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Triple-Input DC-DC Converter (TIC) Design for PV-Battery-UC Hybrid Power System

H. S. Thakur[1*], R. N. Patel[2]

1* Department of Electrical and Electronics Engineering, SSITM, CSVTU, Bhilai, India
2 Department of Electrical and Electronics Engineering, SSTC-SSGI, CSVTU, Bhilai, India

*Corresponding Author: *thakurhitendrasingh@gmail.com*

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Abstract— The insufficiency in terms of energy density and efficient operation faced by the renewable energy sources, have resulted in the development of multiple source integrating systems which can do the needful and effectively fill the deficiency gap which are inherent to the previous works in the same field. In the present work, a power electronics based triple source integration system has been designed which utilizes a Solar Photo Voltaic (SPV) system, a Battery Energy Storage (BES) system and an Ultra-Capacitor (UC) bank to supply the load. The designed converter system not only effectively harvests energy from all the sources having different voltage–current characteristics but also ably provide the provision of connecting each source either individually or collectively to feed the load. The converter topology also bears the benefit of bidirectional power flow capability with the added feature of buck operation, boost operation and buck-boost operation. A pulse width modulated controller is designed for controlling the power electronic switches and the entire simulation study is performed in MATLAB / Simulink environment.

Keywords – Solar Photo Voltaic (SPV), Battery Energy Storage (BES), Ultra-Capacitor (UC), Triple Input Converter (TIC), Hybrid Energy System.

I. INTRODUCTION

The present renewable energy sector is undergoing a crisis in terms of reliability, sufficiency in energy density, sustainability, durability in operation and others, which has led the future of energy technology entirely dependent upon the development of improved techniques for effective integration of multiple energy sources. Single source energy systems are now no more attractive option amidst tight competitive energy market. The proper intervention of power electronic interface makes the hybridization of energy sources meaningful. In the earlier versions of hybridization, different categories of sources are combined together through separate dc-dc converters and their outputs are connected in series or parallel. Such arrangements had limitation of large number of components, high cost, bulk in weight, poor efficiency and complicated design [1-4]. Later, with the development of multiple input dc-dc converter (MIC), almost all of the limitations posed by the traditional converter were effectively addressed. MIC has successfully replaced a single multiple input system by offering a simple, low cost, more compact, multiple single input dc-dc converter [5,6].

Research work on magnetically coupled isolated and electrically coupled non-isolated types of MIC were also conducted in the past. In the isolated MIC a multi-winding transformer is provided to electrically isolate source side from the load side. In such topologies the energy takes the route of magnetic coupling, as offered by transformer core. Whereas, in the non-isolated MIC there is a direct electrical connection between the source and the load [7-24]. In [8] an MIC operation based on flux addition concept is reported. For development of MICs, generalized approach is adopted in [22–24]. Operation of MIC in buck-boost mode is illustrated in [11]. In [25], a novel MIC is proposed for integrating solar – PV with fuel cell. For high/low voltage sources integration, a dual input DC-DC converter is introduced in [26]. The converter with suitable power management technique for electric vehicle application is presented in [26-27]. For bidirectional interfacing of DC voltage source an MIC is proposed in [28]. The converter suffers from power losses linked with the recovery currents of the output diodes which results in lower system efficiency. A non-isolated MIC for SPV application delivering power from one energy source at a time is presented in [29]. A multiport DC-DC converter concept with magnetic and DC-link coupling is described in [30]. A dc boost and a multiple input voltage summation converter are discussed in [30] and [31]. The management of flow of power from the input sources of MICs for application in electric vehicle system is presented in [32]. For fuel cell/EV application, a bidirectional MIC as developed which suffers from discontinuity of input current, and hence the converter is limited in application [33]. In [34], authors proposed two MIC topologies with the capability to simultaneously deliver power to the load from input energy sources. Apart from the capability of primitive topology to perform in the buck, boost, and buck–boost modes of operation, the proposed topology is able to deliver power to the load in the event of failure of any one of the input energy sources using the same structure. A three input dc boost converter hybridizing PV/FC/Battery with the feature of effective integration of energy sources is proposed in [35]. In most of the MIC/DIC topologies presented in previous research work have the limitations of selection of voltage levels, limitation in the operating modes, switching scheme complexity, improper selection of switches, inadequacy in analysis and component counts [34-36].

