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# Research Status on Speed Range Extension of Permanent Magnet Synchronous Motor

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**Abstract**: Nowdays, how to extend the speed range of Permanent Magnet Synchronous Motor(PMSM) has become an important topic of the motor study and attracted attentions of scholars at home and abroad. This paper briefly introduces the principle and existing solutions of speed-rising on structure.

**Keywords**: PMSM, research status, flux-weakening, speed-rising

## I. INTRODUCTION OF PMSM

The concept of flux-weakening in permanent magnet synchronous motor (PMSM) for the purpose of providing a constant power region at speeds above base speed has been a elusive goal for many decades. In wound field machines the method by which the field is weakened simply involves a reduction in the field current. However, to weaken the field in machines were the excitation is provided by permanent magnets is not so straightforward. However, this form of flux-weakening does not truly reduce the magnet field but only superimposes a second field which acts to reduce the net or resultant field. This type of weakening only a relatively small reduction in air gap flux can be achieved at a high cost in increased motor copper losses.

PMSM has the following characteristics: high efficiency, high power density, strong ability to accelerate, smooth torque, high speed operation, high power factor, so people pay more and more attention to PMSM.

## II. THE SPEED CONTROL PRINCIPLE OF PMSM

At present, most PMSM are adopted to improve the speed with vector control technology. Vector control is actually the control of the phase and amplitude of the stator current vector, so the most commonly method to analyze the sine wave current control of the PMSM is the d-axis and q-axis mathematical model (d-axis and q-axis with the stator A, B, C three-phase axis), which can not only analyze the steady state performance, but also can be used to analyze the transient performance [1] [2].

In order to establish the mathematical model of dq axis, the followings are assumed:
1) Neglecting the saturation of the motor core;
2) Ignoring eddy current and hysteresis losses in the motor;
3) The current of the motor is symmetrical three-phase sine wave current.

Resulting the following voltage, flux, electromagnetic torque and mechanical motion equations (quantities are transient value):

Voltage equation:

$$u_d = \frac{d\psi_d}{dt} - \omega\psi_q + R_1 i_d \tag{1}$$

$$u_q = \frac{d\psi_q}{dt} + \omega\psi_d + R_1 i_q \tag{2}$$

Flux equation:

$$\psi_d = L_d i_d + L_{md} i_f \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

Electromagnetic torque equation:

$$T_{em} = p(\psi_d i_q - \psi_q i_d) = p\lfloor L_{md} i_f i_q + (L_d - L_q) i_d i_q \rfloor \tag{5}$$

Where

$u_d$ and $u_q$ = d-axis and q-axis stator voltage;

$L_d$ and $L_q$ = d-axis and q-axis stator inductance;

$\psi_d$ and $\psi_q$ = d-axis and q-axis stator flux;

$\psi_f$ = permanent magnet flux;

$i_f$ = excitation current, $i_f = \psi_f / L_{md}$ .

As the steady state operation of the motor, the voltage can be expressed:

$$u_d = -\omega L_q i_q + R_1 i_d \tag{6}$$

$$u_q = \omega L_d i_d + \omega\psi_f + R_1 i_q \tag{7}$$

By the formula (6) and (7), the amplitude of the voltage vector can be obtained:

$$\begin{aligned} u &= \sqrt{u_d^2 + u_q^2} = \sqrt{(-\omega L_q i_q + R_1 i_d)^2 + (\omega L_d i_d + \omega\psi_f + R_1 i_q)^2} \\ &= \sqrt{(-X_q i_q + R_1 i_d)^2 + (X_d i_d + e_0 + R_1 i_q)^2} \end{aligned} \tag{8}$$

Ignore the resistance, the above formula can be simplified as:

$$u = \sqrt{(-\omega L_q i_q)^2 + (\omega L_d i_d + \omega\psi_f)^2} = \omega\sqrt{(L_q i_q)^2 + (L_d i_d + \psi_f)^2} \tag{9}$$

The control operation of Sine wave PMSM is closely related to the inverter in the system. The performance of the motor should be restricted by the inverter, especially for the limit of the effective phase voltage $U_{\lim}$ and the phase current $I_{\lim}$ of the motor, which will be limited by the inverter dc voltage and the inverter maximum output current. Therefore, voltage in the system of dq shaft also has a limit value $u_{\lim}$ , $u_{\lim} = \sqrt{3}U_{\lim}$ .

