Evaluation of the High Performance Indirect Field Oriented Controlled Dual Induction Motor Drive Fed by a Single Inverter using Type-2 Fuzzy Logic Control

Alaeddine Bounab  
Department of Electrical Engineering  
Batna 2 University  
Batna, Algeria  
bounab_alaeddine@yahoo.fr

Azeddine Chaiba  
Department of Industrial Engineering  
University of Khenchela  
Khenchela, Algeria  
chaiba_azeddine@yahoo.fr

Sebti Belkacem  
Department of Electrical Engineering  
Batna 2 University  
Batna, Algeria  
belkacem_sebti@yahoo.fr

Abstract—In this paper, a high-performance indirect field-oriented controlled dual Induction Motor (IM) drive fed by a single inverter using type-2 fuzzy logic control will be presented. At first, the mathematical model of the IM is implemented in the d-q reference frame. Then, the speed control of the Dual Induction Motor (DIM) operating in parallel configuration with Indirect Field Oriented Control (IFOC) using PI and type-2 Fuzzy Logic Controller (T2-FLC) will be presented. For the control of this system, a DC supply and a Space Vector Pulse Width Modulation (SVPWM) voltage source inverter are introduced with constant switching frequency. Also, the performance of T2-FLC, which is based on the IFOC, is tested and compared to those achieved using the PI controller. The simulation results demonstrate that the T2-FLC is more robust, efficient, and has superior dynamic performance for traction system applications.

Keywords—Indirect Field Oriented Control (IFOC); Type-2 Fuzzy Logic Control (T2-FLC); Dual Induction Motor (DIM); Space Vector Pulse Width Modulation (SVPWM); mean control strategy

I. INTRODUCTION

Nowadays, industrial efforts are focusing on reducing weight and volume and on minimizing costs while guaranteeing high operating performance of the systems. A multi-machine drive system powered by a single inverter presents a desirable solution. These systems are used in several applications such as paper and steel rolling mills [1-3], conveyor systems [4], and electric propulsion systems such as electric traction, ship propulsion and electric vehicles [5-7]. For multi-motor drives, the structure and the control strategy of the drive system depend on the requirements of the application for which they are used as well as the necessary performance, speed and precision of the drive system. Different modeling techniques for two induction motors with a single inverter have already been released. A graphical and a global modeling of a multi-machine system connected in parallel is used in [6, 8].  

Several couplings by criteria merging for multi-machine, multi-converter systems are presented in [9]. Several control solutions have been presented: a modified V/f control strategy for a multi-machine multi-inverter drive system is given in [10] and fuzzy sliding and DTC-SVM control of multi induction motors connected in parallel are presented in [11, 12]. Authors in [13] present an optimal predictive torque control of two parallel permanent magnet synchronous machines fed with a single inverter. A technique based on master slave direct control of two synchronous machines is used in [14]. Dive systems comprising multi-phase and multi-motor induction machines powered by a single inverter are studied in [15-17]. Unlike the three-phase multi-machine system, multi-phase multi-machine systems supplied by a single inverter can be connected in series [18, 19] and in parallel [13, 14, 17, 20], which allows independent control of each machine. In this paper, two induction machines connected in parallel powered by a single inverter as presented in Figure 1 [21] were considered. Here, current and speed feedback is taken from both machines which are fed by a single voltage source inverter for calculating the reference voltages to be applied to the machines.

To obtain a good dynamic response of the drive torque, two performance control strategies can be used to control two-machine systems with a single inverter: Field Oriented Control (FOC) [5, 15, 16, 21-23] and Direct Torque Control (DTC) [1, 4, 6, 12, 24]. The speed control of the dual identical induction motor drive connected in parallel to a SVPWM inverter supply using T2-FLC is investigated in this paper. This system is
suitable for applications using dual Induction Motor (IM) drives with the advantage of compactness, lightness and economy [25-27].

