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Robust Speed Control of a Doubly Fed Induction Motor using State-Space Nonlinear Approach

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Abstract

This paper presents a comparison between two controllers (fuzzy logic and variable gain PI) of the one part and the conventional PI on the other hand, used for speed control with indirect rotor flux orientation of doubly fed Induction Motor (DFIM) fed by two PWM inverters with separate DC bus link. By introducing a new approach for decoupling the motor's currents in a rotating (d-q) frame, based on the state space input-output decoupling method, we obtain the same transfer function (1/s) for all four decoupled currents. Thereafter and in order to improve the performances of the machine's control, the VPGI and fuzzy logic controllers with five subsets were used for the regulation speed. The Results obtained in Matlab/Simulink environment show well the effectiveness of the technique employed for the decoupling and the speed regulation of the machine.

Keywords

Doubly fed induction motor (DFIM); Input output decoupling; Field-oriented control; Modelling; Variable gain PI controller; Fuzzy logic controller, Conventional PI controller.

Introduction

The progress accomplished, in the few past years, in the power electronics and digital fields makes the Doubly Fed Induction Machine (DFIM) an industrial standard due to its low cost and high reliability [1, 15]. Doubly Fed induction motor is an electrical three-phase asynchronous machine with wound rotor accessible for control. Since the power handled by the rotor side (slip power) is proportional to the slip, the energy requires a rotor-side power converter which handles only a small fraction of the overall system power [2]. In recent years, there has been a great amount of activity on back stepping control approach in AC drive fields [2].The non linear control approach has better precision and stability. However, its major problem of is its sensitivity to motor parameter variations and load disturbance.

The DFIM control issues are traditionally handled by fixed gain proportional integral (PI) controllers. However, the fixed gain controllers are very sensitive to parameter variations, cannot provide good dynamic performance. So, the controller parameters have to be continually adapted [3]. The variable gain PI and fuzzy logic controller’s gives better results to parameter variations for nonlinear systems. So, the DFIM is an ideal candidate to test the performances of its regulators [5]. Fuzzy control technique does not need accurate system modelling. It employs the strategy adopted by the human operator to control complex processes and gives superior performance. The fuzzy algorithm is based on human intuition and experience, and can be regarded as set of heuristic decision rules [8, 18].

The present work concerns “field-oriented control with variable gain PI and fuzzy logics controllers of doubly fed induction motor with state space decoupling method”.The vector control of the DFIM with two independent converters has been studied recently in several works. The linearization of the nonlinear model of the machine can be done in different manners with various terms of compensation. In this paper a nonlinear state space is proposed to ensure the decoupling of the multi-variables system input-output that constitutes the DFIM.

Dynamic Model of DFIM

The dynamic model of the DFIM in a (d-q) synchronous rotating frame is given by the equations of the voltages:

$$\begin{cases} \overline{V}_s = R_s\overline{I}_s + \dfrac{d\overline{\phi}_s}{dt} + j\omega_s\overline{\phi}_s \\ \overline{V}_r = R_r\overline{I}_r + \dfrac{d\overline{\phi}_r}{dt} + j\omega_r\overline{\phi}_r \end{cases} \quad (1)$$

Expressions of the fluxes are given by:

$$\begin{cases} \overline{\varphi}_s = L_s\overline{I}_s + M_{sr}\overline{I}_r \\ \overline{\varphi}_r = L_r\overline{I}_r + M_{sr}\overline{I}_s \end{cases} \quad (2)$$

From (1) and (2) the all currents state model is written as follows:

$$\begin{cases} \dfrac{d\overline{I}_s}{dt} = -\dfrac{R_s}{\sigma L_s}\overline{I}_s + \dfrac{M_{sr}R_r}{\sigma L_s L_r}\overline{I}_r + \dfrac{1}{\sigma L_s}\overline{V}_s - \dfrac{M_{sr}R_r}{\sigma L_s L_r}\overline{V}_r \\ \dfrac{d\overline{I}r}{dt} = -\dfrac{R_r}{\sigma L_r}\overline{I}_r + \dfrac{M_{sr}R_s}{\sigma L_s L_r}\overline{I}_s + \dfrac{1}{\sigma L_r}\overline{V}_r - \dfrac{M_{sr}R_r}{\sigma L_s L_r}\overline{V}_s \end{cases} \quad (3)$$

The mechanical equation is expressed by (4):

$$\frac{J}{p}\frac{d\omega}{dt} = T_{em} - \frac{f\omega}{p} - T_r \quad (4)$$

with: $\omega = p.\Omega$

And the electromagnetic torque is given by:

$$T_{em} = pM_{sr}I_m\left(\overline{I}_s\overline{I}_r^*\right) \quad (5)$$

So, the equation for the speed variation becomes:

$$\frac{J}{p}\frac{d\omega}{dt} = pM_{sr}I_m\left(\overline{I}_s\overline{I}_r^*\right) - \frac{f\omega}{p} - T \quad (6)$$

Vector Control Strategy of DFIM by Decoupling State Space

a. Rotor Flux Oriented

The principle for this type of control consists in orienting the flux into the machine, to the rotor, to the stator or in the air gap. Conventionally, we work with an orienting on the *d* axis. The in quadrature axis will therefore carry the current that will participate in the creation of the electromagnetic torque in the machine [5], [9].

