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A New Multi-Input Fed Bidirectional Converter with Independent Power Flow Control

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Abstract

Increased rate of CO_2 emission has paved the way for renewable energy sources. The electrical energy produced by solar PV arrays can be stored in battery and ultra-capacitor and they act as auxiliary sources. In this paper operation of PV-based multiple input bidirectional DC- DC converters for grid tied application is presented. There is a possibility to add more sources to reduce complexity with simple circuit change. The simple dc-dc buck-boost converter is used to charge and discharge the battery and ultra-capacitor with duty ratio control. MATLAB/simulink is used to simulate the different modes of operation and the results are presented.

*Index Terms—**solar panel, battery and ultra-capacitor, grid, Bidirectional dc-dc converter***

INTRODUCTION

Renewable energy sources play an important role to produce the electrical energy to fulfill the demand of energy needs without affecting the environment. Unlike non-renewable energy sources renewable energy sources are nature friendly and they will not pollute the environment. Solar and wind are the prime energy sources. Solar is the ultimate energy source which can easily available to produce maximum energy according to needs. Energy produced by solar PV system will be in the form of DC voltage and current, we use different types of DC-DC converters to buck or boost the voltage according to our needs. The novel method of integrating multiple input dc-dc bidirectional converters for HEV application is discussed for different energy transfer modes [1]. The Solar power generation works on the photoelectric effect, when solar rays fall on the panel are converted into electrical energy [2]. A PV model basically is a dc power source which cannot be supplied directly to the load. The raw electrical power generated by PV panel can be converted to suitable working power by using converters. The generation of power depends on different parameters like temperature and irradiance. Modeling of PV array and how it depends on these parameters is presented in [3]. Maximum power point tracking is the method to absorb maximum power at different solar irradiations and temperature. There are so many techniques used in the MPPT to absorb maximum power. The very basic algorithm in the MPPT is Perturb and Observe technique (P&O) it works with fixed step size. By increasing or decreasing the maximum power because of the oscillations occur during partial shading on the panel.To overcome the partial shading effect the particle swarm optimization (PSO) method is compared with P&O method [4]. Comparative study of P&O and Genetic algorithm (GA) based MPPT is carried out [5]. GA based technique works for optimal solution for PV generation and it traces global maxima and minima by PV curve. An incremental conductance algorithm is discussed in [6] is the efficient and widely used technique in MPPT for solar application. This technique is used in this paper to extract maximum power from PV array. Maximum power point can be determined by checking the condition dP/dV=0. To satisfy this, the ratio of current and voltage is negative that of ratio of differential values of current and voltage as given below.

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Energy storage devices like battery and ultra-capacitor are very essential to store the energy during peak generation and utilizing the same during peak load. There are so many types in batteries: i) Lead–Acid Batteries ii) Nickel–Metal Hydride (NiMH) Batteries iii) Nickel–Zinc (Ni–Zn) Batteries iv) Nickel–Cadmium (Ni–Cd) Batteries v) Lithium-Ion Batteries. Ultra-capacitors used in optional with batteries because of their high power density to give better performance, [7] gives the detailed analysis of the characteristics of these different types of batteries and ultra-capacitor. Almost all batteries having a higher energy density lower power density but ultra-capacitors having higher power density lower energy density therefore by using combination of these two storage devices we can achieve high power and energy density which gives better performance. The ratings of battery and ultra-capacitor for their volume, size and lifetime in FCV application are compared [8]. This paper uses Lithium-Ion battery for its better performance.

Different types of topologies are used in multiple inputs Bidirectional DC-DC converters based on different control methods, number of ports, voltage level, isolation or non-isolation, number of switches and independent control of power flow. By using common high frequency transformer multiple sources are interfaced; for three sources 12 switches are utilized full bridge cell is used to connect each source and both duty ratio and phase shift control is used to control the switches is explained in [9]. Same topology using half bridge circuit, number of switches and capacitors reduced to half is implemented in [10]. A current fed half bridge topology to minimize the ripple current in the battery is proposed with phase shift modulation in [1]. Stability analysis of a multiple input isolated buck-boost and forward converters is presented in [2]. Isolation gives more flexibility and proper safety in choosing voltage levels and power sharing among the sources is difficult to control in these types of converters. To interface multiple dc sources multiple bidirectional boost converters are interfaced across each other and its output given to the inverter through dc link is given in [3]-[7]. Z-source converter is used to achieve same functionality in [18]. In proposed converter number of switches used are 6 with wide voltage range, duty ratio controlled with independent power flow. The topology used is buck-boost without isolation.

