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A Variable Gain PI Controller Used for Speed Control of a Direct Torque Neuro Fuzzy Controlled Induction Machine Drive

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Abstract

This paper presents an original variable gain PI (VGPI) controller for speed control of a direct torque neuro fuzzy controlled (DTNFC) induction motor drive.

First, a VGPI speed controller is designed to replace the classical PI controller in a conventional direct torque controlled induction motor drive. Its simulated performances are then compared to those of a classical PI controller.

Then, a direct torque neuro fuzzy control (DTNFC) for a voltage source PWM inverter fed induction motor drive is presented. This control scheme uses the stator flux amplitude and the electromagnetic torque errors through an adaptive NF inference system (ANFIS) to generate a voltage space vector (reference voltage) which is used by a space vector modulator to generate the inverter switching states. In this paper a modified ANFIS structure is proposed. This structure generates the desired reference voltage by acting on both the amplitude and the angle of its components.

Simulation of the DTNFC induction motor drive using VGPI for speed control shows promising results. The motor reaches the reference speed rapidly and without overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt with.

Key Words: *Induction motor, direct torque control (DTC), direct torque neuro fuzzy control (DTNFC), adaptive NF inference system (ANFIS), variable gain PI controller (VGPI), space vector modulation (SVM).*

1. 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]–[3], [7]–[9], [11]–[17].

In the DTC scheme [1] (Figure 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) [8], [11], [13]–[15], [17].

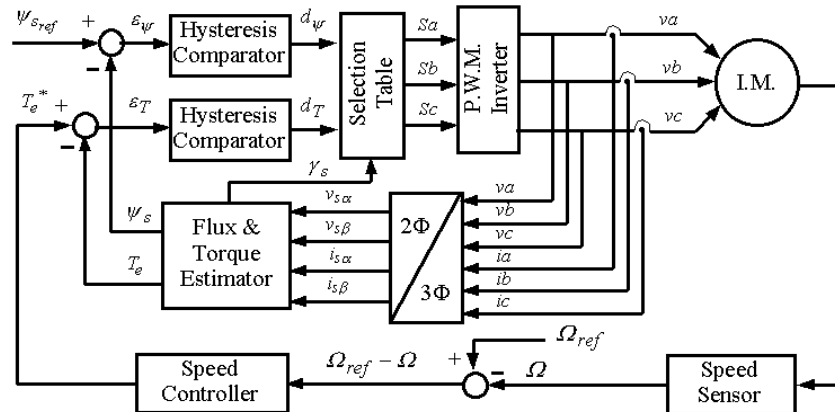


Figure 1. Conventional Direct Torque Control Scheme.

To eliminate the above difficulties, a Direct Torque Neuro Fuzzy Control scheme (DTNFC) has been proposed [17]. This scheme uses a controller based on an adaptive NF inference system (ANFIS) [5], [6], [10] together with a space voltage modulator to replace both the hysteresis comparators and the switching table.

The ANFIS controller combines fuzzy logic and artificial neural networks to evaluate the reference voltage required to drive the flux and torque to the demanded values within a fixed time period. This evaluation is performed using the electromagnetic torque and stator flux magnitude errors together with the stator flux angle. This calculated voltage is then synthesised using Space Vector Modulation (SVM).

To generate the desired reference voltage using this scheme, the ANFIS controller acts only on the amplitude of the reference voltage components whereas the angle is chosen from a table. A proposed modification of this scheme is to design an ANFIS controller in order to act on both the amplitude and the angle of the reference voltage components.

All 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. This will let the DTC scheme take control of the motor speed driving it to a value corresponding to the reference stator flux.

At start up, the PI controller acts only on the error torque value by driving it 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) [18]. 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 modified direct torque neuro fuzzy controlled induction machine drive where the ANFIS of the DTNFC acts on both the amplitude and the angle of space vector components.

2. 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 as given by Figure 2. Each gain of the proposed controller has four tuning parameters:

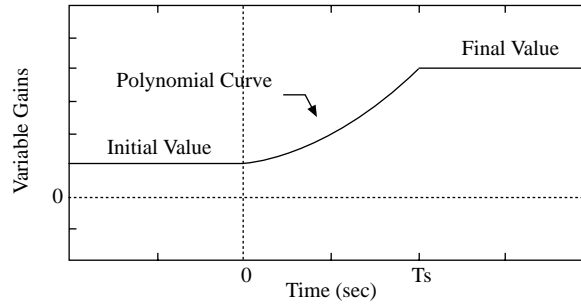


Figure 2. Variable PI Gains Tuning Curve.