To realize the control law, the rotor flux orientation is chosen along the d axis (figure.1). Therefore, we obtain:

$$\varphi_{rq} = 0 \;\; ; \;\; \varphi_r = \varphi_{rd} \quad (7)$$

Then it comes:

$$I_{rq} = -\frac{M_{sr}}{L_r} I_{sq} \tag{8}$$

The magnetization of the machine, allows, to impose the rotor flux module, so we distinguish two strategies [5]:

Working with a unitary power factor to stator or to rotor, which implies that one of the two currents I_{sd} or I_{rd} will be null,whether:

$$\varphi_{rd} = M_{sr} I_{sd}$$

Split the magnetizing current equally between the two converters, ie

$$I_{sd} = I_{rd} = \frac{I_d}{2}$$

whether:

$$\varphi_{rd} = \left(L_r + M_{sr}\right)\frac{I_d}{2} \tag{9}$$

The choice of $I_{rd} = 0$, gives the same expression for the flux to the stator and to the air gap. In addition, the expression depends only on M_{sr}, and with a unitary power factor at the rotor.

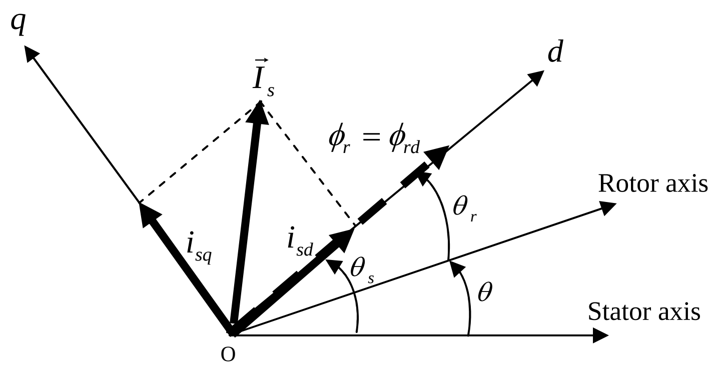

Figure 1. *Rotor Flux Oriented on the d Axis*

b. Currents Decoupling by State Space

b.1 Principle of the method

Consider the following multivariable system:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \text{with} \begin{cases} x \in \Re^n & x = [x_1 \quad x_2 \ldots \quad x_n]^T \\ y \in \Re^m & u = [u_1 \quad u_2 \ldots \quad u_m]^T \\ u \in \Re^m & y = [y_1 \quad y_2 \ldots \quad y_m]^T \end{cases} \tag{10}$$

The objective is to determine a state space of the form:

$$u = -K_d x + Lv, \text{ with } v \in \Re^m \tag{11}$$

v denotes the new input vector, which decouples the system, in a way that the output y_i (i=1 to m) depends only on the input *v*. The output y_i is written:

$$y_i = C_i x$$

where C_i is the ith row of the matrix C. Let us derive y_i a few times in order to bring up the command. We call characteristic index noted δ_i, the number of derivation it takes in order to bring up the command.

We then have successively for each output i:

$$\begin{cases} \dot{y}_i = C_i\dot{x} = C_i(Ax+Bu) = C_iAx \ \text{ with}: C_iBu = 0 \\ \ddot{y}_i = C_iA\dot{x} = C_iA(Ax+Bu) = C_iA^2x \ \text{ with}: C_iABu = 0 \\ \dddot{y}_i^{(3)} = C_iA^2\dot{x} = C_iA^2(Ax+Bu) = C_iA^3x \ \text{ with}: C_iA^2Bu = 0 \\ \vdots \\ y_i^{(\delta_i)} = C_iA^{\delta_i}x + C_iA^{\delta_i-1}Bu \quad \text{with}: (C_iA^{\delta_i}Bu \neq 0) \end{cases} \tag{12}$$

That we can still write in matrix form:

$$\begin{bmatrix} y_1^{(\delta_1)} \\ y_2^{(\delta_2)} \\ \vdots \\ y_2^{(\delta_m)} \end{bmatrix} = \begin{bmatrix} C_1A^{\delta_1} \\ C_2A^{\delta_2} \\ \vdots \\ C_mA^{\delta_m} \end{bmatrix} x + \begin{bmatrix} C_1A^{\delta_1-1}B \\ C_2A^{\delta_2-1}B \\ \vdots \\ C_mA^{\delta_m-1}B \end{bmatrix} u \tag{13}$$

