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A Fuzzy Controlled SEPIC-ZETA Converter with Single Stage Operation for Application in Electric Vehicle

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Abstract: ***In this paper a SEPIC-ZETA power factor correction converter is introduced with fuzzy control for better performance. The controller of the converter is updated with 49 rule base fuzzy interface system with 7 membership functions in each input variable. The novel proposed converter operating modes are observed with change in switching states. For application a three-phase induction machine with inverter is connected to the proposed circuit. The characteristics of the converter and the machine are studied using MATLAB Simulink environment.***

I. INTRODUCTION

In recent years utilization of IC (Internal Combustion) engine vehicles like petrol and diesel engines, are causing huge air pollution and are being one of the major reasons for global warming. These IC engine vehicles are to be replaced with no emission vehicles, where there is no emission of hazardous gases causing air pollution. To achieve this plug-in electric vehicle [1] are used which run on batteries, power electronic converters and electrical motors. All plug-in electric vehicles use buck and boost converters to charge and discharge the batteries. Buck circuits are used for charging the battery and boost circuits [2] are used to run the vehicle motors. There are many ways to charge the battery, which includes charging though conventional single-phase AC supply, or high rating DC charging stations, renewable energy power like solar panels etc. Most of the plug-in electric vehicles are integrated with bidirectional DC-DC converter which can operate as buck and boost which can charge the battery during regenerative braking. The conventional two stage converter with individual buck converter for charge and boost converter for discharge is replaced with novel single bidirectional converter [8] with reduced passive and active components. The reduction in components reduces power losses of passive devices, switching losses of active devices with increase in efficiency and decrease of cost. The proposed converter includes on-board charging circuit which can be plugged to single phase AC mains. To connected AC mains to a DC-DC converter [3] is done by putting a diode bridge rectifier which converts single phase AC to variable DC. A SEPIC-ZETA converter circuit [4] [5] is connected after the diode bridge rectifier which can operate in both buck and boost modes with respect to change in switching states. A three-phase inverter (which converters DC to three phase AC) is connected to the SEPIC-ZETA converter running an induction machine. The three-phase inverter is operated using sinusoidal pulse width modulation technique controlling the speed of the machine. The complete circuit with AC input mains, proposed SEPIC-ZETA converter [6] and induction machine is shown below.

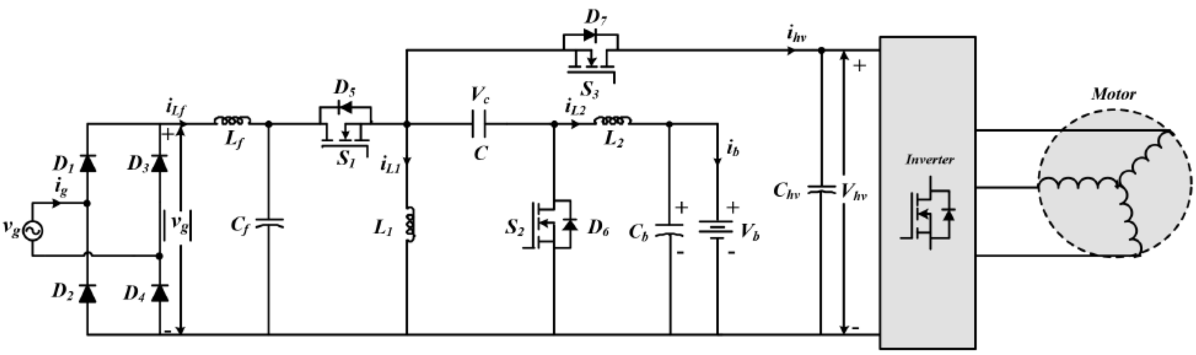

Fig. 1: Proposed SEPIC-ZETA converter with three phase induction machine

In the above proposed circuit S1 is the buck switch and S2 is the boost switch. S3 is the switch which disconnects the induction machine during charging mode. Lf and Cf are input DC filter to reduce ripple in DC voltage. L1 and L2 are charge storage inductors which increase and decrease the voltage . L1 is buck inductor and L2 is boost inductor. The capacitor C is used for resonance and Cb capacitor is used to reduce ripple in voltage Vb across battery.

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The operating states and design of the converter is given in section II, the SEPIC-ZETA fuzzy controller is given in section III followed by results and discussion in section IV and conclusion in section V.

