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Modeling and Analysis of Three Phase Induction Motor Drive System Using Two Parallel Rectifiers for Power Factor Correction

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Abstract*— This paper presents a single-phase to three-phase drive system composed of two parallel single-phase rectifiers, a three-phase inverter, and an induction motor. It gives the comparison between the single-phase rectifier and two parallel single-phase rectifiers drive system. The proposed system permits to reduce the rectifier switch currents, the THD of the grid current with same switching frequency or the switching frequency with same THD of the grid current and to increase the fault tolerance characteristics. In addition, the losses of the proposed system may be lower than that of the conventional one topology. Even with the increase in the number of switches, the total energy loss of the proposed system may be lower than that of a conventional one. A suitable control strategy, including the pulse width modulation technique (PWM), is developed. Finally a MATLAB Simulation based model is developed for single phase rectifier and two rectifier system and simulation results are presented.
***Keywords*— Ac-Dc-Ac power converters, parallel converter, Vector Control, Power factor correction**

I. INTRODUCTION

The ac-dc-ac system is used on a large scale for the three phase drive system. It is quite common to have the single phase supply for commercial and rural areas. So to meet a three phase adjustable drive from single phase supply this topology is proposed. In this paper a single-phase to three-phase drive system composed of two parallel single-phase rectifiers and a three-phase inverter is proposed. The proposed system is conceived to operate where the single-phase supply is available. Compared to the conventional topology, the proposed system permits: to reduce the rectifier switch currents; the total harmonic distortion (THD) of the system current with same switching frequency or the switching frequency with same THD of the drive system current. In addition, the losses of the proposed system may be lower than that of the conventional counterpart. Since three phase motors have many advantages over single phase motors in terms of efficiency, power factor, and torque ripples.

Many technologies for drive system are arising to develop power from various sources, which produces a very high power by using the advanced technologies. One of the methods to develop power from a source is ―Single phase to three phase converter using inversion technique. This technique involves power electronics circuit which is an advanced method to produce or control the voltage or current from the supply. Conventionally the three phase drive system consists of only one rectifier with dc link capacitor. This system consist only 10 switches due to which high rating of switches as shown in figure 1.1 .

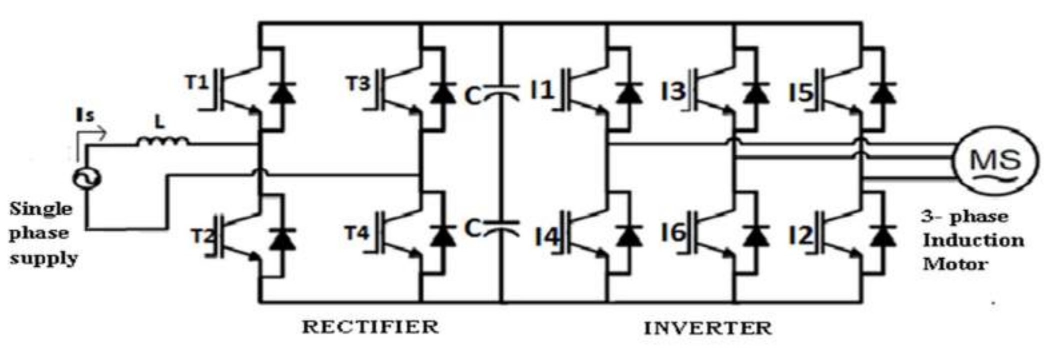

Fig 1.1: Conventional Single Phase to Three Phase Induction Motor Drive

New regulations impose more strict limits on current harmonics injected by power converters. These limits can be achieved with the help of pulse width-modulated rectifiers. These PWM converters, consists of power switches like insulated gate bipolar transistors (IGBTs), gate-turn-off thyristors (GTOs), or integrated gate controlled thyristors (IGCTs) in the power circuit of the rectifier to change actively the waveform of the input current, reducing the distortion [6]-[7]. Parallel converters have been used to improve the power capability, reliability, efficiency, and redundancy. This drive system consists of 14 switches, and the current across the switches of the input side of the supply is less as compared to conventional method as shown in figure 1.2. Parallel converter techniques can be employed to improve the performance of active power filters uninterruptible power supplies (UPS), fault tolerance of doubly fed induction generators, and three-phase drives.