That is:

$$y^* = A^*x + B^*u \tag{14}$$

with $y \in \Re^m$, $A^* \in \Re^{m\times m}$ and $B^* \in \Re^{m\times m}$. We seek a control law $u = -K_dx + L_dv$ such as $y^* = v$. The looped system is written:

$$y^* = A^*x + B^*(-K_dx + L_dv) = (A^* - B^*K_d)x + B^*L_dv \tag{15}$$

To obtain $y^* = v$ we must have $B^*L_d = 1$ and $A^* - B^*K_d = 0$. If the matrix B^* is invertible, the choice of :

$$K_d = (B^*)^{-1}A^* \ \text{and} \ L = (B^*)^{-1} \tag{16}$$

Gives:

$$y^* = v$$

That is:

$$Y_i(s) = \frac{1}{s^{\delta_i+1}}V_i(s) \tag{17}$$

b.2 Application to the DFIM

We search to exploit this method for decoupling the currents of the machine projected on a (d-q) rotating frame [5, 10, 16]. Starting from the expression (3) and choosing a state vector equal to the output vector, formed of four currents of the machine. The input vector is formed of supply voltages. Then we obtain the following expression:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{18}$$

with: $x = \begin{bmatrix} I_{sd} & I_{sq} & I_{rd} & I_{rq} \end{bmatrix}^T$ the state vector (for all currants) and $v = \begin{bmatrix} V_{sd} & V_{sq} & V_{rd} & V_{rq} \end{bmatrix}^T$ the input vector voltages.

$$A = \begin{bmatrix} -a_2 & a_1\omega + \omega_s & a_3 & a_5\omega \\ -a\,\omega - \omega_s & -a_1 & -a_5\omega & a_3 \\ a_4 & -a_6\omega & -a_2 & -\dfrac{\omega}{\sigma} + \omega_s \\ a_6\omega & a_4 & \dfrac{\omega}{\sigma} - \omega_s & -a_2 \end{bmatrix} \tag{19}$$

$$B = \begin{bmatrix} b_1 & 0 & -b_3 & 0 \\ 0 & b_1 & 0 & -b_3 \\ -b_3 & 0 & b_2 & 0 \\ 0 & -b_3 & 0 & b_2 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{20}$$

where:

$$a = \frac{1-\sigma}{\sigma}; \quad a_1 = \frac{R_s}{\sigma L_s}; \quad a_2 = \frac{R_r}{\sigma L_r}; \quad a_3 = \frac{R_r M_{sr}}{\sigma L_s L_r}; \quad a_4 = \frac{R_s M_{sr}}{\sigma L_s L_r}; \quad a_5 = \frac{M_{sr}}{\sigma L_s};$$

$$a_6 = \frac{M_{sr}}{\sigma L_r}; \; b_1 = \frac{1}{\sigma L_s}; \; b_2 = \frac{1}{\sigma L_r}; \; b_3 = \frac{M_{sr}}{\sigma L_s L_r}; \; \sigma = 1 - \frac{M_{sr}^2}{\sigma L_s L_r}$$

The choice of $x = y$ makes the system completely controllable and observable. In applying the decoupling method on this system, it follows that:

$$\forall i;\ \delta_i = 0 \quad \text{and} \quad \begin{cases} L_d = B^{-1} \\ K_d = B^{-1}A \end{cases} \tag{21}$$

$y^* = v$, therefore:

$$\frac{Y_i(s)}{V_i(s)} = \frac{1}{s} \tag{22}$$

The four currents are decoupled and thus governed by the same transfer function in open loop $G(s) = 1/s$.

c. Design the Control Loops

c.1 Currents control

The currents are decoupled, and then we can consider a state space correction with the method of placement of poles. The principal schematic diagram of this correction is given by the figure 2.

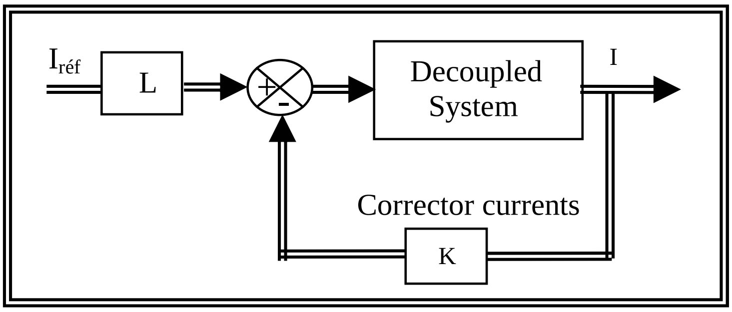

Figure 2. *Current Regulation by State Space*

To ensure the same response for the current loop, the next choice can be adopted.

$$L = K = \begin{bmatrix} k & 0 & 0 & 0 \\ 0 & k & 0 & 0 \\ 0 & 0 & k & 0 \\ 0 & 0 & 0 & k \end{bmatrix} \tag{23}$$

