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Control of Five Phase Two-Motor Series Connected Single Source Drive Systems under Balanced and Unbalanced Conditions

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Abstract: Multi-phase induction machines that contain more than three-phases are becoming popular in many industrial applications, due to the many advantages over three-phase machines such as: reduced line voltage, higher efficiency, lower torque pulsation and density, fault tolerance, stability and lower current ripple. One of the key benefits of multi-phase machines is the additional degrees of control freedom which may be utilized for independent control of single-source multi-motor multiphase drive systems. Another important advantage is their ability to operate under unbalanced conditions. Control of a series-connected five-phase two-motor system using a PI controller is shown in this study. Performance of five-phase two-motor system under a single open-line condition is studied. Results are obtained by simulation in Matlab/Simulink.

Key word: Multi-phase induction machines, two-motor systems, drive system controls, advantages, voltage, pulsation and density

INTRODUCTION

Traditional three-phase electrical power generation and transmission is the main reason three-phase machine drives are the most popularly in industry. However, with the many advances in power semiconductor devices, high efficiency AC-DC and DC-AC conversion is possible with no limitation on the number of power converter legs or output phases.

Over the past few years there has been a growing interest in multi-phase Induction Motor (IM) drives (Levi, 2008; Abu-Rub *et al*., 2012). Considerable attention has been recently paid due to the significant development of power switching devices and micro-controllers. Multi-phase motor-drives have many advantages over traditional three-phase drives (Rosa *et al*., 2014). They have higher torque density and lower torque pulsations (Williamson and Smith, 2003; Apsley *et al*., 2006; Iqbal *et al*., 2010). Due to the additional degrees of freedom in multi-phase drives, they have greater fault tolerance while reducing current rating per inverter leg at the same power level which decreases the power requirements on semiconductor switches in high power applications (Levi, 2008; Abu-Rub *et al*., 2012). The low torque ripple magnitude and the high frequency torque pulsations yield's better noise characteristics (Abu-Rub *et al*., 2012; Rosa *et al*., 2014; Williamson and Smith, 2003; Apsley *et al*., 2006). Multi-phase drives are being considered for use in a magnitude of applications such as: electric ship propulsion, "more-electric" aircrafts, electric traction and electric and hybrid electric vehicles (Levi, 2008). The five-phase induction machine is one of the most studied multiphase motors and will most likely be the first widely used multi-phase system deployed in industry and thus the reason for this study on control of faulted multi-motor systems.

MATERIALS AND METHODS

Five-phase two-motor induction motor drive

A.single five-phase induction motor drive: A single five-phase induction motor drive consists of a five-phase induction machine a five-leg inverter and a controller that applies the chosen control algorithm scheme (Abu-Rub *et al*., 2012; Rosa *et al*., 2014; Williamson and Smith, 2003; Apsley *et al*., 2006; Iqbal *et al*., 2010; Krishnan, 2001). In this research, the inverter used was a voltage-controlled two-level Voltage Source Inverter (VSI) and a sinusoidal PWM algorithm was applied. Figure 1 shows a block diagram of a single five-phase IM drive.

Five-phase induction machine model: Electric motor drives theory described in Krishnan (2001) and Krause *et al*. (2002) are adopted in deriving the model of this machine and transformed to the reference frame models. The main assumption is that the magneto-motive forces of the motor are sinusoidal distributed. The angle between phases in five-phase induction motor is 72°. An arbitrary common stationary reference frame is chosen to provide the simplified model that eliminates the variables

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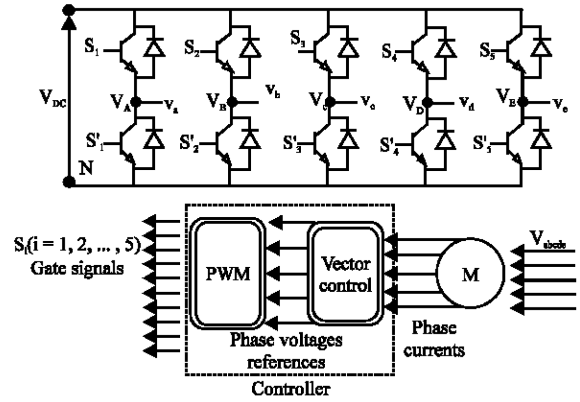

Fig. 1: Block diagram of single five-phase induction motor drive

that depend on the angle between rotor and stator by taking this angle into account in the new machine model (Krishnan, 2001; Krause *et al*., 2002).