These motors [28]. This method is characterized by the single SVPWM inverter is shown in Figure 1. This method has (IFOC) of dual motors connected in parallel associated to a motor speed and load variations. Controllers are used in the speed control loops for the DIMs. Calculation of the angular sliding speed, the stator flux angle and currents, stator flux, and speed as state variables and voltages by:

\[
\begin{align*}
\Phi_{dqi} &= L_s * I_{dqi} + L_m * I_{aqi} \\
\Phi_{qqi} &= L_s * I_{qqi} + L_m * I_{aqi} \\
\Phi_{dri} &= L_r * I_{dri} + L_m * I_{aqi} \\
\Phi_{qri} &= L_r * I_{qri} + L_m * I_{aqi}
\end{align*}
\]

The components of the stator and rotor flux are expressed by:

\[
\Phi_{dqi} = L_s * I_{dqi} + L_m * I_{aqi} \\
\Phi_{qqi} = L_s * I_{qqi} + L_m * I_{aqi} \\
\Phi_{dri} = L_r * I_{dri} + L_m * I_{aqi} \\
\Phi_{qri} = L_r * I_{qri} + L_m * I_{aqi}
\]

The electromagnetic torque equation can be expressed in terms of stator currents and stator flux as:

\[
C_{ei} = \frac{3p \rho_{Dm}}{2\rho_{Dm}} \rho (\Phi_{dri} * I_{qsi} - \Phi_{qri} * I_{dsi})
\]

where \((V_{dsi}, V_{qsi}),(I_{dsi}, I_{qsi}),(\Phi_{dsi}, \Phi_{qsi})\) are the voltages, currents, and stator flux in d-q axis, \((w_{si}, \Omega_i)\) are stator pulsation and mechanical rotor speed, \(i = 1, 2\) are the first and second induction motor, \(R_s, R_r\) the stator and rotor resistance, \((L_s, L_r)\) the stator and rotor cinductive inductance, and \((L_m, p)\) are the mutual inductance and the number of pole pairs.

Due to the similarity of the two induction machines, only the model of one machine is presented.

II. SYSTEM CONFIGURATION

A schematic diagram of the Indirect Field Oriented Control (IFOC) of dual motors connected in parallel associated to a single SVPWM inverter is shown in Figure 1. This method has been adopted in order to avoid the excessive magnetization of these motors [28]. This method is characterized by the calculation of the angular sliding speed, the stator flux angle and the angular speed of the rotor. Speeds of the two induction motors are measured with the help of sensors. T2-FLC or PI controllers are used in the speed control loops for the DIMs. The robustness of the proposed method is checked in terms of motor speed and load variations.

III. MODEL OF THE INDUCTION MOTOR

Among the various types of models used to represent the induction machine, there is one that uses each of the stator currents, stator flux, and speed as state variables and voltages \((V_{dsi}, V_{qsi})\) as control variables. This model is presented in \((d, q)\) reference, related to the rotating field. This model is expressed by the system described in (1)-(4):

\[
\begin{align*}
V_{dsi} &= R_s * I_{dsi} + \frac{\partial \Phi_{dqi}}{\partial t} - w_{si} \Phi_{qqi} \\
V_{qsi} &= R_s * I_{qsi} + \frac{\partial \Phi_{qqi}}{\partial t} + w_{si} \Phi_{dqi} \\
V_{dri} &= 0 = R_r * I_{dri} + \frac{\partial \Phi_{dri}}{\partial t} - (w_{si} - p\Omega_i) \Phi_{qri} \\
V_{qri} &= 0 = R_r * I_{qri} + \frac{\partial \Phi_{qri}}{\partial t} + (w_{si} - p\Omega_i) \Phi_{dri}
\end{align*}
\]

The relation of these currents.

\[
I_s = I_{s1} + I_{s2} \quad (5)
\]

\[
\Delta I_s = \frac{I_{s1} - I_{s2}}{2} \quad (6)
\]

IV. CONTROL STRATEGY OF DIMS

Mean control strategy considers the average of the different input variables of both IMs to create a “virtual mean motor”. The measured variables of both motors are the currents \((I_{s1}, I_{s2})\) and the speeds \((\Omega_1, \Omega_2)\). The average variables are obtained using (7) and (8).

\[
I_s = \frac{I_{s1} + I_{s2}}{2} \quad (7)
\]

\[
\Omega = \frac{\Omega_1 + \Omega_2}{2} \quad (8)
\]

Rotor Field Oriented Control (RFOC) is one of the best methods to drive IMs and presents satisfactory performances. It requires the rotor flux \((\Phi_r)\) and electromagnetic torque \(T_{em}\) to be decoupled. The IM modeling is done in the \((d, q)\) reference frame, with the \(d\) axis linked with the rotor flux vector. The rotor flux can be written as:

\[
\Phi_{dri} = \Phi_{dri} \quad (9)
\]
The reference voltages \( V_{dsi}, V_{qsi} \) are derived by substituting (9) and (10) in (1)

\[
\begin{align*}
V_{dsi} &= R_s \cdot I_{dsi} + L_s \frac{dI_{dsi}}{dt} - w^* \left( L_s \cdot I_{qsi} + \frac{L_m}{L_n} \cdot \Phi^*_{ri} \cdot w^* \right) \\
V_{qsi} &= R_s \cdot I_{qsi} + L_s \frac{dI_{qsi}}{dt} - w^* \left( L_s \cdot I_{dsi} + \Phi^*_{ri} \right)
\end{align*}
\]

