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Speed Range Enhancement for Five Phase Induction Motor Drive using Reconfiguration of Five Phase Supply

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Abstract*: *In modern electrical circumstances of society lead the development of technology in every field of science, due to ever increasing demand of more power it is necessary to supply it at a certain voltage level economically, which restrict it to a particular value. Moreover there are other boundaries on utilization side as well, for energy consumers and producers. The solution for this is use of multiphase systems. These days multiphase systems are being contemplated as a elucidation for the predicament and research in this field is picking up rapidity. There is a need to acquire multiphase supply from the existing three phase supply due to its inherent advantages. One of the advantages of multiphase machine is that it can be used in high speed applications. Enhancement of speed range in the multi phase machine achieved by either the corresponding inverter operated with high voltage or sinking the value of counteract emf of machine using the techniques of field weakening. An n-phase machine (where n>3) can be allied in (n+1)/2 different ways i.e., called reconfiguration. With these available alternatives, the speed range of an n-phase can be significantly increased. In such connection different torque-speed characteristics are realized. For an odd number of phases, the stator winding of a multiphase machine connected in (n+1) different ways. The first two are normal star connection and delta connection. The remaining are the swap delta connections which are obtained by changing the phase sequences.

Index Terms: Conventional Delta, Five leg inverter, Multi Phase machine, Swap Delta

I. INTRODUCTION

In day-to-day applications, Induction motors (IM) plays a major role among all the well known electrical motors because of their extensive utilization, simple in construction, good in performance and cost-effectual features. For low loads, such as fans, motors used to pump water etc., single phase IM's are lavishly used and for high loads such as lathes, drilling machines and pumps used in agricultural etc., classical IM's are used. The phases of IM are increased multiple in number to drive large loads and also reduce torque ripples. Comparing multi-phase with classical the output voltage raises to higher value and the motor performance will not degrade, even with the opening of one or two phases. Hence, by considering the following literature survey the multi phase IM is considered as five phase IM in the proposed work. In order to enhance the speed of the IM reconfiguration has been done. K. Jezernik et al.,[1] in the year 2003 proposed a sensor less IM drive controlled by means of estimation of EMF. The proposed drive operated at low and zero speed and observed effects of torque on both cases. Also by considering the rotor flux observer and estimation of EMF, the output was determined in an effective manner. Here, the VSI fed IM drive was considered by few assumptions taken into account such as eddy and hysteresis currents, magnetic saturation ignored, windings were in sinusoidal distribution and short circuited rotor etc, with basic state equations in stator reference frame were analyzed.

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Shaoan Dai et al., [2] in the year 2003, proposed a new control strategy of 3-level neutral point clamped converters using delta-sigma modulation. Here 2-level inverters were also discussed with convention sinusoidal pulse width modulation but it suffered from few drawbacks such as imbalances in common mode voltage, high noise voltages and poor output voltages. These drawbacks were overcome by the proposed control strategy.

Maurizio et al., [3] in the year 2006, introduced a new strategy of DTC controlled IM operated at less common mode emissions. This technique obtained by stator flux revolved only in even or only in odd voltage vector modes of the proposed drive.

Ruiz-Gonzalez et al., [4] in the year of 2010, proposed a new control scheme for inverter fed IM. The proposed drive operated at low acoustic noise with suitable pulse width modulation technique. By reducing the acoustic noise, then THD also reduced.

Joel Prieto et al., [5] in the year 2011, introduced a various pulse width modulation for VSI fed 5-Φ IM. Based on the PWM techniques total harmonic distortion factor analyzed using all the modulation techniques. Here carrier, continuous space vector and discontinuous space vector approach PWM techniques were discussed. Flux harmonic trajectories were analyzed for various values of modulation index.

Kouzou et al., [6] in the year 2011, introduced a new control strategies for 3-level neutral clamped converter such as SHE pulse width modulation to improve the inverter output voltages. Hence total harmonic distortion was controlled as desired. Determination of space voltage vector angles is the main criteria to analyze the proposed inverter

Ayman S. Abdel-Khalik et al., [7] in the year 2012 focuses on permanent magnet machines with standard or transposable windings. Here, the proposed winding scheme was in terms of concentrated fractional slots. The quality produced revolving field is in-adequate while applied to the conventional 3-Φ IM. 5-Φ induction machines, FSCW's are designed based on the traditional 3-Φ lap wound machine. The proposed drive is applicable to all submersible pumps. Here the harmonics are analyzed in all the winding designs.