- 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 gain initial value to the gain 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.

If $e(t)$ is the signal input to the VPGI controller then the output is given by :

$$y(t) = K_p e(t) + \int_0^t K_i e(\tau) d\tau \quad (1)$$

with

$$K_p = \begin{cases} (K_{pf} - K_{pi}) \left(\frac{t}{T_s}\right)^n + K_{pi} & \text{if } t < T_s \\ K_{pf} & \text{if } t \geq T_s \end{cases} \quad (2)$$

$$K_i = \begin{cases} K_{if} \left(\frac{t}{T_s}\right)^n & \text{if } t < T_s \\ K_{if} & \text{if } t \geq T_s \end{cases} \quad (3)$$

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 classical PI controller is a VGPI controller with degree zero.

The VGPI unit step response is given by:

$$y(t) = \begin{cases} K_{pi} + \left(K_{pf} - K_{pi} + \frac{K_{if}}{n+1}t\right) \left(\frac{t}{T_s}\right)^n & \text{if } t < T_s \\ K_{pf} + K_{if} \left(t - \frac{n}{n+1}T_s\right) & \text{if } t \geq T_s \end{cases} \quad (4)$$

Figure3 gives the unit step response of a VGPI controller for different values of the degree n .

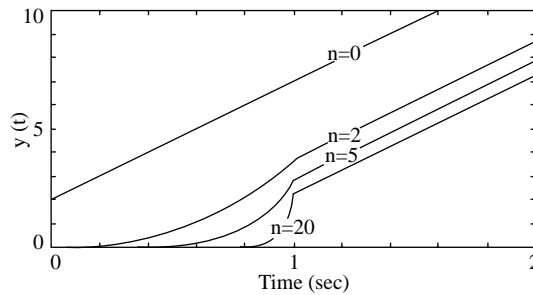


Figure 3. VGPI step response for different values of the degree n .

If $t < T_s$ (transient region), the classical PI unit step response is a linear curve beginning at K_{pf} and finishing at $K_{pf} + T_s K_{if}$, whereas the VGPI 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 a VGPI controller are both linear with slope K_{if} .

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

A VGPI controller could then be used to replace a PI controller when we need to solve the overshoot problem in a direct torque control scheme.

3. VGPI Controller to Improve the Speed Control of a DTC Motor drive

In order to show the effect of varying the gains of a PI controller on DTC motor drive speed control performances, some simulation tests have been performed using the DTC induction motor drive structure illustrated by Figure 1 where the controller block is first replaced by a classical PI controller and then by a VGPI controller.

The parameters of the motor used in the simulation are given in Table 1. The reference speed used is $\Omega_{ref} = 1000$ rpm.

Table 1. 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	

Tuning of the VGPI controller is based on the elimination of the speed overshoot caused by high integrator gains. This could be done 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 VGPI controller.

1. Choose a first degree VGPI controller with a high value of K_{if} (rapid load disturbance rejection).
 - (a) Choose an initial value of the saturation time T_s .
2. 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. Simulation shows that as K_p increases, speed overshoot decreases until an optimal value is obtained, then it begins to increase again. 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. Simulation shows that as K_{pf} increases, speed overshoot decreases until a total elimination or gets to an optimal value. If overshoot is totally eliminated then K_{pf} is obtained and the controller is tuned.
3. If overshoot is not totally eliminated, then the value of the saturation time T_s is not sufficiently high, increase it gradually without exceeding a limiting value and repeat step 3 until overshoot is totally eliminated.
4. 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 $K_{if} = 100$, the tuned VGPI controller is given by:

$$K_p = \begin{cases} 0.5 + 9.5t^3 & \text{if } t < 1 \\ 10 & \text{if } t \geq 1 \end{cases} \quad \& \quad K_i = \begin{cases} 100t^3 & \text{if } t < 1 \\ 100 & \text{if } \geq 1 \end{cases} \quad (5)$$

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

Figure 4. shows a comparison between the performances of the classical PI and the proposed VGPI controller. Initially the machine is started up with a load of 10Nm.

