DIRECT ROTOR FIELD ORIENTED CONTROL OF POLYPHASE INDUCTION MACHINE BASED ON FUZZY LOGIC CONTROLLER

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Key words: Polyphase induction machine, Multilevel voltage source inverter, Robust control, Fuzzy logic controller, Non-sequential currents.

This paper presents a new control system of the seven-phase induction machine supplied by three levels inverter, based on direct rotor field oriented control technique. The dynamic model of the machine shows that non-sequential currents producing no torque appear and degrade the quality of currents. Further, the fuzzy logic controller is proposed to regulate the mechanical speed and non-sequential components. The performance of the aimed system is analysed different acting conditions.

1. INTRODUCTION

The electric machine that best meets the decoupling hypothesis is the direct current machine with separate excitation. Indeed, in this type of structure, it is easy to imagine independent control of flux and torque respectively by inductor currents and armature. The difficulty to control the induction machine reside in the non-linearity of the model and the strong coupling between the stator and rotor sizes.

Since 40 years, thanks to the development of power electronics and fast microprocessors many researches have carried on the area of vector control of conventional ac machines [1]. Various vector control techniques are investigated as rotor-flux-oriented control, stator-flux-oriented control, and magnetizing-flux-oriented control [2, 3]. Several control techniques are elaborated with/without position sensors, associated with several techniques of physical quantities estimation. In high power range, the segmentation of this late is required. An alternative consists to investigate a novel electrical drive family, constituted by high number of phases [4–9]. By increasing the number of phases, it is also possible increasing the torque per ampere for the same machine volume. But, the application of these decoupled control is not sufficient in the case of a multiphase induction machine, the quality of energy conveyed inside the machine is deteriorated by non-sequential currents engendered by voltage harmonics.

A novel control of seven-phase induction machine supplied by three levels inverter with minimization of non-sequential currents using fuzzy logic will be studied in this paper. Several simulations results using Matlab/Simulink will be presented.

2. MODELING OF SEVEN PHASE INDUCTION MACHINE

The winding axes of seven-stator winding are displaced by $2\pi/7$ (Fig.1), generally inductance matrices of polyphase machines are full, which means for controlling in a strongly coupled system. However, like all the stator inductance matrices (or rotor) are circulating, so they are diagonalizable. Hence there exists a unique orthogonal basis of eigenvectors on which the magnetic quantities of the machine are decoupled [8].

Assuming linear magnetic circuits, equal mutual inductances and neglecting iron losses, voltage equations of stator and rotor in the real frame are given by:

$$\begin{align*}
[v_s] &= r_s [i_s] + [L_s] \frac{d}{dt}[i_s] + [M_{ss}] \frac{d}{dt}[i_r] \\
[v_r] &= r_r \frac{d}{dt}[i_r] + [L_r] \frac{d}{dt}[i_r] + [M_{rs}] \frac{d}{dt}[i_s] \\
x_s &= [x_1, x_2, ..., x_7] \quad \text{with} \quad x = v \text{ or } i.
\end{align*}$$

Fig. 1– Configuration scheme of seven-phase induction machine.

$$\begin{bmatrix}
L_{ss}\:&m_{s1}\:&m_{s2}\:&m_{s3}\:&m_{s4}\:&m_{s5}\:&m_{s6}\\
m_{s1}\:&l_{s}\:&m_{s1}\:&m_{s2}\:&m_{s3}\:&m_{s4}\:&m_{s5}\\
m_{s2}\:&m_{s2}\:&l_{s}\:&m_{s1}\:&m_{s2}\:&m_{s3}\:&m_{s4}\\
m_{s3}\:&m_{s4}\:&m_{s5}\:&m_{s6}\:&l_{s}\:&m_{s1}\:&m_{s2}\\
m_{s4}\:&m_{s5}\:&m_{s6}\:&l_{s}\:&m_{s1}\:&m_{s2}\:&m_{s3}\\
m_{s5}\:&m_{s6}\:&l_{s}\:&m_{s1}\:&m_{s2}\:&m_{s3}\:&m_{s4}
\end{bmatrix}$$

with $m_{si} = m_s \cos \left( i \frac{2\pi}{7} \right)$ and $l_s = l_{s1} + m_s$.

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with \( m = m_{sr} \cos \left( \frac{0 - (k - 1)\frac{2\pi}{7}}{7} \right) \), where \( \theta \) is the shift angle between stator and rotor.

