IEEE PEDS 2019, Toulouse, France
9 – 12 July 2019

An Interval Type-2 Fuzzy Based DTC of IMD Using the Hybrid Duty Ratio Control

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***Abstract*-This paper provides an interval type-2 fuzzy based DTC (IT2FDTC) of the induction motor drive (IMD) in which a hybrid duty ratio control (HDRC) technique is used to activate a two-level inverter. Moreover, it is implemented with the help of DSPACE-1104 controller in real-time application using 2HP induction motor and compared its overall performance with a conventional proportional integral DTC (CPIDC) using SVM technique. The IT2FDTC can be provided less torque and flux ripples with fast dynamic performance of IMD over a CPIDTC. A three-dimensional Mamdani type-2 fuzzy controller along with centroid method is used in IT2FDTC. Hence, the proposed method of study not only control the gains of PI effectively, but also control the duty ratios of modulating wave to further improve the dynamic performance and current harmonic profile of IMD.**

I. Introduction

In general, the speed of induction motor (IM) controlled using conventional DTC (CDTC) in which the two-level inverter is activated based on torque and flux errors of switching table. Hence, CDTC provides fast dynamic performance than FOC. Though CDTC provides significant flux and torque distortions due to the hysteresis-band regulator [1]-[2], the hysteresis-band regulator affords the variable switching frequency and therefore difficult to design the filter to reduce the flux and torque distortions of IM [3]-[4]. To maintain the constant switching frequency with slight improvement on torque and flux ripples of the two-level inverter fed IMD, a DTC-SVM is used [4]. The hysteresis controllers are replaced with an interval of type-1 fuzzy controllers (IT1FC) (or) conventional fuzzy controllers (CFCs) and then controlled the duty ratios for DTC to condense the torque and flux ripples of IMD. Also, it provides a less current harmonics of the IM than CDTC in which IT1FC deals moderately with huge uncertainty [4]-[6]. However, an interval type-2 fuzzy control (IT2FC) along with 3D control introduced for effectively dealing of the hefty ambiguous data [6]-[7]. In defuzzification process, there is a reduced fuzzy set employed a centroid method to find the actual crisp value as very close to the real value to further improve the controller performance by selecting an appropriate membership function (MF) [7]-[8]. In addition, the dynamic behavior of DTC of IM for two, three and five-level inverters enhanced with IT2FC than CDTC [8]-[10].

II. Interval-Type2 Fuzzy Based DTC

The block diagram consists of both CPIDTC (as shown by black color) and IT2FDTC (as mentioned in red color) for real time implementation using SVM technique given in Fig. 1. Here, the rotor speed of the IM measured from Tachogenerator (TG) along with voltage sensor through ADC channels of the DSPACE DS-1104. Similarly, three phase voltages ($v_{an/bn/cn}$) and three phase/line currents ($i_{a/b/c}$) of the inverter or IM were taken feedback with the help of respective sensors in order to control either CPIDTC or IT2FDTC scheme.

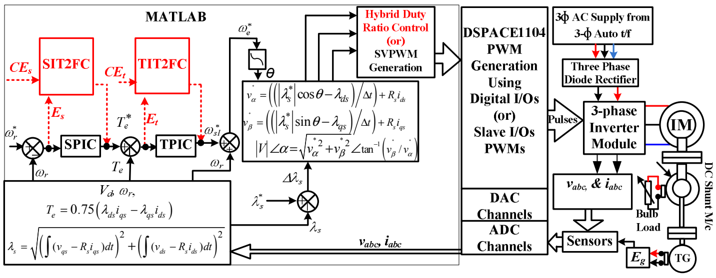

Fig. 1. Block diagram for CPIDTC/IT2FDTC of IMD

Consequently, stator flux λ_s and torque T_e of the IM are estimated from voltages and currents as given in Fig. 1 in which $\lambda_{d/qs}$ $i_{d/qs}$ $v_{d/qs}$ $R_{s/r}$, $\omega_{r/sl}$, and ω_e are stator flux in d/q-axis stator currents in d/q-axis, stator voltages in d/q-axis, stator/rotor resistance, rotor/slip speed and synchronous speed of the IM, respectively. Moreover, the above estimated signals are given to respective controllers for generating the appropriate space vector modulating signals to drive a two-levl inverter. Fig. 1 provides the block diagram for interval type-2 fuzzy direct torque control (IT2FDTC) in red color with dotted line. In IT2FDTC, the PI-controllers exchanged to interval type-2 fuzzy controllers (IT2FC) in which it can be useful for incorporating huge uncertainties than conventional PI-controller and interval type-1 fuzzy control (IT1FC) [8]-[10]. Mamdani IT2F2C process separated by fuzzifier, knowledge base, inference-engine and defuzzifier as similar to IT1FC [7]. The fuzzifier executes measurement of input variables such as scaling, mapping, and fuzzification. In fuzzification process, crisp input values converted into fuzzy (interval type-2 fuzzy) variables. Also, an interval of type reduction is used here for extracting actual crisp value over a IT2FC [15]-[7]-[8]. The output of the speed IT2FC (SIT2FC) can be expressed as [10]

