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POWER QUALITY IMPROVEMENT IN A INDUCTION MOTOR DRIVE USING ZETA CONVERTER AS SINGLE STAGE PFC CONVERTER

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ABSTRACT

New recommendations and present standards have increased the interest in power factor correction circuits. Solid-state switch-mode converters have reached a matured level for improving power quality in terms of Power Factor Correction (PFC), reduced total harmonic distortion at input ac mains and precisely regulated dc output in buck, boost, buck–boost and multilevel modes with unidirectional and bidirectional power flow. In this paper, an improved power quality converter employing Zeta converter topology with conventional PI is used to feed a Induction Motor (IM) drive. Normally, the IM drive consists of a three-phase voltage source inverter (VSI) which is fed from single-phase AC mains through a diode bridge rectifier (DBR). In this proposed system a conventional PI based Zeta converter is used after the DBR and it performs power factor correction (PFC) at input AC mains and voltage control at DC link, in a single-stage. The proposed IM drive is designed, modeled and its performance is evaluated in Matlab-Simulink environment. Obtained results are compared with SEPIC converter fed IM drive and results are presented to demonstrate an improved power quality that is achieved with zeta converter over that of SEPIC converter based IM drive in wide range of the speed control. Due to increasing importants of Energy efficiency issues the PFC technology has become center of attraction of many industries and becomes states of art. Due to energy conversion and regulation it has become mandatory to conserve electric power. Hence PFC becomes the bench mark for energy conservation with (VSD) variable speed drive.

INTRODUCTION

Conventionally, rectifiers called as ac–dc converters, are developed using diodes and thyristors to provide uncontrolled and controlled dc power with unidirectional and bidirectional power flow. The demerits of conventional converters are injected current harmonics, voltage distortion, poor power factor at input, large size of ac and dc filters and low efficiency. These are the fact that need to comply with "standards" or "recommendations" and have forced to use PFC in power supplies. IPQCs are classified on the basis of topology and type of converter used. These converters are sub-classified as boost (Khan and Erickson 1986; Albach 1986), buck (Tso and Chan 1988; King 1991), buck – boost (Manias *et al.*, 1986), and multilevel (Zhang *et al.*, 1995; Maksimovic and Erickon 1995) with unidirectional and bidirectional power flow. The classification based on converter type are sub-classified as step-up/step down choppers, voltage source(VSI) and current-source inverters (CSI), etc., and these two types of classifications of IPQCs are portrayed in Figs. (1) & (2).

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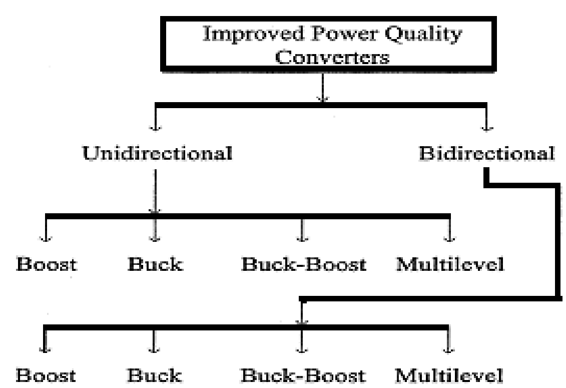

Fig. 1. Topology-based classification of IPQC

Moreover, there are many international PQ standards that are universally accepted such as IEC 61000-3-2 (Limits for Harmonic Current Emissions 2000), IEEE 519 etc. which emphasize on low harmonic contents and near unity PF current to be drawn from AC mains by various loads. There has been some efforts (Mohan *et al.*, 1995; Pressman 1998; Divan *et al.*, 1992) for use of power factor correction (PFC) converters with regard to PQ improvement, however it uses, a two-stage cascaded converter which consist of a boost converter for PFC at front-end followed by DC –DC converter in second stage for voltage regulation. At second stage usually a flyback converter has been used for low power application and a full-bridge converter for higher power applications. However, the demerits of two stage PFC converters are high cost and complexity in implementing two separate switch-mode converters which encourage use of a single stage PFC converter (Oscar Garcia *et al.,* 2003). Therefore, an improved single stage PQ converter based drive is almost essential for the Induction Motor. A Zeta DC-DC converter is employed as a single - stages PFC converter for power quality improvement in the IM drive due to its simplicity and low cost among other single switch converters. Additionally it provides minimum switching losses with reduced voltage drop in the secondary winding of the high frequency transformer resulting in improved efficiency of the PFC converter. The proposed single-stage PFC converter based drive needs a careful design to operate over a wide range of operating conditions for a Induction Motor drive i.e. variable input AC voltage and speed of the motors. the MOSFET of PFC converter. Use of a high switching frequency results in a instantaneous control of DC link voltage and effective PFC action along with additional advantage of reduced size transformer and filters. The switching device, switching losses and operating power level are major factors that decides optimum switching frequency. A metal oxide field effect transistor (MOSFET) is used as the switching device for the proposed PFC converter.

