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Performance Enhancement of 3 Φ IM Drive using Self-Tuning PI-Type Fuzzy Logic Based DTC Technique

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A B S T R A C T

This paper presents a direct flux and torque control (DTC) of three phase induction motor drive (IMD) using Self- tuning PI type fuzzy logic controllers (STPIF) for speed regulator (SR) and to reduce torque ripples. This control method is based on DTC operating principles. The DTC is one of the most excellent direct control strategies of stator flux and torque ripples of IMD. The key issue of the DTC is the strategy of selecting proper stator voltage vectors to force stator flux and developed torque within a prescribed band. Due to the nature of hysteresis control adopted in DTC, there is no difference in control action between a large torque error and a small one. This results in high torque ripple. It is better to divide the torque error into different intervals and give different control voltages for each of them. To deal with this issue a fuzzy logic controller has been introduced. The main drawback with the conventional DTC of IMD is high stator flux and torque ripples and the speed of IMD is reduced under transient and dynamic state of operating condition. This drawback is reduced by the proposed system, the speed is regulated by self-tuned PI type fuzzy logic controller and torque is controlled by PI controller. The rule base for STPIF controller is defined as the function of error and the change of the error for the speed using a most natural and unbiased membership functions (MF). The amplitude of the reference stator flux is kept constant at rated value. The performance of the proposed self-tuning Fuzzy PI controller is compared with the corresponding fuzzy logic controller and PI controller in terms of several performance measures such as settling time and rise time. The simulation results of proposed DTC shows the low stator flux linkage, torque ripples, good speed regulator and ensure fast torque response and low torque ripple in comparison with DTC-SVM with PI controller using MATLAB/SIMULINK.

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INTRODUCTION

At present electric power consumed by electric drives is about 70%.Electric drives are mainly classified into two types namely, AC and DC drives.AC drives are superior compared to DC drives and become more popular in past four decades ,especially induction motor drives (IMD), because of its robustness, high efficiency, high performance, and rugged structure, ease of maintenance so widely used in industrial application, such as paper mills, robotics, steel mills, servos, transportation system, elevators, machines tools etc. Commonly used techniques for speed control of induction motor drive are V/F ratio control, Direct Torque Control (DTC) and Vector Control. In the scalar or the V/F ratio control technique, control of torque or speed is not possible whereas in vector control it is possible. But, vector control is highly complex. Therefore many applications uses DTC with less complexity. As DTC has a simple control scheme current controller, and co-ordinate transformations are not required but it is required in case of FOC. The main feature of DTC is simple structure and good dynamic behaviour and high performance and efficiency (Kang, J.K. and S.K. Sul, 1999; Depenbrock, M., 1988; Kang, J.K. and S.K. Sul, 1999). The new control strategies proposed to replace motor linearization and decoupling via coordinate transformation, by torque and flux hysteresis controllers (Buja, G., 1998). This method is referred as conventional DTC (Maeda, M. and S. Murakami, 1992).

The conventional DTC has some drawbacks such as, variable switching frequency, high torque and flux ripples, problem during starting and low speed operating conditions, and flux and current distortion caused by stator flux vector changing with the sector position and the IDM speed changes under

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transient and dynamic state operating condition. The proposed DTC with PI and FLC is used to overcome the above said problem. The PI controller is used to control speed in the SR loop and the FLC is used to reduce stator flux and torque ripple in the torque control loop (Procyk, T.J. and E.H. Mamdani, 1979).

In it is presented a simple one step stator flux control algorithm which avoids coordinate rotation and predictive controllers. However, this scheme needs a good adjustment of the PI torque controller parameters to achieve a good performance. In general the use of fuzzy control does not require the accurate mathematic model of the process to be controlled. Instead, it uses the experience and knowledge of the involved professionals to construct its control rule base.

Fuzzy logic has been proved to be powerful in the motor control area, e.g., in (Procyk, T.J. and E.H. Mamdani, 1979) the PI and Fuzzy Logic Controllers (FLC) are used to control the load angle which simplifies the IM drive system.

Reference voltage vector is obtained dynamically in terms of torque error, stator flux error and stator flux angle by using FLC is detailed in (Bose, B.K., 2002). Here both torque and stator flux ripples are remarkably reduced. Wide range of controlling the motor speed by using fuzzy PI speed controller is explained in the paper fuzzy logic application in DTC-SVM (Tanscheit, R. and E.M. Scharf, 1988). Self-tuned and self-organized controllers has also been developed and implemented for different type of adaptive FLC (Vas, P., 1999).

