A FUZZY – Pi – BASED TORQUE CONTROLLER FOR DTC OF INDUCTION MOTOR DRIVES

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ABSTRACT

It is well established that the implementation of conventional DTC drive consisting of hysteresis-based torque controller suffers from high torque ripple and variation in switching frequency problems. One of the many approaches to tackle this problem is by introducing a non–hysteresis–based torque controller. This paper presents the simulation and analysis of a proposed fuzzy PI-based torque controller for DTC of induction motor drives. Comparisons and analysis between the proposed controller and the hysteresis - and PI -based controllers are presented. The results show that the proposed controller managed to reduce the torque ripple and produce a constant device switching frequency.

KEYWORDS

Direct Torque Control, AC motor drives, fuzzy controller

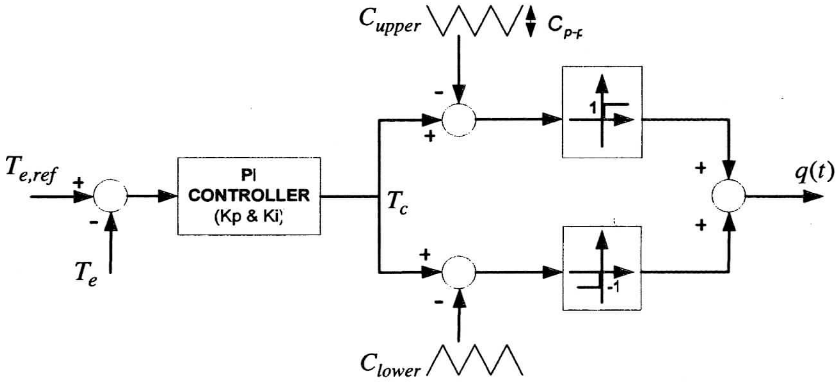
1. INTRODUCTION

Direct torque control (DTC) of induction motor drives has gained popularity due to its simple control structure and sensorless operation. The structure of conventional DTC drive originally introduced in [1], is simple. It consists of torque and flux hysteresis-based controllers, flux and torque estimator and switching look-up table. Despite its simplicity, it was well known that the implementation of the hysteresis-based DTC controllers has resulted in high torque ripple, particularly with microprocessor implementation, due to the delay in the sampling time. On top of that, hysteresis-based controllers also resulted in unpredictable switching frequency of the switching devices. This is undesirable since the switching devices have to be selected based on worst-case condition. Furthermore, the variable switching frequency will generate unpredictable harmonic currents.

Various methods have been proposed to overcome these two drawbacks, such as the use of variable hysteresis band [2], controlled duty cycle techniques [3-8] and space vector modulation approach [11-13]. To some extent, all of these methods have managed to solve the problems, however at the same time the computational and complexity of the DTC drive were significantly increased.

A simple approach to solve the problem was initially proposed in [8]. Using the proposed method, the proportional-integral (PI)-based torque controller depicted in Fig. 1, was used to replace the hysteresis-based torque controller. By comparing its generated control signal *Tc* with triangular carrier waveforms (Fig. 1), a constant torque controller switching frequency is obtained. It was shown in [9] that the inverter switching frequency is mainly determined by the torque controller switching frequency, hence by maintaining a constant torque controller switching, an almost constant inverter switching frequency can be established. However, in order to determine the parameters of the PI controller (*Kp* and *Ki*), the torque loop need to be modelled, and consequently this require the knowledge of the rotor parameters [10]. This paper proposes a fuzzy-PI-based controller to replace the conventional PI controller so that a prior knowledge of rotor parameters are not required in order to design the controller. However as will be discussed in the following sections, the performance of the controller is highly affected by the selection of normalisation gains of the Fuzzy controller.

