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ORIGINAL ARTICLES

Control Methods of the Inverter-Fed Permanent Magnet Synchronous Machines

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ABSTRACT

In this paper some control methods of inverter-fed permanent magnet synchronous motors was discussed, optimal method may be selected from the examined control methods for a given application. One of them is recommended for servo drives, the other for general purpose drives.

Kew words: Control methods, permanent magnet synchronous motor, thyristor converter, DC/AC converter, force commutation, converter controlled synchronous machine.

Introduction

Recently, the large power permanent magnet inverter-fed synchronous machine drives are quite widely applied (Grumbrecht *et al.*, 1990; Grauers, 1996; Lampola, 2000; Gieras, 1999; Waltzer, 2002). Motors e.g. can be applied in ship propulsion, generators as wind turbine generator. For both mentioned applications the direct gearless mechanical connection is usual propeller and wind turbine (Grauers, 1996; Lampola, 2000). In this paper the utilization of the synchronous machine drive is investigated. It has large effect on the cost of the drive system, which is highly effected by the supply and control method (achievable force density, utilization of the components of the system) (Gieras, 1999; Waltzer, 2002). Control method also affects the design of the machine (Grauers, 1996). In this paper only the motor operation is investigated.

Equivalent circuit:

It is assumed, that the permanent magnet excitation of the rotor of generates is mainly a sinusoidal flux density distribution. It is represented by a $\bar{\psi}_p$ pole flux vector in direction *d* with $\Psi_p = const.$ magnitude and the $\bar{u}_p$ pole voltage vector induced in the stator. The calculations are performed for steady-state operation, by fundamental components and in per-unit system (Grumbrecht *et al.*, 1990; Grauers, 1996):

$$\bar{U}_1 = j\omega_1\bar{\Psi}_1,\ \bar{U}_p = j\omega_1\bar{\Psi}_p,\ \Psi_p = const.$$

It is assumed, that the synchronous and sub-transient stator inductances in the *d* and *q* axis directions are identical and the stator resistance is zero:

$$L_d = L_q = L''_d = L''_q = L,\ R = 0$$

Using these assumptions, the equivalent circuits can be drawn for the voltages and the fluxes as shown in Fig.1. ($X=\omega_1 L$).

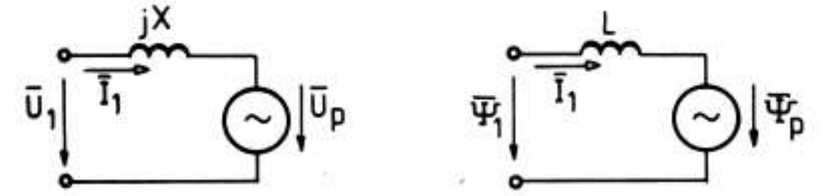

Fig. 1: Equivalent circuits of PMSM.

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According to the equivalent circuits the vector diagram for the fundamental quantities can be drawn as shown in Fig.3., Fig.4., Fig.5. and Fig.6., which are drawn for special selected cases (will be discussed later). The general descriptions are: ϑ_p is the torque angle measured from the pole flux, φ is the phase angle between the supply voltage and the current, φ_p is the phase angle between the pole voltage and the current, and the δ_t is the load angle., The rotor torque, output power, stator flux and stator terminal voltage can be calculated using the vector diagram:

$$M = \Psi_p I_1 \sin\vartheta_p = \Psi_p I_1 \cos\phi_p, \quad P = M\,\omega = M\,\omega_1$$

$$\bar{\Psi}_1 = \bar{\Psi}_p + L\bar{I}_1, \quad \bar{U}_1 = \bar{U}_p + jX\bar{I}_1$$

Summary of the supply and control method:

Inverters using DC link, which used in practice shown in Fig.2. There are mainly two basic types of DC/AC converter:

a. *Thyristor converter:*

Thyristor converter is a machine (load) commutated converter. So, the converter-synchronous machine set is so called “converter controlled synchronous machine”. This system is simpler and cheaper, but can't control the current phase angle.

b. *Inverter:*

Inverter is a force commutated static power converter. IGBT, FET or MOSFET can be used as power-switches in this case. Approximately sine wave phase currents can be produced. Not only the current magnitude, but its phase angle also can be controlled by the current vector controller. The basic properties of examined three control methods (I1, I2 and I3) are listed in figure 2. These control methods will be discussed in the following sections in some details.

