuit diagram

Mode2: As shown in Figure 10 Switches S_5 , S_6 , S_7 , S_8 and S_{12} are turned on. As all the four switches are turned the boost inductor charging process continues. During the end of this time period the boost inductor gets fully charged. Negative of the transformer leakage inductance voltage appears across the transformer primary. Transformed power at the transformer secondary is rectified and doubled by the diode S_{12} and doubler circuit capacitors and it is given to the load.

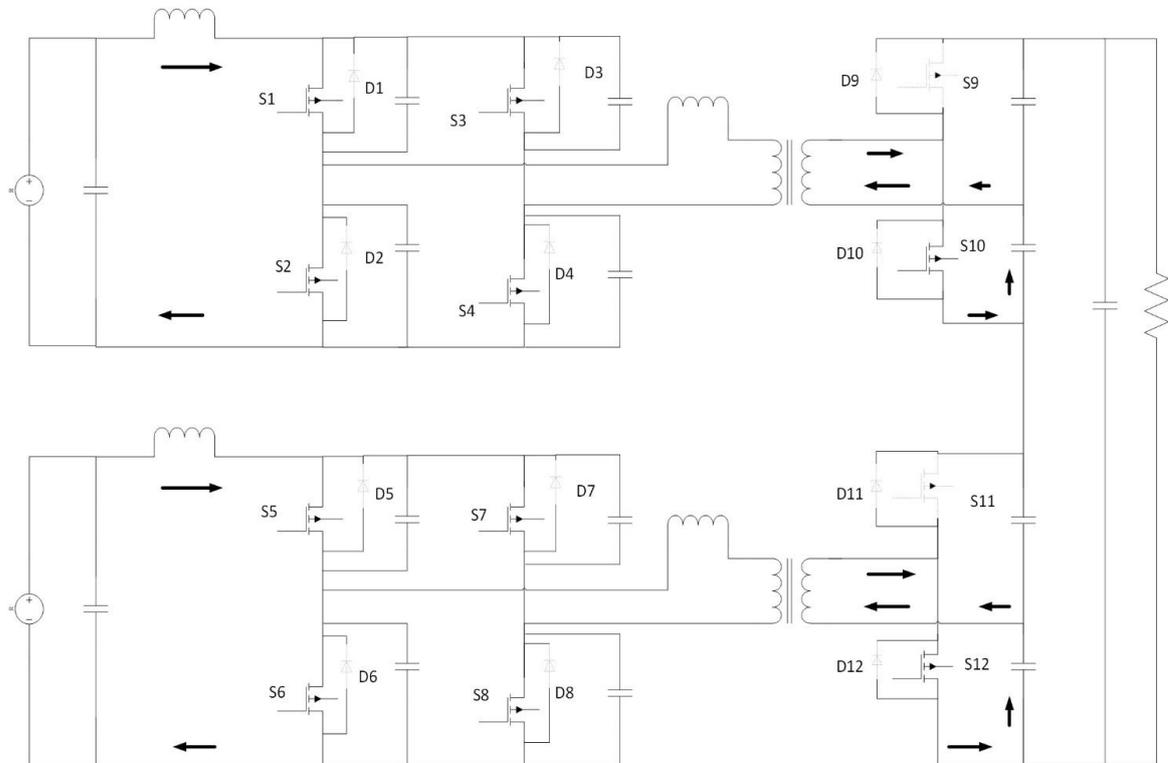


Figure 10.Mode 2 circuit diagram

Mode3: As shown in Figure 11 Switches S_5 , S_8 and body diode D_{11} are turned on during this period. As switches S_5 and S_8 are conducting and boosted input voltage appears across the transformer primary. The charged boost inductor starts discharging. The leakage inductance of transformer discharges at very slow rate. Transformed power at the transformer secondary is rectified and doubled by the diode D_{11} and doubler circuit capacitors and it is given to the load.