Present work is based on the work presented in [3] and takes care of all the frailties encountered in the previous research work. In this work, a bidirectional conducting and bidirectional blocking (BCBB) switch is used in designing the triple input converter (TIC), instead of bidirectional conducting and unidirectional blocking (BCUB) switch. The above mentioned changes take care of defective operating state related to undesired conduction of the BCUB switches under the event of reverse bias being applied across them. The developed TIC is utilized to integrate a solar PV source with a storage battery source and an ultra-capacitor bank. The converter possesses the ability to transfer power from the sources discreetly or concurrently by connecting the sources either in series or in parallel. The converter also offers the effective control of flow of power between the sources and the load. Furthermore, the proposed converter is proficient in bidirectional power flow and buck, boost, buck-boost modes of operation. Compact design, flexibility in control of power and selection of source voltage with least part count are the other features of the proposed converter.

The rest of the paper is organized as follows: Section II discusses the converter architecture with the different working states. Section III presents the control scheme employed for the converter. Section IV presents the simulation results and validates the simulated results with the experimental results. Finally, Section V gives the conclusion of the work**.**

II. PROPOSED WORK

In this section, the detailed description of proposed TIC is illustrated. The proposed converter shown in figure 1 comprises of three voltage sources, (i) V_{PV} obtained from the solar PV system, (ii) V_{BT} obtained from the storage battery and (i) V_{UC} obtained from UC. The switch network that combines the sources, comprises of bidirectional switches (S_1-S_4), unidirectional switches (SS_1, SS_2, S_5) and diodes (D_1, D_2). Switch group (S_1-S_4) is for the parallel operation of the sources. Switch group (SS_1-SS_2) is for series connection of the sources. Diode, D_1 is for freewheeling action. The conduction of switch S_5 and diode D_2 decide the converter operation in buck, boost, buck-boost or bidirectional modes. For bidirectional mode of operation, the Diodes are needed to be replaced by unidirectional controlled switches.

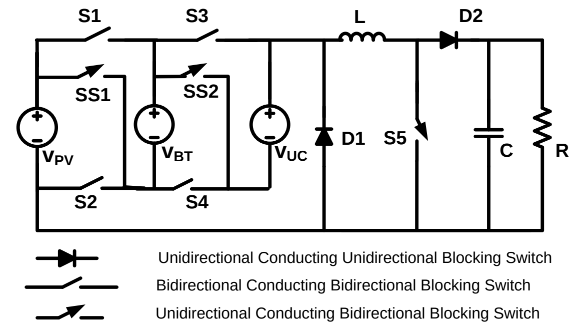

Figure:1 Proposed TIC Topology.

The different working stages of TIC presented in Figure 2 can be described as follows:

State-1: In this state as presented in Fig. 2(a), switches S_1, S_3 and S_5 are turned ON, while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{PV} and the duration lasts for time t_1.

State-2: (Fig. 2b) In this state, switches S_2, S_3 and S_5 are turned ON, which connects V_{BT} to inductor while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{BT} and the duration lasts for time t_2.

State-3: (Fig. 2c) In this state, switches S_2, S_4 and S_5 are turned ON, which connects the V_{UC} to the inductor while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{UC} and the duration lasts for time t_3.

State-4: (Fig. 2d) In this state, switches SS_1, S_3 and S_5 are turned ON, which connects series combination of V_{PV} and V_{BT} to the inductor while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{PV}+V_{BT} and the duration lasts for time t_4.

State-5: (Fig. 2e) In this state, switches SS_2, S_2 and S_5 are turned ON, which connects series combination of V_{BT} and V_{UC} to the inductor while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{BT}+V_{UC} and the duration lasts for time t_5.

State-6: (Fig. 2f) In this state, switches SS_1, SS_2 and S_5 are turned ON, which connects series combination of V_{PV}, V_{BT} and V_{UC} to the inductor while the other switches are remained OFF. Inductor, L gets charged by the source voltage V_{PV}+V_{BT}+V_{UC} and the duration lasts for time t_6.

State-7: (Fig. 2g) In this state, all the switches are turned OFF, and Inductor, L is made to discharged through load resistor R. the period lasts for time t_7 and is known as freewheeling period.

All the above working states shown in figure 2 are summarized in Table 1.

Table 1. Summary of operating states of TIC in buck boost mode

State	Conducting Switches	Active Source	Inductor Voltage	Inductor Status
1	S_1, S_3, S_5	V_{PV}	V_{PV}	Charging
2	S_2, S_3, S_5	V_{BT}	V_{BT}	Charging
3	S_2, S_4, S_5	V_{UC}	V_{UC}	Charging
4	SS_1, S_3, S_5	$V_{PV}+V_{BT}$	$V_{PV}+V_{BT}$	Charging
5	SS_2, S_2, S_5	$V_{BT}+V_{UC}$	$V_{BT}+V_{UC}$	Charging
6	SS_1, SS_2, S_5	$V_{PV}+V_{BT}+V_{UC}$	$V_{PV}+V_{BT}+V_{UC}$	Charging
7	D_1, D_2	$V_L=-V_O$	$-V_O$	Discharging