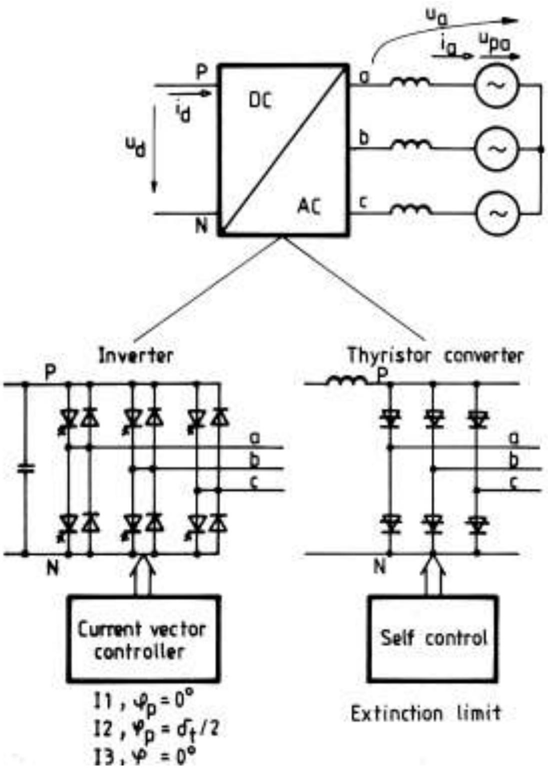

Fig. 2: Supply and control methods of PMSM.

c. *Method I1: $\varphi p=0°$ $\vartheta p=90°$:*

The vector diagram for this method is presented in Fig.3. Developed torque is the best (high force density). For a given Ψ_p pole flux and I_1 current the developed torque is the greatest, so:

- As a developed torque is directly proportional with $\sin\vartheta_p$, so the utilization of the built-in magnets is optimal for (ϑ_p=90°). Also utilization of the allowed stator and inverter current is the best.
- For $U_p<U_1$, $\Psi_p<\Psi_1$ →less permanent magnet, low core-loss at no-load.
- At maximum load, U_1 and Ψ_1 have maximum values. So maximum load torque determines maximum stator flux, while the maximum power determines maximum terminal voltage (design). These values determine the flux and flux density of the stator core and the voltage stress of the machine stator and the inverter.
- Drawback: The power of the machine is not maximized ($\varphi\neq0$).

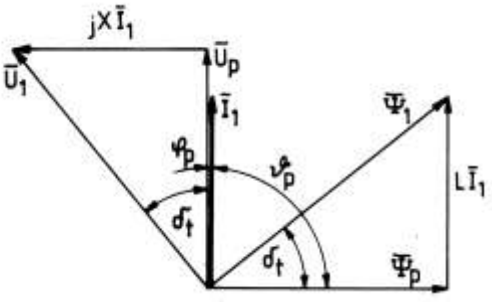

Fig. 3: Method I1: φ_p=0° ϑ_p=90°

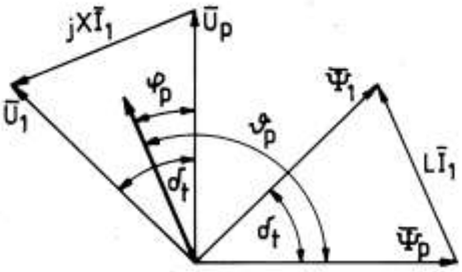

Fig. 4: Method I2: $\varphi_p=\delta_t/2$ $\vartheta_p=90°+\delta_t/2$

According to the vector diagram, developed torque, output power and stator flux magnitude can be expressed:

$$M=\Psi_p I_1=M_{\max}I_1',\ P=U_p I_1=P_{\max}I_1',\ \Psi_1=\Psi_p\sqrt{1+I_1'^2}$$

Where: $I_1'=I_1/I_z$, $I_z=\Psi_p/L$, (ideal short circuit current) $M_{\max}=\Psi_p I_z=\Psi_p^2/L$, $P_{max}=\omega_1 M_{max}$. (the max values are used as the base of relative values).

d. *Method I2: $\varphi p=\delta t/2$ $\vartheta p=90°+\delta t/2$:*

The vector diagram for this method is presented in Fig.4.

