Reduction of Current Sensors in Vector Control of Four-Phase Induction Machines

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***Abstract*— Increasing the phase number enables reduction of the power per inverter leg, improvement of efficiency, reduction in torque ripples and etc. However, increasing the phase number causes the need of more power electronic devices and peripheral equipments such as sensors. Furthermore, in vector control of induction machine for controlling the d-q current components, measuring all independent currents is needed. Therefore, in this paper, a novel and simple structure is proposed for vector control of four-phase induction machines with only two current sensors. Although, it is shown in this paper that zero sequence current components will be eliminated due to the proposed structure. The simulation results verify the performance of proposed structure.**

***Keywords*— Symmetrical four-phase induction machine, vector control, current sensor, multiphase drives.**

I. Introduction

In recent years, many researches have been done on multi-phase electric drives. The reason of attraction to multi-phase electric drives is the numerous advantages of multi-phase machines. Multiphase induction machines often are used in electric ship propulsion, traction and generally in high power applications. Multiphase induction machines has the advantages of more efficiency, less pulsating torque, more reliability, reduction in inverter power per phase and less noise pollution [1-2].

Multiphase induction machines have some advantages over three phase induction machines. Employing multi-phase induction machines would reduce the pulsating torque and would increase the efficiency of the machine. Four-phase induction machines have 3.98% reduction in stator copper loss compared to the same machine wound with an equivalent three-phase winding of the same pitch [3-4].

Also, multiphase induction machines have less noise pollution compared to three-phase ones [5]. Among several benefits, high phase numbers provide better motor performance following loss of one or more phases; in addition using multiphase induction machines obtain the capability to start and run even with some phases open circuited[6-8].

The other advantage is the improvement of torque in multi-phase machines with concentrated winding. Lyra et al. [9] show that additional torque production can be obtained by injecting third harmonic current.

Recently, several control techniques are considered about induction machines which application of each method depends on desired specific condition. One of these methods is called scalar and it is more suitable for low power applications [10]. In contrast, vector control of induction machines was introduced by Blaschke[11] and Hasse[12] which has better dynamic response. Despite of the higher phase number in multiphase induction machines, they have more degrees of freedom. Nevertheless, all these techniques are applicable for multiphase induction machines with little differences [13]. According to the possibility of flowing $x-y$ current components, the tendency is to create sinusoidal voltage at the output of the inverter. The existence of low order harmonics in input supply leads to large stator current harmonics which only restricted by stator leakage impedance [14]. Although with non-sinusoidal voltage source, multiphase machines generally have more stator copper loss, but they always have less rotor copper loss versus three phase machines [15].

With advances in power semiconductor technology and improvement in control methods, the trend to low cost drive systems is increased. By reducing the number of equipments used in these systems, the final cost will be reduced too. Reduction in the number of current sensors will result in lower cost of these drive systems. [16] Presents a rotor field-oriented control of dual-three-phase induction machine, employing only two current sensors. A novel torque and speed control structure for low-cost induction machine drive with a single dc-link current sensor presented in [17].

Some studies related to four-phase induction machines have been conducted so far. The use of four-phase machine drive system is proposed as an alternative to eliminate the common mode voltage [18]. Further, a technique to determine the stator resistance and the stator leakage inductance of a four-phase induction machine in a four-phase drive system is presented in [19].

In vector control of symmetrical four-phase machines, in regular manner, we need at least three current sensors. In this paper, proposed configuration of symmetrical four-phase induction machine leads to minimizing the number of current sensors which only two current sensors will be needed.

II. Indirect Vector Control of Four-Phase Machines

The main objective of vector control of induction machines is to control them like separately excited dc machines. In this section, the model of symmetrical four-phase induction machine and its vector control algorithm will be presented.

A. four-phase Machine Model

An induction machine can be modelled with state-space equations. In these equations, voltage and frequency are as inputs and the outputs of the state-space equations are speed, position, torque, flux, current or a combination of them.

