Fuzzy type-2 Controller for Direct Torque Control PMSM Drives Using Space Vector Technique

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Abstract: *This paper presents a fuzzy type-2 controller applied on a direct torque control (DTC) of a permanent magnet synchronous motor (PMSM), using DTC technique and space vector modulation (SVM). In the conventional DTC a hysteresis controllers are used to limit the flux and torque in the control band while in the SVM DTC the controllers are replaced by PI FLC controllers. The torque dynamic response is very rapid and the system achieves the steady state in a very short time.*

The performance for two fuzzy logic Controller (FLC), (fuzzy type-1 and fuzzy type-2) are presented and compared to verify that the extra degrees of freedom provided by the footprint of uncertainty enables a type-2 FLC to produce outputs that cannot be achieved by type-1 FLCs with the same number of membership.

Key words: *Permanent Magnet Synchronous Motor, Direct Torque Control, Space Vector Modulation, Fuzzy Logic Controller, Fuzzy Type-2.*

1. Introduction

Traditionally, control system design has been tackled using mathematical models derived from physical laws. In fact, most of the parameters and structure of the system are unknown due to modeling errors and unmodeled dynamics. To overcome the above problems in the design of control systems several techniques have been emerged in the recent years especially techniques based on the intelligent technology such as neural networks, fuzzy logic, genetic algorithms and evolutionary computation.

In particular, fuzzy logic systems (FLS) have been successfully applied to control complex or ill-defined processes whose mathematical models are difficult to obtain. The ability of converting linguistic descriptions into automatic control strategy has made it a practical and promising alternative to the classical control scheme for achieving control of complex nonlinear systems. Many researchers have shown that type-1 FLS have difficulties in modeling and minimizing the effect of uncertainties. One reason is that a type-1 fuzzy set is certain in the sense that the membership grade for a particular input is a crisp value, type-2 fuzzy sets, characterized by membership functions (MF) that are themselves fuzzy, have been attracting interest.

The concept of type-2 fuzzy sets was initially proposed by Zadeh as an extension of typical fuzzy sets (called type-1) (Zadeh, 1975). Mendel and Karnik developed a complete theory of interval type-2 fuzzy logic systems (IT2FLSs) (Karnik et al, 1999; Liang & Mendel, 2000; Mendel, 2001). Recently, T2FLSs have attracted more attention in many literatures and special issue of IEEE Transactions on Fuzzy systems (John & Coupland, 2007; Lee & Lin,2005; Liang & Mendel, 2000; Mendel, 2001, Hagras, 2007; Ozen & Garibaldi, 2004; Pan et al,2007; Wang et al, 2004). T2FLSs are more complex than type-1, the major difference being the present of type-2 is their antecedent and consequent sets. T2FLSs result better performance than type-1 Fuzzy Logic Systems (T1FLSs) on the applications of function approximation, modeling, and control. The wide ranges of applications of type-2 FLS have shown that it provide good solutions, especially in the presence of uncertainties [1] – [6].

2. Type-2 fuzzy logic system

A type-2 fuzzy set is characterized by a fuzzy MF, i.e. the membership value (or membership grade) for each element of this set is a fuzzy set in [0, 1], unlike a type-1 fuzzy set where the membership grade is a crisp number in [0, 1]. Imagine type-1 membership function depicted in Fig. 1 by shifting the points on the triangle either to the left or to the right, as in Fig. 2. Then, at a specific value of (x), say (x`), there no longer is a single value for the membership function (u`), instead, the membership function takes on values wherever the vertical line intersects the blur. Those values need not all be weighted the same; hence, we can assign an amplitude distribution to all of those points. Doing this for all , we create a three-dimensional membership function Fig. 3.

The third-dimension of the type-2 fuzzy sets and the footprint of uncertainty that provide additional degrees of freedom making it possible to better model and handle uncertainties [7], [8].

