PERFORMANCE IMPROVEMENT OF ADAPTIVE FUZZY SYSTEM BASED DTC INDUCTION MOTOR DRIVE

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Abstract

Better torque control can be obtained by the use of Direct torque control (DTC) instead of Field oriented control (FOC) in steady state and transient state operating conditions because of its simple control structure. Robustness and fast torque response are the advantages of Direct torque control (DTC). Stator flux estimation is difficult under low speed operation due to existence of open loop integrator and improper working of an open loop voltage model, hence an adaptive fuzzy system is adopted which improves the machine performance by eliminating open loop integration, minimizing stator current distortions, constant switching frequency, fast response of rotor speed and stator flux electro-magnetic torque without ripples. In this paper an adaptive fuzzy controller is adopted which improves system performance and subdues high torque ripples. For the proposed system simulation results are carried out.

Keywords: Direct torque control, Adaptive fuzzy system (AFS), Modelling of induction motor drive.

I. Introduction

Owing for controlling of induction motors a mature technology have been developed in past few years in absence of speed sensor. For controlling of ac drives a well-known method is used which is known as Direct torque control (DTC). For fast torque response Direct torque control (DTC) method is used for ac motor control method which had been developed by German and Japan researchers more than a decade ago. Even at zero speed it works, hence it attained a great interest which is very important in industrial contribution. Directly and indirectly electro-magnetic

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The Paper Presented at National Conference on Recent Trends & Challenges in Engineering Organized by Rajive Gandhi Memorial College, AP, India
torque and flux linkages are controlled by inverter switching modes. To get fast response, low inverter switching frequency and low harmonic losses, the electromagnetic torque and flux linkage errors are restricted within flux and torque hysteresis band. For torque ripple reduction many techniques have been developed. To reduce ripples to obtain torque ripples with reduced flux and constant switching frequency to the inverter an adaptive fuzzy system technique is used. Minimizing stator current distortions, stator flux electro-magnetic torque without ripples and constant switching are obtained by developing adaptive fuzzy system. In this paper an adaptive fuzzy system is adapted as an innovative technology to improve the system performance with engineering expertise’s and improves conventional system by maintaining constant switching frequency and reducing torque ripples.

II. System Configuration

Fig.1 models Direct torque control (DTC) with adaptive fuzzy modulation. The modified version i.e Direct torque control (DTC) with adaptive fuzzy is no longer based on hysteresis regulation with variable frequency switching but with PWM inverter fixed frequency. By using universal bridge block for a PWM voltage source inverter an induction motor is driven. To produce flux and torque references for DTC block, speed control loop uses an adaptive fuzzy controller. Computed flux and torque are compared with respective references. To compute a reference voltage sector torque and flux are controlled by an adaptive fuzzy controller which gives desired voltage to output. Speed under no load condition, electro-magnetic torque, DC bus voltage, stator current and supply voltage are available at output of block. After simulation was started speed under no load condition, electro-magnetic torque, DC bus voltage, stator current and supply voltages can be observed on the scope.

Fig [1]: Block diagram of Adaptive fuzzy with DTC-SVM
III. Modelling Of 3-Phase Induction Motor

Scrutinizing of steady state of electrical machines below unbalanced and transient conditions. Modelling represents the connection between mechanical and electrical quantities of electrical machines. Mathematical model of an induction motor is derived by the following assumptions a) it should be squirrel cage b) Uniform air gap c) balanced stator and rotor windings with sinusoidal distributed winding[I][III]. Generally an induction motor is contemplated as rotating transformer in an induction motor due to the production of rotor currents by induction as that of transformer. Compared with other electrical machines no need to have any internal and external exciter. Stationary magnetic field is produced when three phase supply is given to the stator winding is rotated when flux cuts the rotor slot, hence rotor starts to rotate. Because of relative motion between stator and rotor a mutual emf is generated[III]. For transforming three phase AC quantities into two phase DC quantities mathematical modelling of an induction motor is mostly done. This type of transmutation is called dq0 transmutation(Parks transformation). dq0 transmutation is usually mentioned when the eminence of phase quantities onto rotating two axis frame, whereas the eminence of phase quantities onto stationary two axes frame is mentioned as αβγ transmutation. The αβγ transmutation mathematical model is more precise [IV].