Due to the difficulty of solving the system in the real base, we will move to the orthogonal basis \((\alpha, \beta, x_1, x_2, y_2)\) using the transformation \( T_7 \):

\[
T_7^i = \begin{bmatrix}
1 & a_1 & a_2 & a_3 & a_4 & a_5 & a_6 \\
0 & b_1 & b_2 & b_3 & b_4 & b_5 & b_6 \\
0 & a_1 & a_2 & a_3 & a_4 & a_5 & a_6 \\
0 & b_2 & b_4 & b_6 & b_8 & b_{10} & b_{12} \\
0 & a_3 & a_6 & a_{10} & a_{12} & a_{15} & a_{18} \\
c & c & c & c & c & c & c
\end{bmatrix},
\]

Applying this transformation to the system (1) and after calculation and simplification, the voltage equation in the orthogonal basis are obtained:

\[
\begin{bmatrix}
V_s(\alpha) \\
V_s(x_1,y_1) \\
V_s(x_2,y_2) \\
V_r(\alpha) \\
V_r(x_1,y_1) \\
V_r(x_2,y_2)
\end{bmatrix} =
\begin{bmatrix}
L_{sa} & \frac{dl}{dt} & \frac{dl}{dt} & \frac{dl}{dt} & \frac{dl}{dt} & \frac{dl}{dt}
\end{bmatrix}
\begin{bmatrix}
i_s(\alpha) \\
i_s(x_1,y_1) \\
i_s(x_2,y_2) \\
i_r(\alpha) \\
i_r(x_1,y_1) \\
i_r(x_2,y_2)
\end{bmatrix}
+ \frac{7}{2} m_{sr} [p(\theta)] \frac{dl}{dt}
\]

One advantage of the \( T_7 \) transformation is diagonalization inductance matrix, replacing \( g \) with \( s \) we get the matrix stator inductance, and replacing \( g \) with \( r \) we get the matrix rotor inductance.

\[
L_{sa} =
\begin{bmatrix}
l_{x_1} + l_a & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & l_{x_1} + l_{w_1} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & l_{x_2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & l_{x_2} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & l_{x_2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & l_{x_2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & l_{x_2}
\end{bmatrix}
\]

System of equations (6) expresses the modeling of seven-phase induction machine, which is composed by three parts. In fact, the \((\alpha, \beta)\) part is the principal and only submachine providing the torque. The two parts \((x_1, y_1), (x_2, y_2))\) express the machine’s losses; they do not contribute to the torque production.

The model developed in the system (6) is not practical for the development of a command because of the reference immobility, this is why the proposed model is moved to the \((d, q, x_1, y_1, x_2, y_2)\) using \( T_6 = p(\theta) T_7 \). The voltage equations of the seven phase induction motor are rewritten as follows:

\[
p(\theta) =
\begin{bmatrix}
\cos(\theta) & -\sin(\theta) & 0 & 0 & 0 & 0 & 0 \\
\sin(\theta) & \cos(\theta) & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
2.1. \text{MODEL OF SEVEN PHASES} \\
\text{INDUCTION MACHINE} \\
\text{IN THE ROTATING BASIS}
\]

The model developed in the system (6) is not practical for the development of a command because of the reference immobility, this is why the proposed model is moved to the \((d, q, x_1, y_1, x_2, y_2)\) using \( T_6 = p(\theta) T_7 \). The voltage equations of the seven phase induction motor are rewritten as follows:
where the flux equations are given by:

\[
\begin{align*}
\varphi_{ds} &= (L_m + l_{fs}) i_{ds} + L_m i_{dr} \\
\varphi_{qs} &= (L_m + l_{fs}) i_{qs} + L_m i_{qr} \\
\varphi_{x1s} &= l_{fs} i_{x1s} \\
\varphi_{y1s} &= l_{fs} i_{y1s} \\
\varphi_{x2s} &= l_{fs} i_{x2s} \\
\varphi_{y2s} &= l_{fs} i_{y2s} \\
\varphi_{dr} &= (L_m + l_{fs}) i_{dr} + L_m i_{ds} \\
\varphi_{qr} &= (L_m + l_{fs}) i_{qr} + L_m i_{qs}
\end{align*}
\]