- Uncertainties in inputs to the FLC which translate to uncertainties in the antecedent Membership Functions (MFs) as the sensor measurements are typically noisy and are affected by the conditions of observation.
- Uncertainties in control outputs which translate to uncertainties in the consequent MFs of the FLC. Such uncertainties can result from the change of the actuators characteristics which can be due to wear, tear, environmental changes, etc.
- Linguistic uncertainties as the meaning of words that are used in the antecedent and consequent linguistic labels can be uncertain - words mean different things to different people

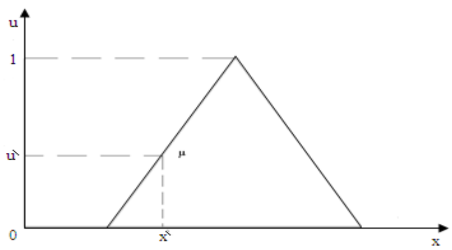

Fig1. Membership function of fuzzy type-1

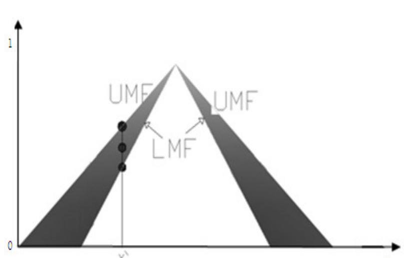

Fig2. Membership function of fuzzy type-2

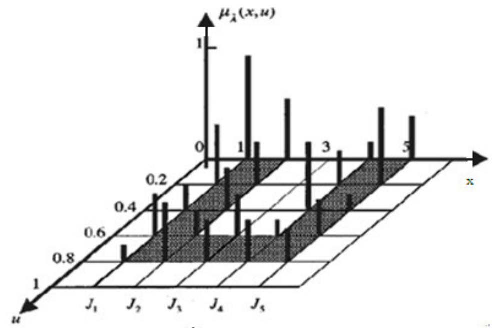

Fig.3. Three-dimensional membership function

The basic configuration of a fuzzy logic system consists of a fuzzifier, a fuzzy rule base, a fuzzy inference engine and a defuzzifier. The structure of a type-2 FLS is similar to type-1 counterpart, the major difference being that at least one the fuzzy set in the rule base is type-2. A type-2 fuzzy set characterized by membership functions that are themselves fuzzy. The key concept is footprint of uncertainly (FOU), which models the uncertainties in the shape and position of the type-1 fuzzy set. Fig. 2 illustrates a type-2 fuzzy MF with FOU shown as shaded area. The output of inference engine for a type-2 FLS is type-2 sets, hence a type-reducer is needed to convert them into type-1 sets before defuzzification can be carried out Fig. 4

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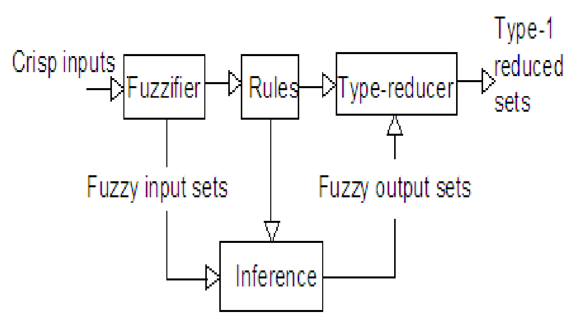


Fig4. Configuration of a fuzzy type-2 logic system

The interval type-2 FLC works as follows: the crisp inputs from the input sensors are first fuzzified into input type-2 fuzzy sets. The input type-2 fuzzy sets then activate the inference engine and the rule base to produce output type-2 fuzzy sets. The type-2 FLC rules will remain the same as in a type-1 FLC but the antecedents and/or the consequents will be represented by interval type-2 fuzzy sets. The inference engine combines the fired rules and gives a mapping from input type-2 fuzzy sets to output type-

2 fuzzy sets. The type-2 fuzzy outputs of the inference engine are then processed by the type-reducer which combines the output sets and performs a calculation which leads to type-1 fuzzy sets called the type-reduced sets. After the type-reduction process, the type-reduced sets are defuzzified to obtain crisp outputs that are sent to the actuators [9]. It has been argued that using interval type-2 fuzzy sets to represent the inputs and/or outputs of FLCs has many advantages when compared to type-1 fuzzy sets; we summaries some of these advantages as follows:

- As the type-2 fuzzy set membership functions are themselves fuzzy and contain a footprint of uncertainty, they can model and handle the linguistic and numerical uncertainties associated with the inputs and outputs of the FLC. Therefore, FLCs that are based on type-2 fuzzy sets will have the potential to produce a better performance than type-1 FLCs when dealing with uncertainties.
- Using type-2 fuzzy sets to represent the FLC inputs and outputs will result in the reduction of the FLC rule base when compared to using type-1 fuzzy sets as the uncertainty represented in the footprint of uncertainty in type-2 fuzzy sets lets us cover the same range as type-1 fuzzy sets with a smaller number of labels. The rule reduction will be greater as the number of the FLC inputs increases.
- Each input and output will be represented by a large number of type-1 fuzzy sets which are embedded in the type-2 fuzzy sets. The use of such a large number of type-1 fuzzy sets to describe the input and output variables allows for a detailed description of the analytical control surface as the addition of the extra levels of classification gives a much smoother control surface and response.
- It has been shown in [10], [11] that the extra degrees of freedom provided by the footprint of uncertainty enables a type-2 FLC to produce outputs that cannot be achieved by type-1 FLCs with the same number of membership which will be verified latter.

3. Direct torque control.

In the mid 1980's the DTC was introduced for induction motor by Takahashi et al.[12]. In the 1990's, DTC for PMSM was developed [13]. Compared with Field Oriented Control, the DTC has many advantages such as less machine parameter dependence, simpler implementation and quicker dynamic torque response. There is no current controller needed in DTC, because it selects the voltage space vectors according to the errors of flux linkage and torque. Although DTC is getting more and more popular, it also has some drawbacks, such as the high torque and flux ripples. Many researchers already paid some attention to these problems. For example, Casadei et al.[14] replaced one switching table with more switching tables; which are called discrete space Vector modulation.. Takahashi et al. [15] proposed new inverter structure; and Mei et al. [16] used variable switching sector to minimize the torque and flux ripple.

The vector control system for motor drive has been widely used because of their advantages such as simplicity, rugged structure, reliability, high maintainability and economy. However the vector control technique incorporating fast microprocessor and digital signal processing have made possible the application of motor drive system using a position/speed sensor for high performance drives. Due to sophisticated and large computational time DTC recognized as a viable solution to achieve these requirements and reduce the complexity of vector control.

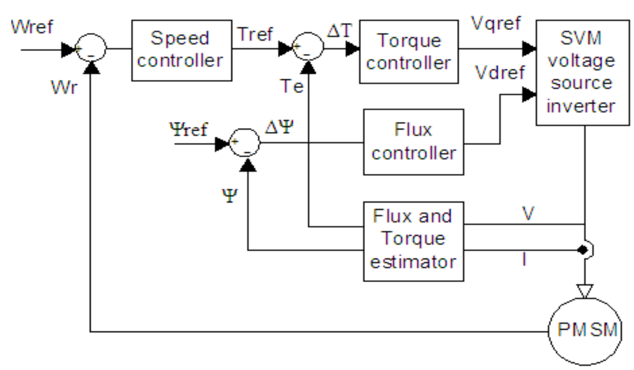


Fig5. Block diagram of a PMSM drive with DTC-SVM system

4. Mathematical model of PMSM

The stator flux linkage vector ψ_s and rotor flux linkage ψm can be drawn in the rotor reference frame (*d-q*), stator reference frame (*ds-qs*) and stationary reference frame(α-β) as in Fig. 6. [17].