Barry Venugopal Reddy et al., [8] in the year 2013, introduced a new 4-level open phase IM drive operated with two inverters in fixed rectifier and inverter mode. Here total 64 voltage space vectors builds up due to dual mode of inverters. Also zero state vectors were to be omitted to improve the proposed drive performance.

Ahmad A. Al-Abduallah et al., [9] in the year 2013, 5-Φ IM drive operated with inverter along with LC filter design. In general there are higher order harmonics which were induced in the voltage and current waveforms during the operation of proposed drive. These harmonics vanished by using filters and the total harmonic distortion was analyzed.

V.T. Somasekhar et al., [10] in the year 2016 proposed a 4-level IM drive with open ending for SVPWM technique. This PWM scheme is named as the Sampled Average Zero Sequence Elimination (SAZE) SVPWM scheme, wherein the zero sequence voltage was suppressed in each sampling time period in the average sense. Both of the aforementioned problems encountered in this drive were successfully overcome for this power circuit configuration by resorting to the proposed SVPWM strategy.

II. OBJECTIVES OF THE PROPOSED WORK

In order to reconfigure the five phase supply, the following objectives are defined. Two problems were acknowledged to steer the study:

- To interpret Multiphase Stator Winding Machine Connections.
- To analyze Five Phase Stator Winding Machine Connections.

III. CONVERTER RECONFIGURATION METHODS

The foremost step in this work is to elaborate and interpret the generalized Multiphase Stator Winding Machine Connections and subsequently enlightened the Five Phase Stator Winding Machine Connections for converter reconfiguration.

3.1 MULTIPHASE STATOR WINDING MACHINE CONNECTIONS

In a multiphase machine the stator winding can be allied in (n+1)/2 dissimilar ways to accomplish odd digit of phases. The former two are the standard star and delta topologies. The residual configurations are the swap delta connections which are acquired by altering the phase sequences.

In order to attain the swap connections, the machine windings are hypothetical to be allied in delta across the inverter legs. In this section, the peaks of the voltages across the phase windings of the five and seven five machines are calculated as examples. Since the machine is supplied through an inverter, it is easiest to implement the connection changeover from one delta configuration to the other by changing the modulation signals sent to the base drives of the inverter legs.

3.2 ANALYSIS OF FIVE PHASE STATOR WINDING MACHINE CONNECTIONS

In the five-phase machine, there are three possible connections one star and two alternate delta connections. Fig 1 (a) shows the schematic representation of a five phase stator winding connected in star configuration. Figs 1 (b) and (c) show the delta connections of the five phase stator winding of the induction machine in the conventional and alternate configurations, respectively. It is obvious that the difference between the configuration of Fig 1 (b) and that of Fig 1 (c) is the phase sequence orientation, which will eventually result in different magnitudes of the peak voltages across the machine phase windings. The phase sequence for the delta connection of the five-phase machine are *abcde* and *acebd*.

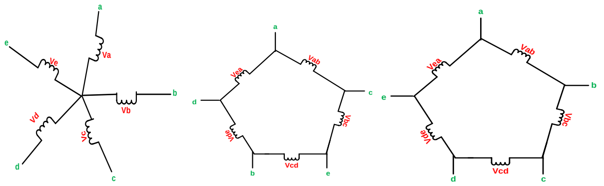

Fig 1. Different stator winding connections for a five-phase stator winding (a) Star (b) Normal (conventional) delta, *abcde* and (c) Swap delta, *acebd*.