Based on (i) status of the sources (availability in case of PV, state of charge in case of storage battery and ultra-capacitor), (ii) schemes adopted for the control action and (iii) the load profile, the sequence of working states of the converter can be decided. In the proposed work, three asymmetrical voltage sources are made to supply the load individually and simultaneously, due to which the load voltage experiences significant variation. In this matter, the design of inductor (L) and capacitor (C) plays a vital role for the stabilization of the voltage at the load terminals by minimizing ripples in the current flowing through the inductor and the voltage appearing across the capacitor [3]. The proposed converter is compared with the existing work in the same field and the details regarding the comparison is presented in Table:2. From the table data it can be observed and concluded that the proposed scheme stands affront amongst its companion research work.

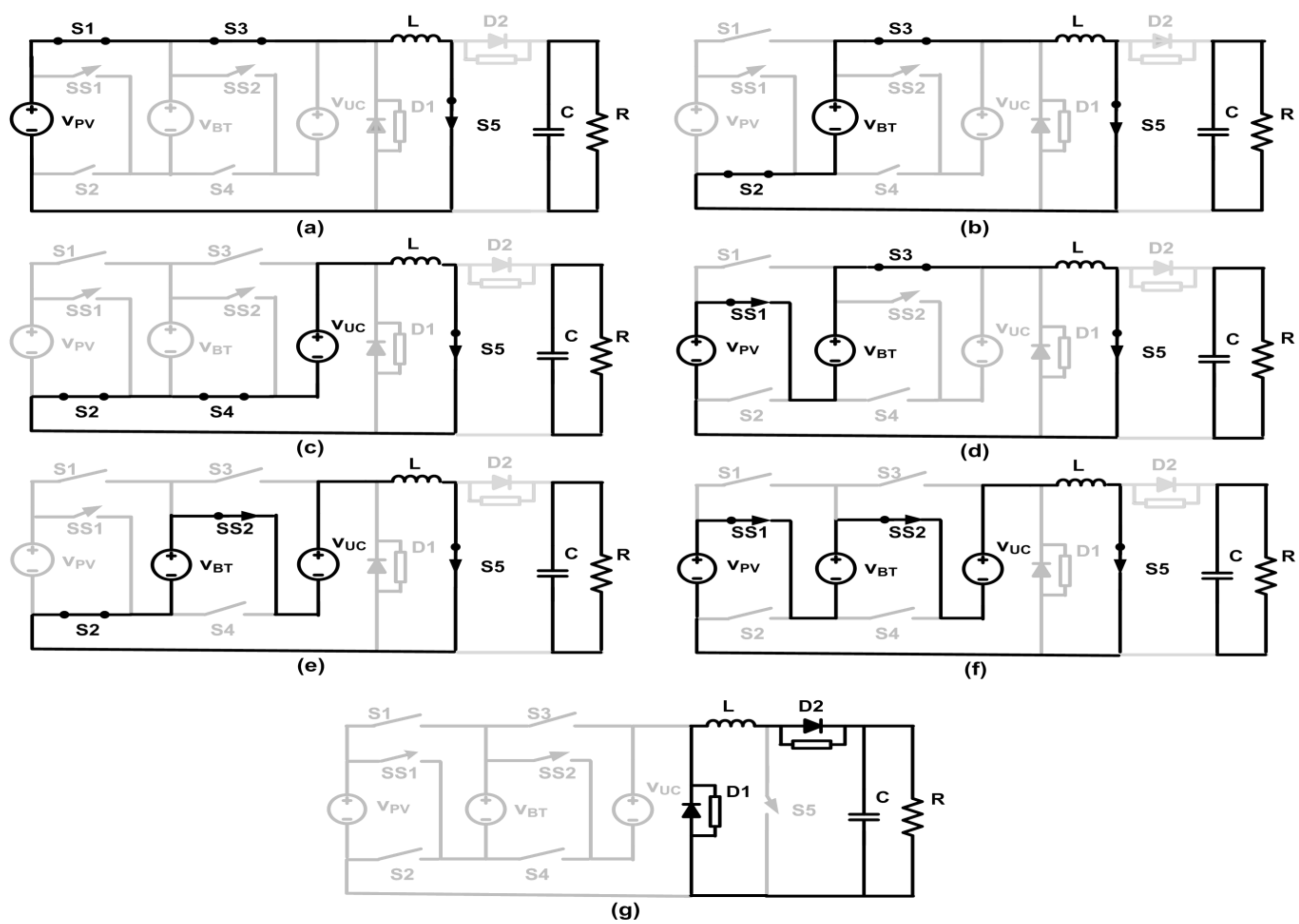

Figure: 2 Different operating states of TIC converter during buck-boost mode of operation (a) Contribution of PV source (b) Contribution of Battery Source (c) Contribution of ultra-capacitor (d) Contribution of PV & Battery sources (e) Contribution of Battery & ultra-capacitor Sources (f) Contribution of PV, Battery & ultra-capacitor sources (g) Freewheeling period

