Evaluation of SMC Synchronous Motor Using Soft Magnetic Compounds and Direct Fuzzy Torque Control

H. Refahi[1*]

Abstract –About 60% of industrial electrical energy is consumed by electric motors. Hence. Extensive efforts have been adopted in order to increase the efficiency of these motors under different operating conditions. Among these motors, the use of three-phase synchronous motors, made of Soft Magnetic Composites (SMC) type, has been growing up in the world during the past decade. The optimal efficiency of these motors is highly sensitive to their mathematical model parameters. In this article, first, the performance of SMC motors is evaluated in detail and the corresponding pros and cons are highlighted in different fields. Then, a mathematical model based on exhaustive simulation, is presented for an SMC motor using Fuzzy Inference Systems (FIS). Given that torque and speed as the outputs, nonlinear methods based on FIS are used. To do so, we assume that only one input at a time can go through the FIS model to account for the input/output relationships. Last but not the least, the parametric model of the motor is cross-evaluated using exhaustive simulation in MATLAB/Simulink.

Keywords: Soft Magnetic Composites Machines (SMC), soft magnetic compounds, synchronous motor.

I. Introduction

Since most of the world's generated electrical energy is consumed by electrical motors, there has been accented attention to the reduction of their losses and performance optimization. As of to date, there have been greatly important and many efforts in order to create electric motors with low weight, high efficiency and small size for optimization of torque-speed of synchronous motors. The advances in materials science have provided the ability to produce high quality materials of soft magnetic compounds (SMC). As the production cost of SMCs are roughly equal or less than the steel sheets, therefore, a new perspective was embodied in the design of electric motors since mid-80s upon entering SMCs into market [1].Due to attractive property of SMCs in keeping eddy current very low, these materials are appropriate for making the cores of AC electric motors, resulting in more compact and small electrical machines.

II. Structure of soft magnetic compounds (SMC)

1* **Corresponding Author :** Electrical and Electronic Engineering Department, Shahed University, Tehran, Iran,
Email: h.refahi@shahed.ac.ir
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Chemically, matters are characterized by their atomic as well as mass numbers. Atomic number indicates the number of protons in that element and mass number indicates the total number of neutrons and protons [2]. Materials with two or more mass numbers are known as isotopes. These materials may exist either naturally or synthetically. Isotopes of an element have similar chemical properties but some or all of their physical properties are different; in case of core of the used iron, composed magnetic core is isotope.

A. The basic and raw materials used in the manufacture of SMC

The main raw materials for the production SMC are iron powder with high purity and compression; alloy powders are sometimes used based on the needs according to Table 1[3].

Table 1: curve of magnetic material losses

Row	Alloy Name
1	Fe – Ni
2	Fe – Si
3	Fe_3 P
4	Fe – Si – Al

These alloys have special significance in mixtures and have special applications. They exist in general magnetic isotope due to their powder nature, and are appropriate for manufacture of electrical devices with three-dimensional magnetic flux. These magnetic isotopes have features which can be used to design magnetic circuits with three-dimensional paths.

III. Method of manufacturing SMC cores

Iron powder is the base of soft magnetic compounds. Powder particles are covered with a layer of electrical insulation with high electrical resistance. Then, the covered powder is pressed in form of ingots and placed on desired cover by heating. Iron turns into powder to an extent that each particle can alone be capable of magnetization. Then, each particle is turned into insulation using advanced technique. Now, particles can be turned into permanent magnet or can be used without manipulation according to the intended application. These materials can be compressed in desired form without any restrictions; shapes which seemed impossible to manufacture otherwise by machine designers can be achieved in this way.

IV. Advantages and disadvantages of soft magnetic compounds (SMC)

The benefits of replacing conventional laminated cores with soft magnetic substances are listed in table (2).

Table 2: Benefits of soft magnetic components

Row	Advantages
1	Copper backfilling factor increase (66% vs. 33% normal)
2	Increasing the compression ratio of iron
3	Reducing the air gap
4	Reducing the volume of copper as a result increasing backfilling factor and reducing the length of windings
5	Reducing copper losses as a reduction of reduction in volume of copper
6	Reduction of wave losses (obtained from) indentations in high frequency
7	Ability to create three-dimensional flux pattern in SMC materials
8	Lack of requirement to fuzzy insulation as a result of using non-overlapping windings
9	Savings costs for manufacturing up to 50%compared to the laminated core in SMC materials

V. Disadvantages of soft magnetic compounds (SMC)

Fig. 1 and 2 compare the magnetic and loss properties of electrical steel and SMC. It can be observed that SMC materials are inherently weaker than electrical steel in terms of these properties. In order to compensate for these disadvantages, the designed machine should be manufactured with SMC materials using short magnetic path length and low weight [4].

