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Power Quality Improvement in PMSM Drive Using Zeta Converter

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Abstract: This paper presents a various speed control strategies applied to improve the power quality in direct torque control of permanent magnet synchronous motor drive. Due to the higher efficiency, compact size and fast response, PMSM drive is considered. Zeta converter is proposed as it provides improved power quality in terms of low total harmonic distortion (THD), better efficiency and power factor correction in discontinuous mode of operation. The control schemes used for PMSM is include direct torque control (DTC) in this scheme electrical power conversion is performed by converting the AC mains voltage to a DC voltage is converted into a variable frequency, variable voltage AC by means of voltage sources inverter to feeds the PMSM.

The objective function is to achieve desired speed by using the proposed Zeta converter. Three case studies are implemented i.e., PMSM drive without speed control, Conventional DTC of PMSM Drive and PMSM drive DTC control using Zeta converter which describes the results regarding to various characteristics of PMSM drive. Also by using the Simulink model of proposed AC-DC ZETA converter fed DTC of PMSM drive using 2 level inverter and 3 level inverter Torque response, stator currents of proposed AC-DC ZETA converter fed DTC of PMSM drive results are presented by using MATLAB/SIMULINK.
Keywords: PMSM, PQ, PFC, VSI, PI, FC.

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM's) are finding application in air conditioning system, refrigerators, washing machines equipment due to their high efficiency, small size and fast dynamics response[1-3]. The control schemes used for PMSM's include direct torque control (DTC) technique [3].By using this scheme electrical power conversion is performed by converting the AC mains voltage to a DC voltage is converted into a variable frequency; variable voltage AC by means of voltage sources inverter to feeds the PMSM.

In normal cases AC-DC conversion is carried out by simply rectifying the AC input and the rectifier output is filtered by means of a large valued capacitor to get a nearly constant DC voltage output. In this conversion the input AC supply current is drawn in narrow pulses since the capacitor voltage variation is nearly constant. This large peak narrow pulse current causes power quality problems to nearly consumers, which includes a high values of Total harmonic distortion(THD)of supply current, high THD of input supply voltage ,low value of power factor (PF) and displacement factor (DPF) and poor distortion factor(DF).

In this paper, an AC-DC Zeta converter topology is used for providing regulated DC voltage to feed the voltage source inverter (VSI) employed in the direct torque controlled PMSM drive[4-9]. The proposed converter provides improved power quality in terms of low total harmonic distortion (THD), reduced crest factor (CF) of the AC supply current, high power factor of the AC mains and regulated output DC voltage. This converter topology is best for low cost variable speed drive applications employing a PMSM drive system.

II. SYSTEM CONFIGURATION

The schematic diagram of the direct torque controlled PMSM drive system is shown in figure. The output of the zeta converter is fed to the voltage source inverter of the direct torque controlled PMSM drive. That feed the three phase currents in the stator winding of the motor. This control stateragy can be used to control the speed of the PMSM drive by using direct torque controlled VSI.

The VSI is made up of six active bi-directional switches (her we used IGBT's with freewheeling diode). The motor is built with a position sensor for sensing the rotor position in the form of two signals, which are the sine and cosine waves of rotor position angle. The rotor speed (ω_r) of the motor is derived from these signals and is compared with the reference speed (ω_r^*). And that error signal (speed(ω_e)) is processed by the PI speed controller, which generates a reference torque ($T^*_{(K)}$). This reference torque is limited by a limiter. The limited reference torque (T^{*}_{ref}) is used to generate the torque error by comparing it with the estimated torque of the motor (T^{*}_{est}). Similarly the, reference flux (φ_{sref}) is obtained from the rotor speed of the motor and is also compared with the estimated stator flux of the motor (φ_s). Both torque error (ΔT_e) and flux error ($\Delta\varphi$) signals are used to determine the optimum switching vectors (S_a, S_b,S_c).By using this signals, the VSI controls the winding currents of the PMSM, there by controlling the speed of the motor in a desired manner.

Table 1: switching table for selection of inverter optimum voltage vector

Flux Error $d\varphi_s$	Torque Error dT_e	Sector					
		I	II	III	IV	V	VI
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_8	V_7	V_8	V_7	V_8	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_8	V_7	V_8	V_7	V_8
	-1	V_5	V_6	V_1	V_2	V_3	V_4