Five-phase two-level voltage source inverter: The circuit schematic of a five-phase VSI is shown in Fig. 1. The input of the inverter is a DC voltage. Inverter voltage outputs (phase voltages) are defined in Fig. 1 by (V_A-V_E). The phase voltage is the voltage between the terminal of the inverter output and the neutral of the load while the voltage between the neutral of the DC link and the neutral of the load is the common mode voltage. The voltage difference between any two output terminals of the load is called the 'Line voltage' which can be either adjacent line or non-adjacent line voltage depending on the position of the two output terminals. In each inverter leg, if the upper switch is turned on, the lower must be off and vice versa.

Control of two five-phase induction motors connected in series to a single VSI: Usually, three-phase two-motor systems require two three-phase inverters with a common DC source for proper operation. Multiphase machines provide an additional degrees of freedom resulting from spatial harmonic components that can be used to control two multiphase machines connected in series to a single multiphase inverter with the same number of phases (Levi *et al*., 2003, 2004). Vector control requires only two current components for independent control of torque and flux of IM. These currents can be used to control flux and torque of other machines when a proper phase transposition is done. In five-phase IM, there are two additional current components which can be used to control flux and torque of another machine (Levi *et al*., 2003). The phase rearrangement is done so that the fundamental αβ currents of one machine becomes the harmonic xy currents of the other machine. If the two machines are named IM1 and IM2 where IM1 is the machine connected directly to the source, then αβ currents of IM2 and xy currents of IM1 in terms of phase currents are:

$$i_{\alpha 2} = \frac{\sqrt{2}}{5}\begin{pmatrix} i_{a2} + \cos\alpha\ i_{b2} + \cos 2\alpha\ i_{c2} + \\ \cos 3\alpha\, i_{d2} + \cos 4\alpha\, i_{e2} \end{pmatrix} \quad (1)$$

$$i_{\beta 2} = \frac{\sqrt{2}}{5}\left(\sin\alpha\, i_{d2} + \sin 2\alpha\, i_{c2} + \sin 3\alpha\, i_{d2} + \sin 4\alpha\, i_{e2}\right) \quad (2)$$

$$i_{x1} = \frac{\sqrt{2}}{5}\begin{pmatrix} i_{\alpha 2} + \cos 2\alpha\ i_{bs} + \cos 4\alpha\ i_{c1} + \\ \cos 6\alpha\ i_{d1} + \cos 8\alpha\ i_{e1} \end{pmatrix} \quad (3)$$

$$i_{y1} = \frac{\sqrt{2}}{5}\left(\sin 2\alpha\, i_{d1} + \sin 4\alpha\, i_{c1} + \sin 6\alpha\, i_{d1} + \sin 8\alpha\, i_{e1}\right) \quad (4)$$

Since, the two machines are connected in series, the same current flows in the connected phases of the two machines. From the equations above, rewiring such that the harmonic currents of IM1 (i_{x1} and i_{y1}) become the fundamental currents of IM2 ($i_{\alpha 2}$ and $i_{\beta 2}$). Phase 'a' of the two machines are directly connected. Phase 'b' of IM2 should be transposed by α phase angle by connecting phase 'b' of IM1 with phase 'c' of IM2. Phase 'c' is transposed by 2α by connecting phase 'c' of IM1 with phase 'e' of IM2. In the same way, phase 'd' of IM1 is connected to phase 'b' of IM2 and so, phase 'e' of IM1 to phase 'd' of IM2. A block diagram of vector control of two series connected five-phase machines that shows the connection of the two motors with the VSI is shown in Fig. 2.