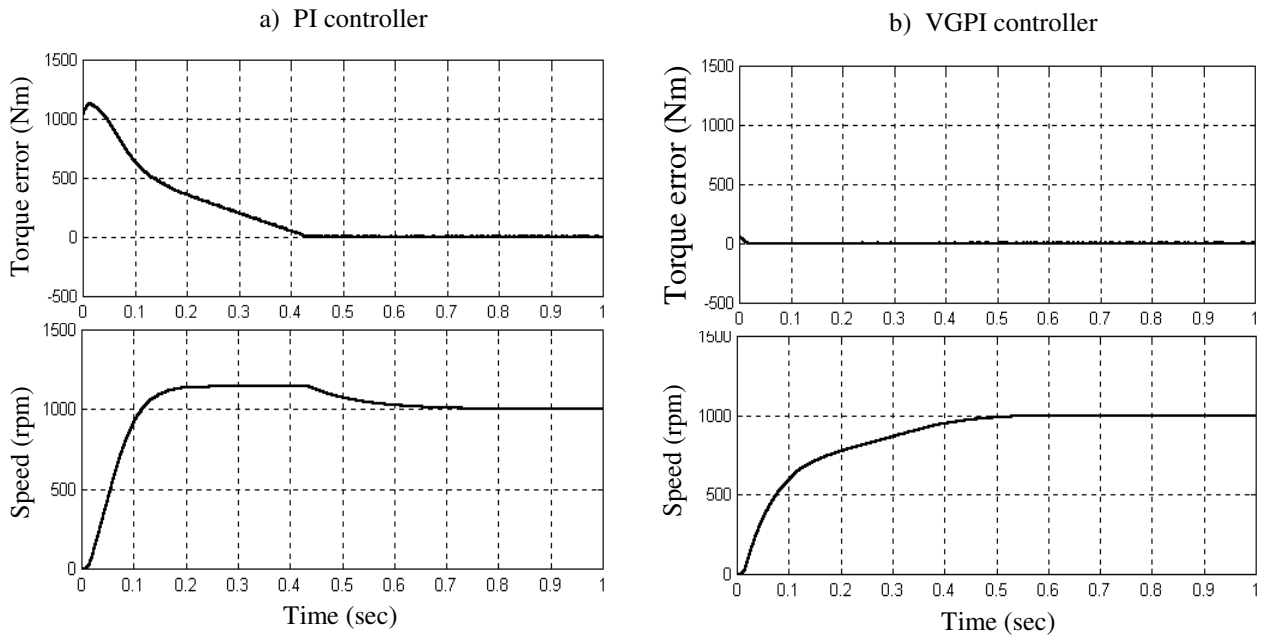


Figure 4. Speed settling performances comparison between a PI controller and a VGPI controller for a Direct Torque Controlled machine drive.

For the classical PI controller, the torque error takes a value of 1047 Nm at start up and due to the action of the speed controller increases gradually to a maximum value of 1133 Nm at $t=0.0138$ s before it begins to decrease. This causes the DTC to take control of the motor speed which increases gradually to reach, at $t=0.28$ s, a value of 1145 rpm (11.45% overshoot). This speed which corresponds to a stator flux reference value of 1.4 Wb is then maintained nearly constant until $t=0.44$ s, time at which the torque error crosses the zero border. The PI controller takes then control of the motor speed and decreases it to the reference value $\Omega_{ref} = 1000$ rpm which is reached at nearly $t=1$ s.

For the VGPI controller, the speed of the motor reaches Ω_{ref} at 0.6s without overshoot. At start up the torque error takes a value of 52.4 Nm and reaches the zero border at $t=0.021$ s. The VGPI controller takes then control of the speed after only 0.021s.

Unlike for a PI controller, the stator flux reference value seems to have no apparent effect on the induction motor speed if a VGPI speed controller is used.

We can remark however that the computational burden introduced due to the replacement of the PI controller by the VGPI controller increases only by about 50% (1.6 μ s for a PI controller to 2.42 μ s for a VGPI controller when programming under Windows XP environment using Turbo Pascal and a 3 GHz Pentium IV computer). This will slightly increase the overall calculation time without exceeding the control cycle which is chosen to be 100 μ s.

