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PERFORMANCE OF FIVE PHASE INDUCTION MOTOR USING SPECIALLY CONNECTED TRANSFORMER

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ABSTRACT

Multi-Phase Machines are Ac machines characterized by a stator winding composed of standard number of phases. In today's electric drive & Generation technology Multiphase machine has several advantages over the traditional three phase machine such as sinking the amplitude and raising the frequency of torque pulsation, reducing the rotor harmonic current per phase without increasing the voltage per phase, lowering the dc-link current harmonics and higher reliability, high fault tolerance. Earlier multiphase motor where not used widely because that the supply for the multi-phase motor was not available, with the advancement of the electrical technology there is a choice to get the multiphase motor supply system. The proposed specially connected transformer takes the conventional three phase supply and it will give the five phase supply by proper combination of the secondary winding terminals. The induction motor (five phase) feed by the five phase output of the specially connected transformer. The performance of the motor is analysed under balanced as well as unbalanced supply conditions and also under stator fault conditions.

Keywords: multi-winding transformer, turns ratio, five phase induction motor, balanced and unbalanced power supply.

1. INTRODUCTION

Induction motor is one of the most familiar electrical motors used in day to day applications. It is used widely because of its rugged, reliable and cost-effective features. Single phase induction motors are used abundantly for smaller loads, such as house hold appliances like fans and water pumping motors. Whereas three phase induction motors are applicable for larger loads like lathes, drilling machine, agricultural pumps and industrial drives.

In order to drive large loads the number of phases of the induction motor must be increased to reduce the torque ripples. By using multi-phase [1] over the conventional three phase the output torque is high and even with the opening of one or two phases the motor performance will not degrade.

In a squirrel cage induction motor the stator is excited by source and the rotor bars are short circuited. So there is a flexibility of increasing the number of phases in the stator side. Which can be done through transformer connections.The rotor phases get automatically adjusted.

In this paper instead of going to an inverter for five phase supply a special transformer connection scheme is employed [2], which transforms three phase grid supply to five phase system. Three multi-winding single phase transformers are used for implementing this transformation. The primary side of multi-winding transformer consists of one winding. Secondary side consists of two or three windings each depending on the type of connection. In this paper first different types of transformer connections are explained and later five phase induction motor modelling is elaborated. The output of the transformer can be varied by using auto transformer at the primary side [2]. The below diagram shows specially connected transformer with three phase supply as input and five phase supply as output given to five phase induction motor.

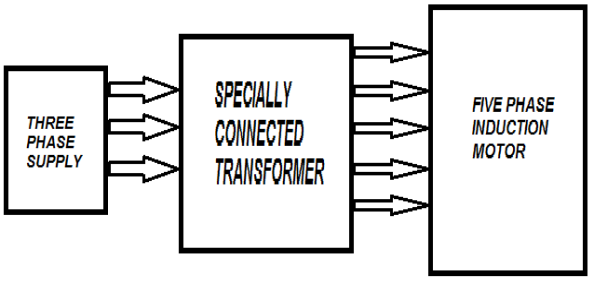

Figure-1. Block diagram.

1.1 Three phase to five phase transformation

The transformers primary three phases and secondary five phases can be connected in four different ways

a) Star- Star
b) Star- Polygon
c) Delta- Star
d) Delta-Polygon

The phase difference between two consecutive phases is 72° and this exact phase difference is obtained by properly selecting the turn's ratio [2]. Here conversion is done by considering three multi-winding transformers MW_1, MW_2, MW_3. The primaries of three multi-winding transformer have only one winding each. Secondary side of MW_2 and MW_3transformers have three windings and MW_1transformer has two windings in case of star connection and three windings in case of polygon connection. The phases are labelled "A", "B", C" of the input supply and "a", "b", "c", "d", and "e" are phases of output supply.

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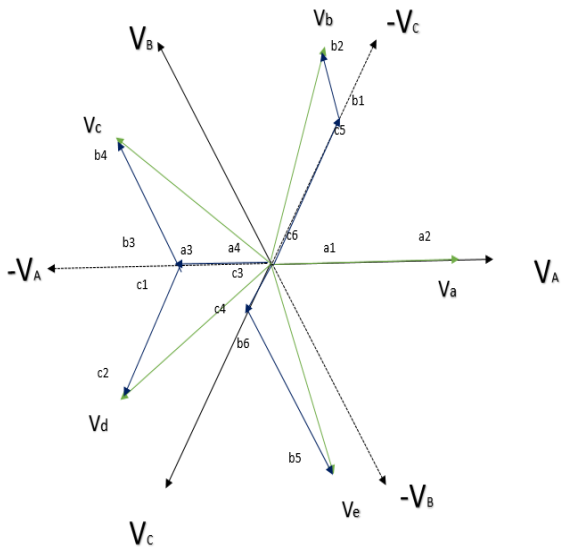
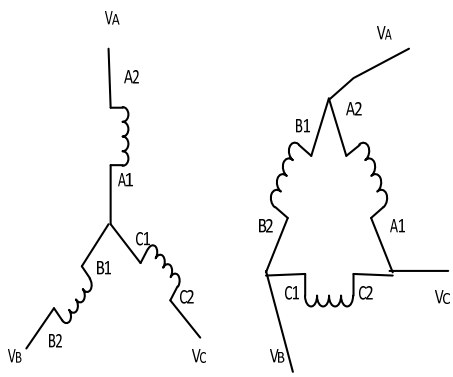
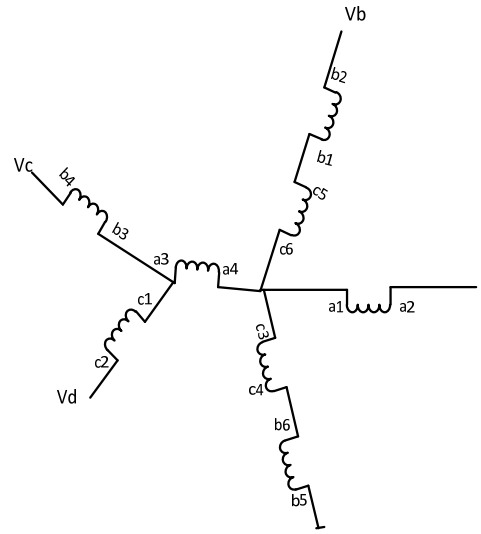