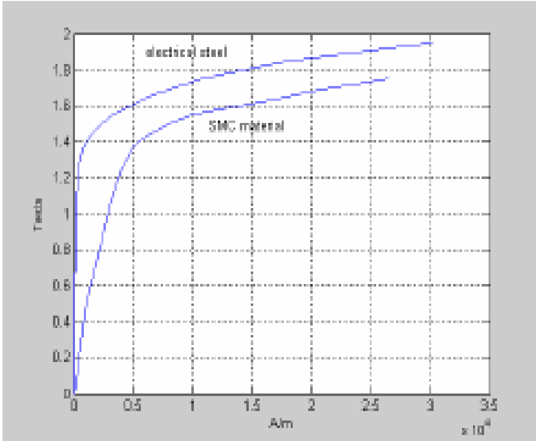

Fig. 1: B-H curve of SMC Materials

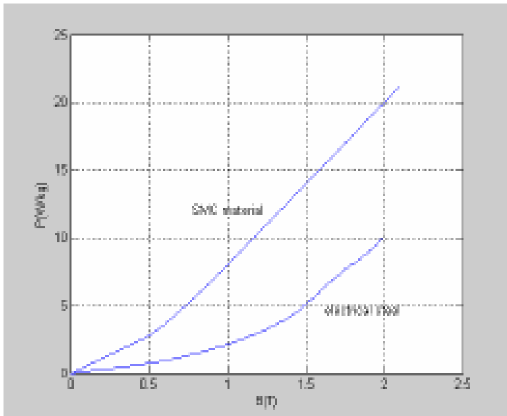

Fig. 2: curve of magnetic losses for SMC Materials

VI. Limitations of conventional windings of three-phase synchronous motors

A. Evaluation of limitations of three-phase windings with a pitch of 60 °[5]

Conventional windings of AC stator either overlap or are concentric which are expanded along the winding between 1, 2 and 3 poles pitch so the maximum flux is obtained. A stator created with a similar manner using SMC materials, the corresponding slot packing factor will not be significantly different compared to laminated stator. Such a device will surely have a weak performance. Because low permeability of SMC will lead to magnetizing current penalty which cannot be overcome without using copper. We can achieve high compression ratio only when each indentation is directly wrapped in a method known as "race track". Hence, an important distinction between ordinary and SMC machines is the need for wrapping wire around each indentation (prong), which has its own disadvantages [6].

Diagram 1 shows MMF created by a simple three-phase winding with a pitch of 60 degrees (one slot per each pole in each phase) [7].

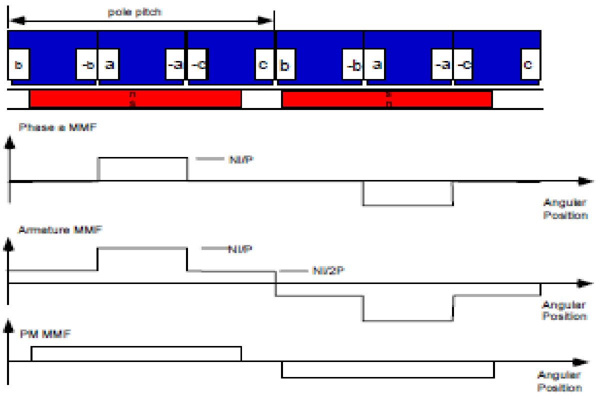

Diagram 1: created MMF

Winding factor is obtained for main component of MMF using formula related to conventional machine design by a simple three-phase winding with a pitch of 60 degrees,

$$k_1 = \sin(\frac{\gamma}{2}) = \frac{1}{2} \tag{1}$$

Whereby is the length of the wire in terms of radians when short wire is used. Also, six indentations of structures are wrapped for each pair of poles and as a result, assembly of stator's structure will be relatively complicated.

VII. Fuzzy logic

Fuzzy Logic has recently emerged as an attractive field in control researches. The most important principle of fuzzy controllers is the use of the language Knowledge of exports in their structures [8]. There are several methods to use the human knowledge in fuzzy systems. Here, Mamdani fuzzy controller has been used. As it can be seen in fig. 1, a fuzzy controller has four parts; two parts of it perform the task of conversion: Fuzzy maker (first conversion), database, fuzzy inference engine and debugger (second conversion) .Fuzzy maker turns input variables (real signals) into fuzzy ones. Database includes basic information and languages rules. It provides information required in determination of linguistic rules. Database (expert rules) provides the main purpose of control by a set of language control rules. The inference engine is the brain of a fuzzy logic controller and is capable of simulating human decision making in fuzzy form. It is capable of concluding fuzzy control function using fuzzy logic rules. The second conversion, i.e., the one performed by fuzzy debugger, converts fuzzy value output of inference engine into actual and numerical values by membership function [9]. Again, different techniques exist for defuzzification; the method of mean centers is used for ease of use due to its greater simplicity.

