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Hybrid fuzzy PI controlled multi-input DC/DC converter for electric vehicle application

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ABSTRACT

Power electronic interface with its effective control scheme plays a major role in the utilization of energy sources for electric vehicle application. For this purpose, a hybrid fuzzy PI based control scheme for a multiple input converter (MIC) topology is proposed. The proposed hybrid fuzzy PI controller includes a conventional PI controller at steady state and fuzzy PI at transient state. Also, the proposed control design helps in tracking a predefined speed profile to have complete realization of electric vehicle. Detailed simulation study and performance comparisons with conventional controller are performed. The results show that the developed control scheme is robust providing bidirectional power management, fast tracking capability with less steady state error, better dynamic response by enhancing the flexibility and proper utilization of energy sources. Simulation in MATLAB/SIMULINK environment is carried out to verify the performance of the multi-input converter with the developed control scheme. An experimental set-up is constructed to validate the same.

1. Introduction

Nowadays, hybridizing energy systems has gained popularity in transportation applications. For this hybridization, the major focus is on power electronic interface to enable better utilization of energy systems which necessitates a high efficiency unidirectional/bidirectional DC–DC power converter [1,2]. Traditionally, energy systems are connected independently through several power electronic converters (PECs) and their output forms a common bus. Due to their complex design, increased component count and decreased efficiency, multi- input PECs prove to be a promising choice in hybridizing energy systems. Figure 1 shows Multi-input PEC interfacing different energy systems to form a hybrid energy system [3–7]. Energy systems like ultracapacitor, battery, fuel cell and renewable sources are combined together to supply the load simultaneously or individually through multi-input PEC.

Several topologies of isolated and non-isolated multi- input PECs are found in literature [3–9]. Most of the presented multi-input topologies integrate energy systems in parallel. Parallel configurations suffer from various issues such as increase in device count, energy sources need to be asymmetric, increased complexity and reduced reliability. The major limitation is that the input energy systems should supply power to the load individually at a time to avoid power coupling effect [3–5]. To address this major limitation of power

coupling effect, transformer with multiple primary windings is introduced [7]. Although it provides electrical isolation, it requires larger core to accommodate both primary and secondary windings, which makes the system bulkier and costlier and leads to EMI issues. All the above mentioned drawbacks are well addressed by the series integration of input energy systems [6,8,9]. In this series integration, each source can bypass other source to form parallel configuration through individual diode. The concept of pulsating source cell, its connecting rules and the systematic approaches to synthesize multi-input DC/DC converters are introduced for the purpose of series integration [10–12]. Most of the literature proposes multi-input converters employing pulsating source cell concept which are unidirectional and cannot be applied for energy storage systems or electric vehicle application. These applications require regenerative braking scheme for the reverse flow of power. Efficiency is one of the major aspects in multi-input PEC, which depend on the total number of components, regenerative ratio and energy storage system operating modes. Higher the system components lower the efficiency [13–16].

In this paper, a multi-input non-isolated PEC topology integrating multiple energy sources with the possibility of bidirectional power flow is chosen. Energy sources are connected in series through power switches, which form a pulsating source cell (PSC) in the presented topology and they offer inherent bypass circuitry
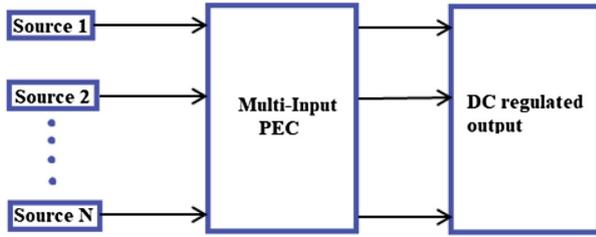
CONTACT S. Devi Vidhya ✉ devividhyas@ssn.edu.in 🏠 No:12/48, Seevaram 3rd street, Perungudi, Chennai-96, India

Figure 1. Multi-input PEC interfacing different energy sources.

for other sources. Diversification of energy from different energy sources and flexibility in source voltage magnitude (can be symmetric or asymmetric) is provided by this converter. Moreover, the load can be supplied individually or simultaneously by the connected energy sources. Possibilities of bidirectional power flow with buck and boost modes of operation have been explored with conventional controller [17–20]. This multi- input PEC has simple and compact structure with fault tolerant capability which enhances the reliability of the converter. Conventional PI controllers are employed for the closed loop voltage and current control of the system, which provides sluggish response [21,22]. Moreover, when the converter is used for electric vehicle application, a conventional controller does not provide robust speed tracking of predefined speed profile. For this purpose, Hybrid fuzzy PI controller is proposed in this paper to have a robust control. The hybrid fuzzy PI controller includes a conventional PI controller at steady state and a fuzzy PI controller at transient state [23].The performance of the proposed controller is compared with the conventional controller to spotlight the performance of the proposed scheme.

The paper is organized into various sections as follows. Section 2 introduces configurations of pulsating source cell (PSC). Section 3 deals with the Multi-input converter; Section 4 explains the proposed control strategy. The detailed simulation results using conventional and proposed control scheme are given in Section 5. Section 6 explains the experimental verification of proposed system followed by the conclusion in Section 7.

2. Configuration of pulsating source cell (PSC)

In the systematic design of multiple input DC-DC converters, input sources are configured using pulsating
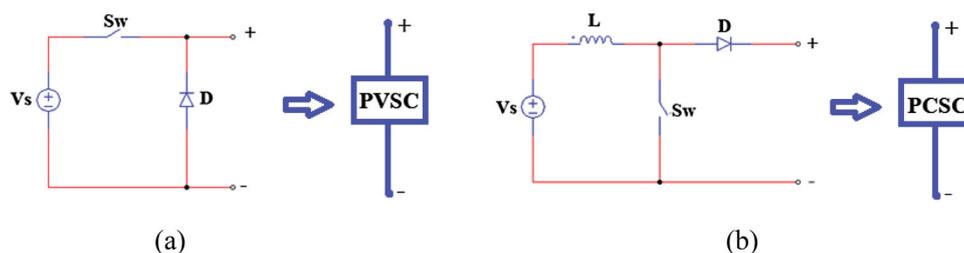
source cells (PSCs). The concept of Pulsating Source Cells (PSC) was introduced and families of Multiple Input Converters (MIC) were generated and analyzed in [10]. The concept of PSC is extended in [11] to basic non-isolated converters and rules are proposed to synthesize them. Besides topology derivation, several studies have been done on the control of MICs. With the large variety of non-isolated converters available in the literature [3–9], a limited amount of work has been done on the simultaneous utilization of different power sources. PSCs are of two types-pulsating voltage source cells (PVSC) and pulsating current source cells (PCSC). The configurations of PSC are shown in Figure 2.

The pulsating voltage source cells comprises of a DC voltage source connected in series with a controllable switch. A diode is connected in parallel with this combination [8]. The PVSCs are not connected in parallel with any branch of the converter because the voltage across the connected branch will be clamped by the PVSC. The parallel diode in PVSC produces circulating current which arises due to differences between PVSC and the connected branch of the converter. It provides a high frequency pulse wave voltage. When the active switch is on, the terminal voltage of the PVSC has a non-zero value. When the active switch is off, the terminal voltage is zero. Pulsating current source cells are formed by a voltage source along with series inductor and parallel connected controllable switch [8]. A diode is connected in series to block the possible voltage difference between the voltages imposed on the pulsating current source and the connected branch of the PWM converter.

When PSCs are connected to converter cell, it must be connected either in series or in parallel. On parallel connection, only one source can supply power to the load at a time. Alternatively, in series connection of PSCs, all the sources can supply the load either individually or simultaneously.