The voltage generated by solar panel is dc voltage and is maintained constant at dc link which is converted to three phase ac voltage by inverter; this can be done by three phase inverter. The single phase full bridge inverter configuration for photovoltaic system application with perturb and observe is explained in [9]. The detailed technical study of grid tied PV inverter including solar panel, mppt, dc-dc converter, inverter and grid using PSCAD is discussed in this paper DC to AC conversion is obtained by voltage source inverter to get the desired output.

WORKING ANALYSIS

The proposed topology consists of a solar PV panel with MPPT control system which produces the electrical energy that is supplied to grid by using the three phase inverter.

Block diagram is shown in fig.1. During peak power generation the generated voltage is greater at maximum insolation, then energy will be utilized to charge the battery and ultra-capacitor. In that condition converter operates in buck mode. These auxiliary sources discharge to dc link, during low power generation by PV modules at less insolation to supply the grid by operating converter in boost mode. Different types of energy transfer modes of converter are discussed in the following section.

PV PANEL:

An electrical equivalent circuit of solar cell modeled in matlab is shown in fig. 2. It consists of a photovoltaic current source with an anti-parallel diode, when cells are exposed to light the dc current will be generated which varies linearly with the irradiance. The current in the diode is responsible for producing the non-linear characteristics of current and voltage in the PV cell [3].

The specifications of solar panel used to generate power of 25kW are given in table 1.

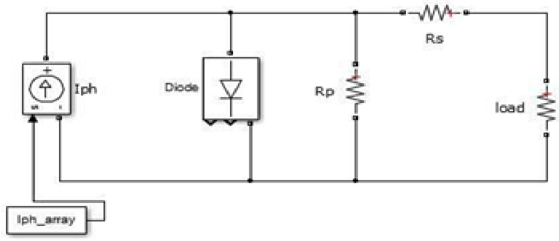

Fig.2. Matlab equivalent circuit of solar cell

The output power of the solar panel is mainly depends on the functions of voltage and current (V-I) characteristics. At certain point in the I-V curve the power is maximum that is called maximum power point. For the solar panel used in simulation I-V and P-V curve for irradiance 1000W/m ^{2} and temperature at 25^{0}C is shown in fig. 3.

Table 1
Sun Power SPR-305-WHT specifications

no		
1	Peak Power (P_{max})	305W
2	Rated Voltage (V_{mp})	54.7V
3	Rated Current (I_{mp})	5.58A
4	Open circuit voltage (V_{oc})	64.2V
5	Short circuit current (I_{sc})	5.96A
6	Series resistance (R_s)	0.0038 E
7	Parallel resistance (R_p)	993.5 E
8	Diode saturation current (I_{sat})	$3.194*10^{-8}$A
9	Photovoltaic current (I_{ph})	5.9602A
10	No. of cells per module	96