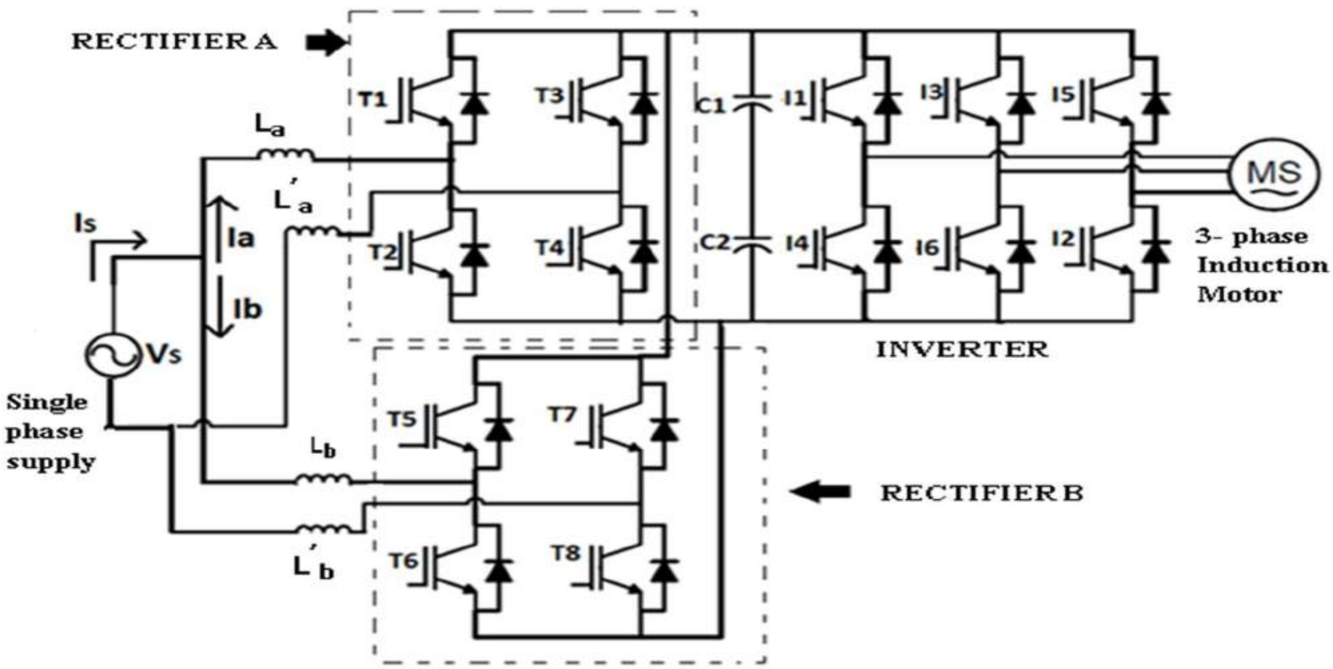

Fig 1.2: Parallel Rectifier Connected Single Phase to Three Phase Induction Motor Drive.

II. SYSTEM MODEL

A. Two rectifier system

The two rectifier system as shown in Figure 2 (consist of parallel connected front end rectifier supplied from single phase supply, input inductors (La, L'a, Lb, and L'b), dc link capacitor bank and an inverter whose control signals are generated from vector control method which is discussed later in this paper. Upper rectifier is made up of switches T1, T2, T3 and T4 and lower rectifier is made up of switches T5, T6, T7 and T8. These two rectifiers are connected in parallel. The system is composed of input inductors. The three phase inverter is composed of three legs having switches I1, I2, I3, I4, I5, and I6. The dc link capacitor banks which are connected between rectifiers and inverter helps in removing the ripple content of rectifier output. All switches are IGBT switches. Three phase induction motor is supplied from the three phase inverter output.

From Figure 1.2, the following equations can be derived for the front-end rectifier

$$V_{a10} - V_{a20} = e_g - (r_a + l_a p)i_a - (r'_a + l'_a p)i'_a \quad (1)$$

$$V_{b10} - V_{b20} = e_g - (r_b + l_b p)i_b - (r'_b + l'_b p)i'_b \quad (2)$$

$$V_{a10} - V_{b10} = (r_b + l_b p)i_b - (r_a + l_a p)i_a \quad (3)$$

$$V_{a20} - V_{b20} = (r'_a + l'_a p)i'_a - (r'_b + l'_b p)i'_b \quad (4)$$

$$i_g = i_a + i_b = i'_a + i'_b \quad (5)$$

Where p =d/dt and symbols like r and l represents the resistance and inductances of the input inductors l_a, l'_a, l_b, and l'_b
The circulating current i_o can be defined from i_a and i'_a or i_b and i'_b i.e.

$$i_o = i_a - i'_a = -i_b + i'_b \quad (6)$$

Introducing i_o and adding (3) and (4), relations (1)-(4) become

$$V_a = e_g - [r_a + r'_a + (l_a + l'_a)p]i_a - (r'_a + l'_a p)i'_a \quad (7)$$

$$V_b = e_g - [(r_b + r'_b + (l_b + l'_b)p]i_b - (r'_b + l'_b p)i'_b \quad (8)$$

$$V_o = -[r'_a + r'_b + (l'_a + l'_b)p]i_o - [r_a - r'_a + (l_a - l'_a)p]i_a + [(r_b - r'_b + (l_b - l'_b)p]i_b \quad (9)$$

Where

$$V_a = V_{a10} - V_{a20} \quad (10)$$

$$V_b = V_{b10} - V_{b20} \quad (11)$$

$$V_o = V_{a10} + V_{a20} - V_{b10} - V_{b20} \quad (12)$$

Equations (7)-(9) and (5) constitute the front-end rectifier dynamic model. Therefore, V_a (rectifier A), V_b (rectifier B), and V_o (rectifiers A and B) are used to regulate currents i_a, i_b and i_o, respectively. Reference currents i_a^*, and i_b^* are chosen equal to $i_g^*/2$ and the reference circulating current i_o^* is chosen equal to 0. In order to both facilitates the control and share equally current voltage and power between the rectifier, the four inductors should be equal, i.e. $r'_g = r_a = r'_a = r_b = r'_b$ and $l'_g = l_a = l'_a = l_b = l'_b$. In this case, the equation (7)-(9) can be simplified to

$$V_a + \frac{V_o}{2} = e_g - 2(r'_g + l'_g p)i_a \quad (13)$$

$$V_b + \frac{V_o}{2} = e_g - 2(r'_g + l'_g p)i_b \quad (14)$$

$$V_o = -2(r'_g + l'_g p)i_o \quad (15)$$

Same equations can be written for currents i'_a, i'_b and i_g also.
In this ideal case (four identical inductors), the circulating current can be reduced to zero imposing

$$V_o = V_{a10} + V_{a20} - V_{b10} - V_{b20} = 0 \quad (16)$$

When $i_o = 0$ ($i_a = i'_a$, $i_b = i'_b$) the system equation (7)-(9) is reduced to

$$V_a = e_g - 2(r'_g + l'_g p)i_a \quad (17)$$

$$V_b = e_g - 2(r'_g + l'_g p)i_b \quad (18)$$

Then the model of the proposed system becomes similar to that of a system composed of two conventional independent rectifiers.

B. Working principle of PWM rectifier

To understand the working, consider the conventional circuit of fully controlled single phase PWM rectifier as shown in figure 2.1 below. It consists of four controlled power switches with anti-parallel diode (IGBT). For the proper working of this rectifier the output voltage V_o must be greater than at least 10% from input voltage V_S any time [7].This rectifier can work in two or three levels. The possible combination is as follows.

1	T1 = T4 = ON T2 = T3 = OFF	$V_{AB} = V_O$	Figure 2.2(a)
2	T1 = T4 = OFF T2 = T3 = ON	$V_{AB} = -V_O$	Figure 2.2(b)
3	T1 = T3 = ON T2 = T4 = OFF	$V_{AB} = 0$	Figure 2.2(c)

And voltage across inductor is given by

$$V_l = L\frac{di_s}{dt} \tag{19}$$

$$V_l = V_{s(t)} - KV_O \tag{20}$$

Where K= 1, - 1 or 0.
If k=1 then the inductor voltage will be negative, so the input current will decrease its value.
If K=-1 then the inductor voltage will be positive, so the input current will increase its value.
If K=0 the input current increase or decrease its value depending on V_s . This allows for a complete control of the input current [7].