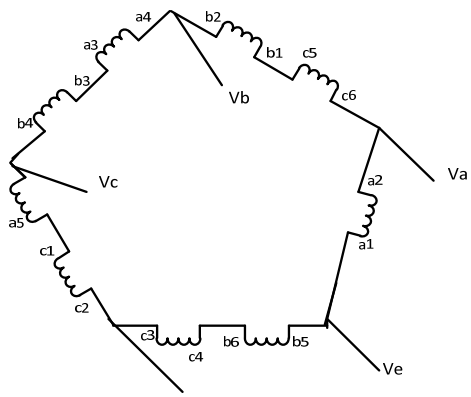
Figure-2. Phasordiagram for calculating turns ratios.



3 (a)



3 (b)



3 (c)

Figure-3 (a) Winding arrangements for primary star and delta connections. (b) Winding arrangements forsecondary star. (c) Winding arrangements for secondary polygon.

Table-1. Turns ratio's for all four types of connection.

Primary	Star-Star		Star-Polygon		Delta -Star		Delta-Polygon	
	Secondary	Turns ratio(N_s/N_p)	Secondary	Turns ratio(N_s/N_p)	Secondary	Turns ratio(N_s/N_p)	Secondary	Turns ratio(N_s/N_p)
Phase-A	a_1 a_2	1	a_1 a_2	1	a_1 a_2	1	a_1 a_2	1
			a_3 a_4	0.47	a_4 a_3	0.47	a_3 a_4	0.47
	a_3 a_4	0.47	a_5a_6	0.47			a_5a_6	0.47
Phase -B	b_1 b_2	0.24	b_1 b_2	0.24	b_1 b_2	0.24	b_1 b_2	0.24
	b_3 b_4	0.68	b_3b_4	0.68	b_4 b_3	0.68	b_3b_4	0.68
	b_5 b_6	0.858	b_5b_6	0.858	b_5 b_6	0.858	b_5 b_6	0.858
Phase -C	c_1 c_2	0.68	c_1 c_2	0.68	c_1 c_2	0.68	c_1 c_2	0.68
	c_3 c_4	0.24	c_3c_4	0.24	c_4 c_3	0.24	c_3c_4	0.24
	c_3,c_5	0.858	c_5 c_6	0.858	c_5 c_6	0.858	c_5 c_6	0.858

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- **Star-Star**

Six terminals of primaries and the sixteen terminals of secondaries are connected in star. The connection scheme of primary and secondary windings is shown in Figures3 (a) and 3(b). Turns ratios of secondary windings with respect to primary are given in Table-1. The phasor equations for star-star connection are given in (1)-(9).Balanced three phase supply is given to the input terminals A, B, and C.V_A, V_B, V_C are the phase to neutral voltages. V_a to V_e are the output phase voltages to neutral.

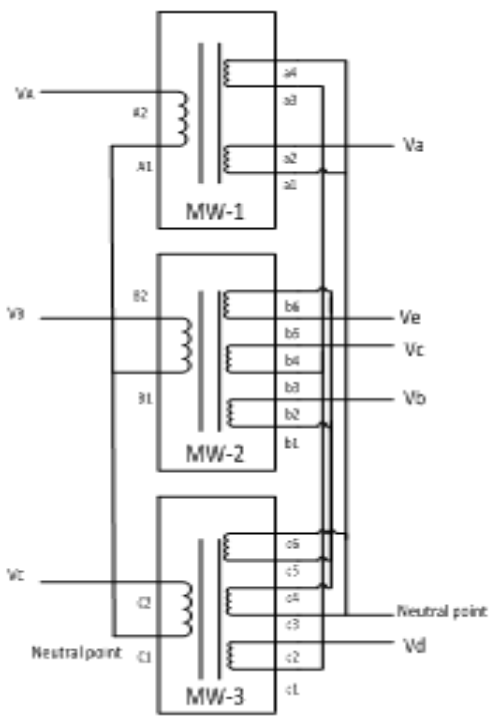

Figure- 4. Connection diagram for Star-Star.