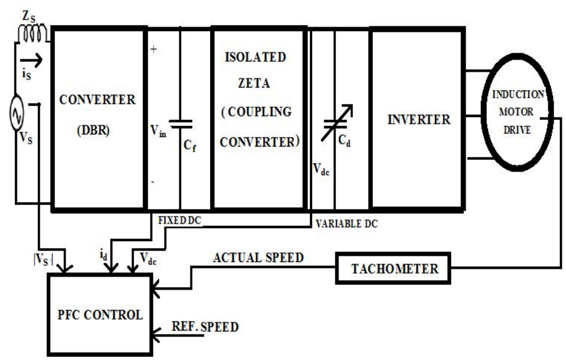

Fig.3. Schematic diagram of the proposed Zeta PFC converter fed IM drive

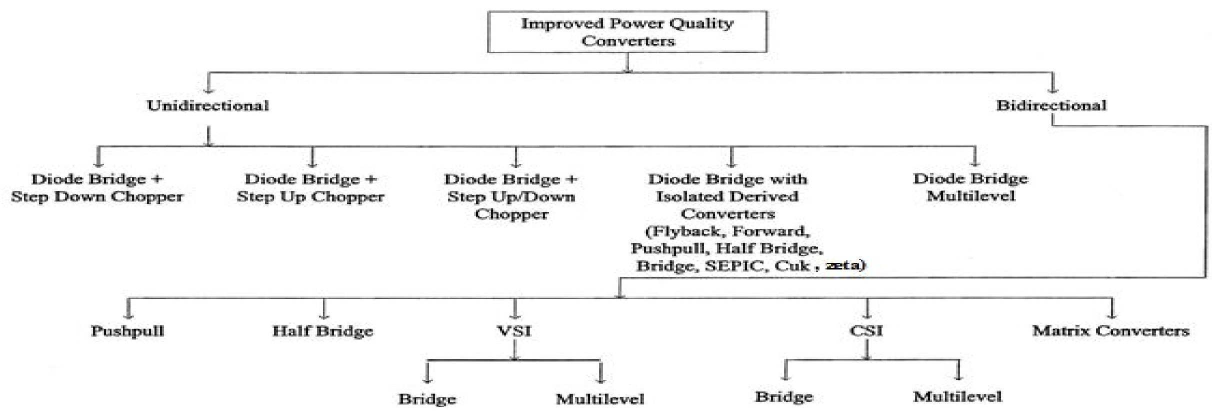

Fig. 2. Converter-based classification of improved power quality converters

Proposed control scheme for PFC converter

The prefered control scheme for improved PQ converter i.e. the Zeta converter as PFC converter is shown schematically in Fig. 3 which uses average current control with current multiplier approach. The Zeta converter controls the DC link voltage as well as performs PFC action by its duty ratio (D) at a constant switching frequency (f_s). The PFC control scheme also employs an inner current loop and an outer voltage loop. The PFC can be achieved by tracking the average current to a reference value generated by multiplying the output of voltage error amplifier and a fraction of rectified input voltage. Fig. 4. display the continuous current mode (CCM) operation of the proposed PFC converter. A proportional-integral (PI) controller which forms an integral part of the controller processes the voltage error resulting from the comparison of set voltage reference and sensed voltage at DC link. The output signal from PI controller is then multiplied with a unit template of input AC voltage and compared with DC current sensed after the DBR. The resultant current error is amplified and compared with a saw-tooth carrier wave of fixed frequency (f_s) for generating the PWM pulses for controlling

Design of PFC zeta converter for induction motor drive

The suggested PFC isolated Zeta converter is designed to drive an induction motor with an objective of PQ improvement at AC mains. The proposed scheme consists of a DBR, a Zeta converter and an output ripple filter.