II. CONVERTER CONFIGURATION AND WORKING

The proposed circuit operates in three modes

a) Charging through AC mains supply
b) Motoring mode running the induction motor through battery
c) Regenerative braking mode, charging the battery from the machine

In the first mode of operation (buck mode) power electronic switches S2 and S3 is maintained in OFF state where only S1 is operating. The current flow of ON and OFF states of the switch S1 in AC mains charging state is shown below.

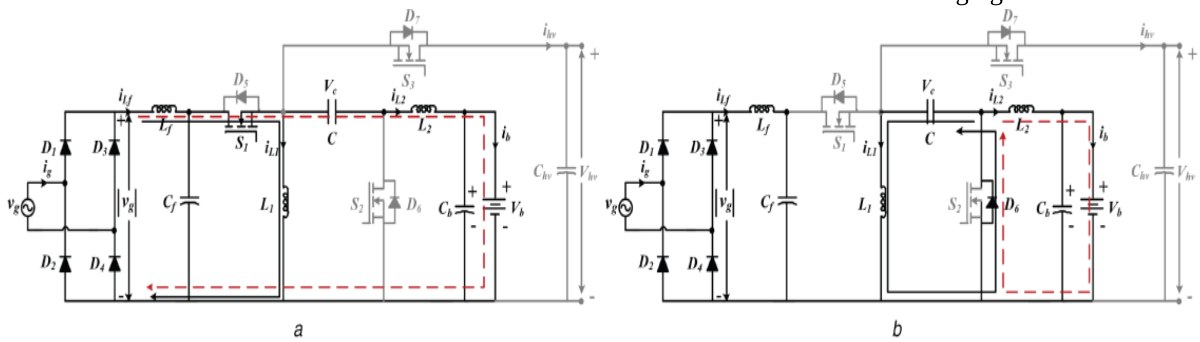


Fig. 2: AC mains charging buck mode a) Switch ON state of S2; b) Switch OFF state of S2

It can be observed that with switch S3 in OFF state the inverter circuit is completely cut off from the proposed circuit which doesn't drive the machine in this mode. The only operating switch is S1 which makes the circuit to work in buck mode. During ON state of switch S1 the battery is charged trough AC mains diode bridge rectifier, inductor Lf, S1, C and L2 inductor. When the voltage required [9] goes beyond the required voltage for charging the battery the switch S1 is turned OFF, making the battery charge through the charge of inductors L1 L2 and capacitor C. The body diode of switch S2 acts as freewheeling to avoid circulating currents. When the charge of the battery reaches maximum the circuit operation is now changed to mode 2 which is discharge mode (boost mode) where the operating switch is only S2. In this mode the switch S1 is maintained OFF as the AC mains supply is disconnected during vehicle movement. The switch S3 is also maintained OFF as the body diode of S3 will be operating during the discharge from the battery. The operating states of mode 2 (boost mode) is shown below.

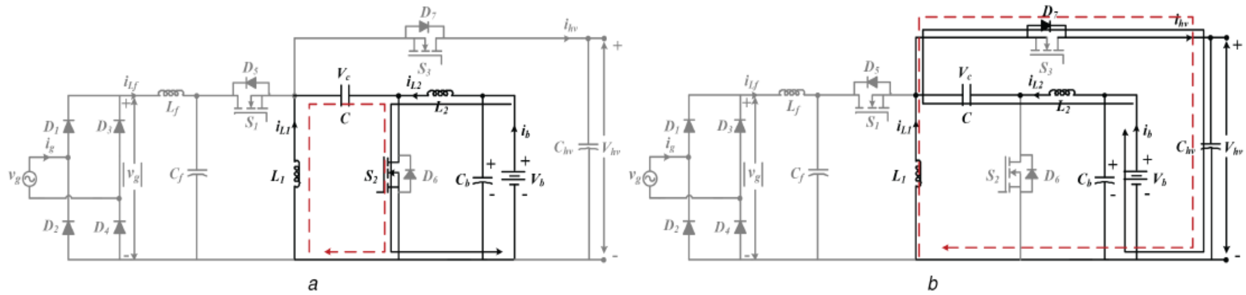
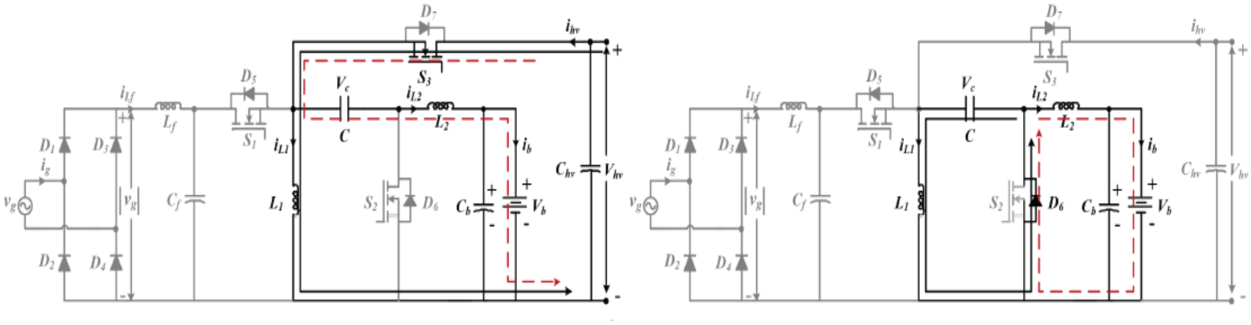