In this paper, the series connection of PVSC type of PSC synthesizing the Multi –input PEC has been discussed.

3. Multiple input DC/DC converter

The basic operation of multi-input DC/DC converter is to charge the inductor by connecting or disconnecting multiple sources to inductor. The multiple sources
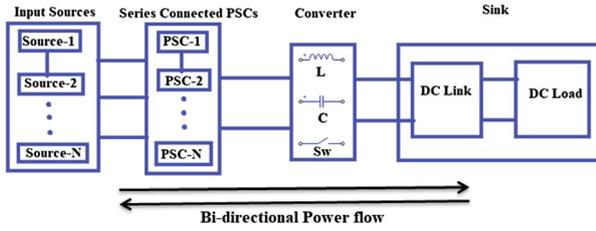

(a)   (b)

Figure 2. Configuration of PSC (a) PVSC; (b) PCSC.

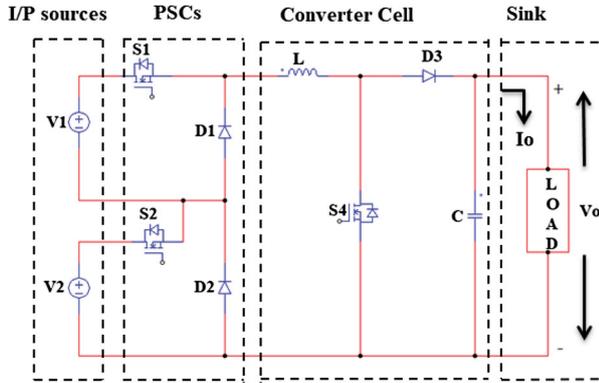**Figure 3.** Architecture of multi-input converter.

Figure 4. Multi-input converter system with two input sources.

are connected individually or simultaneously during a single switching cycle by adopting appropriate switching pattern. The basic structure of multi-input DC/DC converter shown in Figure 3 consists of an input portion, converter cell and an output sink [8,9]. The input portion consists of multiple PSCs namely PVSC connected in series, which are fed from multiple energy sources. The converter cell consists of inductor, capacitor and switches. These elements provide energy buffering and filtered output voltage. The output sink consist of load, where the output voltage and current are measured.

3.1. Topology

The multi-input PEC topology using two series connected pulsating voltage source cells is shown in Figure 4. PVSC1 constitutes a voltage source (V1) in series with a switch (S1) and a parallel diode (D1) and PVSC2 consists of a voltage source (V2) in series with a switch (S1) and a parallel diode (D1). Input voltage source of PVSC can be symmetric or asymmetric. The converter cell has an inductor L, capacitor C, switch S4 and a diode D3. Conduction of switches S1 and S2 in PSC decides the operating state and voltage source in operation depending on load requirement. Modes of unidirectional operation (Buck, Boost and Buck–Boost) are controlled by the conduction of diode D3 and switch S4. Bi-directional modes of operation are also possible using this topology by including switches S3, S1' and S2' in anti-parallel to diodes D3, D1 and D2.

Table 1. Various working state of multi-input converter.

S.No	State	Conduction of switches & diodes						Operation
		S1	S2	S4	D1	D2	D3	
1	I	ON	OFF	OFF	RB	FB	FB	Individual utilization of source V1
2	II	OFF	ON	OFF	FB	RB	FB	Individual utilization of source V2
3	III	ON	ON	OFF	RB	RB	FB	Simultaneous utilization of sources V1 and V2
4	IV	OFF	OFF	OFF	FB	FB	FB	Freewheeling of load current

Note: RB-Reverse biased; FB-Forward biased.

3.1.1. Design of multi-input converter

The Multi-input converter (MIC) is designed to have a low side voltage of (30–50) V and a high side voltage of (15–85) V. The maximum power rating of the converter is 1.5 KW, and the steady-state switching frequency is 20 kHz. The ripple requirements are 10% for the inductor current and 5% for the capacitor voltage. The average current of the inductor is given by

$$I_{L(\text{avg})} = \frac{I_{\text{load}}}{1 - d_{\text{boost}}} = 30.51\text{A} \tag{1}$$

The minimum inductance ($L_{\min}$) of the converter can be calculated as

$$L_{\min} = \frac{V_{\text{in}}}{\Delta I_L f_s} d_{\text{boost}} = 0.4\,\text{mH} \tag{2}$$

The inductance of the converter should be larger than or equal to 0.4 mH. The high voltage side output capacitance can be calculated as

$$C_o = \frac{(1 - d_{\text{boost}}) d_{\text{boost}} I_{L(\text{avg})}}{n V_o f_s} = 88\,\mu\text{F} \tag{3}$$

3.2. Working states

Depending on individual or simultaneous utilization of energy sources, several possible working states are possible by controlling the switching signals of S1 and S2 [8,9]. These states are listed in Table 1. The possible working states of the multi-input converter by utilizing energy sources V1 and V2 individually or simultaneously are shown in Figure 5.

3.3. Unidirectional operation

For unidirectional operation, the power flow is from source to load, provided that the load demand must be met by the voltage sources individually or simultaneously. This MIC provides unidirectional operation without any inclusion of switches and diodes. Conduction of switches S1 and S2 decides the utilization of voltage sources as per load profile. If the magnitude of voltage source is symmetric, then the control signals for the switches S1 and S2 are equal. If it is asymmetric, then the better utilization is the lower magnitude voltage source. Control of switch S4 decides the modes
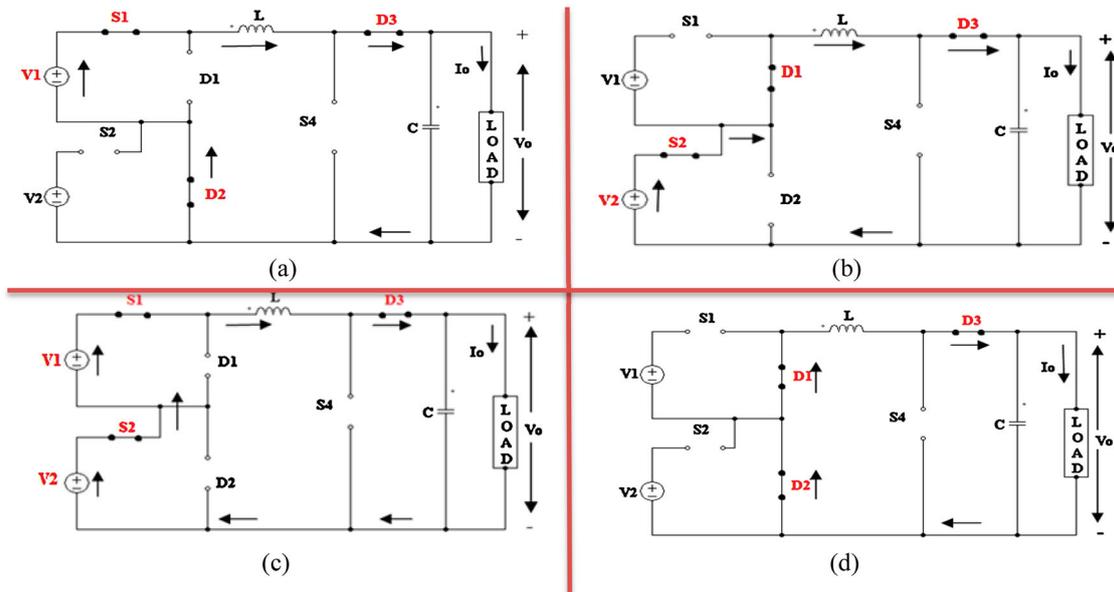
Figure 5. Various possible working states (a) Individual utilization of voltage source V1; (b) Individual utilization of voltage source V2; (c) Simultaneous utilization of V1 and V2; (d) Freewheeling of load current.

