Contribution to the Fuzzy Direct Control of Torque Application Utilising Double Stars Induction Motor.

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Abstract: This paper concerns the study of a control strategy known as fuzzy direct control for the study of the control of torque when using speed loop regulation of double start induction motor. Thus hysteresis comparators used on the classical method of direct control of torque has been replaced with fuzzy blocs. As results we achieved can be summarised as follows:
1-amelioration the responding time of the system
2-Minimization of the torque ripples.
Key words: the double start asynchronous motor, the fuzzy logic, direct control of torque. Regulator PI.

I. INTRODUCTION.

Significant developments have occurred in recent years regarding the material advances in many different fields (magnetic, mechanical, thermal ...), the power electronics (high powers, high frequencies, new topologies ...), machine control (digital technologies, control methods), the sensors and also the engines structures. All these advances have been considered earlier in the electrical machine control[4].

The multi-phase machine is one case increasingly used in dual applications mode, tri mode application for reasons of reliability and power segmentation. We propose to study in this paper about the double star asynchronous machine. whose figure(1) expresses the windings of the double star induction machine and the offset angle between the two stars windings.

- A1,B1,C1: Winding of stator 01.
- A2,B2,C2: Winding of stator 02
- γ: offset angle between Two stators.
- θ: offset angle between the rotative part and the stators 01&02.

The control of the double star asynchronous machine has progressed significantly in recent times, in particularly with the method of torque control and specifically the direct control of torque. This method law controls the direct opening and closing of the inverter switches from the values calculated by using the stator flux and electromagnetic torque references, the Classic DTC uses the errors signs of torque and electromagnetic flux values (regardless of whether they are large or small are very large or very little) to determine the states of the switches, and with the meaning of the terms “high” or “very small” are being vague and imprecise, hence the name of the concept contain a makes reference to the notion of being ‘fuzzy’. It seems natural to think of using other nomenclature so in our paper we have used ‘fuzzy logic’ for this control method.

II. MODELING OF THE DOUBLE STAR INDUCTION MOTOR.

The mathematical model of the machine is can be expressed by the following set of electrical/mechanical equations
The first star:

\[
[v_{abc}, s_1] = [RS_1][abc, s_1] + \frac{d[\varphi_{abc}, s_1]}{dt}
\]  \hspace{1cm} (2.1)

For the rotative part:

\[
[v_{abc}, r] = [Rr][abc, r] + \frac{d[\varphi_{abc}, r]}{dt}
\]  \hspace{1cm} (2.2)

The mechanical equations:

\[
J \frac{d\Omega}{dt} = Tem - Tr - kf \Omega
\]  \hspace{1cm} (2.4)

Where J is the moment inertia of the rotating parts, Kf is the friction coefficient related to the engine bearings, and Tem represents the torque loading[5].

The electrical state variables in "αβ" system are the electrical flux, and the input variable in the system "αβ" expressed by the vector [U] then the state space representation of the machine can be modeled and expressed in the form:

\[
\dot{X} = \frac{dX}{dt} = AX + BU
\]  \hspace{1cm} (2.5)

With ;
X : state variables
\[ X = [\phi_{s\alpha 1}, \phi_{s\beta 1}, \phi_{s\alpha 2}, \phi_{s\beta 2}, \varphi_R, \alpha_R] \]

A: system evolution matrix
\[ A = [A_{11}, A_{12}, A_{13}, A_{14}, A_{15}, A_{16}, A_{21}, A_{22}, A_{23}, A_{24}, A_{25}, A_{26}, A_{31}, A_{32}, A_{33}, A_{34}, A_{35}, A_{36}, A_{41}, A_{42}, A_{43}, A_{44}, A_{45}, A_{46}, A_{51}, A_{52}, A_{53}, A_{54}, A_{55}, A_{56}, A_{61}, A_{62}, A_{63}, A_{64}, A_{65}, A_{66}] \] (2.6)

B: control Vector
\[ B = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0] \] (2.7)

U: input vector, in this case is represented by the tension vector
\[ u = [V_{s\alpha 1}, V_{s\beta 1}, V_{s\alpha 2}, V_{s\beta 2}] \] (2.8)

III. PRINCIPLE OF DIRECTE CONTROL OF TORQUE

Direct control of torque, is an approach that allows control of the direct switch converter using a simple algorithm. The DTC (Direct Torque control) appeared in the 1980 [1], after a variety of algorithms has been proposed based on refinements developed from heuristic switching choices [6].

