Direct torque control of induction motor with fuzzy logic robust controllers

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Abstract

In recent years, a lot of effort has been made to develop various advanced control techniques in electric motors drive for industrial applications. Induction motors are the most common motors used in motion control systems. Simple and robust design, cheap price and low maintenance cost are the main advantages of induction motors. In this article, the three-phase induction motor drive is selected as a suitable electric drive according to the wide range of speed control and its performance in classical controls is examined. The main goal of this paper is to provide a robust control method for three-phase induction electric drive. The presented control method is capable of better starting the motor in a wide range of speed and torque. Also, the use of fuzzy controller has improved the stator flux and reduced the steady state fault of the drive. The performance of the proposed engine and drive is analyzed using MATLAB/Simulink software and the results are shown in different conditions.

Keywords: Classical controller, direct torque control, induction motor, phase control.

1. Introduction

Today in the industry, different electric machines with variable speeds are used in applications such as metal cutting machines, electric cranes, transportation tools and various types of printing devices. In most of the mentioned applications, the electric machine must be equipped with drive control to be able to control quantities such as speed, power and load [1]. Drive or frequency converter or motor speed controller are used to adjust the speed of AC electric motors. The drives are able to continuously change the motor speed from zero to several times the rated speed. The ability of electric drives in soft start and stop causes a significant reduction of mechanical stresses in mechanical connections and other rotating devices [2]. Three-phase induction motors (asynchronous) are used in electric drive systems that need to change and adjust the distance due to their basic benefits such as simple structure, low consumption and high starting torque compared to direct current motors with brushes. Advances in the use of induction motors date back to the mid-1960s. The main use of induction motors can be mentioned in industrial equipment, household products, space industries, cars and robots. Today, the most important application of these motors is in the industry and traction equipment, such as electric and hybrid cars, as well as in the drive of electric trains [3]. Therefore, recent research has focused on the optimal design of induction motor drive for variable speed applications. Extensive research is done on induction motor drive systems in laboratories and industrial centers, as a result of which various control methods have been provided for these motors. Due to the use of induction drives, the control circuit of these drives should be designed optimally and robustly. Also, the main control parameters in these drives such as speed, current and torque should be well controlled. In order to obtain a constant torque in these drives, assuming a sinusoidal anti-drive force of the motor, field rotation control with constant current references, direct torque control and current vector control are often used. Some of these methods have a good dynamic response but are dependent on motor parameters and low accuracy. In general, to achieve fast dynamic response for high torque and drive power efficiency, induction motors with high performance torque speed controllers are usually used [5]. It is possible to control the speed and torque of the induction motor by applying resistance in the rotor circuit (slip changes) in the form of open loop control. By placing a resistor in the rotor circuit of the machine, I can determine that it changed its speed [3]. It should be noted that speed control in this method requires energy loss, which is directly proportional to the slip in the rotor circuit [4]. The simplest method of controlling induction motors is the method of stabilizing the voltage to frequency ratio. This method is widely used in industrial applications such as oil and gas industries that require heavy and high power induction motors as well as fans, pumps, compressors and air conditioners. These types of controllers are scalar type and operate in an open loop with good stability. The advantage of this method is the simplicity of its control systems. On the contrary, these types of controllers are not suitable for fast response applications [7]. Robots and machine tools are examples of high dynamic applications. Vector control methods are often used in these applications. In vector control methods, by separating the components of the stator current into two components, the torque generator and the flux generator, and controlling them using PI regulators, an arrangement is made to control the AC motor like a DC motor, and in this way, all the advantages of the DC motor, including the response Their fast torque will also be available in AC motors. Vector control is widely used for high efficiency in starting induction motors. As with DC motors, the torque control of the induction motor is done independently by controlling the torque and flux [8]. In reference [12], an algorithm for the direct control of the induction motor torque in the field debilitation region is presented. In the presented method, the maximum DC voltage of the inverter is used. Independent control of current and torque in an induction machine is usually done through field oriented control (FOC) or direct torque control (DTC). In the first case, the stator current controller injects a current along with the rotor current to control the current size. At the same time, it controls the vertical component of the stator torque flow [13]. The second method does not have an internal current loop and is based on adjusting the stator voltage vector relative to torque and flux. In both mentioned control methods, the current is kept at a value lower than the specified permissible value, and this value is reduced when the drive enters the high speed area [13]. In this paper, direct torque control of induction motor with intelligent fuzzy control for speed and flux is presented. The direct motor torque control strategy is based on torque and flux estimation. Estimation of torque and flux has been done using the parameters of the motor and its governing relations. The overall structure of the proposed motor and drive is fully described. Finally, the simulation results related to the performance of the motor and the proposed propellant in different operating conditions are shown.