$$vd = rs.id - wr\psi q \quad (1)$$

$$vq = rs.iq + wr\psi d \quad (2)$$

$$\psi d = Ld.i \quad (3)$$

$$\psi q \quad (4)$$

$$Tc = \frac{3}{2}\, p\, (\psi d.\, iq - \qquad (5)$$

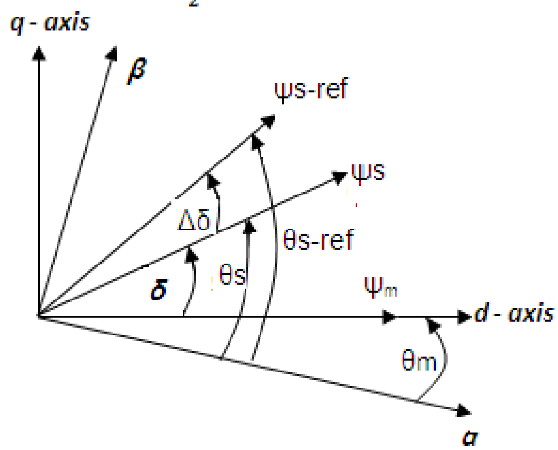


Fig.5. The stator and rotor flux linkages in different reference frame

Where *vd*, and *vq* are the *d-q* axis voltages, *id* and *iq* are the d-q axis stator currents, *Ld* and *Lq*, are the *d-q* axis inductances, , and , are the *d-q* axis stator flux linkages, is the stator resistance per phase, the rotor speed and , is the stator flux linkage due to the rotor magnets. By transforming the rotor reference flux component ψd, *ψq* and current *id, iq* to the stator reference flux component ψds, *ψq*s and current component *ids, iqs* with the transformation (6) and (7), torque (5) can be transformed as in (8).

$$\begin{bmatrix} ids \\ iqs \end{bmatrix} = \begin{bmatrix} \cos\delta & si \\ -\sin\delta & cc \end{bmatrix} \qquad (6)$$

$$si \quad \text{and} \quad co \qquad (7)$$

$$Te = \frac{3}{2}\frac{1}{Ls}\, p\, |\psi s||\psi \qquad (8)$$

$$\psi s = \int (vs - \qquad (9)$$

Equation (8) means that the electromagnetic torque can be controlled by controlling the load angle δ if the amplitude of the stator flux linkage (ψs) is kept constant, neglecting the variation of ψs torque variation can be expressed as

$$\Delta Te = (\frac{3}{2}\frac{1}{Ls}\, p\, |\psi s||\psi m|\, cc \qquad (10)$$

Equation (10) shows that to increase torque, δ should be increased; to increase δ stator flux should turn faster than rotor flux by the selection of optimum voltage vector according to difference between the reference and actual values of torque and flux [18].

5. CONTINUOUS SPACE VECTOR MODULATION

An inverter is nowadays commonly used in variable speed AC motor drives to produce a variable three phase, AC output voltage from a constant DC voltage. The main advantages of the space vector modulation (SVM) are: A 15% increase in DC link voltage utilization compared with the sine-triangle technique. Lower harmonic content, particularly at high modulation indices compared with the sine-triangle technique.

For a three-phase voltage source inverter each pole voltage may assume one of two values depending on whether the upper or lower switch is turned on. Consequently, there are only eight possible states (s0, s1, …,s7) for the three-phase voltage source inverter. These different states are illustrated in Fig (7)

It emerges that the eight-inverter states comprise six active states, state 1 to state 6 and two zero states, state 0 and 7. The six active states occur when either one upper and two lower or two upper and one lower switch conduct simultaneously. The zero states occur when either the three upper or the three lower switches are turned on. In one sampling interval, the output voltage vector can be written as

$$U = \frac{t0}{Ts}U0 + \frac{t1}{Ts}U1 + \cdots \qquad (11)$$

Where t_0, t_1,………, t_7 are the turn-on time of the vectors,U0,…..,U7 , t_0, t_1,….., $t_7 \geq 0$, $\sum_{i=}^{i=}$ and Ts is the switching time.