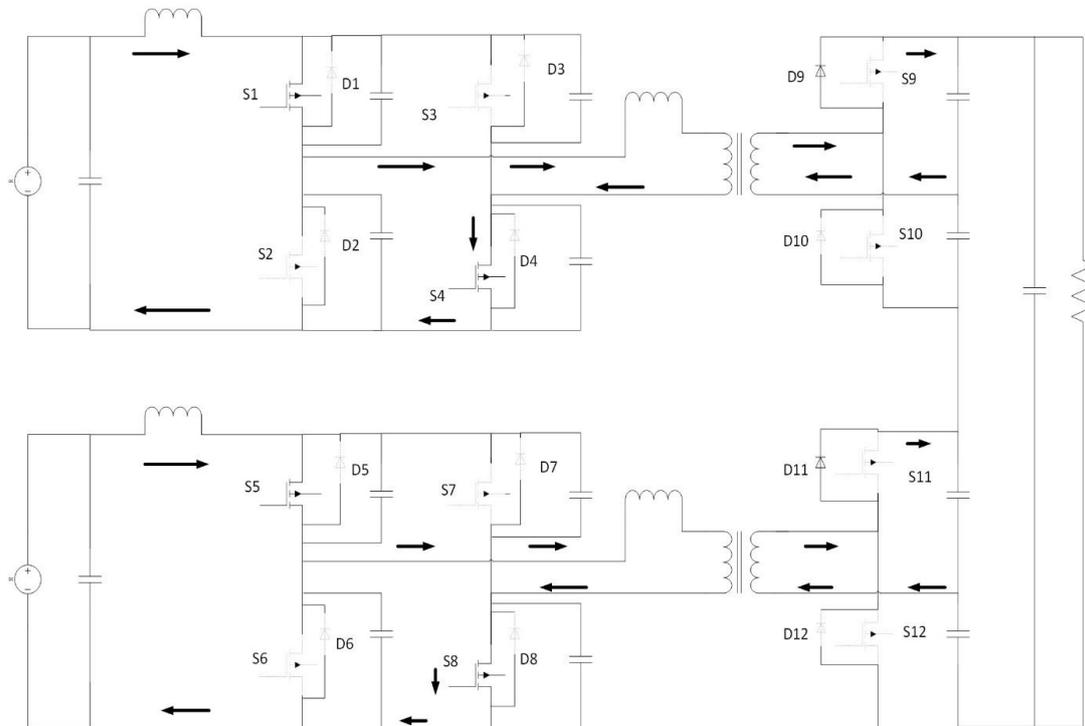


Figure 11. Mode 3 circuit diagram

Mode4: As shown in Figure 12 Switches S_5 , S_6 , S_7 , S_8 and body diode D_{11} are turned on during this time period. As all the four switches are turned the boost inductor starts charging. Current through the leakage inductance starts to fall. Negative of the transformer leakage inductance voltage appears across the transformer primary. Transformed power at the transformer secondary is rectified and doubled by the diode D_{11} and doubler circuit capacitors and it is given to the load.