Just as demonstrated in Figure-2, phase "A" of the input and phase "a" of the output are in same phase. Phase "b" of the output, obtained from the phasor sum of winding voltage "c_6 c_5" and "b_1 b_2".Similarly "c" , "d" ,"e" output phases are obtained from phasor sum of "a_4 a_3" and "b_4 b_3", "a_4 a_3" and "c_1 c_2", "c_4 c_3" and "b_5 b_6"respectively.by proper connection winding terminals the five phase output would be obtained.[2]

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \frac{1}{Sin\left(\frac{\pi}{3}\right)} \begin{bmatrix} Sin\left(\frac{\pi}{3}\right) & 0 & 0 \\ 0 & Sin\left(\frac{\pi}{15}\right) & -Sin\left(\frac{4\pi}{15}\right) \\ -Sin\left(\frac{2\pi}{15}\right) & Sin\left(\frac{\pi}{5}\right) & 0 \\ -Sin\left(\frac{2\pi}{15}\right) & 0 & Sin\left(\frac{\pi}{5}\right) \\ 0 & -Sin\left(\frac{4\pi}{15}\right) & Sin\left(\frac{\pi}{15}\right) \end{bmatrix} \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} \quad (1)$$

$$V_a = V_{\max} Sin(\omega t) \quad (2)$$

$$V_b = V_{\max} Sin\left(\omega t + \frac{2\pi}{5}\right) \quad (3)$$

$$V_c = V_{\max} Sin\left(\omega t + \frac{4\pi}{5}\right) \quad (4)$$

$$V_d = V_{\max} Sin\left(\omega t - \frac{4\pi}{5}\right) \quad (5)$$

$$V_e = V_{\max} Sin\left(\omega t - \frac{2\pi}{5}\right) \quad (6)$$

$$V_X = V_{\max} Sin(\omega t) \quad (7)$$

$$V_Y = V_{\max} Sin\left(\omega t + \frac{2\pi}{3}\right) \quad (8)$$

$$V_Z = V_{\max} Sin\left(\omega t - \frac{2\pi}{3}\right) \quad (9)$$

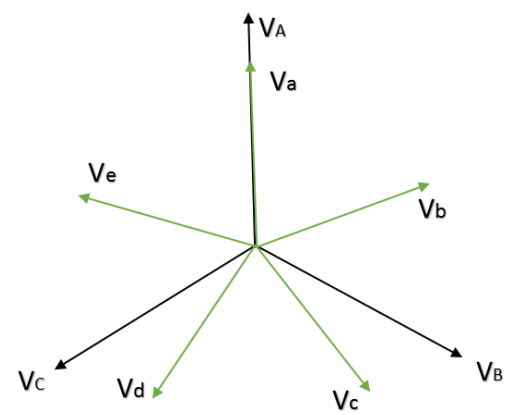

Figure-5. Phasordiagram for input Star-output Star arrangement of a transformer.

Here, the two windings of the transformer are connected in star. So primary phase-A and secondary phase-a are in phase as shown in Figure-5.

- **Star-Polygon**

In view of this connection primary winding is in star and secondary winding is in polygon type of connections. So the supply voltage will be in phase with the primary windings whereas on the secondary side as it is connected as polygon connection phase to phase voltage will appear across the secondary terminals. Hence the output will be 54° lagging from the primary as well as the supply voltage as shown in Figure-6.

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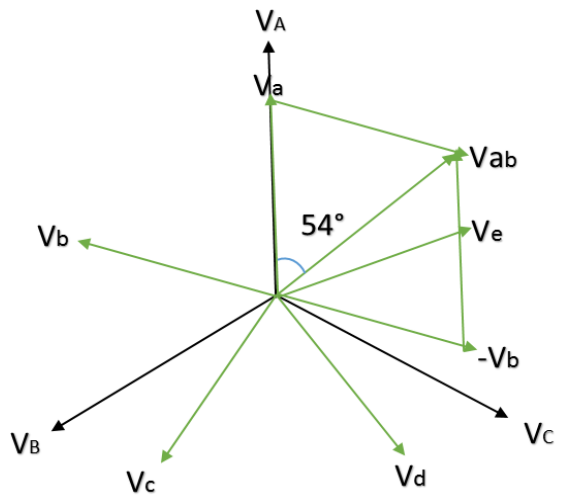

Figure-6. Phasordiagram for star-polygon connection.

- **Delta-Star**

Here, primary winding is in delta and secondary in star mode. So the supply voltage will lead the voltage across the primary winding by 30°. As the secondary is connected in star the voltage of secondary phase-a will be in phase with the primary phase-A. By this way the secondary voltage will be lag behind the supply voltage by 30° as shown in Figure-7.