In steady state, assuming that the torque producing current in IM1 has an RMS value of I_1 and the machine operates at an electrical speed of ω_1. Similarly, assume that the torque producing current in IM2 has an RMS value of I_2 and the machine operates at an electrical speed of ω_2. After series connection and according to the described phase transposition and connection shown in Fig. 2, phase currents of the two machines at steady state will be as following (where symbols A-E denote the inverter phases):

$$\begin{aligned} i_A &= i_{a1} = \sqrt{2}\ I_1\ \sin(\omega_1 t) + \sqrt{2}\ I_2\ \sin(\omega_2 t) = i_{a2} \\ i_B &= i_{b1} = \sqrt{2}\ I_1\ \sin(\omega_1 t - \alpha) + \sqrt{2}\ I_2 \sin(\omega_2 t - 2\alpha) = i_{c2} \\ i_C &= i_{c1} = \sqrt{2}\ I_1\ \sin(\omega_1 t - 2\alpha) + \sqrt{2}\ I_2 \sin(\omega_2 t - 4\alpha) = i_{e2} \\ i_D &= i_{d1} = \sqrt{2}\ I_1\ \sin(\omega_1 t - 3\alpha) + \sqrt{2}\ I_2 \sin(\omega_2 t - \alpha) = i_{b2} \\ i_E &= i_{e1} = \sqrt{2}\ I_1\ \sin(\omega_1 t - 4\alpha) + \sqrt{2}\ I_2 \sin(\omega_2 t - 3\alpha) = i_{d2} \end{aligned} \quad (5)$$