The paper is organized as follows. In section 2, the topology of the proposed fuzzy PI-based torque controller is introduced. Section 3 gives the analysis towards the gains' selection of the proposed controller. Section 4 presents the simulations and comparison of the DTC drive with the hysteresis -, PI -based controllers and the proposed torque controller. Finally, conclusion is given in Section 5.



$$q(t) = \begin{cases} 1 \text{ for } T_c \geq C_{upper} \\ 0 \text{ for } C_{lower} < T_c < C_{lower} \\ -1 \text{ for } T_c \leq C_{lower} \end{cases} \quad (1)$$

Fig. 1. PI-based torque controller

2. PROPOSED TORQUE CONTROLLER

The structure of fuzzy PI controller is depicted in Fig 2. It has two inputs: the torque error signal, $TE=T_{e,ref} - T_e$ ($T_{e,ref}$ is torque reference and T_e is estimated torque), and the change of torque error, $dTE=TE(t) - TE(t-\Delta t)$. Both inputs are being normalized (TE_n, dTE_n) using *input normalization gains* (G0 and G1) before being fed to the fuzzy controller. The output of the controller is a normalized change of control signal dTc_n. The actual change of control signal value dTc is obtained by using *output unnormalization gain* G2.

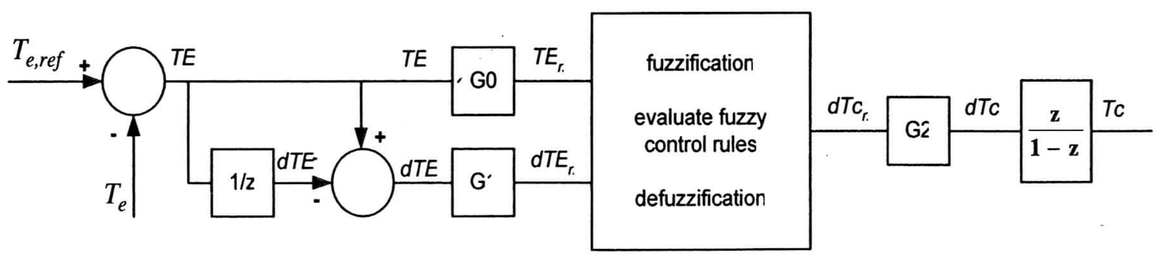


Fig 2. Fuzzy PI controller block

2.1 FUZZIFICATION OF INPUTS AND OUTPUT

The universes of discourse (range) of the fuzzy controller's inputs and output are divided into seven overlapping fuzzy subsets as shown in Fig. 3. The triangular shape of the membership functions presumes that for any particular input, there is only one dominant fuzzy subset. The chosen normalized universe of discourse is defined from -3 to 3, and over this universe, seven fuzzy subsets are defined:

Linguistic terms	Symbols	Fuzzy subsets
Positive Big	PB	+3
Positive Medium	PM	+2
Positive Small	PS	+1
Zero	ZE	0
Negative Small	NS	-1
Negative Medium	NM	-2
Negative Big	NB	-3