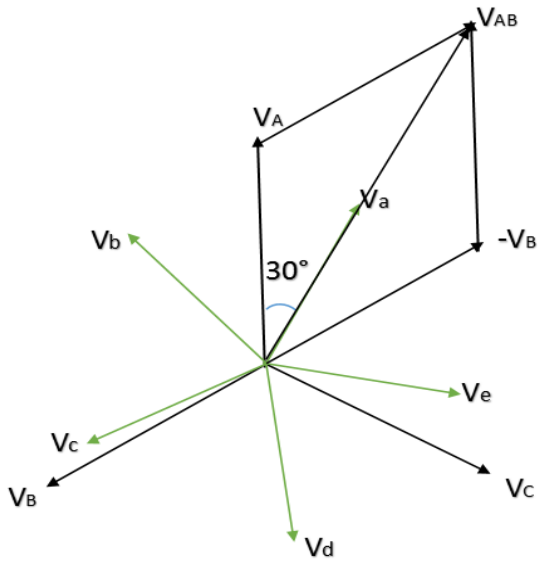

Figure-7. Phasordiagram for Delta-Star connection.

- **Delta-Polygon**

Similar to the above type of connections, here primary winding is in delta and secondary is in polygon mode. So primary lags behind the supply voltage by 30° and secondary lags behind the primary by 54°. There by a total of 84° phase shift is observed from supply to the secondary side as shown in Figure-8.

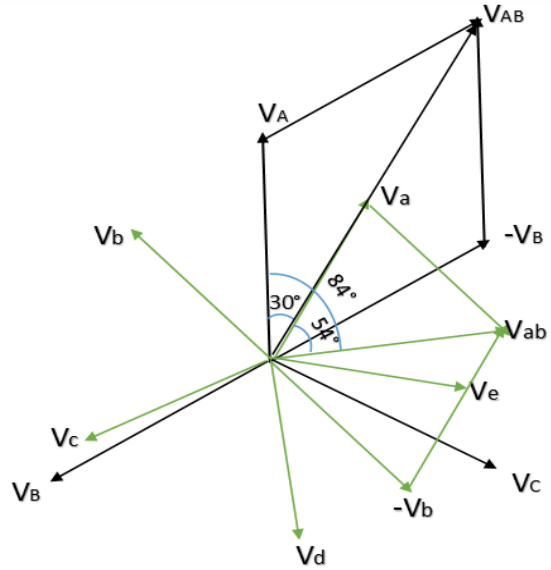

Figure-8. Phasordiagram for delta-polygon connection.

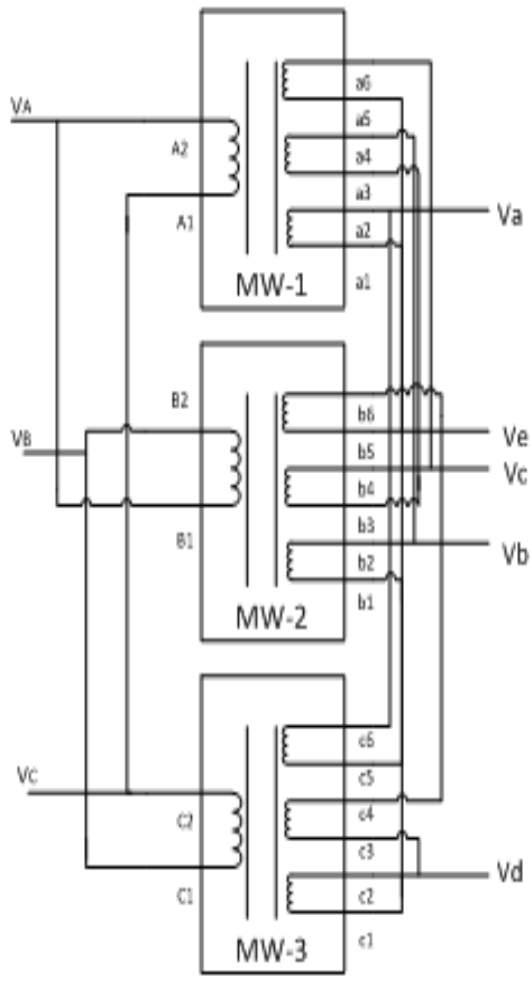

Figure-9. Connection diagram for Delta-Polygon.

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2. FIVE PHASE INDUCTION MOTOR

The output five phase supply of specially connected transformer fed to five phase induction motor and observe all the connection scheme results.

Modelling of the Induction motor implemented by using Simulink library, in which the mathematical equations are modelled and used for computations of various inputs. Modelling of machines has become an important tool for machines.[4]-[8]

3. DYNAMIC EQUATIONS

The output five phase voltages [6] from the transformer, converted to two phase in order to reduce the complexity in the modelling. This is done by using Park's transformation which is given in equation (10).

Equation (10) indicates five phase to two phase transformation which is used for voltages, currents and flux linkages.