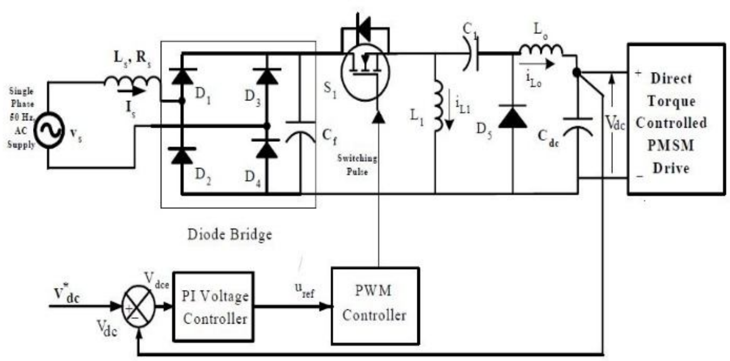

Fig1: Zeta converter fed direct torque controlled PMSM drive

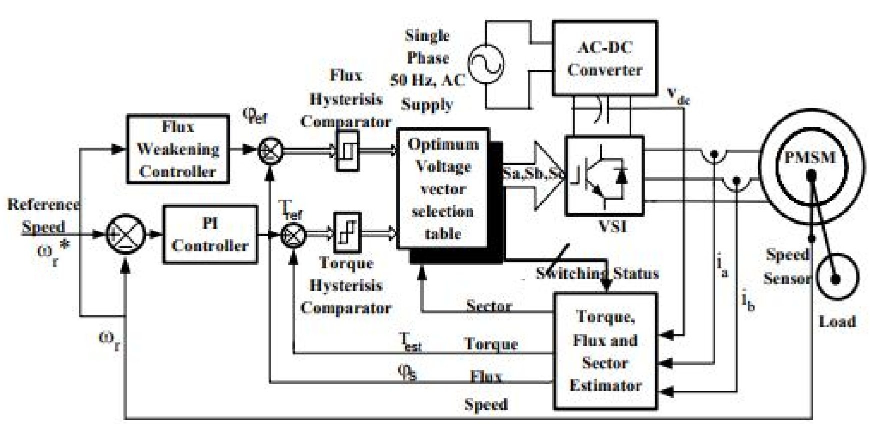

Fig2 . Block Diagram of Direct Torque Control Scheme Based PMSM Drive

III. DESIGN OF AC-DC ZETA CONVERTERSYSTEM

The Zeta converter is designed to operate in discontinuous current mode (DCM) as a voltage follower while providing inherent power factor correction at the input AC mains. The equivalent circuit of the zeta converter is shown in below figure. Circuit diagram of zeta converter is shown below.

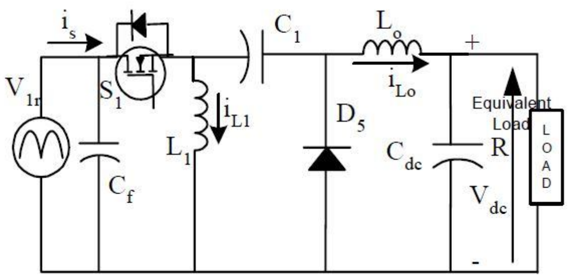

Fig 3: Circuit diagram of Zeta Converter

Zeta converter can be operated in three modes. There are,

A. *Mode1:*In this stage, switched S_1 is turned on (here MOSFET is acts as switch) and the input source supply energy transferred to the input inductor (L_1) and output inductor (L_0) through the intermediate capacitor (C_1). The current in the output inductor and input inductor (i_{L1}) increase linearly. The intermediate capacitor voltage (V_{c1}) and the output DC-link capacitor voltage (V_{dc}) are considered constant in this stage. They are equal to the DC voltage (V_{dc}). This stage shown in below figure.

B. *Mode2*: In this second stage, switch S_1 is turned off and diode D_5 starts conducting. The stored energy from output inductance and the input inductance are transferred to the intermediate capacitor C_1 and the DC –link capacitor filter (C_{dc}) respectively. This stage continuous upto i_{Lo1} becomes equal and negative value of the output inductance current (i_{Lo}) that can be shown in below figure. In this stage, MOSFET switch S_1 is in off stage and diode D_5 is in on stage.

C. *Mode3:*In this stage of operation, freewheeling starts until the start of a new switching period and is shown in below figure. In this stage of operation neither switch 'S_1' nor output diode D_5 the start of the new switching cycle.The currents i_{Lo} and i_{L1} becomes equal and opposite at time t_{off}. Therefore, in this stage the output diode current is zero. The switch and output diode off. Three modes of operation can be shown in below figure.

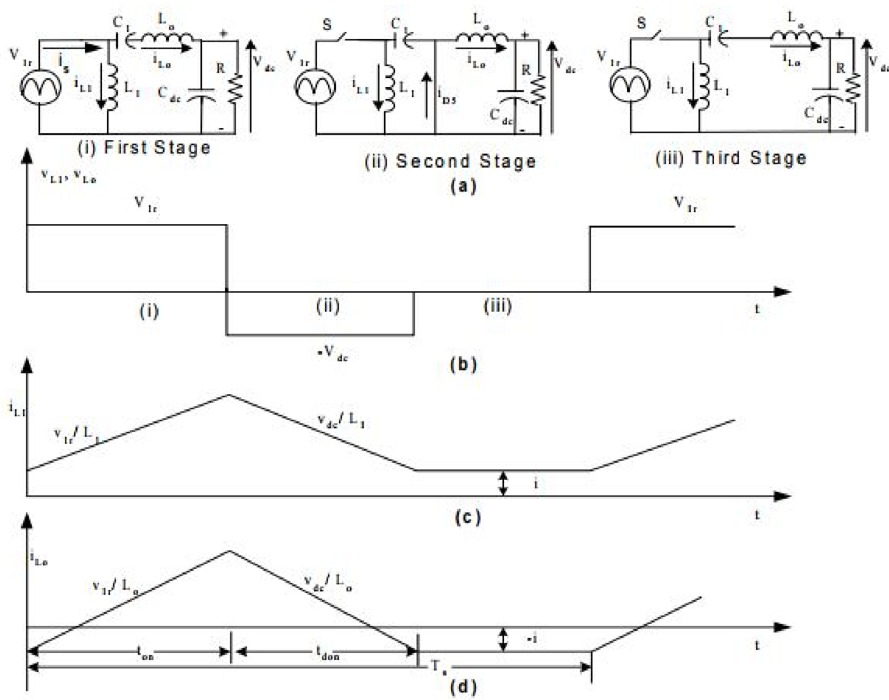

Fig.4 (a) Three Different Operating Stages (i), (ii) and (iii) of Zeta Converter in DCM of Operation and its (b) Voltage Waveforms (c) and (d) Inductors Current Waveform

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IV. MODELLING OF THE DRIVE SYSTEM

The AC-DC Zeta converter feeding the variable speed direct torque controlled-PMSM drive system is modelled and simulated in a standard MATLAB/Simulink. The model of the drive is described in following sections.