\[
V_a(t) = \sqrt{2}V_{rms}\sin(\omega t)
\]

\[
V_b(t) = \sqrt{2}V_{rms}\sin(\omega t - 120)
\]

\[
V_c(t) = \sqrt{2}V_{rms}\sin(\omega t - 240)
\]

here \(V_a(t), V_b(t), V_c(t)\) are line voltages and alliance between abc and αβγ are given as below

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & \frac{1}{2} & -1 \\
0 & \sqrt{3} & 0 \\
0 & 0 & 2 \\
\end{bmatrix} \begin{bmatrix}
V_A \\
V_B \\
V_C \\
\end{bmatrix}
\] (1)

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & \frac{1}{2} & -1 \\
0 & \sqrt{3} & 0 \\
0 & 0 & 2 \\
\end{bmatrix} \begin{bmatrix}
i_A \\
i_B \\
i_C \\
\end{bmatrix}
\] (2)

III.i. Modelling of an Induction motor mathematically

Mathematical modelling of an induction motor can be derived by general electrical scheme of induction motor. Stator phase windings are denoted by ABC, where as rotor phase windings are denoted by abc. The voltages concerned to three phase of stator windings can be obtained by applying KVL

\[
V_A = R_Ai_A + \frac{d}{dt}[\psi_A]
\] (3)
\[ V_B = R^B_s i_s^B + \frac{d}{dt}[\psi_s^B] \]  \hspace{1cm} (4)

\[ V_C = R^C_s i_s^C + \frac{d}{dt}[\psi_s^C] \]  \hspace{1cm} (5)

Stator resistances of phase A, B and C are given by \( R^A_s, R^B_s, R^C_s \).

Similarly induced voltages in rotor circuit can be concerned by KVL

\[ 0 = R^A_r i_r^A + \frac{d}{dt}[\psi_r^A] - j\omega_r^A \psi_r^A \]  \hspace{1cm} (6)

\[ 0 = R^B_r i_r^B + \frac{d}{dt}[\psi_r^B] - j\omega_r^B \psi_r^B \]  \hspace{1cm} (7)

\[ 0 = R^C_r i_r^C + \frac{d}{dt}[\psi_r^C] - j\omega_r^C \psi_r^C \]  \hspace{1cm} (8)

Stator and rotor winding flux generated can be given as

\[ \psi_s^A = L_s^A i_s^A + L_{m}^A i_r^A \]  \hspace{1cm} (9)

\[ \psi_s^B = L_s^B i_s^B + L_{m}^B i_r^B \]  \hspace{1cm} (10)

\[ \psi_s^C = L_s^C i_s^C + L_{m}^C i_r^C \]  \hspace{1cm} (11)

\[ \psi_r^A = L_r^A i_r^A + L_{m}^A i_s^A \]  \hspace{1cm} (12)

\[ \psi_r^B = L_r^B i_r^B + L_{m}^B i_s^B \]  \hspace{1cm} (13)

\[ \psi_r^C = L_r^C i_r^C + L_{m}^C i_s^C \]  \hspace{1cm} (14)

On substituting equations (9),(10)&(11) in equations (3),(4)&(5) we get

\[ V_A = R^A_s i_s^A + L_s^A \frac{d}{dt}[i_s^A] + L_{m}^A \frac{d}{dt}[i_r^A] \]  \hspace{1cm} (15)

\[ V_B = R^B_s i_s^B + L_s^B \frac{d}{dt}[i_s^B] + L_{m}^B \frac{d}{dt}[i_r^B] \]  \hspace{1cm} (16)

\[ V_C = R^C_s i_s^C + L_s^C \frac{d}{dt}[i_s^C] + L_{m}^C \frac{d}{dt}[i_r^C] \]  \hspace{1cm} (17)

Similarly by substituting equations (12),(13)& (14) in equations (6),(7)& (8) we get

\[ 0 = R^A_r i_r^A + L_s^A \frac{d}{dt}[i_r^A] + L_{m}^A \frac{d}{dt}[i_s^A] - j\omega_r^A [L_r^A i_r^A + L_{m}^A i_s^A] \]  \hspace{1cm} (18)

\[ 0 = R^B_r i_r^B + L_s^B \frac{d}{dt}[i_r^B] + L_{m}^B \frac{d}{dt}[i_s^B] - j\omega_r^B [L_r^B i_r^B + L_{m}^B i_s^B] \]  \hspace{1cm} (19)

\[ 0 = R^C_r i_r^C + L_s^C \frac{d}{dt}[i_r^C] + L_{m}^C \frac{d}{dt}[i_s^C] - j\omega_r^C [L_r^C i_r^C + L_{m}^C i_s^C] \]  \hspace{1cm} (20)