Table:2 MIC Topology Comparison

Topology	Components				Voltage Stress	Inductor	Capacitor	Efficiency	Operating modes
	Switches		Diode	Total				(in %)	
	BD	UD			V	L	C		BD
Chen et al. [8]	0	N	2	N+2	V_N, V_N+V_O	1	1	80-93	UD, b, b-B
Khaliga et.al [6]	N	2	1	N+3	V_N-V_{N-1}	1	1	78-90	B, b, b-B, B
Ahmadi et. al [30]	0	4N	1	4N+1	V_N	1	1	73-91	UD, b, b-B
Jiang et. al [5]	0	2N	0	2N	V_O	N	1	80-92	BD, B
Chapman et. al [11]	N	0	1	N+1	V_N, V_N+V_O	1	1	80-94	UD, b-B
Proposed work	N+1	N-1	2	2N+3	V_N	1	1	82-91	BD, b, b-B, B

N=number of input sources; UD=unidirectional; BD=bidirectional; b=buck, B=boost

III. CONTROL TECHNIQUE

There are four different ways to derive the gate pulses for driving the converter switches, these are (1) leading edge synchronization, (2) trailing edge synchronization, (3) intermediate synchronization and (4) independent synchronization. The operation of proposed TIC depends on the switching of converter switches. For proper utilization of power harvested from SPV source, storage battery and UC, the appropriate selection of switching scheme is essential. To achieve this objective, independent synchronization technique is adopted in this work which is shown in Figure 3.

Related to Figure 3, for a single switching cycle T_S, the different operating time (t_1- t_7) in terms of the respective duty cycles (D_1-D_7) can be obtained by following expressions:

$$t_1 = (D_1) \cdot T_S \qquad (1a)$$

$$t_2 = (D_2) \cdot T_S \qquad (1b)$$

$$t_3 = (D_3) \cdot T_S \qquad (1c)$$

$$t_4 = (D_4) \cdot T_S \qquad (1d)$$

$$t_5 = (D_5) \cdot T_S \qquad (1e)$$

$$t_6 = (D_6) \cdot T_S \qquad (1f)$$

$$t_7 = T_{OFF} = (1 - D_T)T_S \qquad (1g)$$

where,

$$D_T = D_1 + D_2 + D_3 + D_4 + D_5 + D_6$$

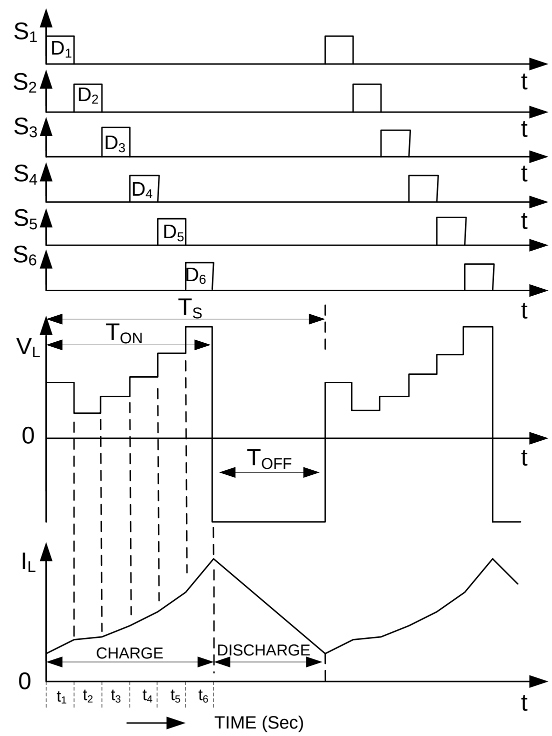

Figure 3. Switching signals (S_1-S_6) using independent switching scheme, Inductor voltage and current waveforms.