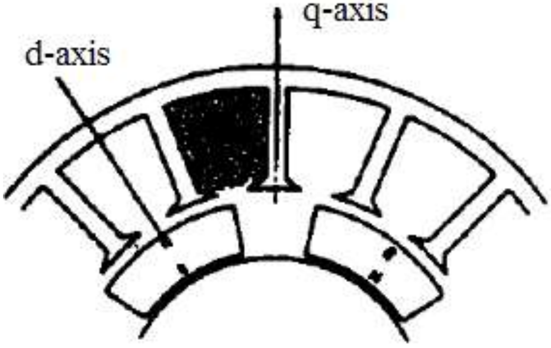
The idea of PMSM flux-weakening control comes from the adjustable magnetic control of the separately excited DC motor [3] [4]. When the voltage of the DC motor reaches its limit, the excitation current of the motor should be reduced, in order to keep the motor running at a higher speed and ensure the balance of the voltage. Separately excited dc motor can raise speed flux-weakening, in other words, by reducing excitation current. The excitation magnetomotive force of PMSM cannot adjust, resulting from permanent magnet. The only way is to adjust the stator current, namely increase the stator direct axis degaussing current to keep the voltage balance at a high speed, to achieve the goal of raising speed flux-weakening. When the motor voltage reaches the inverter output voltage limit, namely when $u = u_{\lim}$ , $u_{\lim}$ in lieu of u:

$$\left(L_q i_q\right)^2 + \left(L_d i_d + \psi_f\right)^2 = \left(u_{\lim}/\omega\right)^2 \quad 10$$

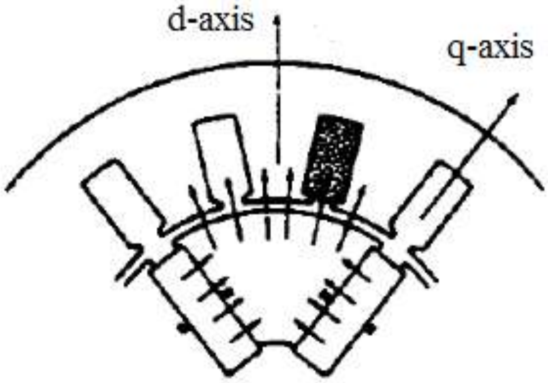
Therefore, only by adjusting $i_d$ and $i_q$ , can increase the speed continually. This is the motor operation principle of flux-weakening.

## III. THE DIFFICULTY OF FLUX-WEAKENING

The reason for the difficulty of PMSM flux-weakening is the particularity of the magnetic circuit structure [5]. Although the PMSM has a variety of rotor structures, but the permanent magnet is always in series in the direct axis magnetic circuit and accounts for a part of the magnetic circuit, whether parallel connection permanent magnet rotor or series connection permanent magnet rotor (as shown in Fig.1).Therefore, the magnetic circuit equivalent gap of dc and ac axis are large, $X_d$ and $X_q$ are smaller than the electrically excited synchronous motor. The normal PMSM structure does not meet the condition of wide constant power speed flux-weakening.



**(a) Aseries connection permanent magnet rotor**



**(b) Parallel connection permanent magnet rotor**

**Fig.1 PMSMof different rotor structure**

Visibly, increasing $X_d$ can satisfy the PMSM rise speed flux-weakening. Increasing $I_n$ or decreasing $E_0$ has the same effect (but not conducive to give full play to the advantages of the permanent magnet high magnetic energy product and the high torque density of PMSM. But flux-weakening control mode of the permanent magnet motor has irreversible demagnetization risk. If the temperature and reverse direct axis of magnetomotive force are large enough, the working point of permanent magnet will move to under the inflection point of the normal demagnetization curve, which will cause irreversible changes in the nature of permanent magnet.