The stator equations in arbitrary common reference frame are as equation (1) [20]:

$$\begin{aligned}
V_{ds} &= R_s i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \quad , \quad \lambda_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \\
V_{qs} &= R_s i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \quad , \quad \lambda_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \\
V_{0+s} &= R_s i_{0+s} + \frac{d\lambda_{0+s}}{dt} \quad , \quad \lambda_{0+s} = L_{ls} i_{0+s} \\
V_{0-s} &= R_s i_{0-s} + \frac{d\lambda_{0-s}}{dt} \quad , \quad \lambda_{0-s} = L_{ls} i_{0-s}
\end{aligned} \tag{1}$$

And rotor equations are as follow:

$$\begin{aligned}
V_{dr} &= 0 = R_r i_{dr} - \omega_s \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \quad , \quad \lambda_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds} \\
V_{qr} &= 0 = R_s i_{qr} + \omega_s \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \quad , \quad \lambda_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs} \\
V_{0+r} &= 0 = R_r i_{0+r} + \frac{d\lambda_{0+r}}{dt} \quad , \quad \lambda_{x1r} = L_{lr} i_{0+r} \\
V_{0-r} &= 0 = R_r i_{0-r} + \frac{d\lambda_{0-r}}{dt} \quad , \quad \lambda_{0-r} = L_{lr} i_{0-r}
\end{aligned} \tag{2}$$

Where L_m is equal to $2M$ which M is the maximum value of the stator to rotor mutual inductance. The torque equation is as follows:

$$T_e = P L_m [i_{dr} i_{qs} - i_{ds} i_{qr}] \tag{3}$$

B. four-phase induction machine vector control algorithm

Since the considered induction machine is symmetrical with sinusoidally stator winding, then the only difference between vector control scheme of a three-phase and a four-phase induction machine is due to decoupling transformation matrix [13]. In vector control of induction machines, the direct axis should be aligned with rotor flux vector, then the quadrature component of rotor flux will be equal to zero:

$$\begin{aligned}
&\lambda_r = \lambda_{dr} \\
&\lambda_{qr} = L_m i_{qs} + L_r i_{qr} = 0 \\
&i_{qr} = -\frac{L_m}{L_r} i_{qs} \\
&\lambda_{qr} = 0 \\
&\frac{d}{dt} \lambda_{qr} = 0
\end{aligned} \tag{4}$$

By substituting the equation (4) in equation (1), the followings are obtained:

$$\begin{aligned}
&i_{ds} = \frac{1}{L_m} [1 + T_r \frac{d}{dt}] \lambda_r \\
&\omega_s - \omega_r = \frac{1}{T_r} . \frac{i_{qs}}{i_{ds}}
\end{aligned} \tag{5}$$

It should be noted that, in these equations, rotor time constant, T_r, will be equal to $\frac{(L_{lr} + L_m)}{R_r}$. Under these conditions, with using equations (3) and (4), the torque equation will become as:

$$T_e = K \lambda_{dr} i_{qs} \tag{6}$$

Where K is torque constant. This equation shows that if rotor flux won't be distorted, then the quadrature component of stator current, i_{qs}, can control the torque and the rotor flux can be controlled with direct component of stator current.

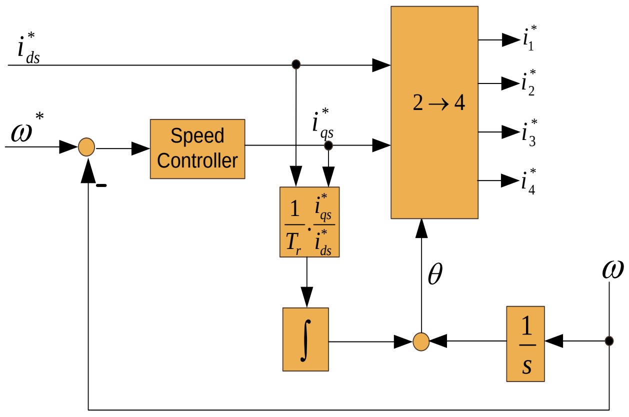


Fig.1: Indirect vector control diagram of four-phase induction machine

III. Proposed Structure for Minimizing the Independent Currents in Four-Phase Induction Machines

In this section, the proposed structure for reducing current sensors is considered. The current references in the block diagram of fig.1 are as follows:

$$i_1^* = \sqrt{\frac{2}{4}}(i_{ds}^* \cos\theta - i_{qs}^* \sin\theta)$$
$$i_2^* = \sqrt{\frac{2}{4}}(i_{ds}^* \cos(\theta - \frac{2\pi}{4}) - i_{qs}^* \sin(\theta - \frac{2\pi}{4})) \quad (7)$$
$$\vdots$$
$$i_4^* = \sqrt{\frac{2}{4}}(i_{ds}^* \cos(\theta - \frac{6\pi}{4}) - i_{qs}^* \sin(\theta - \frac{6\pi}{4}))$$

If these current references will be applied to a machine with configuration of Fig.(2-a), then the relation between motor currents would be as:

$$i_1 + i_2 + i_3 + i_4 = 0 \;\rightarrow\; i_1 = -i_2 - i_3 - i_4 \quad (8)$$

This equation shows that there are three independent currents for a four-phase machine. Respectively, according to the structure of Fig. (2-a), just a single current sensor can be eliminated.

In symmetrical four-phase induction machines, under symmetrical and balanced source, the current of mth phase is equal to the negative of the ($m+2$)th phase current ($i_m = -i_{(m+2)}$).

So in four-phase induction machines, there is the possibility of using the structure of Fig. (2-b). As shown in Fig. (2-b), the second end of mth phase is directly connected the second end of ($m+2$)th phase. Hence, it is clear that the current of mth phase is instantaneously equal to the current of ($m+2$)th phase. So the relation between phase currents will be as follows:

$$i_1 = -i_3$$
$$i_2 = -i_4 \quad (9)$$

This equation shows that with using the structure of Fig.(2-b), the number of independent currents will be equal to 2 and consequently the number of current sensors can be reduced to two sensors.

IV. Analysis of the Proposed Structure

In this section, the effect of this structure on the different current components of four-phase induction machines is considered. For this purpose, the currents of four-phase induction machines are transformed using decoupling transformation matrix of equation (10) [20].

$$C = \sqrt{\frac{2}{4}} \begin{array}{c} \alpha \\ \beta \\ 0+ \\ 0- \end{array} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \quad (10)$$

Where in this equation $\alpha = 2\pi/4$. By applying the matrix of equation (10), the $\alpha-\beta$ current component will be as:

$$i_\alpha = i_1 + i_2\cos(\alpha) + \ldots + i_4\cos((n-1)\alpha)$$
$$i_\beta = 0 + i_2\sin(\alpha) + \ldots + i_4\sin((n-1)\alpha) \quad (11)$$

With substituting equation (9) in equation (11), the followings are obtained:

$$i_\alpha = i_1[1-\cos(2\alpha)] + i_2[\cos(\alpha) - \cos(3\alpha)]]$$
$$i_\beta = i_1[0-\sin(2\alpha)] + i_2[\sin(\alpha) - \sin(3\alpha)]] \quad (12)$$

It is clear that $\cos((m-1)\alpha) = -\cos((m+2)\alpha)$ and $\sin((m-1)\alpha) = -\sin((m+2)\alpha)$ which m=1 and 2. So, it would be concluded that:

$$i_\alpha = 2i_1 + 2i_2\cos(\alpha) \quad (13)$$
$$i_\beta = 0 + 2i_2\sin(\alpha)$$

For considering the effect of this structure on the zero sequence current components, the positive and negative current component equations are considered. By applying the transformation matrix of equation (10) to four-phase currents, the zero sequence currents are as:

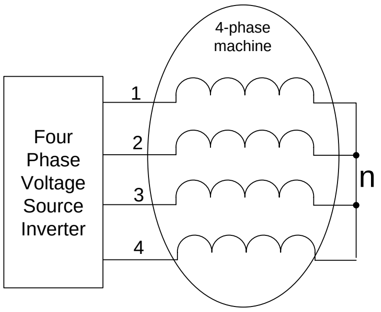
$$i_{0+} = \frac{1}{\sqrt{2}}[i_1 + i_2 + i_3 + i_4]$$
$$i_{0-} = \frac{1}{\sqrt{2}}[i_1 - i_2 + i_3 - i_4] \quad (14)$$

By substituting the equation (9) in equation (14), the followings are obtained:

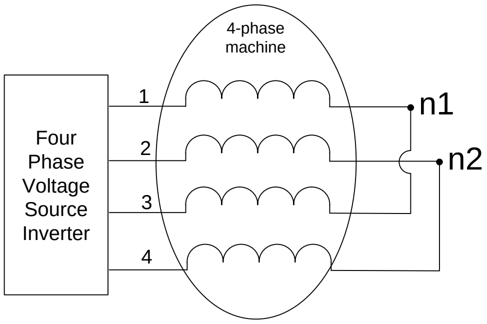
$$i_{0+} = 0 \quad (15)$$

$i_{0-} = 0$

These equations show that i_{0+} and i_{0-} are eliminated due to the proposed structure. It should be noted that i_{0+} and i_{0-} don't contribute in torque production.



(a)



(b)

Fig.2: Connection diagram of four-phase induction machine
(a): star connected, (b): proposed structure

V. Hysteresis Modulation

The reference currents for hysteresis control are obtained from vector control block diagram of Fig.1. The injected currents of phase 1 and phase 2 are measured and fed back to hysteresis control block. So the switching status of each switch is characterized by the difference between reference current and actual current (Δi).

$$\Delta i_m = i_m^* - i_m^{real} \quad , \quad m \le 2 \qquad (20)$$

The following equation is used for characterizing the status of the switches of each branch:

$$S_m = \begin{cases} 1 & \Delta i_m > b \\ 0 & \Delta i_m < -b \end{cases} \quad m \le 2 \qquad (21)$$

Where, S_m is the status of the switches in *m*th branch and b is the hysteresis band. Hence, $S_m = 1$ represent that the upper switch in *m*th branch is on and the lower switch is off. Similarly, $S_m = 0$ represent that upper switch is off and lower switch is on.

For characterizing the switching status of the switches in the branches with number greater than 2, the structure in Fig.2 is used. As it would be concluded from Fig.(2-b), the switching status of the switch the switches in branch ($m+2$) is opposite of the switches in *m*th branch.

$$S_{m+2} = \begin{cases} 0 & S_m = 1 \\ 1 & S_m = 0 \end{cases} \quad m \le 2 \qquad (22)$$

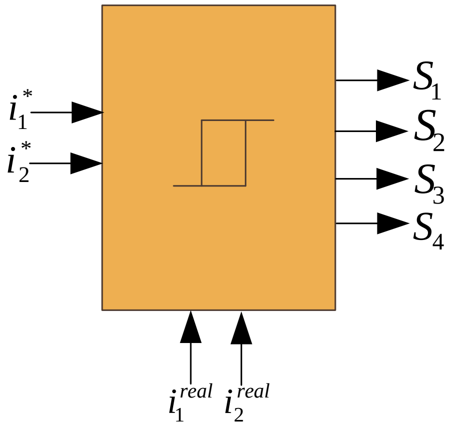


Fig.3: Hysteresis block diagram (S_m determines the switching status of the *m*th branch switches)

So, just the first two phase currents are measured and fed back to the hysteresis block and the switching status of all eight switches of four-phase inverter would be determined from theses two currents.