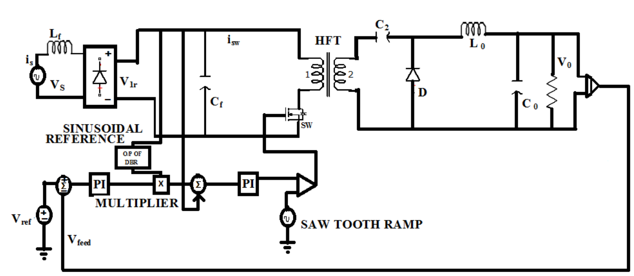

Fig. 4. Average current control of Zeta converter for CCM operation

The Zeta converter controls the DC link voltage at a given set reference value V_{dc}. The design equations for DC link voltage of PFC converter is given by,

$$V_{dc} = (N_2/N_1)\, V_{in}\, D/(1-D) \quad (1)$$

Where V_{dc} is DC Link voltage, N_1, N_2 are number of turns in primary, secondary windings of the high frequency (HF) isolation transformer, respectively.

The DBR has average output voltage (V_{in}) for a given AC input voltage (V_s) related as,

$$V_{in} = 2\sqrt{2}V_s/\pi \quad (2)$$

The design equations for intermediate capacitor of PFC converter can be written as,

$$L_m = D\, V_{in} / \{f_s\, (\Delta I_{Lm})\} \quad (3)$$

The output ripple filter is designed for constant output voltage with output inductance (L_o) and capacitance (C_d) so that the peak to peak ripple of inductor current (ΔI_{Lo}) and capacitor voltage (ΔV_{Cd}) is maintained within specified value for the given switching frequency (f_s). The values of output filter inductor and capacitor are calculated as,

$$L_0 = 1-D\, V_{dc}/\{f_s\, (\Delta I_{L0})\} \quad (4)$$

$$C_d = I_{dc}/(2\omega \Delta V_{cd}) \quad (5)$$

Modeling of proposed IM drive

The modeling of proposed isolated Zeta converter fed IM drive involves modeling of the PFC converter and IM drive in the form of mathematical equations. The combination of these individual models represents a complete model of proposed PFC drive.

PFC Converter

The modeling of PFC converter involves the modeling of DC link voltage controller, reference current generator and PWM controller.

DC Link Voltage Controller

A PI controller is used as DC link voltage controller which provides a control output signal (I_c) to minimize the input voltage error. If, $V^*_{dc}(k)$ is reference DC link voltage, $V_{dc}(k)$ is sensed DC link voltage at k^{th} instant of time then, the voltage error $V_e(k)$ is calculated as,

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \quad (6)$$

At k^{th} instant the controller output is given as, Ic

$$I_C(k) = I_C(k-1) + K_{pv}\{V_e(k) - V_e(k-1)\} + K_{iv}V_c(k) \quad (7)$$

Where $I_C(k)$ is controller output, K_{pv} and K_{iv} are the gains of the voltage PI controller.

Reference Converter Current

The reference input current of the Zeta converter (i^*_d) is given as,

$$i^*_d = I_c\, (k)\, u_{vi} \quad (8)$$

The reference input current is generated using the unit template of the voltage at AC mains and output of the PI controller. where u_{vi} is the unit template of AC mains voltage at input, calculated as,

$$u_{vi} = v_d/V_{sm}; \ = |v_s|;\ v_s = V_{sm}\sin\omega t \quad (9)$$

Where ω is the frequency in rad/sec at input AC mains.

