VARIABLE GAIN PI SPEED CONTROL OF A DIRECT TORQUE NEURO FUZZY CONTROLLED INDUCTION MOTOR DRIVE

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ABSTRACT

In this study, an original variable gain PI controller (VGPI) is designed to replace the classical PI controller in the speed control of a direct torque neuro fuzzy controlled (DTNFC) induction motor drive. Simulation tests have been performed to study the dynamical performances of the DTNFC motor drive for both the classical PI and the VGPI speed controllers.

I. INTRODUCTION

THE apparition of the field oriented control (FOC) made induction machine drives a major candidate in high performance motion control applications. However, the complexity of field oriented algorithms led to the development in recent years of many studies to find out different solutions for the induction motor control having the features of precise and quick torque response. The direct torque control technique (DTC) proposed by I. Takahashi [1] and M. Depenbrock [2] in the mid eighties has been recognised to be a viable solution to achieve these requirements [1]–[2], [6]–[7], [9]–[13].

In the DTC scheme [1] (Fig. 1), the electromagnetic torque and flux signals are delivered to two hysteresis comparators. The corresponding output variables and the stator flux position sector are used to select the appropriate voltage vector from a switching table which generates pulses to control the power switches in the inverter. This scheme presents many disadvantages (variable switching frequency - violence of polarity consistency rules - current and torque distortion caused by sector changes - start and low-speed operation problems - high sampling frequency needed for digital implementation of hysteresis comparators) [6], [9], [10]–[11], [13].

To eliminate the above difficulties, a Direct Torque Neuro Fuzzy Control scheme (DTNFC) has been proposed [13]. This scheme uses a controller based on an adaptive NF inference system (ANFIS) [4], [5], [8] together with a space voltage modulator to replace both the hysteresis comparators and the switching table.

The schemes cited above use a PI controller for speed control. The use of PI controllers to command a high performance direct torque controlled induction motor drive is often characterised by an overshoot during start up. This is mainly caused by the fact that the high value of the PI gains needed for rapid load disturbance rejection generates a positive high torque error.

At start up, the PI controller drives the torque error value to the zero border. When this border is crossed, the PI controller takes control of the motor speed and drives it to the reference value.

To overcome this problem, we propose the use of a variable gains PI controller (VGPI) [14]. A VGPI controller is a generalisation of a classical PI controller where the proportional and integrator gains vary along a tuning curve.

In this paper, a variable gain PI controller is used to replace the classical PI controller in the speed control of a direct torque neuro fuzzy controlled induction machine drive.

II. DIRECT TORQUE NEURO FUZZY CONTROLLER

Fuzzy logic and artificial neural networks can be combined to design a direct torque neuro fuzzy controller. Human expert knowledge can be used to build an initial artificial neural network structure whose parameters could be obtained using o*nline* or *offline* learning processes.

The adaptive NF inference system (ANFIS) [4], [5], [8] is one of the proposed methods to combine fuzzy logic and artificial neural networks. Fig. 1 shows the adaptive NF inference system structure proposed in [4], [5], [8]. It is composed of five functional blocks (rule base, database, a decision making unit, a fuzzyfication interface and a defuzzyfication interface) which are generated using five network layers :

Layer 1: Composed of a number of computing nodes whose activation functions are fuzzy logic membership functions.
Layer 2: Chooses the minimum value of the inputs.
Layer 3: Normalises each input with respect to the others.
Layer 4: Includes linear functions of the input signals.
Layer 5: Sums all the incoming signals.

The ANFIS structure can be tuned automatically by a least-square estimation (for output membership functions)

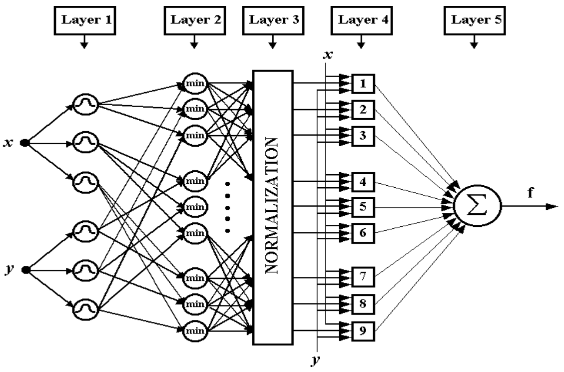

Fig. 1. Two - input NF controller

and a back propagation algorithm (for output and input membership functions).