Analysis of TIC

For the analysis of TIC presented in this paper, following idealistic assumptions are taken into consideration (1) switching losses are assumed negligible, (2) resistive drop of inductor and capacitor are taken negligible, (3) capacitor has large value to accommodate the ripple in the output voltage waveform and hence maintain the output voltage constant. Furthermore, a detailed analysis for Buck-Boost mode of operation for continuous conduction mode under steady state conditions is worked out in this section. From figure 3, switch T_A conducts for duration t_1 and connects source V_{PV} to load, switch T_B conducts for the duration t_3 and connects source V_{BT} to the load, switch T_S conducts for duration t_2 and connects both the sources V_{PV} and V_{BT} (in series) to the load. For duration t_4 the inductor energy is freewheeled through load and diodes. Duty cycle for switch T_S depends on duty-cycles D_1 and D_2. The expressions for voltage across inductor for different time durations can be obtained as follows:

Voltage across Inductor for time t_1 will be $v_L = V_{PV} \times t_1$ similarly for time t_2 $v_L = (V_{PV} + V_{BT}) \times t_2$ in the similar manner the voltage across inductor for different time intervals can be evaluated.

It is evident from the inductor volt second balance equation that in the steady state and for a given switching cycle the average voltage across inductor would be always zero. Therefore, Average inductor voltage is given by:

$$V_L = \int_0^{T_S} v_L = 0 \qquad (2a)$$

$$\int_0^{T_S} v_L = (V_{PV} \times t_1) + (V_{BT} \times t_2) + (V_{UC} \times t_3) + \{(V_{PV} + V_{BT}) \times t_4\} + \{(V_{BT} + V_{uc}) \times t_5\} + \{(V_{PV} + V_{BT} + V_{uc}) \times t_6\} + (-V_O \times t_7) = 0 \qquad (2b)$$

Substituting for the values of time durations from equation (1) in equation (6) and solving gives

$$V_O = \frac{U_T}{1 - D_T} \qquad (3)$$

where,

$U_T = U_1 + U_2 + U_3 + U_4 + U_5 + U_6$;
$U_1 = V_{PV} D_1; U_2 = V_{BT} D_2;\ U_3 = V_{UC} D_3$;
$U_4 = (V_{PV} + V_{BT}) D_4; U_5 = (V_{UC} + V_{BT}) D_5$;
$U_6 = (V_{PV} + V_{BT} + V_{UC}) D_6$;

Where, values of $D_1\ to\ D_6$ can be obtained by utilizing equation (1).

Similarly, to derive the relationship between input and output currents, we begin with equating the input and out power of the converter.

$$P_o = P_{in}$$

$$V_o \cdot I_o = V_{in} \cdot I_{in} = V_{PV} \cdot I_{PV} + V_{BT} \cdot I_{BT} + V_{UC} \cdot I_{UC}$$

$$I_o = \frac{V_{PV} \cdot I_{PV} + V_{BT} \cdot I_{BT} + V_{UC} \cdot I_{UC}}{V_o} = \frac{P_T}{V_o} \qquad (4)$$

Substituting from equation (3) the value of V_O in equation (4) gives

$$I_o = \frac{P_T(1 - D_T)}{V_{PV} D_{PV} + V_{BT} D_{BT} + V_{UC} D_{UC}} \qquad (5)$$

The values of inductor and capacitor can be obtained by observing the ripple content present in the current flowing through the inductor Δi_L and voltage appearing across capacitor Δv_C. The values of L and C for buck- boost converter can be obtained by:[3]

$$L = \frac{V_O \cdot T_S}{\Delta i_L}(1 - D_T) \qquad (6)$$

$$C = \frac{V_O \cdot T_S}{R \cdot \Delta v_C}(1 - D_T) \qquad (7)$$

IV. RESULTS AND DISCUSSION

Simulation Results

To analyze the performance of proposed triple input converter, the topology is simulated in MATLAB/ Simulink environment. The simulation work is performed with three different input sources, one is solar photo voltaic source and another is battery storage system and yet another is UC bank. The converter is operated with continuous conduction in buck-boost mode and all the results are analyzed under steady state conditions. Independent switching scheme is used for the generation of the gate pulses to the converter switches. The converter circuit parameters used for the simulation are mentioned in Table: II. The simulation results of switching pulses, voltage appearing across inductor, current through inductor, load voltage, and load current for buck- boost mode of operation with converter on time T_{ON} >0.5 (voltage boost) and T_{ON} <0.5 (voltage buck) are presented respectively in Figures 4 to 7. The respective inductor current waveform indicates that for every level change in voltage, there is a corresponding change in slope of current waveform in Figures 5 and 7. The slope of current waveform increases with the increase in magnitude of voltage pulse and has a positive slope for positive voltage. For negative voltage the slope of inductor current becomes negative. It can also be observed that during complete switching cycle the inductor current attains the same level from where it started. The voltage across the load and hence the load current can be varied through suitable adjustments in the duty ratios D_1 to D_6. The proposed converter is also equally capable to be used as buck converter or boost converter. Furthermore, it can also be used for bidirectional power flow operation for particular application. The non-idealistic behavior of converter components causes small deviations from idealistic results due to the presence of conduction and switching losses and the voltage drop associated with that. Table 3 gives the detail of the values of parameters employed for simulation.