Substituting the equations of flux in the equations of voltages:

\[
\begin{align*}
v_{ds} &= r_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_r \varphi_{qs} \\
v_{qs} &= r_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_r \varphi_{ds} \\
v_{x1s} &= r_s i_{x1s} + \frac{d\varphi_{x1s}}{dt} \\
v_{y1s} &= r_s i_{y1s} + \frac{d\varphi_{y1s}}{dt} \\
v_{x2s} &= r_s i_{x2s} + \frac{d\varphi_{x2s}}{dt} \\
v_{y2s} &= r_s i_{y2s} + \frac{d\varphi_{y2s}}{dt} \\
0 &= r_s i_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_r \varphi_{qr} \\
0 &= r_s i_{qr} + \frac{d\varphi_{qr}}{dt} + \omega_r \varphi_{dr}
\end{align*}
\]

and it is expressed in the D–Q basis using \( T_{76} \) transformation as follow:

\[
\begin{align*}
\Gamma_{em} &= pL_m \left( (i_{dr} \cdot i_{qr}) - (i_{ds} \cdot i_{qs}) \right) - \frac{pL_m}{j} \left( \varphi_{dr} i_{ds} - \varphi_{qr} i_{ds} \right) \\
\Gamma_{em} - \Gamma_r &= \frac{j}{dt} \frac{d\Omega}{dt},
\end{align*}
\]

with \( i_{dr}, i_{ds}, i_{x1s}, i_{y1s}, i_{x2s}, i_{y2s}, i_{dr}, i_{qr} \) are respectively the stator and rotor currents components, \( v_{ds}, v_{qs}, v_{dts}, v_{dts}, v_{s2s}, v_{s2s}, v_{dtr}, v_{qtr} \) are stator and rotor voltages components, \( \varphi_{dr}, \varphi_{qs}, \varphi_{dts}, \varphi_{dts}, \varphi_{s2s}, \varphi_{s2s}, \varphi_{dtr}, \varphi_{qtr} \) are respectively the stator and rotor fluxes components. \( J \) and \( \Omega \) are the inertia and speed of the machine respectively, \( p \) and \( \omega_r \) are respectively number of pole pair and electric pulsation.

### 3. CONTROL METHOD FIELD ORIENTED

This section is devoted to the development of the seven phase induction machine control, the decoupling between rotor flux and electromagnetic torque is very important. This vector control is not very different from the conventional vector control; the aim is always to assimilate the behaviour of induction machine to that to the machine separately excited by decoupling control of torque of the flux. But the difference lies in the minimization of non-sequential components [9]. This section allowed us to identify a new problem related to this type of machine. Several authors [5, 10, 11] have neglected these non-sequential components, making the controls developed over the incomplete work, the minimization of copper losses are very important for improving the efficiency of the machine. Otherwise the power segmentation loses its importance, the control without consideration of its parasitic currents is incomplete. These components have an uncertain behaviour, frequencies and scales variants making their filtering in transient regime via conventional filter (low pass, high pass, ... etc.) difficult and sometimes impossible. The solution that the author proposed in [12], consists of placed impedance filters in series with the stator windings of the machine with high harmonics and low fundamental frequencies. This solution is not only cumbersome but also very limited as it is valid in the steady state. In this section filtering of these streams and minimization via fuzzy logic is presented.

To simplify the model given by equation (11), the stator currents \( (i_{ds}, i_{qs}) \), the rotor flux \( (\varphi_{dr}, \varphi_{qr}) \), and the mechanical speed \( \Omega \), are considered as state variables. The orientation control by the rotor flux is to provide a decoupling between the magnitudes of the generating electromagnetic torque and rotor flux [6]. This can be done if the rotor flux coincides with the d-axis of the reference related to the rotating field. Thus, by acting on the variables \( i_{ds}, i_{qs} \), quantities \( \Gamma_{em} \) and \( \varphi_r \) are controlled separately; this means, align the rotor flux vector on the d-axis: \( \varphi_{dr} = \varphi_r \) and \( \varphi_{qr} = 0 \). The non-sequential components are not affected by the necessary processing for the orientation of the rotor field. By using this concept, the mathematical models of the seven phase induction machine become:
Direct rotor field oriented control of polyphase induction machine

\[
v_{ds} = \left(\frac{L_m}{L_p} + \frac{L_p^2}{L_p^2} r_p \right) i_{ds} + \frac{d}{dr} \frac{1}{L_p} \sigma R_p i_{rs} - \frac{L_m}{L_p^2} \omega \phi_r
\]

\[
v_{qs} = \left(\frac{L_m}{L_p} + \frac{L_p^2}{L_p^2} r_p \right) i_{qs} + \frac{d}{dr} \frac{1}{L_p} \sigma R_p i_{qs} + \frac{L_m}{L_p^2} \omega \phi_r
\]

\[
\frac{d}{dr} \phi_r = \frac{L_m}{L_p} - \frac{1}{L_p} \phi_r
\]

\[
\phi_r = \frac{L_m}{L_p} \omega
\]

\[
\Gamma_{em} = \frac{L_m}{L_p} \phi_r
\]

\[
\frac{d}{dr} \Omega = \Gamma_{em} - \Gamma_r - f \Omega
\]

\[
\varphi_0 = \frac{L_m}{L_p} i_{ds}
\]

\[
\Gamma_{em} = \frac{L_m}{L_p} i_{ds} \varphi_r, \quad \text{with} \quad \sigma = 1 - \frac{L_m}{L_p} i_{ds}
\]

\[
\omega_0 = \frac{L_m}{L_p} i_{qs} + \omega_r
\]

\[
\Gamma_r = \Gamma_{em} - \Gamma_r - f \Omega
\]

\[\text{and} \quad T_r = \frac{I_r + L_{wu}}{r_p}, \quad \text{where} \quad \varepsilon = 0.001.\]

