Analysis of Fuzzy Logic Controlled Permanent Magnet Synchronous Motor (PMSM) Drive

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ABSTRACT
Recent development in power semiconductor technology, digital electronics, magnetic materials and control theory have enabled modern AC motor drives to face challenging high efficiency and high performance requirements in the industry. The Permanent Magnet Synchronous Motors (PMSM) is becoming popular in high performance applications compared to other types of AC motors due to its advantages features including high torque to current ratio, higher efficiency, low noise and robustness [1]. Fuzzy logic control is one of the most interesting fields where fuzzy theory can be effectively applied. Fuzzy logic techniques attempt to imitate human thought processes in technical environments. This paper presents a study on fuzzy rule-base of fuzzy logic controlled permanent magnet synchronous motor (PMSM) drive. Fuzzy rule-base design is viewed as control strategy. All fuzzy rules contribute to some degree in obtaining the desired performance. However, some rules fired weakly do not contribute significantly to the final result and can be eliminated. In this case total 27 rules are designed. Simulation results that verify appropriateness of the approach are included. Fuzzy logic based motor stator condition monitoring control of PMSM drive is presented in this paper.

Keywords

PMSM; fuzzy logic, current controller

1.INTRODUCTION
Permanent magnet synchronous motors(PMSM) are gaining increasing importance in recent years in industrial drive applications ranging from small servo drives to high performance machine tool drives[2].The Permanent Magnet Synchronous motor (PMSM) is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the Permanent Magnet Synchronous motor is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors. Basically, a current controller is usually preferred to follow the current command in some apparatus. These apparatus can be ac motor drives, active filters, UPS, and so on. Due to the application requirements and the advances of power electronics, current controller techniques have become an intensive research subject and various techniques for current controller have been proposed in recent years. Fuzzy logic is recently finding increasing applications that include management, economics, and medicine and recently in closed loop operation of variable speed drives. The objective of the fuzzy control is to design a system with acceptable performance characteristics over a wide range of uncertainty. The fuzzy control is basically nonlinear and adoptive in nature, giving robust performance in the face of parameter variation and load disturbance effects.

The paper is organized as follows: Section 2 presents the mathematical model of the PMSM. 3. Speed control of PMSM ,Section 4 consist of fuzzy system input output variables. Sections 5 and 6 have the results and conclusion, respectively.

2. MATHEMATICAL MODEL
The equations of PMSM are in rotating reference frames. The stator of the PMSM and the wound rotor synchronous motor are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistively, so induced currents in the rotor are negligible. In addition, there is no difference between the back EMF produced by permanent magnet and that produced by an excited coil. Hence the mathematical model of PMSM is similar to that of the wound rotor Synchronous Motor [9]. The model of the PMSM is developed using the following assumptions.

1. Saturation is neglected
2. The induced EMF is sinusoidal
3. Eddy current and hysteresis losses are negligible
4. There are no field current dynamics.

With these assumptions, the stator d, q equations of the PMSM in the rotor reference frame are [10],

$$V_q = R_s i_q + L_q p i_q + \omega_r L_d i_d + \omega_r \varphi_f \text{ ------------------(1)}$$

$$V_d = R_s i_d + L_d p i_d - \omega_r L_q i_q \text{ --------------------------(2)}$$

Also flux linkage equation can be written as,

$$\varphi_d = L_d i_d + \varphi_f \text{ ---(3)}$$

$$\varphi_q = L_q i_q \text{ ---(4)}$$

Where V_d and V_q are the d, q axis voltages, i_d , i_q are the d, q axis stator currents, L_d, and L_q are the d, q axis inductances, φ_d and φ_q are the d, q axis stator flux linkages, R_s is the stator winding resistance per phase and ω_r is rotor electrical speed. The electro mechanical torque is given by

$$T_e = (3/2)(P/2)[\varphi_f i_q - (L_d - L_q) i_d i_q] \text{ -----------(5)}$$

and the equation of motor dynamics is,

$$T_e = T_L + B\omega_m + Jp\,\omega_m \text{ -----------------------------(6)}$$

Where

P is the number of poles,
TL is the load torque,
B is the damping co-efficient,
ωm is the rotor mechanical speed,
J is the moment of inertia
p is the differential operator.

$\omega r = (P/2)\ \omega m$ ---(7)

The model equations of PMSM can be rearranged in the form of following first order differential equations as [11],

$pid = (Vd - Rsid + \omega r\ Lq\ iq)\ /Ld$ ------------------------(8)

$piq = (Vq - Rsiq - \omega r\ Ld\ id - \omega r\ \varphi f)\ /\ Lq$------------- (9)

$p\omega m = (Te - TL - B\ \omega m)\ /\ J$ (10)

$p\theta m = \omega m$ --(11)

$\theta m = \int \omega m$--- (12)

θm is the position angle of rotor.