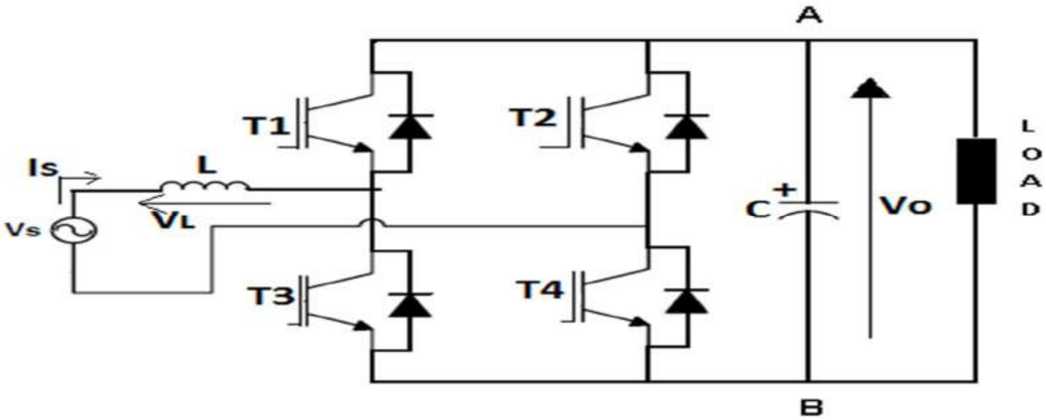

Fig 2.1: Single phase PWM Rectifier Circuit

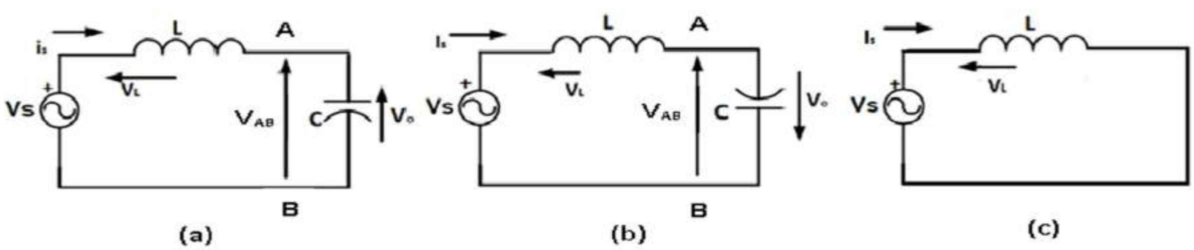

Fig 2.2: Working of Single phase PWM Rectifier Circuit

(a) T1 = T4 = ON (b) T2 = T3 = ON (c) T1 = T3 = ON

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III. CONTROL STRATEGY

The main objective of PWM rectifier (converter) is to maintain dc link voltage constant and to maintain input power factor close to unity. The dc-link voltage V_c is adjusted or maintain constant to its reference value V_c^* using the standard PI controller. This controller provides the amplitude of the reference supply current I_s^* as shown in figure 3.1. To control the power factor and maintain it close to unity and harmonics in the supply side, the instantaneous reference current I_s^* is synchronized with supply voltage V_s , as given in the voltage-oriented control (VOC) for three-phase system [8]-[9]. This synchronization is obtained by a phased locked loop (PLL) scheme in MATLAB. The reference currents I_a^* is again given to the controller which defines the input reference voltages V_a^* and then it is compared with the triangular wave to obtain the gating signals for rectifier as shown in figure 3.2. The scheme for two rectifiers system is shown in the figures below. The only thing which needs to be done in two rectifier system is to divide grid current equally to obtain pulses for both the rectifiers.

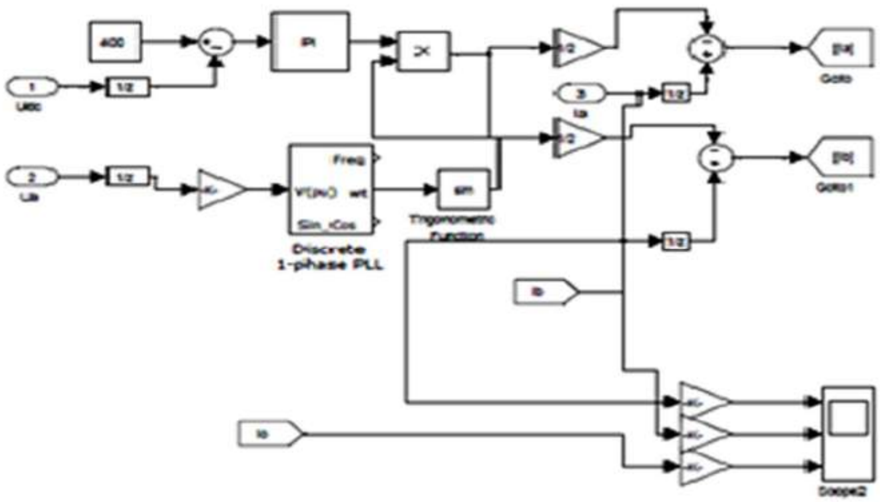

Fig 3.1: Control circuit for rectifier (part1)