## IV. RESEARCH STATUS OF FLUX-WEAKENING PMSM

For a long time, weak flux and increase speed is difficult for PMSM and is a hot issue. Reports of relevant products are often found in the literature [5] [6].

### 4.1 Different opinions and concrete implementation of PMSM flux-weakening control

Shigeo Morimotor from Japan and Richard F.Schiferl from America did some research on the flux-weakening of PMSM from the viewpoint of control. They deduced the conditions of a wide range of constant power speed of the motor, when the inverter output voltage U and current I reach the rated value with the speed of the motor increasing. They believed that when $E_0 = X_d I_d$, the larger $X_q - X_d$ is better; and when $E_0 \neq X_d I_d$, the former believed that the little $E_0$ is better; while the latter took a contrarian view.

### 4.2 Improvement of the rotor structure of traditional PMSM

From the structure, the direct axis reactance of traditional structure PMSM is very small. In normal armature voltage, it is impossible to get a large direct current and the flux-weakening effect is not obvious. S.Russenschuck and H.Weh introduced the improved structure of the rotor of PMSM, in order to improve the output characteristic and the speed regulation characteristic of PMSM (as shown in Fig.2). This plan does not make the $X_d$ significantly increased, but make $X_q$ significantly reduced. The scheme adopts permanent magnet with larger load, but compares with normal permanent magnet is very small, and this plan may cause irreversible demagnetization. WemerMuhlegger did some research on the motor with the structure of composite permanent magnet (as shown in Fig.3),which coupled by a common permanent magnet rotor and a reactive reluctance rotor coaxial , significantly increase $X_d$ .This motor gets obviously effect on flux-weakening expansion speed, but at the same time reduces the motor torque density, more ferromagnetic loss when high speed. J.Chalmers and R.Akmese developed a two-part rotor of PMSM, by changing the proportion of the two rotor reluctance to change direct axis magnetic circuit (as shown in Fig.4) [7].