Fig. 3: Discharge mode a) switch S2 ON state b) switch S2 OFF state

During the ON state of the switch S2 the inductor L2 is charge from the battery [10]. The capacitor C and inductor L1 are also charged with low current. When the switch S2 is turned OFF the charged inductor is now in series with the battery which increase the voltage at the node of S3 switch. The high voltage $V_b + V_{L2}$ is discharged into the inverter circuit through body diode of switch S3 and makes the induction machine to operate. This cycle switching of S2 is done at very high frequency, making the output of the converter very high helps to run the induction machine. The last mode of operation is regenerative braking mode where only switch S3 operates and switches S1 S2 are maintained in OFF state. The operating states of mode 3 are shown below.



a b

Fig. 4: Regenerative breaking mode a) switch S3 ON state b) switch S3 OFF state

During regenerative braking mode, the induction machine operates as generator where the current flows from machine to battery. As the voltage from the machine will be high, the circuit operates in buck mode where S3 acts as buck switch. During the ON state of switch S3 the charge from the machine is fed to battery through capacitor C and L2 inductor. When the voltage at the terminals of the battery is beyond the required level the switch S3 is turned OFF making the battery to charge through inductor L2. When the inductor L2 is charged the body diode of switch S2 acts in freewheeling. The switching of the S3 is done at very high frequency until the charge from the machine is completely transferred to the battery making it to stop. The passive element parameter selection for the SEPIC-ZETA converter [5] [7] are taken with respect to input voltage (Vg), battery voltage (Vb) and switching frequency (fs).

L1 and L2 inductor selection

$$L1 = \frac{V_g^2 . V_b}{2p_g fsV_{gmax}+V_b} \text{ ....(1)}$$

Here, pg is power input to the circuit

$$L2 = \frac{R_L V_{gmax}}{2.V_{gmax}+2fsV_b} \text{ ....(2)}$$

Here RL is the resistance of the load connected to the circuit.

The selection of coupling capacitor depends on L1 and L2 inductors. It is given as

$$C = \left(\frac{1}{2\pi fr}\right)^2 \left(\frac{1}{L1+L2}\right) \text{ ....(3)}$$

The filter inductance Lf and filter capacitor Cf are given as

$$C_f = \frac{Ig \tan \theta}{2\pi f_L V_g} \text{ ....(4)}$$

Here, Ig is the input current from the single-phase AC source, ϴ is the power factor angle considered to be very low as 2^0, fL is the frequency of the single phase source.

$$Lf = \frac{1}{4\pi^2 f_c^2 C_f} \text{ ....(5)}$$

The value of Lf depends on filter capacitance Cf value. fc is the the cut off frequency.

The battery capacitor parameter is given as

$$Cb > \frac{Pb}{4f_L \Delta Vb.Vb} \text{ ....(6)}$$

Here Pb is power output of battery, Vb is battery terminal voltage and ΔVb is ripple in battery voltage considered to be 2%.

With input voltage of Vg = 230V; fL = 50Hz; fs = 20kHz, Vb = 300V; Pb = 1kW the value of the passive elements for the circuit are finalized as

L1 = L2 = 2mH; C = 10uF; Cb = 2200uF; Lf = 1.58mH; Cf = 1.14uF.