So the transfer function of each current closed loop will be of the form:

$$H(s) = \frac{k}{s+k} \tag{24}$$

c.2 Speed Control

The mechanical equation is given by:

$$J\frac{d\Omega}{dt} = T_{em} - f\Omega - T_r \tag{25}$$

The orientation of the rotor flux on the d axis, and the hypothesis to working with $I_{rd} = 0$, confer on the electromagnetic torque the following expression:

$$T_{em} = -pM_{sr}I_{rq}I_{sd} = -p\,\varphi_{rd}I_{rq} \tag{26}$$

As we proceed to the magnetization of the machine before applying a speed reference, φ_{rd} can be replaced by its reference φ_{rdref} in the relation (26), therefore:

$$T_{em} = -p\,\varphi_{rdref}I_{rq} = K_{em}I_{rq} \tag{27}$$

and

$$J\frac{d\Omega}{dt} = K_{em}I_{rq} - f\Omega - T_r \tag{28}$$

Such as K_{em} is the constant torque.

Thus, the transfer function of the speed will be expressed by:

$$\Omega(s) = \frac{K_{em}}{f + Js} I_{rq}(s) - \frac{1}{f + Js} T_r(s) \tag{29}$$

The magnitude $T_r(s)$ plays the role of a disturbance input for speed, the principal input being $I_{rq}(s)$. The block diagram of the regulation will be in conformity with that of figure 3.

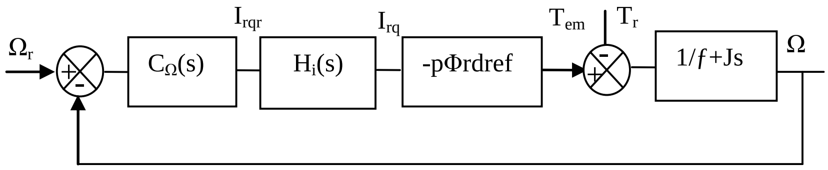

Figure 3. *Speed Control Chain*

VPGI and Fuzzy Logic Controllers in Speed Control of DFIM

a. VPGI Controller

a.1 VPGI Controller Structure

A variable gain PI (VPGI) controller is a generalization of classical PI controller where the proportional and integrator gains vary along a tuning curve as given by figure 4. Each gain of the proposed controller has four tuning parameters [4]:

- Gain initial value or start up setting which permits overshoot elimination.
- Gain final value or steady state mode setting which permits rapid load disturbance rejection.
- Gain transient mode function which is a polynomial curve that joints the gain initial value to the gain final value.
- Saturation time which is the time at which the gain reach its final value.
-

The degree n of the gain transient mode polynomial function is defined as the degree of the variable gain PI controller.

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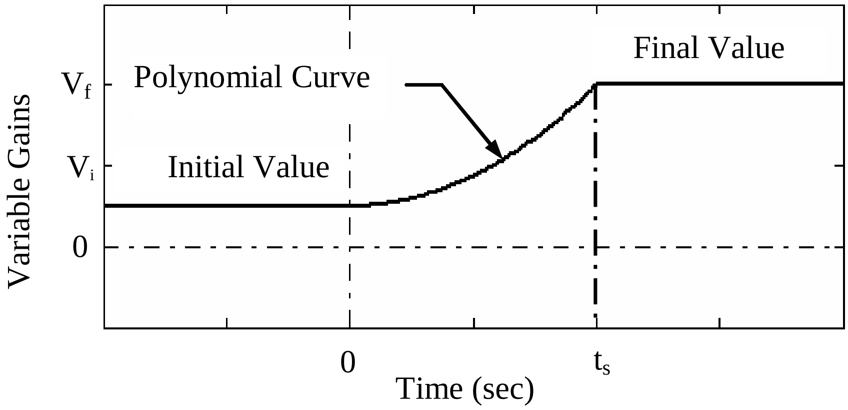

Figure 4. *Variable PI Gains Turning Curve*

It e(t) is the signal input to the VPGI controller the output is given by :

$$y(t) = K_p e(t) + \int_0^t K_i e(\tau) d\tau \tag{30}$$

with:

$$K_p = \begin{cases} (K_{pf} - K_{pi})\left(\frac{t}{t_s}\right)^n + K_{pi} & \text{if} \quad t < t_s \\ K_{pf} & \text{if} \quad t \geq t_s \end{cases} \tag{31}$$

$$K_i = \begin{cases} K_{if}\left(\frac{t}{t_s}\right)^n & \text{if} \quad t < t_s \\ K_{if} & \text{if} \quad t \geq t_s \end{cases} \tag{32}$$

where K_{pi} and K_{pf} are the initial and final value of the proportional gain K_p, and K_{if} is the final value of the integrator gain K_i. The initial value of K_i is taken to be zero. It is noted that a classic PI controller is a VPGI controller of degree zero.