PWM Controller

The reference input current of the Zeta converter (i^*_d) is compared with its sensed current (i_d) to generate the current error $\Delta i_d = (i^*_d - i_d)$. This current error is amplified by gain k_d and compared with fixed frequency (f_s) saw-tooth carrier waveform $m_d(t)$ to generate PWM signals for the MOSFET of the PFC converter as,

If $k_d\Delta i_d > m_d(t)$ then S =1 (10)

If $k_d\Delta i_d <= m_d(t)$ then S = 0 (11)

where S is the switching function representing "ON" position of the MOSFET of the Zeta converter with S=1 and its "OFF" position with S=0.

Induction Motor Drive

The IM drive has a speed controller, a reference winding current generator, a PWM current controller, a VSI and a Induction motor as major components.

Speed controller

A PI controller is used as speed controller which closely follows the reference speed. If at k^{th} instant of time, $\omega^*_r(k)$ is the reference speed, $\omega_r(k)$ is the actual rotor speed then the speed error ωe(k) can be calculated as,

$$\omega_e(k) = \omega^*_r(k) - \omega_r(k) \quad (12)$$

This error in speed is fed to a speed controller to get a control signal. The controller's output at k^{th} instant T(k) is given as,

$$T(k) = T(k-1) + K_{p\omega}\{\ (k) - \omega_e(k-1)\} + K_{i\omega}\omega_e(k) \quad (13)$$

Where $K_{p\omega}$ and $K_{i\omega}$ are the proportional and integral gains of the speed PI controller.

Reference Winding Current Generator

The stator winding current amplitude can be calculated using vector model approach. The reference phase currents of the Induction Motor are denoted by i^*_a, i^*_b, i^* for phases a, b, c respectively. For duration of 0-60º the reference currents are given as,

$$i^*_a = I,\ i^*_b = -I^* \text{ and } i^*_c = 0 \quad (14)$$

Similarly, the reference winding currents during other 60º duration are generated in rectangular 120º block form in Phase with sinusoidal voltage of respective phases.

PWM Current Controller

The sensed currents (i_a, i_b, i_c) are compared with reference winding currents in a PWM current controller to get the current errors $\Delta i_a=(i^*_a - i_a)$, $\Delta i_b=(i^*_b - i_b)$, $\Delta i_c=(i^*_c - i_c)$ for three phases of the motor. Before comparison with a fixed frequency carrier waveform m(t) to generate the switching sequence for the VSI, the current errors (Δi_a, Δi_b, Δi_c) are amplified by gain k_1 and is shown for phase "a",

If $k_1\Delta i_a > m(t)$ then $S_a = 1$ (MOSFET "ON") (15)

If $k_1\Delta i_a \leq m(t)$ then $S_a = 0$ (MOSFET "OFF") (16)

The switching sequences S_b and S_c are generated using similar logic for other two phases of the motor.

Voltage Source Inverter

The VSI bridge feeding Induction motor uses Metal Oxide Semiconductor Field Effect Transistor (MOSFETs) to reduce the switching stress, because of its efficiency increases at high switching frequency. Fig. 5 shows an equivalent circuit of a VSI fed Induction Motor. The output of VSI for phase "a" is given as,

$v_{a0} = (V_{dc}/2)$ for $S_{a1} = 1$, and $S_{a2} = 0$ (17)

$v_{a0} = (-V_{dc}/2)$ for $S_{a2} = 1$, and $S_{a1} = 0$ (18)

$v_{a0} = 0$ for Sa1 = 0, and Sa2 = 0 (19)

The voltages (v_{bo}, v_{co}, v_{bn}, v_{cn}) for other phases of the VSI fed Induction motor are generated using similar logic

$$v_{an}=v_{ao}-v_{n0} \quad (20)$$

where v_{ao}, v_{bo}, v_{co}, and v_{no} are voltages of 3-phases and neutral point (n) with respect to virtual mid-point of the DC link voltage shown as "o" in Fig. 5. The voltages V_{an}, v_{bn}, v_{cn} are voltages of 3-phases with respect to neutral point (n). The values 1 and 0 for S_{a1} or S_{a2} represent "ON" and "OFF" condition of respective MOSFETs of the VSI. The switching of other MOSFETs of the VSI i.e. S_b and S_c are obtained in a similar way.