If the n-phase machine is supplied through an m-leg inverter, the voltages across the machine phases changes based on the way of connecting the windings. If the winding of the machine is connected in star, then the voltage of each phase is equal to the output voltage of inverter leg. For the remaining connections, the voltage of each phase is equal to the difference between the voltages of two inverter legs for which the phase windings are connected. For the five-phase machine, the magnitude of the voltage across each phase winding will be 1.1756V_m and 1.902 V_m for *abcde* and *acebd*, respectively.

$$V_A = V_{max} \operatorname{Sin}(\omega t) \tag{1}$$

$$V_B = V_{max} \operatorname{Sin}\left(\omega t + \frac{2\pi}{5}\right) \tag{2}$$

$$V_C = V_{max} \operatorname{Sin}\left(\omega t + \frac{4\pi}{5}\right) \tag{3}$$

$$V_D = V_{max}\,\mathrm{Sin}\left(\omega t - \frac{4\pi}{5}\right) \qquad (4)$$

$$V_E = V_{max}\,\mathrm{Sin}\left(\omega t - \frac{2\pi}{5}\right) \qquad (5)$$

In a balanced five phase system phase voltages V_A, V_B, V_C, V_D, V_E are displaced by 72^0. In every phase, the magnitude of phase voltage is signified as V_{ph} for balanced star allied system. The angle between V_A and V_B is 120° and the angle between V_A and $-V_B$ is 180° – 72° = 108° is shown in Fig.2

$$\therefore V_A = V_B = V_C = V_D = V_E = V_{ph}$$

- Line voltages $V_{AB}, V_{BC}, V_{CD}, V_{DE}, V_{EA}$, are 72° apart from each other
- Line voltages are 54° leading from the corresponding phase voltages

We know that in case of star connection, line current is identical as the phase current and whose magnitude is identical in all the three phases i.e., I_L.

$$\therefore I_A = I_B = I_C = I_D = I_E = I_L$$

Where, I_A, I_B, I_C, I_D and I_E are line currents of phases A, B, C, D, and E respectively.

$$\therefore I_A = I_B = I_C = I_D = I_E = I_L = I_{ph}$$

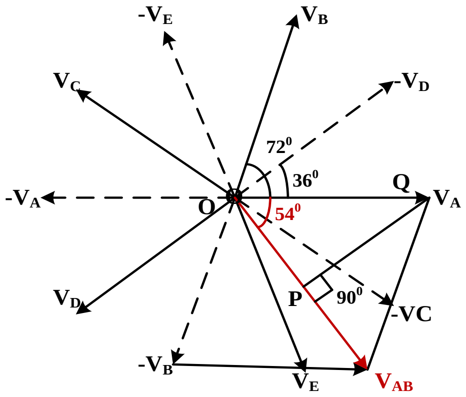

Fig 2. Relationship between Five Phase Voltages

In the above Phasor diagram, from right angled triangle OPQ; we have

$$\mathrm{Cos}54^0 = \frac{\frac{V_{AB}}{2}}{V_A}$$

$$\Rightarrow \mathrm{Cos}54^0 = \frac{V_{AB}}{2V_A}$$

$$\Rightarrow V_{AB} = 2 * \mathrm{Cos}54^0 * V_A$$

$$\Rightarrow V_{AB} = 1.18V_A$$

$$V_L = 1.18V_{ph} \qquad (9)$$

Five-Phase Power (in the case of balanced system):

$P = 5V_{Ph}\, I_{Ph}\cos\text{Ø}$ or $P = 4.25\, V_L I_L \cos\text{Ø}$ (10)

A comparison is made between three phase and five phase supply, and it is observed that five-phase power supply is more than three-phase power supply, i.e. and single phase power supply, five-phase power is 2.52 times more than the three- phase power supply and 4.25 times more than the single-phase power supply[11]