The VPGI unit step response is given by:

$$y(t) = \begin{cases} K_{pi} + \left(K_{pf} - K_{pi} + \frac{K_{if}}{n+1} t\right)\left(\frac{t}{t_s}\right)^n & \text{if} \quad t < t_s \\ K_{pf} + K_{if}\left(t - \frac{n}{n+1} t_s\right) & \text{if} \quad t \geq t_s \end{cases} \tag{33}$$

Figure 5 give the unit step response of a VPGI controller of different values of the degree n.

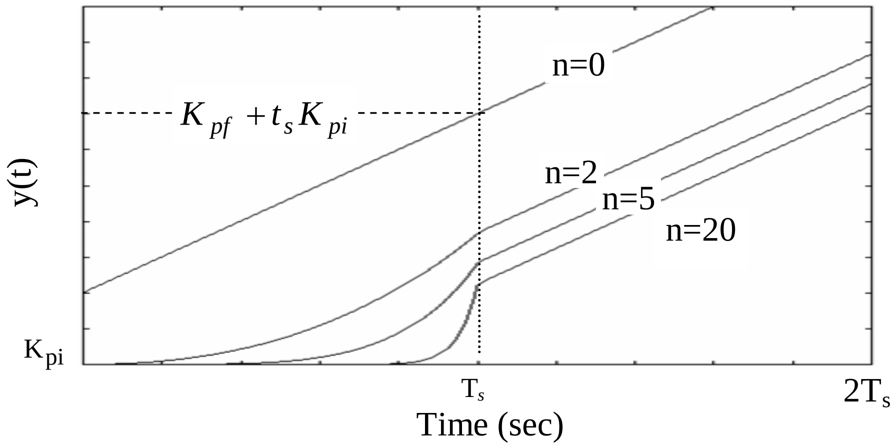

Figure 5. *VGPI Step Response for Different Values of the Degree n*

If $t \langle t_s$ (transient region) the classical PI unit step response is a linear curve beginning at K_{pf} and finishing at $K_{pf} + t_s K_{pi}$, whereas the VPGI unit step response $(n \neq 0)$ varies along a polynomial curve of degree $n+1$ beginning at K_{pi} and finishing at $K_{pf} + t_s K_{if} / (n+1)$.

If $t \geq t_s$ (permanent region), the unit step responses of a PI and VPGI controller are both linear with slope K_{if}.

From these results, one can say that a VPGI controller has the same properties than a classical PI controller in the permanent region with damped step response in the transient.

A VPGI controller could then be used to replace PI controller when we need to solve the load disturbance rejection and overshoot problems simultaneously.

a.2 Setting method of the VPGI controller

Unlike the classical PI controller, tuning of the VPGI controller does not need compromising. Speed overshoot caused by high integrator gains could be eliminated by increasing either the saturation time or the degree of the controller. One can choose the final value of the integrator gain needed for the application and then tune the other controller parameters so as to eliminate speed overshoot.

Here is a proposed method of tuning a VPGI controller.

1. Choose a first degree VPGI controller with a high value of K_{if} (rapid load disturbance rejection).
2. Choose an initial value of the saturation time t_s.

3. Determine K_{pi} and K_{pf} for speed overshoot elimination by using the following steps:
   - Consider K_p to be constant and simulate the controlled system for a small initial value of K_p.
   - Increase K_p gradually and simulate the controlled system again until speed overshoot gets to its optimum. Choose K_{pi} to be the value of K_p that gives optimal overshoot.
   - Simulate the controlled system for an initial value of K_{pf} equal to the chosen value of K_{pi}.
   - Increase gradually the value of K_{pf} and simulate the controlled system again until speed overshoot is totally eliminated or gets to its optimal value. If overshoot is totally eliminated y then K_{pf} is obtained and the controller is tuned.
4. If overshoot is not eliminated, then the value of the saturation time t_s is not sufficiency high, increase it gradually without exceeding a limiting value and repeat step 3 until overshoot is totally eliminated.
5. If at the limiting value of t_s overshoot is still not eliminated, then the degree of the controller is not high enough. Increase it and repeat the controller tuning again.

Using this tuning method with $K_{if} = 14$, the tuned VPGI controlled is given by:

$$K_p = \begin{cases} 1.5\ t + 0.4 & \text{if} \quad t < 1 \\ 1.9 & \text{if} \quad t \geq 1 \end{cases} \qquad K_i = \begin{cases} 14\,t & \text{if} \quad t < 1 \\ 14 & \text{if} \quad t \geq 1 \end{cases} \tag{34}$$

b. Fuzzy Logic Controller

The structure of a complete fuzzy control system is composed from the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification. Figure 6 shows the structure of a fuzzy controller.