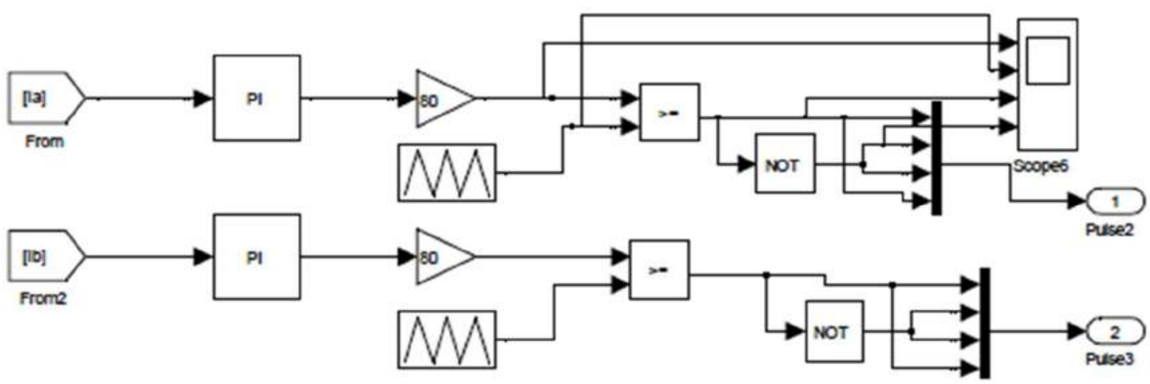

Fig 3.2: Control circuit of rectifier (part 2)

IV. VECTOR CONTROL

Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine. In the case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis (d) is aligned with the rotor flux space vector. That means that the q-axis component of the rotor flux space vector is always zero

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$$\psi_{rq} = 0 \text{ and } \frac{d\psi_{rq}}{dt} = 0 \quad (21)$$

The rotor flux space vector calculation and transformation to the d-q coordinate system require the high computational power of a microcontroller; a digital signal processor is suitable for this task. The following sections describe the space vector transformations and the rotor flux space vector calculation. Figure 4.1 shows the basic block diagram of vector control of an Induction motor.

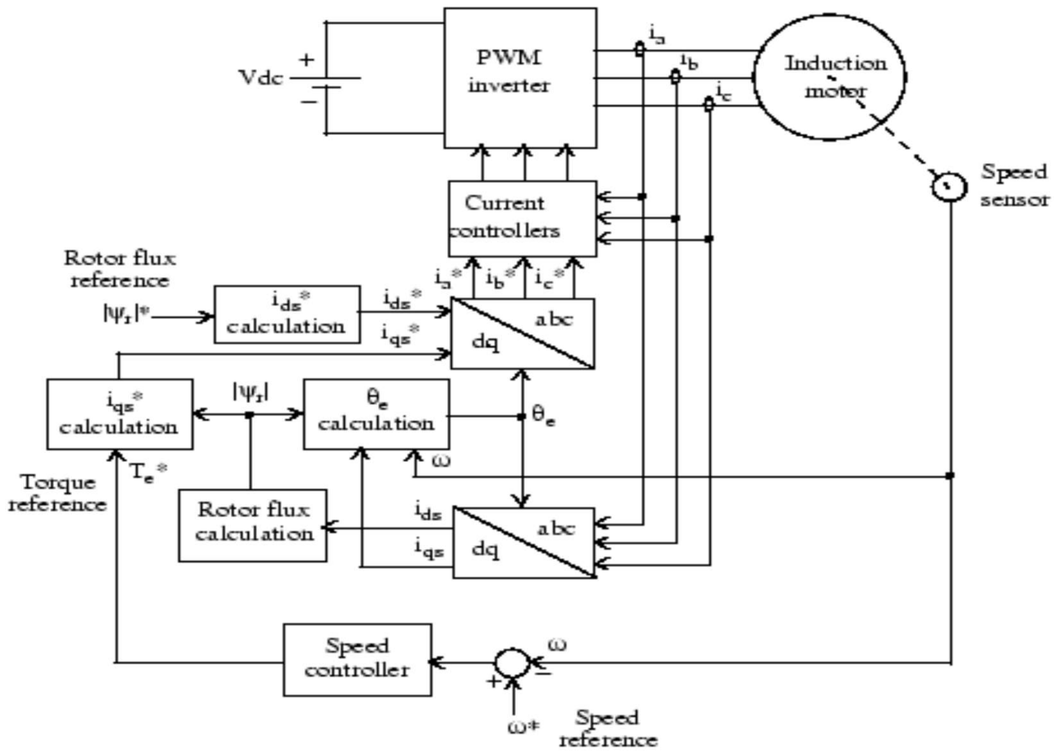

Fig 4.1: Block diagram of vector control of induction motor.

In vector control the motor speed ω from the speed sensor of the motor is compared with reference speed ω^* and the error is processed by the speed controller to produce a torque command T_e^* for stator quadrature current. The stator quadrature axis reference current i_{qs}^* is calculated from reference torque T_e^* using equation (22). The flux component of current i_{ds}^* for the desired rotor flux is calculated from equation (26). The rotor flux position θ_e required for coordinates transformation is generated by integrating the rotor speed ω_m and slip frequency ω_{ls} given by equation (26). The reference quadrature axis i_{qs}^* and direct axis i_{ds}^* current are converted into three reference currents i_a^*, i_b^* and i_c^* for the current regulators by two phase to three phase transformation [10]. Then the current controller process the measured actual and reference currents to produce the inverter gating signals as shown in figure 5.

Where

$$i_{qs}^* = \frac{2}{3}\cdot\frac{2}{p}\cdot\frac{L_r}{L_m}\frac{T_e^*}{\psi_r} \quad (22)$$

And

$$\psi_r = \frac{L_m . i_{ds}}{1+\tau_r s} \quad (23)$$

Rotor constant is given by

$$\tau_r = \frac{L_r}{R_r} \quad (24)$$

$$i_{ds}^* = \frac{\psi_r^*}{L_m} \quad (25)$$

$$\theta_e = \int(\omega_m + \omega_{sl})dt \tag{26}$$

The slip frequency ω_{sl} can be calculated by

$$\omega_{sl} = \frac{L_m R_r}{\psi_r L_r} i_{qs}^* \tag{27}$$

Figure 4.2 shows the MATLAB simulation of the block diagram of vector control of I.M.