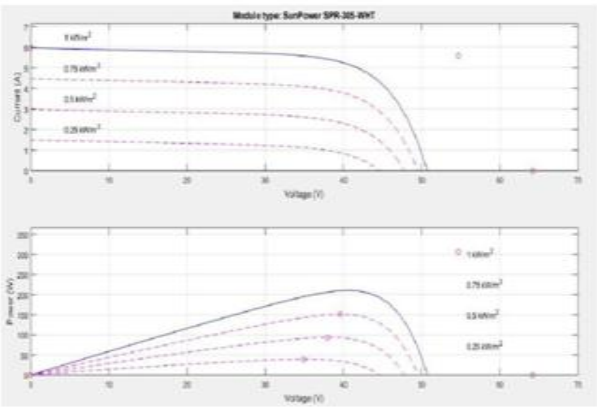

Fig.3. I-V and P-V curve for solar panel

POWER TRANSFER MODES OF CONVERTER
MODE 1: DC LINK AND BATTERY

This operating mode explains, battery energy is supplied to load through dc link. The switches S_2 and S_3 are turned on for the first interval (T_1), voltage of battery V_{bt} arrives across inductor L_1 which raises the current in it with slope of V_{bt} / $L_{1.}$ In the second interval (T_2) these two switches turned off and current (i_{L1}) will flow through the diodes D_1 and D_4 to the DC link by discharging the energy stored in the inductor with a slope of V_{dc} / $L_{1.}$ As the voltage drop across diode is more the current flowing through it results in drop of 1-1.2 V in each. For the duration of third time interval (T_3) S_1 and S_4 are turned on to flow current continuously from inductor to DC link, this results in a less voltage drop about 0.2 V switches are made to operate as synchronous rectifiers, which improves the efficiency of system [7].

In steady state condition the relationship between two voltages in the form of duty ratio .Where D is the duty ratio given by $T_1/T_{s.}$ T_s is the total time period. There are two conditions in this mode of operation. First is, if voltage of the battery is smaller than the voltage across dc link, the converter operates in boost mode and boosts the battery voltage to dc link voltage at the operating duty ratio D > 0.5. If battery voltage is greater than dc link voltage by operating at D < 0.5 converter charges battery from the dc link voltage. The principal of energy transfer is remains same in this operation as explained above. In interval (T_1) energy will store in inductor L_1, in intervals T_2 and T_3 it is used to charge battery.

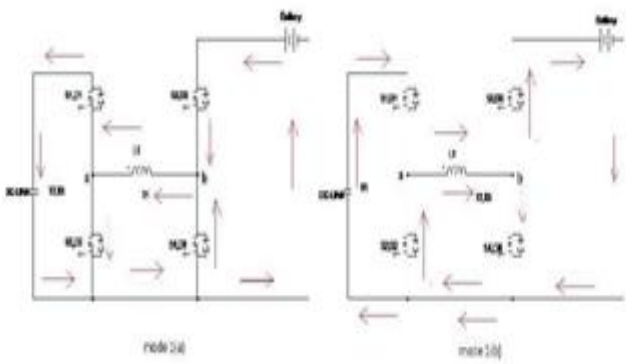

Fig.4. Battery and dc-link

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MODE 2: DC LINK AND ULTRACAPACITOR

In this mode of operation, energy transfer takes place between the dc link and ultra-capacitor to supply the load. It is similar to that of first mode explained above; switches S_5 and S_2 are turned on during interval T_1 to store energy in inductor L_2. During interval T_2 switches are turned off, and then inductor discharges to dc link through diodes D_6 and D_1. To minimize drop across diodes during interval T_3 switches S_1 and S_6 are turned on and they act as synchronous rectifiers. The relationship between voltages V_{dc} and V_{uc} .charge ultra-capacitor from dc link the switches S_1 and S_6 are turned on first to charge the inductor during T_1 then it is discharges to charge the ultra-capacitor during intervals T_2 and T $_3$ by turning on switches S_2 and S_5.