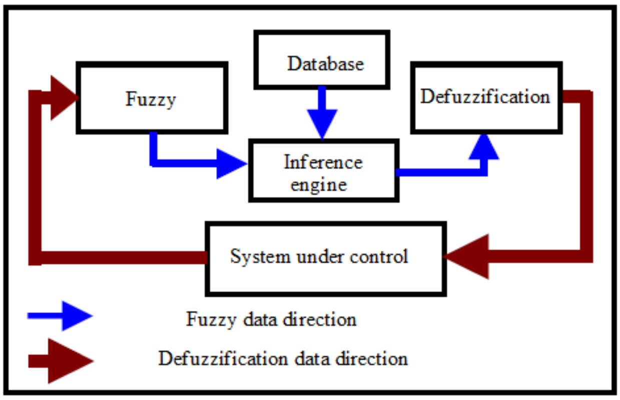

Fig. 3: block diagram of a control system with fuzzy controller

VIII. The principles of Direct Torque Control

In this method, a SMC synchronous motor is fed by a voltage source inverter; the stator flux linkage and electromagnetic torque are controlled directly by optimal voltage switching vectors of the inverter. The main purpose of selecting voltage switching vector is to obtain the fastest response of the electromagnetic torque. The active switching vectors (u1, u2, . . . , u6) are shown in fig. 5. In fig. 4 , electromagnetic torque and stator linkage flux errors are, respectively, inputs to the hysteresis torque and flux linkage comparators.[10] Flux linkage and electromagnetic torque comparators are, accordingly, three-level and two level comparators.

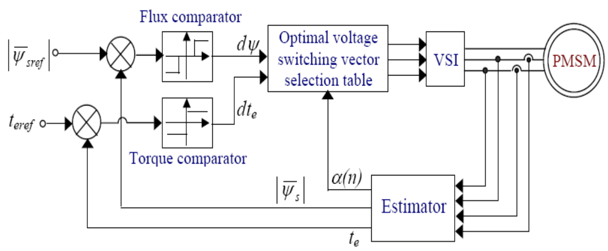

Fig. 4: Direct control of flux linkage and electromagnetic torque of synchronous motor fed by VSI, control design

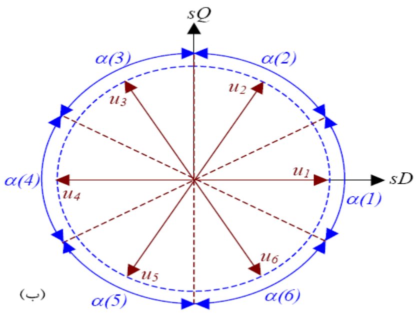

Fig. 5: Direct control of flux linkage and electromagnetic torque of synchronous motor fed by VSI, Six vectors of discrete outputs of hysteresis comparators

(D_ψ, dt_e) are inputs of the optimal voltage switching table. Although information related to the position of stator's flux linkage space vector is a different input to the switching table inputs. Figure 5 shows six voltage switching vector with six sectors.

IX. Simulation results

Figure 6 shows the overall block diagram of fuzzy direct torque controller designed for the permanent magnet synchronous motor. Inputs of fuzzy system are stator flux linkage and torque errors; the flux linkage angles and their fuzzy counterparts are shown in figures 4 to 5 based on direct torque control theory. Fuzzy output is space vector of switching voltage whose fuzzy membership functions have been shown in Figure 7which are adopted similar to the input membership functions. The Fuzzy rules of the controller are listed in table 3[11]. The results of the simulation have been shown in figures 7 to 9.