In order to achieve maximum torque per ampere and maximum efficiency with linear characteristics, direct axis current component id forced to zero [12] and the reluctance torque is zero.

$Te = (3/2)\ (P/2)\ \varphi f\ iq$ --(13)

The d, q variables are obtained from a, b, c variables through the park transform as [13],

$Vq=2/3[Va\cos\theta+Vb\cos(\theta-2\Pi/3)+Vc\cos(\theta+2\Pi/3)]$ ---(14)

$Vd=2/3[Va\sin\theta+Vb\sin(\theta-2\Pi/3)+Vc\sin(\theta+2\Pi/3)]$ ----(15)

The a, b, c variables are obtained from the d, q variables through the inverse of the park transform as,

$Va = Vq\cos\theta + Vd\sin\theta$---------------------------------- (16)

$Vb = Vq\cos(\theta-2\Pi/3) + Vd\sin(\theta-2\Pi/3)$ ---------------(17)

$Vc = Vq\cos(\theta+2\Pi/3) + Vd\sin(\theta+2\Pi/3)$ --------------(18)

The torque equation is similar to that of separately excited DC motor, and this completes the transformation of a PMSM to an equivalent separately excited dc motor [13].

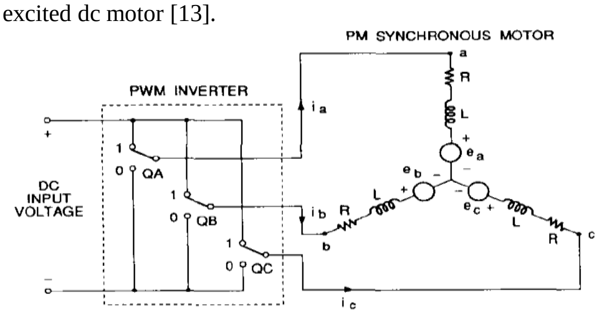


Fig 1 Equivalent circuit of drive

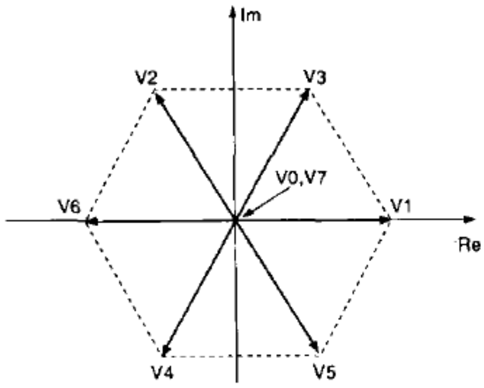


Fig 2 Inverter voltage space vectors.

3. SPEED CONTROL OF PMSM

For the speed control of PMSM, many controllers are used. In conventional P, PI and PID controllers, very fine tuning is required which cannot cope up with system's parameter variations. Also the performance of such controllers is affected due to variations in physical parameters like temperature, noise, saturation etc. Many control systems use adaptive controllers for PMSM, which can track only linear systems. Therefore, fuzzy logic based controller may be used to achieve more accurate and faster solutions and to handle complicated non-linear characteristics.

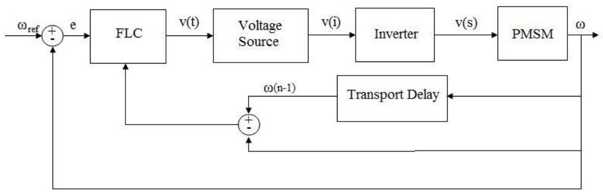


Fig 3 Speed control using FLC for PMSM.

4. FUZZY SYSTEM INPUT OUTPUT VARIABLE

Fuzzy systems rely on a set of rules. These rules, while superficially similar, allow the input to be fuzzy, i.e. more like the natural way that humans express knowledge. Thus, a power engineer might refer to an electrical machine as "somewhat secure" or a "little overloaded". This linguistic input can be expressed directly by a fuzzy system.

4.1 Fuzzy System Input-Output Variables

The motor condition can be deduced by observing the stator current amplitudes. Interpretation of results is difficult as relationships between the motor condition and the current amplitudes are vague. Therefore, using fuzzy logic, numerical data are represented as linguistic information.

The stator current amplitudes *Ia*, *Ib*, and *Ic* are considered as the input variables to the fuzzy system. The stator condition, *CM*, is chosen as the output variable. All the system inputs and outputs are defined using fuzzy set theory.

$$I_a = \{\mu_{Ia}(i_{aj})/i_{aj} \in I_a\}$$
$$I_b = \{\mu_{Ib}(i_{bj})/i_{bj} \in I_b\}$$
$$I_c = \{\mu_{Ic}(i_{cj})/i_{cj} \in I_c\}$$
$$CM = \{\mu_{CM}(cm_j)/cm_j \in CM\}$$

Where i_{aj}, i_{bj}, icj and CM are respectively, the elements of the discrete universe of discourse *Ia ,Ib,Ic and CM.* μ_{Ia}

(i_{aj}),μ_{Ib} (i_{bj}),μ_{Ic} (i_{cj}) and , μ_{CM} (cm_j),are, respectively the corresponding membership functions.