III. CONTROLLER OF PROPOSED CONVERTER

The control structure of the proposed circuit is shown below with feedback signals taken from the circuit. The current controllers used in the control structure are PI controllers [11] which are further updated with fuzzy logic controller [12] for better performance [13] [14].

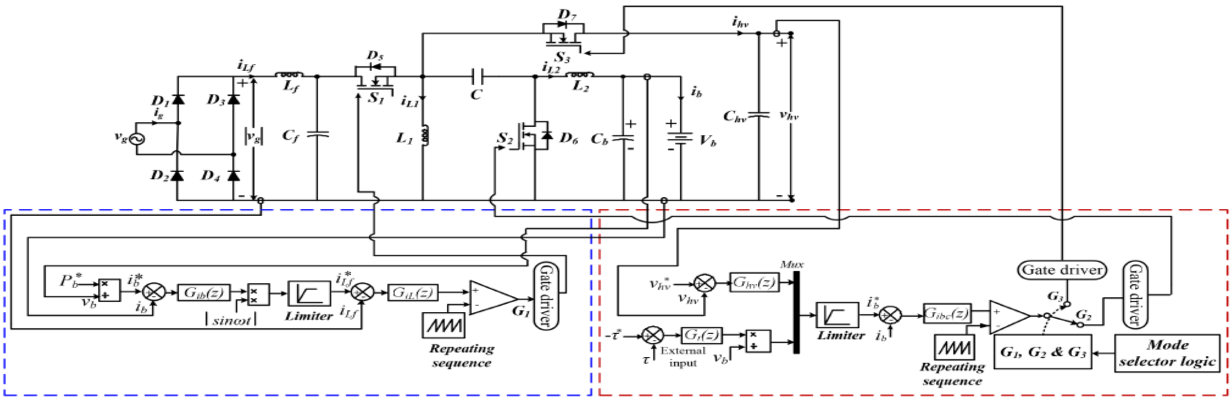


Fig. 5: Control structure of proposed circuit

The complete control structure is divides into two parts, in which one-part controls only switch S2 during mode 1. The other part control switches S2 and S3 during modes 2 and 3 respectively. The compares signals of reference and measured values are fed to current controllers which are PI controllers. These controllers calculate the required value for generation of reference signal [5] with which the switches are operated. All the generated values from the controllers are duty ratios (D) which are compared to high frequency (20kHz) sawtooth wave, generating pulses for driving the power electronic switches. The controller for switch S1 takes feedback of voltage from the battery (Vb) from which reference battery current ib* is calculated, give as

$$I_b^* = \frac{P_b^*}{V_b} \dots\dots\dots\dots\dots\dots\dots(7)$$

The error from the comparison is fed to PI current controller [11] generating reference maximum current value (Im). The resultant Im value is multiplied by |sinwt| creating reference filter inductor current (iLf*). Now the reference filter inductance value is compared to measured filter inductance current and fed to PI controller which generated required duty ratio for the switch S1. The duty ratio of the switch S1 is controlled with respect to reference power input to the battery (Pb*). The second controller takes feedback [9] of DC link voltage (Vhv) of the circuit and electromagnetic torque (Te) from the induction motor. The Vb comparison and Te comparison generates the required current of the battery ib*. The required power of the motor is calculated by electromagnetic toque reference Te*, and the required current is calculated by battery voltage (Vb). The reference current (ib*) and measured current (ib) are compared and fed to PI controller generating duty ratio for the switches S2 or S3. The PI controller is further updated with fuzzy logic controller with seven membership functions in each variable and 49 rule base [12]. Input membership functions of the fuzzy controller are taken as gauss and output membership functions are taken as triangular which are set in particular range as per the requirement. The input and output variable membership functions with rules base are shown below.