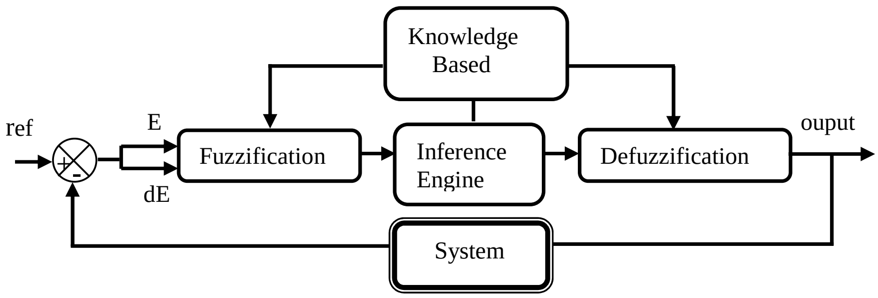

Figure 6. *The Structure of a Fuzzy Logic Controller*

The fuzzification module converts the crisp values of the control inputs into fuzzy values. A fuzzy variable has values, which are defined by linguistic variables (fuzzy sets or subsets) such as low, medium, high, slow where each is defined by gradually varying membership function. In fuzzy set terminology, all the possible values that a variable can assume are named universe of discourse, and fuzzy sets (characterized by membership function) cover whole universe of discourse. The shape fuzzy sets can be triangular, trapezoidal, etc [6, 11, 12].

A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of a designer and researcher. The data base and the rules form the knowledge base which is used to obtain the inference relation R. The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristic; it contains a collection of fuzzy conditional statements expressed as a set of IF-THEN rules, such as:

$$\begin{aligned} R^{(i)}: \text{IF} \;\; x_1 \;\; \text{is} \;\; F_1 \;\; \text{and} \;\; x_2 \;\; \text{is} \;\; F_2 \ldots \text{and} \;\; x_n \;\; \text{is} \;\; F_n \\ \text{THEN} \;\; Y \;\; \text{is} \;\; G^{(i)},\; i = 1, \ldots, M \end{aligned} \tag{35}$$

were: $(x_1, x_2, ..., x_n)$ is the input variables vector, *Y* is the control variable, *M* is the number of rules, *n* is the number fuzzy variables $(F_1, F_2, ...F_n)$ are the fuzzy sets.

For given rule base of a control system, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (the output fuzzy variable) [7, 8, 17].

The composition operation is the method by which such a control output can be generated using the rule base. Several composition methods, such as max-min or sup-min and max-dot have been proposed in the literature.

The mathematical procedure of converting fuzzy values into crisp values is known as ‘defuzzification’. A number of defuzzification methods have been suggested. The choice of defuzzification methods usually depends on the application and the available processing power. This operation can be performed by several methods of which center of gravity (or centroid) and height methods are commons [7, 13, 19].

b.1 Fuzzy-PI controller

The fuzzy PI controller is basically an input/ output static non-linear mapping, the

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controller action can be written in the form [13]:

$$u = K_e.E + K_{de}.dE \quad (36)$$

The Fuzzy-PI output is:

$$y = K_p.u + K_i.u \quad (37)$$

where: K_e is the gain of the speed error, K_{de} is the gain of the change of speed error, K_p is the proportional factor, K_i is the integral factor, E is the speed error, dE is the change of the speed error, u is the fuzzy output. The Fuzzy-PI controller in vector control of Dfim is used as presented in Figure 7.

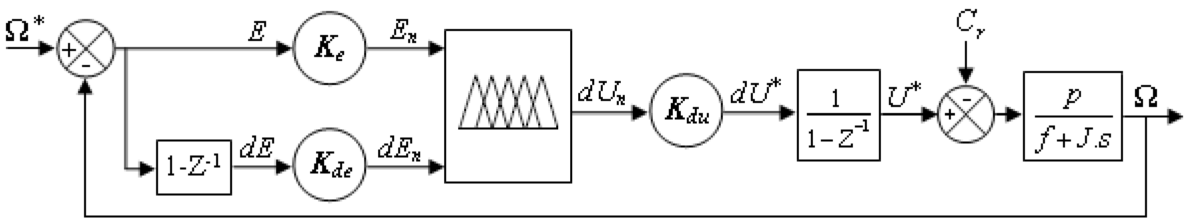

Figure 7. *The Structure of a Fuzzy –PI Controller in a Vector Control of Dfim*

b.2 Knowledge Base Proposed

Figure 8 and 9 shows respectively the triangle-shaped membership functions of error E and Change of error dE .The fuzzy sets are desingnated by the labels: Negative big (NB), Negative medium (NM), Negative small (NS), Zero (Z), Positive small (PS), Positive medium (PM), Positive big (PB)