Table: 3 Simulation Parameters

Mode Buck(b)/Boost(B)	V_{PV}	V_{BT}	V_{UC}	T_{ON}	T_{OFF}	L	C	f_S	V_O	R
$T_{ON} > 0.5T_S$ (B)	40V	30V	16V	$0.6T_S$	$0.4T_S$	7mH	470μF	20kHz	77.5V	10Ω
$T_{ON} < 0.5T_S$ (b)	40V	30V	16V	$0.4T_S$	$0.6T_S$	7mH	470μF	20kHz	21V	10Ω

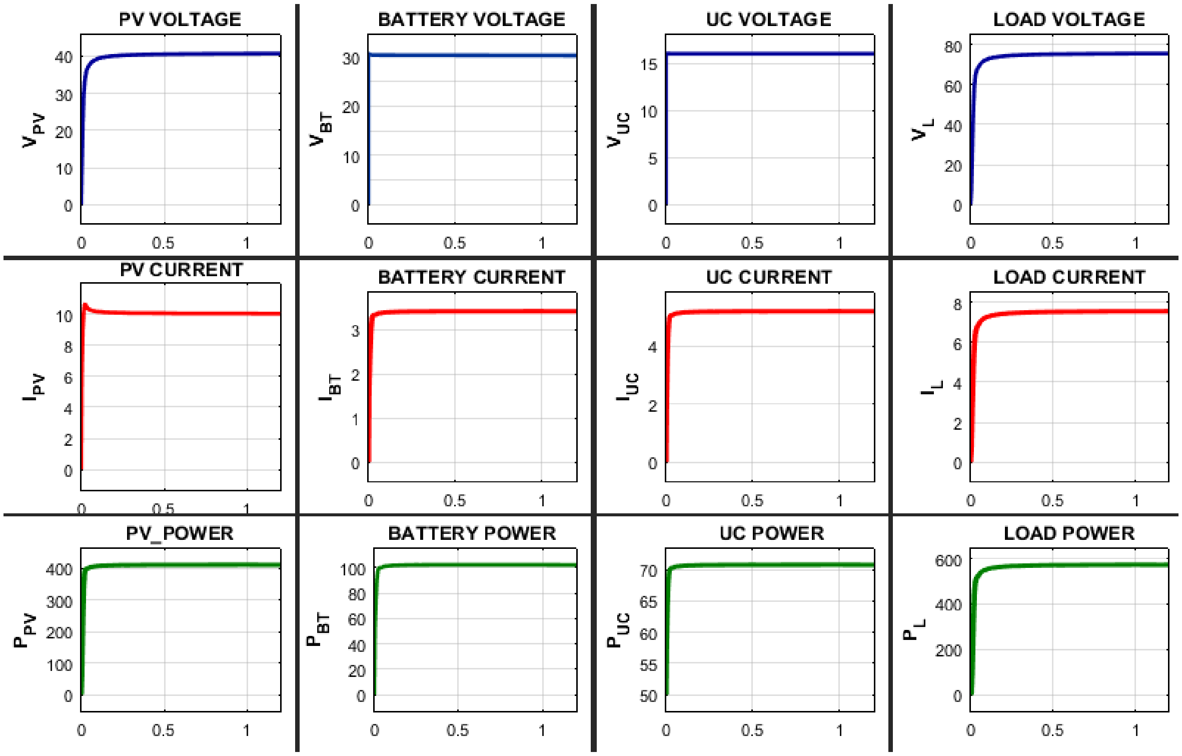

Figure:4 Buck Boost mode of operation $T_{ON}>0.5T_S$

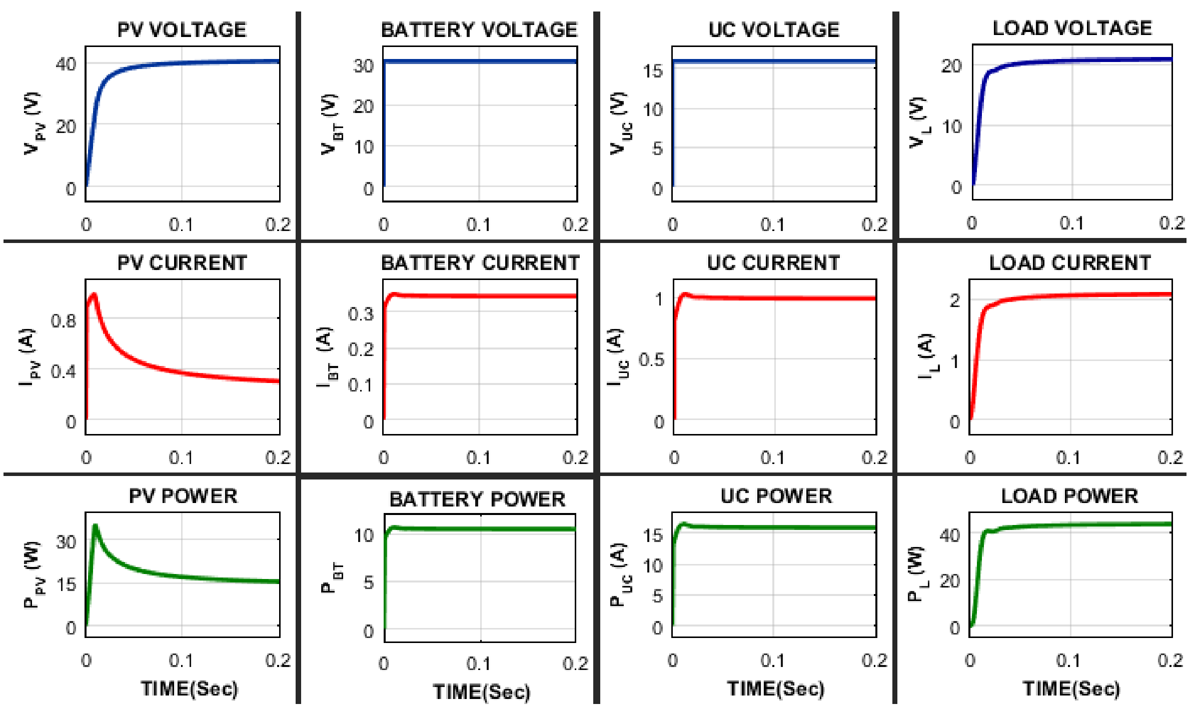

Figure:5 Buck Boost mode of operation $T_{ON}<0.5T_S$

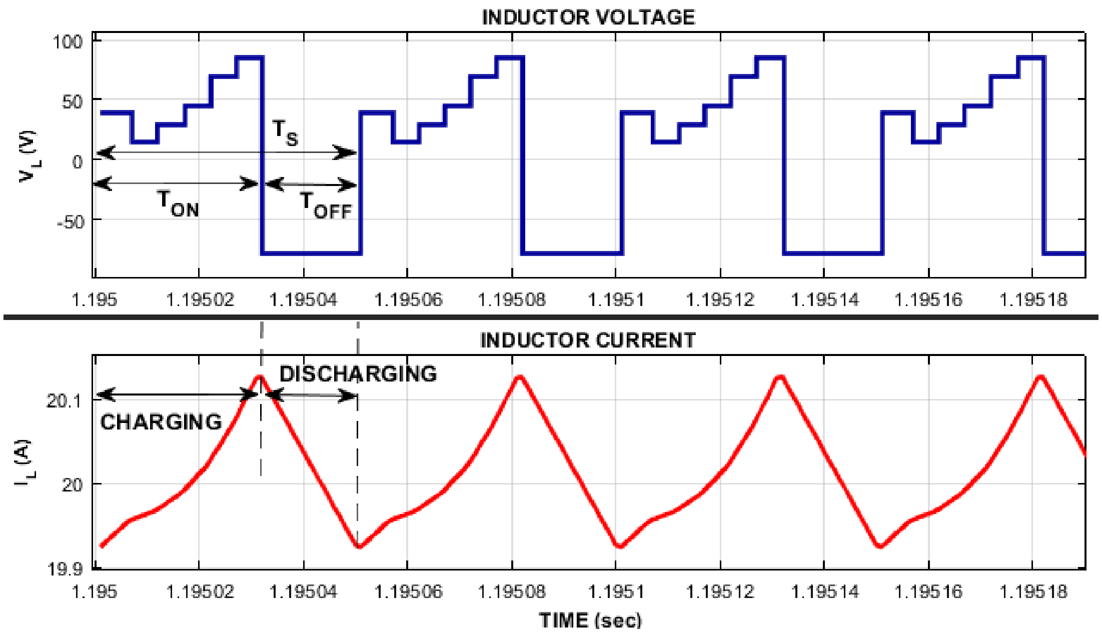

Figure:6 V_L I_L for Buck Boost mode of operation $T_{ON}>0.5T_S$

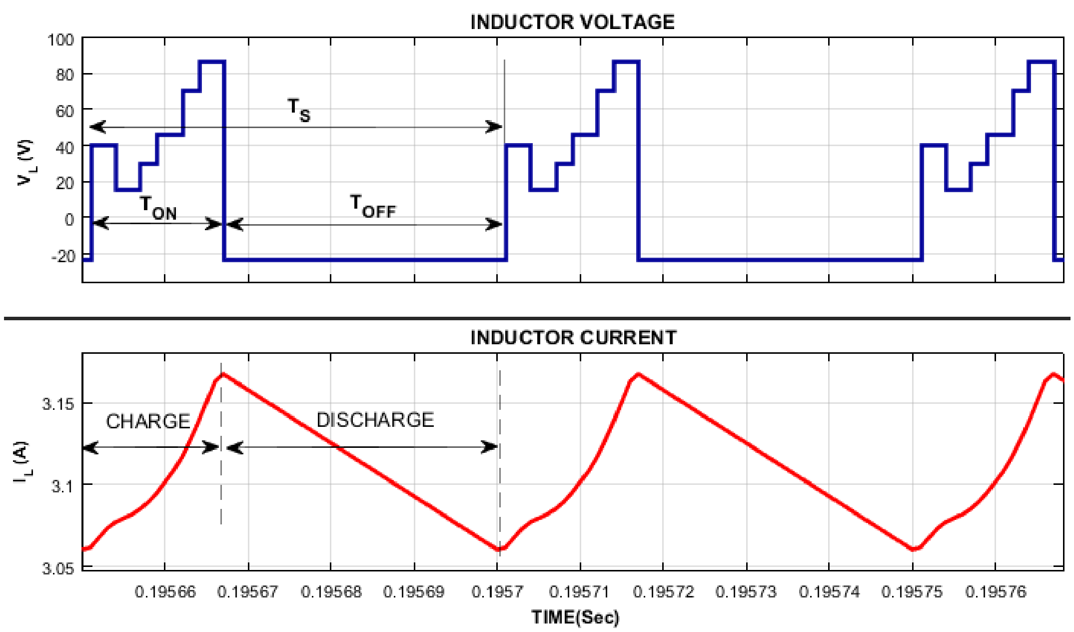

Figure:7 V_L I_L for Buck Boost mode of operation $T_{ON}<0.5T_S$

V. CONCLUSION

In this paper, a triple input dc-dc converter (TIC) topology is presented which is capable of harvesting energy from three different energy sources (PV/Battery/UC) with different voltage current characteristics. The proposed topology works well in buck, boost and buck-boost mode of operation (in this paper only Buck-Boost mode is discussed) with a facility of connecting the load individually or collectively in series or parallel as per requirement of the load. The formulation of mathematical equations followed by