4. Direct-Torque-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 *online* or *offline* learning processes.

The adaptive NF inference system (ANFIS) [5], [6], [10] is one of the proposed methods to combine fuzzy logic and artificial neural networks. Figure 5 shows the adaptive NF inference system structure proposed in [5], [6], [10]. 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:

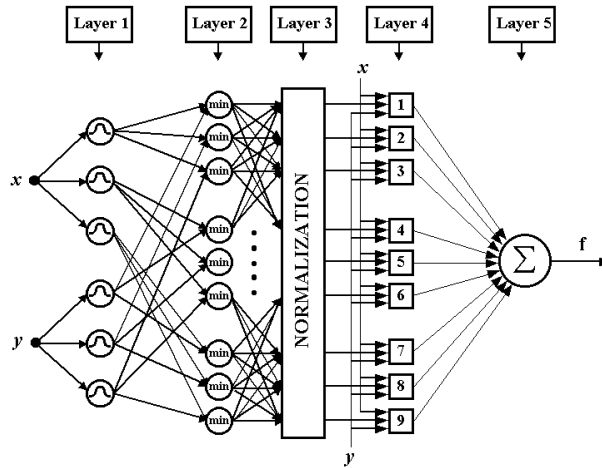


Figure 5. Two - input NF controller structure.

Layer 1: This layer is composed of a number of computing nodes whose activation functions are fuzzy logic membership functions (usually, triangular or bell-shaped functions).

Layer 2: This layer chooses the minimum value of the inputs.

Layer 3: This layer normalises each input with respect to the others (The i^{th} node output is the i^{th} input divided the sum of all the other inputs).

Layer 4: This layer's i^{th} node output is a linear function of the third layer's i^{th} node output and the ANFIS input signals.

Layer 5: This layer sums all the incoming signals.

The ANFIS structure can be tuned automatically by a least-square estimation (for output membership functions) 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 Figure 6. The internal structure of the NFC is shown in Figure7.

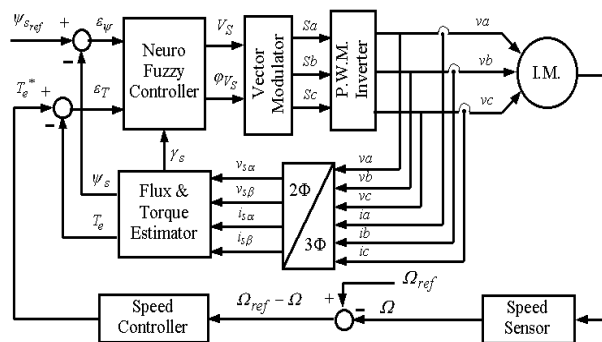


Figure 6. Direct Torque Neuro Fuzzy Controller scheme.

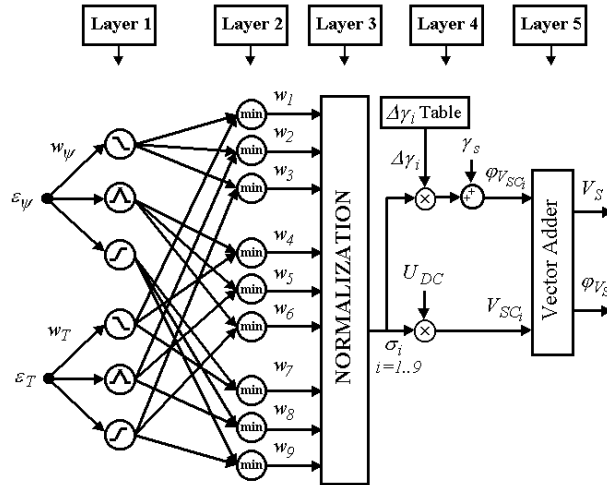


Figure 7. Proposed Neuro Fuzzy Controller Structure.

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 Figure 7.

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

$$\sigma_i = \frac{w_i}{\sum_k w_k} \quad (6)$$

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. In the DTNFC scheme given by [17] the increment angle of each desired voltage component is chosen from a table independently of the weight σ_i . In this paper a modified increment table is constructed and each value of this table is multiplied by the weight σ_i in order to obtain the increment angle of the desired reference voltage i^{th} component, so that:

$$V_{Si} = \sigma_i \cdot U_{dc} \quad (7)$$

$$\varphi_{V_{Si}} = \gamma_s + \sigma_i \Delta\gamma_i \quad (8)$$

where :

V_{Si} : i^{th} component amplitude of the desired reference voltage.

$\varphi_{V_{Si}}$: i^{th} component angle of the desired reference voltage.;

γ_s : actual angle of the stator flux vector;

$\Delta\gamma_i$: increment angle (from Table 2).