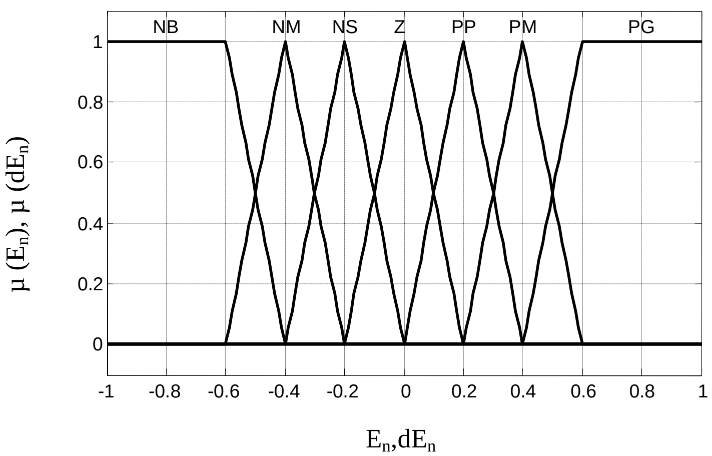

Figure 8. *Membership Functions Distribution for Input Variables*

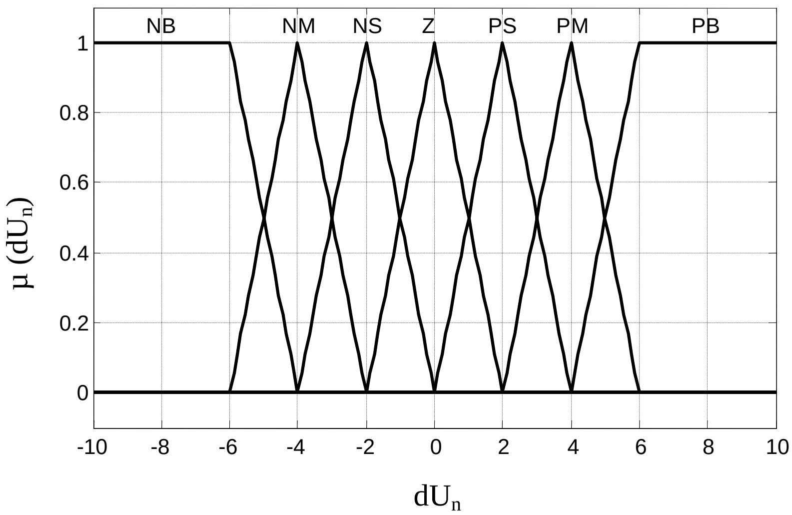

Figure 9. *Membership Functions Distribution for Output Variables*

In this paper, the triangular membership functions, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are most frequently used in many literatures [14, 20]. The inference strategy used in this system is the Mamdani algorithm.

Table1. Linguistic Rule Table

dE \ *E*	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NG	NG	NG	NG	NM	NP	EZ
NM	NG	NG	NG	NM	NP	EZ	PP
NS	NG	NG	NM	NP	EZ	PP	PM
Z	NG	NM	NP	EZ	PP	PM	PG
PS	NM	NP	EZ	PP	PM	PG	PG
PM	NP	EZ	PP	PM	PG	PG	PG
PB	EZ	PP	PM	PG	PG	PG	PG

All the membership functions (MFs) are asymmetrical because near the origin (steady state), the signals require more precision. Seven MFs are chosen for E, dE signals and for ouput. All the MFs are symmetrical for positive and negative values of the variables. Thus, maximum 7×7 = 49 rules can be formed as tabulated in Table 1 [7, 14].

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Simulation Results

The DFIM used in this work is a 1.5 Kw-50Hz, whose parameters are reported in appendix. The global schema of the State-Space Nonlinear control of a doubly fed Induction motor Using variable gain PI and fuzzy logic controllers as presented in figure 10.

A. Fuzzy Speed Reversal of Rated Value

In order to make a comparison between the behavior of the conventional PI controller and that of the fuzzy logic and VPGI controllers, studied under different operating conditions, a direct start of the motor under no load is realized with a set point of 157 rad / s followed by an inversion of the rotation direction at time t = 3s, the external perturbations are introduced by a sudden application of a 10N.m nominal charge at t = 1 s and removed at t = 2s.

The results given by figures (11 – 12) show excellent performance in regulation for the variable-gain and the fuzzy logic controllers with a very good monitoring of the reference speed.