The matrix form of equations (15),(16),(17),(18),(19),(20) are

\[ \psi_s^A = L_s^A i_s^A + L_{m}^A i_r^A \]  \hspace{1cm} (9)

\[ \psi_s^B = L_s^B i_s^B + L_{m}^B i_r^B \]  \hspace{1cm} (10)

\[ \psi_s^C = L_s^C i_s^C + L_{m}^C i_r^C \]  \hspace{1cm} (11)

\[ \psi_r^A = L_r^A i_r^A + L_{m}^A i_s^A \]  \hspace{1cm} (12)

\[ \psi_r^B = L_r^B i_r^B + L_{m}^B i_s^B \]  \hspace{1cm} (13)

\[ \psi_r^C = L_r^C i_r^C + L_{m}^C i_s^C \]  \hspace{1cm} (14)

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On applying above equations in equations (15),(16),(17) we get

\[ V_A = V_A^a + jV_A^b \]  
\[ V_B = V_B^a + jV_B^b \]  
\[ V_C = V_C^a + jV_C^b \]

Identically stator and rotor currents are given as

\[ i_s^A = i_s^A + ji_s^B(25)i_r^{SA} = i_s^A + ji_s^{SA} \]  
\[ i_s^B = i_s^B + ji_s^B(26)i_r^{SB} = i_s^B + ji_s^{SB} \]  
\[ i_s^C = i_s^C + ji_s^C(27) i_r^{SC} = i_s^C + ji_s^{SC} \]

On applying above equations in equations (15),(16),(17) we get

\[ V_A^a + jV_A^b = R_s^A (i_{sa}^a + ji_{sb}^a) + L_s^A \frac{d}{dt}[i_{sa}^A + ji_{sb}^A] + L_m^A \frac{d}{dt}[i_{sa}^{SA} + ji_{sb}^{SA}] \]  
\[ V_B^a + jV_B^b = R_s^B (i_{sa}^b + ji_{sb}^b) + L_s^B \frac{d}{dt}[i_{sa}^B + ji_{sb}^B] + L_m^B \frac{d}{dt}[i_{sa}^{SB} + ji_{sb}^{SB}] \]  
\[ V_C^a + jV_C^b = R_s^C (i_{sa}^c + ji_{sb}^c) + L_s^C \frac{d}{dt}[i_{sa}^C + ji_{sb}^C] + L_m^C \frac{d}{dt}[i_{sa}^{SC} + ji_{sb}^{SC}] \]

Similarly apply above equations in equations (18),(19),(20) we get

\[ 0 = R_r^A (i_{ra}^A + ji_{rb}^{SA}) + L_r^A \frac{d}{dt}[i_{ra}^A + ji_{rb}^{SA}] + L_m^A \frac{d}{dt}[i_{sa}^A + ji_{sb}^{SA}] - j \omega_0^A [L_r^A (i_{ra}^A + ji_{rb}^{SA}) + L_m^A (i_{sa}^A + ji_{sb}^{SA})] \]
Controller output equation is acquired for defuzzification through center of gravity eventuates from cost equation given below

\[ 0 = R^B_s (i^B_{sa} + j^B_{sb}) + L^B_r \frac{d}{dt} [i^B_{sa} + j^B_{sb}] + L^B_m \frac{d}{dt} [i^B_{sa} + j^B_{sb}] - j \omega^B_r [L^B_r (i^B_{sa} + j^B_{sb}) + L^B_m (i^B_{sa} + j^B_{sb})] \quad (35) \]

\[ 0 = R^C_s (i^C_{sa} + j^C_{sb}) + L^C_r \frac{d}{dt} [i^C_{sa} + j^C_{sb}] + L^C_m \frac{d}{dt} [i^C_{sa} + j^C_{sb}] - j \omega^C_r [L^C_r (i^C_{sa} + j^C_{sb}) + L^C_m (i^C_{sa} + j^C_{sb})] \quad (36) \]