If we consider the first start and the equations used for vectorial representation of the stator characteristics of the machine which binds to the stator reference.

\[ \begin{align*}
V_{s\alpha 1} &= R_s I_{s\alpha 1} + \frac{d\phi_{s\alpha 1}}{dt} \\
V_r &= 0 = R_r I_r + \frac{d\phi_r}{dt} - j\omega \phi_r
\end{align*} \] (3.1)

From the electrical flux expression the rotor current can be expressed as:
\[ I_r = \frac{1}{\sigma} \left( \frac{\phi_r}{L_r} - \frac{L_m}{L_s L_r} \phi_{s\alpha 1} \right) \] (3.2)

With the dispersion coefficient
\[ \sigma = 1 - \frac{L_m^2}{L_s L_r} \]

The expressions (3.1) become
\[ \begin{align*}
\frac{d\phi_{s\alpha 1}}{dt} &= R_s I_{s\alpha 1} + \frac{d\phi_{s\alpha 1}}{dt} \\
\frac{d\phi_r}{dt} &= \left( \frac{1}{\sigma \tau_r} - j \omega \right) \phi_r - \frac{L_m}{L_s} \frac{1}{\sigma \tau_r} \phi_{s\alpha 1}
\end{align*} \] (3.3)

Relation (3.3) shows that:
It is possible to control the vector \( \phi_{s\alpha 1} \) from the vector \( V_s \) to the voltage drop near \( R_{s\alpha 1} \).

The vector follow the variation of \( \phi_{s\alpha 1} \) with \( \sigma \tau_r \) as a time term constant, the rotor act as a filter (time constant \( \sigma \tau_r \)) between the flux \( \phi_{s\alpha 1} \) and \( \phi_r \).

Moreover \( \phi_r \) reach in the steady state value:
\[ \phi_r = \frac{L_m}{L_s} \frac{\phi_{s\alpha 1}}{1 + j \omega \sigma \tau_r} \] (3.4)

By putting \( \gamma = \left( \frac{\phi_r}{\phi_{s\alpha 1}} \right) \) the representation of torque expression becomes.
\[ \Gamma_{elm} = p \frac{L_m}{L_s L_r} \phi_{s\alpha 1} \phi_r \sin \gamma \] (3.5)

From the expression (3.6) we know that, the torques value is dependents on the amplitude of the two vectors \( \phi_{s\alpha 1} \) and \( \phi_r \) with relative position. If flux control \( \phi_{s\alpha 1} \) can be perfectly managed from the module and the position of tension vector \( V_s \). It is therefore possible to control the amplitude and the relative position of \( \phi_r \) so clearly changes to the torque value and thus torque control will be a consequence of course this is possible only if the control period \( Te \) of the voltage \( V_s \) satisfies the fault condition.

\[ Te \ll \sigma \tau_r \]

One of the most important characteristics of the Direct Control of torque is the nonlinear regulation of the stator flux and electromagnetic torque.

Figure (2.1) shows a block diagram representation of direct fuzzy control of torque.

III.1. SETTING OF THE STATOR FLUX

![Block diagram of the fuzzy direct control of torque](image-url)
Let’s apply at time to an adequate voltage vector \( \mathbf{V}_s \), and we impose along with a pulse \( \Delta \omega_s \) as rotational speed and immediately after \( t_0 \), we can note a modification in the value on the terms of stator and rotor flux:

\[
\varphi_s(t) = \varphi_{s0} e^{j(\omega_s t + \Delta \theta_s)}
\]

\[
\varphi_r = (\varphi_{r0} + \Delta \varphi_r) e^{j(\omega_{sr} t + \Delta \theta_r)}
\]

\[
\Delta \theta_i = (\omega_{si} + \Delta \omega_{si})(t - t_0)
\]