$$T_e^*(k) = k_1\omega_{re}^*(k-1) + k_2\omega_{re}^*(k) \quad (1)$$

where, $\omega_{re}^*(k-1) / \omega_{re}^*(k)$ and k_1/k_2 are prior/current speed error value and prior/current controlled proportional/integral gains of SIT2FC, respectively. Also, it provides input and output MFs of SIT2FC in which the input (E_s and CE_s) MFs and the output MFs $\left(T_e^*(k)\right)$ have the same number of MFs *i.e.,* 7

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[10]. Also, the same names of input and output MFs for SIT2FC are NB_s, NM_s, NS_s, Z_s, PS_s, PM_s, and PB_s. Hence, the number of possible IF and THEN rules are 49 as shown in Table-1. In defuzzification process, a singleton left and right crisp values of THEN-ingredient after type reduction are δ_{T_l} and δ_{T_r} , respectively. Therefore, the defuzzified crisp output from SIT2FC is the average crisp value of δ_{T_l} and δ_{T_r} as [7]-[8]:

$$\delta_{T_{ac}} = \left(\delta_{T_r} + \delta_{T_l}\right)/2 \qquad (2)$$

TABLE I FOR SIT2FC

CE_s ↓ / E_s →	NB_s	NM_s	NS_s	Z_s	PS_s	PM_s	PB_s
NB_s	NB_s	NB_s	NB_s	NB_s	NM_s	NS_s	Z_s
NM_s	NB_s	NB_s	NB_s	NM_s	NS_s	Zs	PS_s
NS_s	NB	NB	NM	NS_s	Z_s	PS_s	PM_s
Z_s	NM_s	NS_s	NS_s	Z_s	PS_s	PM_s	PB_s
PS_s	NM_s	NS_s	Z_s	PS_s	PM_s	PB_s	PB_s
PM_s	NS_s	Z_s	PS_s	PM_s	PB_s	PB_s	PB_s
PB_s	Z_s	PS_s	PM_s	PB_s	PB	PB_s	PB_s

Likewise, the method for torque IT2FC (TIT2FC) remains similar to the SIT2FC. Moreover, TIT2FC has same number of input and output MFs along with number of rules as presented in Table-3. Though, it provides dissimilar crisp and fuzzy values in both the input and output side of TIT2FC along with similar names of MFs employed in SIT2FC. Consequently, the crisp outputs of TIT2FC assessed like SIT2FC as [8]-[10]:

$$\delta_{\omega_{slc}} = \left(\delta_{\omega_{slcr}} + \delta_{\omega_{slcl}}\right)/2 \qquad (3)$$

where, $\delta_{\omega_{slc}}$ *and* $\delta_{\omega_{slcr/l}}$ are the average crisp output value of slip speed for TIT2FC, left/right most crisp positions for the output of TIT2FC. The interval of type-2 fuzzy rules created in a way for fast settling time with fewer overshoots of speed/capacitor voltages of IMD. Generally, these rules strong-minded by humanoid experts via pre-learned procedure, *i.e.*, the person practiced while learning the IM performance at each and every mode of operation and consequently adapted the rules of MFs [7]-[9]. Moreover, k_p and k_i values of respective PI-controllers varied a little as per the load/speed variations. Therefore, they are not similar at all working modes of IMD. A Mamdani type IT2FC sets the gains appropriately for all modes of the IMD using simple IF and THEN rules to further improve the dynamic performance of IT2FDTC of IMD over a CPIDTC [7]-[9]. In addition, the duty ratios of IT2FDTC developed in the location of the reference vector at sector region-1 as [8]-[10]

$$d_{k-1} = t_{k-1}/t_s = \frac{M\,Sin(\alpha)}{Sin(60°)} \qquad (4)$$

$$d_k = t_k/t_s = \frac{M\,Sin(60°-\alpha)}{Sin(60°)} \qquad (5)$$

$$d_{k-2} = t_{k-2}/t_s = 1-(d_{k-1}+d_k) \qquad (6)$$

where, *k, α,* and *M* are three phases of the inverter, reference vector angle and modulation index *i.e., 1.5*V_r/V_d in which V_d V_r are the dc-link and the reference voltage vector, respectively. The RMS stator flux ripple (λ) can be expressed for different possible switching states of 0127, 012, 721, 0121, and 7212 as [5],[9]