The matrix form of equations (31),(32),(33),(34),(35),(36) are

\[
\begin{bmatrix}
V^A_s \\
V^B_s \\
V^C_s \\
0
\end{bmatrix} + j
\begin{bmatrix}
V^A_s \\
V^B_s \\
V^C_s \\
0
\end{bmatrix} = \begin{bmatrix}
R^A_s & 0 & 0 & 0 & 0 & 0 \\
0 & R^B_s & 0 & 0 & 0 & 0 \\
0 & 0 & R^C_s & 0 & 0 & 0 \\
0 & 0 & 0 & R^B_s & 0 & 0 \\
0 & 0 & 0 & 0 & R^C_s & 0
\end{bmatrix}
\begin{bmatrix}
i^A_{sa} + j^A_{sb} \\
i^B_{sa} + j^B_{sb} \\
i^C_{sa} + j^C_{sb} \\
i^A_{sa} + j^A_{sb} \\
i^B_{sa} + j^B_{sb} \\
i^C_{sa} + j^C_{sb}
\end{bmatrix}
\]

\[
\begin{bmatrix}
l^A_s & 0 & 0 & L^A_m & 0 & 0 \\
l^B_s & 0 & 0 & L^B_m & 0 & 0 \\
l^C_s & 0 & 0 & L^C_m & 0 & 0 \\
l^A_m & 0 & 0 & L^A_r & 0 & 0 \\
l^B_m & 0 & 0 & L^B_r & 0 & 0 \\
l^C_m & 0 & 0 & L^C_r & 0 & 0
\end{bmatrix}
- j
\begin{bmatrix}
\omega^A_r & L^A_m & 0 & 0 & \omega^A_r & L^A_m \\
0 & \omega^B_r & L^B_m & 0 & 0 & \omega^B_r & L^B_m \\
0 & 0 & \omega^C_r & L^C_m & 0 & 0 & \omega^C_r & L^C_m
\end{bmatrix}
\]

\[ (37) \]

IV. Adaptive Fuzzy System

Levenberg-Marquardt algorithm based controller design curtails both linear and non linear functions and amply consign for MIMO systems. The design eventuates from cost equation given below

\[ e_m = \frac{1}{2} [f_m - y_{ref}]^2 \quad (38) \]

Controller output equation is acquired for defuzzification through center of gravity methodology

\[ f_m = \frac{\left( \sum_{i=1}^{R} b_i M_i(x^m_{i,k}) \right)}{\left( \sum_{i=1}^{R} M_i(x^m_{i,k}) \right)} \quad (39) \]

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The output and input membership function (MF) adaptive fuzzy logic controller (AFLC) can be improved by above equation, extend to membership function (MF) of output variable. Alternatively Gaussian membership function (GMF) is used behind generalized triangular, bell shaped and trapezoidal. Gaussian membership function (GMF) uses two parameters instead of three which is beneficial for continuous function, moreover it updates fast.

\[
\mu_i \left( x_j^m, k \right) = \exp \left[ -\frac{1}{2} \left( \frac{x_j^m - c_j^i}{\sigma_j^i} \right)^2 \right]
\]  

(40)

For improving the parameter the equation can be derived as

\[
e_m = \frac{1}{2} \left[ f_m - y_{ref} \right]^2
\]  

(41)

On derivating above equation w.r.t. output membership function we get

\[
\frac{\partial e_m}{\partial b_i} = \left[ f_m - y_{ref} \right] \frac{\partial e}{\partial b_i}
\]  

(42)

On substituting GMF in equation (42) we get

\[
\frac{\partial e_m}{\partial b_i} = \sum_{\eta=1}^{R_i} \frac{b_i \mu_i(x_j^m, k)}{\sum_{\eta=1}^{R_i} \mu_i(x_j^m, k)}
\]  

(43)

Output membership function (OMF) Jacobean, variance, center are intended by conveying derivative of error equation. Jacobian of output membership function (OMF) \( b_i \) equation is shown below. On derivating cost equation w.r.t \( \sigma_i \) and \( C_i \) we obtain center of Jacobean and Gaussian membership function (GMF) variance individually

\[
\frac{\partial e_m}{\partial b_i} = \sum_{\eta=1}^{R_i} \frac{b_i \mu_i(x_j^m, k)}{\sum_{\eta=1}^{R_i} \mu_i(x_j^m, k)}
\]  

(44)