However, In order to obtain optimum harmonic performance and the minimum switching frequency for each of the power devices, the state sequence is arranged such that the transition from one state to the next is performed by switching only one inverter leg, then a vector U is commonly split into the two nearest adjacent voltage vectors and zero vectors U0 and U7. In an arbitrary sector for example, in sector I, in one sampling interval, vector U can be expressed as Fig. 7.

$$U = \frac{T1}{Ts}U1 + \frac{T2}{Ts}U2 + \frac{T0}{Ts}U0 \qquad (12)$$

$$T_s - T_1 - T_2 = T_0 + T_7 \quad (13)$$

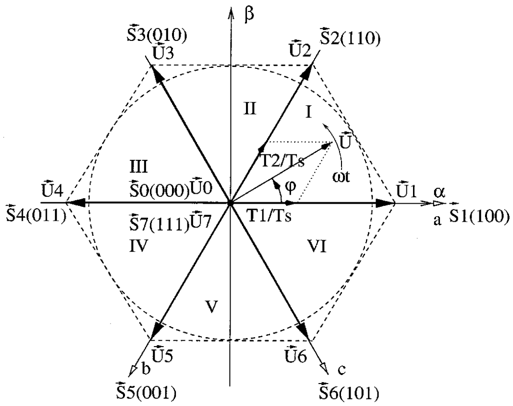
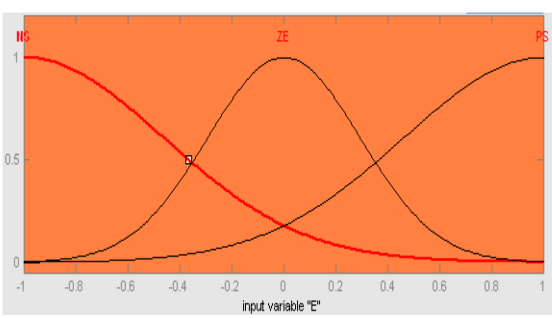


Fig7. Voltage vector space

6. Fuzzy logic controllers.

A standard approach for speed control in drives is the use of a PI controller. Recent developments in artificial intelligence based control have brought in to focus a possibility of replacing a PI controller with a fuzzy logic (FL).

The membership functions for input and output variables for the PI-type fuzzy type-2 and type-1 with the same number of memberships in the input and output Fig. 8, Fig. 9 are error (*E*), change of error (*ΔE*), and change of torque (*ΔT*) are used to compare the response of fuzzy type-1 and fuzzy type-2.



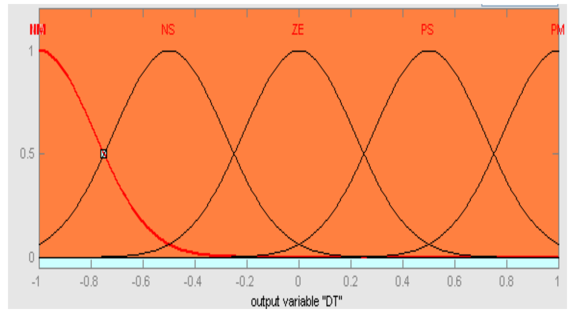
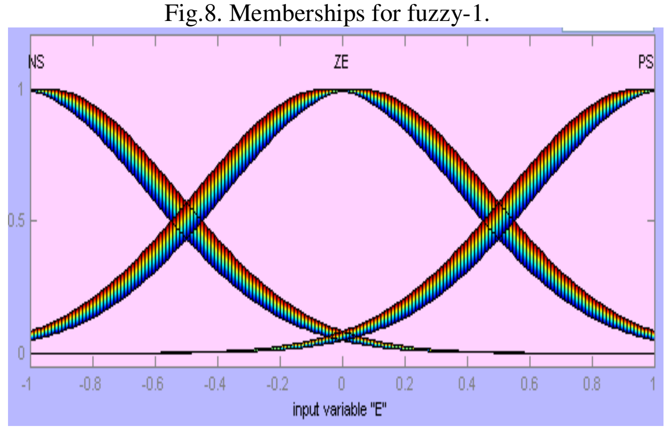


Fig.8. Memberships for fuzzy-1.



