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THE ANALYSIS, ADVANTAGES AND USES OF FIVE-PHASE INDUCTION MOTOR DRIVES

ANALIZA, KORZYŚCI I ZASTOSOWANIE PIĘCIOFAZOWEGO SILNIKA INDUKCYJNEGO

Abstract: Multi-phase (more than three-phase) motors have attracted much attention in recent years due to some advantages which they offer when compared to the three-phase motor drive system. Presently, the grid power available is only limited to three-phase. Electric drives with variable speed are predominately utilized with three-phase machines. However, when fed by a converter, there is no need for a fixed number of phases. The supply to multi-phase motors is invariably provided from power electronic converters. Since used for AC supply is the power electronic converter (in vast majority of cases an inverter with a DC link), the number of converter phases (thus also of electric machine) is essentially not limited. The paper presents the inherent advantages, properties and uses of five-phase induction motor drives with the power electronic converter supplied.

Streszczenie: Silniki wielofazowe (więcej niż 3-fazowe) przyciągnęły w ostatnich latach wiele uwagi ze względu na pewne zalety, które oferują w porównaniu z trójfazowym układem napędowym silnika. Obecnie dostępna moc sieci jest ograniczona tylko do trzech faz. Napędy elektryczne o zmiennej prędkości są stosowane głównie w maszynach trójfazowych. Jednak po zasileniu przez konwerter nie jest wymagana stała liczba faz. Zasilanie silników wielofazowych odbywa się niezmiennie z przetwornic energoelektronicznych. Ponieważ do zasilania prądem przemiennym wykorzystywany jest elektroniczny konwerter mocy (w zdecydowanej większości przypadków falownik z łączem prądu stałego), liczba faz konwertera (a więc również maszyny elektrycznej) zasadniczo nie jest ograniczona. W pracy przedstawiono główne zalety, właściwości i zastosowania pięciofazowych napędów silników indukcyjnych z dostarczonym przetwornikiem mocy.

Keywords: *multiphase induction motor, five-phase induction motor, five-phase drive system*
Słowa kluczowe: *wielofazowy silnik indukcyjny, 5-fazowy silnik indukcyjny, 5-fazowy układ napędowy*

1. Introduction

Three phase induction motors (with squirrel cage) are known for their simple construction, low maintenance and cost. The speed control of induction motor is complicated, however, due to the development in the power electronic devices and convertors, the control of induction motor has become easier. The development of the solid-state inverter and control schemes has opened a new range of applications for induction machines in multiple areas (e.g. where DC machines were dominant) and the numbers of phases have become a design parameter. Higher numbers of phases is more advantageous.

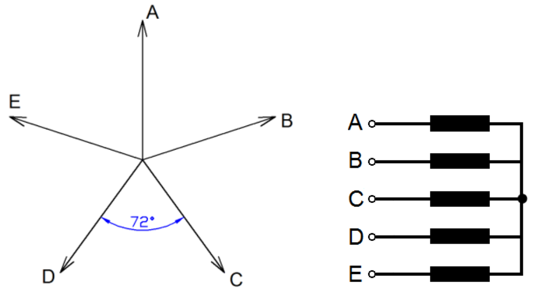
The multiphase induction motor has several advantages over the conventional three phase machine such as reduced torque pulsation [1], reduced per phase rotor harmonic current, high reliability and high fault tolerance [2, 3]. The first time, in 1969, Ward and Harrer presented the preliminary investigation on inverter fed five phase induction motor and suggested that the amplitude of the torque pulsation can be reduced by increasing the number of phases [4]. Compared to three–phase induction motors, fault–tolerance may be the most interesting feature of multiphase induction motors because it allows the drive to operate even after a fault occurs. Fault tolerant operation has been described at squirrel cage induction machines [5-8]. The analysis of standard symmetrical multi-phase induction machines is presented in several papers [9-13].

In principle, control methods for five-phase induction machines are the same as for three-phase machines. Dynamics, achievable with a five-phase vector controlled induction machine, are shown to be essentially identical to those obtainable with a three-phase induction [14]. Studies in the literature have shown that the five-phase induction machines drive operates satisfactorily when fed from a pulse width modulation (PWM) inverter [15, 16].

2. The analysis and description of 5-phase induction motor

The smallest phase number of multiphase motor most commonly used is five-phase.