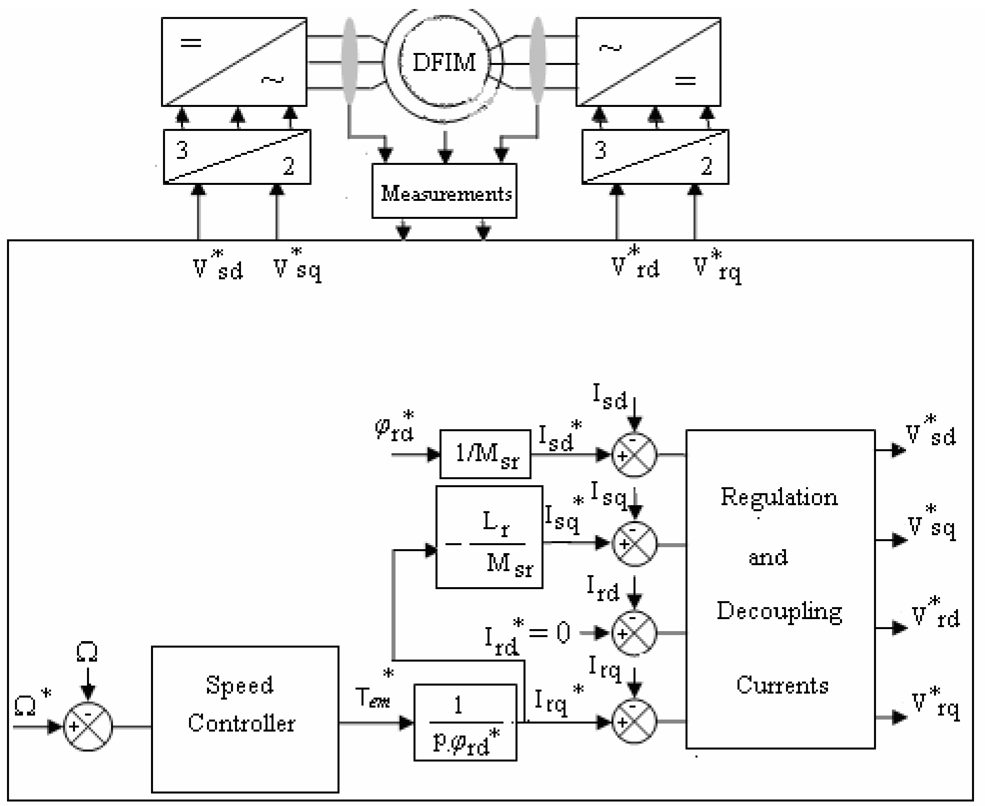

Figure 10. *Block Diagram of Speed Control of Dfim using a State Space Nonlinear Approach*

This will result in a much lower tracking error than that obtained using the conventional PI structure. Note also that the orientation of the rotor flux is fully realized;

furthermore, the developed electromagnetic torque reproduces its reference satisfactorily.

It can also be noted that the low sensitivity and disturbance rejection are excellent for the two structures; both Fuzzy logic and VPGI controllers also provide better performance in terms of speed and time disturbance rejection.

B. Robust Control for Different Values of Rotor Resistance

In order to verifier the robustness of VPGI and Fuzzy-PI regulators under motor parameters variations, we have simulated the system with different values of the parameter considered and compared to nominal value (real value), one case is considered:

The rotor resistance variations (increase at 50% of nominal value rotor resistance). Figures (13-14) shows the responses speed, torque and rotor flux in the test of robustness for different values of rotor resistance. The results indicate that the VPGI and Fuzzy-PI regulators are insensitive to the resistance change, which results in the no influence on the torque and rotor flux.

For the robustness of control, an increase of the resistance does not have any effect on the performances of the proposed controllers.

Conclusions

In this paper, we presented the principle of speed control of a double-fed induction motor using a variable gain PI and a fuzzy logic speed controller.

Taking advantage of the accessibility of the current measurement of the motor, a new approach was discussed to allow the decoupling of its currents in a rotating (dq) frame.

This principle is based on an input-output decoupling by state space feedback that will lead to obtain very simple currents transfer functions, and therefore, a simplified calculation of the correction.

Subsequently, we demonstrated the improvement made by the variable gain PI and fuzzy logic speed controllers on the performance of the DFIM compared to the conventional

PI controller. Simulation results demonstrate that VPGI and fuzzy-PI controllers outperforms the classical PI controller in speed control.

The simulation results showed a remarkable behaviour of the fuzzy-PI and variable gain PI controllers during regulation and tracking, with a significantly better disturbance rejection than the classic PI controller and a good performance towards robustness.

Appendix

DFIM Doubly Fed Induction Motor.
VPGI Variable Gain PI Controller.
s, r Stator and Rotor indices,
d,q Indices of the orthogonal components direct and quadrature.
$\overline{X}$ Complex variable such as: $X = Re\left[\overline{X}\right] + j\,Im\left[\overline{X}\right]$.
R_s , R_r Stator and Rotor resistances.
L_s , L_r Stator and Rotor inductances.
T_s ,T_r Stator and rotor time constant.
σ Leakage factor $(\sigma = 1 - M_{sr}^2 / L_s\, L_r\,)$.
M_{sr} Mutual inductance.
θ The electrical rotor position.
θ_s ,θ_r Statoric flux position, Rotoric flux position.
ω The mechanical rotor frequency.
Ω Mechanical speed.
ω_s The electrical stator frequency.
P Number of pole pairs.
T_{em} The electromagnetic torque.
T_r The load torque.
J The moment of inertia.
f The friction coefficient.

Rated data of the simulated doubly fed induction motor:

Rated values: 1.5KW; 220/380V-50Hz;

Rated parameters:

$R_s = 1.75\,\Omega$

$R_r = 1.68\,\Omega$

$L_s = 0.295\,H$

$L_r = 0.104\,H$

$M = 0.165\,H$

$P = 2.0$

Mechanical constants

$J = 0.01 Kg.m^2$

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