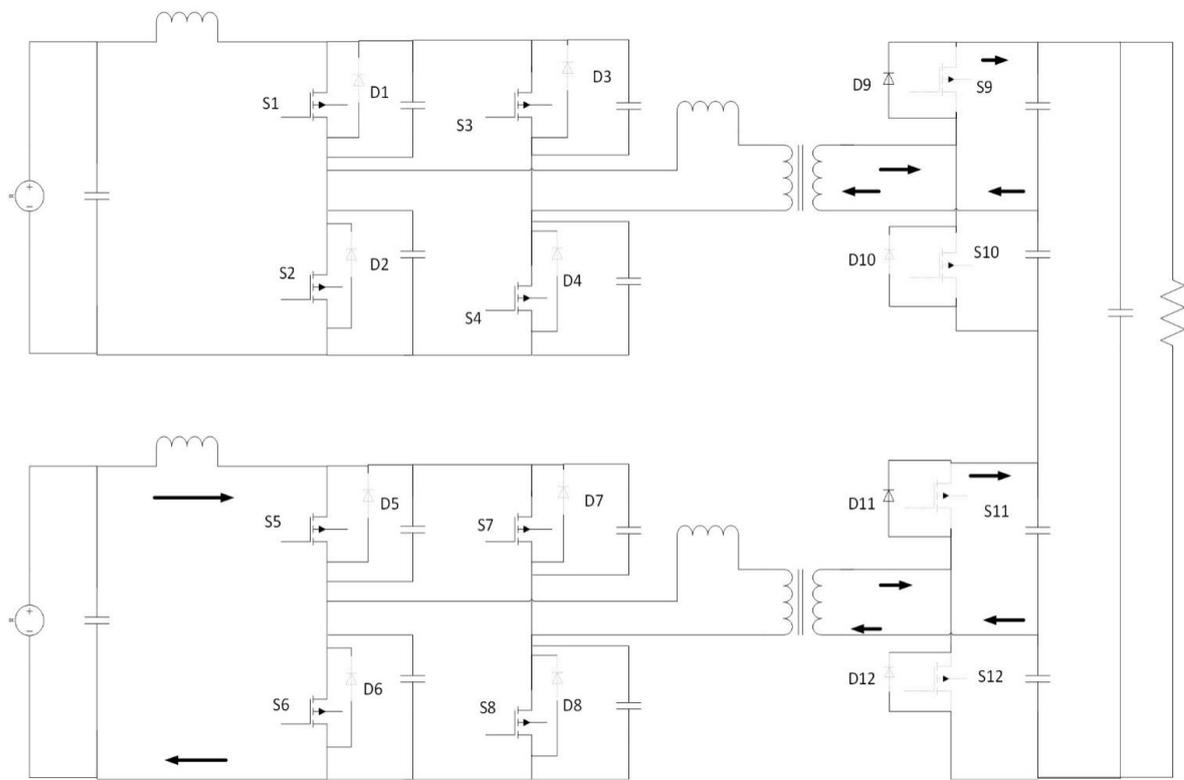


Figure 12. Mode 4 circuit diagram

Mode5: As shown in Figure 13 Switches S_5 , S_6 , S_7 , S_8 and S_{11} are turned on. As all the four switches are turned the boost inductor charging process continues. During the end of this time period the boost inductor gets fully charged. Negative of the transformer leakage inductance voltage appears across the transformer primary. Transformed power at the transformer secondary is rectified and doubled by the diode S_{11} and doubler circuit capacitors and it is given to the load.

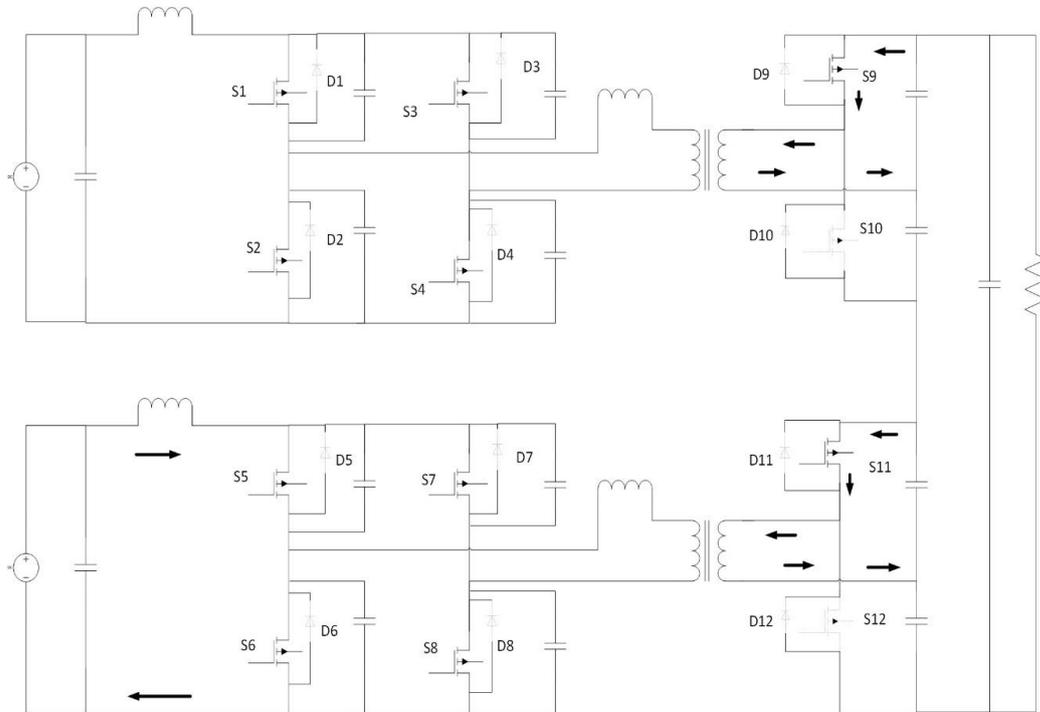


Figure 13. Mode 5 circuit diagram

Mode6: As shown in Figure 14 Switches S_6 , S_7 and body diode D_{12} are turned on. As switches S_6 and S_7 are conducting the voltage across the primary of the transformer is negative. The charged boost inductor starts to discharge. The leakage inductance of transformer discharges at very slow rate. Transformed power at the transformer secondary is rectified and doubled by the diode D_{12} and doubler circuit capacitors and it is given to the load.