The five-phase induction motor works, when five-phase AC supply is given to the stator winding that is spatially and time displaced by 72° (Fig. 1). The magnetic field of stator rotates at synchronous speed. In squirrel cage rotor an EMF is induced and due to this, current starts flowing in the rotor conductor and sets up its own magnetic field. Due to interaction of these two magnetic fields a torque is produced [13]. Stator winding of a five-phase machine is designed in such a way that the spatial displacement between consecutive stator phases is 72 degrees as shown in Fig. 2 [17].



(a) (b)

Fig. 1. Phasor diagram for 5-phase source (a) and Stator winding connection in star (b)

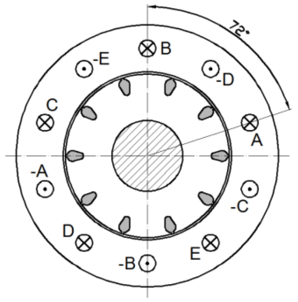


Fig. 2. Five-phase concentrated-winding induction motor

The voltage equations of individual phases (A to E) of five phase induction machine are:

$$
\begin{aligned}
v_A &= \sqrt{2}\cdot V\cdot cos(\omega t)\\
v_B &= \sqrt{2}\cdot V\cdot cos(\omega t - 2\pi/5)\\
v_C &= \sqrt{2}\cdot V\cdot cos(\omega t - 4\pi/5)\\
v_D &= \sqrt{2}\cdot V\cdot cos(\omega t + 4\pi/5)\\
v_E &= \sqrt{2}\cdot V\cdot cos(\omega t + 2\pi/5)
\end{aligned}
\qquad (1)
$$

where V is rms of voltage.

The voltage equation that describes dynamic behavior of a five-phase induction motor are time varying. The voltage equations have some complexity therefore a change of variable can be used to reduce the complexity of these equations by eliminating all time varying variables from the voltage equation of the machine. By this approach a five-phase winding can be reduced to a set of two phase winding. The stator and rotor variables of the induction machine are transferred to a reference frame which may rotate at angular speed or remain stationary.

The five-phase induction motor can be represented as a d-q-x-y-0 model [6]. Components d-q are responsible for power, torque and fluxes. Components x-y cause losses in the machine. The zero component is only used to show machine as a power invariant after transformation. The transformation matrix (2) for stator is:

$$
A_S = \sqrt{\frac{2}{5}}\cdot
\begin{vmatrix}
cos(\theta_S) & cos(\theta_S - \alpha) & cos(\theta_S - 2\alpha) & cos(\theta_S + 2\alpha) & cos(\theta_S + \alpha)\\
-sin(\theta_S) & -sin(\theta_S - \alpha) & -sin(\theta_S - 2\alpha) & -sin(\theta_S + 2\alpha) & -sin(\theta_S + \alpha)\\
1 & cos(2\alpha) & cos(4\alpha) & cos(4\alpha) & cos(2\alpha)\\
0 & sin(2\alpha) & sin(4\alpha) & -sin(4\alpha) & -sin(2\alpha)\\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{vmatrix}
\qquad (2)
$$

where θ_s is the instantaneous angular position of the d-axis of the common reference frame with respect to phase „A“ magnetic axis of the stator and $\alpha = 2\pi/5$.

Transformation of rotor variables (3) is performed using the same transformation expression, where θ_s is replaced with β:

$$
A_R = \sqrt{\frac{2}{5}}\cdot
\begin{vmatrix}
cos(\beta) & cos(\beta - \alpha) & cos(\beta - 2\alpha) & cos(\beta + 2\alpha) & cos(\beta + \alpha)\\
-sin(\beta) & -sin(\beta - \alpha) & -sin(\beta - 2\alpha) & -sin(\beta + 2\alpha) & -sin(\beta + \alpha)\\
1 & cos(2\alpha) & cos(4\alpha) & cos(4\alpha) & cos(2\alpha)\\
0 & sin(2\alpha) & sin(4\alpha) & -sin(4\alpha) & -sin(2\alpha)\\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{vmatrix}
\qquad (3)
$$

where β is the instantaneous angular position of the d-axis of the common reference frame with respect to phase „A“ magnetic axis of the rotor. The angles of transformation for stator and rotor quantities are related to the arbitrary speed of the selected common reference frame through

$$\theta_s = \int \omega_a \cdot dt \qquad (4)$$

$$\beta = \theta_s - \theta = \int \left(\omega_a - \omega\right) \cdot dt \qquad (5)$$

where ω is the instantaneous electrical angular speed of rotor rotation.