In (Harris, C.J., 1993) controlling a second-order linear and marginally stable system was done using a self-tuning PI-type fuzzy controller. This method requires three scaling factors (SF) or gains. The performance analysis of this controller was compared to the regular PI controller and the results were very encouraging. The same technique was done in (Dirankov, D., 1993) where the self-tuning PI-type fuzzy controller was used in an industrial weigh belt feeder control process successfully. In both methods only the output scaling factor was adjusted online depending on the process trend.

DTC-SVM three-phase IM based was designed for STPIF, where fuzzy rules is used to control only the output gain and it is equivalent to controller gain. Here the highest priority is given to the output SF tuning due to its strong influence on the performance and stability of the system.

In this paper, the STPIF generates corrective control actions based on the real torque trend. This controller was tuned dynamically online during the control operation by adjusting its output SF by a gain updating factor. The value of this is determined from the fuzzy rule base defined as the function of control error and the variations of the control error are shown in the tables provided in the paper body and derived from the knowledge of the control process.

Based on the torque error and the change of torque error, the required load angle is provided by a STPIF. With this angle the reference stator flux is calculated and the stator voltage vector necessary for tracking the reference torque is synthesized.

The simulation results show that the proposed STPIF controller for the DTC-SVM three-phase IM outperforms the same scheme with conventional PI.

This paper is organized as follows. In section 2 the basic Direct Torque control principles of the three-phase induction motor is presented and in section 3 the operation of PI controller is explained. In section 4 the basic concept of Fuzzy logic controller is described and in section 5 the proposed STPIF is described in details mentioning different aspects of its design consideration.

Section 6 presents the simulations results of STPIF controller performance in comparison with the conventional PI controller. Both controllers were applied to three-phase induction motor DTC-SVM scheme. Finally, conclusion is given in Section 7.

II. *Direct Torque Control:*

The conventional DTC of IMD is supplied by a three phase, two level voltage source inverter (VSI). The main aim is to directly control the stator flux linkage or rotor flux linkage and electromagnetic torque by selection of proper voltage switching states of inverter. DTC is mostly used in variable frequency drives to control torque of three phase AC motors. In this technique voltage and current of the motor is measured to estimate the magnetic flux and torque.

The block diagram of conventional DTC of IMD is shown in Fig2.1. Here phase currents and voltages are given to the flux and torque estimation block. Stator voltages are integrated to get stator flux linkage and stator flux linkage vector is multiplied with current vector to get torque. The calculated flux and torque values are compared with the reference values and the deviation from the reference value is given to the lookup table. If the deviation is above the tolerance value then transistors are turned off and on to give control signals so that deviation is within the allowed tolerance. It is also called as bang-bang control.

High efficiency & low switching losses because the transistors are switched only when it is needed to keep torque and flux within their hysteresis bands. Digital control equipment is used to prevent the flux and torque from deviating far from the tolerance bands. Typically the control algorithm is performed for every 10-30 micro seconds. Speed sensors are not necessary for this method. The minimum frequency range to start the IM from standstill position ranges from 0.5 to 1 Hz.

III. *Pi Controller:*

PI controller is the reduced form of PID controller in which derivative term is not used only proportional and integral terms are used. In the figure 3.1 P represents present error and I represents

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accumulation of past errors. The input to the system is given as R and the output from the system is Y. Error (e) is given as the input to the PI controller and the output from the controller is the plant input (u).

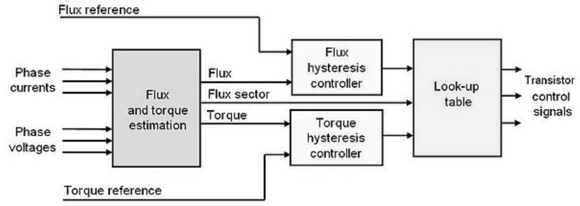

Fig. 2.1: Block diagram of conventional DTC.

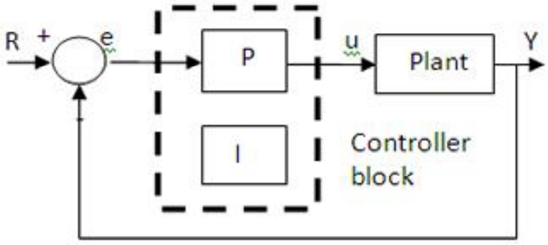

Fig. 3.1: proportional integral block diagram.