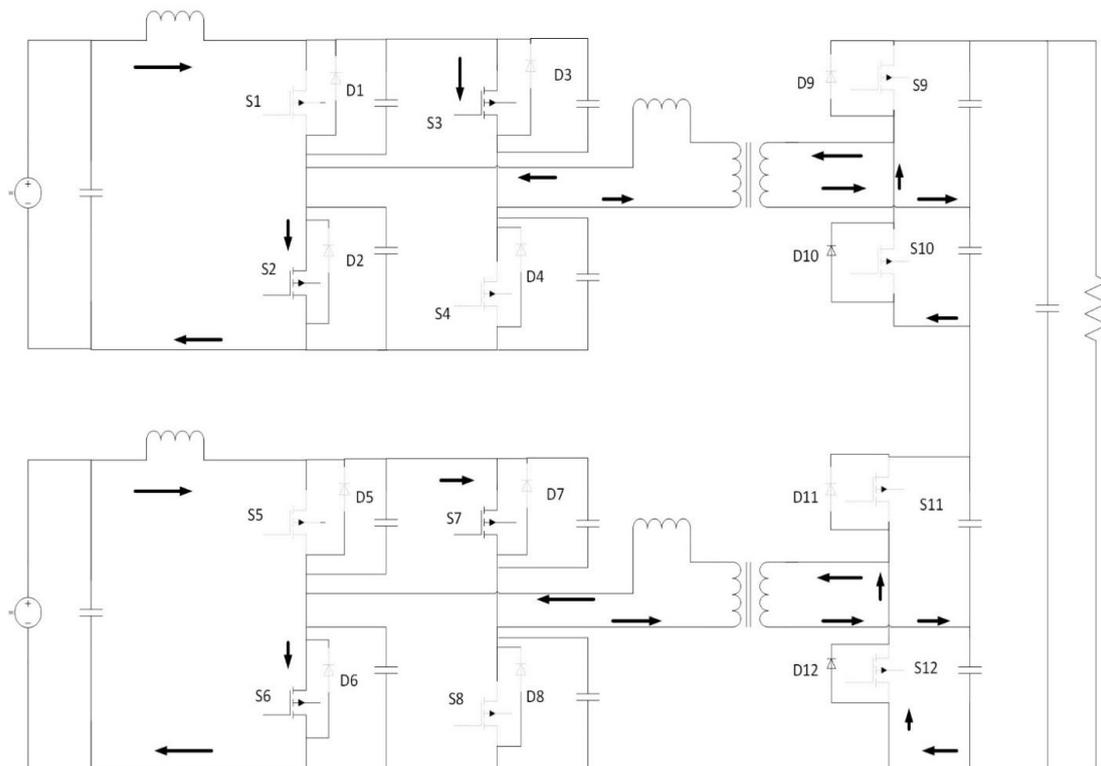


Figure 14. Mode 6 circuit diagram

By suitably adjusting the firing pulses to the switches bidirectional power flow can be achieved. The main advantages of using a current fed converter when compared with voltage fed converter is that current fed.

3.2.2. Design of the converter:

In this section the design procedure of the converter is explained. The design equations are presented to calculate the component ratings. V_s represents the source voltage V_o represents the output voltage, f_s represents the switching frequency of the mosfet switches.

1. Overlap period (d_c) represents the period during which all four switches are turned on. D represents the duty at which the switches are triggered.

$$d_c = d - 0.5 \quad (4)$$

2. The value of the boost inductor L is given by

$$L = \frac{V_s d c}{\Delta I f_s} \quad (5)$$

Where ΔI represents the peak to value of ripple in the inductor current and it is assumed as 10% of the inductor current

3. The value of the voltage doubler capacitance is given by

$$C = \frac{I_{load} * t}{\Delta V} \quad (6)$$

Where ΔV represents the ripple in the output it is taken as 1% of the output voltage

3.2.3. Specifications:

Table 3 represents the ratings of the components used in battery converter, Table 4 represents the ratings of the components used in super capacitor converter and Table 5 represents the overall rating of the converter.