We can notice that only the direct component \( i_{ds} \) determines the amplitude of the rotor flux, while the torque depends only on the quadrature component \( i_{qs} \) if the rotor flux is kept constant. Thus, the decomposition is carried out of the stator current into two terms corresponding to the flux and torque. For this, we obtain a similar structure to that of a dc machine. The new DRFOC diagram of seven-phase induction motor is presented in Fig. 3. For the minimization of the non-sequential components the fuzzy logic controller is used. About the definition of membership function, these controllers adheres to inputs \((e(k), \ v_r(k))\), and single output \(S(x)\). The membership functions illustrate the degrees to which specify attention belongs to the fuzzy set [13]. The membership degrees of account indicate each degree can be accounted quantitatively accomplished a set of formulae of membership functions. To convert these variables in the linguistic variables, the following seven membership functions are chosen for the input and output: NB: Negative Big, NM: Negative Medium, NS: Negative small, ZE: Zero Equal, PS: Positive Small, PM: Positive Medium, PB: Positive Big. Figure 2 illustrates the correction evaluation rules as well as the surface of regulator respectively. Constriction domain variable Z provides better system responsiveness when the static error is small. The input of this controller variables are error “e” and the derivative of the error “de”. It is possible to choose a large number of inferences tables. The one presented in Table 1 is chosen. All parameters of this regulator have been fit using several simulations. Algorithmic cost is very high, but the rejection of disturbances is effective. In addition, this controller can do without compensation algorithms. Further, to decrease the torque ripples the three levels neutral point clamped (NPC) inverter is used.

| Table 1 |
| Rules base for fuzzy logic control |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| De | e | NB | NM | NS | ZE | PS | PM | PB |
| NB | NB | NB | NB | NB | NB | NM | NS | ZE |
| NM | NB | NB | NB | NM | NS | ZE | PS | PM |
| NS | NB | NB | NM | NS | ZE | PS | PM | PB |
| ZE | NB | NM | NS | ZE | PS | PM | PB | PB |
| PS | NM | NS | ZE | PS | PM | PB | PB | PB |
| PM | NS | ZE | PS | PM | PB | PB | PB | PB |
| PB | ZE | PS | PM | PB | PB | PB | PB | PB |

Fig. 2 – Configuring dual stars induction machine.
4. SIMULATION AND RESULTS

In this section, the simulation results acquired with MATLAB/Simulink are demonstrated. The aimed configuration is analyzed under different acting conditions namely speed reference reversal \([120, -120(\text{rad/s})]\) reference speed, load torque changes. Fig. 4 shows the mechanical speed with its different zoom.

Figure 5 shows electromagnetic torque and quadratic current, the torque is the image of this current, and the flux is the image of direct current show in the Fig. 6, which confirms theory’s development. Minimization of non-sequential currents of the first and second parts showed in Fig. 8a and b respectively, gives better quality of energy, a better estimation of physical quantities; we noticed that the currents are better quality illustrated in Fig. 7. The using of three levels inverter contributes to the currents cleaning.

Fig. 3 – Control scheme of the seven-phase induction machine.

Fig. 4 – Mechanical speed and different zoom parts.

Fig. 5 – Torque and quadratic current.

Fig. 6 – Rotor flux and direct current.
5. CONCLUSION

In this paper, the vector control of seven phase induction machine with fuzzy controllers is presented. The modeling of seven-phase induction machine shows that is composed by three parts. Firstly, \((\alpha, \beta)\) components are the principal part that produces electromagnetical torque. On the other hand, \(((x_1, y_1), (x_2, y_2))\) parts do not contribute to the torque production, but this is a real problem of the electrical and mechanical power's quality, the degradation of this last are caused by voltage harmonics. One inconvenient of using the polyphase induction machine is non-sequential currents overlapping the main currents of the machine. The behavior of these currents is unknown, hence the need to use fuzzy logic to minimize these parasitic currents and minimizing losses and leaks in the machine. This paper develops innovative design method to control a polyphase induction machine, robust tracking and disturbance attenuation.

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