Table 2. Various working state of multi-input converter.

S.No	Mode	Conduction of switches & diodes					
		S1	S2	S4	D1	D2	D3
1	Buck	TON	ON	ON	OFF	RB	RB	FB
		TOFF	OFF	OFF	OFF	FB	FB	RB
2	Boost	TON	ON	ON	ON	RB	RB	RB
		TOFF	ON	ON	OFF	RB	RB	FB
3	Buck-Boost	TON	ON	ON	ON	RB	RB	RB
		TOFF	OFF	OFF	OFF	FB	FB	FB

of operation (buck, boost and buck–boost mode). By adopting suitable control strategy, the multi-input converter not only supplies power to the load and also regulates output voltage at predefined level by choosing appropriate modes of operation.

All possible operating modes and the conduction of converter switches are tabulated in Table 2 considering simultaneous utilization of both sources. The equivalent circuits during all possible operating modes are shown in Figure 6.

3.4. Bidirectional operation

For electric vehicle application with energy storage capability, bidirectional power flow operation plays an important role in re-using the regenerated energy during deceleration of motor. To meet the energy and power demands of the vehicle during motoring and braking operation, combination of battery and/or ultra-capacitor becomes vital. Such energy storage devices are utilized to recharge with regenerated energy during braking operation [15]. For interfacing of energy sources and their better utilization in electric vehicle systems, multi-input PEC with bidirectional power flow

capability is a potential option. For bi-directional operation to occur, switch S3 is added in anti-parallel to diode D3, which always conducts during braking mode.

As in unidirectional operation, the voltage regulation for the input side in bidirectional operation is also achieved under the different modes of operation (buck, boost, and buck–boost) to accomplish the desired voltage level so that the storage unit can be charged appropriately. During this operation, the converter behaves as a single input multiple output (SIMO) converter. To achieve controlled and independent charging of each input sources, switch S1' and S2' are included anti-parallel to diodes D1 and D2. The suitable control of switch S1' and S2' provides bypass path for the corresponding source and offers individual or simultaneous charging of storage sources. The bi-directional modes of operation are shown in Figure 7. All the working states and operating conditions as shown in Figures 5 and 6 are also valid for bidirectional operation, considering a single input source converter.

4. Design of the proposed control scheme

Power flow management is an important issue that needs to be addressed by a suitable control scheme [16–18]. An appropriate control scheme generating control signals (shown in Figure 8) to draw demanded power from the input sources individually or simultaneously by maintaining regulated output voltage is proposed.

The analysis and sampling of measured signals are done before introducing it to the controller. In this scheme, the operating mode (buck/buck–boost/boost) is chosen based on the load demand and source status and the control switching signals S1 and S2 are generated accordingly. The independent control of switching
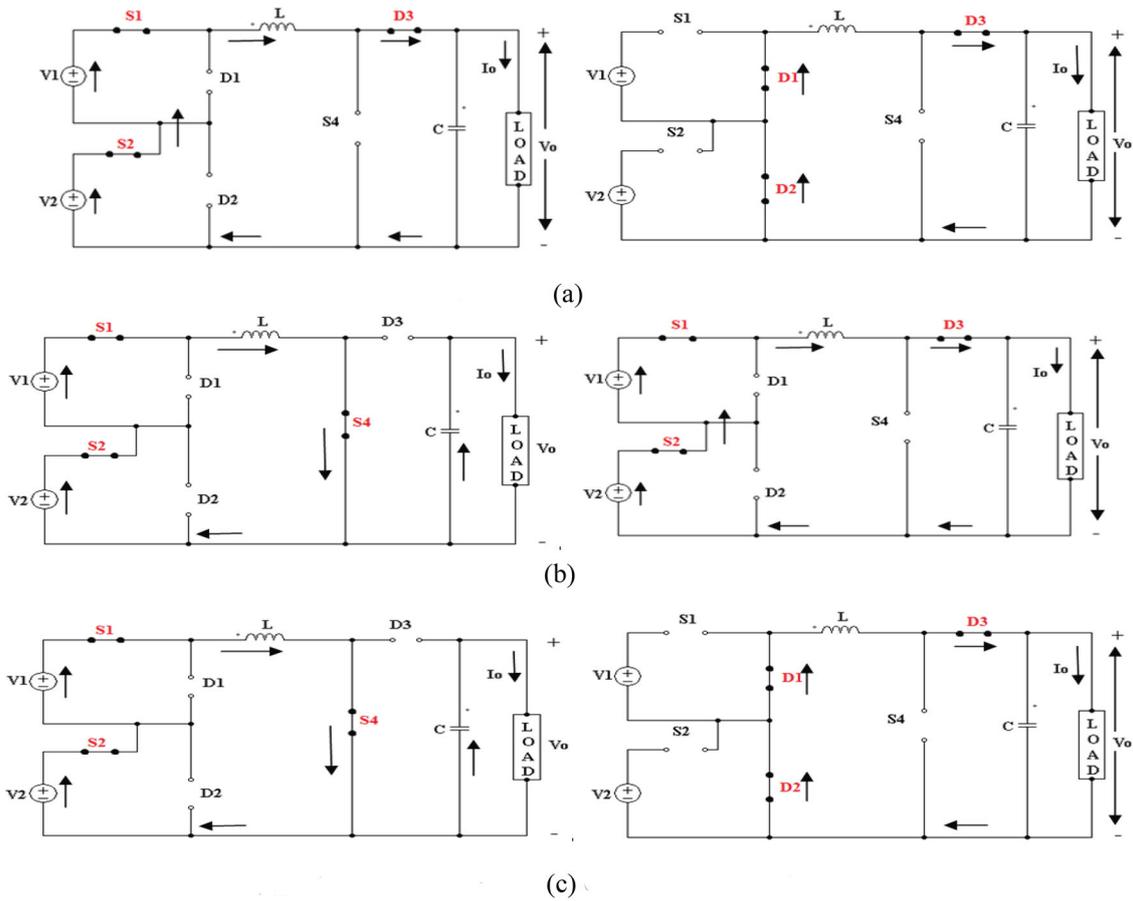
Figure 6. Various operating modes (a) Circuit configuration during buck mode of operation; (b) Circuit configuration during boost mode of operation; (c) Circuit configuration during buck-boost mode of operation.
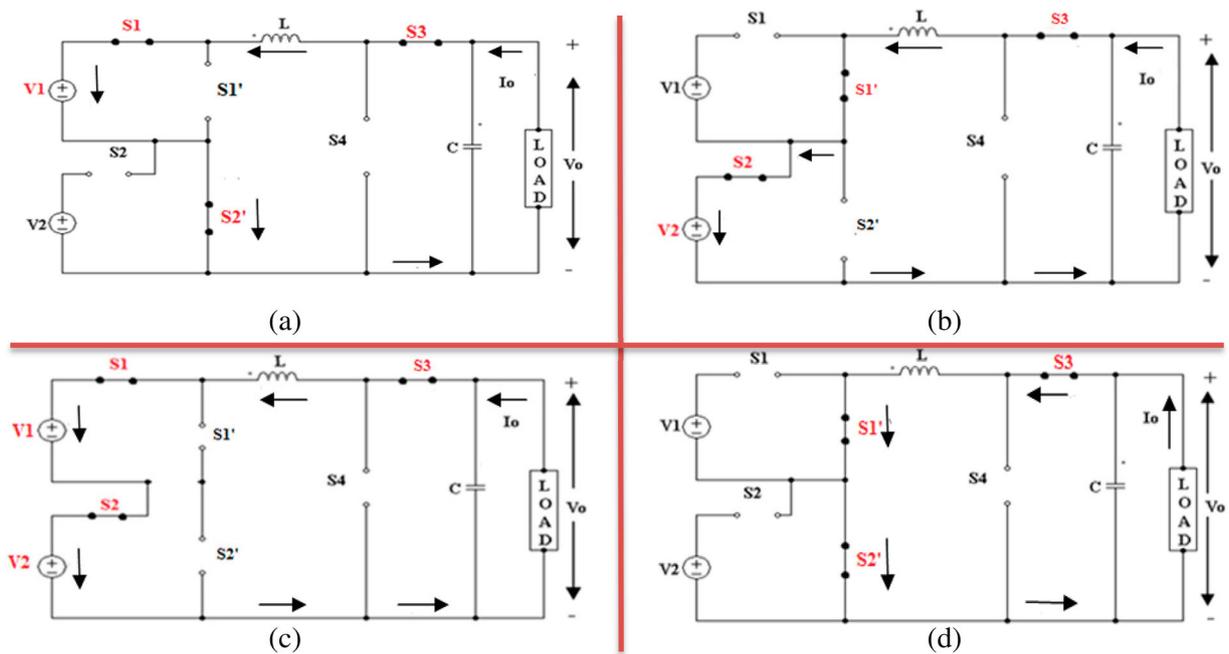