Provided that the machine equations are transformed into frame of references rotating at angular speed ω_a, the model of five phase induction machine with Stator side voltage equations in d- and q- reference frame are given as:

$$\begin{aligned} v_{ds} &= R_s \cdot i_{ds} - \omega_a \cdot \psi_{qs} + p \cdot \psi_{ds} \\ v_{qs} &= R_s \cdot i_{qs} + \omega_a \cdot \psi_{ds} + p \cdot \psi_{qs} \\ v_{xs} &= R_s \cdot i_{xs} + p \cdot \psi_{xs} \\ v_{ys} &= R_s \cdot i_{ys} + p \cdot \psi_{ys} \\ v_{0s} &= R_s \cdot i_{0s} + p \cdot \psi_{0s} \end{aligned} \qquad (6)$$

Rotor side voltage equations in d- and q- reference frame are given as:

$$\begin{aligned} v_{dr} &= R_r \cdot i_{dr} - \left(\omega_a - \omega\right) \cdot \psi_{qr} + p \cdot \psi_{dr} \\ v_{qr} &= R_r \cdot i_{qr} + \left(\omega_a - \omega\right) \cdot \psi_{dr} + p \cdot \psi_{qr} \\ v_{xr} &= R_r \cdot i_{xr} + p \cdot \psi_{xr} \\ v_{yr} &= R_r \cdot i_{yr} + p \cdot \psi_{yr} \\ v_{0r} &= R_r \cdot i_{0r} + p \cdot \psi_{0r} \end{aligned} \qquad (7)$$

Flux equations of stator side are given as:

$$\begin{aligned} \psi_{ds} &= \left(L_{1s} + L_m\right) \cdot i_{ds} + L_m \cdot i_{dr} \\ \psi_{qs} &= \left(L_{1s} + L_m\right) \cdot i_{qs} + L_m \cdot i_{qr} \\ \psi_{xs} &= L_{1s} \cdot i_{xs} \\ \psi_{ys} &= L_{1s} \cdot i_{ys} \\ \psi_{0s} &= L_{1s} \cdot i_{0s} \end{aligned} \qquad (8)$$

Flux equations of the rotor side are given as:

$$\begin{aligned} \psi_{dr} &= \left(L_{1r} + L_m\right) \cdot i_{dr} + L_m \cdot i_{ds} \\ \psi_{qr} &= \left(L_{1r} + L_m\right) \cdot i_{qr} + L_m \cdot i_{qs} \\ \psi_{xr} &= L_{1r} \cdot i_{xr} \\ \psi_{yr} &= L_{1r} \cdot i_{yr} \\ \psi_{0r} &= L_{1r} \cdot i_{0r} \end{aligned} \qquad (9)$$

In equations *(6)* - *(9)* the indices *s* and *r* identify stator and rotor variables/parameters. Symbols *R* and *L* stand for resistance and inductance, and symbols *v*, *i* and ψ denote voltage, current and flux. In equations *(8)* and *(9)* $L_m=(5/2)M$ and *M* is the maximum value of the stator to rotor mutual inductance in the model of motor.

The d-q-0 model of five-phase induction motor in arbitrary reference frame is shown in Fig. 3.

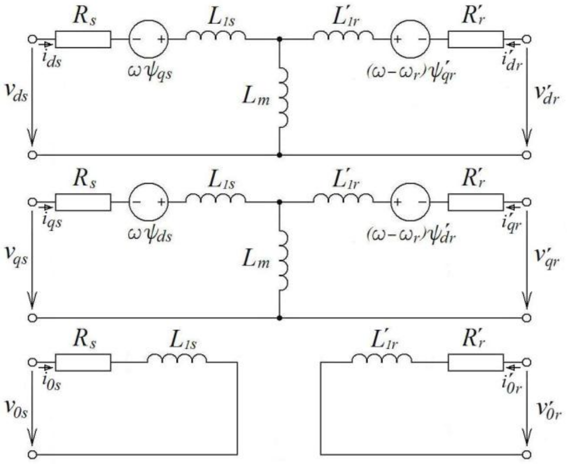


Fig. 3. An equivalent circuit of five phase induction machine in d-q-0 axis

From the above equations *(6)* - *(9)* determined can be the torque and rotor speed as:

$$T_e = \frac{5}{2} \cdot \frac{P}{2} \cdot \left(\psi_{ds} \cdot i_{qs} + \psi_{qs} \cdot i_{ds}\right) \qquad (8)$$

$$T_e = \frac{5}{2} \cdot P \cdot M \cdot \left(i_{dr} \cdot i_{qs} + i_{ds} \cdot i_{qr}\right) \qquad (9)$$

$$\omega = \frac{P}{2 \cdot J} \cdot \int \left(T_e - T_L\right) \qquad (10)$$

where *P* is the number of poles, *J* is the moment of inertia, T_L is load torque, T_e is electromechanical torque and ω is the rotor speed.