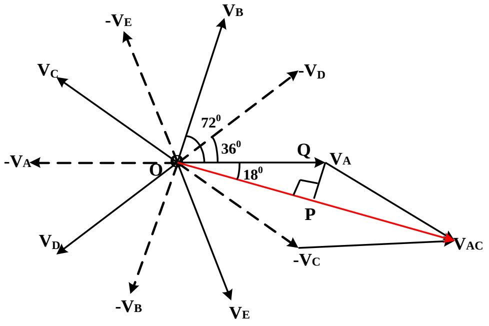

Fig 3. Relationship between Five Phase Voltages after Reconfiguration

In the above Phasor diagram, from right angled triangle OPQ; we have

$$\mathrm{Cos}18^0 = \frac{\frac{V_{AC}}{2}}{V_A}$$

$$\Rightarrow \mathrm{Cos}18^0 = \frac{V_{AC}}{2V_A}$$

$$\Rightarrow V_{AC} = 2 * \mathrm{Cos}18^0 * V_A$$

$$\Rightarrow V_{AC} = 1.902V_A$$

$$\Rightarrow V_L = 1.902V_{ph}$$

The configurations with lower voltages are appropriate for higher torque, lower speed range operation even as with higher voltages will give lower torques, high speed range operating points. The phase angles of the inverter voltages shown in Fig1(c) are assumed as correspondingly 0, 2π/5, 4π/5, 6π/5 and 8π/5 for legs *a*, *b*, *c*, *d*, and *e*. The magnitude of the machine winding phase voltage is 1.1756 V_m , which is similar to the configuration of Fig 1(a). If the magnitude of the voltage across each machine phase will be 1.902V_m, When the phase angles are multiplied by a factor of 3, which is equal to the magnitude of machine phase voltage for the (*acebd*) delta configuration of Fig 1.(b). Realization of this configuration can be done through the phase angles of the modulation signals. In general, given the modulation signals for the five legs of the star connection of the machine windings of the induction machine, the respective factors (k_i) with which the phase angles are multiplied by to attain the *ith* delta configuration are given by $k_i = odd(1, 3, , n - 2)$, where $n(odd)$ is the number of phases and i= 1, 2, 3,… (n-1)/2. Accordingly by altering the phase angles of the modulation signals, as illustrated in Table 1 for a five-phase machine, an automatic changeover between the delta winding configurations without adding any mechanical or semiconductor switches. Fig 3 illustrates the phase windings of a five phase induction machine connected across the outputs of the voltage source five phase inverter in a conventional delta connection. Fig 4 illustrates the phase windings of a five phase induction machine connected across the outputs of the voltage source five phase inverter in an swap delta connection.

Physical switching between the windings should be required if a switching occurs from the connection in Fig 3 to that of Fig 4. As an alternative, using a physical switch, the proposed approach oblige one to change the modulation angle of the modulating signals for the respective legs and by so doing, the voltages across the windings in Fig 3 will be as if the windings are connected as shown in Fig 4.

Table 1 Modulation signals for star connection and changeover from delta connection I to delta connection II

Phase	Star connection (abcde-n)	Delta connection I (abcde)	Delta connection II (acebd)
a	$M\sin(\omega t+\delta)$	$M\sin(\omega t+\delta)$	$M\sin(\omega t+3\delta)$
b	$M\sin\left(\omega t-\frac{2\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{2\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{6\pi}{5}+3\delta\right)$
c	$M\sin\left(\omega t-\frac{4\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{4\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{12\pi}{5}+3\delta\right)$
d	$M\sin\left(\omega t-\frac{6\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{6\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{18\pi}{5}+3\delta\right)$
e	$M\sin\left(\omega t-\frac{8\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{8\pi}{5}+\delta\right)$	$M\sin\left(\omega t-\frac{24\pi}{5}+3\delta\right)$

Where M is the magnitude of the modulation index and δ is the phase angle.

3.3 FIVE-LEG INVERTER FED FIVE-PHASE INDUCTION MACHINE

The topology of five-phase VSI is depicted in Fig.4 which consists of ten switches each phase delayed by 36^0. Each phase conducts for 72^0. Upper leg switches are S_1, S_3, S_5, S_7, S_9 and lower leg switches are S_6, S_8, S_{10}, S_2, S_4. In each phase, two switches (i.eS_1S_6, S_3S_8, S_5S_{10}, S_7S_2, S_9S_4) cannot be switched ON at the same time because a short circuit occurs across the dc link supply voltage [12]-[14].

Control of two level five phase VSI can be done in ten operating modes. In every mode only five switches are conducting among them two from upper leg and three from the lower leg or vice versa. Each leg has a phase shift of 72^0. In order to get the enhancement in speed range of the proposed Five Phase Induction Motor Drive (FPIMD), by reconfiguring the input phases of the five leg inverter and shown in Fig.4 and the torque equation is determined as follows.