A. *Modelling of AC-DC Zeta converter*

The control scheme is used to improve power quality. The converter topology in this case, consists of the following subsystems.
DC-link Voltage Controller:-
The error between the reference DC link voltage (V* dc) and the sensed DC link voltage ($\mathbf{V_{dc}}$) is fed to the PI voltage controller. The output of the controller at the nth sampling instant is given as:

$$u_{ref(n)} = u_{ref(n-1)} + K_{pdc}\{V_{dce(n)} - V_{dce(n-1)}\} + K_{idc}V_{dce(n)} \quad (1)$$

Where,$u_{ref(n)}$ is the output of the voltage controller atthe nth sampling instant.$u_{ref(n-1)}$is the output of the voltage controller at the $(n-1)^{th}$sampling instant.$V_{dce(n)}$is the error in the DC-link voltage at the nth sampling instant.$K_{pdc}$is the proportional gain of the voltage controller and $K_{idc}$is the integral gain of the voltage controller.
The voltage error in the DC link voltage at the nth instant is given as:

$$V_{dce(n)} = V^*_{dc(n)} - V_{dc(n)} \quad (2)$$

The output of the voltage controller (u_{ref}), after limiting, is considered a modulating signal for the Pulse Width Modulation (PWM) controller to generate the appropriate duty ratio of switch S1. In the PWM controller, the modulating signal which is output of voltage controller (u_{ref}) is compared with the instantaneous value of the triangular carrier wave. If the modulating signal is greater than the triangular carrier wave, then a switching signal is generated for the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) used as switch S1. Otherwise, it is not gated and the freewheeling diode conducts.

B. *Modelling of Direct Torque Controlled PMSM Drive System*

The various components used in the DTC based PMSM drive system are shown in the Fig.2. The modelling equations for the different blocks, which include the PI speed controller, field weakening controller, flux and torque hysteresis comparators, estimators, Permanent Magnet Synchronous Motor (PMSM) and VSI are given in this section as per the following modelling equations.
PI Speed Controller: The speed controller input is the speed error $\omega_{e(k)}$ between the reference speed $\omega^*_{r(k)}$and and the sensed motor speed ($\omega_{r(k)}$). The error is calculated atk^{th}sampling instantis

$$\omega_{e(k)} = \omega^*_{r(k)} - \omega_{r(k)} \quad (3)$$

The error is processed in the PI speed controller and the output of the controller is given by the reference torque $T^*_{(K)}$ at k^{th} sampling instant

$$T^*_{(K)} = T^*_{(K-1)} + K_P\{\omega_{e(k)} - \omega_{e(k-1)}\} + K_1\omega_{e(k)} \quad (4)$$

Where K_P and K_1 are proportional and integral gainsof the PI controller, respectively. After limiting the output of the PI controller $T^*_{(K)}$ is taken as reference torque$T^*_{(ref)}$

C. *Field Weakening Control*

Below the base speed the reference value of the stator flux linkage is expressed as,

$$|\varphi_{sref}| = \varphi_C \quad (5)$$

The reference value of the stator flux linkage is the function of rotor speed for the rotor speed above the base speed. It can be expressed as,

$$|\varphi_{sref}| = \varphi_C(\omega_b/|\omega_r|) \quad (6)$$

Where$\varphi_C$is the rated flux, ω_b is base speed and $\omega_r$is the rotor speed of the motor.

D. *Torque and Flux Hysteresis Comparator*

The stator flux linkage and torque are used as feedback in comparisons of their reference values. The torque error and flux error are fed to the hysteresis band controller which is used for selecting the appropriate voltage vector according to the table of optimum switching (TOS) given in Table 1. The flux error is

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$$\Delta\varphi_s = |\varphi_{sref}| - |\varphi_s| \tag{7}$$

And the torque error is

$$\Delta T_e = |T_{ref}| - |T_{est}| \tag{8}$$

These are the output signals of the hysteresis comparator. The below set of equations can be used to define the output of the hysteresis controller.

$$\text{If } |\varphi_{sref}| - |\varphi_s| \leq \Delta\varphi_s \text{ then } d\varphi_s = 0 \tag{9}$$
$$\text{If } |\varphi_{sref}| - |\varphi_s| > \Delta\varphi_s \text{ then } d\varphi_s = 1 \tag{10}$$
$$\text{If } |T_{ref}| - |T_{est}| < \Delta|T_e| \text{ then } dT_e = -1 \tag{11}$$
$$\text{If } |T_{ref}| - |T_{est}| = \Delta|T_e| \text{ then } dT_e = 0 \tag{12}$$
$$\text{If } |T_{ref}| - |T_{est}| > \Delta|T_e| \text{ then } dT_e = 1 \tag{13}$$

E. Flux, Torque and Sector Estimator

In this section, the stator fluxes in the stationary reference frame are estimated and from the obtained values of these fluxes and sensed winding currents of the PMSM, the developed electromagnetic torque (Test) is estimated. Finally, the sector in which the flux vector is present is computed from the stator flux. The modelling of the complete estimator block is subdivided into three parts and is given below.