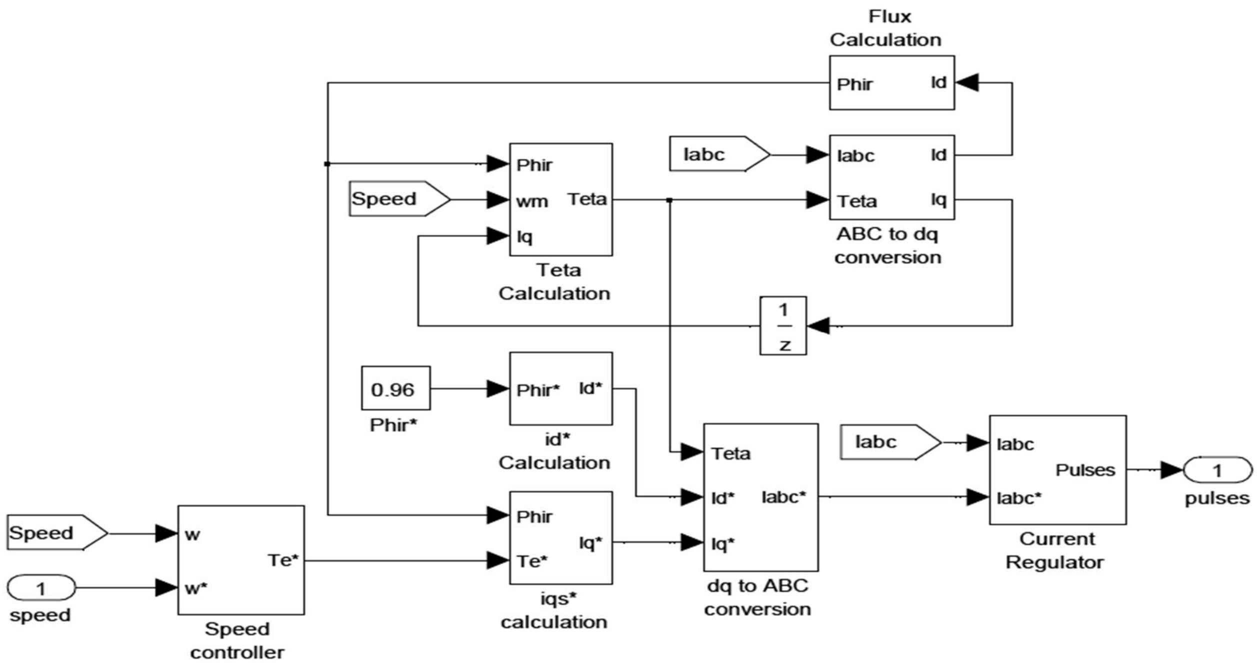

Fig 4.2: Block diagram of Vector control in MATLAB simulation.

V. SPECIFICATION OF INDUCTION MOTOR

1 Hp, 3 phase squirrel cage induction motor		
Parameter		Value
R_s, L_{ls}	Stator resistance & leakage inductance	0.087Ω, 0.8e-3 H
L_m	Magnetizing inductance	34.7 e-3 H
p	Number of pole pairs	2
R_r, L_{lr}	Rotor resistance & leakage inductance	0.228Ω, 0.8e-3 H
F	Frequency	50 Hz
V_{L-L}	Line to line voltage	400V(Rms)

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VI. SIMULATION MODEL IN MATLAB