Mathematical model equations for d-q components and the torque equation are similar for a three-phase IM, but the discrepancy between five phase machine model and the corresponding three phase machine model is the presence of x-y components in voltage and flux equations. Rotor x-y components are fully decoupled from d-q components and one from other. Since rotor winding is short circuited, x-y components does not appear in the rotor winding. Zero sequence component equations for both stator and rotor can be omitted from further consideration due to short-circuited rotor winding and star connection of stator winding.

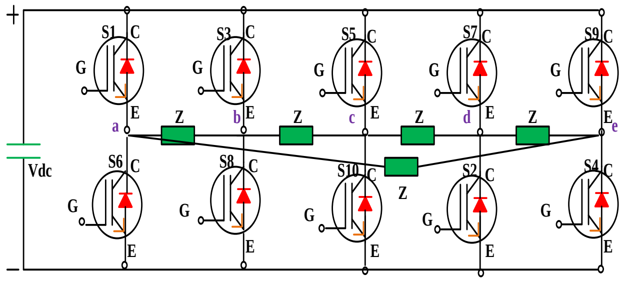

Fig. 4a. Five-Leg Inverter Fed Five-Phase Induction Machine in “abcde” Delta Connection

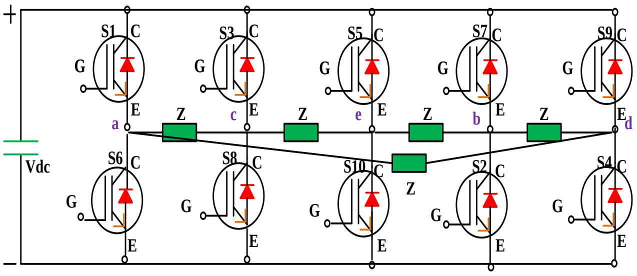

Fig. 4b. Five-Leg Inverter Fed Five-Phase Induction Machine in “acebd” Delta Connection

The torque was expressed in its more general form, relating the variables of d-q components as

$$T_e=\left(\frac{5}{2}\right)\left(\frac{P}{2}\right)\left(\frac{L_m}{L_m+L_{lr}}\right)\left(i_{qs}\psi_{dr}-i_{ds}\psi_{qr}\right) \tag{11}$$

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

$$T_e=\left(\frac{2}{P}\right)\left(J\frac{d\omega}{dt}+B\omega_r\right)+T_L \tag{12}$$

$$T_e=PL_m\left(i_{qs}i_{dr}-i_{ds}i_{qr}\right) \tag{13}$$

$$\omega_r=\int\frac{P}{2J}\left(T_e-T_L\right)dt \tag{14}$$

3.4 CONSTANT TORQUE REGION

In this province, despite the fact that the rotor flux producing current is kept constant, the speed increases from zero to base speed, as shown in Fig 5 during which the q- and d-axis currents are constant. The rated stator current is careworn under this condition. Under this condition, the phase machine winding voltage also increases from zero to the maximum tolerable rated value. The torque is constant as portrayed in Fig 6.

The constraints on the inverter voltage and currents are

$$v_{qs}^2+v_{ds}^2\le V_s^2 \tag{15.a}$$

$$i_{qs}^2+i_{ds}^2\le I_s^2 \tag{15.b}$$

V_s and I_s are the peak values of the inverter maximum allowable voltage and current. If the stator resistance drop is neglected, then the transition stator frequency from constant torque region to field weakening region I (when the machine phase voltage and current are rated values concurrently) is

$$\omega_1=\frac{V_s}{\sqrt{L_s^2 i_{ds-rated}^2+L_\sigma^2\left(I_s^2-i_{ds-rated}^2\right)}} \tag{16}$$

Where $i_{ds-rated}$ is the stator d-axis rated current at rated flux.

3.4.1 Field Weakening Region I

The stator qd voltages and currents are given by the equality constraint version of equation 15 which tranquil hold true in the field weakening region I. For this region of operation, the speed increases ahead of bas speed and the d-axis stator currents show a discrepancy with rotor speed. They are given in equation (17).

$$i_{qs} = \sqrt{\frac{\omega^2 L_s^2 I_s^2 - V_s^2}{\omega^2 L_s^2 - \omega^2 L_\sigma^2}} \qquad (17.a)$$

$$i_{ds} = \sqrt{\frac{V_s^2 - \omega^2 L_\sigma^2 I_s^2}{\omega^2 L_s^2 - \omega^2 L_\sigma^2}} \qquad (17.b)$$

The rotor speed increases until the voltage is no longer able to supply the rated current. Thus the current constraint in (15) does not hold any more, Fig 5. This is the point at transition from field weakening region I to region II which is discussed in the next subsection. That is, the phase voltage corresponds to the rated phase voltage but the phase current drawn by the motor is less than the rated phase current.