It also represents the power invariant matrix, here the first two rows variables contribute the elementary air gap flux and production of the torque. Here , the equations represents the voltages, currents, flux linkages and self ,mutual inductance of both a stator and rotor of five phase induction motor.

$$\begin{bmatrix} V_q \\ V_d \\ V_x \\ V_y \\ V_0 \end{bmatrix} == \sqrt{\frac{2}{5}} \begin{bmatrix} Cos\theta & Cos\left(\theta-\frac{2\pi}{5}\right) & Cos\left(\theta-\frac{4\pi}{5}\right) & Cos\left(\theta+\frac{4\pi}{5}\right) & Cos\left(\theta+\frac{2\pi}{5}\right) \\ Sin\theta & Sin\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) \\ Cos\theta & Cos\left(\theta+\frac{4\pi}{5}\right) & Cos\left(\theta-\frac{2\pi}{5}\right) & Cos\left(\theta+\frac{2\pi}{5}\right) & Cos\left(\theta-\frac{4\pi}{5}\right) \\ Sin\theta & Sin\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \tag{10}$$

$$[V_{axis}] = [T][Vphase] \tag{11}$$

Equation [11] indicates the relationship between axis voltages, currents and flux linkages on the stator side.

The relation between transformed currents and transformed flux linkages is shown below.

$$[\psi_{phase}] = [M][i_{phase}] \tag{12}$$

$$[T^{-1}][\psi_{axis}] = [M][T^{-1}][i_{axis}] \tag{13}$$

$$[\psi_{axis}] = [TMT^{-1}][i_{axis}] \tag{14}$$

$$[\psi_{axis}] = [L][i_{axis}] \tag{15}$$

Where [M] is the phase inductance matrix
[L] is the axis inductance matrix

$$[T] == \begin{bmatrix} Cos\,\theta & Cos\left(\theta-\frac{2\pi}{5}\right) & Cos\left(\theta-\frac{4\pi}{5}\right) & Cos\left(\theta+\frac{4\pi}{5}\right) & Cos\left(\theta+\frac{2\pi}{5}\right) \\ Sin\,\theta & Sin\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) \\ Cos\,\theta & Cos\left(\theta+\frac{4\pi}{5}\right) & Cos\left(\theta-\frac{2\pi}{5}\right) & Cos\left(\theta+\frac{2\pi}{5}\right) & Cos\left(\theta-\frac{4\pi}{5}\right) \\ Sin\,\theta & Sin\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{16}$$

$$[T^{-1}] == \begin{bmatrix} Cos\,\theta & Sin\,\theta & Cos\,\theta & Sin\,\theta & \frac{1}{\sqrt{2}} \\ Cos\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) & Cos\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{4\pi}{5}\right) & \frac{1}{\sqrt{2}} \\ Cos\left(\theta-\frac{4\pi}{5}\right) & Sin\left(\theta-\frac{4\pi}{5}\right) & Cos\left(\theta-\frac{2\pi}{5}\right) & Sin\left(\theta-\frac{2\pi}{5}\right) & \frac{1}{\sqrt{2}} \\ Cos\left(\theta+\frac{4\pi}{5}\right) & Sin\left(\theta+\frac{4\pi}{5}\right) & Cos\left(\theta+\frac{2\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) & \frac{1}{\sqrt{2}} \\ Cos\left(\theta+\frac{2\pi}{5}\right) & Sin\left(\theta+\frac{2\pi}{5}\right) & Cos\left(\theta-\frac{4\pi}{5}\right) & Sin\left(\theta-\frac{4\pi}{5}\right) & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{17}$$

$$[M] == \begin{bmatrix} L_S & -M_1 & -M_2 & -M_2 & -M_1 \\ -M_1 & L_S & -M_1 & -M_2 & -M_2 \\ -M_2 & -M_1 & L_S & -M_1 & -M_2 \\ -M_2 & -M_2 & -M_1 & L_S & -M_1 \\ -M_1 & -M_2 & -M_2 & -M_1 & L_S \end{bmatrix} \tag{18}$$

$$[L] = [T][M][T^{-1}] \tag{19}$$

$$i_{ds} = \frac{\psi_{ds}(L_{lr} + L_m) - L_m\psi_{dr}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)}$$

$$i_{qs} = \frac{\psi_{qs}(L_{lr} + L_m) - L_m\psi_{qr}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \tag{20}$$

Equation [20] indicates that the relationship between axis currents, self and mutual inductances and flux linkages on the stator side.

$$I_{dr} = \frac{\psi_{dr}(L_{ls} + L_m) - L_m\psi_{ds}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)}$$

$$i_{qr} = \frac{\psi_{qr}(L_{ls} + L_m) - L_m\psi_{qs}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \tag{21}$$

Equation [21] indicates that the relationship between axis currents, self and mutual inductances and flux linkages on the rotor side

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_a\psi_{qs}$$

$$V_{qr} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_a\psi_{ds}$$

$$V_{xs} = R_s i_{xs} + \frac{d\psi_{xs}}{dt}$$

$$V_{ys} = R_s i_{ys} + \frac{d\psi_{ys}}{dt}$$

$$V_{0s} = R_s i_{0s} + \frac{d\psi_{0s}}{dt} \tag{22}$$

Equation [22] indicates that the relationship between axis voltages, currents and flux linkages on the stator side.

$$V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_a - \omega_r)\psi_{dr}$$
$$V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_a - \omega_r)\psi_{dr}$$
$$V_{xr} = R_r i_{xr} + \frac{d\psi_{xr}}{dt}$$
$$V_{yr} = R_r i_{yr} + \frac{d\psi_{yr}}{dt}$$
$$V_{0r} = R_r i_{0r} + \frac{d\psi_{0r}}{dt} \quad (23)$$

Equation [23] indicates that the relationship between axis voltages, currents and flux linkages on the rotor side.