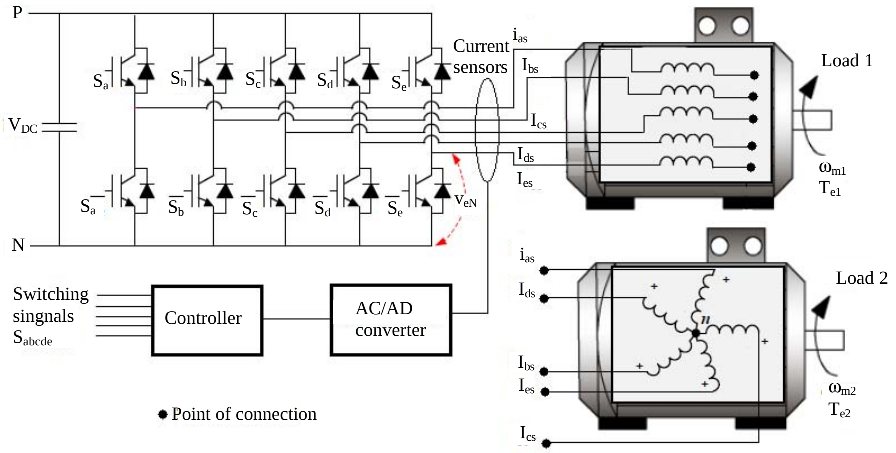

Fig. 2: Five-phase series-connected two-motor drive system

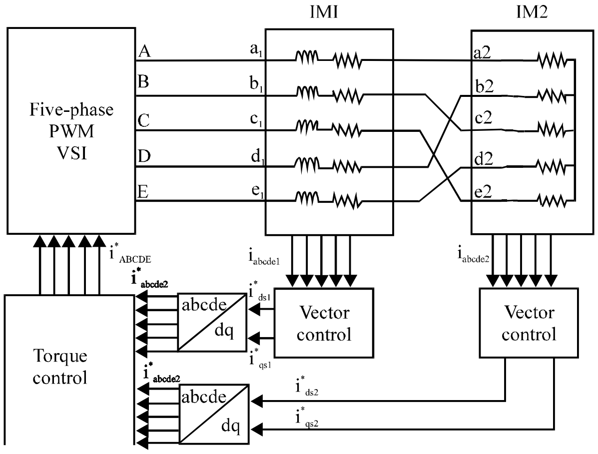

Fig. 3: Control of two five-phase motors connected in series to a single VSI

Fault-tolerant control of five-phase induction motor drive with an opened phase: One of the most important properties of multiphase induction machines is the high fault-tolerance capability (Fu and Lipo, 1994; Zheng *et al*., 2006; Tani *et al*., 2012) (Fig. 3). Usually in three-phase induction machines, there should be a connection between motor neutral and the midpoint of the DC source after a single open-phase fault occurs to individually control the remaining two phases (Toliyat, 1998; Jacobina *et al*., 2004; Hussain *et al*., 2008). This means that a zero-sequence current is required to maintain undisturbed rotating MMF. This is not the case in five-phase IM and multi-phase machines generally where harmonic current components can be used to provide infinite number of solutions of phase current combinations after a single or double open-phase fault occurs. These combinations can maintain undisturbed MMF and produce non-pulsating torque without the need for a neutral connection (Karugaba *et al*., 2008; Heising *et al*., 2009; Guzman *et al*., 2012). A single open-phase fault in phase 'a' is considered. The objective is to provide a solution of phase currents that leads to minimum phase current magnitudes and minimum I^2R loss. According to the problem established before, there is a set of equations with 2(n-1) unknowns. The problem above can be used for any machine with n phases. It can be noticed that for five-phase IM, there are 6 equations and 8 unknowns. In other words, there are two additional degrees of freedom to solve this problem and the solution is not unique.

RESULTS AND DISCUSSION

Matlab/Simulink Software was used as a test bed to verify the capability of reducing the single open-phase fault effects on the two-motor drive system. The five-phase induction machine model that is used for simulation is the stationary reference frame model discussed before. The motor drive system is controlled using indirect rotor field oriented control method, synchronous reference frame currents, i_d and i_q are controlled using a traditional PI controllers.

After using the additional current components of the five-phase induction machine in the independent fault tolerant control of two motors connected to a single VSI, the two-motor system response to an open-circuit one-leg line fault is studied. The fault is chosen to be on phase (a) line of the inverter which means that both machines will lose phase 'a'. IM1 speed reference is 1000 rpm and its load torque is 2 Nm. Speed reference and load torque of IM2 are 500 rpm and 4 Nm, respectively. Fault occurs at the beginning of the simulation. Figure 4-7 show torque,

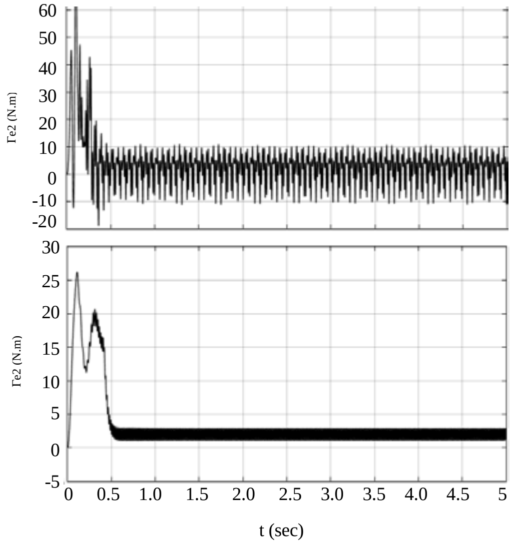

Fig. 4: Torque response of IM1 in faulted series-connected two-motor drive without change in control: a) and with fault tolerant control and b). Speed reference of IM1 is 1000 rpm and the load torque is 2 Nm

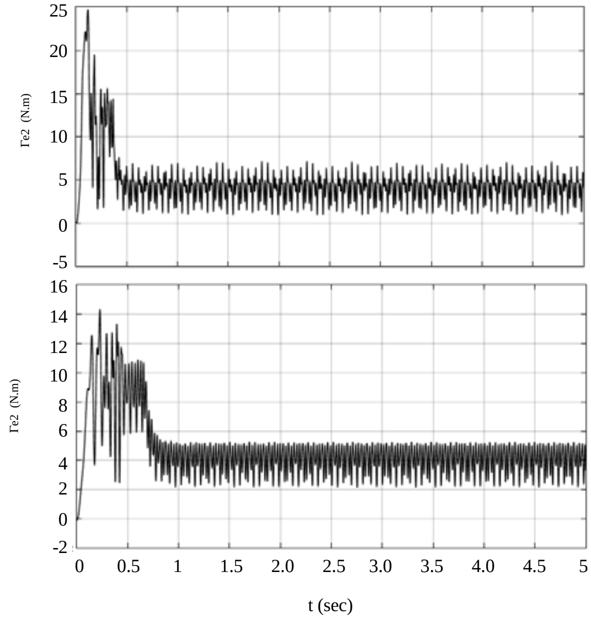

Fig. 5: Torque response of IM2 in faulted series-connected two-motor drive without change in control: a) and with fault tolerant control; b). Speed reference of IM2 is 500 rpm and the load torque is 4 Nm