3.4.2 Field Weakening Region II

The current constraint in field weakening region II, no longer holds true. In this case there is not adequate phase voltage from the source to supply the rated phase current. Consequently by using the torque optimization approach, the optimum q-axis and d-axis stator currents and slip speed can be acquired as

$$\frac{dT_e}{di_{qs}} = 0 \qquad (18)$$

$$i_{qs-opt} = \frac{V_s}{\sqrt{2}\omega_{opt} L_\sigma} \qquad (19.a)$$

$$i_{ds-opt} = \frac{V_s}{\sqrt{2}\omega_{opt} L_s} \qquad (19.b)$$

The optimum value of slip speed is given by

$$\omega_{slip-opt} = \frac{r_r^1 L_s}{L_r^1 L_\sigma} \qquad (20)$$

Where ω_{opt} is the transition frequency between field weakening regions I and II given by

$$\omega_{opt} = \frac{V_s}{L_s L_\sigma I_s}\sqrt{\frac{L_s^2 + L_\sigma^2}{2}} \qquad (21)$$

As the frequency increases beyond ω_{opt} the stator currents decrease as

$$i_{qs} = \frac{V_s}{\sqrt{2}\omega L_\sigma} \qquad (22.a)$$

$$i_{ds} = \frac{V_s}{\sqrt{2}\omega L_s} \qquad (22.b)$$

IV. RESULTS AND DISCUSSIONS

The proposed IM performance was analyzed through MATLAB environment and the following discussions are concluded. Observing the Fig.5 the five phase motor starting currents are 5A for five leg inverter fed FPIMD. Fig.6 shows output balanced line voltages of proposed FPIMD. Observe the line voltage of each phase is 415V. The magnitude of starting torque of the FPIMD shown in Fig.7, i.e 13.8N-m and the settling time of the torque will be 0.3Sec.

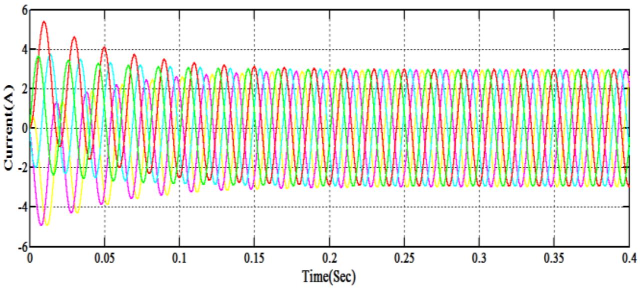

Fig 5. Line Currents of FPIMD for Swap Delta Connection

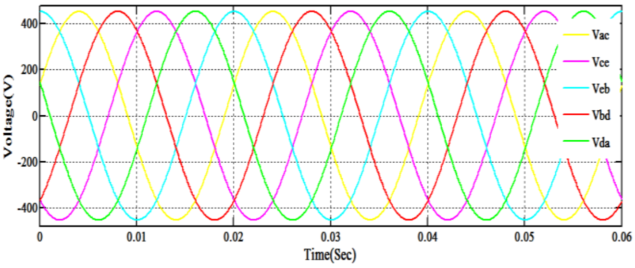

Fig 6. Line Voltages of Swap Delta Connection

Steady-state results for the five-phase induction machine in different stator winding configurations are presented in this section. Fig 8 and Fig 9 illustrate the steady state results for different stator winding connections. It can be glimpsed that the base speeds depend on the type of winding connection. Lower torque values results with connections that have higher magnitudes of the phase winding voltage, but with an extensive speed range.