Output membership function updation is done by below equation which is controller output to plant. Based to fuzzy logic controller (FLC) Levenberg-Marquardt (LM) algorithm learning rule is updated.
Output membership function (OFC) center is illustrated by $b_i$ variable. Accordingly to plant output the output membership function (OFC) center assimilates itself to reduce the error.

$$b_i(k) = b_i(k-1) - \lambda \left[ \mathcal{E} \left[ \frac{\mu_i(x^m_{\тzeichnen k})}{\sum_{m=1}^{M_тzeichnen} \mu_i(x^m_{\тzeichnen k})} \right] + \mu I \right]^{-1} \mathcal{E} \left[ \frac{\mu_i(x^m_{\тzeichnen k})}{\sum_{m=1}^{M_тzeichnen} \mu_i(x^m_{\тzeichnen k})} \right]$$

(45)

The expansion of Gaussian membership function (GMF) is depicted by variance which beneficially improves himself by following derived equation. Gaussian membership function (GMF) swings in reverse to variance. Larger the value of variance when notch is lowered and vice-versa.

$$\sigma_i(k) = \sigma_i(k-1) - \lambda [AA^T + \mu I]^{-1} \Delta \mathcal{E}$$

(46)

Gaussian membership function center is updated by succeeding equation, which clinches different values leading to real input to controller.

$$C_i(k) = C_i(k-1) - \lambda [BB^T + \mu I]^{-1} B \mathcal{E}$$

(47)

The four main stages of fuzzy logic controller i.e rule base, fuzzifier, inference engine and de-fuzzifier are shown in fig[III][VII]. Updated equation of controller output is obtained by updating $b_i, C_i, \sigma_i$ by progressing through these four stages.

V. Conclusions

In this paper an adaptive fuzzy system is put forwarded with direct torque control to minimize the torque ripples. It also improves the performance of the system as fuzzy logic controller finds out the desired amplitude of torque within hysteresis band. Thus minimum noise and switching losses are seen even at low speeds.
VI. Results And Discussion

Matlab/Simulink setup is used to simulate results for speed, electromagnetic torque, Stator current and supply voltages. DC bus voltage and switching states are used to define voltage signals instead of using voltage measurement sensors. Proposed DTC-SVM method was tested in different conditions. Steady state performance and normal running up are firstly evaluated then investigation for system operation under low speed region is done.

Fig [3]: Voltage distortions due to non-linear inverter devices

Fig [5]: DC bus voltage distortions

Fig [4]: Current distortions due to non-linear inverter devices

Fig [6]: Speed response under low speed region
Fig[7]: Electro-magnetic torque under low speed region

References

I. B. M. Wilamowski, H. Yu, “Improved Computation for Levenberg–Marquardt Training” IEEE Transactions on neural network. Vol.: 21, Issue: 6, pp. 930-937, 2010.

II. K. Zeb, W. U. Din, M. A. Khan, A. Khan, U. Younas, T. D. C. Busarello, H. J. Kim, “Dynamic Simulations of Adaptive Design Approaches to Control the Speed of an Induction Machine Considering Parameter Uncertainties and External Perturbations.” Energies, vol.: 11, Issue: 9 pp. 2339, 2018.

III. L. A. Brooks, J. L. Castro, L. Castro, “Speed and position controllers using indirect field-oriented control: a classical control approach.” IEEE Trans. Ind. Electron, Vol. 61, Issue: 4, pp. 1928–1943, 2014.

IV. L. J. Phukon, N. Baruah, "A Generalized MATLAB Simulink Model of a Three Phase Induction Motor", International Journal of Innovative Research in Science, Engineering and Technology, Vol.: 04, Issue: 05, 2015.

V. L. P. Ratnani, A. G. Thosar, "Mathematical Modelling of an 3 Phase Induction Motor Using MATLAB/Simulink", International Journal Of Modern Engineering Research (IJMER), Vol.: 04, Issue: 06, 2014.

VI. P. C. Krause, C. H. Thomas, “Simulation of Symmetrical Induction Machinery”, IEEE Transaction on Power Apparatus and Systems, Vol.: 84, 1965.

VII. S. D. Sudhoff, O. Wasynezuk, P. C. Krause, “Analysis of Electric machinery and drive systems”, IEEE press, A John wiley& sons, Inc. publication second edition, 2002.