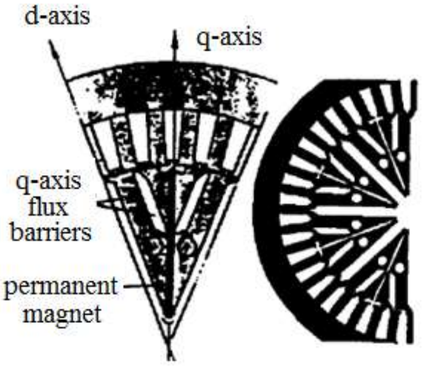


**Fig.2 Improvement of the rotor structure of traditional PMSM**

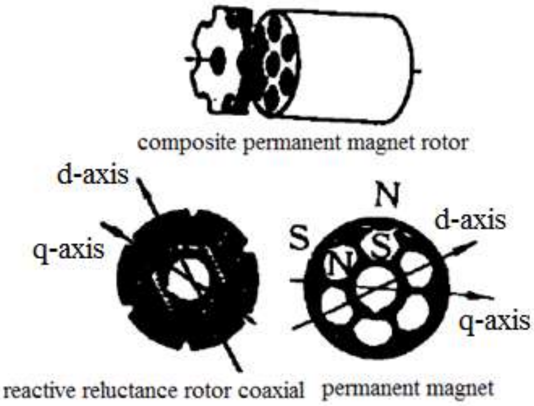


**Fig.3 The structure of composite permanent magnet motor**

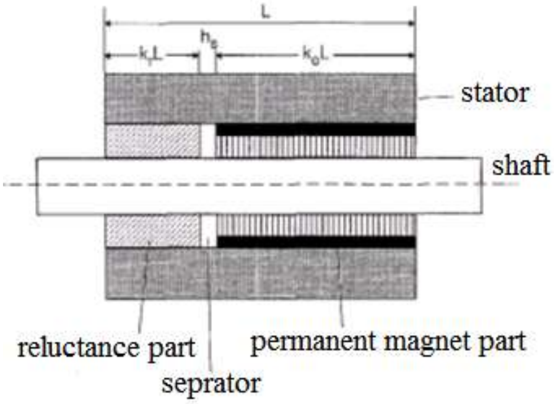


**Fig.4 Schematic arrangement of two-part rotor**

### 4.3 Flux-weakening scheme to change the magnetic path

Longya Xu and Lurong Yeproposed another method of weak magnetism speed expansion. This method joined four ring soft iron in the rotor (as shown in Fig. 5). In the role of the direct axis current, the magnetic flux generated by the permanent magnet will change the flow path and realize the flux-weakening of air gap magnetic field, no longer through the no-load air gap [8].

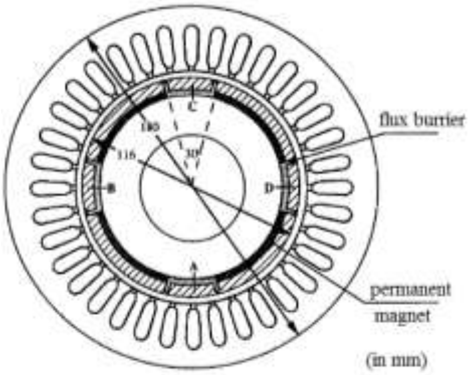


**Fig.5 Cross section of the PM machine**

### 4.4 Change the structure of the stator winding

In addition to the above plans of flux-weakening, some scholars attempted to change the structure of the stator windings to achieve weak magnetism. Eckart. NIPPProposed to use different connectors to adjusted accordingly the induced voltage in the stator winding [9]. A. Shakal proposed to install the permanent magnets on the stator, which relieved the flux-weakening by changing the magnetic circuit reluctance (as shown in Fig.6) [10]. T. Sebastian proposed to increase a field winding through strengthening the exciting field of the permanent magnet flux or weakening the magnetic field to achieve change. In order to achieve the purpose of control, the permanent magnets and field windings are installed on the stator [11]. Juan A obtained variable air gap magnetic field by controlling the field winding current beam, Motor excitation co-produced by the permanent magnets on the rotor and the stator field winding (as shown in Fig.7) [12].

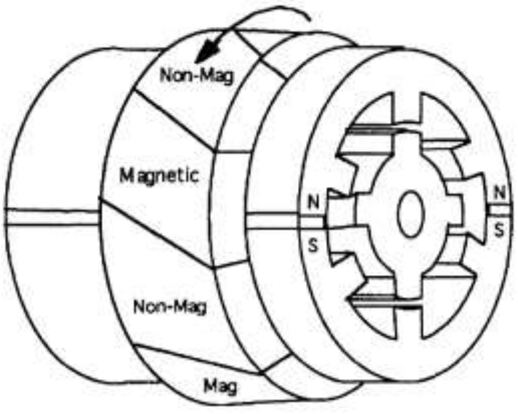


**Fig.6 Field Weakening Using a Magnetic/Non-Magnetic Collar Driven by an Actuator**

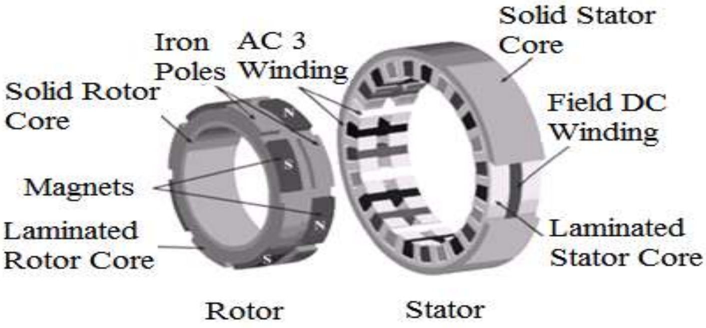
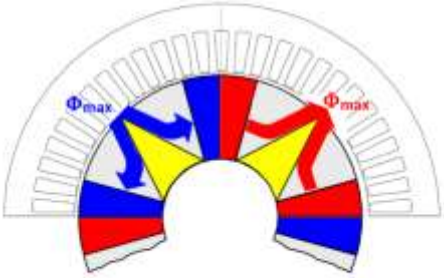