1) *Estimation of Stator Flux Linkages:* The stator flux linkages, in direct torque controlled PMSM drives, are needed for three reasons. First, these fluxes are required for the identification of the sector for the optimum voltage vector selection table. Secondly, the estimation of the developed torque of the PMSM drive requires stator flux linkages. And finally, estimation of rotor mechanical speed also needs these fluxes.

The flux linkage in the stationary reference frame can be obtained from the sensed winding currents (i_a and i_b), and stator voltage (v_a and v_b) which are computed by asensed DC link voltage (v_{dc}) and switching functions (s_a, s_b and s_c). These voltages and currents are transformed toa stationary reference frame. The flux estimator providesstator flux linkage in the stationary reference frame(α and β)coordinates as:

$$\varphi_\alpha = \int (V_\alpha - Ri_\alpha)dt \tag{14}$$
$$\varphi_\beta = \int (V_\beta - Ri_\beta)dt \tag{15}$$

Where

$$V_\alpha = V_a \tag{16}$$
$$V_\beta = (V_a + 2V_b)/\sqrt{3} \tag{17}$$
$$i_\alpha = i_a \tag{18}$$
$$i_\beta = (i_a + 2i_b)/\sqrt{3} \tag{19}$$

These are obtained from the stationary reference frame transformation.
The estimated stator flux-linkage modulus can be expressed as,

$$|\varphi_s| = \sqrt{(\varphi_\alpha^2 + \varphi_\beta^2)} \tag{20}$$

2) *Estimation of Torque:* The electromagnetic torque developed by the PMSM can be obtained from the stator flux linkage and currents in the stationary reference (α and β)frame is,

$$T_{est} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha\right) \tag{21}$$

Where P is the no of poles

3) *Estimation of Sector Location of Stator Flux Linkage Vector:* The stationary reference frame (α and β) stator flux components are compared to obtain information on which sector the stator flux vector is lies. These sectors are shown in Fig 8. The sectors can be determined on the basis of following mathematical equations as

$$\varphi_\alpha \geq \sqrt{3}\,\varphi_\beta \text{and} \varphi_\alpha \geq 0, \text{then Sector=1} \tag{22}$$
$$\varphi_\alpha < \sqrt{3}\,\varphi_\beta \text{and} \varphi_\alpha \geq 0, \text{then Sector=2} \tag{23}$$
$$\text{If} |\varphi_\alpha| < \sqrt{3}\varphi_\beta \text{and} \varphi_\alpha < 0, \text{then sector} = 3 \tag{24}$$

$$\text{If}\left|\varphi_\alpha\right| \geq \sqrt{3}\varphi_\beta \text{and } \varphi_\alpha < 0, \text{then sector} = 4 \tag{25}$$

$$\text{If}\left|\varphi_\alpha\right| \leq \sqrt{3}\left|\varphi_\beta\right|, \varphi_\alpha < 0 \text{ and} \varphi_\beta < 0, \text{then sector} = 5 \tag{26}$$

$$\text{If}\varphi_\alpha \leq \sqrt{3}\left|\varphi_\beta\right|, \varphi_\alpha < 0 \text{ and} \varphi_\beta < 0, \text{then sector} = 6 \tag{27}$$

F. Modelling of PMSM

The stator of the PMSM consists of a balanced three phase winding similar to the conventional synchronous motor. The mathematical model of the PMSM is derived from the synchronous motor under the assumption that the armature EMF is induced by the permanent magnets in place of DC excitation. Assuming that the induced EMF is sinusoidal, and the eddy current and hysteresis losses are negligible, the stator voltage equations in the rotor reference frame are given as

$$V_q = Ri_q + p\varphi_q + \omega_r\varphi_d \tag{28}$$

$$V_d = Ri_d + p\varphi_d - \omega_r\varphi_q \tag{29}$$

Where $\varphi_d = L_q i_q$ and $\varphi_d = L_d i_d + \varphi_f$,and$V_d$,$V_q$are the d,q axis stator voltages. $i_d$and$i_q$are the d,q axis stator currents. L_d andL_q are the d,q axis inductances. $\varphi_f$is the stator flux linkage produced by permanent magnets. R is the stator-winding resistance per phase. $\omega_r$is the rotor speed in rad/sec (electrical).

The developed electromagnetic torque is given as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\varphi_f i_q + (L_d - L_q)i_d i_q\right) \tag{30}$$

Where, P is the number of poles. The electromagnetic torque is balanced by the load torque, accelerating torque and damping torque of the system and can be expressed in an electromechanical equation is

$$T_e = T_L + B\omega_r + Jp\omega_r \tag{31}$$

Where, $T_L$is the load torque, B is the damping, Coefficient and J is the moment of inertia.