Table 2. Reference Voltage Increment Angle Table

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

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 S_a , S_b and S_c according to the well known algorithm [4], [8], [15].

5. VGPI Controller in Speed Control of the Modified DTNFC Motor Drive

It has been shown in section 3 that the VGPI controller improves the settling performances of a conventional DTC motor drive. In this section a simulation study of the performances of the modified direct torque neuro fuzzy controlled induction motor drive is performed by using a VGPI to replace the PI speed controller.

The Direct Torque Neuro Fuzzy Control scheme is used in order to deal with the problems observed when using the DTC scheme and which are caused by the use of the hysteresis comparators (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). This is done by replacing the hysteresis comparators and the selection table by a direct torque neuro fuzzy controller and a space vector modulator [17]. In our paper we propose to modify the ANFIS controller in order to act on both the amplitude and the angle of the reference voltage components.

The VGPI speed controller is used to replace the PI speed controller in order to improve the dynamic performances of the modified direct torque neuro fuzzy controlled induction motor drive.

We should remark however that the computational burden introduced due to the replacement of the DTC scheme by the DTNFC scheme increases by about 700% ($4 \mu s$ for the DTC scheme to $31.6 \mu s$ for a DTNFC scheme when programming under Windows XP environment using Turbo Pascal and a 3 GHz Pentium IV computer). Although this increase seems huge, the overall calculation time will still stay below 50% of the control cycle which is chosen to be $100 \mu s$.

Tuning the modified DTNFC system comes to tuning the weights ω_ψ and ω_T so as to minimise the flux and torque errors. These weights are the scaling factors of the flux and torque errors and their tuning corresponds to the three ANFIS structure membership functions width.

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 [17] that for nonzero synchronous angular speed, the changes of the flux influence 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, 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, then by using this value, searches in a grid of values of ω_T the value that gives the minimum torque error. Using this method the tuning values of the DTNFC are given by $\omega_\psi = 100$ and $\omega_T = 10$.

Figure 9 shows the settling performance and the disturbance rejection capability of the modified DTNFC motor drive with the VGPI speed controller given by equation 1. Initially the machine is started up with a load of 10Nm. At 1s, a 5Nm load disturbance is applied during a period of 0.5s. The sampling time used is $100 \mu s$. The space vector modulator sampling frequency used is 1 kHz, that is the space vector modulator generates the desired reference vector after each ten sampling times.

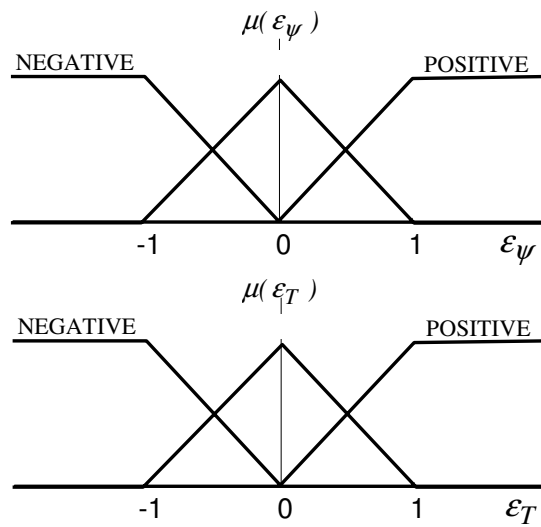


Figure 8. Triangular membership function sets.