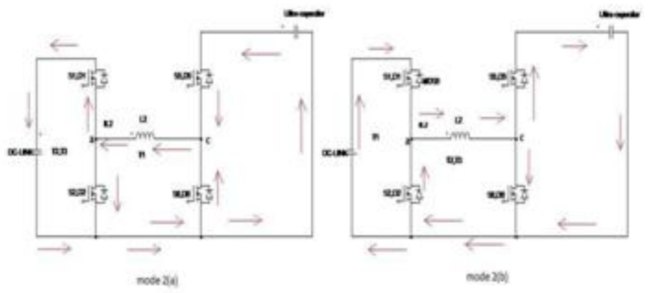

Fig.5. Ultra-capacitor and dc link

MODE 3: ULTRACAPACITOR AND BATTERY

This mode explains the transfer of energy from battery to ultra-capacitor and vice versa. While charging the ultra-capacitor from battery in interval T_1 switches S_3 and S_6 are turned on then the energy is stored in both inductors L_1 and L_2. During the interval T_2 switch S_6 is closed and inductor currents take path through diode D_5, in interval T_3 switch S_5 is turned on to reduce voltage drop across diode and gives path to the currents. While charging the ultra-capacitor, the converter can be operated in any one of three modes i.e. buck, boost or buck-boost mode. If the ripple current in the battery is lesser as compared to explained in the mode 1 and 2 then only boost mode of operation is used, this improves the life time of the battery by decreasing the maximum value of charging and discharging current. If the ultra-capacitor voltage is smaller than the battery voltage, it is operated in buck mode, and if its voltage increases above the value of battery voltage then the controller needs to operate in boost mode. Buck-boost mode also can be implemented by changing the value of duty ratio. The voltage relation between battery and ultra-capacitor is given below to boost the ultra-capacitor from battery.

If V_{at} is less than V_{ic} then only energy can be transferred in this mode, if this condition is not met, then different operating modes boost or buck-boost can be used to control the switches without changing the circuit [2]

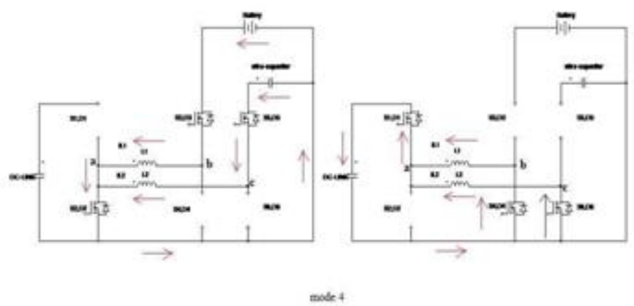

Fig.6. Battery and ultra-capacitor

MODE 4: BATTERY AND ULTRACAPACITOR TO DC LINK

In the peak time, load demands maximum power that will be provided by battery and ultra-capacitor. This mode of operation takes place in the less irradiance from solar. Switching cycle T_s is divided into five intervals. Switches S_1 and S_6 are triggered by identical gate signals having duty ratio d_2 and complementary of these signals are given to switches S_2 and S_5. The gate signal of switch S_3 is synchronized with that of S_1 having duty ratio d_1 and switch S_4 is triggered complementary to S_3 with a dead time. During interval T_1 switches S_2, S_3 and S_5 are on that result in charging both the inductors to their corresponding values of sources battery and ultra-capacitor. The slopes of current are V_{bt}/L_1 and V_{uc}/L_2 respectively. At the end of this interval switch S_3 is turned off, providing freewheeling path to current i_{L1} through D_4, thi s is the interval T_2. During T_3 switch S_4 is turned on to red uce the drop across d iode, at the end of this interval switches S_2 and S_5 are turned off forcing current to flows through the diodes D_1 and D6, this is interval T_4. To reduce the drop across D_1 switch S1 is

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gated on during the interval T_5 to transfer the e nergy from inductors L_1 L_2 to dc link [9].

The relationship between three voltages V_{ic}, V_{at}, and Vic are given below under steady state condition

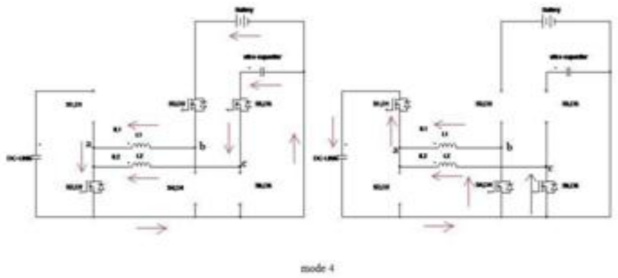

Fig.7. Battery and ultra-capacitor to dc link

MODE 6: DC LINK TO BOTH BATTERY AND ULTRACAPACITOR

In this mode the power transfer takes place from dc link to ultra-capacitor during maximum irradiance. The dc link voltage is much greater than what the battery and ultra-capacitor can draw, therefore remaining power is supplied to grid. The switching sequence for this mode of operation is given in table II. During the interval T_1 switches $S_{1,}$ S_3 and S_5 are turned on by transferring the energy to both the auxiliary sources from dc link. At the end of T_1, S_1 is turned off and freewheeling path will be provided to the inductor currents through D_2. In order to reduce drop across diode switch S_2 is turned on and function as synchronous rectifier in interval T_3. Charging of two auxiliary sources can be independently controlled by turning off switch S_3 and S_4 is turned on. The inductor current i_{L2} continues to charge the ultra-capacitor in this interval. At the end of the interval T_4 switches S_2 and S_4 are turned off. The currents in inductor flows to battery and ultra-capacitor through the switches S_1, S_5 and $D_{3.}$