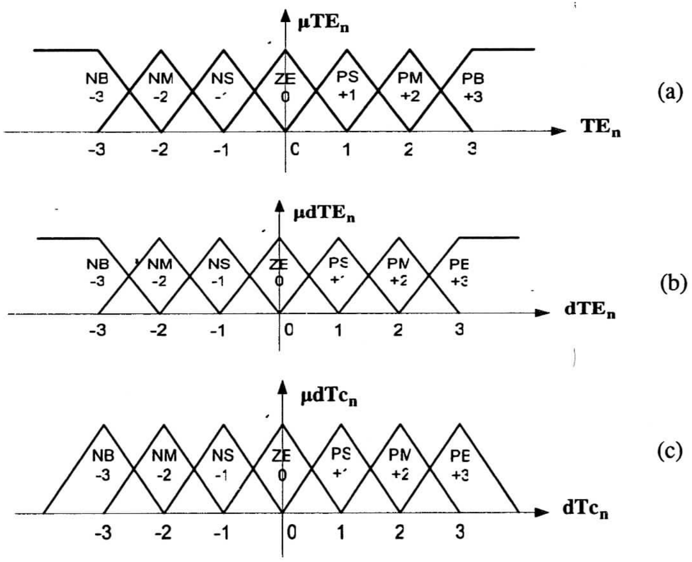


Fig. 3. Membership function of fuzzy controller (a) inputs (b) output

2.2 CONTROL RULES

The rules that connect the inputs and outputs are developed based on emulating an ideal response of a second order system shown in Fig. 4. The developed rules are aimed to produce a system that has good stability and good system's performances (response time, overshoot, damping factor, and etc). These set of rules are summarized using the decision table presented in Table I. The inputs are combined using AND operator, while IF-THEN rules is used to connect the inputs and the output.

Table 1. Decision Table Of Fuzzy Control Rules

TE_n / dTE_n	-3	-2	-1	0	+1	+2	+3
-3	-3	-3	-2	-2	-1	-1	0
-2	-3	-2	-2	-1	-1	0	+1
-1	-2	-2	-1	-1	0	+1	+1
0	-2	-1	-1	0	+1	+1	+2
+1	-1	-1	0	+1	+1	+2	+2
+2	-1	0	+1	+1	+2	+2	+3
+3	0	+1	+1	+2	+2	+3	+3

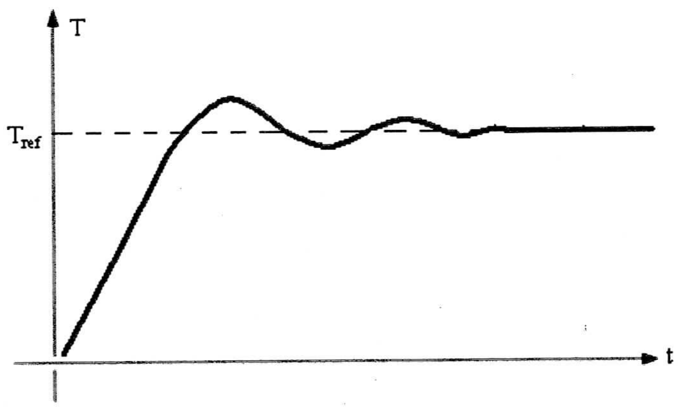


Fig. 4: Response of second order system

2.3 DEFUZZIFICATION

To obtain the output of the fuzzy controller, the method of *center of area* (COA) is used. Using this method, the crisp output, y is chosen as the center of area for the membership function of the overall implied fuzzy set $\hat{B}$. For a continuous output of universe of discourse γ, the center of area output is denoted by [15]:

$$y = \frac{\int_{y} y\mu_{\hat{B}}(y)dy}{\int_{y} \mu_{\hat{B}}(y)dy} \qquad (2)$$

3. FUZZY CONTROLLER GAIN SELECTION

To ensure that the proposed torque controller could produce a torque ripple reduction and obtain a constant switching frequency, the gains of the fuzzy controller (G0, G1, and G2) need to be selected such that the response of system fulfils two main criteria. Firstly, it should produce a good torque response and secondly, it must ensure that the absolute slope of T_c does not exceed the absolute slope of the triangular carrier. By applying a step reference torque to the torque loop, the gains' values are properly adjusted using try and error method until the desired response is achieved. It has been found that there is more than one gains' combinations that can produce the desired result. If a higher value of G0 and G1 are used, a lower value of G2 should be selected, and vice versa.

This condition can be more clearly understood by investigating the effect of each gain towards the system response. Table 2 summarizes the effect of each gain towards the system's response. It can be seen from the table that, the changes of G0 and G1 will give an effect to torque response and slope of *Tc*. In order to maintain a good system performance, an opposite adjustment is needed on G2 in order to compensate the incremental and decrement effect produced by G0 and G1.

Table 2. General response of fuzzy controller with the increasing and decreasing values of G0, G1 and G2.● denotes strong effect; ○ denotes weak effect.