The model equations can be rearranged in the form of following first order differential equations are,

$$pi_d = \left(V_d - Ri_d + \omega_r L_q i_q\right)/L_d \tag{32}$$

$$pi_q = \left(V_q - Ri_q + \omega_r L_d i_d - \omega_r\varphi_f\right)/L_q \tag{33}$$

$$p\omega_r = (T_e - T_L - B\omega_r)/J \tag{34}$$

$$p\theta_r = \omega_r \tag{35}$$

The phase currents are computed using an inverse
Park's transformation.

$$i_a = i_d \text{Cos}\theta_r \text{-} i_q \text{Sin}\theta_r \tag{36}$$

$$i_b = i_d \text{Cos}(\theta_r - 2\pi/3) - i_q \text{Sin}(\theta_r - 2\pi/3) \tag{37}$$

$$i_c = i_d \text{Cos}(\theta_r - 4\pi/3) - i_q \text{Sin}(\theta_r - 4\pi/3) \tag{38}$$

Where angle θ_r is the position of the rotor.

G. Modelling of VSI

This particular block models the insulated gate bipolar transistor (IGBT) based three-phase voltage source inverter (VSI). The optimum voltage vector is obtained from the output of the hysteresis torque and flux comparators and the sector in which the stator flux vector lies. The inverter voltage can be given by following equations from switching signals Sa, Sb and Sc as:

$$V_a = \left(\frac{V_{dc}}{3}\right)(2S_a - S_b - S_c) \tag{39}$$

$$V_b = \left(\frac{V_{dc}}{3}\right)(2S_b - S_a - S_c) \tag{40}$$

$$V_c = \left(\frac{V_{dc}}{3}\right)(2S_c - S_a - S_b) \tag{41}$$

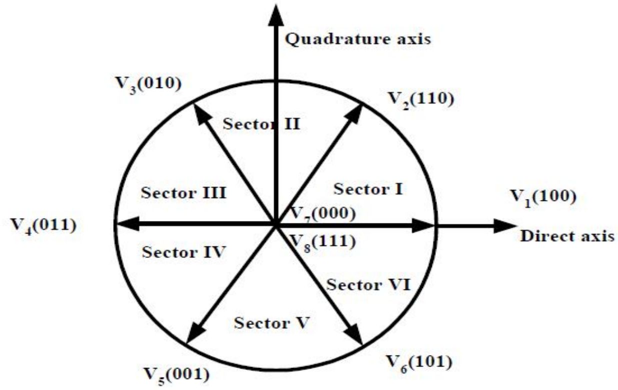

Fig 8: Sectors for Stator flux linkage space vector

Where, S_a, S_b and $S_c$are switching functions (which are either one or zero). V_a ,V_b,V_c and $V_{dc}$are voltagesof phase winding a, b, c and the DC link, respectively.Depending on the output of flux error and torque error the appropriate stator voltage vector is selected according to Table 1. These voltages can be expressed in the rotor reference frame as the forcing functions $V_q$and V_d by using the Park's transformation.

$$V_d = \left(\frac{2}{3}\right)\{V_a \mathrm{Cos}\theta_r + V_b \mathrm{Cos}(\theta_r - 2\pi/3) + V_c \mathrm{Cos}(\theta_r - 4\pi/3)\} \quad (42)$$

$$V_q = \left(-\frac{2}{3}\right)\{V_a \mathrm{Sin}\theta_r + V_b \mathrm{Sin}(\theta_r - 2\pi/3) + V_c \mathrm{Sin}(\theta_r - 4\pi/3)\} \quad (43)$$