In star connection the voltage across the machine phase winding is assumed to be 1 per unit (p.u.), then when the winding is connected in conventional delta (Fig 8(a)), the peak voltage across the machine phase winding is 1.1765 p.u, whereas for the swap delta connection (Fig 8(b)) the peak voltage across the machine's phase winding is 1.902 p.u. In Fig 8, it has been clearly exposed that for the delta connection with a phase peak voltage of1.902 p.u., the torque in the high speed range is higher than that for the other delta and star connections. Consequently in high speed applications, comparatively high torque can be acquired by altering the voltages across the machine winding as it has been presented.

In Fig 9, as soon as the machine winding is star connected, higher torque is attained during the constant torque operation region until the speed is 1 p.u., at a point where field weakening region I starts. The torque due to the conventional delta connection is higher than those of the other two connections at a rotor speed of about 2 p.u., and as a result the converter has to switch from star connection to delta connection until at appoint when the torque produced due to the alternate delta connection other two connections.

Thus at a rotor speed of about 2.4 p.u. the changeover from conventional delta to swap delta will take place.

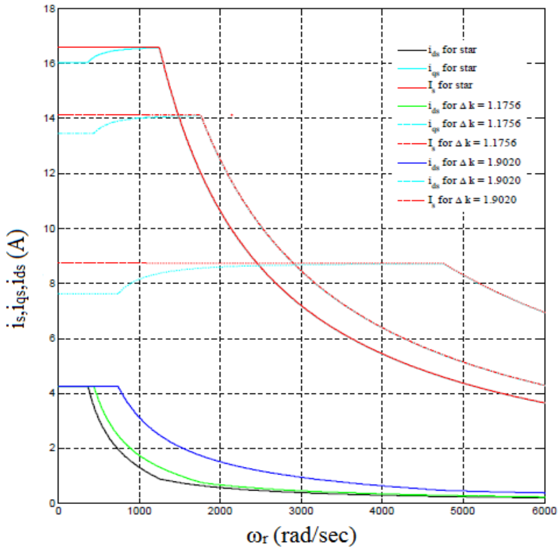

Fig 8. Stator Peak, q-axis and d-axis Currents of Rotor Speed for the Three Different Connections of the Five-Phase Induction Motor.

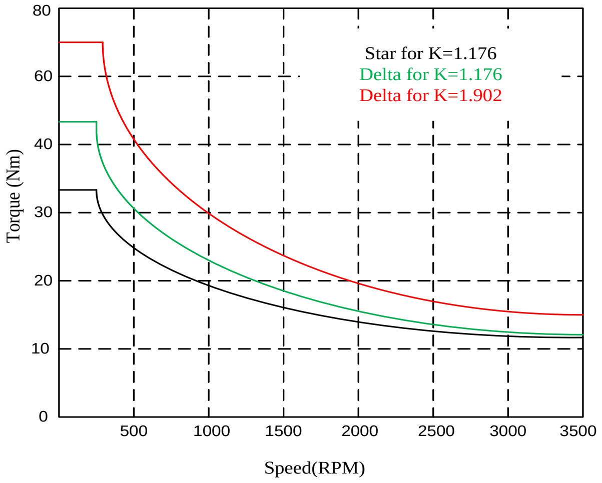

Fig 9 Torque as a Function of Rotor Speed for the Three Different Connections of Five-Phase Induction Motor.

Fig 10 shows the simulation results for rotor field oriented control of a five phase induction machine for varying speed commands in which the actual rotor speed closely follows the command rotor speed. The reference d-axis rotor flux linkage is 0.4574 Wb. Fig 8 shows the electromagnetic torque and both the actual and reference rotor speed. Fig 8 also shows the simulation results for the field weakening control. It can be observed that before base speed (i.e. 1 p.u.), the torque is approximately constant and as the speed increases, the torque and the flux are gradually reduced. At about 2 p.u. speed, the machine winding connection is changed from star to delta configuration until the speed is about 2.4 p.u.