Figure 7. Bidirectional modes of operation (a) Individual charging of source 1 alone; (b) Individual charging of source 2 alone; (c) Simultaneous charging of energy sources 1 and 2; (d) Freewheeling of load current.
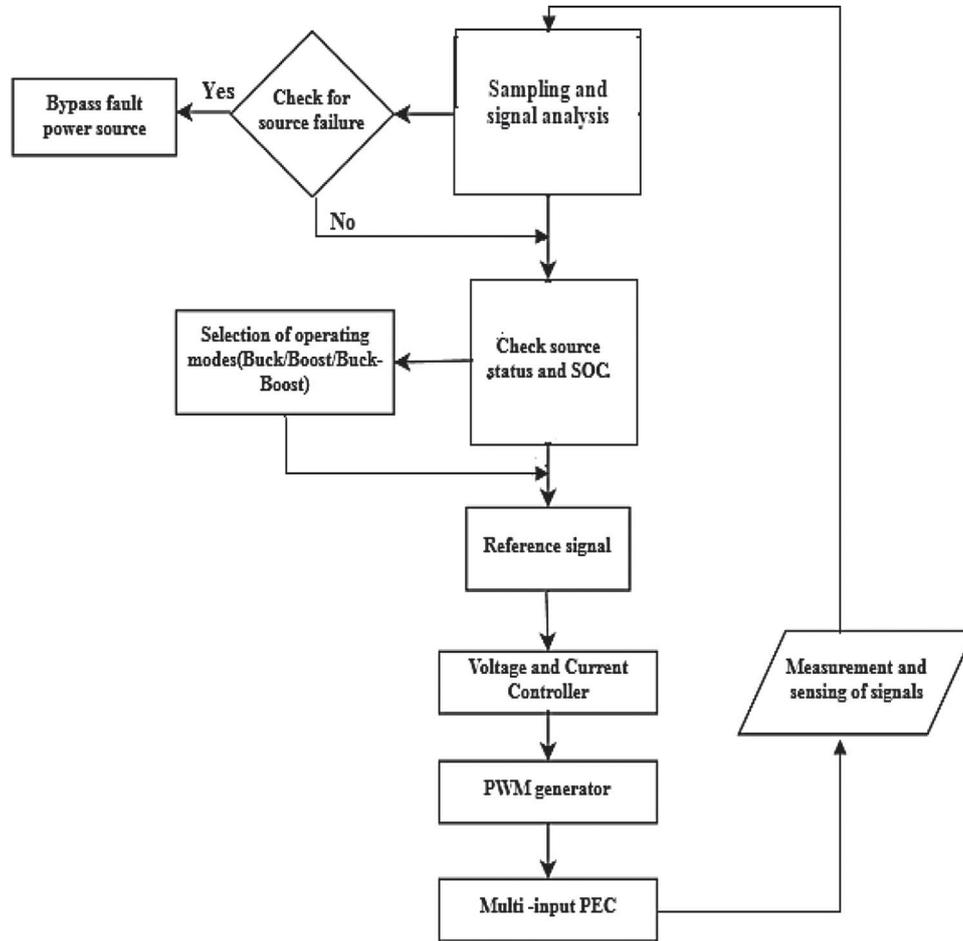
Figure 8. Control signals generating scheme for multi-input Converter.

signal S4 decides the boosting level, which depends on the mode of operation. The conventional PI control scheme employs a source side average current mode control, which involves outer voltage loop and inner current control loop. Using this approach, the current through inductor is controlled by controlling each source current individually for a given load [8,9]. In this work, the conventional PI of voltage and current controller is replaced by hybrid fuzzy PI controller. It provides better flexibility to combine different characteristics sources to operate at their optimal points, thus offering effective utilization and better dynamic response [18].

For Electric vehicle application, the load side should employ a motor and the energy sources like fuel cell, ultracapacitor, battery or a PV source can be used. In this work, battery and ultracapacitors with asymmetric voltage magnitudes are employed as energy sources. Both have a distinct V-I characteristics and power handling capacities in addition to its different dynamic and steady state performance. And the PMDC motor is employed as a load.

Therefore, the power management algorithm should be re-designed in such case by considering the speed regulation of the motor during motoring and braking conditions, which is shown in Figure 9. Outer loop

speed regulation and inner loop two parallel current regulation is achieved by employing hybrid fuzzy PI controller. The rule base for the fuzzy controller I_{ref} is given in Table 3 and the rule base for fuzzy controller I_{ref1} and I_{ref2} are shown in Table 4. Error (e) and change in error (de) represents the fuzzy inputs and the output is I_{ref}.