4.2 Linguistic Variables

Basic tools of fuzzy logic are linguistic variables. Their values are words or sentences in a natural or artificial language, providing a means of systematic manipulation of vague and imprecise concepts. More specifically, a linguistic variable is characterized by a quintuple (x, T(x), U, G, M), where x is the variable name; T(x) is the set of names of the linguistic values of x, each a fuzzy variable, denoted generically by x and ranging over a universe of discourse U. G is a syntactic rule for generating the names of x values; M is the semantic rule associating a meaning with each value.the input variables Ia, Ib, and Ic are interpreted as linguistic variables,

T (Q) =□{Zero, Small, Medium, Big}

Where Q = Ia, Ib, Ic, respectively.

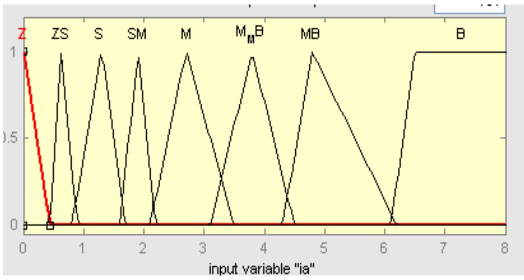


Fig 4 Membership Function "Input Variable

T(CM) , interpreting stator condition, CM, as a linguistic variable, could be

T(CM)=□{Healthy, Incipient, Damage, Seriously Damaged}

Where each term in T(CM) is characterized by a fuzzy subset, in a universe of discourse CM. Healthy might be interpreted as a stator with no faults, damaged as a stator with voltage unbalance, and seriously damaged as a stator with an open phase.

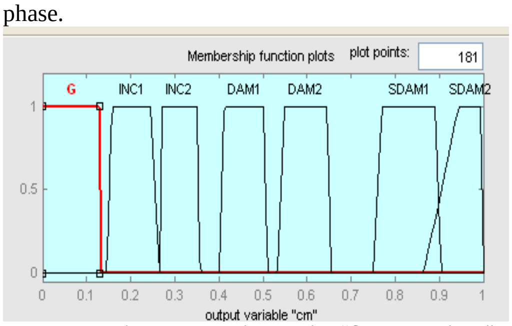


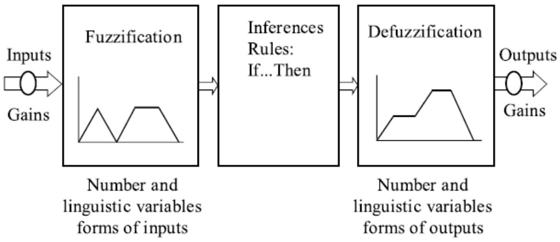
Fig 5 Membership Function "Output Variable"

4.3 Fundamentals of FLC

Fuzzification: is defined as the mapping from a real valued point to fuzzy set. In most fuzzy decision systems, non fuzzy input data is mapped to fuzzy sets by treating them as triangular membership functions, Gaussian membership functions.

Inference mechanism: Fuzzy inference is used to combine the fuzzy IF-THEN in the fuzzy rule base, and to convert input information into output membership functions. An inference mechanism emulates the experts decision making in interpreting and applying knowledge about how to perform good control. The rule may use the experts experience and control engineering knowledge.

Defuzzification: There are many methods which can be used for converting the conclusions of the inference mechanism into the actual input for the plant. Center of gravity defuzzification method is often used. Other defuzzification strategies can be found in technique literatures.



1. If (ia is ZS) and (ib is S) and (ic is Z) then (cm is G) (1)
2. If (ia is S) and (ib is S) and (ic is ZS) then (cm is G) (1)
3. If (ia is M) and (ib is SM) and (ic is SM) then (cm is G) (1)
4. If (ia is MB) and (ib is MB) and (ic is M) then (cm is G) (1)
5. If (ia is ZS) and (ib is ZS) and (ic is ZS) then (cm is INC) (1)
6. If (ia is SM) and (ib is S) and (ic is SM) then (cm is INC) (1)
7. If (ia is MB) and (ib is MB) and (ic is S) then (cm is INC) (1)
8. If (ia is MB) and (ib is B) and (ic is SM) then (cm is INC) (1)
9. If (ia is S) and (ib is S) and (ic is S) then (cm is D) (1)
10. If (ia is SM) and (ib is SM) and (ic is SM) then (cm is D) (1)
11. If (ia is M) and (ib is M_MB) and (ic is M_MB) then (cm is D) (1)
12. If (ia is M_MB) and (ib is B) and (ic is M_MB) then (cm is D) (1)
13. If (ia is SM) and (ib is B) and (ic is B) then (cm is SD) (1)
14. If (ia is M_MB) and (ib is B) and (ic is B) then (cm is SD) (1)
15. If (ia is MB) and (ib is B) and (ic is B) then (cm is SD) (1)
16. If (ia is B) and (ib is B) and (ic is B) then (cm is SD) (1)