theoretical analysis is done for the source side and load side voltages and currents under steady state, continuous conduction mode of operation. The successful operation of the presented TIC topology is due to the extensive simulation and mathematical study of the converter functioning in the buck, boost and buck-boost mode. From the results obtained through simulation work it could be concluded that the proposed converter is proficient in not only harvesting energy from the different sources with different characteristics (PV, Battery and UC in present case), but it also offers higher degree of source electability, flexibility and availability. Amongst these, the other attributes of the converter include hassle free integration of the renewable energy sources and enhance the power sharing capability of the hybrid energy system.

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Authors Profile

Mr. H S Thakur pursed BE in Electrical Engineering from RGPV University Bhopal, M.P, India in 2005 and Master of Engineering from CSVTU University in 2012. He is currently pursuing Ph.D. and working as Assistant Professor in Department of Electrical and Electronics Engineering, SSTC-SSITM, Bhilai, C.G. since 2008. His main research work focuses on Power Electronics converter development for Solar PV systems, Hybridization of multiple sources. He has 10 years of teaching experience and 4 years of Research Experience.

Mr R N Patel pursed BE in Electrical Engineering from SGSITS, Indore, M.P. India in 1997 and and M.Tech and PhD from IIT Delhi in 1999 and 2003 respectively. Dr. Patel has served as faculty in the Electrical Engineering Department at IIT Roorkee (year 2003 to 2006) and at the Birla Institute of Technology and Science (BITS), Pilani (year 2003). Currently, he is Professor in the Department of Electrical and Electronics Engineering, Shri Shankaracharya Technical Campus (SSTC), Bhilai (CG), India. He is a Senior member of IEEE. He has published more than 40 research papers in reputed international journals and conferences including IEEE. He has also authored a Book, 'Programming in MATLAB- A Problem Solving Approach' with Pearson in the year 2014. His main research work focuses on dynamic and steady state analysis of different components of Power Systems, FACTS devices, Control Systems and Power system protection. He has 15 years of teaching and Research Experience.