Since the converter output voltage is determined by the motor speed, voltage control is automatically achieved by the speed control. The inner current controller serves the purpose of input source current regulation by modulating the duty cycle of corresponding switch of the source that will supply limited amount of power. The objective of the proposed hybrid controller is to utilize best features of the PI and fuzzy controllers to provide a better response than either the PI or the fuzzy controller. A logical switching mechanism is implemented in this proposed hybrid controller to change the control action from PI controller to fuzzy controller or vice-versa based on the speed error value. The conventional PI controller is active when the speed error is less than 5 rpm whereas the fuzzy controller is active when the error is greater than 5 rpm. The structure of hybrid fuzzy PI controller is shown in Figure 10. For motoring condition, it is based on amount of power drawn from the sources during particular period
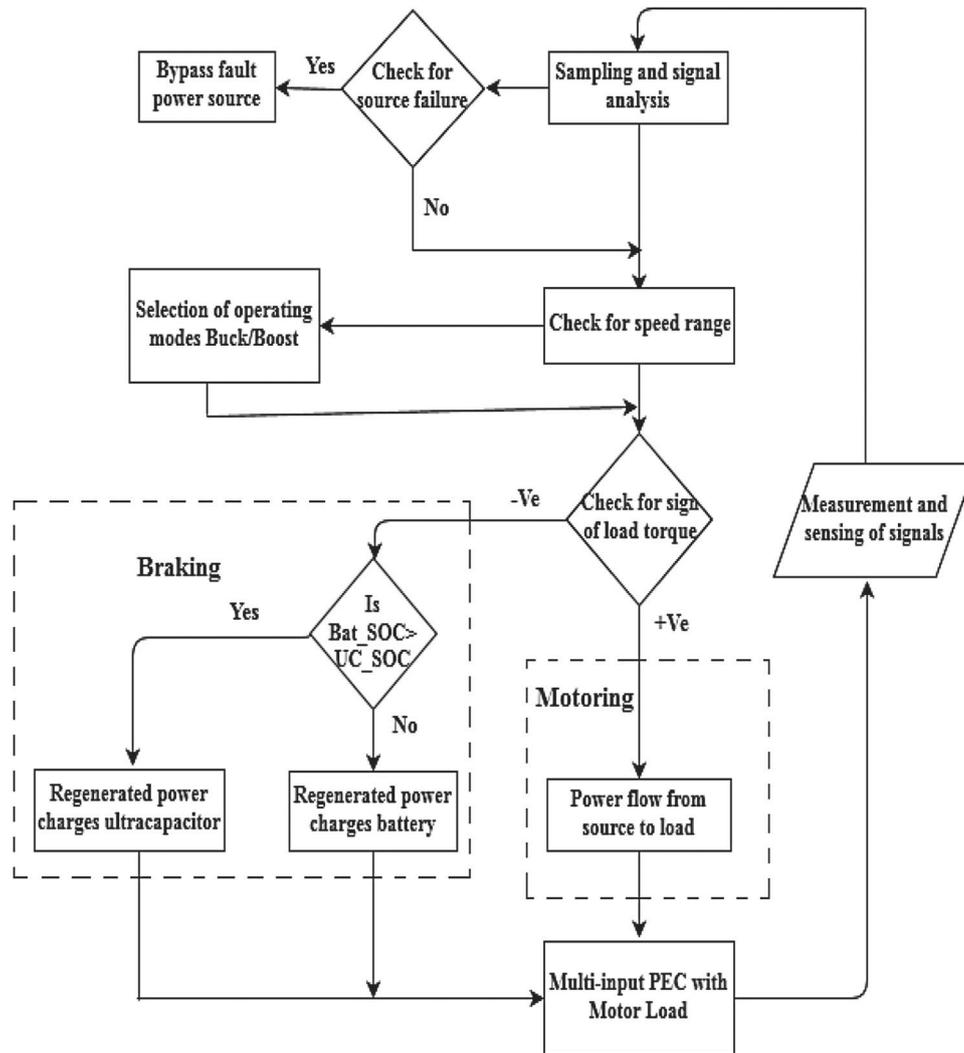
Figure 9. Power management algorithm for bi-directional power flow.

Table 3. Rule base for fuzzy controller I_{ref}.

	de	
e	N	P
NL	NL	NL
NS	NS	NS
ZE	NS	PS
PS	PS	PS
PL	PL	PL

Note: N-Negative; P-Positive; NL-Negative Large; NS-Negative Small; ZE-Zero; PS-Positive Small; PL-Positive Large.

Table 4. Rule base for fuzzy controller I_{ref1} & I_{ref2}.

	de				
e	NL	NS	Z	PS	PL
NL	NL	NL	NL	NS	Z
NS	NL	NS	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PS	PL
PL	Z	PS	PL	PL	PL

Figure 10. Structure of hybrid fuzzy PI controller.

be fed back to any of the energy sources based on their SOC status.

The proposed controller provides speed control operation both during motoring and regenerative braking modes.

5. Simulation results

To determine the performance of the proposed controller, initially stabilization of voltage control is performed. The multi-input converter is simulated with