The block scheme of the proposed self-tuned direct torque neuro-fuzzy controller (DTNFC) for a voltage source PWM inverter fed induction motor is presented in Fig.2. The internal structure of the NFC is shown in Fig.3.

In the first layer of the NF structure, sampled flux error ε_ψ and torque error ε_T , multiplied by respective weights w_ψ and w_T, are each mapped through three fuzzy logic membership functions. These functions are chosen to be triangular shaped as shown in Fig. 4.

The second layer calculates the minimum of the input signals. The output values are normalised in the third layer, to satisfy the following relation:

$$\sigma_i = \frac{w_i}{\sum_k w_k} \tag{1}$$

where w_i and σ_i are the i^{th} output signal of the second and third layer respectively. σ_i is considered to be the weight of both the increment angle and the amplitude of the desired reference voltage i^{th} component, so that :

$$V_{Si} = \sigma_i \cdot U_{dc} \tag{2}$$

$$\varphi_{V_{Si}} = \gamma_s + \Delta\gamma_i \tag{3}$$

Where V_{Si} is the i^{th} component amplitude of the desired reference voltage, $\varphi_{V_{Si}}$ is the i^{th} component angle of the desired reference voltage, γ_s is the actual angle of the stator flux vector and $\Delta\gamma_i$ is the increment angle (from Table 1).

TABLE I
REFERENCE VOLTAGE INCREMENT ANGLE TABLE

ε_ψ	P			Z			N		
ε_T	P	Z	N	P	Z	N	P	Z	N
$\Delta\gamma_i$	$+\frac{\pi}{4}$	0	$-\frac{\pi}{4}$	$+\frac{\pi}{2}$	$+\frac{\pi}{2}$	$-\frac{\pi}{2}$	$+\frac{3\pi}{4}$	$+\pi$	$-\frac{3\pi}{4}$

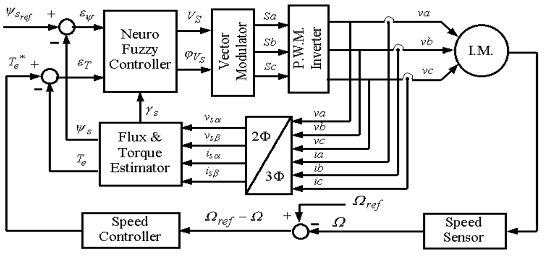

Fig. 2. Direct Torque Neuro Fuzzy Controller scheme

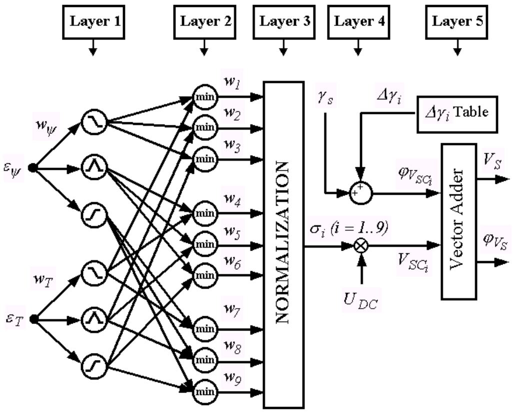

Fig. 3. Proposed Neuro Fuzzy Controller Structure

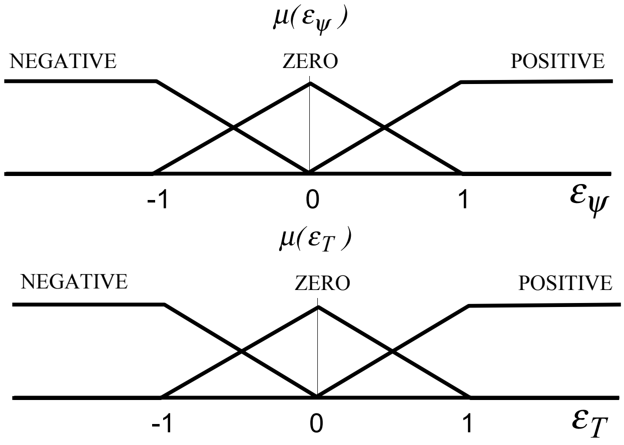

Fig. 4. Triangular membership function sets

The components of the desired reference voltage vector are added to each other and the result, is delivered to the space vector modulator which calculates the switching states Sa, Sb and Sc according to the well known algorithm [3], [6], [11].