2. Mathematical model of induction motor and principles of direct torque control

2.1 Mathematical model of induction motor

In the induction motor, the anti-motive force of the motor and the current are sinusoidal. The induction motor model can be expressed in reference to the rotating frame of the rotor with the angular speed of the motor with the following matrix [6]:

$$\frac{d}{dt}\begin{bmatrix}\psi_s\\ \psi_r\end{bmatrix}=\begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{bmatrix}\psi_s\\ \psi_r\end{bmatrix}+\begin{bmatrix}B_1\\ 0\end{bmatrix}u_s = Ax+Bu_s \quad (1)$$

$$i_s = Cx \quad (2)$$

which ψ_s and ψ_r are equal to the vector of stator and rotor fluxes of the induction motor, respectively. u_s and i_s is equal to the stator voltage vector and current vector, respectively.

$$\psi_s = [\psi_{sx} \quad \psi_{sy}]^T, \quad \psi_r = [\psi_{rx} \quad \psi_{ry}]^T \quad (3)$$

$$u_s = [u_{sx} \quad u_{sy}]^T, \quad i_s = [i_{sx} \quad i_{sy}]^T \quad (4)$$

The coefficients of A, B and C in equation (1) are equal to the following:

$$A_{11} = -R_s/(\sigma L_s)I - \omega_r J = a_{r11}I + a_{i11}J \quad (5)$$

$$A_{12} = R_s/(1-\sigma)(\sigma L_m)I = a_{r12}I \quad (6)$$

$$A_{21} = R_s/(1-\sigma)(\sigma L_m)I = a_{r21}I \quad (7)$$

$$A_{22} = -R_r/(\sigma L_r)I = a_{r22}I \quad (8)$$

$$B_1 = I \quad (9)$$

$$C = [1/(\sigma L_s)I(\sigma-1)/(\sigma L_m)I] \quad (10)$$

I and J matrices in the above coefficients are equal to the following matrix values:

$$I = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} \quad (11)$$

$$J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} \quad (12)$$

Which R_s and R_r is equal to the resistances of the stator and rotor, L_s and L_r the inductances of each phase of the stator and rotor and L_m the magnetic inductance. $\sigma = 1 - L_m^2/(L_s L_r)$ is the leakage coefficient and ω_r the angular velocity of the motor. The mechanical equation of the motor obtained from Newton's law is expressed by the following equation.

$$T_{em} = J.\frac{d\omega_m}{dt} + B.\omega_m + T_L \qquad (13)$$

In the mechanical equation of the motor, they are the load torque and the electromagnetic torque of the motor, respectively. The moment of inertia of the rotor is the coefficient of friction and the angular velocity of the rotor. By using the equations of state, the three-phase induction motor can be modeled. In most cases, to simplify and improve the computational efficiency, the transfer of the electric machine model to the synchronous reference frame is used.

2.2 Principles of direct torque control (DTC)

Its main characteristics are: good performance, obtaining results as good as the classic vector control method. But due to its simple structure and control diagram, it has advantages over it. The torque response in vector control methods is about 10 to 20 milliseconds. While this time is about 5 milliseconds in direct torque control methods. Unlike vector control, where the torque is changed by changing the stator current vectors, in DTC the control variables are the stator flux linkage vectors. The general block diagram of the DTC strategy is shown in Figure (1). Linkage flux variation is achieved by power switches of the voltage source inverters that feed the motor. In this method, all power elements are locked based on the electromagnetic state of the motor. Like the control method in the direction of the field, in this method, flux and torque are controlled independently [9, 11].

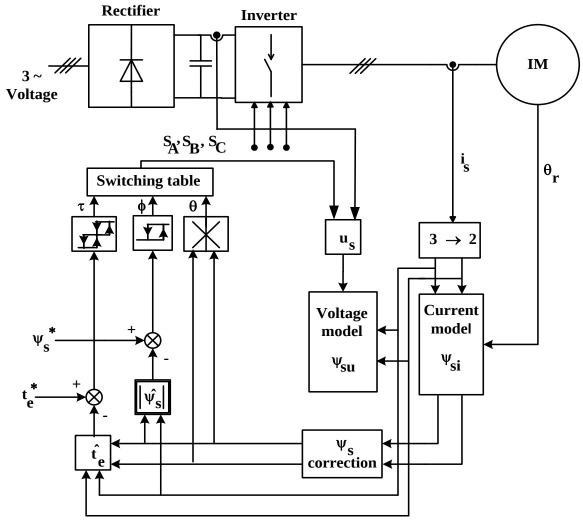


Fig. 1. General block diagram of direct torque control.