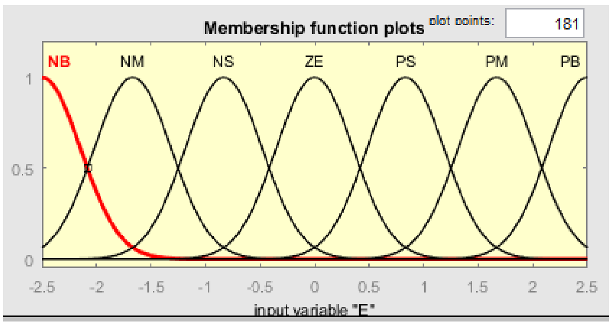


Fig. 6: Input membership functions

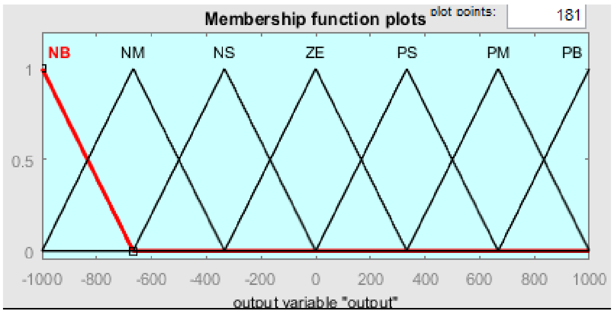


Fig. 7: Output membership functions

	← e →	NB	NM	NS	EZ	PS	PM	PB
	PB	**Z**	PS	PM	PB	PB	PB	PB
↑	**PM**	NS	**Z**	PS	PM	PB	PB	PB
	PS	NM	NS	**Z**	PS	PM	PB	PB
de	**EZ**	NB	NM	NS	**Z**	PS	PM	PB
	NS	NB	NB	NM	NS	**Z**	PS	PM
↓	**NM**	NB	NB	NB	NM	NS	**Z**	PS
	NB	NB	NB	NB	NB	NM	NS	**Z**

Fig. 8: Rule base for fuzzy interface system

With the above proposed circuit and controller [12] the design is modelled in MATLAB software with results generated in graphs with respect to time.

IV. RESULTS AND DISCUSSION

The simulation of the proposed circuit with induction motor drive is run for 1sec with sampling time Ts = 1μsec. The rating of the induction machine is taken as 4kW, 230V, 50Hz. Rs = 1.405ohms, Rr = 1.395, Ls = Lr = 5.839mH, Lm = 0.1722, J = 0.0131 Kg-mt2, number of poles p = 4. The same passive elements parameters and induction machine are used for both the controller structure and results are compared.

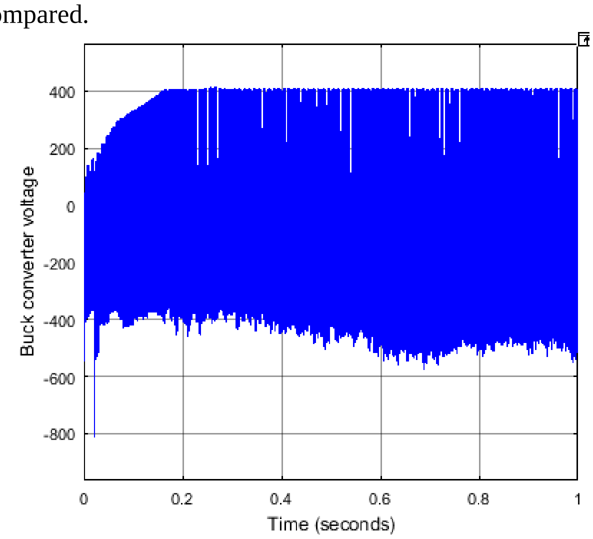


Fig. 9: Buck converter voltage during mode 1

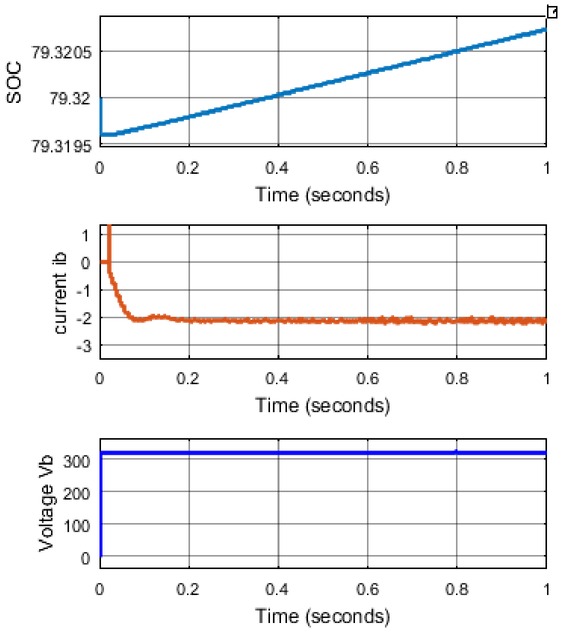


Fig. 10: Battery characteristics during charging condition

In the above graph the current is in negative direction as the battery is charging from the AC main supply. The SOC (State Of Charge) of the battery is raising as the battery is charging.