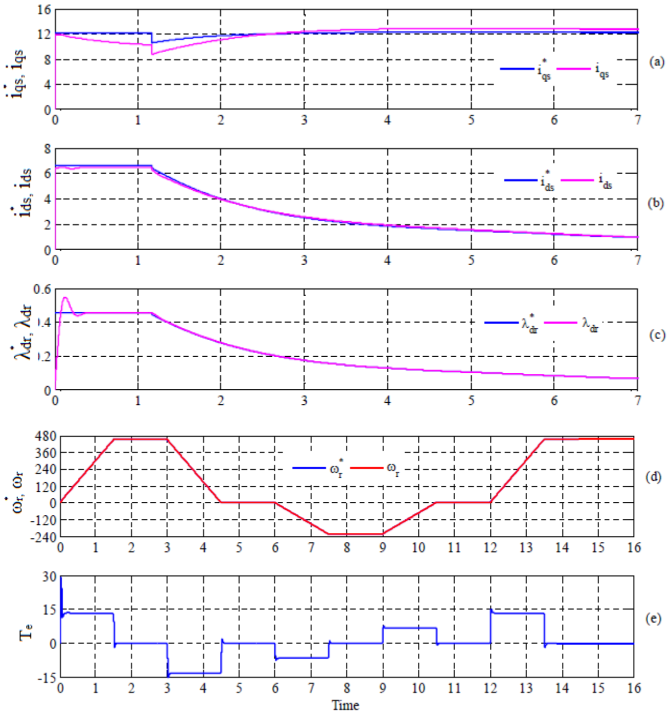

Fig 10 Speed Controlled Five-Phase Machine, (a) Actual and Reference q-axis Stator Currents (b) Actual and Reference d-axis Stator Currents (c) Actual and Reference d-axis Rotor Flux Linkages (d) Actual and Reference Rotor Speed and (e) Electromagnetic Torque.

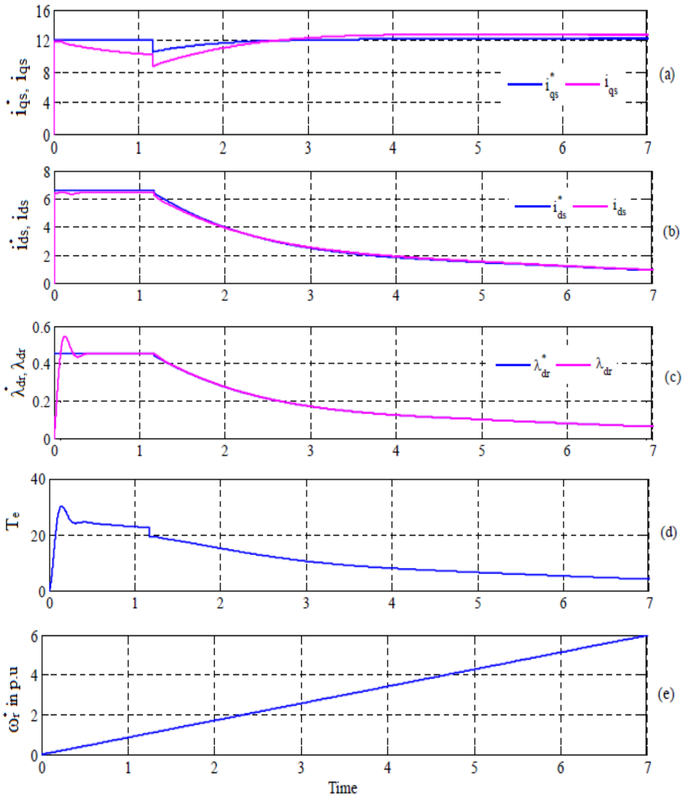

Fig 11. Speed Field Weakening Control of a Five-Phase Machine, (a) Actual and Reference q-Axis Stator Currents (b) Actual and Reference d-Axis Stator Currents (c) Actual and Reference d-Axis Rotor Flux Linkages (d) Electromagnetic Torque and (e) Reference Rotor Speed.

V. CONCLUSION

The approach to reconfigure the inverter in order to achieve wider speed range of operation for the multiphase machines has been presented. The multiphase machines offer extended range speeds of operations when connected in different delta schemes across the inverter output phases. By changing the phase angles of the modulation signals, changeover connection from one delta configuration to the other is achieved. The higher the voltage across the machine phase winding, the higher the speed range and lower the operating torque point. Steady state and simulation results for the rotor flux oriented control have been presented and clearly show that it is possible to operate at higher speeds with a relatively high torque when other connections of the stator windings of the multiphase machine are explored

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