The steady state model and equivalent circuit of five-phase induction motor are useful for modeling performance of the machine in steady state.

3. Five-phase inverter topology

The three-phase induction motors have some inherent disadvantages. For that multiphase induction motors are employed in industrial applications too. Generating multi-phase supply for multiphase induction motors is difficult and complex as practically beyond 3-phase generation is not available. That is why for supplying multiphase induction motors voltage source inverter with multiphase has been incorporated. As five phase case is used here so five phase voltage source inverter has been taken.

In five-phase inverter there are two different output line voltages (adjacent and non-adjacent). The voltage between two consecutive phases is known as adjacent-line voltage. The voltage between two non-consecutive phases is called non-adjacent line voltage. The voltage between output terminal of inverter and neutral of the load is considered to be the phase voltage. Marking five phase system as "A,B,C,D,E", the phase voltages are given as v_A, v_B, v_C, v_D, v_E (Fig. 1a), the adjacent line voltages are represented as v_{AB}, v_{BC}, v_{CA}, v_{DE}, v_{EA} and non-adjacent line voltage are denoted as v_{AC}, v_{BD}, v_{CE}, v_{DA}, v_{EB}.

The number of output phases in an inverter is equal to the number of legs and hence five–phase inverter consists of five legs. The leg has two switches. It may be any two power semiconductor devices in operation (e.g. IGBT, MOSFET, etc.). Advantage is taken as switches for inverter operation because of its inherent properties. An antiparallel diode is connected with these switches (Fig. 4). The quality of output voltage is the main priority of inverter.

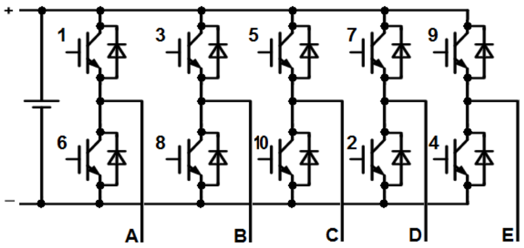


Fig. 4. Five-phase inverter topology

Generally, the five phase inverter must have these basic characteristics:

- the THD (%) of the output voltage must be as low as possible,
- the fundamental component of the output phase voltage should be as high as possible,
- the circuit of inverter should be simple,
- the number of components used in an inverter should be low.

The IGBT switches in one leg of an inverter must conduct alternatively in a full conduction cycle to avoid short-circuit. The one switch in one leg should conduct 180^o as full conduction is 360^o. The spatial displacement between two phases in a five phase is 72^o and is being used as delay between two consecutive phases. Multiple times of delay can be taken as conduction mode.

For variable-speed multiphase motor drives are used PWM methods for voltage source inverter control. For five phase induction motor drive three switches from top and two switches from bottom turn-on at a time and vice versa. The switching sequence and the mode of operation of five of five phase inverter (Fig. 4) is given in Table 1.

Table 1
Switching Sequeance of Five Phase Inverter

Mode	Switches ON	Angle [°]
9.	1,7,8,9,10	36
10.	8,9,10,1,2,	72
1.	9,10, 1,2,3	108
2.	10,1,2,3,4	144
3.	1,2,3,4,5	180
4.	2,3,4,5,6	216
5.	3,4,5,6,7	252
6.	4,5,6,7,8	288
7.	5,6,7,8,9	324
8.	6,7,8,9,10	360

Five phase inverter drive constructed using 10 IGBT switches is shown in Fig. 4. The switching signals 1-10 are generated by pulse generators. Switches 1-10 are turned on for a period of 180° conduction mode with 72° out of phase with each phase leg. Inverter output voltage can be obtained by proper switching on and off of IGBT's.

The sinusoidal pulse width modulation (SPWM) technique is used to generate the pulses for the power IGBT switch. In this technique a carrier wave is compared with the sine wave.

4. The drive with five-phase induction motor

The three phase AC voltage is converted to DC voltage either by uncontrolled or controlled rectifier. The ripple in the DC voltage is removed by using a LC filter in input of the DC-AC inverter. The five-phase inverter and a controller are used to generate the SPWM output voltage. The inverter output voltage supplies the five-phase induction machine. Complete arrangement of the block diagram of the five-phase drive system is shown in Fig. 5.