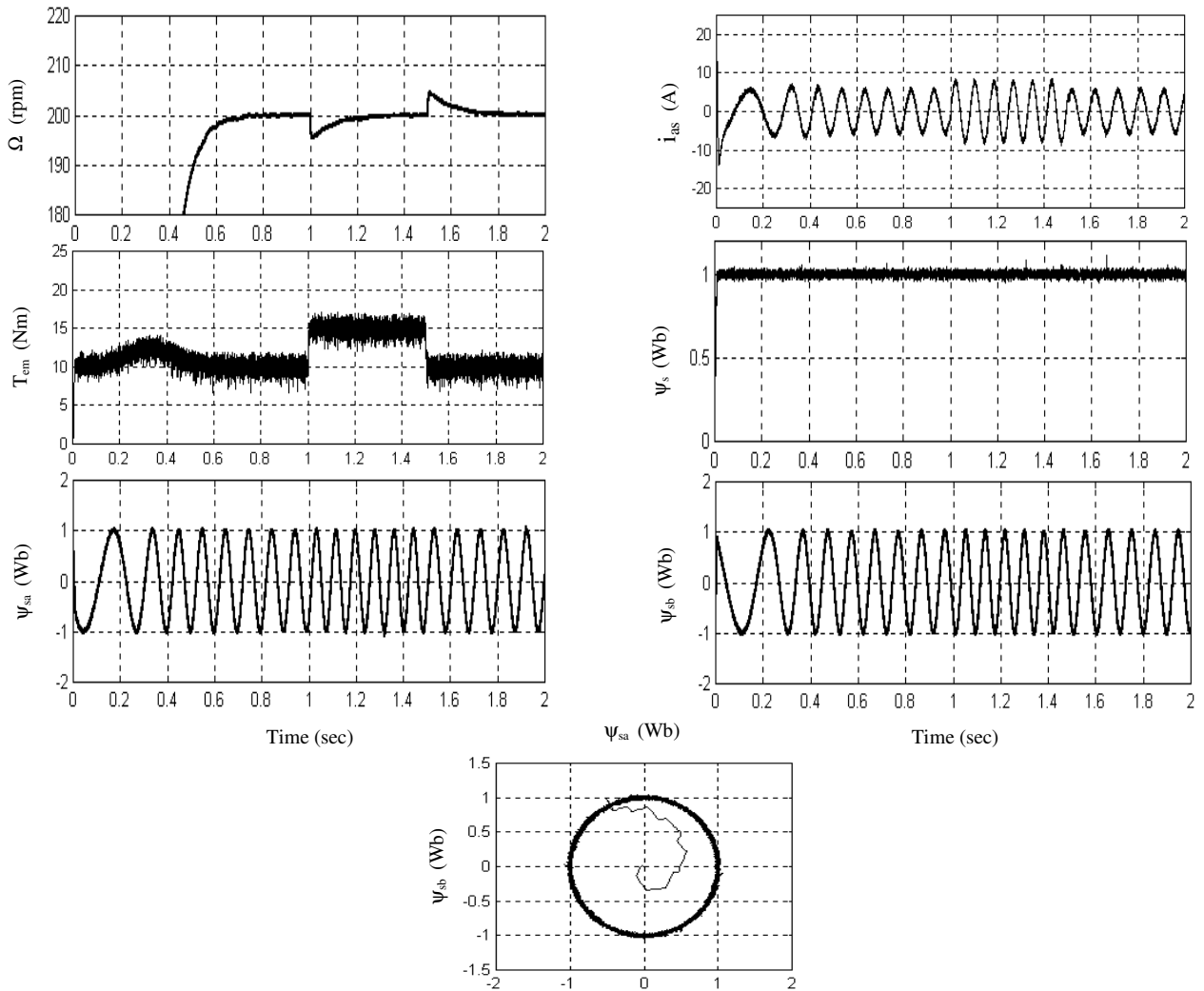


Figure 9. Settling performance of the proposed DTNFC motor drive using a VGPI speed controller.

The speed of the motor reaches the 200 rpm reference speed at 0.75s without overshoot. The controller rejects the 5Nm load disturbance in less than 0.25s with a maximum speed dip of 4.5 rpm (2.25%).

Table 3 shows the settling performance comparison between the proposed DTNFC motor drive using a VGPI speed controller and the conventional DTC drive using a PI speed controller, this comparison is based on some measurable performance criteria such as overshoot, settling time, maximum start up current and the computational effort.

Table 3. Comparison between the DTNFC motor drive with a VGPI speed controller and the conventional DTC motor drive with a PI speed controller ($\Omega_{ref} = 200$ rpm)

	DTNFC with VGPI	DTC with PI
Overshoot	0 %	35 %
Settling time	0.75 s	0.7 s
Start up current	13 A	25 A
Computation effort	36 μ s	7.5 μ s

This table shows that DTNFC scheme with VGPI speed controller gives better performances than the conventional DTC scheme with PI controller. We can remark however that the high value of the DTNFC scheme computational effort does not affect the control cycle since it stays below 50% of its value.

Figure 10 shows the speed tracking performance of the system under no load. The slope of the trapezoidal command speed is 500 rpm/s. The motor speed crosses Ω_{ref} by making a 2.5% overshoot before it returns to it after 0.25 seconds.

Simulations given by Figure11 and 12 examine the robustness of the proposed VGPI controller to machine parameters variation.