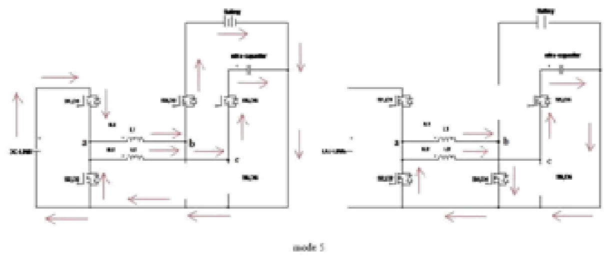

Fig.8. DC link to Battery and ultra-capacitor

Table 2
Switching of devices in different time intervals for Mode 5

	T_1	T_2	T_3	T_4	T_5
Mode 5	S_1 S_3 S_5	D_2 S_3 S_5	S_2 S_3 S_5	S_2 S_4 S_5	S_1 D_3 S_5

MODE 6: BATTERY/ULTRACAPACITOR AND DC LINK

In this proposed mode of operation pulses are generated for both charging and discharging of battery and ultra-capacitor. During maximum radiation time solar cells produce maximum power during this time interval converter operates in buck mode this is similar to mode 5 as explained and power is supplied to charge the battery and ultra-capacitor from the DC link. Whenever solar radiations are less the power generated by cells is also less therefore energy stored in the battery and ultra-capacitor discharges by boosting the voltage levels of both the auxiliary sources to DC link voltage as explained in mode 4 to supply the grid. The circuit operates in this mode is shown in below fig.7.

Matlab/simulink model of proposed topology as depicted in block diagram is shown in fig.8.

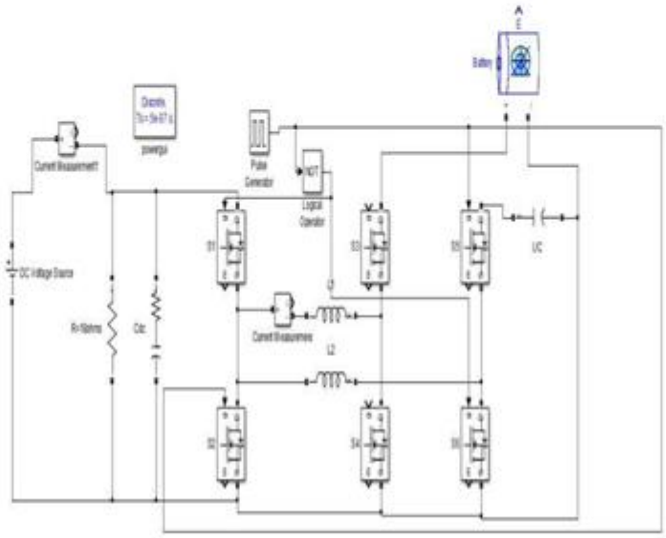

Fig.9. Matlab model for both charging and discharging of Battery and ultra-capacitor

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It consists of solar panel with mppt control generating 25kW power and is used to supply the grid. By using proposed converter we can charge and discharge the auxiliary sources (battery and ultra-capacitor).

These auxiliary sources draw the energy from dc link during charging period. During discharging period they supply the power to grid along with solar panel. The dc voltage maintained at dc link is 500V and is converted to three phase AC voltage by using three phase voltage source inverter.