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr})$$
$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr})$$
$$\psi_{xs} = L_{ls} i_{xs}$$
$$\psi_{ys} = L_{ls} i_{ys}$$
$$\psi_{0s} = L_{ls} i_{0s} \quad (24)$$

Equation [24] indicates Stator side Flux linkages, self inductance and mutual inductance.

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr})$$
$$\psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr})$$
$$\psi_{xr} = L_{lr} i_{xr}$$
$$\psi_{yr} = L_{lr} i_{yr}$$
$$\psi_{0r} = L_{lr} i_{0r} \quad (25)$$

Equation [25] indicates Rotor side Flux linkages, self inductance and mutual inductance.

The output electrical torque is given as below:

$$T_e = \left(\frac{5}{2}\right)\left(\frac{P}{2}\right)\left(\frac{L_m}{L_m + L_{lr}}\right)(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}) \quad (26)$$

The mechanical torque associated with the rotor speed as given below in terms of rotor inertia (J), viscous friction coefficient (B), number of poles (P) with mechanical load.

$$T_e = \left(\frac{2}{P}\right)\left(J\frac{d\omega}{dt} + B\omega_r\right) + T_L \quad (27)$$

4. SIMULATION RESULTS

The output voltages of all four types of transformer connections are fed to the five phase induction motor and observe the torque, speed and stator currents of the motor are obtained by using MATLAB. Here the induction motor is tested for both balanced and unbalanced supply conditions [10]-[11].unbalanced applied voltages to the motor is done to simulate fault conditions.

The following parameters are used for the implementation of the five phase induction motor.

Stator resistance R_s	0.75 Ω
Rotor resistance R_r	0.60 Ω
Stator inductance L_{Ls}	3.65e-3 H
Rotor inductance L_{Lr}	3.65e-3 H
Mutual inductance L_m	28.5e-3 H
Moment of inertia J	0.0415 kg/m^2
Viscous friction coefficient B	0.0415N.m.s
Number of poles	4

- **Star-Star**

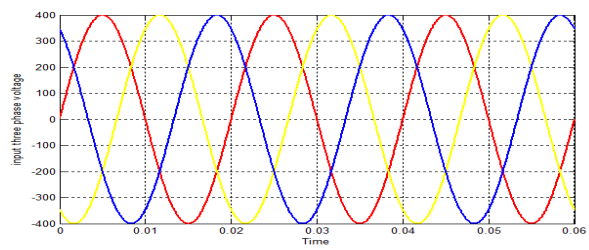

Figure-10. Input voltage (Star-Star)-balanced supply.

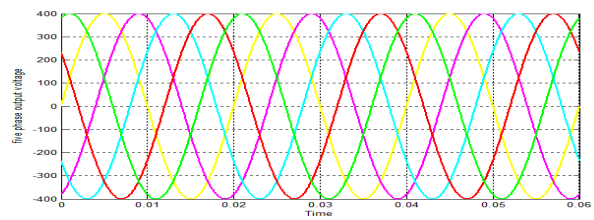

Figure-11. Output voltage (Star-Star)- Balanced supply.

Figures 10 and 11 shows the input and output voltages of balanced supply of the transformer Star-Star connection. Both the primary and secondary winding voltages of the transformer are in phase respectively. Input transformer is assumed to be ideal. Input and output voltages are 400V/ph.

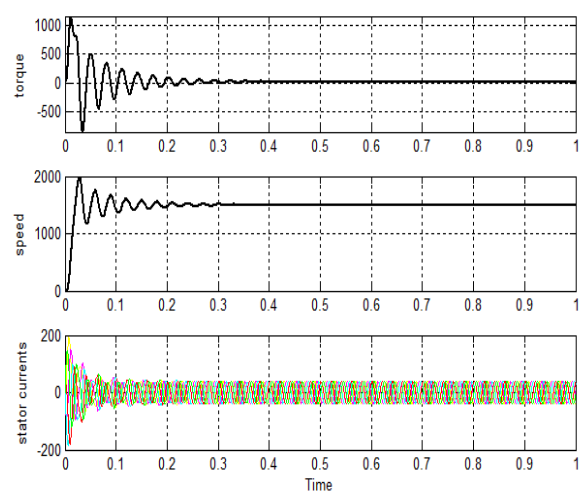

Figure-12. Torque, speed and stator currents (Star-Star)- Balanced supply.

Figure-12 shows the peak torque is of 1130 N-m at 0.001sec, and then it will be settled down at 0.5sec on

words with a magnitude of 13.55 N-m. The steady state speed is 1497 RPM.