From the flux rotor (3.2.3) expression, we can deduce the value derivative relation of this quantity with respect to time (3.3.4), namely:

\[
\frac{d\varphi_r}{dt} = \frac{d\Delta \varphi_r}{dt} e^{j\omega_s t} + j \frac{d\Delta \theta_r}{dt} \varphi_{r0}
\]

With:

\[
\Delta \theta_i = \Delta \theta_s - \Delta \gamma
\]

So we can improve the rotor flux \( \varphi_r \) vector by continuous rotation with the same pulsation \( \omega_{sr} \), and by maintaining a similar amplitude \( \varphi_{r0} \). Also after \( t_0 \), the torque value can be expressed as:

\[
\Gamma_{em} = P \frac{L_m}{\sigma L_s L_r} \varphi_{r0} \varphi_{r0} \sin(\gamma_0 + \Delta \gamma)
\]

III.3. SELECTION OF THE VOLTAGE VECTOR

The choice of tension vector \( \mathbf{V}_s \) depends on the desired variation of the flux module, but also for the desired change of the rotational speed and therefore for the couple. It generally defines the evolution space \( \varphi_s \) between the fixed reference, and stator reference, by dividing the space into six symmetrical areas (\( N = 6 \)) with respect to the direction of nonzero voltage vectors. The position of the flow vector in these areas is determined from its components \( \varphi_{salpha} \) and \( \varphi_{sbeta} \). When the vector flow is located inside zone \( i \), the two vectors \( \mathbf{V}_i \) and \( \mathbf{V}_{i+3} \) have the bigger flux component. Also their effect on the torque depends on the position of the flow vector in the same area.

Both the flow and the torque control are ensured by selecting one of the four non-zero vectors or one of the two null vectors:

- If \( \mathbf{V}_{i+1} \) is selected, the flux amplitude will increase and the torque will increase.
- If \( \mathbf{V}_{i+1} \) is selected, the flux amplitude will increase and the torque will increase.
- If \( \mathbf{V}_{i+2} \) is selected, the flux amplitude will increase and the torque will decrease.
- If \( \mathbf{V}_{i-2} \) is selected, the flux amplitude will decrease and the torque will decrease.
- If \( \mathbf{V}_0 \) or \( \mathbf{V}_7 \) is selected, the vector flux will maintain its value and the torque will decrease if the speed is positive and will increase if speed is negative.
III.4. DEVELOPMENT OF FUZZY SWITCHING TABLE

Errors of both torque and the flux are directly used to select the inverter voltage switch’s state with no distinction between a very big error or relatively small in the classical direct control of torque, also the switching state selected in case an important error occurs while starting or with different consigns of torque or flux is the same as during the normal operation.

As consequence in a transient regime response of the system is slower, however the voltage vector is selected, and by taking into account the magnitude (amplitude) and signs of the errors of torque and flux and not just their signs, then the responses of the system during starting and when changing the flux control or torque can be greatly improved.

We propose in this paper a study of direct control of torque application on the double star asynchronous machine based on fuzzy logic. The hysteresis controllers and switching table of conventional DTC are replaced by a fuzzy controller. The fuzzy controller has three variable state inputs and a fuzzy control variable as output to produce a constant control of torque and flux. As is shown in Figure (3.4.1) the first fuzzy variable, consisting of three fuzzy sets, is a difference between the amplitude of the flow reference and the estimated flux. The second fuzzy variable slower consisting of five fuzzy sets figure (3.4.2) is the difference between the reference torque and estimated torque. The third fuzzy variable is the angle between the flow stator and the reference axis “angle of the stator flux” as show figure (3.4.3).

The discourse universe of the first fuzzy variable is divided into three fuzzy sets; positive error of the flow (P), flow error close to zero (Z) and the error flow negative (N). The membership functions with a triangular type of fuzzy sets as represented.

To account for the slight variations in torque, the discourse universe of the second fuzzy variable is divided into five fuzzy sets; large positive error (PL), small positive error (PS), error close to zero (Z), small negative error (NS) and large negative error (NL). The distribution of membership functions is shown in Figure (3.4.2).