**Fig.7 Magnetic structure of the consequent-pole permanent-magnet machine**

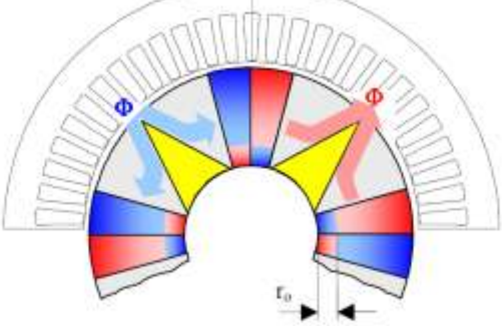
### 4.5 The new class of controllable flux PMSM

VladoOstovicdescribed a new class of PM machines, called Memory Motors for their ability to change the intensity of magnetization and memorize the flux density level in rotor magnets, is described. A memory motor can be built as a variable flux (VFMM) motor (as shown in Fig.8). The demagnetizing current flows through stator windings, supplied from the same source as the stator current [13].

The cross-sectional view of a four-pole VFMM is shown in (a).Tangentially magnetized permanent magnets with red denoted N-poles and blue denoted S-pole drive flux $\phi_{\max}$ through air gap into the stator. The rotor is built as a sandwich of permanent magnets, soft iron (gray) and non-magnetic material (yellow), all of them being mechanically fixed to a non-magnetic shaft. After applying opposite stator current $i_d$ , the magnets is created on a distance $r_0$ from the shaft surface (b).



**(a) Cross-sectional view of a fully magnetized variable flux memory motor**



**(b) Cross-sectional view of a partially magnetized variable flux memory motor**

**Fig.8 A variable flux memory motor**

### 4.6 The Radial-Flux Anti-Rotary PMSM

The Radial-Flux Anti-Rotary PMSM (RFAR PMSM), whose topology of with 6 poles is shown in Fig.9, has one stator and 2 PM rotors. One rotor is inside the stator and the other is outside the stator. Two rotors of the motor can both generate mechanical torque through two shafts nested in one side of the motor. Unlike conventional anti-rotary propulsive motors, the stator keeps static with the vechel, so that the slip ring is not essential [14].

Radially polarized permanent magnets made of rare earth are surface mounted on both inside surface of the outer rotor and outside surface of the inner rotor. This special topology with low copper loss and flux leakage will result in higher efficiency. The windings on each surface of the stator are opposite in phase sequence, so rotating field in each gap (inside and outside of the stator) with equal amplitude and opposite direction are produced with single power supply. Both rotors which are surface mounted PMs are used for torque production, therefore, high torque density is expected since the air gap is doubled.

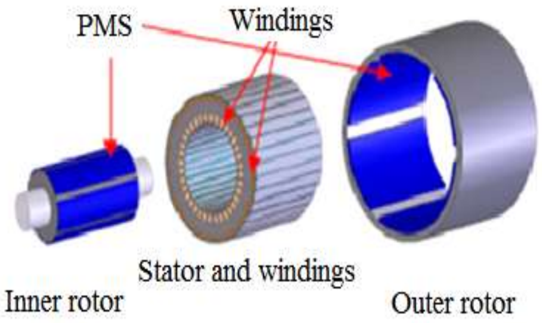


**Fig.9 The topology of RFAR PMSM**

## ACKNOWLEDGEMENTS

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