5. RESULT:

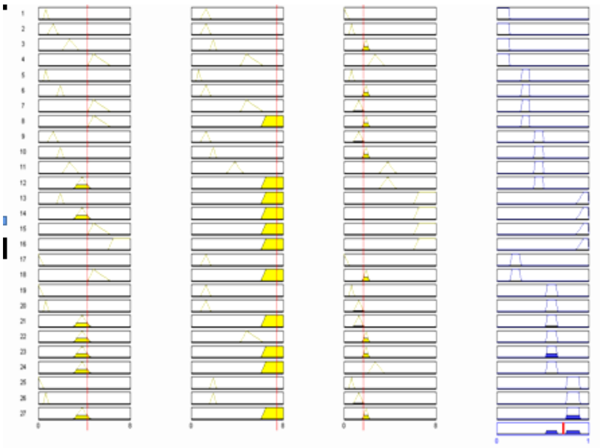


Fig 6 Healthy Condition

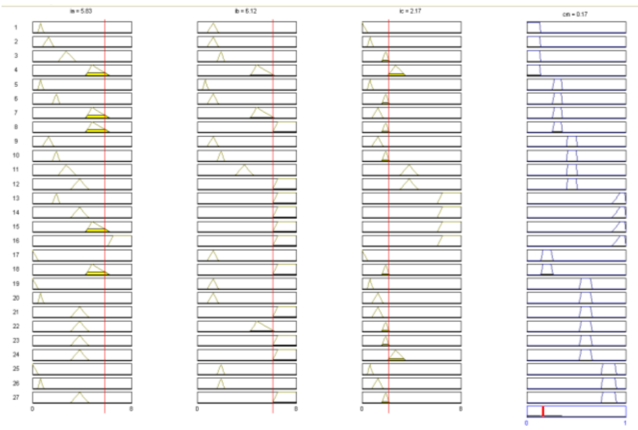


Fig 7 Incipient Condition

Fig 8 Damage Condition

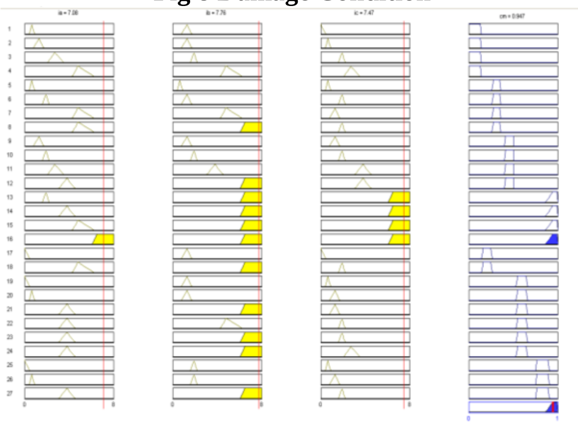


Fig 9 Severely Damaged Conditions

S. N.	IA	IB	IC	CM	CM
1	4.39	4.39	3.42	0.065	Good
2	1.11	1.4	0.819	0.0985	
3	1.59	1.4	0.819	0.1	
4	5.83	6.12	2.17	0.171	Incipient
5	0.337	1.01	0.337	0.205	
6	1.89	1.38	1.98	0.311	
7	4.39	4.48	1.59	0.31	
8	2.17	4.29	4	0.455	Damaged
9	3.81	6.6	3.33	0.518	
10	4.03	4.52	2.07	0.595	
11	4.29	7.47	1.69	0.724	
12	0.241	2.17	0.627	0.83	Severely
13	7.08	7.76	7.47	0.947	

Table 1: Condition of Motor (CM)

6. CONCLUSION

A method of using fuzzy logic to interpret current sensors signal of PMSM for its stator condition monitoring was presented. When Condition of motor (CM) is in between 0-0.1, motor performance is good/healthy. In incipient case motor condition is in between 0.11 to 0.43. The motor is damaged when the condition of motor occurs from 0.44 – 1. Correctly processing theses current signals and inputting them to a fuzzy decision system achieved high diagnosis accuracy. There is most likely still room for improvement by using an intelligent means of optimization.

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