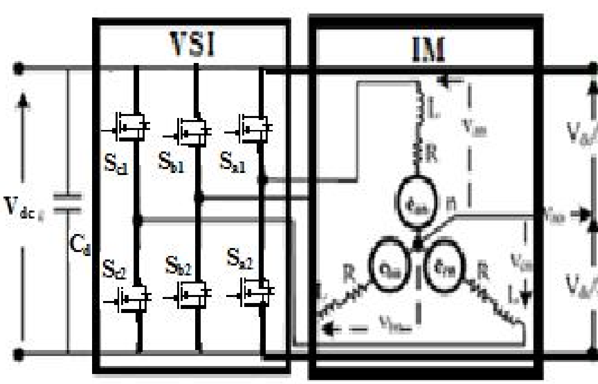

Fig. 5. Equivalent Circuit of a VSI fed IM Drive.

Performance of proposed PFC drive

The isolated Zeta PFC converter fed IM drive is modeled in Matlab-Simulink environment and its performance is studied. The performance of the proposed PFC drive is evaluated in terms of total harmonic distortion (THD) and stator current of IM drive and PF at different speeds of the motor with and without load. Obtained results are compared with SEPIC converter fed IM drive. Obtained results are summarized in Tables I-IV and the responses are displayed in Figs.6-18.

Matlab/Simulink modelling and simulation results

Here the simulation is carried out for two cases involving isolated SEPIC and Zeta converter feeding IM drive.

Case1: MATLAB schematic of isolated SEPIC converter fed IM drive.