- The best property of this method is: $U_p=U_1$, $\Psi_p=\Psi_1$, they are constant, independently of the machine load.
- Design principles: The stator core must be designed for constant pole flux Ψ_p=const. Stator winding and inverter must be designed as $U_{pmax}=\omega_{1max}\Psi_p$. The maximum current is determined by the developed maximum torque.
- Simultaneously good utilization of the main parts of the machine (magnets, core, winding) and the inverter can be got not optimal parameters but all are good.
- The power ratings of the machine and the converter are equal.

As it's clear from the vector diagram, the torque, the power and the stator flux magnitude can be expressed:
$M=M_{max}\sin\delta_t$, $P=P_{max}\sin\delta_t$,

$$\sin\delta_t = I_1'\sqrt{1-\left(\frac{I_1'}{2}\right)^2}, \quad \sin\frac{\delta}{2}=\frac{I_1'}{2}, \quad \Psi_1=\Psi_p.$$

e. Method I3: $\varphi=0°$ $\vartheta p=90°+\delta t$:

The vector diagram for this control method is presented in Fig.5.

- This method results in the maximization of the terminal power factor.
- In spite of the *cos* $\varphi=1$, it does not maximize the power, since increasing the load torque, the ϑ_p torque angle becomes worse and the stator flux decreases ($U_p>U_1$, $\Psi_p>\Psi_1$).
- The maximum speed at no-load determines the voltage stress, while the maximum developed torque determines the stator current of the machine.
- Required power ratings are high (machine, converter).
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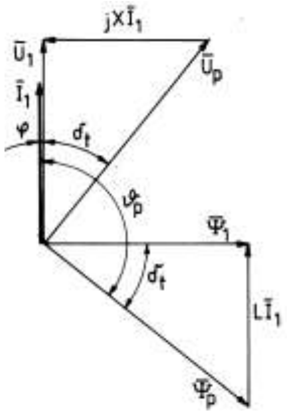

Fig. 5: Method I3: $\varphi=0°$ $\vartheta_p=90°+\delta_t$

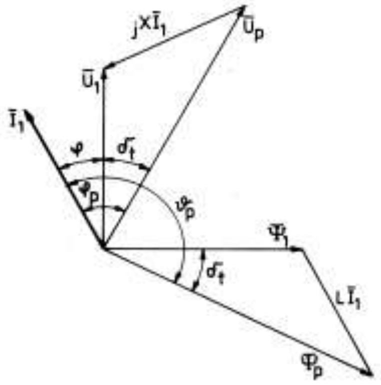

Fig. 6: Method T: thyristor converter.

From the vector diagram shown in fig. 5, the torque, the power and the stator flux magnitude can be expressed:

$$M=M_{\max}I_1'\sqrt{1-I_1'^2}, \quad P=P_{\max}I_1'\sqrt{1-I_1'^2},$$

$$\sin\delta_t=-\cos\vartheta_p=I_1', \quad \Psi_1=\Psi_p\sqrt{1-I_1'^2}.$$

f. Method T: machine commutated thyristor converter:

The vector diagram for this control method is presented in Fig.6.

- This case is the converter controlled synchronous machine.

- The best properties can be achieved by controlling the machine side converter to the inverter mode limit (extinction limit) by a self-controlled firing controller.
- The maximum power and developed torque are as in control method II. Operating region of the converter (Lázár, 1987), which known from the theory of the converter controlled synchronous machine, that the greatest motor mode torque Mb is got at α=105° firing and δ=60° overlap angle ($I_1 \approx 0.649 I_z$):

$$M_b = \frac{3}{\pi}\frac{\sqrt{3}}{4} M_{\max} \approx 0.4135 M_{\max}.$$

Comparison of the different control methods:

The $M/M_{max}=P/P_{max}$ torque and power ratios are presented as the function of the $I_1' = I_1 / I_z$ current ratio for all four methods in Fig.7.

- The methods I2, I3 and T provide breakdown property (maximum).
- Increasing the I_1' current, the difference between the achievable torque and power by the different methods is increasing. Really high torque and power can be provided only by the methods I1 and I2. Besides, the achievable torque by the T converter controlled synchronous machine method is practically 10-15% less than the values on the figure, since it is not possible to operate on the extinction limit exactly, it can be only safely approached.
- Method I1 is recommended for servo drives, providing good dynamics.
- Method I2 is recommended for general purpose drives.