III.5. SELECTION TABLE FOR THE VOLTAGE VECTORS

Tables 01 & 02 shows the order of voltage vectors used in the fuzzy direct control method of torque according to voltage vector position and the variation of the torque and flux errors.

![Member Function](image)

The universe of discourse of the third fuzzy variable is divided into twelve fuzzy symmetrical sets. The distribution function of these membership functions is shown in Figure (3.4.3).

![Member Function](image)

The output of fuzzy controller is the proper voltage vector. These voltage vectors are discrete values, they are represented by singletons as in Figure (3.4.4).

![Member Function](image)

### Tab. 01.

<table>
<thead>
<tr>
<th>Ø1.5.9</th>
<th>Ø2.6.10</th>
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</tr>
<tr>
<td>Z</td>
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![Member Function](image)
Tab.02.

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IV. FIS ALGORITHEM USED

The fis that we used, is fuzzy inference system is a system that uses fuzzy set theory to map inputs & outputs.

IV.1. FIS INPUTS, OUTPUTS

we have put all our input; flux errors $cf[N Z P]$, torque error $cpl[NS NL ZE PS PL]$, and the location of the tension vector $N[01 02 03 04 05 06 07 08 09 010 011 012]$ then as output variables we have put six membership singleton $S[E1 E2 E3 E4 E5 E6]$. the fis type we used in our paper is Mamdani with if – and – and-then rule structure.
i.e rule Number 01 [if $cf$ is $P$ and $cpl$ is $PL$ and $N$ is $O1$ then $Etat$ is $E1$].

IV.2. FIS RULES

We create the rules by using the list box and check box choices for input and output variables, connections, and weights.

IV.3. CHARACTERISTIC SURFACE

The figure(04) shows the characteristic surface of the fuzzy table used in model of FDCT

V. SIMULATION RESULTS

Figure (5.1) Demonstrates the dynamic performance of the PI controller at starting and in the event of load disturbance. The starting type is characterized by an excess of 0.06% and a response time of 0.66 seconds. at $t = 1.5s$ we apply 10N.m as load on the motor, the classical controller PI rejects the disturbance with a speed drop of 0.015% and a rejection time 0.002s.

The figure (5.2) illustrates motor behavior in the event of load disturbance and also the enlarged view shows the electromagnetic torque ripples encountered while using the fuzzy direct method of torque control, The torque ripple is reduced by 50% compared with the classical method of direct control of torque.

![Fig.4. Fis characteristic surface](image1)

![Fig.5.2. Enlarged view of resultant torque ripple](image2)
Figure (5.3) shows the form of the electromagnetic flux when using the direct method of torque control, also the perfect uncoupling between flux and torque, it also shown the flux reaching the reference value with a ripple rate of 0.41%. In the same figure we can see the evolution of the component flow ($\phi_{s1\beta}$) versus the other component ($\phi_{s1\alpha}$) with a uniform test flux.

VI. CONCLUSION.

First we did developed the theory of the direct fuzzy method of torque utilizing a double star induction motor whose mathematical model was used to construct a simulation model using the (Simulink) as a simulation tool. This allowed us in the second step to make some investigation on the speed control using the PI as a regulator and direct fuzzy control of torque as a control method.

The speed simulation of the double star induction motor using direct fuzzy control of torque showed superior performance of fuzzy direct torque control when compared with the speed conventional direct control of torque. We have managed to demonstrate that with this new type of control there are following performance advantages:

1. Faster response times on the torque;
2. Total elimination of the excess and considerable decrease the starting time;
3. Significant reduction of the load disturbance rejection time with a low speed dropout rate;
4. Significant minimization of the electromagnetic torque ripple.

Finally as shown in Figure (5.2) by simulation we improved the direct fuzzy method of torque control of a double star induction motor with conventional PI speed controller is far more efficient than the direct torque control method, but it requires a high capacity of calculation and an optimal choice of parameters of the memberships functions associated.

VII. REFERENCE