Table 3. Component ratings of the battery converter

| S.No | Components specification | Value |
|------|--------------------------------|----------|
| 1 | Input capacitor | 10 mF |
| 2 | Boost inductor | 21.48 uH |
| 3 | Transformer leakage inductance | 1.5 uH |
| 4 | Transformer turn ratio | 1:2 |
| 5 | Doubler capacitance | 10 uF |
| 6 | Output capacitance | 5 uF |

Table 4. Component ratings of the SC converter

| S.No | Component specification | Value |
|------|--------------------------------|---------|
| 1 | Input capacitor | 10 mF |
| 2 | Boost inductor | 6.66 uH |
| 3 | Transformer leakage inductance | 1.5 uH |
| 4 | Transformer turn ratio | 1:2 |
| 5 | Doubler capacitance | 10 uF |
| 6 | Output capacitance | 5 uF |

Table 5. Overall converter ratings.

| S.No | Converter specifications | Value |
|------|---|----------------|
| 1 | Battery voltage | 24 V |
| 2 | Super capacitor voltage | 12 V |
| 3 | Output voltage | 420 V |
| 4 | Output power | 1300 W |
| 5 | Switching frequency | 100 kHz |
| 6 | Load resistance | 135.6 Ω |
| 7 | Duty ratio of battery converter | 0.741 |
| 8 | Duty ratio of super capacitor converter | 0.8 |

3.2.4. Model developed in PSIM:

Figure 15 represents the bidirectional converter model developed in PSIM

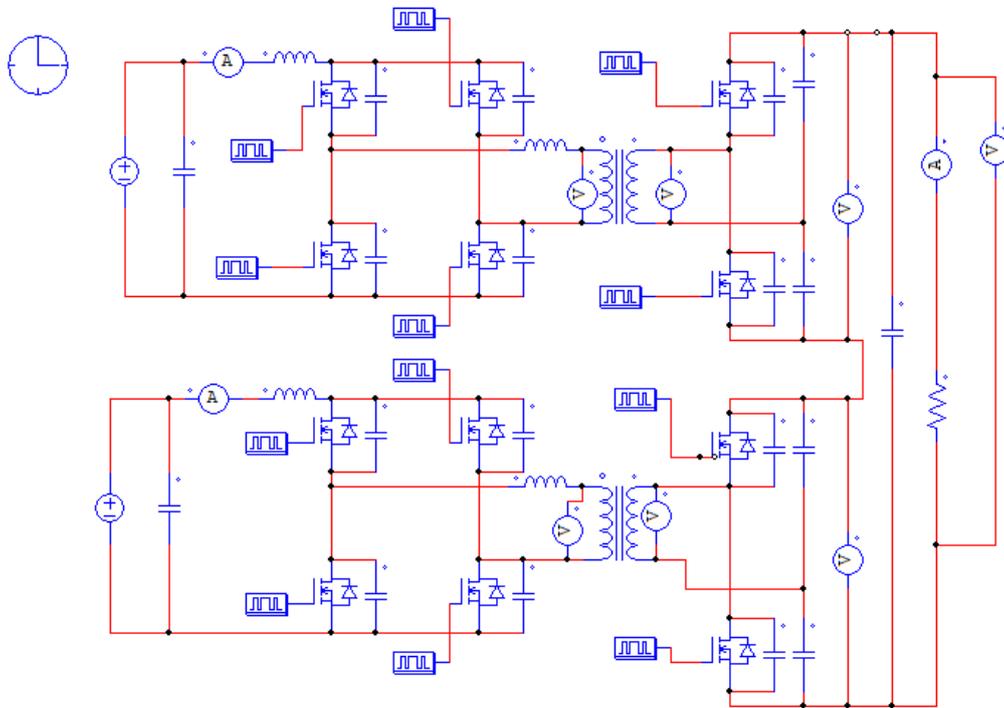


Figure 15. Circuit model of bidirectional converter developed in PSIM

3.2.5. Simulation results:

The below section explains the simulation results of the bidirectional converter

3.2.5.1. Super capacitor converter:

The below Figure 16 represents the switching pulse pattern for switches ($S_5, S_6, S_7, S_8, S_{11}, S_{12}$), primary voltage of the transformer, boost inductor current and transformer leakage inductor current Lithium ion battery converter:

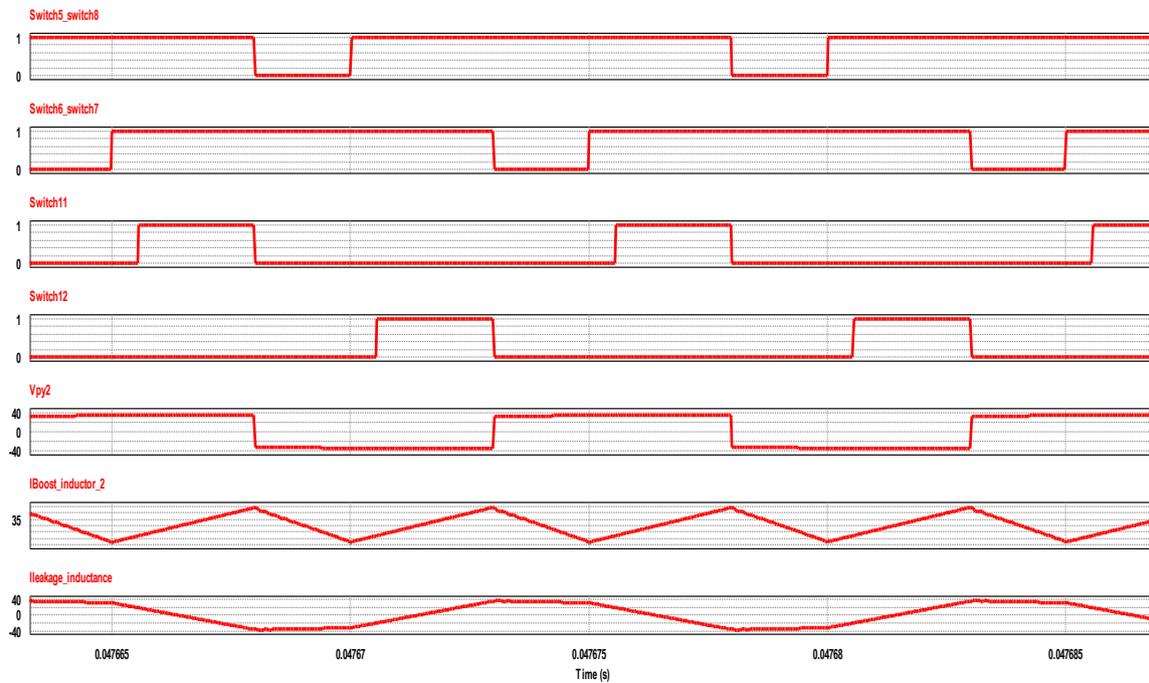


Figure 16. Switching pattern, Primary voltage, boost inductor current and leakage inductor current of super capacitor converter

The below Figure 17 represents the switching pulse pattern of the switches ($S_1, S_2, S_3, S_4, S_9, S_{10}$), primary voltage of the transformer, boost inductor current and transformer leakage inductor current.