(11)

The component references of stator current and slip speed \( w^*_{sl} \) can be expressed as:

\[
\begin{align*}
I^*_{dsi} &= \frac{1}{l_m} \cdot \Phi^*_{ri} \\
I^*_{qsi} &= \frac{l_m + \Phi^*_{ri}}{p = \frac{l_m + \Phi^*_{ri}}{C^*_{ei}} \\
w^*_{sl} &= \frac{R_s \cdot I_{gs} \cdot (l_m + \Phi^*_{ri})}{l_m + \Phi^*_{ri}} \cdot I^*_{qsi}
\end{align*}
\]

(12)

(13)

The index (*) represents the command variable. Mean RFOC control offers symmetric behaviors of both motors to obtain stable average performance. On undisturbed functioning, both motors are identical so they have the same behavior. However, when a disturbance affects one motor the second reacts to compensate it, so it is also disturbed. The mean control reacts to offer stable average signals. To generate the reference voltage vectors \( V_{dsi}, V_{qsi} \), PI controllers are introduced as shown in Figure 1.

V. PI CONTROLLERS

The overall system shown in Figure 1 contains two PI controllers. The first is an inner loop for current control, and the second is an outer loop for speed control. The design of the two controllers is detailed in Figures 3 and 4.

\[
G_s(s) = \frac{1}{1 + j\tau_s} = \frac{1}{1 + (j\tau_s) \cdot s} = k \left( \frac{1}{1 + \tau_s^2} \right) \quad (15)
\]

where, \( \tau_s \) and \( k \) are the time constant and the system gain.

The open loop transfer function of the system \( G_{OL}(s) \) is presented as follows:

\[
G_{OL}(s) = G_{C}(s), G_{s}(s) = K_{SP} \left( \frac{1 + T_f \cdot s}{T_f S + k \cdot K_{SP}} \right) \left( \frac{k}{1 + \tau_s S} \right) \quad (16)
\]

\[
\begin{align*}
(1 + T_f, S) &= (1 + T_f, S) \\
G_{CL}(s) &= \frac{G_{OL}(s)}{1 + G_{OL}(s)} = \frac{(k \cdot K_{SP})/(T_f S)}{(T_f S + k \cdot K_{SP})/(T_f S)} \\
&= \frac{1}{(T_f / k \cdot K_{SP}) \cdot S + 1} = \frac{1}{T_0^* \cdot S + 1} \quad (17)
\end{align*}
\]

where \( T_0^* \) is the time constant of the closed loop of the system.

According to (14), (15) and (17) the gains of the controller are calculated as:

\[
K_{Si} = \frac{K_{SP}}{T_i} \quad (18)
\]

\[
K_{SP} = \frac{T_i}{k \cdot T_0^*} \quad (19)
\]

The value of the time constant of the closed loop of the system \( (T_0^*) \), is the same as the time constant of the system \( (T_0) \). In the same way the gains \( (K_{CI}) \) and \( (K_{CP}) \) of the PI controller of the current in Figure 4 are obtained from the transfer function of the system which is defined as:

\[
G_{CLS}(s) = \frac{1}{R_s + \tau_s S} = k_c \left( \frac{1}{1 + \tau_s^2} \right) \quad (20)
\]

\[
\begin{align*}
K_{Ci} &= \frac{K_{SP}}{T_i} \quad (21)
K_{CP} &= \frac{T_i}{k \cdot T_0^*} \quad (22)
\end{align*}
\]

VI. TYPE 2 FUZZY LOGIC CONTROLLER

The fuzzy logic control based on Type 2 Fuzzy Sets (T2-FS) present a suitable solution for the control of non-linear systems [29]. T2-FS were first proposed in [33-35] as an extension to Type 1 Fuzzy Sets (T1-FS), to increase the...
fuzziness of the relations. Several studies have shown the high performance of T2-FLC, which uses the T2-FS interval instead of Type 1 FLC (T1-FLC) in terms of handling the uncertainties [17, 28, 34].