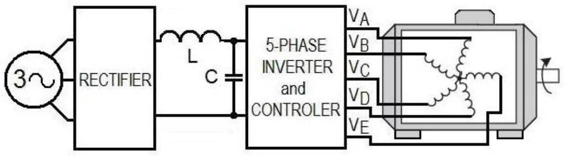


Fig. 5. Block diagram of five-phase induction motor drive

Windings of the five-phase induction motor housed in the stator are excited by five-phase inverter.

4. Characteristic and uses of the five phase induction motor

With drives with high fault-tolerant it is important to choose the motor exhibiting an intrinsic fault–tolerant capability. Fractional slot winding motors with non–overlapped coils are suitable for fault–tolerant applications [18]. The multi-phase induction motors allow a physical separation among the phases, limiting the propagation of the fault. In addition, a suitable combination of slots and poles yields a very low mutual coupling between phases, so that when fault occurs on one phase of a machine it is not carried to the other phase mutually. The five-phase induction motors are also characterized by a high self-inductance, necessary to limit the short circuit current. For better characteristics of the motor, the mutual coupling between the phases should be less.

The stator excitation in five phase induction motor produces an electromagnetic field with lower harmonic content than that in a three phase machine. The efficiency of the five phase induction motor is higher than that in three phase machine. The five phase induction motor has greater fault tolerance than that of three phase. If one phase of the three phases motor becomes open-circuited the motor becomes single phase. It may continue to run but requires some external means for starting. In case of five-phase motor if one phase is open-circuited, so it will self-start and will run at lower power. The five-phase induction motors are less susceptible to time harmonic components in the excitation waveform. Such excitation components produce pulsating torques at even multiple of fundamental excitation frequency [18].

The advantages of five-phase motors that have been recognized: high density of motor torque, reduced torque ripples and harmonic currents, better transient and steady-state performance and more robust control offered by current harmonic injection. The advantages and drawbacks of five-phase motor drive are as follow:

- ➢ The main advantage of using a five phase motor drive is found in its reliability to operate properly also in faulty conditions. The five phase motor drives can operate with one or two open phases giving the drive a high tolerance to faults. The faulty phases are the ones that are disconnected, while other phases remain operating as in the normal working conditions in three phase supply.
- ➢ In faulty cases, a proper current control strategy of inverter is required so as to limit the torque ripple, and this could be a requirement in applications of drives with five phase motors.
- ➢ For stators of five phase motors have to be designed and stamped custom laminations.
- ➢ To control the motor needed is a non-standard five phase inverter.

The five phase motor are used in safety critical applications that require wide fault tolerant capabilities and higher reliability.

The applications of five phase motor are: compressors, pumps, electric ships, hybrid vehicles, and electric aircrafts. For example, in applications for naval electric ships high availability is a must [15].

With the higher number of phases, and consequently the available degrees of freedom offered by five phase induction motors, the motor power is split across the five phases. In the five phase motor reduced are the per-phase inverter ratings, a highly desirable feature in medium-voltage applications [16].

6. Conclusions

The five phase (as the case may be multiphase) drives have gained special relevance in present time for their use in applications where high overall system reliability and reduction in the total power per phase are required (e.g. in electric ships, electric vehicles and trains, electric aircrafts, etc.).

The research has recently focused on the design of five phase motors and the effect of the stator winding connection [19, 20], on power inverters topologies and on new control schemes [21].

Improving the fault-tolerant capability is an important topic in five phase induction motor drives. Although different types of faults can occur, the most serious is the open-phase one that leads to a reduction in the number of active phases in the five phase drive [22].

Important requirement in the open-phase fault is, for example, the stator currents value that must be modified to preserve the fundamental component of the air gap magnetic field, which is different post-fault (e.g. for reduce copper losses or ensure maximum torque capability). Two implementations of the five–phase electrical machine are described in the literature [1], [17]:

The first five–phase motor is based on a sinusoidal magnetomotive force distribution. This five–phase drive requires only sinusoidal voltages, when low order harmonics are undesirable in the machine input. The second five–phase motor is designed with concentrated stator windings. In this case, torque production is enhanced using stator harmonic current. Particularly, the third harmonic can be used for this purpose in the reference voltage.

The predictive flux control for a five phase induction motor drive is considered as an effective alternative to the direct torque control with the advantage of reducing the ripples content in the values of torque, flux and current.

The paper presents the properties, advantages and uses of five-phase induction motor drives with the power electronic converter supplied.

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