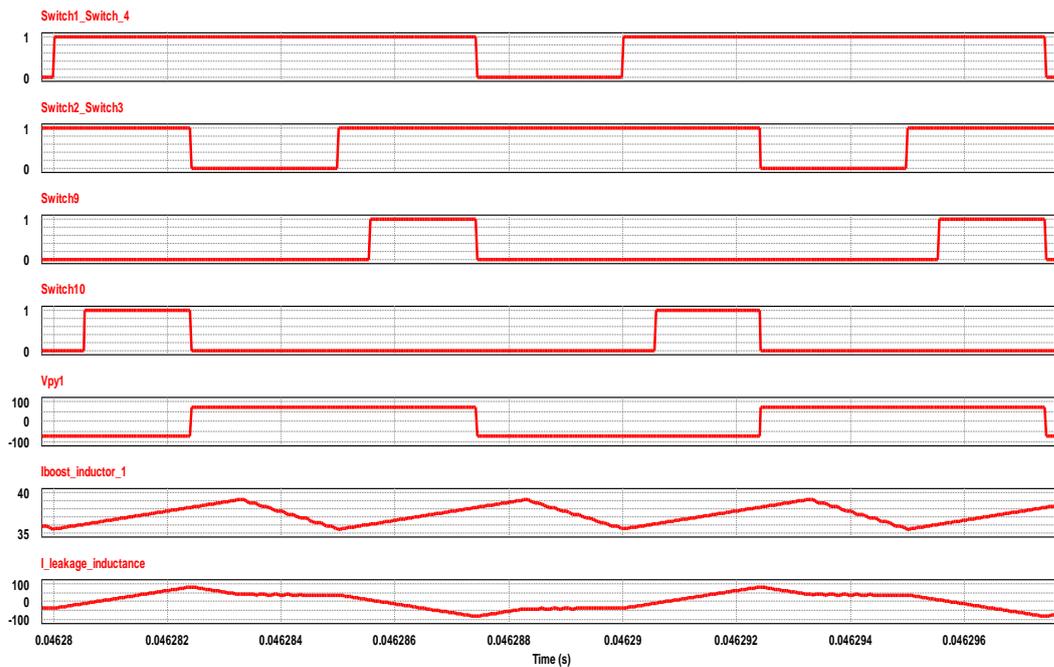


Figure 17. Switching pattern, Primary voltage, boost inductor current and leakage inductor current of super capacitor converter

Figure 18 represents the output voltage and current waveforms of the bidirectional converter.

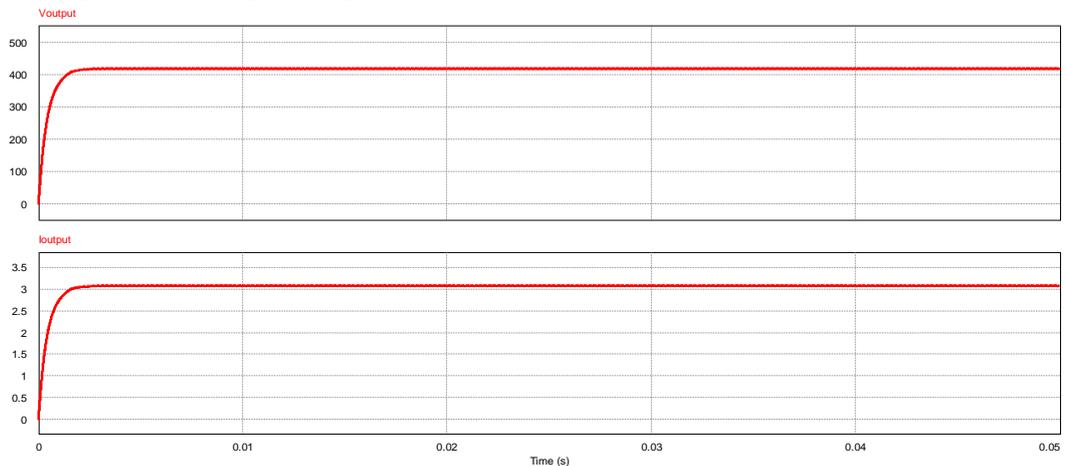


Figure 18. Output voltage and current waveforms of bidirectional converter

4. Control Strategy

Control strategy is designed with a main aim of reducing the hydrogen consumption. Fuel cell is operated in two set points one is ON and another point is OFF. These operating points are discussed below.

- When $SOC_K < SOC_{initial}$, then FC is turned ON and it caters the load and also charges the battery and super capacitor.
- When $SOC_K > SOC_{initial}$, Then FC is turned OFF and energy storage systems supplies the required load power.

SOC_K represents the present/actual SOC of the energy storage system and $SOC_{initial}$ represents the initial SOC of the energy storage system [10]

5. Conclusion

Thus the proposed unidirectional FC converter and bidirectional energy storage converters are modeled, designed and simulated. The main advantage of the proposed bidirectional converter is that power flow from the individual energy storage sources can be individually and independently controlled, the converter has high boost ratio and can be used for high current applications, Input current ripple is low, low voltage sources can be connected and they are isolated from the high voltage side.

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