In Figure 5, we can see that the T2-FLC differs from the T1-FLC by the output processing block. In addition to the defuzzifier, it includes a block type reducer which allows transforming T2-FS to T1-FS. The Type 2 Fuzzy Controller used in this work has two inputs: the first is the speed error (\(e_s\)) and the second is the variation of the speed error (\(\Delta e_s\)). The output variable (\(U_f\)) generated from the output processing, corresponds to the component of torque (\(T_c\)).

![Fig. 6. T2-FLC speed controller.](image)

The membership functions used for the inputs and the output are presented in Figures 7 and 8. The T2-FLC in Figure 6 is characterized by IF-THEN fuzzy rules-base, but its antecedents and consequents are now T2-FS [29, 31, 32].

- Rule 1: if \(e_s\) is NL, and \(\Delta e_s\) is NL then \(U_f\) is NL.
- Rule 2: if \(e_s\) is NL, and \(\Delta e_s\) is NM then \(U_f\) is NL.
- Rule 3: if \(e_s\) is NL, and \(\Delta e_s\) is ZR then \(U_f\) is NL.
- Rule 25: if \(e_s\) is PL, and \(\Delta e_s\) is PL then \(U_f\) is PL.

![Fig. 7. Inputs membership functions.](image)

![Fig. 8. Output membership function.](image)

The use of a T2-FLC proves to be more advantageous than the use of a PI/PID controller, thanks to its modifiable control surface which offers better performance, especially when the order of the system is greater than two, while it includes oscillatory modes [30].

VII. SPACE VECTOR PULSE WIDTH MODULATION

The voltage vectors, produced by the 3-phase PWM inverter, divide the space vector plane into six sectors as shown in Figure 9. In every sector, the voltage vector is arbitrary synthesized by the basic space voltage vector of the two sides of one sector and zero vectors. For example, in the first sector, \(V_s\) ref is a synthesized voltage space vector and its equation is given by [7, 32]:

\[
\bar{V}_{s\text{ ref}} = V_0 \ast T_0 + \bar{V}_1 \ast T_1 + \bar{V}_2 \ast T_2 \quad (23)
\]

\[
T_2 = T_0 + T_1 + T_2 \quad (24)
\]

where \(T_0, T_1\), and \(T_2\) are the work times of basic space voltage vectors \(V_0, \bar{V}_1,\) and \(\bar{V}_2\), respectively. The determination of times \(T_i\) and \(T_2\) given by mere projections is given in Figure 10.

![Fig. 9. The diagram of voltage space vectors.](image)

\[
\begin{align*}
V_s\alpha_{\text{ ref}} &= \frac{T_s}{T_2} \times |\bar{V}_1| + x \\
V_s\beta_{\text{ ref}} &= \frac{T_s}{T_2} \times |\bar{V}_2| \times \sin \left(\frac{n}{3}\right) \\
x &= \frac{V_s\beta_{\text{ ref}}}{\tan \left(\frac{n}{3}\right)}
\end{align*}
\]
The switching duration is calculated for every sector. The times of the vector implementation can all be related to the following variables:

\[
\begin{align*}
T_1 &= \frac{T_s}{2u_{DC}}(\sqrt{6}v_s\alpha_{ref} - \sqrt{2}v_s\beta_{ref}) \\
T_2 &= \frac{T_s}{2u_{DC}}(\sqrt{2}v_s\beta_{ref})
\end{align*}
\] 

The rest of the period is applying the null-vector. The implementation of the duration sector boundary vectors can be seen in Table I.

| Sector | 1 | 2 | 3 | 4 | 5 | 6 |
|--------|---|---|---|---|---|---|
| \(T_1\) | \(-Z\) | \(Y\) | \(X\) | \(Z\) | \(-Y\) | \(-X\) |
| \(T_{i+1}\) | \(X\) | \(Z\) | \(-Y\) | \(-X\) | \(Y\) |

The third step is to compute the duty cycles to have the three necessary times:

\[
\begin{align*}
T_{a_{on}} &= \frac{T_s}{2} - T_i - T_{i+1} \\
T_{b_{on}} &= T_{a_{on}} + T_i \\
T_{c_{on}} &= T_{b_{on}} + T_{i+1}
\end{align*}
\] 

The last step is to assign the duty cycle \(T_{x_{on}}\) to the motor phase according to the sector.