Gain	Torque Response: Rise time	Torque Response: Damping	Slope of *Tc*
(G0) increasing	increase●	increase●	increase●
(G0) decreasing	decrease●	decrease●	decrease●
(G1) increasing	decrease○	decrease○	increase●
(G1) decreasing	increase○	increase○	decrease●
(G2) increasing	increase●	increase●	increase●
(G2) decreasing	decrease●	decrease●	decrease●

4. PERFORMANCE COMPARISON

Comparison study of the drive performance produced by hysteresis-based, PI-based and the proposed fuzzy PI-based torque controller is simulated using the induction machine parameters listed in Table 3.For hysteresis-based torque controller, the width of the torque hysteresis band is set at 0.12 Wb which is 20% of the rated torque. The *Kp* and *Ki* of PI-based torque controller is set at 330 and 112826 respectively [9]. For fuzzy PI-based torque controller, the chosen value of G1, G2, and G3 are 1, 0.05 and 400, respectively

Table 3. Induction Machine Parameters

Nominal power	1/4 HP	Mutual inductance	0.829 H
Stator resistance	10.9 Ω	Moment of inertia	0.0029kgm^2
Rotor resistance	9.244 Ω	Number of poles	2
Stator self inductance	0.859 H	Stator flux reference	0.495 Wb
Rotor self inductance	0.859 H	Inverter DC voltage	120 V

4.1 RESPONSE TO STEP REFERENCE TORQUE

In terms of response to a step reference torque, hysteresis-based and fuzzy PI-based torque controller produce a faster torque response compared to PI-based torque controller. As depicted in Fig. 5, the rise time of both torque controllers is about 1ms compared to 2ms produced by the later

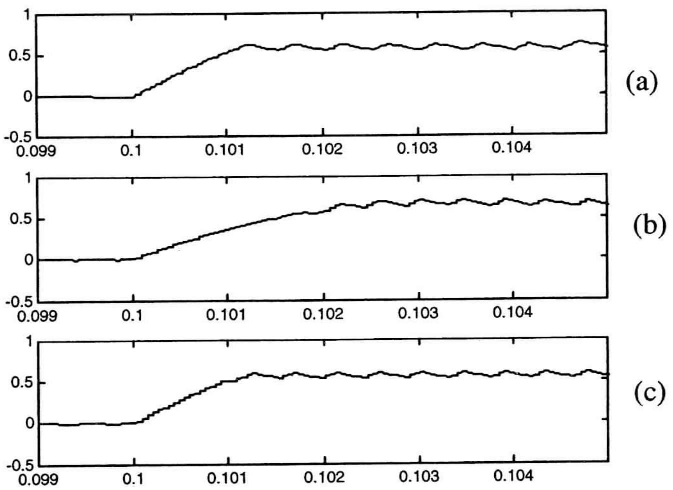


Fig. 5. Response to step torque reference for (a) hysteresis-based (b) PI-based (c) fuzzy PI-based torque controller

For PI-based torque controller, the value of *Kp* is restricted to ensure that the absolute slope of *Tc* does not exceed the absolute slope of the triangular carrier[10]. Due to this, the maximum torque bandwidth that can be achieved using PI-based torque controller is restricted by the frequency of triangular carrier. Since this bandwidth is small compared to extremely high torque bandwidth of the hysteresis-based torque controller, the torque response obtained for PI-based torque controller is slower. Although the same slope restriction has been applied to fuzzy PI-based torque controller, the designated control rules has ensured that the higher torque increase is being applied when the torque error is very large. As the result, it manages to produce a faster torque response than the PI-based torque controller.

4.2 TORQUE RIPPLE

Fig. 6 shows the torque ripple produced by each torque controller at rotor speed of 20 rad/s. The figure indicates that hysteresis-based torque controller has the highest peak-peak torque ripple which is about 0.09 N-m, while PI-based and fuzzy PI-based torque controller has a lower peak-peak torque ripple which is about 0.04 N-m.