V.SIMULATION AND RESULTS

A. Case study-1

1) PMSM drive without speed control

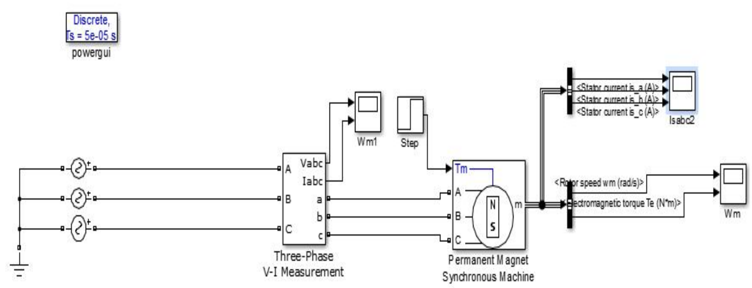

Figure 5.1 Simulink model of PMSM without speed control

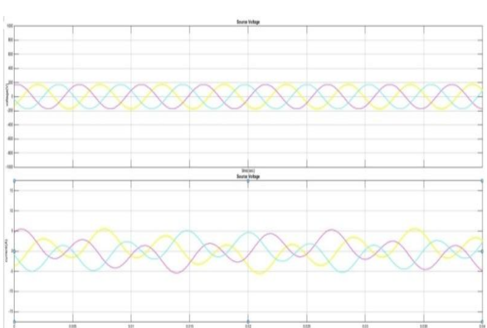

Figure 5.2 Source voltage and current waveforms

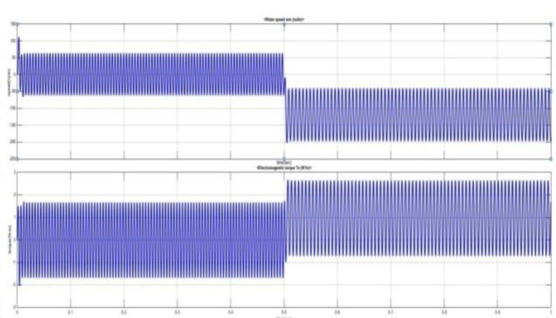

Figure 5.3 Speed and torque of PMSM drive

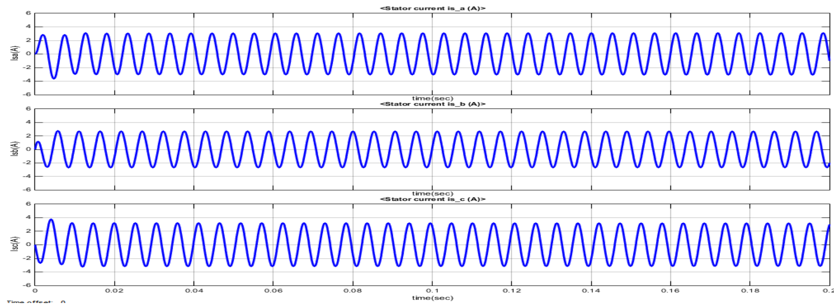

Figure 5.4 Stator currents of PMSM drive

B. Case study-2

1) Conventional DTC of PMSM Drive

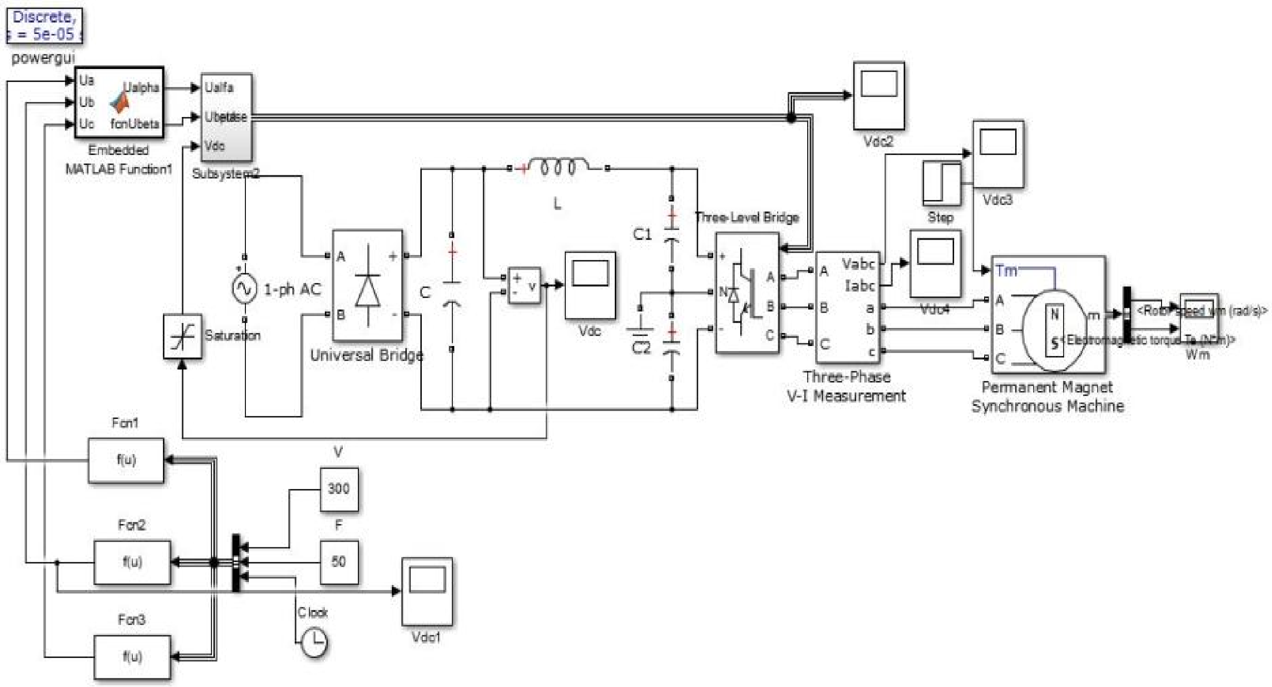

Figure 5.5 Simulink model of speed control of PMSM drive using DTC

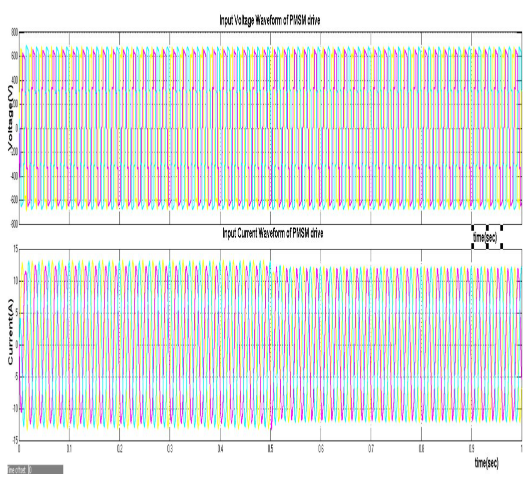

Figure 5.6 Voltage and current waveforms at input

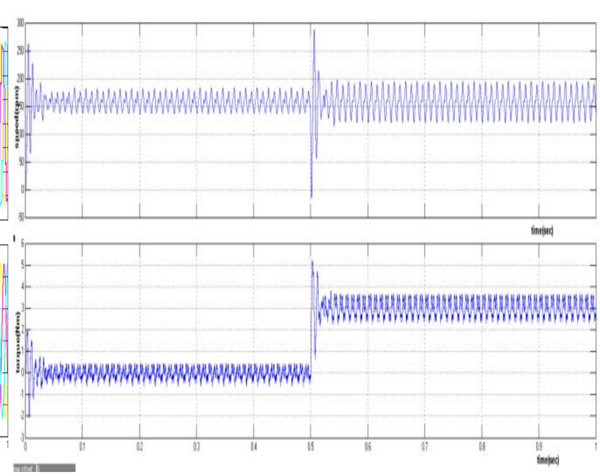