III. VGPI CONTROLLER STRUCTURE

The use of PI controllers to command a high performance direct torque controlled induction motor drive is often characterised by an overshoot during start up. This is mainly caused by the fact that the high value of the PI gains needed for rapid load disturbance rejection generates a positive high torque error which will cause the speed to increase until it reaches the value corresponding to the reference stator flux. The DTC takes control of the speed until the torque error value crosses the zero border due to the action of the PI controller. The PI controller takes then control of the motor speed and decreases it to the reference value. The overshoot value and the time needed for the PI controller to take control of the motor speed is function of the PI gains, the stator flux reference and the speed reference.

To overcome this problem, we propose the use of variable gains PI controllers. A variable gain PI (VGPI) controller is a generalisation of a classical PI controller where the proportional and integrator gains vary along a tuning curve. Each gain of the proposed controller has four tuning parameters:

- 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 joins the initial value to the final value.
- Saturation time which is the time at which the gain reaches its final value.

The degree n of the gain transient mode polynomial function is defined as the degree of the variable gain PI controller. The gains of the VGPI controller are given by :

$$K_p = \begin{cases} \left(K_{pf} - K_{pi}\right)\left(\dfrac{t}{T_s}\right)^n + K_{pi} & if \quad t < T_s \\ K_{pf} & if \quad t \geq T_s \end{cases} \tag{4}$$

$$K_i = \begin{cases} K_{if}\left(\dfrac{t}{T_s}\right)^n & if \quad t < T_s \\ K_{if} & if \quad t \geq T_s \end{cases} \tag{5}$$

Where K_{pi} and K_{pf} are the proportional gain initial and final value, and K_{if} is the integrator gain final value.

IV. VGPI CONTROLLER IN SPEED CONTROL OF THE DTNFC MOTOR DRIVE

In order to show the improvement of the VGPI controller over the PI controller for speed control of a DTNFC motor drive, some simulation tests have been performed using the DTNFC scheme given by Fig. 2 where the speed controller is first replaced by a classical PI controller then by a VGPI controller. The parameters of the motor used in the simulation are given in Table 2.

The VGPI controller is tuned using the method given in [14]. The classical PI gains are taken to be the terminal values of the VGPI controller in order to have the same performance than the VGPI in the permanent region. The machine is started up with a load of 10 Nm.

TABLE II
INDUCTION MACHINE PARAMETERS

2 pairs of poles, 50Hz	$R_s = 4.85\,\Omega$	$L_s = 274\,mH$
220/380 V, 6.4/3.7 A	$R_r = 3.805\,\Omega$	$L_r = 274\,mH$
2 hp , 1420 rpm	$L_m = 258\,mH$	
$J = 0.031\ kgm^2$	$f = 0.00114\ Nms$	

With an integrator gain $K_i=100$ (rapid load disturbance rejection), the tuning method resulted in the following VGPI gain values :

$$K_p = \begin{cases} 0.5 + 9.5\,t^3 & if \quad t < 1 \\ 10 & if \quad t \geq 1 \end{cases} \qquad K_i = \begin{cases} 100\,t^3 & if \quad t < 1 \\ 100 & if \quad t \geq 1 \end{cases} \tag{6}$$

The classical PI controller gains are given by $K_p=10$ and $K_i=100$..

Tuning the DTNFC system comes to tuning the weights ω_ψ and ω_T so as to obtain a fixed inverter switching frequency with minimum values of the flux and torque errors. Since the proposed DTNFC is a high order non linear system, a simple way of tuning it is the successive trials method. It has been shown in [13] that for nonzero synchronous angular speed, the changes of the flux influences the output torque, while the changes in the torque does not influence the flux. That is why the proposed method searches first the flux error minimum that gives a fixed inverter frequency, before searching the torque error minimum. The tuning method proposed searches by successive trials method in a grid of values of ω_ψ the value that gives the minimum stator flux error with fixed stator frequency, then by using this value, searches in a grid of values of ω_T the value that gives the minimum torque error with fixed stator frequency. Using this method the tuning values of the DTNFC are given by $\omega_\psi = 2$ and $\omega_T = 0.04$.