of time either individually or simultaneously to meet varying load profile by operating in any mode. During braking condition, the re-generated power should
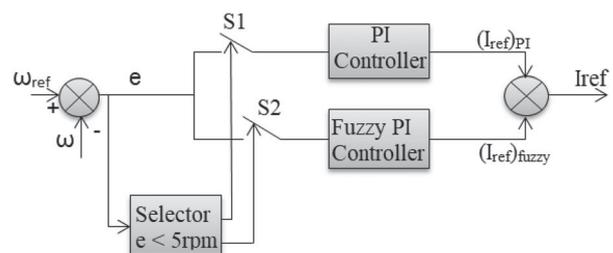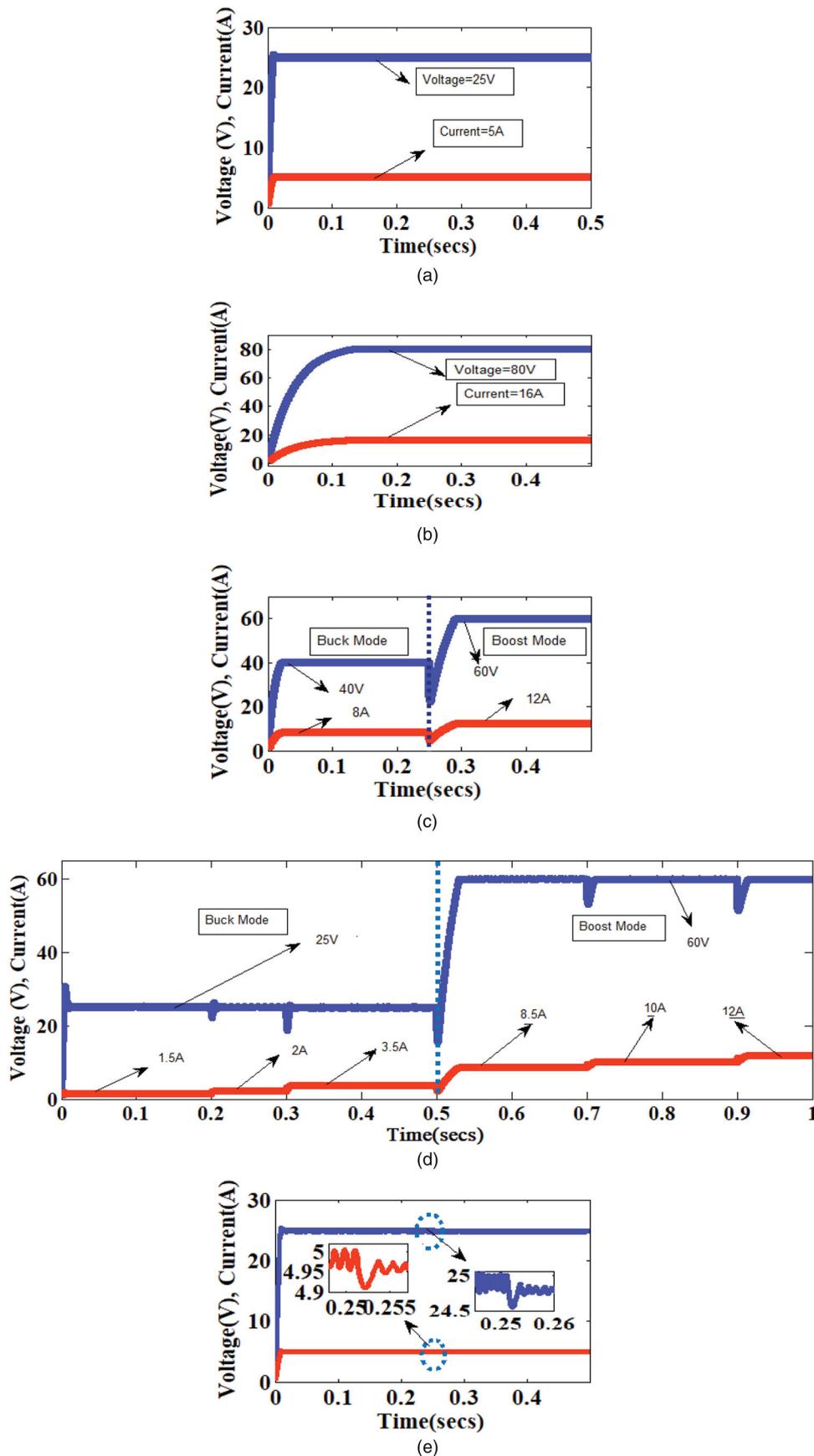
Figure 11. (a) Output voltage and load current waveforms for buck mode; (b) Output voltage and load current waveforms for boost mode; (c) Step change in output voltage during buck and boost mode; (d) Voltage and current waveform for buck and boost mode during different loading condition; (e) Regulation of voltage under the faulty condition.
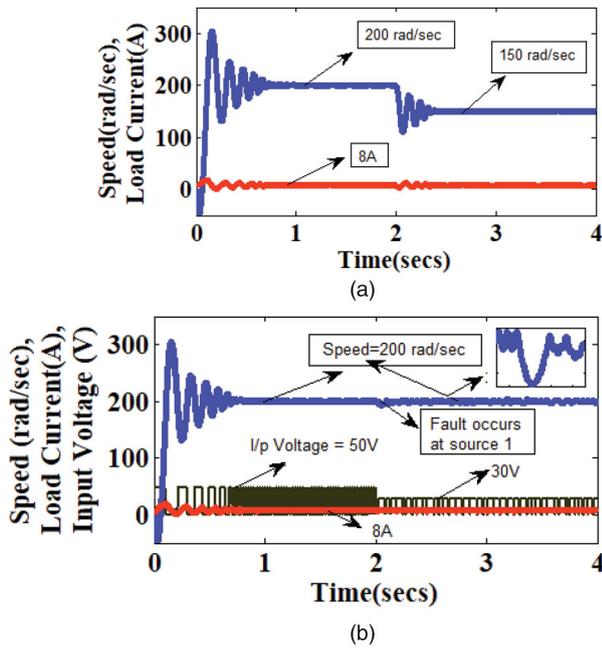
Figure 12. (a) Speed regulation for step change and the armature current waveform; (b) Speed regulation under healthy and faulty condition of source.
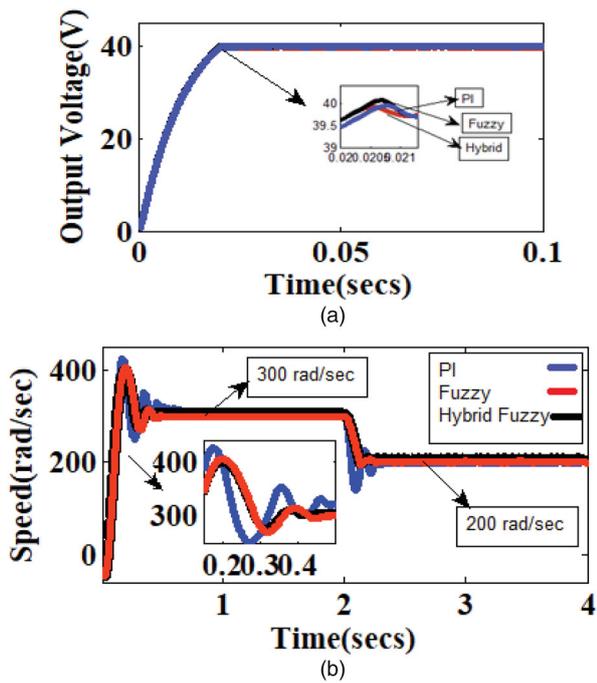

Figure 13. (a) Comparison of PI, fuzzy and hybrid Fuzzy PI controller for voltage regulation; (b) Comparison of PI, fuzzy and hybrid fuzzy PI controller for speed regulation.

Table 5. Performance analysis of various controllers for voltage regulation.

S.No	Controller	Rise time (sec)	Peak time (sec)	Settling time (sec)	Steady state error (V)
1	Conventional PI	0.015	0.0208	0.0281	0.1151
2	Fuzzy PI	0.0147	0.0205	0.0246	0.2337
3	Hybrid Fuzzy PI	0.0144	0.020	0.022	0.1494

constant DC sources of asymmetric voltage magnitude V1 = 20 V and V2 = 30 V. The load is assumed as resistive load $R = 5$ ohm. These two input sources are connected in series to provide the input voltage. Hybrid fuzzy PI controllers are utilized as voltage and current controllers with adjustment in their parallel current gain values. If the demanded voltage is lesser than input voltage, the converter operates in buck mode by controlling the source current drawn from individual sources ensuring regulated output voltage or else operates in boost mode. The output voltage and load current waveforms for buck and boost mode are shown in Figure 11(a,b).

Step change in demanded output voltage during buck and boost mode of operation is shown in Figure 11(c). If the load is varied over a period of time for a demanded voltage during buck and boost mode of operation, it results in dip in output voltage for very short duration to get recovered to its desired level, whereas there are short spikes in load current waveform shown in Figure 11(d). The proposed controller provides the regulated voltage even under the faulty condition of any source, shown in Figure 11(e).

For electrical vehicle application, the speed regulation is achieved for both buck and boost mode of operation. Figure 12(a) shows the speed regulation for step change from 200 rad/sec to 150 rad/sec and the armature current through the motor. The variation of speed limit corresponds to variation in mode selection. Figure 12(b) shows the speed regulation under healthy and faulty condition. At time $t = 2$ s, voltage source 1 becomes faulty, the healthy source 2 alone contributes to the load requirement. It is observed that after the

Table 6. Performance analysis of various controllers for speed regulation.

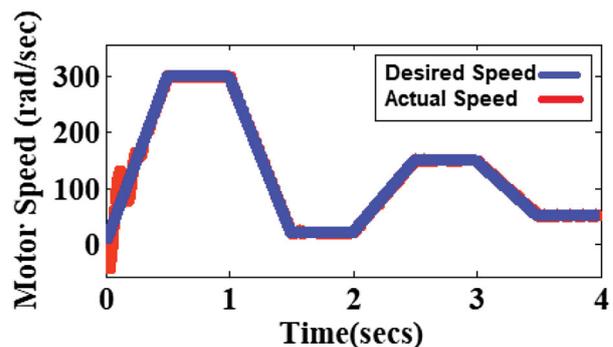| S.No	Controller	Rise time (sec)	Peak time (sec)	Settling time (sec)	Steady state error (rpm)
1	Conventional PI	0.054	0.175	0.49	0.7339
2	Fuzzy PI	0.052	0.172	0.3453	0.885
3	Hybrid Fuzzy PI	0.05	0.1706	0.339	0.784