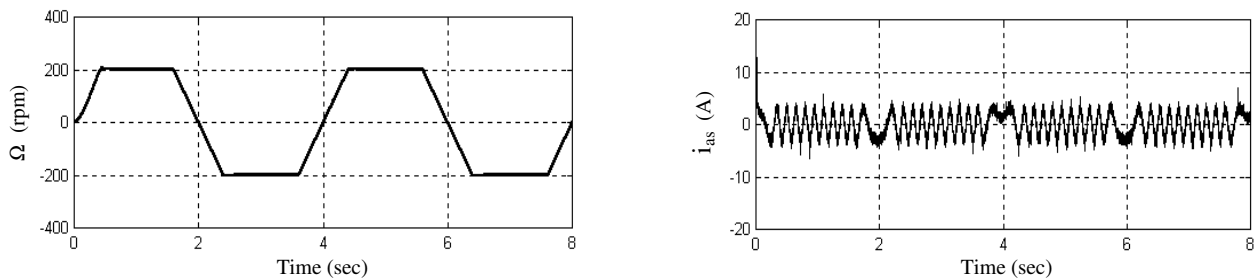


Figure 10. Speed tracking performance of the proposed DTNFC motor drive using a VGPI speed controller.

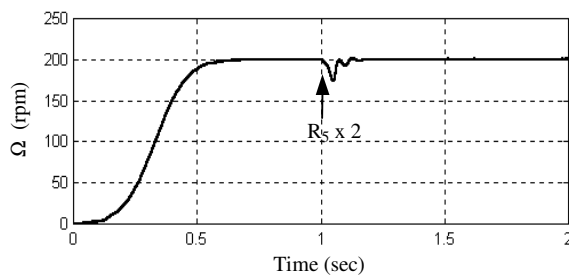


Figure 11. Variation of the stator's resistance.

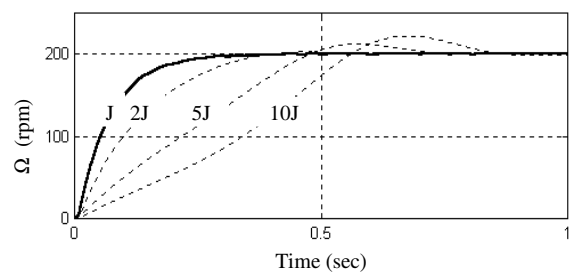


Figure 12. Variation of the moment of inertia.

Figure11 shows the controllers reaction to moment of inertia variation. The motor's speed is simulated, under no load, for moments of inertia equal to J , $J \times 2$, $J \times 5$ and $J \times 10$. Simulation results show that

the variation in the value of the moment of inertia affects both the time to peak and the overshoot values. When the moment of inertia is multiplied by 10, the time to peak value changes from 0.35s to 0.68s and the overshoot value changes from 0% to 10.5%.

Figure12 shows the reaction of the proposed VGPI controller to stator resistance variation. The motor is started up with a load of 10 Nm. The rotor resistance is supposed to double at 1sec.

Stator resistance variation is shown to affect the mean value of the estimated electromagnetic torque which changes from 10 Nm to 20 Nm.

The VGPI controller compensates the torque estimator detuning problem by increasing the mean value of the torque command to about 97% of its rated value.

The VGPI controller rejects the stator resistance disturbance in less than 0.17s with a maximum speed dip of 25.7 rpm (12.85%).

6. Conclusion

In this paper a direct torque neuro fuzzy controlled induction motor drive is presented. This control scheme uses the stator flux amplitude and the electromagnetic torque errors through an adaptive NF inference system (ANFIS) to act on both the amplitude and the angle of the desired reference voltage. This vector is used by a space vector modulator to generate the inverter switching states.

A VGPI controller has been designed to replace the PI speed controller in the DTNFC control scheme.

Simulation of the settling performance of a conventional DTC scheme using first a PI controller then a VPGI controller gave the following transient mode results:

- The PI controller cannot prevent the DTC scheme from driving the motor speed to the stator flux corresponding speed. This will most likely result in a speed overshoot.
- The VGPI controller however takes immediate control of the speed and drives the motor directly to the reference speed without overshoot.

Simulation of the DTNFC induction motor drive using VGPI for speed control shows promising results. The motor reaches the reference speed rapidly and without overshoot, trapezoidal commands under no load are tracked with zero steady state error and almost no overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt with.

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