- **Star-Polygon**

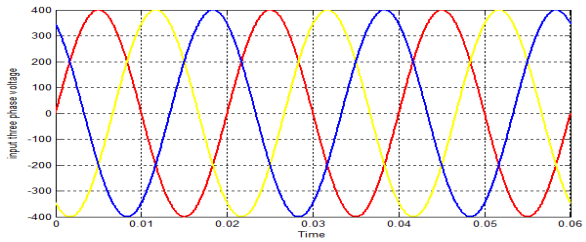

Figure-13. Input voltage (Star-Polygon) - Balanced supply.

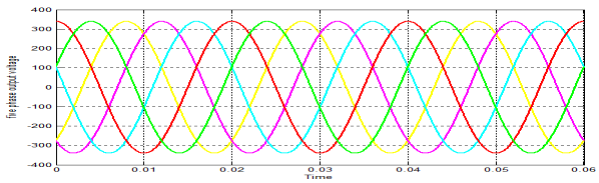

Figure-14. Output voltage (Star-Polygon)- Balanced supply.

Supply voltage will be in phase with the primary coil voltages whereas on the secondary side as it is connected as polygon connection phase to phase voltage will appear across the secondary terminals. Hence the output will be 54° lagging from the primary as well as the supply voltage. Here the input voltage 400V/ph as shown in Figure-13, and output voltage 341.8V/ph as show in Figure-14 of a Star-Polygon transformer connection.

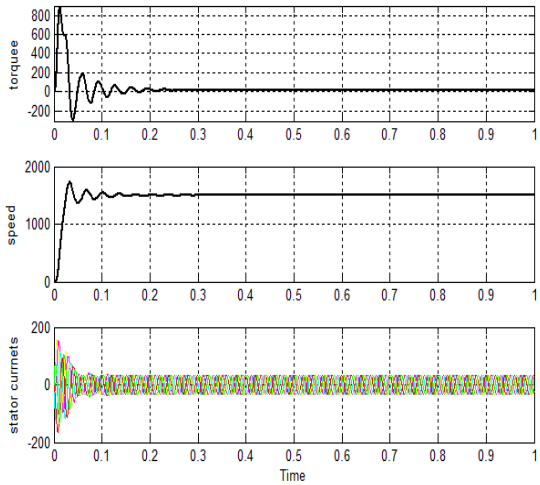

Figure-15. Torque, speed and stator currents (Star-Polygon) - Balanced supply.

Figure-15 shows the peak torque is of 900 N-m at 0.001sec and settled down at 0.3sec with a magnitude of 13.64 N-m. The steady state speed is 1496 RPM.

- **Delta-Star**

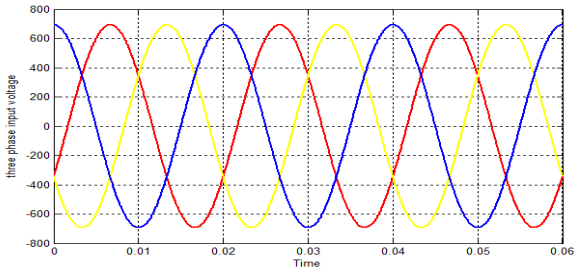

Figure-16. Input voltage (Delta-Star)- Balanced supply.

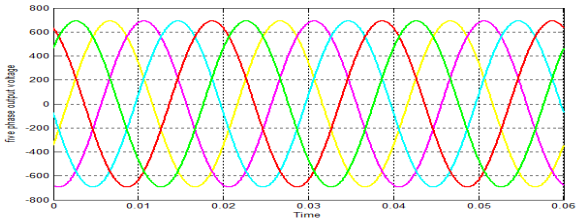

Figure-17. Output voltage (Delta-Star)- Balanced supply.

Here, the Supply voltage will lead the voltage across the primary winding by 30°. As the secondary is connected in star the voltage of secondary phase-a will be in phase with the primary phase-A. By this way the secondary voltage will lag behind the supply voltage by 30°.The input and output voltages shown in Figures 16 and 17 are 692.8V/ph for a Delta-Star connection of a transformer.

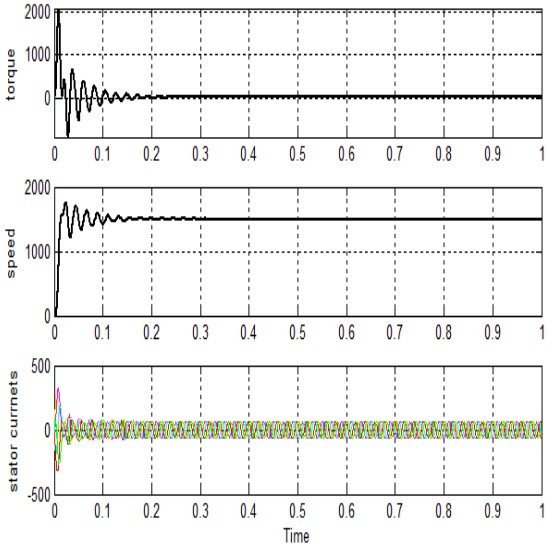

Figure-18. Torque, speed and stator currents (Delta-Star)- Balanced supply.

Figure-18 shows the peak torque of 2060 N-m at 0.001sec and settled down at 0.3sec on words with a magnitude of 13.68 N-m. The steady state speed is 1499 RPM.