Based on the references of flux and torque applied to the machine, faults of flux and torque are calculated and with the help of appropriate and optimal switching table, switching commands are issued [11], [9]. The use of non-hysteresis flux and torque controllers leads to the reduction of the harmonics of the feeding current and the motor's torque output. As a result, various losses, especially switching losses and drive system noise, are reduced. In this method, the stator torque and flux are estimated using the following equations:

$$T_e = \frac{3}{2} p \frac{1}{L_s} |\psi_s||\psi_r| \sin(\gamma) \qquad (14)$$

$$\psi_s(t) = \int (u_s - R_s i_s) dt + \psi_{s0} \qquad (15)$$

L_s which is the leakage inductance of the stator, ψ_r the rotor flux and γ the angle between the rotor flux and the stato (16) Ignoring the voltage drop on the winding resistance, the simplified equation (16) becomes:

$$\psi_s(t) = \int (u_s) dt + \psi_{s0}$$

According to Figure (2), based on the connection or disconnection state of each of the inverter switches shown, we will have one of the voltage vectors. The two vectors and are actually zero vectors, in these two states, all the keys are in the up or down position, and as a result, the output voltage vector is equal to zero. If one of the voltage vectors or are applied, the geometric location of the flux vectors remains almost constant, because in this case we have only a small amount of voltage drop on the resistance of the windings, this allows to freely rotate the speed of the linked flux vector by changing the zero voltage vectors and the Control active voltage [11]. To estimate the stator flux and motor torque, the current and voltage values of the motor input must be known at any moment, so current and voltage sensors must be installed on two phases of the input lines.

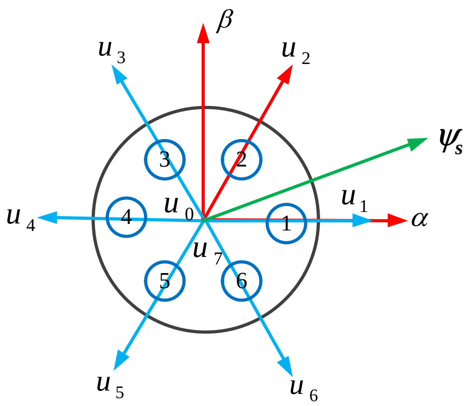


Fig .2. The six sections of the flux circle.

But on the other hand, by knowing the state of the keys and the battery voltage, and using the three axis to two axis conversion, the need to measure the voltage can be ruled out, and in this way, only two phase currents can be measured. Based on triaxial to biaxial conversion, the stator voltage vector can be written as the following equation:

$$v_s = \sqrt{\frac{2}{3}(v_{s1} + v_{s2}e^{j\frac{2\pi}{3}} + v_{s3}e^{-j\frac{2\pi}{3}})} \qquad (17)$$

If the key is connected to any of the phases in the 1 or 0 positions, the voltage of that phase will be equal to the DC source voltage or zero, respectively. Therefore, the above relationship can be changed based on the battery voltage and the state of the keys as follows:

$$v_s = \sqrt{\frac{2}{3}V_{dc}(s1 + s2e^{j\frac{2\pi}{3}} + s3e^{-j\frac{2\pi}{3}})} \qquad (18)$$

In this way, the input voltage vector of the stator is calculated and there is no need to measure it [10-11].

2.3 Proposed fuzzy controller for motor speed and flux

Conceptually, fuzzy logic is multi-valued and allows values between two values such as (true/false), (yes/no) or (high/low) and . . . defined .Concepts such as; Very, relatively, almost and . . . which are the foundations of ordinary human thought and reasoning, to be understood by the computer and in this way to create computer programs that are closer to human logic and thinking [14]. In the fuzzy control method, a pair of input and output information from the real system is available. Based on this information and through the following steps, the system can be modeled. A fuzzy controller consists of four main parts: fuzzifier, rule base, decision making part and non-fuzzifier. Figure (3) shows a view of a fuzzy controller. Usually, preprocessor and postprocessor are used before and after the fuzzy controller as shown in Figure (3) [14].

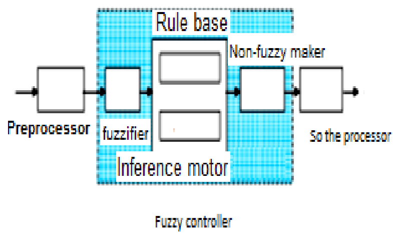


Fig .3.A view of a fuzzy control.