speed and reference frame currents due to the loss of phase 'a' of the two-motor series connected system, with and without control modification. It can be noticed that the disturbance is extremely high and large before fault tolerant control using resonant PI is applied.

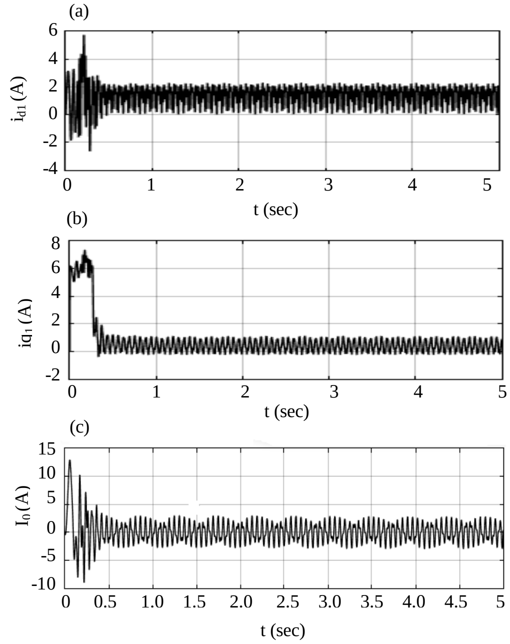

Fig. 6: Synchronous currents of IM1 and current in faulted series-connected two-motor drive without change in control

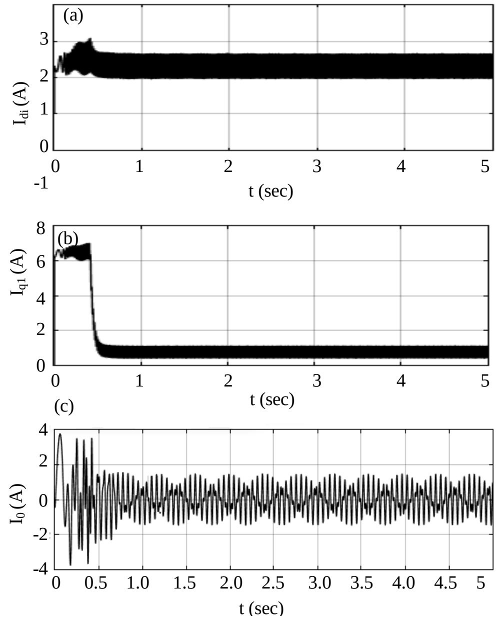

Fig. 7: Synchronous currents and current of IM1 in faulted series-connected two-motor drive controlled using PI-resonant controllers

It is noticed from the figures that the torque disturbance of the IM1 reduces to 2 Nm peak-to-peak instead of 16 N.m and from 6 Nm peak-to-peak value to 2.5 Nm in IM2. As shown in the Fig. 4-7, the synchronous reference frame currents performance improves.

CONCLUSION

Control of two five-phase induction motors connected in series to a single VSI: The modelling and control of a Series-connected five-phase two-motor system controlled using PI controllers was presented. Advantages and disadvantages of this configuration were presented. Moreover, the performance of the five-phase two-motor system under a single open-line condition was studied. Using additional degrees of freedom in faulted two-motor systems for elimination disturbance is not possible because they are used for independent two-motor control.

In multi-phase two-motor systems with number of phases more than five it would be possible to use part of the additional degrees of freedom for fault-tolerance. The stationary transformation matrix in the five-phase two-motor system was modified in order to compensate for the back EMF in the open-circuited phase. This could reduce the effects of the open-phase fault on the two motor system. Results were obtained by simulation using Matlab/Simulink Software.

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