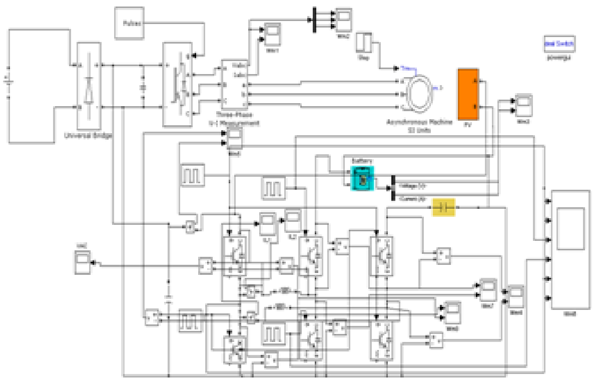

Fig.10. Matlab model of proposed topology

DESIGN OF THE CONVERTER

A lithium ion Battery bank of capacity 144-V 17-Ah, voltage varies from 120 to 150 V. Coupling this with ultra- capacitor rated 125 V and 15 F. A fixed 500V dc link is chosen as input to the voltage source inverter to supply the grid. DC link capacitor is 3mF and inductors are 0.75mH each. For switching frequency of 20 kHz the inductors values are designed to limit the ripple in the current to a specific amount.

SIMULATION

SIMULATIONAL RESULTS

Simulations are carried out using MATLAB/simulink to obtain the results of different power transferring modes. In mode 1 energy transfer between battery and DC link is explained. The DC link voltage of 500V appears across inductor L_1 and is being bucked to battery voltage level (Nominal value is 144V) to charge the battery. The SOC of battery under charging condition and voltage, current waveforms are explained in modes [10].

Mat lab results:

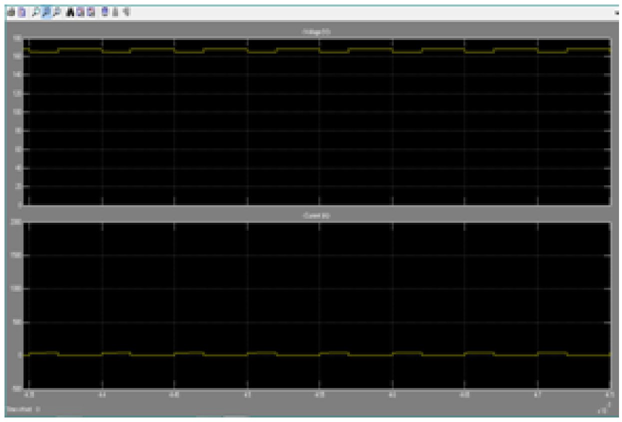

Fig. 11 Results for operation in mode D: (a) Current flowing from the battery, *iBt* and current flowing into dc link, *i*dc.

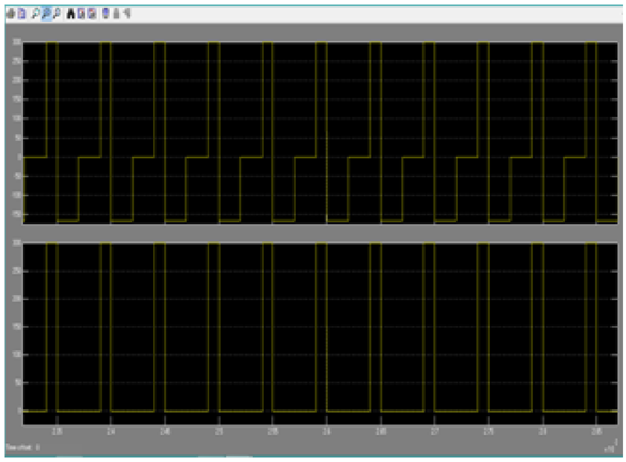

Fig.12 Steady-state results for operation in mode E: a) voltage across inductor, *VAC*, b) voltage across battery Vcb.