Figure 5.7 speed and torque of PMSM drive of PMSM drive

C. CASE STUDY 3

1) PMSM drive DTC control using zeta converter

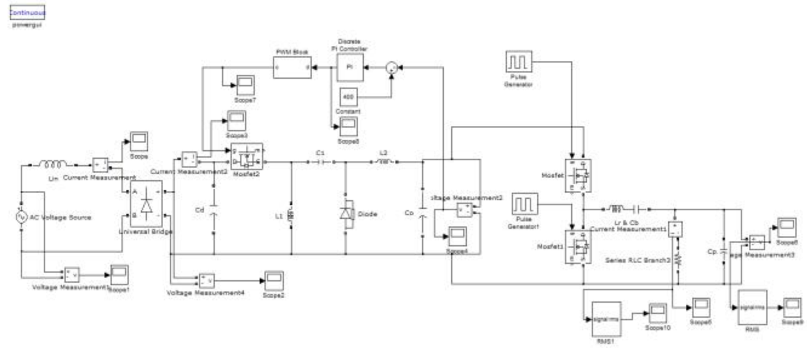

Figure 5.8 Simulink model of proposed AC-DC ZETA converter

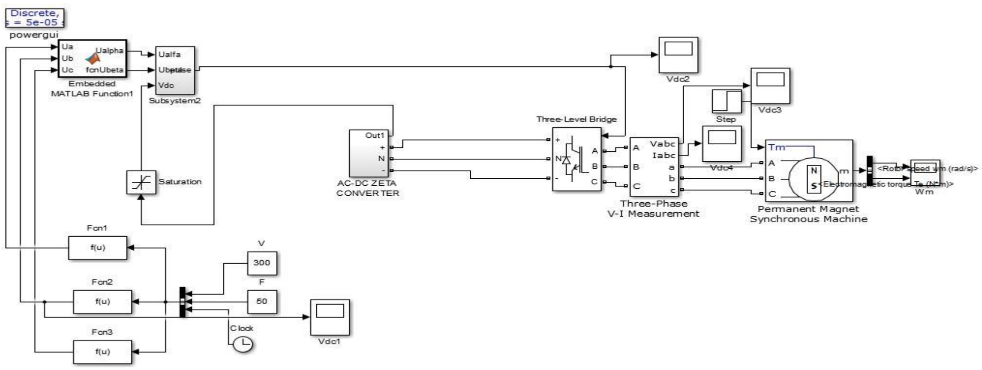

Figure 5.9 Simulink model of proposed AC-DC ZETA converter fed DTC of PMSM drive

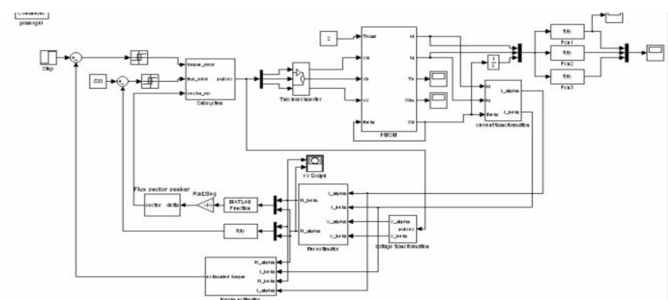

Figure 5.10 Simulink model of proposed AC-DC ZETA converter fed DTC of PMSM

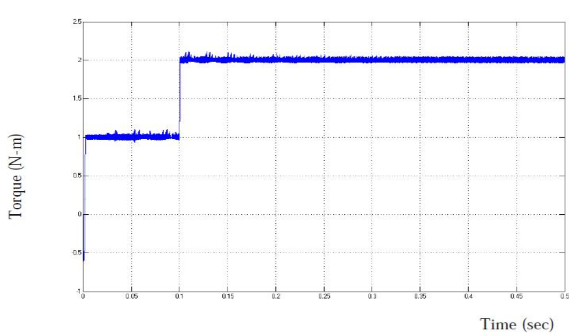

Figure 5.11 Torque response of PMSM drive using converter

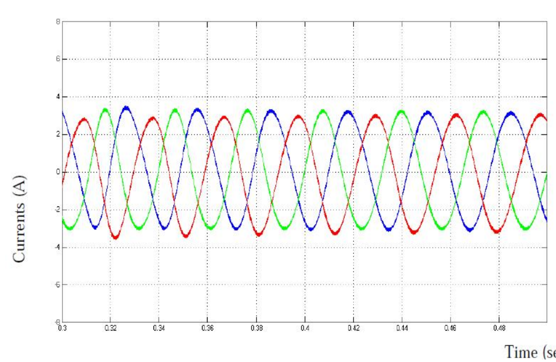

Figure 5.12 Stator currents of PMSM drive using proposed proposed converter

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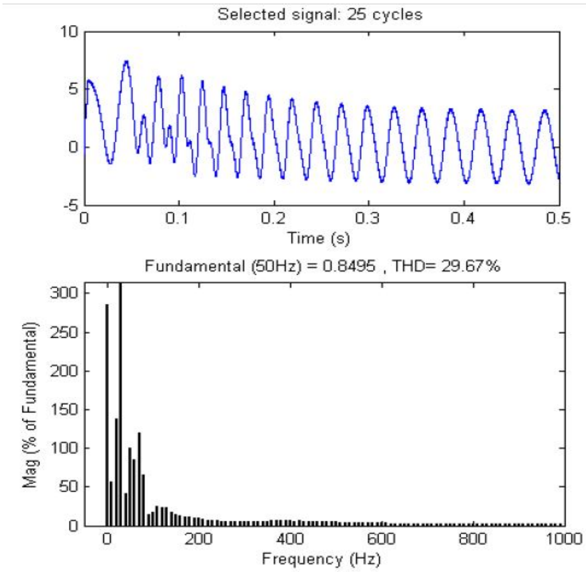