In the proposed electric drive, the input of the fuzzy controller and the error changes (e) is the fault of the control quantity of the motor speed and flux. for example; Linguistic labels are divided into seven groups, which are: large negative nl, medium negative nm, small negative ns, zero z, small positive ps, medium positive pm, large positive pl. Triangular membership functions are used to reduce online implementation calculations [15].

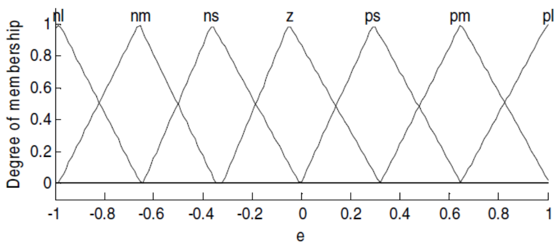
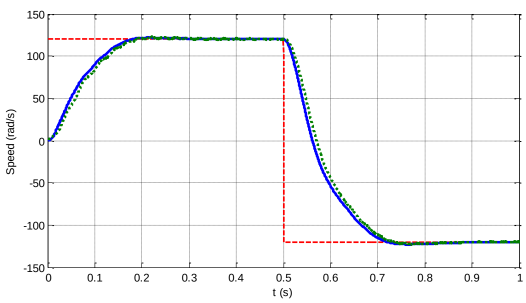


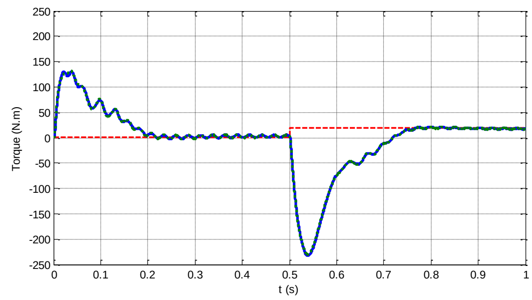
Fig .4. Membership functions for the fault and derivative of the fuzzy controller fault.

3. Simulation results of the proposed propulsion system

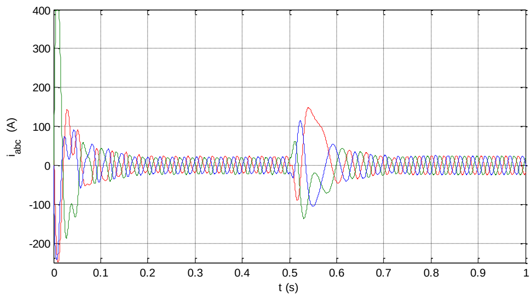
In the presented structure, a direct torque control strategy based on high efficiency and robust phase control for induction motor is presented. This control strategy is based on the generation of current sinusoidal waveforms. To measure the performance of the proposed system, the system model is simulated by MATLAB/SIMULINK software. Figure (5) shows the speed waveforms, phase currents, and electromagnetic torque of the three phase induction motor under variable speed and load conditions from start up to steady state. According to figure (5-a), the speed reference is first equal to 120 radians/s (nominal value) until 0.5 seconds, then -120 radians/s is selected. The blue curve shows the output speed of the motor and the green curve shows the estimated speed that closely followed the reference values. According to figure (5-b), the torque reference is equal to zero (no load) until 0.5 seconds and finally it is selected as 20 N-meter. The blue curve of the torque shows the value of the output torque and the green curve shows the estimated torque of the motor, which has followed the reference values of the load torque well. According to this figure, the speed has increased and reached its reference value with a delay of about 0.17 seconds without overshooting. The torque of the load has also increased to several times its nominal value due to the start up which requires a lot of energy and has reached its reference value after passing the transient states. The waveforms of the currents of the phases are close to sinusoid according to Figure (5-c).



(a)



(b)



(c)

Fig .5. Three-phase induction motor output waveforms in reference values (a) speed curve, (b) electromagnetic torque, (c) phase current.

Conclusion

Using electric drives with efficiency and high torque density and power is one of the ways to improve industrial and traction drives. Induction drives are suitable for industrial applications due to their range of speed and high torque and low depreciation and cost. Considering the fact that the use of a simple and small volume control system and at the same time accurate is an essential requirement of electric drives, the discussion of the economic and optimal design of the induction motor drive came up. A controlling attitude and a motivational structure take place. The method of direct torque control is introduced to improve the performance of the induction motor. The DTC strategy enables fast torque and speed responses and the use of a constant switching frequency. Robust and intelligent controllers such as fuzzy have higher dynamic response and less ripple than linear controllers.

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