$$\lambda_{0127} = \sqrt{q_z^2(2t_s+t_1)+q_1^2(t_1+t_2)+2q_zq_1(3t_1+t_2)+4d^2(t_1+t_2) \Big/ 12t_s} \qquad (7)$$

$$\lambda_{012} = \sqrt{4q_z^2(t_s+2t_1)+4q_1^2(t_1+t_2)+4q_zq_1(3t_1+2t_2)+4d^2(t_1+t_2) \Big/ 27t_s} \qquad (8)$$

$$\lambda_{721} = \sqrt{4q_z^2(t_s+2t_2)+4q_2^2(t_1+t_2)+4q_zq_2(2t_1+3t_2)+4d^2(t_1+t_2) \Big/ 27t_s} \qquad (9)$$

where, q_z, q_1 , q_2 , and *d* are -Mt_z, (*Cosα-M)* t_1, (*Cos(60-α)-M)*t_2, Mt_1*Sinα* in *d-q* axes plane. Fig. 2 shows the stator RMS flux ripple vs sector angle for three switching states at M=0.7866. Now, an appropriate switching sequence is used to trigger the inverter when the amplitude of RMS flux ripple is less than remaining four switching states and this process can be repeated in remaining sectors as well.

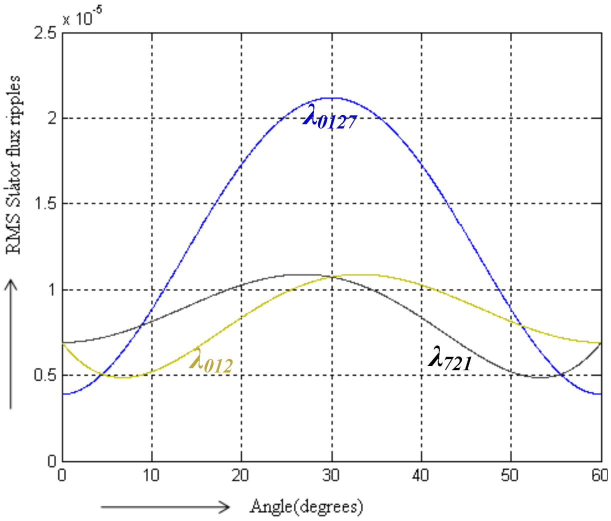

Fig. 2 RMS flux ripples vs sector angle at *M*=0.786

Also, the duty ratios for two-level inverter developed for all six sectors. From (4)-(6), it is clearly concluded that the duty ratios independent of the sampling time provides improvements in voltage and current profile of the inverter. Consequently, a further improvement of flux and torque distortion will be achieved in proposed control scheme over a CPIDTC [8]-[10].

III. Results and Discussion

At first, the CPIDTC of IM experimental setup developed using a DSPACE DS1104 controller and control setup detailed parameters mentioned in Appendix A. Initially, the reference speed of 1450rpm (303.67rad/s) is initiated and controlling signals are generated through a DSPACE kit and set the required DC-voltage (640V) by adjusting three-phase auto-transformer as shown in Fig.1. At the start, the IM is achieved to steady state when a reference speed of 1450rpm is applied for both CPIDTC and IT2FDTC schemes. The IM has mechanically coupled with dc-shunt generator to check drive performance during sudden application of the load. Now, a step load of 4N-m applied to IM at 500ms as shown in Fig. 3 (a) and (b). Consequently, electromagnetic torque (T_e), speed (N_r), flux (λ_s), and current (i_a) waveforms of 3ϕ IM are shown in Fig. 4(a) and (b) for checking ripple/harmonic performance of both the control schemes. Though, the flux is maintained here as constant throughout the operation, the electromagnetic torque and current of the IM suddenly increases to 4N-m and 2.2A, whereas the speed decelerates to1440rpm at 500ms and then settled to 1450rpm at 800ms due to the applied load.