VI. Simulation Results

To verify the proposed structure, the vector control of a symmetrical four-phase induction machine is simulated in MATLAB/SIMULINK. The parameters of four-phase machine are represented in appendix I. First in this section, the performance of the vector control of four-phase induction machine with proposed structure is investigated under load variations which the results are shown in Fig. (4-6). For this purpose, the four-phase machine connections are similar to Fig. 2(b) and just currents of phase 1and phase 2 are fed back to hysteresis block and The switching status of all switches is specified from section V; so the exact control on the current of the other phases is easily achievable. In simulation of this system, the speed command is set to 600rpm; the motor runs under no-load condition and an 12N.m torque is applied to the motor as load at t=10s. Fig. 4 and Fig. 5 show the electromagnetic torque and the speed response of the four-phase induction machine. The current of phase 1, as sample, is illustrated in Fig. 6. As shown in these figures, results verify the performance of vector control with proposed structure under load variation.

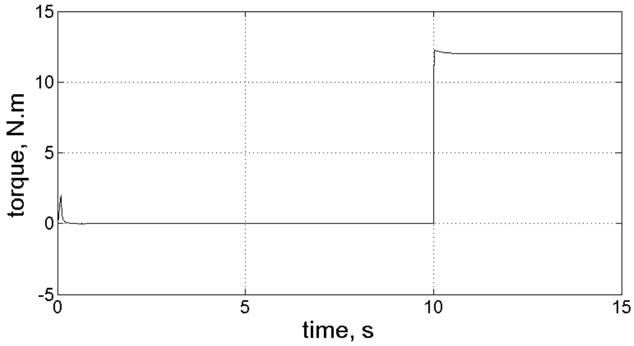


Fig.4: Electromagnetic torque of symmetrical four-phase induction machine (a load of 12N.m is applied at t=10s)

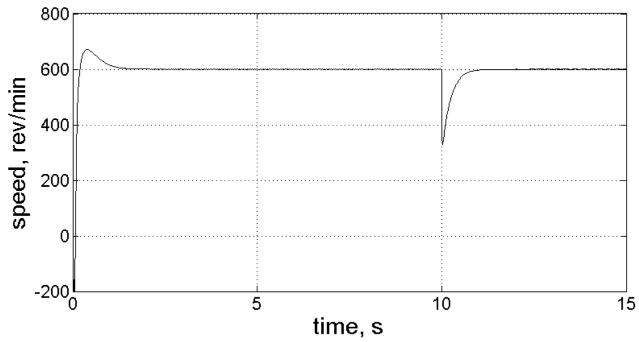


Fig.5: Speed response of symmetrical four-phase induction machine (the speed command is 600 rpm)

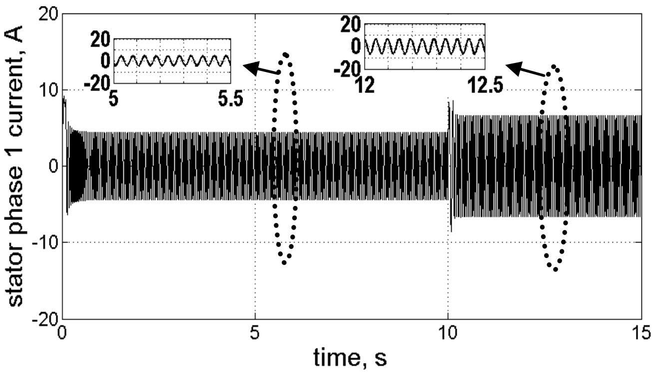


Fig.6: phase 1 current (speed command is set to 600 rpm and a 12N.m load is applied at t=10s)