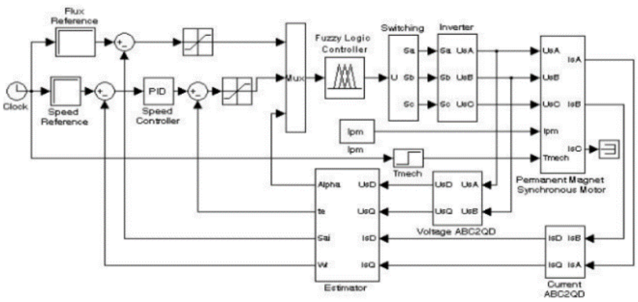

Fig. 6: general block diagram of fuzzy direct torque control of a synchronous motor

Table 3: fuzzy rules

Fuzzy Rule Base		$d\psi=N$		$d\psi=P$	
		$dt_e=N$	$dt_e=P$	$dt_e=N$	$dt_e=P$
α	Z	V_5	V_3	V_6	V_2
	PS	V_6	V_4	V_1	V_3
	PM	V_1	V_5	V_2	V_4
	NL or PL	V_2	V_6	V_3	V_5
	NM	V_3	V_1	V_4	V_6
	NS	V_4	V_2	V_5	V_1

Figures 7 to 9 are, respectively, reference and actual flux of stator, Electromagnetic torque, Reference and actual rotor speed, flux of first phase of stator, and voltage of first phase of stator, all versus time; the direct axial flux of stator compared with the stator's vertical axis flux has also been shown[12].

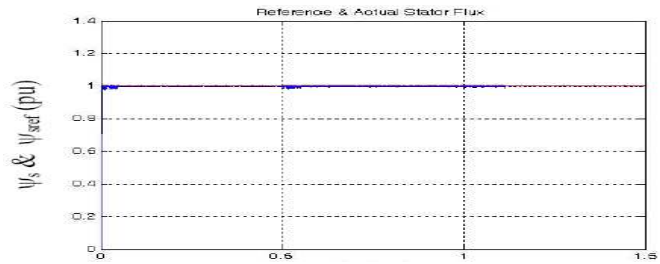

Fig. 7: reference and actual flux of stator versus time

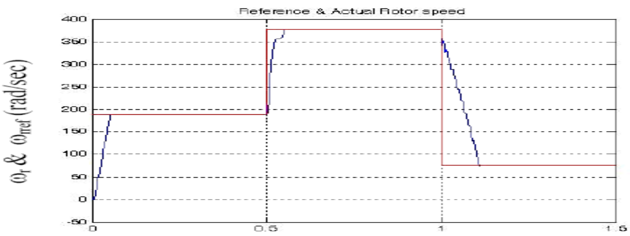

Fig. 8: Reference and actual rotor speed versus time

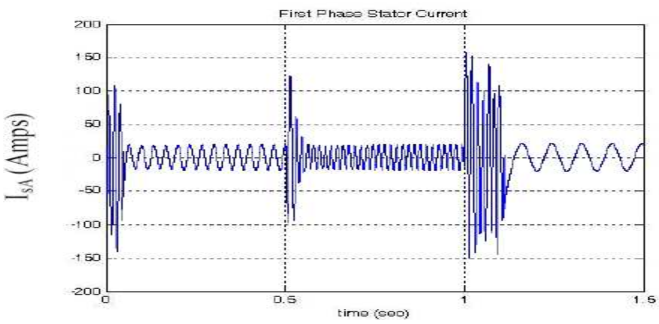

Fig. 9: flux of first phase of stator versus time

We have compared the results of applying the proposed fuzzy based control against the traditional control. To this end, the inputs assumed to be unit step functions for the speed and stator flux linkage. The desired outputs are speed and congruent ripples of the speed error, ripples of torque, stator flux linkage and stator current. It should be noted that these results have been obtained in almost identical switching frequency [13-14]. In other words, since reduction of the comparator hysteresis can reduce fluctuations (this will increase switching frequency), fuzzy method has reduced these fluctuations without any changes in the frequency. Table 4 evaluates the simulation results for direct control of conventional as against the fuzzy torque control [15].

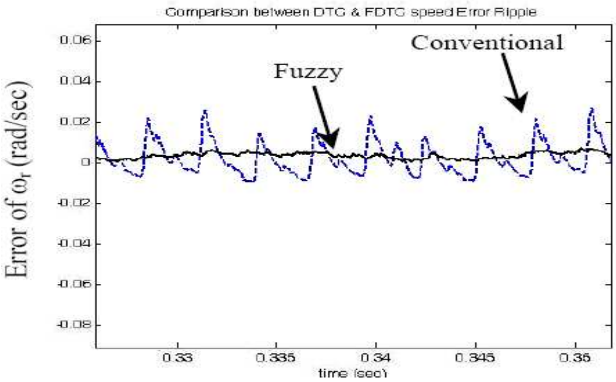

Fig. 10: comparison of ripples in speed error in direct conventional and fuzzytorques cotrols