Fig.5 shows the settling performance comparison between a PI and a VGPI speed controller for the DTNFC motor drive where the two controllers are tuned for rapid load disturbance rejection. Initially the machine is started up with a load of 10Nm. At 2s, a 5Nm load disturbance is applied during a period of 1s. The sampling time used is 100µs. The space vector modulator sampling frequency used is 1 kHz, this means that the space vector modulator generates the desired reference vector after each ten sampling times.

For the PI controller, the torque error takes a value of 199 Nm at start up and due to the action of the speed controller increases gradually to a value of 527 Nm at t=0.33s before it begins to decrease. This causes the DTNFC to take control of the motor speed which increases gradually to reach, at t=0.7s, a value of 417 rpm (108.5% overshoot). At this time, the torque error crosses

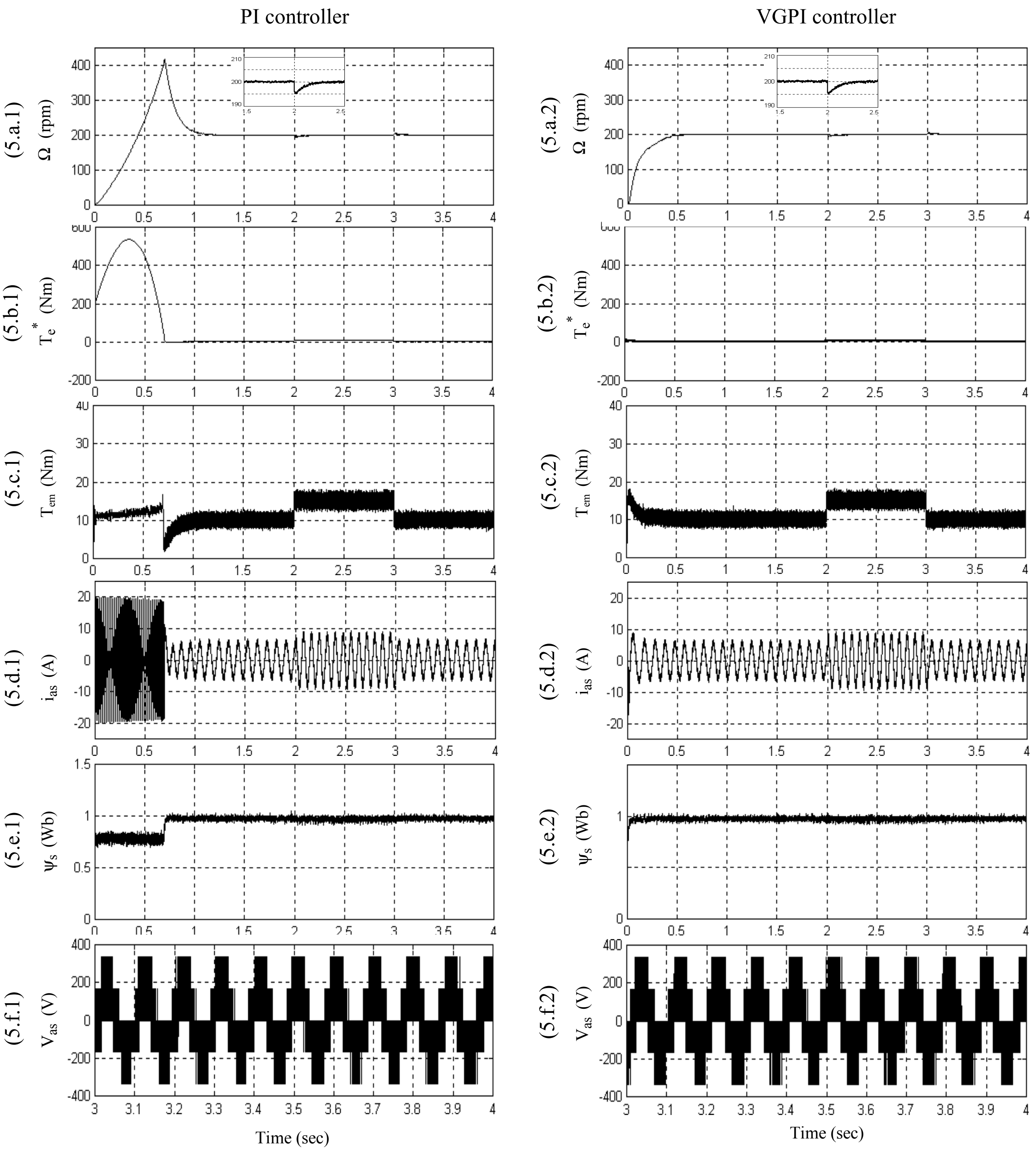

Fig. 5. Settling performance comparison between a PI and a VGPI speed controller for the DTNFC motor drive.

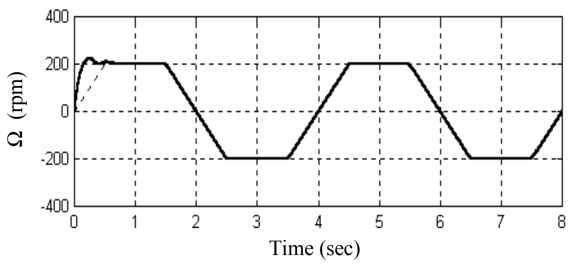

Fig. 6. VGPI speed tracking performance

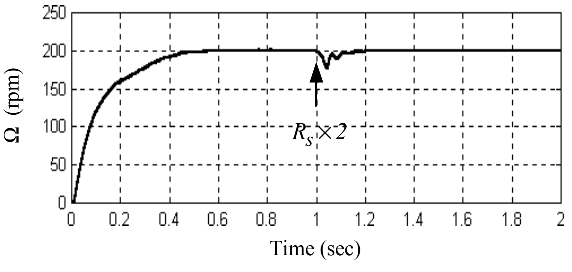

Fig. 7. VGPI controller robustness to stator resistance variation.

the zero border making the PI controller able to decrease the motor speed to the reference value which is reached at 1.4s. The 5Nm load disturbance is rejected in less than 0.3s with a maximum speed dip of 4.91rpm (2.45%).

On the other hand it is observed that until t=0.7s, time at which the torque error crosses the zero border, the stator flux amplitude is maintained constant at 0.8 Wb and the stator current amplitude is maintained nearly constant at about 20A. After this time, the stator flux amplitude reaches its reference value and the stator current amplitude reaches its nominal value.