Figure 5.13 stator current harmonic spectrum of proposed converter based DTC of PMSM drive

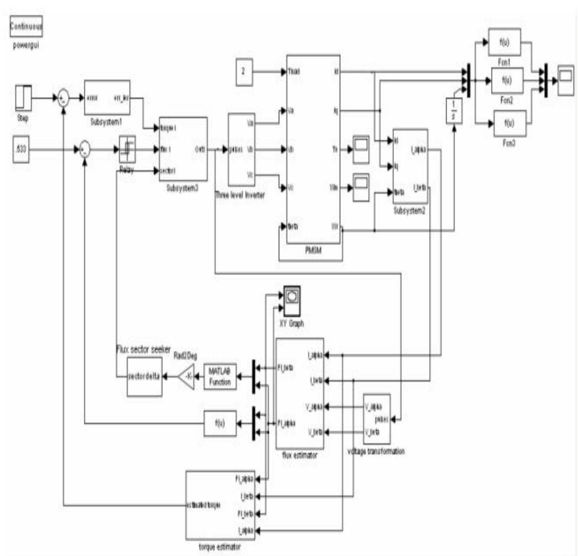

Figure 5.14 Simulink model of proposed AC-DC zeta converter with 3 level inverter for DTC of PMSM drive

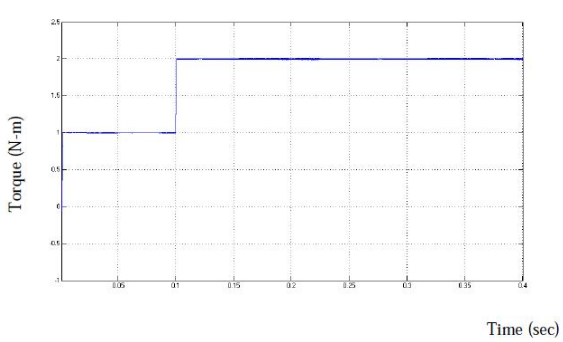

Figure 5.15 Torque response of PMSM drive using proposed converter

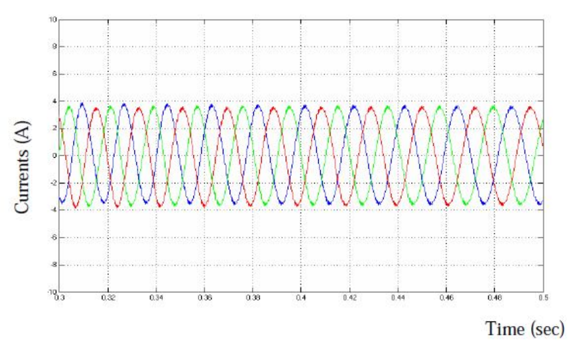

Figure 5.16 Stator currents of PMSM drive using proposed converter

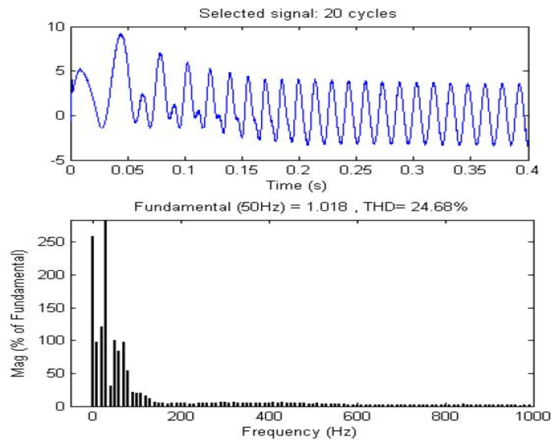

Figure 5.17 stator current harmonic spectrum of proposed converter based DTC of PMSM drive

System Specification	Fundamental component of current	% THD
With 2-level inverter	0.8495	29.67
With 3-level inverter	1.018	24.68

Table 5.1 Comparison of PMSM with proposed converter topologies

VI.CONCLUSION

In this thesis design and simulation of the PMSM motor without speed control and conventional DTC of PMSM drive and PMSM drive DTC control using Zeta converter. In this proposed AC-DC Zeta converter fed DTC of PMSM drive using 2-level inverter and 3-level inverter are also simulated and results are presented. The design modelling and development of an AC-DC Zeta converter was operated in DCM of current operation to fed a DTC controlled PMSM drive. By observing the experiment results improved performance of the proposed AC-DC Zeta converter fed DTC of PMSM drive using 3-level inverter better than 2- level inverter in terms of low THD of supply current and improved power factor at the AC mains. The DTC controlled PMSM drive provides acceptable power quality and high efficiency and these are suitable for the adjustable speed drive applications like refrigerators and air conditioning.

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