Table 4: comparison of the results of simulation in the conventional and fuzzy torques controls

	Speed Ripple	*Rise Time*	*Flux Ripple*	*Torque Ripple*
Fuzzy	*0.002*	*0.0965*	*0.003*	*0.5*
Conventional	*0.03*	*0.0977*	*0.06*	*1.3*

V. Conclusion

In Electrical machines with three-dimensional magnetic flux are needed for high efficiency motor applications. At the same time, new applications requiring high operating frequencies are becoming more relevant and also available. Soft magnetic powder composites (SMC) are the upcoming development in the powder metallurgy, offering optimal magnetic properties at elevated frequencies and contributing to the increase of the power density as well as miniaturization of electric machines. This makes SMC perfect for applications with limited space e.g., in the automotive industry and robotics or selected home appliances. In these applications SMC can even outperform the commercially available electrical steels.

In general it can be concluded that use of SMCs has opened a promising wide horizons for design of electrical machines with different topology for involved utilities in the field of electric machines in a way that they can hope to have more compact machines with high efficiency and low cost of production and maintenance. However, quick replacing steel sheets with SMC materials is not generally logical; thus, researches must focus on production optimization and optimal design tools in order to compensate for inherent weaknesses of SMC materials.

References

[1] H.Yuwen, T.Cun, G.Yikang, .Zhiqing, L.X.Tang, M.F.Rahman, "In-depth research on direct torque control of permanent magnet synchronous motor", IEEE 2002 28th Annual Conference of the Industrial Electronics Society, Vol. 2, 5-8 Nov. 2002,Page(s):1060

[2] L.Zhong, M.F.Rahman, W.Y.Hu, K.W.Lim, M.A.Rahman, "A direct torque controller for permanent magnet synchronous motor drives", IEEE Transactions on Energy Conversion, Vol. 14, Issue 3, Sept. 1999 Page(s):637 – 642.

[3] D.Swierczynski, M.P.Kazmierkowski,"Direct torque control of permanent magnet synchronous motor (PMSM) using space vector modulation (DTC-SVM)-simulation and experimental results", IEEE 28th Annual Conference of the Industrial Electronics Society, Vol. 1, 5-8 Nov. 2002 Page(s):751 - 755.

[4] Yicheng Chen SiemensAtlantayicheng.chen@siemens.com Pragasen Pillay, FIEEE Department of Electrical & Computer Engineering Clarkson University Potsdam, NY 13699-5720, USApillayp@clarkson.edu

[5] V. IANCU, T. CANTA, D.C. POPA, L. SZABÓ Technical University of Cluj-Napoca, 400020 Cluj-Napoca, 15 Daicoviciu, Romania

[6] Brod D.M. “Current control of VSI PWM Inverter “IEEE Trans. Ind. APPL. Vol.IA. 21, PP. 562-570, May-June 1985.

[7] Huy H. "A self Controlled synchronous Motor Drive Using Terminal Voltage system” IEEE Trans. Ind. APPL. Vol. IA 18. No.1, PP. 46-53, Jun - Feb, 1982

[8] Cornell E.P. and No votni D.W, “Commutation by Armature Induced Voltage in self-controlled synchronous Machines ", IEEE Trans. Ind. APP. Vol.A. 20. PP. 760-766, Feb, 1979

[9] Rashid M.H.: “Power Electronics”, Prentice – Hall, New jersey 1988

[10] L. Zhong, M. F. Rahman, W. Y. Hu, K. W. Lim, “Analysis of direct torque control in permanet magnet synchronous motor drives”, IEEE Transactions on Power Electronics, vol.12, no.3, pp. 528-536, 1997.

[11] Siemens AG, “Permanent magnet excited synchronous motor”, Siemosyn Motor Catalog DA•48, 2003.

[12] Soltani, C. salvation, the "three-phase salient pole synchronous motor vector control with pulse width modulation voltage source inverter fed", independence, 1377, 20 Isfahan University of Technology, No. 2, pp 1-20, 1377.

[13] Mohammad Reza Zarei, M. boundaries, Seyed Morteza-E race to determine optimal parameters salient pole synchronous motor vector control algorithm using fuzzy - genetic.

[14] K. Minoru, “Application of permanent magnet

synchronous motor to driving railway vehicles", Railway Technology Avalanche, vol.1, no.1, pp. 6, 2003.

[15] S. Özçıra, "Control methods and industrial applications of permanent magnet synchronous motors", M.S. Thesis, Advisor. Bekiroglu, N. Asst. Prof, Yildiz, Technical University, Istanbul, Turkey, 2007.