For the VGPI controller, the speed of the motor reaches the reference value at 0.6s without overshoot. The 5Nm load disturbance is rejected in less than 0.3s with a maximum speed dip of 4.97rpm (2.49%). At start up the torque error takes a value of 0.47 Nm and reaches the zero border at t=0.015s. The VGPI controller takes then control of the speed after only 0.015s. The stator flux amplitude reaches the reference value immediately after start up and the stator current takes an amplitude of 17A before reaching its nominal value after only 0.2s.

It is also observed that unlike the DTC scheme where the inverter switching frequency is variable, the stator voltage obtained using a DTNFC scheme for both controllers shows that the inverter switching frequency seems to be fixed.

Fig.6 shows the speed tracking performance of the system under no load. The slope of the trapezoidal command speed is 400 rpm/s. Apart from start up the command speed is fairly well tracked.

Fig.7 shows the robustness of the proposed VGPI controller to rotor resistance variation. The motor is started up with a load of 10 Nm. The rotor resistance is supposed to double at 1sec. The VGPI controller rejects the stator resistance disturbance in less than 0.2s with a maximum speed dip of 27 rpm (13.5%).

V. CONCLUSION

In this paper a variable gain PI controller has been used to replace the PI controller in the speed control of a direct torque neuro fuzzy controlled induction motor drive. Simulation tests on a DTNFC motor drive using both controllers gave the following results :

- For rapid load disturbance rejection, the PI controller generates high speed overshoot at start up (108.3%). The VGPI however obtains the same load disturbance rejection performance without overshoot.
- The PI speed controller generates a high constant stator current during start up whereas the VGPI controller lead the stator current immediately to its nominal value.
- The DTNFC scheme generates a fixed inverter switching frequency.

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In conclusion it seems that the VGPI controller outperforms the classical PI controller in speed control of high performance DTNFC motor drives.

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