Proportional and integral terms are given by:

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

Where kp and ki are proportional and integral gain respectively

The main aim of PI controller is to increase the speed of the response and also to eliminate the steady state error. The value of ki is to be taken larger so that steady state response is attained faster. PI controller is tuned by turning OFF the integral part and the proportional gain is tuned until the result becomes ok. If the result is not obtained correctly kp is reduced to half and the value of ki is increased. PI controller is used where fast response of the system is not needed, large disturbances and noise are present, there is only one energy storage, there are large transport delays in the system .

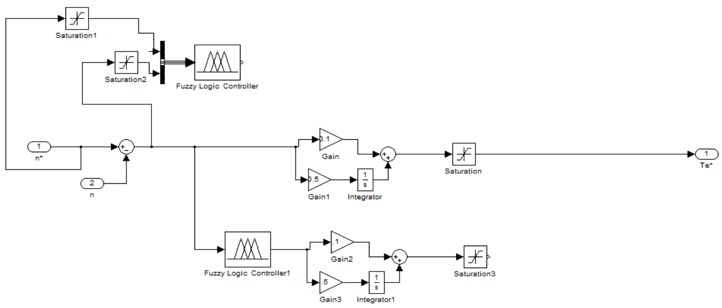

Fig. 3.2: SIMULATION for PI Controller.

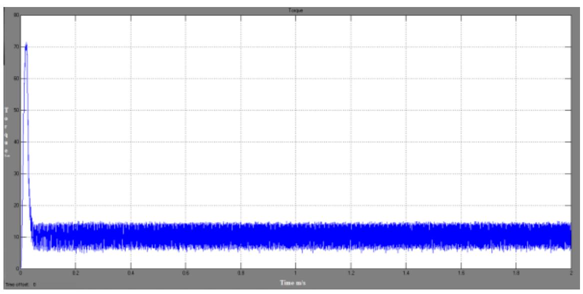

Fig. 3.3 Torque (PI Controller).

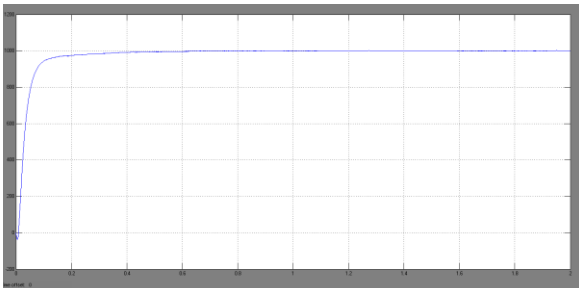

Fig. 3.4: Speed (PI Controller).

Fig. 3.5: Torque Ripple (PI controller).

IV. *Fuzzy Logic Controller:*

The fuzzy logic controller is one of the controllers in the artificial intelligence techniques. Fig.4.1 shows the schematic model of Fuzzy based DTC for IMD. In this project, Mamdani type FLC is used and the DTC of IMD using PI controller based SR (speed regulator) requires the precise mathematical model of the system. Therefore, unexpected change in load conditions would produce overshoot, oscillation of the IMD speed, long settling time, high torque ripple, and high stator flux ripples. To overcome this problem, a fuzzy control rule look-up table is designed from the performance of torque response of the DTC of IMD. According to the torque error and change in torque error, the proportional gain values are adjusted on-line.

The fuzzy controller is characterized as follows:

1) Seven fuzzy sets for each input and output variables,
2) Fuzzification using continuous universe of discourse,
3) Implication using Mamdani's “min” operator,
4) De-fuzzification using the “centroid” method.

***Fuzzification*:**

The control process of converting a crisp sets (real number) into a fuzzy set (linguistic variable) is called fuzzification.

***De-fuzzification*:**

The rules of the FLC generate required output variable called linguistic variable (Fuzzy Number), according to the real world requirements, linguistic variables have to be transformed to crisp output (Real number).

***Database*:**

The database stores the definition of the membership Function required by fuzzifier and defuzzifier.

A. Fuzzy Variables:

In the crisp variables of the torque error and change in torque error are converted into fuzzy variables $\Delta T_e(k)$ and $\Delta T_e*(k)$ that can be identified by the level of membership functions in the fuzzy set. The fuzzy sets are defined with the triangular membership functions.

B. Fuzzy Control Rules:

In the fuzzy membership function there are two input variables and each input variable have seven linguistic values, so 7x7=49 fuzzy control rules are in the fuzzy reasoning is shown in Table.5 and flowchart of FLC is shown.

Table 4.1: fuzzy logic control rules.