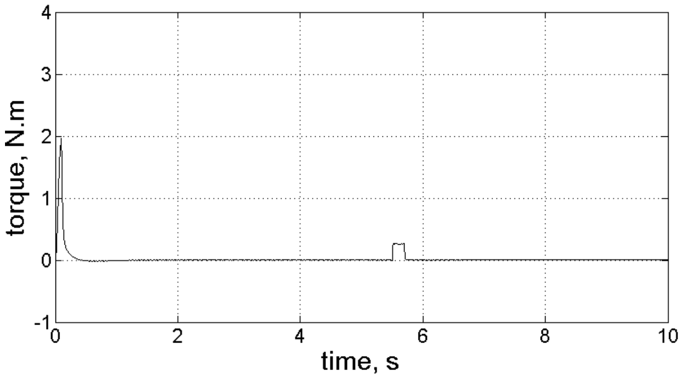


Fig.7: Electromagnetic torque of symmetrical four-phase induction machine (the motor is working under no-load condition)

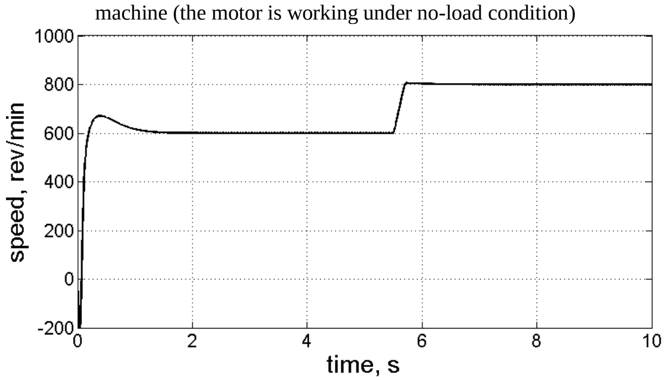


Fig.8: Speed response of symmetrical four-phase induction machine (the speed command varies from 600rpm to 800rpm at t=5.5s)

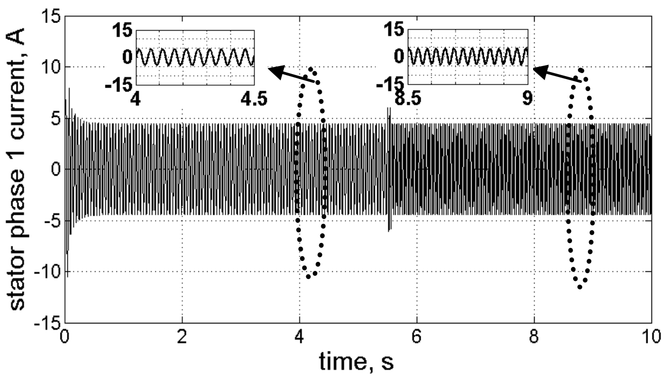


Fig.9: phase 1 current (the motor is under no-load condition and the speed command varies from 600rpm to 800rpm at t=5.5s)

The simulation results for investigating the performance of vector control under speed command variation are shown in Figs. (7-9). In this simulation, the motor works under no-load condition; and the speed command is 600rpm which increases to the 800rpm at t=5.5s. The electromagnetic torque and speed response are illustrated in Fig. (7) and Fig. (8). As depicted in Fig. 8, the motor speed follows the speed command.

As the vector control is in speed control mode, the motor speed should follow the speed command and should be kept constant under load changes. So, these results verify the vector control of four-phase induction machine using two current sensors with proposed.

VII. Conclusion

This paper presents a new structure for vector control of four-phase induction machines with minimum independent currents.

The independent currents are minimized as a result of increasing the neutral points. The analytical equations verify that not only this structure reduce the current sensors, but also causes eliminating i_{0+} and i_{0-} current components which do not contribute in torque production. In this paper the hysteresis modulation of four-phase induction machines using two current sensors considered. Simulation results verified the vector control of symmetrical four-phase induction machines with proposed structure.

APPENDIX I

The motor parameters are as:

$$n_s = 1500rpm\ ,\ p_n = 3hp\ ,\ r_r = 0.50\Omega\ ,\ r_s = 1.32\Omega\ ,$$

$$L_m = .119H\ ,\ L_{lr} = L_{ls} = 3.67mH\ ,\ J = 0.028kg.m^2\ .$$

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