Using hysteresis-based torque controller, torque increasing or decreasing is done by applying active or zero voltage vector for the entire switching period. For PI-based and fuzzy-PI based torque controllers, these two voltage vectors (active and zero voltage vector) are used consecutively to increase and decrease the torque within triangular waveform period. It should be noted that it is possible to increase this frequency higher than the sampling frequency as long as it is synchronized with the latter [letter]. Since the torque ripple is directly proportional to the switching frequency, increasing the triangular waveform frequency can significantly reduce the ripple.

However, as the speed increased, the slope of *Tc* becomes steeper hence increasing the duration of applying the active voltage vector. As a result, the torque is being increased for a longer duration and this in turn, increasing the torque ripple. This situation is clearly shown in Fig. 7 for a speed of 20 and 90 rad/s. Torque ripple produced by each torque controller for a speed of 90 rad/s is depicted in Fig. 8. It can be seen that, at this speed value, each torque controller gives almost the same amount of torque ripple.

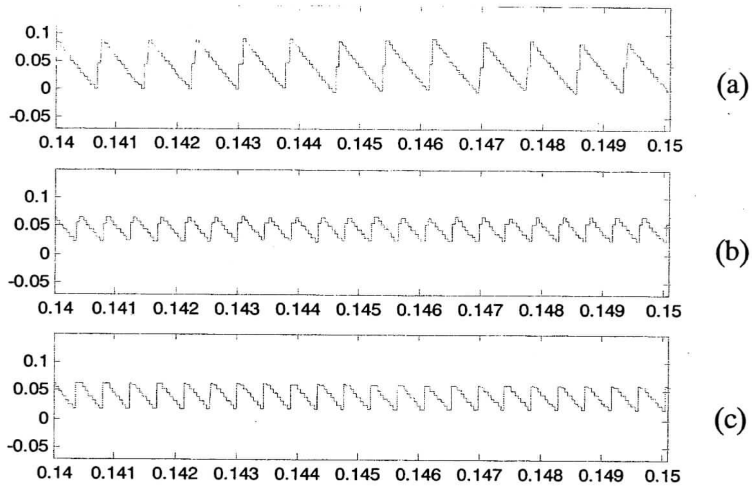


Fig. 6. Torque ripple at speed of 20 rad/s for (a) hysteresis-based (b) PI-based (c) fuzzy PI-based torque controller.

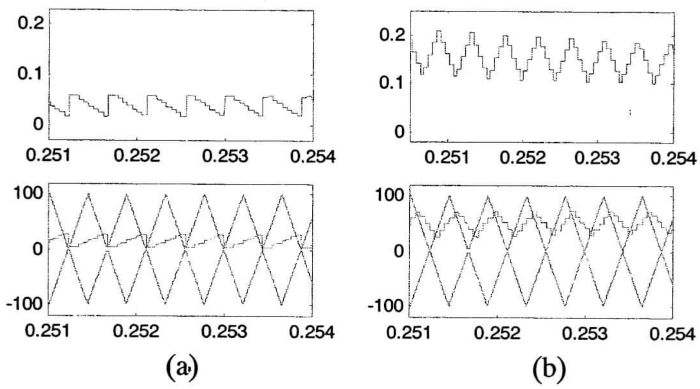


Fig. 7. Torque ripple, slope of *Tc* and duration of applying active voltage vector at speed of (a) 20 rad/s (b) 90 rad/s.