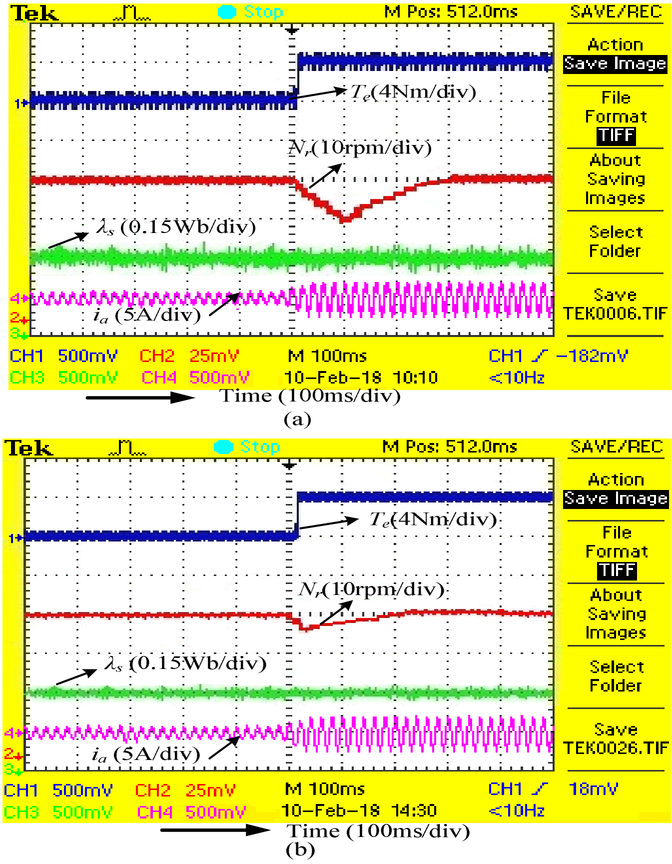

Fig. 3 Experimental performance of IMD when applied a load of 4N-m for (a) CPIDTC and (b) IT2FDTC of the IM in which torque (T_e), speed (N_r), flux (λ_s), and current (i_A) waveforms are shown

The torque and flux distortion for IT2FDTC are roughly ±0.54N-m and ±0.037Wb, correspondingly as shown in Fig. 3(a). Whereas with CPIDTC, the flux and torque distortion are ±0.85N-m and ±0.06Wb as shown Fig. 3(b), respectively. Therefore, IT2FDTC improves torque and flux distortion by 36.4% and 38.3% over CPIDTC, correspondingly. The speed fluctuation with IT2FDTC and CPIDTC during load perturbation is ±5rpm and ±10rpm, respectively. The settling time taken by IT2FDTC and CPIDTC of IM back to reach the required speed during the load perturbation is 200ms and 300ms, respectively. Moreover, the current THD at no-load for CPIDTC and IT2FDTC are 4.2% and 3.3%, individually. Therefore, the IT2FDTC provides better ripple improvement in current, flux, and torque, with enhanced dynamics of IM than CPIDTC. Because, the IT2FC efficiently deals with a large foot print of uncertainty involved than the conventional PI-controllers and also controlled duty cycles to further improve the firing strength of the inverter, consequently there by better improvement on ripple performance of the IMD than conventional control scheme.

IV. Conclusion

The 2HP-IM drive fed with a 3-phase inverter module has implemented in the real time applications for both IT2FDTC and CPIDTC control schemes. In addition, an interface of DSPACE DS-1104 controller setup used here for both the control schemes to provide the controlled pulse directly from the Matlab simulation. However, IT2FDTC of IM provides less current THD than CPIDTC, which results in less distortion in flux and torque, and reached quickly to the steady state during load perturbation of the IM. In addition, IT2FDTC provides smaller amount alps/swims in speed of IMD. This is mainly due to the effective control of hybrid duty-ratios and gains of PI-controllers from the huge ambiguous data in three-dimensional control using Mamdani-IT2FC. Finally, a significant reduction of torque and flux ripples of IT2FDTC-IM obtained by 36.4% and 38.3% than CPIDTC, respectively. As compared to conventional control scheme, the proposed scheme provides a faster dynamic response such as; dc-link capacitor voltages and speed of IM settled down very quickly with fewer peak over shoots during load perturbations.

Appendix. A

3ϕ-Induction motor: 2HP, 50Hz, 440V (*L-L*), 1460RPM, 4pole, Rs=7.83Ω, R_r=7.55 Ω, L_s =L_r =0.4751H, L_m=0.4535H, Moment of inertia (J)=0.06Kg-m^2

3ϕ-two-level-Inverter: Opto-coupler for isolation of drver circuit from main power, Power Diodes (1000V/40A), DC-Link capacitors (C_1=C_2=2200µF/450V), MOSFETs (SPW47N60C3) 650V/45A, Voltage sensors (AD2OKY) 1000V, Current sensors (Telcon-HTP50) 50A, Deadband for two complementary switces 5µs, Speed PI-control (k_p=55 and k_i=0.05), and Torque PI-control (k_p=35 and k_i=2.5), Sampling time=40µs and switching frequency= 2kHz.

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