Figure 14. Comparison of desired drive cycle speed profile and actual speed.
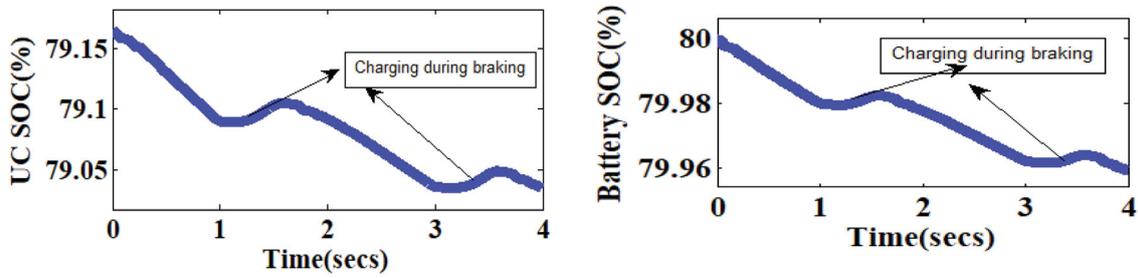
Figure 15. Charging and discharging of UC and battery during various operation of speed profile.
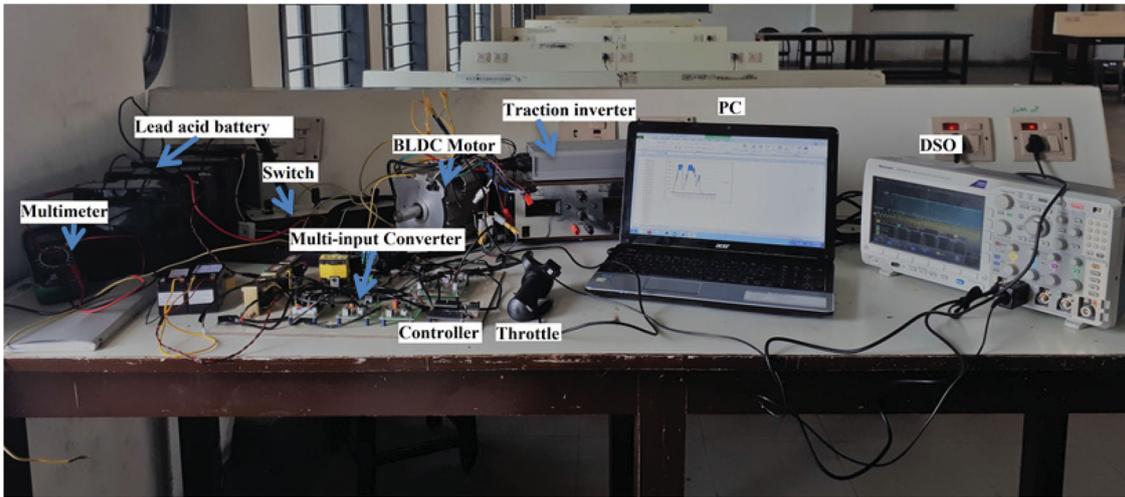

Figure 16. Experimental setup.

transient, the desired speed is maintained by the controller in a very short duration by utilizing the healthy source. The control of speed both during motoring and braking should be maintained for the proper electric vehicle operation.

Figure 13(a,b) shows the comparison plot of conventional PI, fuzzy and hybrid Fuzzy PI controller for the output voltage regulation and speed regulation. The performance analysis of different controllers for Figure 13 is tabulated in Tables 5 and 6. It is evident from the table that the proposed hybrid fuzzy PI controller

Table 7. Components of experimental setup.

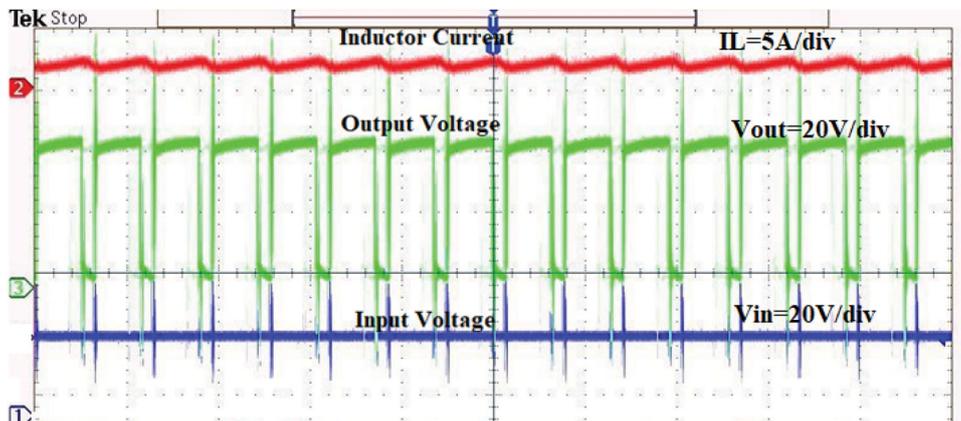| S.No	Components	Rating
1	Lead acid battery	12 V/9 AH
2	BLDC motor	1 KW/48 V
3	Inductor	2.5 mH
4	Capacitor	1000 uf/100 V
5	MOSFET	IRFP450
6	Traction inverter	48 V/40 A
7	Resistive load	10 ohm
8	DPST switch	
9	PC	
10	Arduino controller	

Figure 17. The inductor current, output voltage and input voltage of the MIC with $R = 10\,\Omega$.

performs better than conventional PI and fuzzy controller. The proposed controller is tested for tracking the desired drive cycle profile, which includes acceleration, constant speed and braking operation as shown in Figure 14. For acceleration and constant speed motoring operation, the speed control is performed by the flow of power from sources (individually or simultaneously corresponding to their SOC level) to the motor. In this case, both the battery and UC discharges to attain the desired speed. During deceleration, the regenerated power is fed back to any of the sources with less SOC or to both the sources. Here, both the sources are assumed to have 80% SOC. Therefore charging of both the sources takes place during braking operation of speed profile, which is depicted in Figure 15. It is found from the Figure 15 that the UC charges and discharges faster compared to battery.

6. Experimental verification

To validate the multi-input system with the proposed hybrid controller, a small-scale experimental platform was built and is shown in Figure 16. The main components of the experimental platform are listed in Table 7. Arduino is used as the real-time controller on the
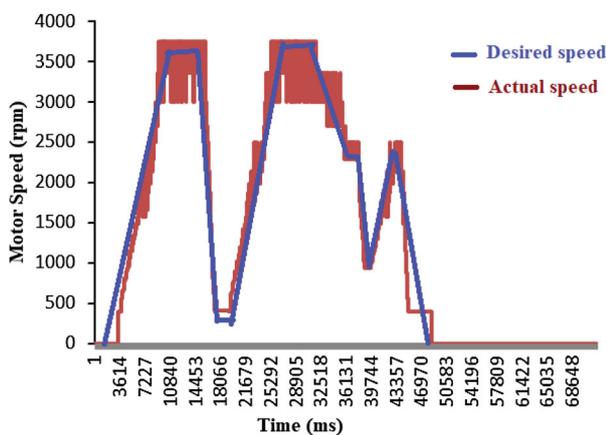

Figure 18. Speed profile tracking.

platform. The sources of the system are 4 numbers of 12 V lead acid battery bank with the current rating of 9 AH. 2 batteries are connected in parallel as source 1 (12 V, 18 Ah) and other 2 batteries connected in parallel as source 2 (symmetric voltage source). The minimum allowable voltage of the battery bank is 12 V, while the maximum voltage is 27 V and the maximum rating of the multi-input converter is 1 KW. Initially, the multi-input converter (MIC) is tested with the resistive load of 10 Ω. The obtained inductor current, output voltage and input voltage of the MIC with both voltage source utilization (24 V) is shown in Figure 17. A BLDC motor is connected as a load to the output of the converter through a traction inverter. The throttle controls the speed and direction of the rotation of BLDC motor. The desired speed profile is set using MATLAB programme and the actual speed profile is obtained and plotted using PC by feeding the hall signals from the BLDC motor controller. The proposed controller helps in tracking the desired speed profile which is shown in Figure 18.