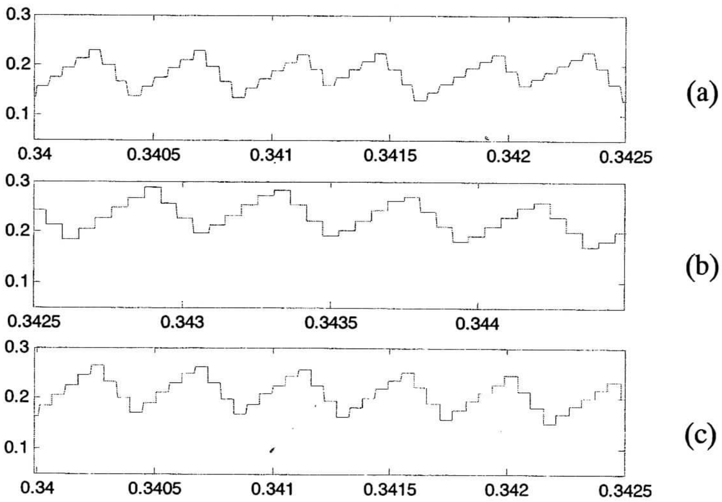


Fig. 8. Torque ripple at speed of 90 rad/s for (a) hysteresis-based (b) PI-based (c) fuzzy PI-based torque controller.

4.3 SWITCHING FREQUENCY

For VSI, its switching frequency is directly affected the harmonic content of the line-line voltage. Table 4 shows the dominant harmonic of line-line voltage for each torque controller at different speed value.

For hysteresis-based torque controller, there is a big variation on the switching frequency as the speed increased. As oppose to the former, PI-based and fuzzy PI-based torque controller has managed to maintain the switching frequency around the value of the triangular carrier frequency, which is 2272Hz, regardless of rotor speed. The small increases in the switching frequency when the speed increases is mainly contributed by the switching of stator flux.

Table 4. Dominant harmonic of line-line voltage for different rotor speed value.

Rotor speed (rad/s)	Hysteresis-based torque controller (Hz)	PI-based torque controller (Hz)	Fuzzy PI-based torque controller (Hz)
20	1341	2276	2270
50	2185	2281	2282
70	2395	2284	2285
90	2410	2286	2287
Δ	1069	10	17

4.4 STATOR FLUX CONTROL PERFORMANCE

Fig. 9 shows the stator flux vector locus for each type of torque controller. It can be seen from that figure that there is no distinct difference in steady state control performance of stator flux, between the three types of torque controller. It can be said that the usage of PI-based and fuzzy PI-based torque controllers have not deteriorate the steady state control performance of the stator flux. For each torque controller, stator flux is regulated at its rated value, which is 0.495 Wb.

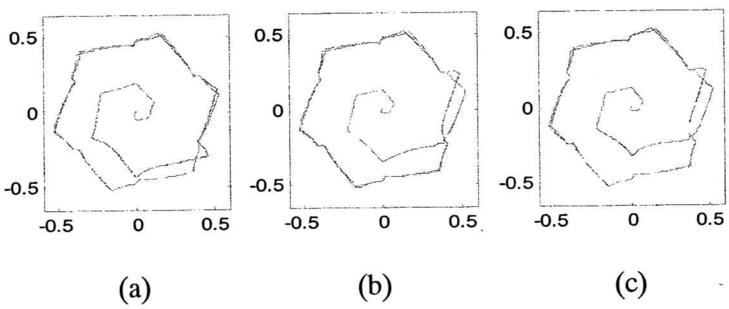


Fig. 9. Stator flux vector locus for (a) hysteresis-based (b) PI-based (c) fuzzy PI-based torque controller.

5. CONCLUSION

A new fuzzy-PI based torque controller for DTC drive has been introduced. A comparison study on the drive performance utilizing the hysteresis-, PI- and fuzzy PI -based torque controllers have been presented. With the PI-based and fuzzy PI-based torque controller, the fixed switching frequency is obtained while the torque ripple, especially at low speed is significantly reduced. In terms of dynamic response and stator flux control, the performance of fuzzy PI-based torque controller is comparable to that of the hysteresis-based torque controller. Compared to the PI-based torque controller, the performance of a fuzzy PI-based torque controller is maintained, if not better. A further study on selecting the normalization gains of the proposed controller need to be carried out.

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