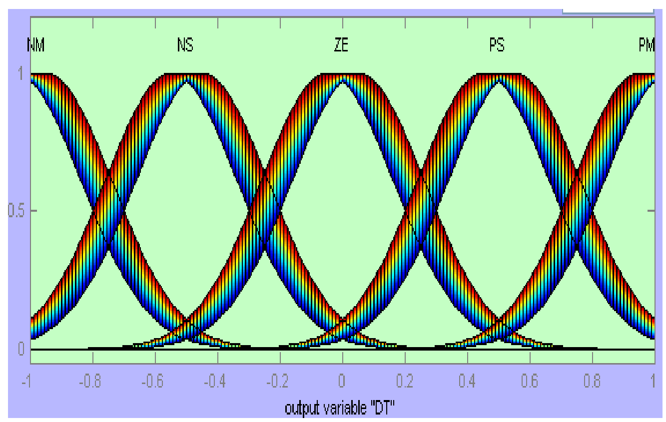


Fig.9. Memberships for fuzzy type-2.

7. Simulation parameters and results.

There are many control strategies for DTC PMSM drives [19]. Fuzzy typ-1 was used in control of DTC PMSM drives and now we apply fuzzy type-2.

FL controller is used for speed loop, torque and flux loops controllers are of conventional PI controller type.

The system is modeled with MATLAB SIMULINK using fuzzy logic toolbox and pmsm data in appendix (A), with switching time Ts=0.0002sec.

Fig. 10 and Fig. 11 shows the speed response at speed reference (Wref) (157 rad/sec), Fig. 12 and Fig. 13 shows the load torque response (TL) at load step change from 0.25 NM to 0.4 N.M at 1 sec time, Fig. 14 and Fig. 15 shows the flux response at reference stator flux value 0.0826 (Wb), and the current response shown in the Fig.16 to Fig. 19 with fuzzy type-1 and fuzzy type-2 controllers with the same number of memberships [10], [11].

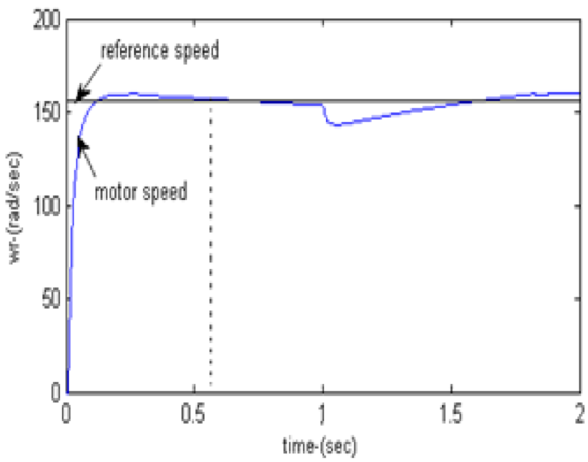


Fig.10. Speed response with fuzzy type-1 speed controller.