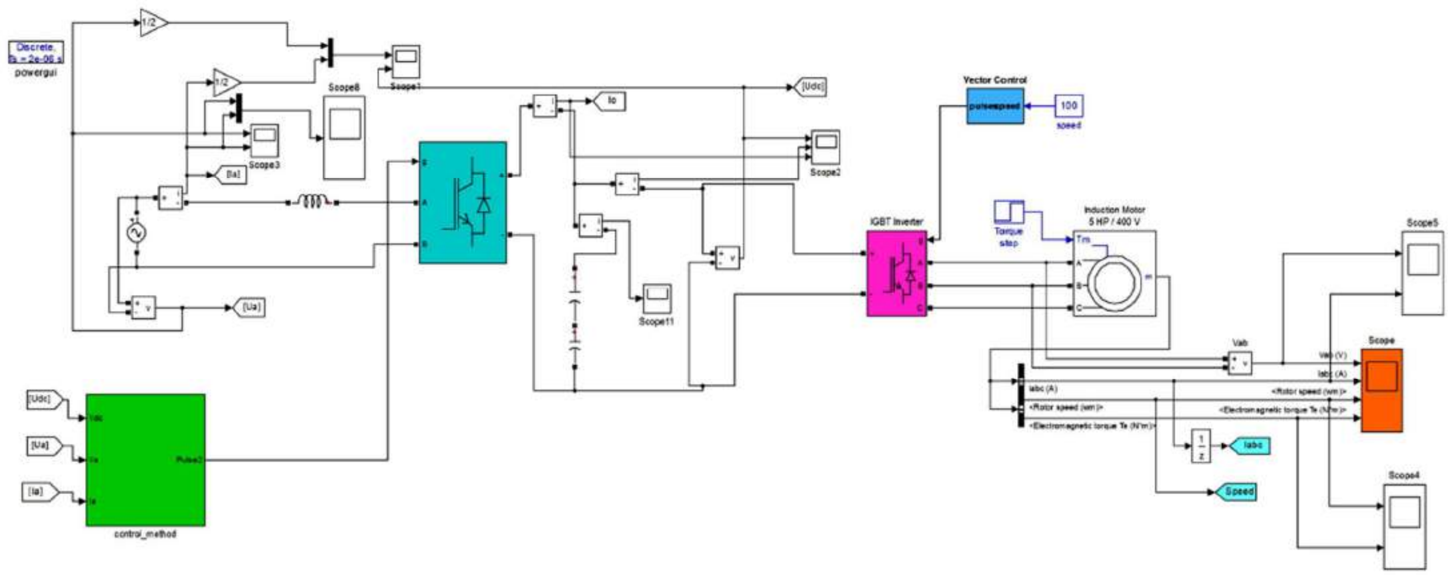

Fig 6.1 MATALB model of one rectifier system

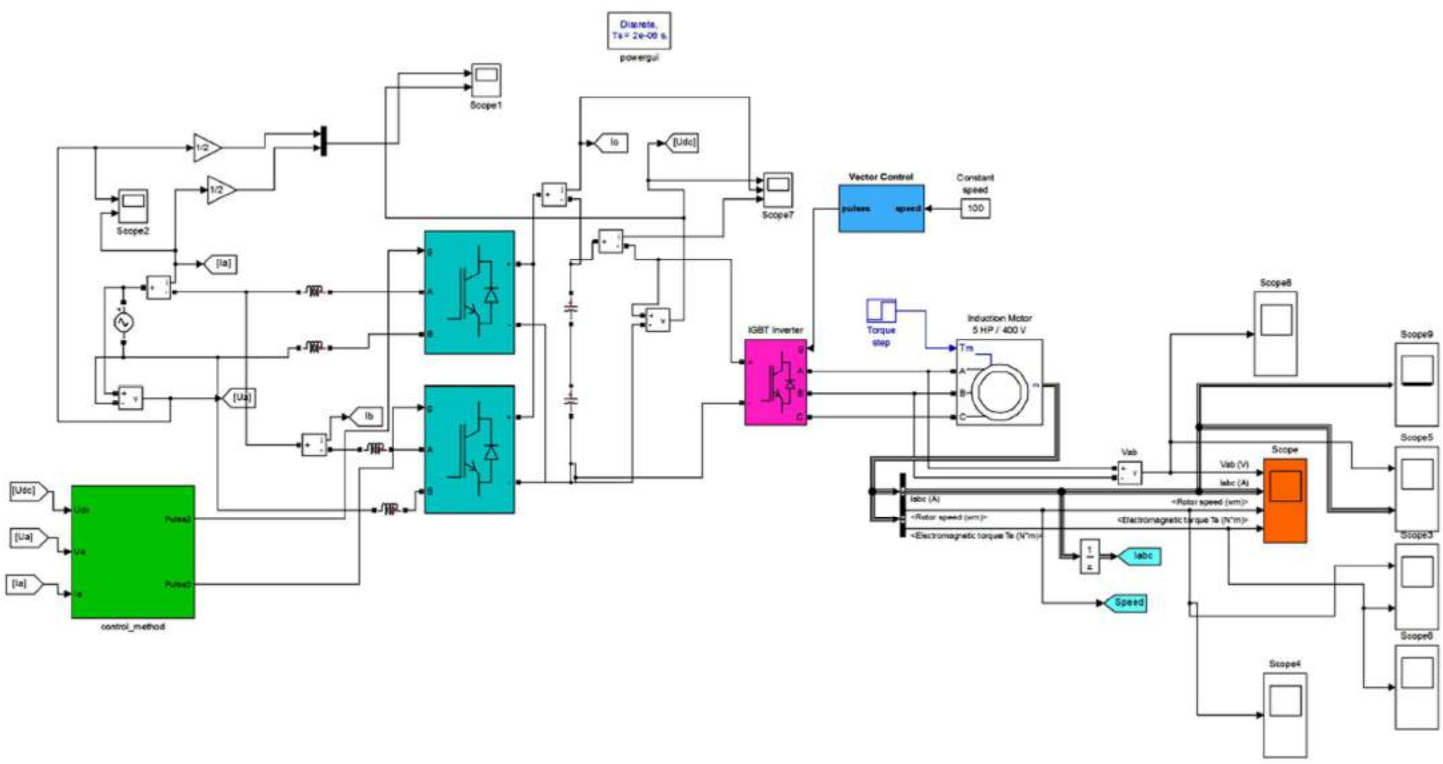

Fig 6.2 MATALB model of two rectifier system

Both systems are developed in MATLAB software. The specification of the motor used in simulation is given in table 1. Figure 6.1 shows the complete developed model of one rectifier (conventional) system and figure 6.2 shows the developed model of two

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rectifier systems in MATLAB.