ΔT_e	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

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A FLC converts a linguistic control strategy into an automatic control strategy and fuzzy rules are constructed by expert knowledge or experience database. Firstly, the input torque ΔT_e (k) and the change in torque error ΔT_e*(k) have been placed of the torque to be the input variables of the FLC. Then the output variable of the FLC is presented by the control of change in torque ΔT_e. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PL (positive large) as shown in Table 4.1.

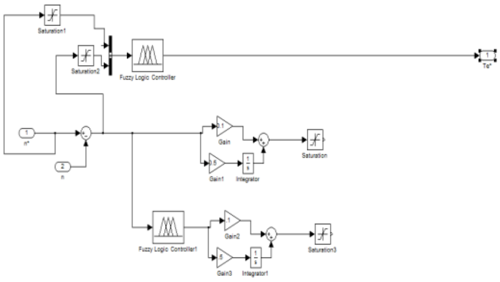

Fig. 4.1: SIMULATION for Fuzzy logic controller.

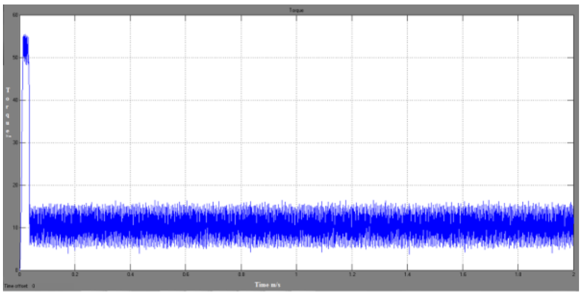

Fig. 4.2: Torque (Fuzzy logic controller).

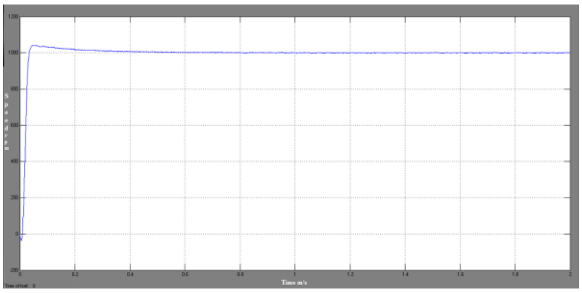

Fig. 4.3: Speed (Fuzzy logic controller).

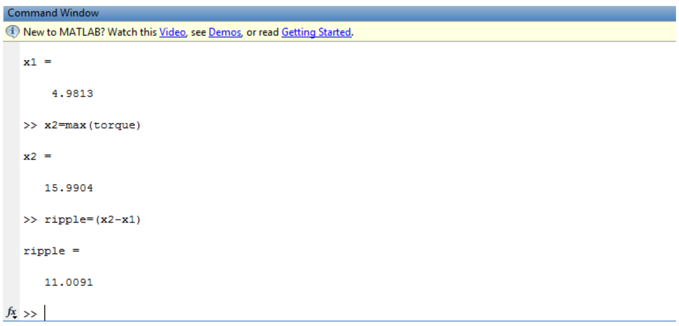

Fig. 4.4: Torque Ripple (Fuzzy logic controller).

V. *Fuzzy Logic Controller Tuned Pi:*

The main objectives of the proposed fuzzy logic PI controller are to decrease the control scheme complexity and, improve the static and the dynamic performances of the system. In this case, the kp and ki values are adjusted by the fuzzy controller in order to meet the appropriate required characteristics such that maximum overshoot, rise time, settling time and steady state error. The performance of the system is considered during design of fuzzy rules to tune the PI parameters ΔK p and ΔKi. If the error e is small, value of ΔK p and value of ΔKi are considered to be large in order to maintain the system stability. If the value of the error e is medium, then the small value of ΔK p and the adequate value of ΔKi are considered to improve decreasing overshoot. If the value of the error e is big, then the great value of ΔK p and ΔKi equal zero that to get suitable settling time, suitable rise time and at the same time decrease the overshoot. From the previous experience, the required fuzzy rules to tune the PI parameters are obtained. Extraction of the FLC Rules is based on rise time (Tr), maximum overshoot (Mp) and steady-state error (SSE).Selection of membership function is based on error, change in error, sampling period and rise time.

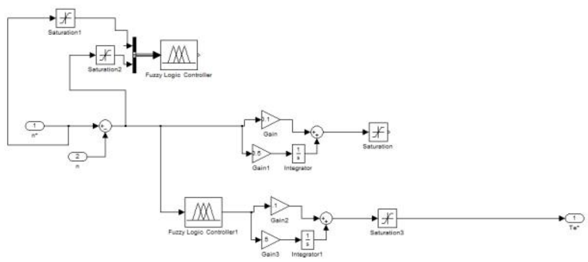

Fig. 5.1: SIMULINK for both PI & Fuzzy logic controller.