The modeling and simulation of the system presented in Figure 1 was carried out in MATLAB/Simulink environment. The parameters of the two 4KW motors used in the simulation are shown in the Appendix. In order to properly test and compare the two speed controllers proposed in terms of performance, firstly both motors are subjected to a trapezoidal speed profile which includes positive and negative values respectively, as shown in Figure 11. Then, each motor undergoes a different load torque, as shown in Figure 12.
The speed response of the two motors with the speed profile introduced is shown in Figures 13 and 14. We can see that the response of both motors is identical, and the amplitude of the transient speed oscillations is lower with T2-FLC which has better rejection of perturbations and responds well to speed reversal as shown in Figures 15 and 16.

### TABLE III. COMPARISON OF CALCULATED PERFORMANCE INDICES

| Controller | MP (rad/s) | SE | IAE | ITAE |
|------------|-----------|----|-----|------|
| PI         | 104.17    | -104.36 | 5.489 | 1.347 | 2.094 |
| T2 FLC     | 100.02    | -100.01 | 0.994 | 0.887 | 1.196 |

For a clear comparison between the conventional PI controller and T2-FLC, several performance measures such as Maximum Peak overshoot (MP %), Integral Squared Error (ISE), Integral Absolute Error (IAE), and Integral of Time Multiplied Absolute Error (ITAE), are computed as shown in Table III. When the operating conditions are not similar for each IM (the introduction of the load torque disturbance profile) the engines react in a complementary way, i.e. their speeds deviate in an opposite way from the reference, in order to keep the average value of the speed close to the command value. For this, the control by T2-FLC showed better results compared to the PI controller. Finally, the simulation results of the electromagnetic torque of the DIMs connected in parallel associated with IFOC using T2-FLC and PI controllers are presented in Figure 19 for first the IM and Figure 20 for the second IM. These results confirm that the T2-FLC controller offers better performance under changing operating conditions.

The mean control strategy used in this paper, allowed the identical control of the two-motor drive. The simulation results are supported by the results of [1]. Also the use of T1-FLC proves its high performance for speed control of induction machines compared to the conventional PI/PID controllers, especially in transient mode, which is confirmed by the results obtained by [18], but the T2-FLC developed in this paper gave better results compared to those achieved by [18], which are confirmed by the performance criteria presented in Table III.
In this paper, a high performance indirect field oriented controlled dual induction motor drive fed by a single inverter using type-2 fuzzy logic control has been proposed. This study is based in general on speed control of two induction motors connected in parallel associated to a single SVPWM inverter with constant switching frequency, which uses IFOC as control technique. A comparison of the performances of the two controllers, PI and T2-FLC has been conducted. The proposed IFOC algorithm has been implemented in Matlab/Simulink. The simulation results have shown that the T2-FLC offers better performances compared to the PI controller in terms of DIM speed reference tracking. Also, the transient and steady state response of the motors speed is improved as compared to the IFOC algorithm has been implemented in Matlab/Simulink.

IX. CONCLUSION

In this paper, a high performance indirect field oriented controlled dual induction motor drive fed by a single inverter using type-2 fuzzy logic control has been proposed. This study is based in general on speed control of two induction motors connected in parallel associated to a single SVPWM inverter with constant switching frequency, which uses IFOC as control technique. A comparison of the performances of the two controllers, PI and T2-FLC has been conducted. The proposed IFOC algorithm has been implemented in Matlab/Simulink. The simulation results have shown that the T2-FLC offers better performances compared to the PI controller in terms of DIM speed reference tracking. Also, the transient and steady state response of the motors speed is improved as compared to the conventional PI controller. The presented results show that control based on T2-fuzzy logic offers a desirable solution for applications with several induction motors.

APPENDIX

INDUCTION MOTOR PARAMETERS

| Designation          | Symbol | Value      |
|----------------------|--------|------------|
| Rated power          | \( P_u \) | 4KW        |
| Rated voltage        | \( V_s \) | 380V       |
| Nominal frequency    | \( f \)  | 50Hz       |
| Rated speed          | \( N \)  | 1440rpm    |
| Number of pole pairs | \( p \)  | 2          |
| Stator resistance    | \( R_s \) | 1.2Ω       |
| Rotor resistance     | \( R_r \) | 1.8Ω       |
| Stator cyclic inductance | \( L_s \) | 0.1554H |
| Mutual cyclic Inductance | \( L_m \) | 0.15H |
| Rotor cyclic inductance | \( L_r \) | 0.1568H |
| Rotor inertia        | \( J \)  | 0.07kgm²   |
| Viscosity coefficient | \( f \)  | 0.001N.m/s |

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