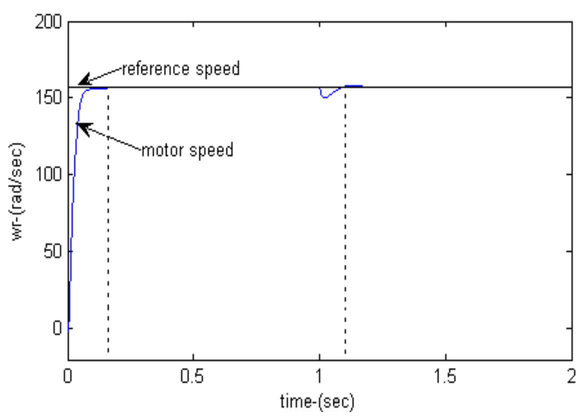


Fig.11. Speed response with fuzzy type-2 speed controller

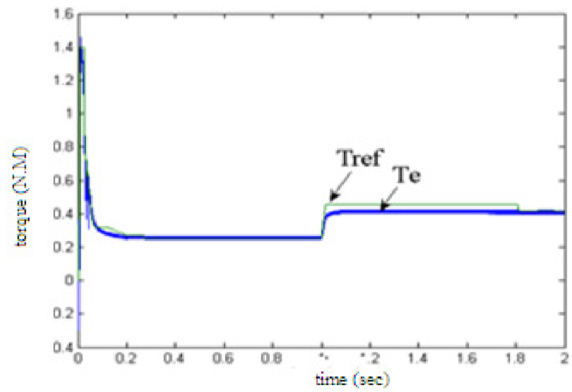


Fig.12. Torque response with fuzzy type-1 speed controller

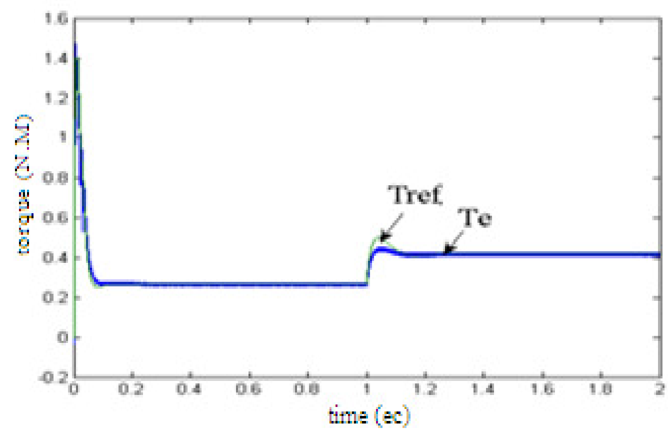


Fig.13. Torque response with fuzzy type-2 speed controller

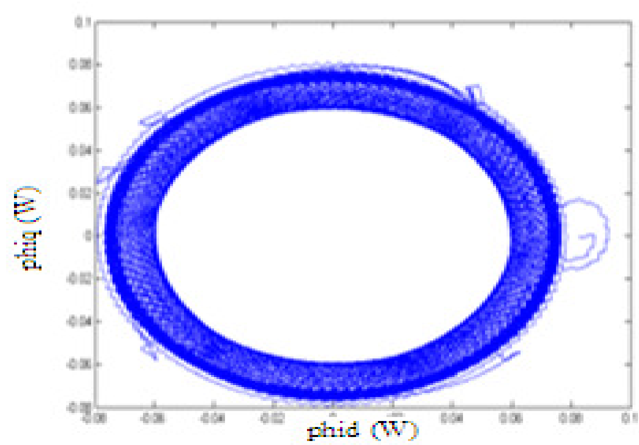


Fig.14. Flux response with fuzzy type-1 speed controller

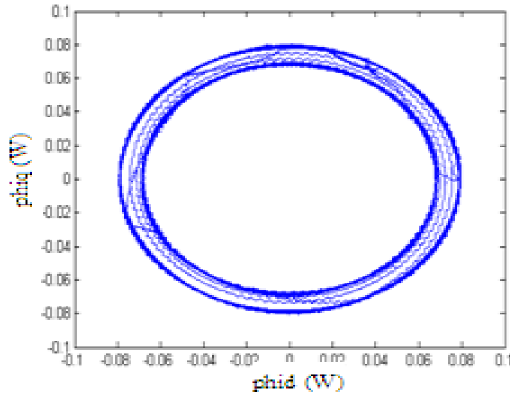


Fig.15. Flux response with fuzzy type-2 controller

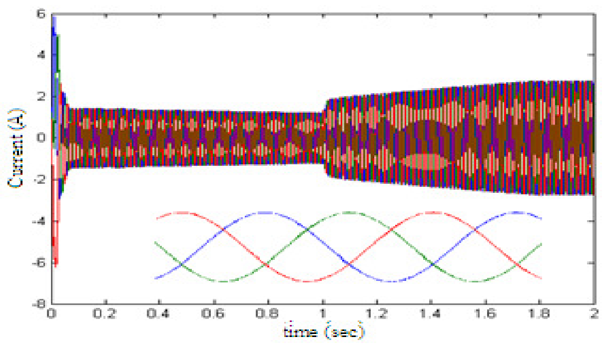


Fig.16. Three phase current with fuzzy type-1 speed controller

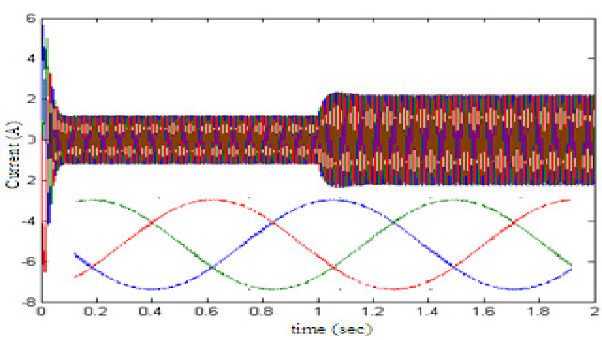


Fig.17. Three phase current with fuzzy type-2 speed controller

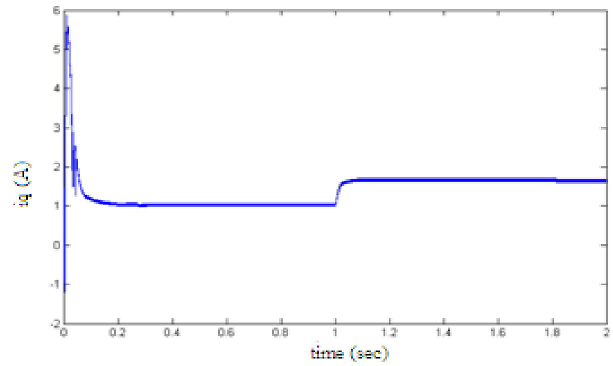


Fig.18. Motor current (iq) with fuzzy type-1 speed controller

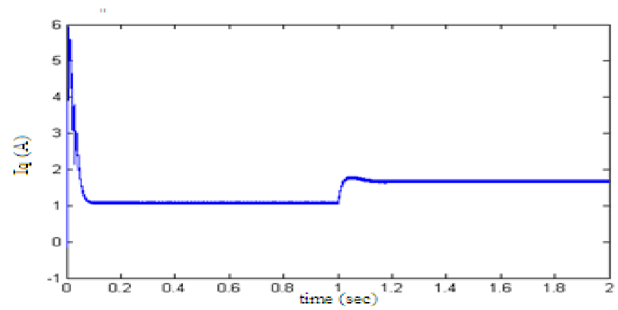


Fig.19. Motor current (iq) with fuzzy type-2 speed controller.

8. Conclusions

In this paper a Fuzzy typy-2 is proposed that provide additional degrees of freedom making it possible to better model and handle systems uncertainties.

DTC-SVM is proposed a viable solution to reduce a current torque and flux ripple in conventional DTC. The PMSM machine model and DTC equation and analysis have been derived. The drive system component has been simulated and tested using MATLAB SIMULINK. Simulation is performed and comparison study for Fuzzy type-1controller and Fuzzy type-2 controller are presented.

It has been shown by replacing the fuzzy type-1 controller by fuzzy type-2 with the same number of memberships the system operation more smooth and reaches steady state faster Fig. 10 to Fig. 19, but the fuzzy type-2 need large computational time.

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APPENDIX (A)

PMSM Data

Power =100 watt.
R =3.4 ohm
Ld =12 mH.
Lq =12 mH.
J =0.0002 Kg-m2.
B =0.0001 (N.m)/rad/sec.
Ym =0.0826 Volt/rad/sec.
Vdc =52.7 volt.
Ts =0.0002 sec.
2p =4

APPENDIX (B)

LIST OF SYMBOLS

Iq Indirect current component in rotor coordinate system
Id Direct current component in rotor coordinate system
Iqs Indirect current component in stator coordinate system

Ids Direct current component in stator coordinate system
Iβ Indirect current component in stationary coordinate system
Iα Direct current component in stationary coordinate system
L Inductance
wr Motor speed
P Number of pole pair.
p Differentiation coefficient
rs Stator resistance
Te Electromagnetic torque
vd Direct voltage component in rotor coordinate system
vq Indirect voltage component in rotor coordinate system
Ψm Flux of Permanent Magnet
ó Load angle
θm Rotor angle