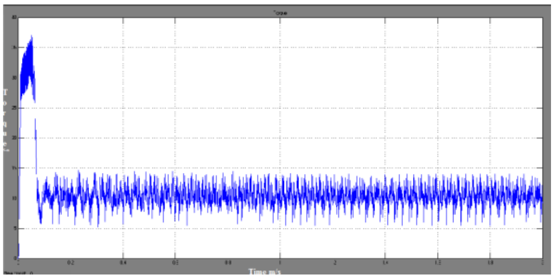

Fig. 5.2: Torque (PI & Fuzzy logic controller).

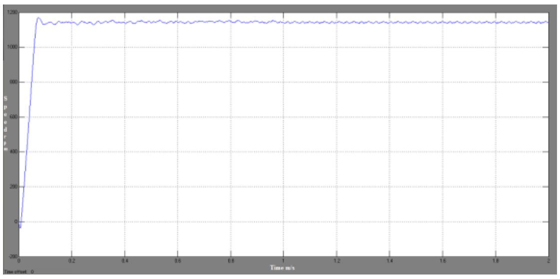

Fig. 5.3: Speed (PI & Fuzzy logic controller).

VI. ***Simulation Result Comparision:***

The conventional and proposed DTC MATLAB models were developed for 3hp IMD. The simulation results of conventional and proposed DTC for forward motoring operation are shown in Fig.3.3, and Fig.5.2, it represents the stator current, stator flux, developed torque at no load and full load, speed, and stator dq-axis.

The simulations were performed using MATLAB environment with Simulink block sets and fuzzy logic toolbox. The switching frequency considered for the three-phase two level inverter was 10 kHz. The reference stator flux considered was 0.47 Wb which is the rated stator flux of the IM under consideration.

In order to investigate the effectiveness of the proposed control system and to check the closed-loop stability of the complete system several tests were performed.

Different dynamic operating conditions were simulated such as step change in the motor, no load sudden change in the reference speed and finally a specific load torque profile.

```
x1 =

    5.5597

>> x2=max(torque)

x2 =

   14.0031

>> ripple=(x2-x1)

ripple =

    8.4434

>>
```

Fig. 5.4: Torque Ripple (PI & Fuzzy logic controller).

The Fig. 5.2 and Fig. 5.3 shows similar behaviors of the torque, current and the motor speed when it is imposed a no-load reference speed step change from 0.5 pu to -0.5 pu in the DTC-SVM scheme with STPIF and PI controllers respectively. The sinusoidal shape of the current shows that this control technique leads also a good current control. A comparison table for fuzzy, PI, fuzzy & PI controllers minimum and maximum torque and Torque ripple is shown in table 6.1.From the table we conclude that torque ripples have been reduced in proposed system.

Table 6.1: Torque and ripple comparison for varying controllers

Type of Controller	Minimum torque	Maximum torque	Torque Ripple
Fuzzy	4.9813	15.9904	11.0091
PI	5.6324	15.0332	9.4008
Fuzzy & PI	5.5597	14.0031	8.4434

VII. *Conclusion:*

In this paper, an effective control technique is presented for direct flux and torque control of three-phase IMD. The self-tuned fuzzy PI scheme has been proposed and results have been compared to the conventional PI and fuzzy controllers. This technique regulates the speed of IMD and reduces the stator flux and torque ripples. There is a decoupled space vector control between the stator flux and electromagnetic torque hysteresis controller for generating the pulses for VSI. The two independent torque and flux hysteresis band controllers are used in order to control the limits of the torque and flux. Simulations at different operating conditions have been carried out. The simulation results verify that the proposed DTC-SVM scheme with STPIF controller achieves a fast torque response and low torque ripple, in comparison to the DTC-SVM scheme with PI controller, in a wide range of operating condition such as sudden change in the command speed, reverse operation and step change of the load.

The simulation results of both conventional and proposed techniques are carried out for DTC of three-phase IMD, among both of them proposed control technique is superior for good speed regulator, low stator flux linkage, and torque ripples under transient and dynamic state operating conditions using MATLAB/SIMULINK. The main advantage is the improvement of torque and flux ripple characteristics at low speed region; this provides an opportunity for motor operation under minimum switching loss and noise.

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