VII. SIMULATION RESULT FOR ONE RECTIFIER SYSTEM

Figure 7 shows the output of conventional rectifier system

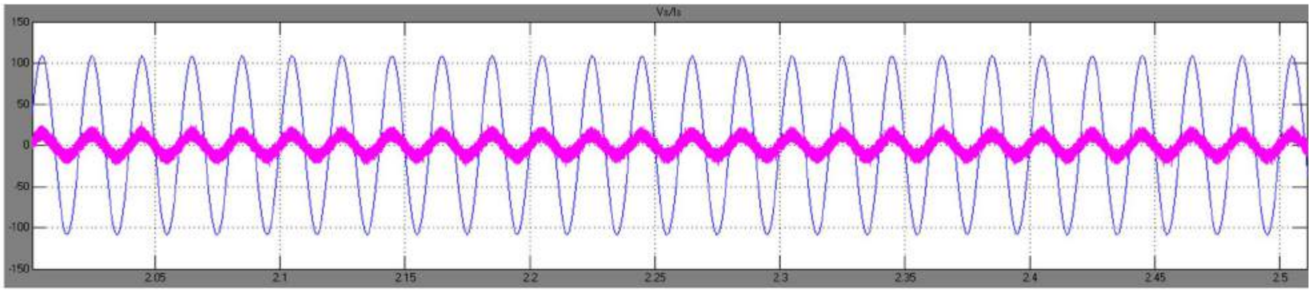

Fig 7.1: Input voltage and current

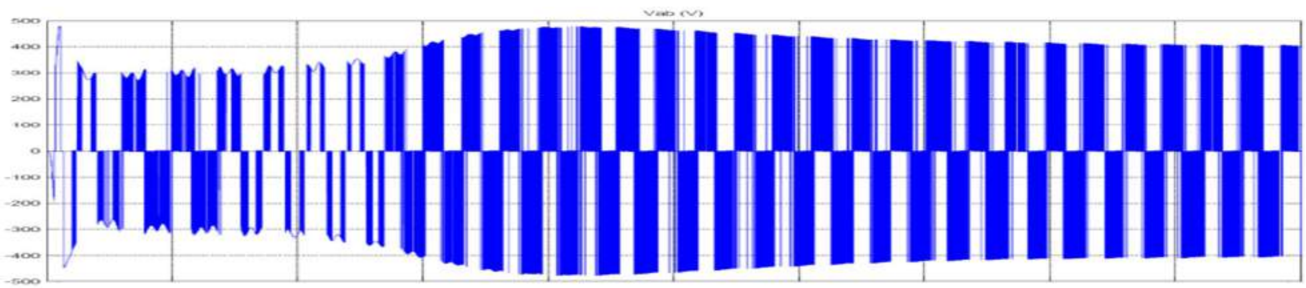

Fig 7.2: Phase voltage V_{a-b}

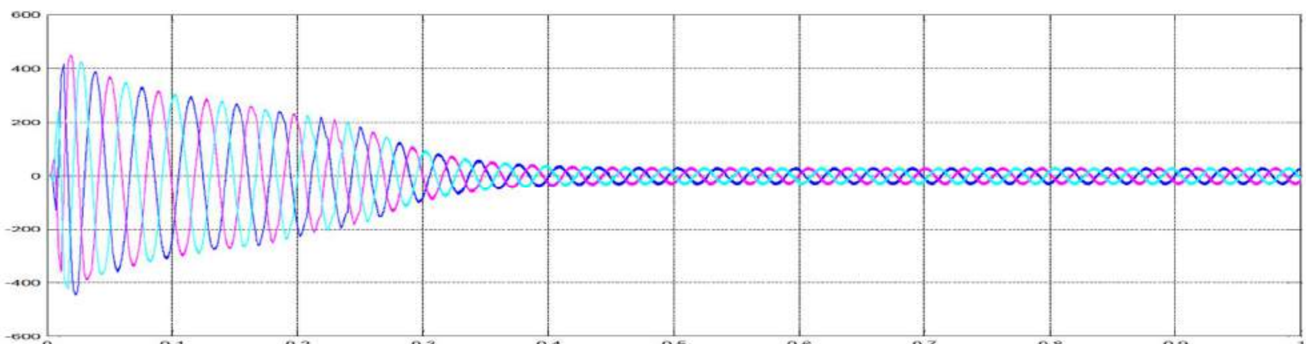

Fig 7.3: Three phase current

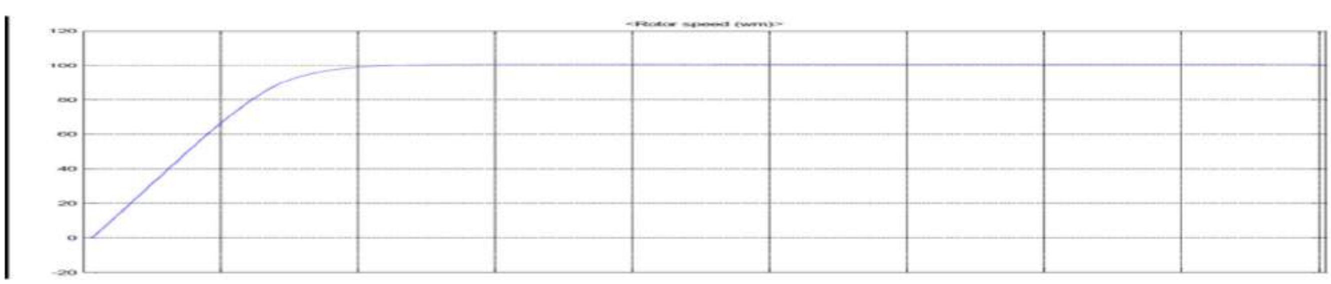

Fig 7.4: Speed characteristics of the motor

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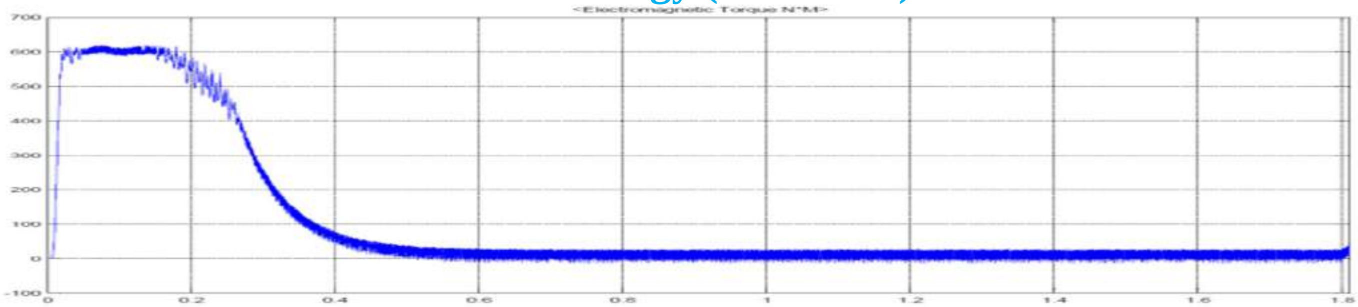

Fig 7.5: Electromagnetic Torque ($T_e^* = 0$)

VIII. SIMULATION RESULT FOR TWO RECTIFIER SYSTEM

Figure 8 shows the output of two rectifier system.