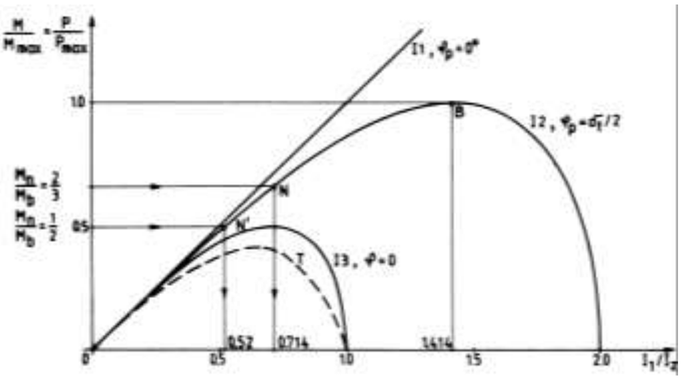

Fig. 7: Comparison of the different control methods.

Application of specific design (Method I2):

M_n/M_b demonstrates the overload capability (M_b is the greatest, breakdown torque). This ratio must be selected for the application. Selecting M_n/M_b=2/3 (50% overload capability), the nominal operating point is N (Fig.7.). At this point the rated current is: I_{1n}/I_z=0.714, I_{1n}=0.714I_z=0.714Ψ_p/L=1, using Ψ_p=1= Ψ_1, the required inductance is L=0.714. In the same way, selecting M_n/M_b=0.5 (100% overload capability), the nominal operating point is N', and the required inductance is: L=0.52. i.e. selecting the overload capability in the case of method I2, the value of the L inductance providing this property can be got from Fig.7.

Implementation support:

Two other figures are presented to support the implementation:

In Fig.8. Ψ1/Ψp=U1/Up flux and voltage ratios vs. I_1' are shown for the different control methods. From this figure the variation of the Ψ1 stator flux magnitude caused by the armature reaction can be got. Its maximum value can be determined, which provides the magnetic load of the core, necessary for the design. Fig.9. presents the ϑ_p torque angle vs. I_1' for different control methods. These curves provide the angle of the current vector to be set by the pole flux oriented current vector control.

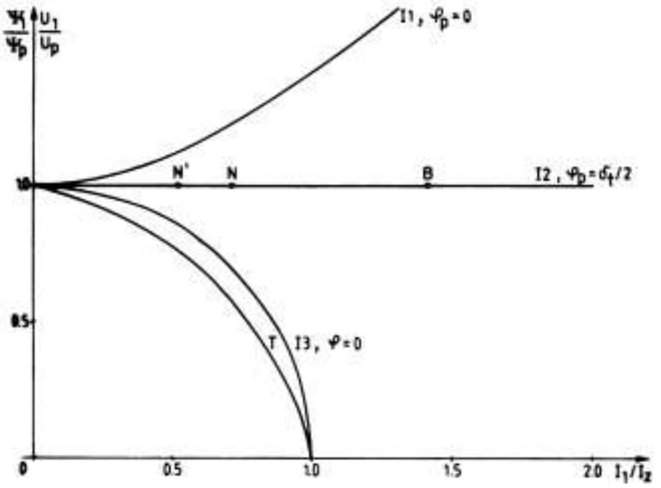

Fig. 8: The armature reaction.

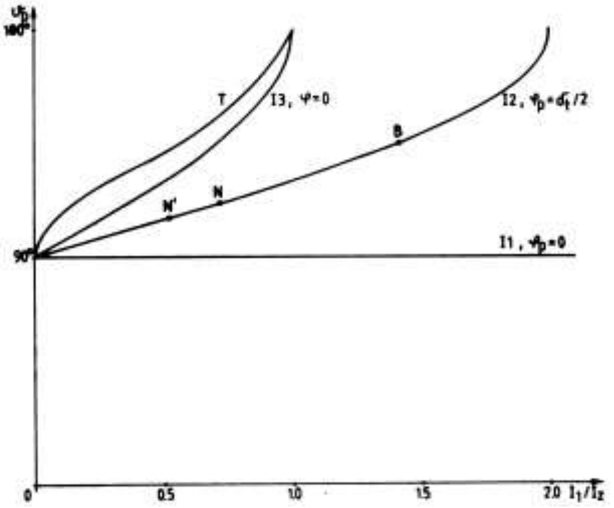

Fig. 9: ϑp for the pole flux oriented current vector control.

Conclusion:

From the examined control methods the optimal one can be selected for a given application. One of them (I1) is recommended for servo drives, the other (I2) for general purpose drives. Design hints of the system are given for the different methods, one particular for method I2 (the calculation of the *L* inductance).

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