- **Delta-Polygon**

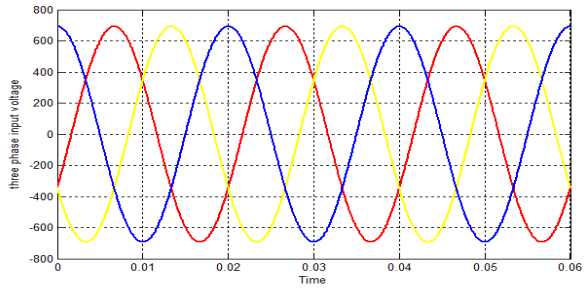

Figure-19. Input voltage (Delta-Polygon) Balanced supply.

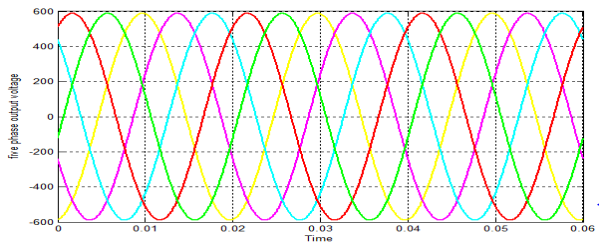

Figure-20. Output voltage (Delta-Polygon)- Balanced supply.

Primary voltage lags behind the supply voltage by 30° and secondary lags behind the primary by 54°. There by a total of 84° phase shift is observed from supply to the secondary side. Here the input voltage 692.8V/ph as shown in Figure-19, and output voltage 592.15V/ph as show in Figure-20 for the Delta-Polygon transformer connection.

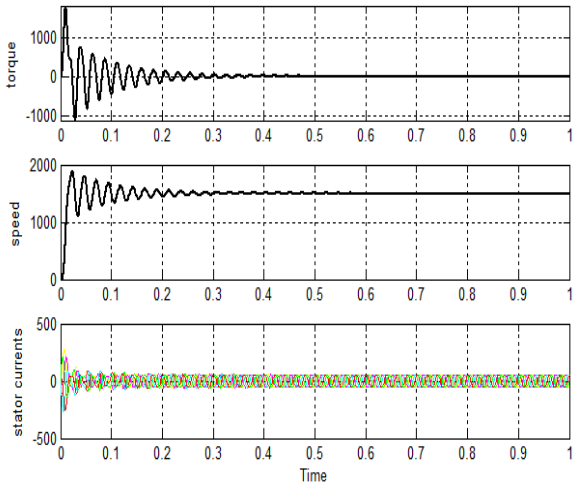

Figure- 21. Torque, speed and stator currents (Delta-Polygon)- Balanced supply.

Figure-21 shows the peak torque 1780 N-m at 0.001sec and settled at 0.8sec on words with a magnitude of 13.68 N-m. The steady state speed is 1499 RPM.

- **Unbalanced supply**

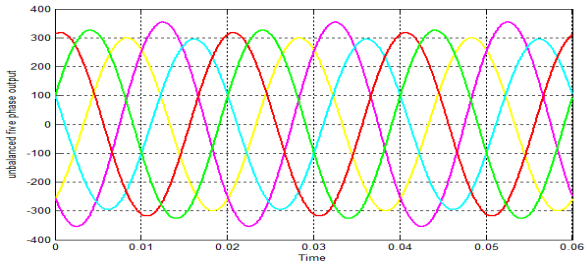

Figure-22. Unbalanced five phase supply.

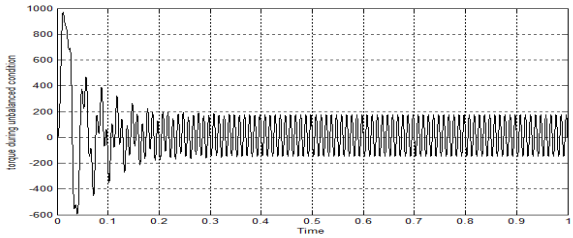

Figure-23. Torque during unbalanced supply

In this case an unbalanced five phase voltage is fed to the induction motor and the output torque is observed to oscillate with an average value of 13.25 N-m. Star-Star connection is used for the transformer and unbalancing is done by varying the applied three phase voltages.

Under unbalanced conditions the X,Y and zero sequence component voltages will be non zero but they do not contribute to torque. However as shown in Equation (11) and (12) these components produce corresponding transformed currents in rotor.

5. CONCLUSIONS

In view of the proposed system, it is observed from the outputs of each transformer connection that star-polygon type of connection has low peak value of torque during transient period and also steady state is attained quickly when compared to other connections. Reliability of the five phase induction motor is observed by employing phase loss condition to simulate fault condition.

Under unbalanced condition, the torque is found to oscillate with twice the supply frequency in steady state (Figure-23).

Even under failure of any one phase out of five phases the motor performance does not reduced; it runs with the same condition when five phases are acting. This feature was not present in the conventional three phase induction motor. If anyone phase under faulty condition, it acts like a single phase machine with degraded efficiency. Therefore, the performance of the three phase induction motor is less compared to the proposed five phase induction motor.

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