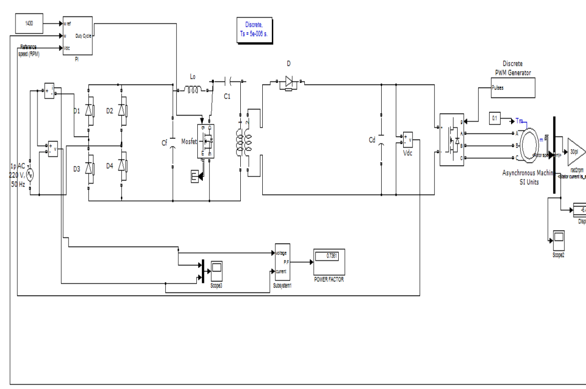

Fig. 6. Matlab/Simulink model of proposed isolated SEPIC converter fed IM drive

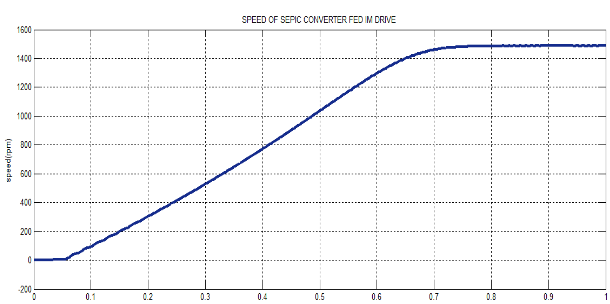

Fig. 7. Speed of SEPIC converter fed IM drive

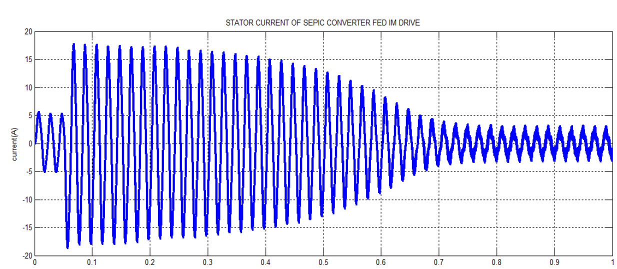

Fig. 8. Stator current fed by SEPIC converter

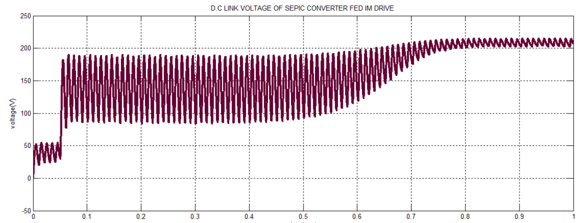

Fig. 9. Output voltage of SEPIC converter

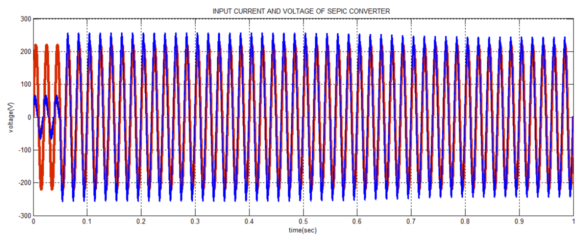

Fig. 10. Input current and voltage of SEPIC converter

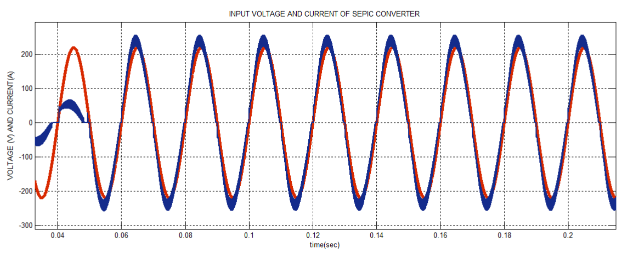

Fig. 11. Zoomed view of input current and voltage of SEPIC converter

Fig. 7. Displays the speed response of IM drive obtained with isolated SEPIC converter. Fig. 8. Portrays Stator current fed by isolated SEPIC converter. Fig. 9. Displays the output voltage obtained from SEPIC converter and Input current and voltage response of SEPIC converter are displayed in Fig. 10 and Fig. 11. Shows the zoomed view of input current and voltage of SEPIC converter. Since the voltage and current waveforms are approximately in-phase with each other, the power factor Fig. 13. expected to be near unity.

Table I. Pq indices with different load torque in p.u.

Reference speed=1430

Input current THD	P.F at input side	Speed	Torque in p.u
0.537	0.9483	1427	0.1
0.537	0.9483	1424	0.15
0.537	0.9484	1424	0.2
0.538	0.9485	1322	0.25
0.538	0.9487	1422	0.3

Table II. Performance of drive under speed control at 220v input ac voltage

S.NO	SPEED (rpm)	THD IN CURRENT	P.F
1	500	0.537	0.9482
2	800	0.537	0.9482
3	1000	0.537	0.9482
4	1200	0.538	0.9481
5	1400	0.539	0.9480