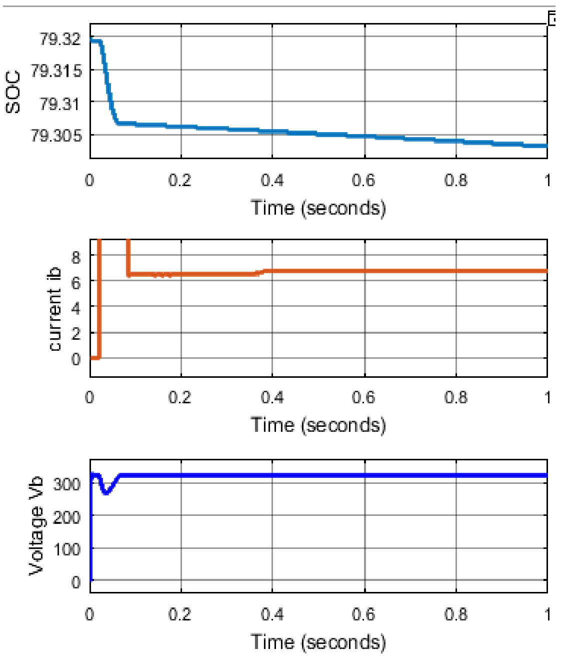


Fig. 11: Battery characteristics during discharging condition

In the above mode the battery current is in positive direction which implicates that the battery is discharging to the induction machine. The SOC of the battery is also dropping with respect to the discharge current rate.

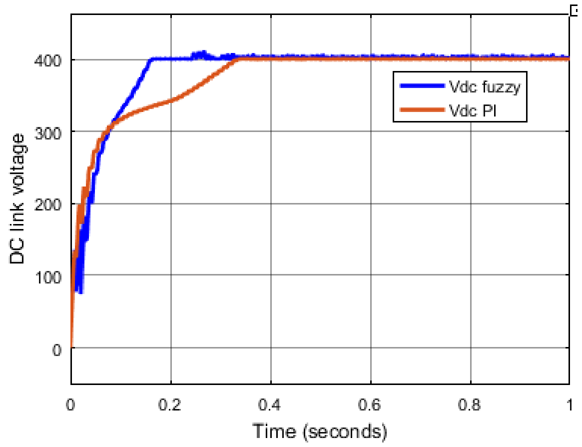


Fig. 12: DC link voltage comparison of PI and fuzzy logic controller

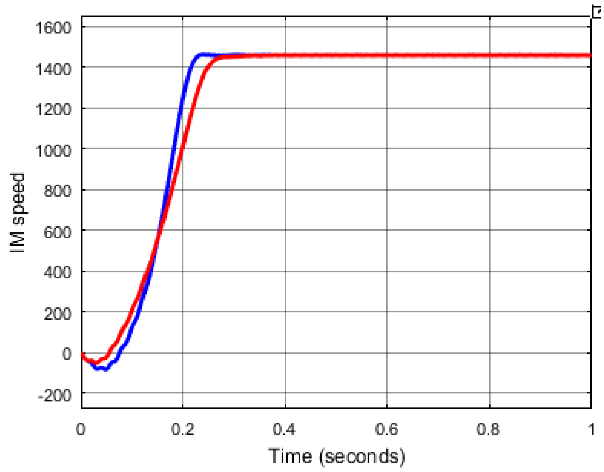


Fig. 13: Speed comparison of induction machine with PI and fuzzy controller

V. CONCLUSION

With the above results from the simulation of the proposed SEPIC-ZETA converter in two conditions (charge and discharge) with comparison of PI and fuzzy controller it can be observed that the DC link voltage with fuzzy controller settles faster compared to PI controller. As the DC link voltage settles faster the speed of the machine also settles at required speed with faster response rate. It can be concluded that the controller with fuzzy interface system has less response time compared to PI control structure.

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