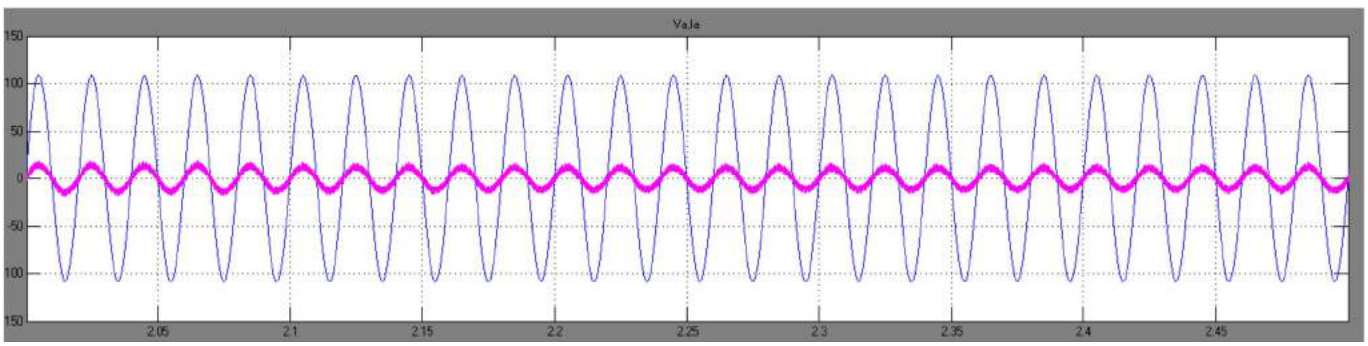

Fig 81: Input voltage and current

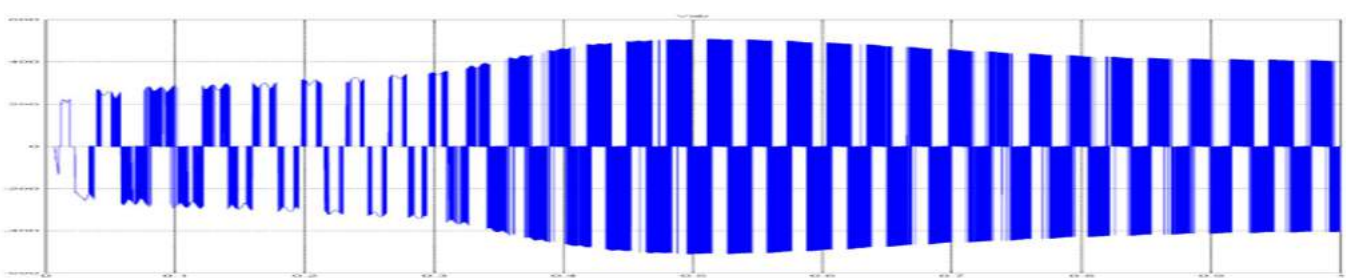

Fig 8.2: Phase voltage V_{a-b}

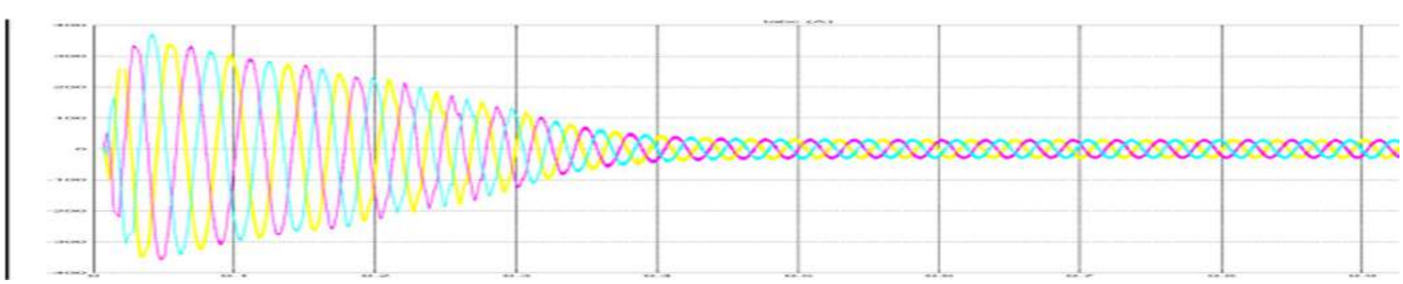

Fig 8.3: Three phase current

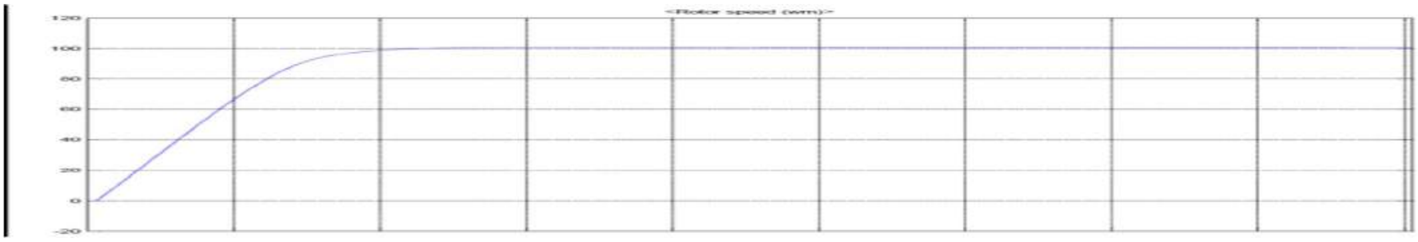

Fig 8.4: Speed characteristics of the motor

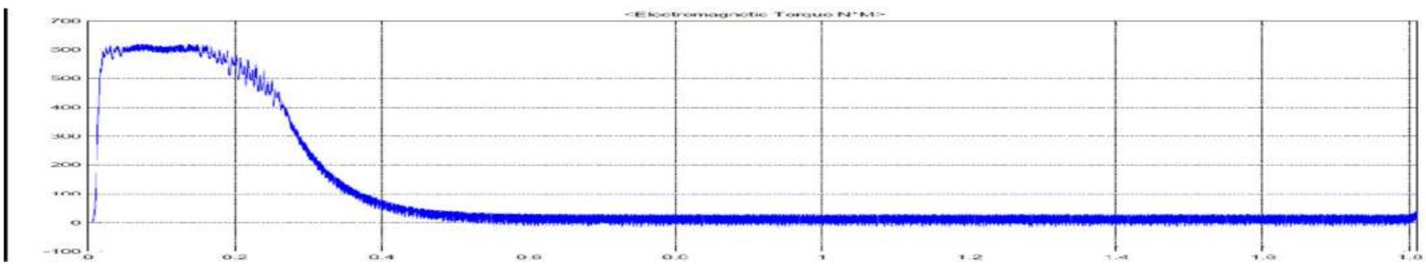

Figure 8.5: Electromagnetic Torque ($T_e^* = 0$)

IX. COMPARISON OF TWO SYSTEM

Sr. No.	Parameters	One Rectifier	Two Rectifier
1	THD	More	Less
2	No of component	10	14
3	Cost	More	Less
4	Input current shaping	Yes	Yes
5	Boost conductor	1	4

X. CONCLUSION

MATLAB simulation of three phase induction motor drive supplied from single phase supply with two parallel connected rectifiers and with one rectifier is developed in this paper. The parallel rectifier system helps to reduce the rectifier switching currents, and the total harmonic distortion (THD) of the grid current with same switching frequency. In addition, the losses of the proposed system may be lower than that of the conventional system. The system control strategy is fully developed and all the simulation results are presented. Because of the decrease in the rectifier switch current, the rating of switches decreases in rectifier circuit of proposed configuration which may helps in reducing cost of the system.

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