Case2: MATLAB schematic of isolated Zeta converter fed IM drive

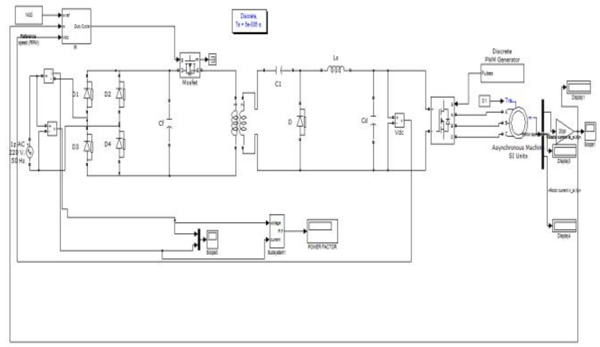

Fig. 12. Matlab/Simulink model of proposed isolated Zeta converter fed IM drive

Fig. 13. Speed response of Zeta converter fed IM drive

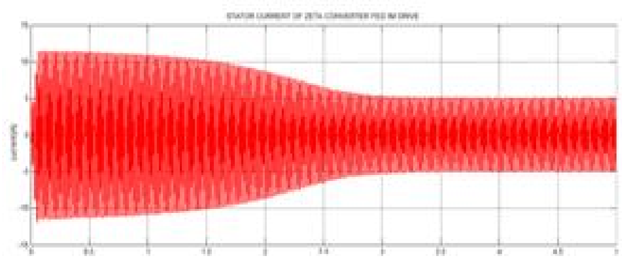

Fig. 14. Stator current of Zeta converter fed IM drive

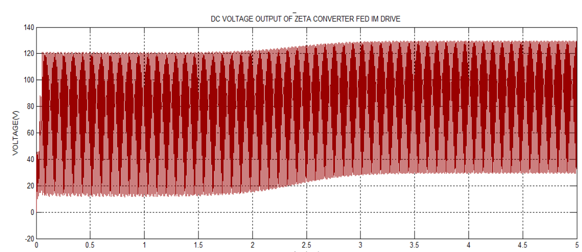

Fig. 15. Output D.C link voltage of Zeta converter fed IM drive

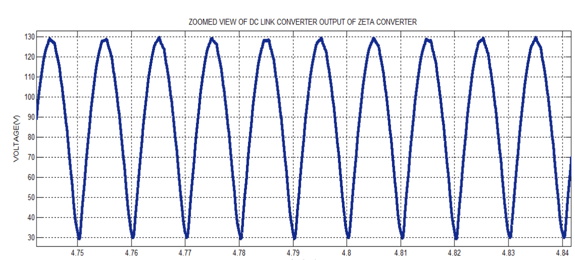

Fig. 16. Zoomed view of Output D.C link voltage of Zeta converter fed IM drive

Fig. 13. Portrays Speed response of Zeta converter fed IM drive, Fig. 14. Displays the stator current of Zeta converter fed IM drive, Output D.C link voltage of Zeta converter fed IM drive is displayed in Fig. 15. Fig. 16. Shows the zoomed view of Output D.C link voltage of Zeta converter fed IM drive.

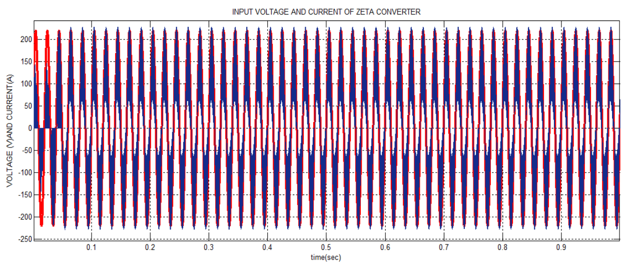

Fig. 17. Input current and voltage wave form of Zeta converter

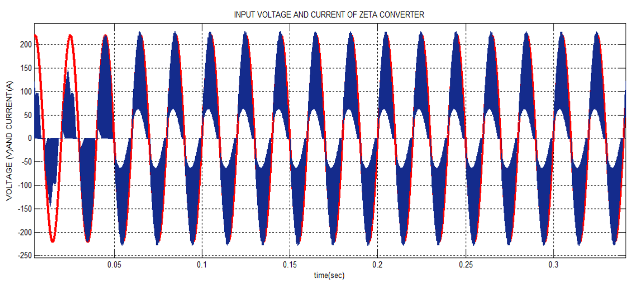

Fig. 18. Zoomed view of Input current and voltage wave form of Zeta converter

Table III. pq indices with different load torque in p.u.

Reference speed=1430

Input current THD	P.F at input side	Speed	Torque in p.u
0.5288	0.9533	1422	0.1
0.5288	0.9546	1413	0.15
0.5288	0.9558	1403	0.2
0.5288	0.9571	1393	0.25
0.5288	0.9585	1382	0.3

Table IV. Performance of drive under speed control at 220v input ac voltage

S.NO	SPEED (rpm)	THD IN CURRENT	P.F
1	500	0.5288	0.9658
2	800	0.5288	0.9546
3	1000	0.5288	0.951
4	1200	0.5289	0.9508
5	1400	0.5289	0.9508

Conclusion

Single stage isolated Zeta PFC converter has been preferred for speed control of induction motor drive. The speed of induction motor has been found proportional to the DC link voltage, thereby a smooth speed control is observed with Zeta PFC converter while controlling the DC link voltage and found to be better than SEPIC converter fed drive. An effective control of motor current within the desired limits during the transient conditions has been achieved by using a rate limiter in the reference DC link voltage. The based Zeta PFC converter has ensured nearly unity PF in wide range of the speed and the input AC voltage which is found to be worst in case of SEPIC based PFC converter fed IM drive. The stator current transient are observed to be well within the limit incase of Zeta converter fed drive than that of the SEPIC converter fed drive. From the careful comparison of the result it is observed that Zeta topology is most suitable for speed control of IM drive with improved performance measures. High input power factor is the index which is related to maximum efficiency of the drive. When drive operates at maximum efficiency the loss are optimum with reduced intake of power resulting in energy conservation.

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