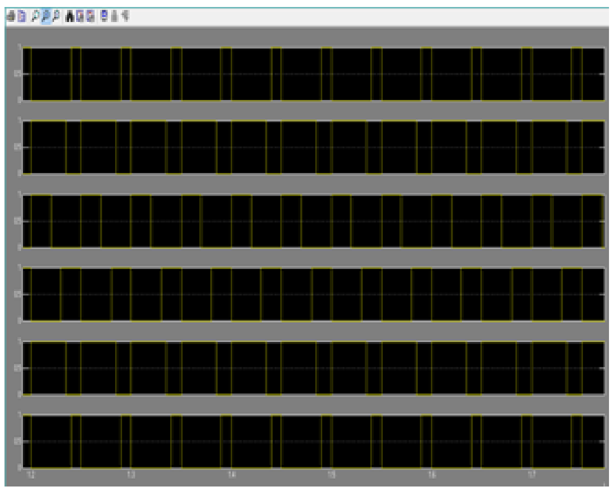

Fig.13 Time periods of the switches

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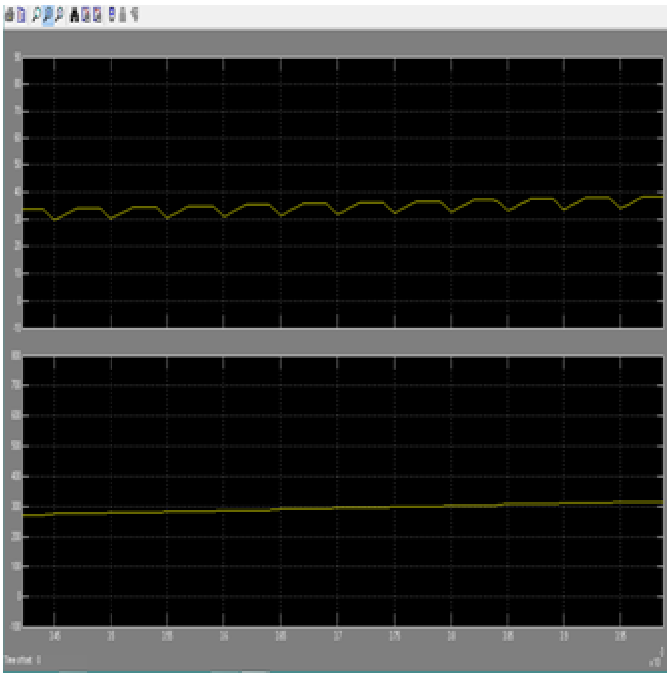

Fig.14 Results for operation in mode D: (a) Current flowing from the *iL*1, *iL*2.

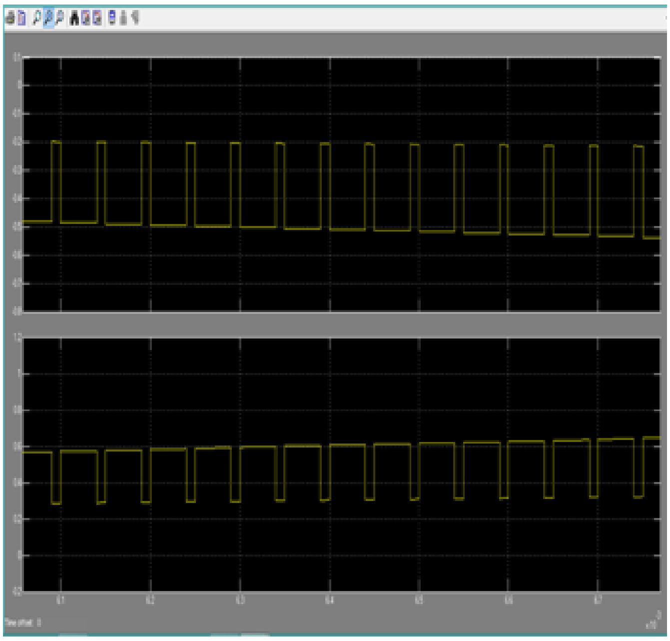

Fig. 15 Waveforms for operation in mode B(i): (a) Voltage across switch *S*2, *VS*2, voltage across switch *S*6, *VS*6.

CONCLUSION

This paper explains various modes of power transfer operation of different levels of voltage sources. Multiple sources such as solar pv, battery and ultra-capacitor are used to overcome the intermittency in power generation due to peak power demand. The state of charge of battery and ultra-capacitor shows charging and discharging characteristics in different modes as shown in results. With change in solar insolation shown in fig.18 the corresponding output of the dc-dc converter varies but due to mppt and the proposed method output of 500V dc is maintained constant at dc link with this we can achieve maximum power point. During peak generation auxiliary sources charge along with power supplied to grid from pv and during less insolation these auxiliary sources discharge to grid along with pv as shown in fig.19. This converter finds application in where more than two sources with bidirectional power flow can be interfaced like solar, FCV and battery management etc.

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