During the acceleration mode, both the battery bank sources provide the demanded power and the MIC works in boost mode. It is assumed that for the constant speed mode, one battery bank source provides the demanded power to the load and also charges the other source by making the MIC to operate in buck mode. The experimental plot showing inductor current, boost and buck pulses corresponding to acceleration and constant speed operation are shown in Figure 19. The generation of hall signals during acceleration is shown in Figure 20(a) and its corresponding BLDC motor stator current is shown in Figure 20(b). Thus the experimental results verify the simulation results for motoring conditions.

7. Conclusion

In this paper, a hybrid fuzzy PI control scheme of a multiple input converter (MIC) topology for electric vehicle
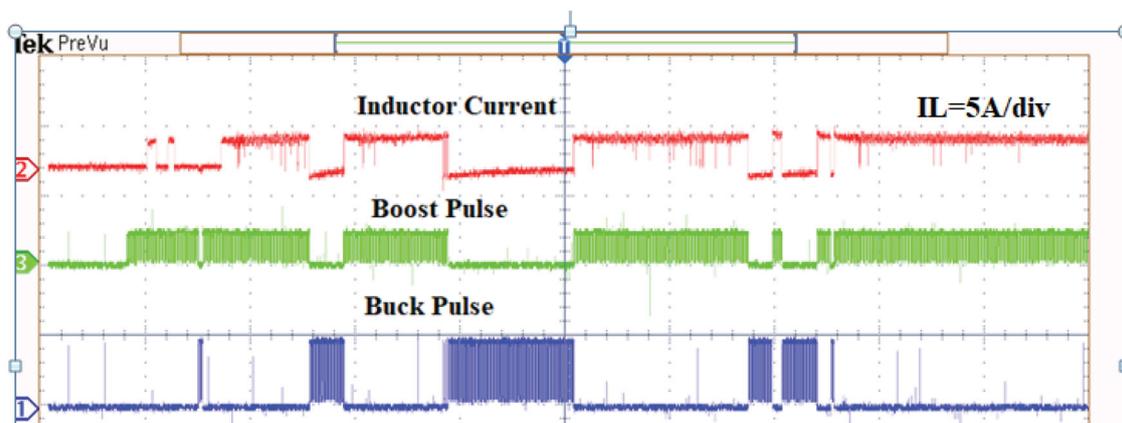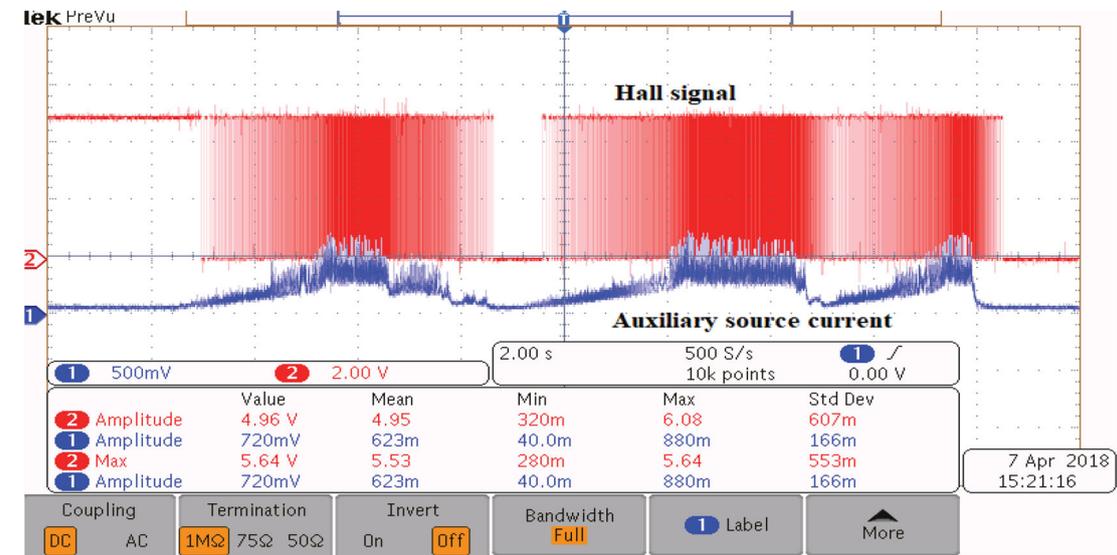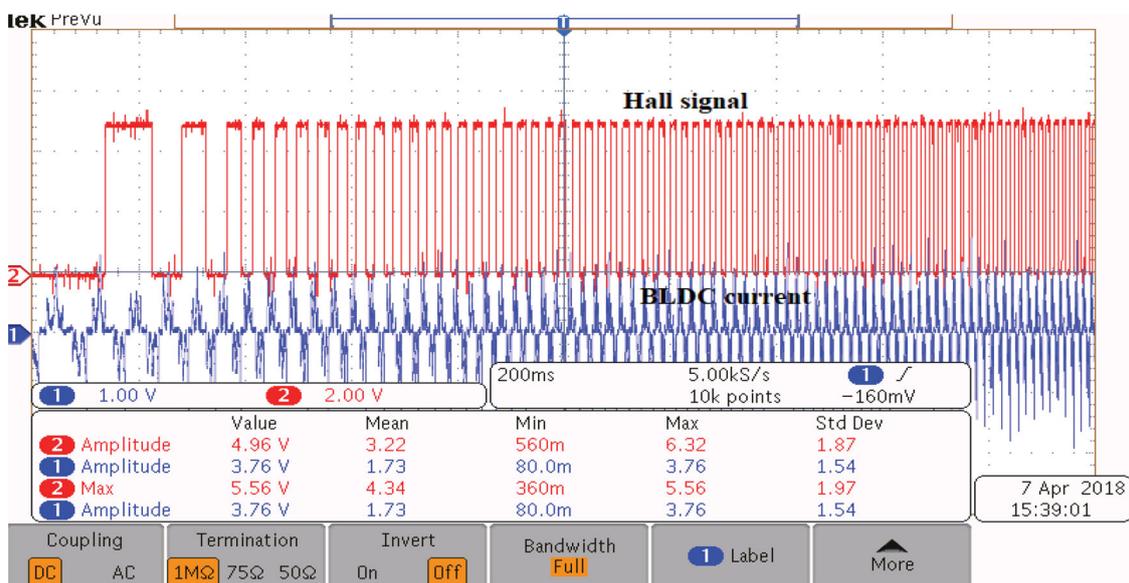

Figure 19. Inductor current, boost and buck pulse waveform for acceleration and constant speed operation.

Figure 20. (a) Hall signals during acceleration; (b) Hall signal and stator current of BLDC Motor during acceleration.

application is proposed. The developed power management control scheme using hybrid fuzzy PI controller offers bidirectional power management and robust fast tracking capability. It also provides better flexibility to combine different characteristics sources to operate at their optimal points. Thus effective utilization of sources and better dynamic responses are provided. Detailed simulation study and performance comparisons with conventional controller are performed to highlight the performance of the proposed controller, which inhibits the best attributes of PI and fuzzy controller to produce better response. The performance of the PSC based multi-input converter system with the proposed hybrid controller is verified and compared with the conventional PI and fuzzy controller. The experimental verification is conducted with the proposed controller in tracking a pre-defined speed profile to have the realization of electric vehicle.

Disclosure statement

No potential conflict of interest was reported by the authors.

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