SYNCHRONOUS MOTORS IN ELECTRIC TRACTION DRIVES

Petr Fajkus

Doctoral Degree Programme (1), FEEC BUT

E-mail: xfajku01@stud.feec.vutbr.cz

Supervised by: Bohumil Klíma

E-mail: klima@feec.vutbr.cz

Abstract: The paper deals with suitable permanent magnet synchronous motors for electric traction drives, especially usable in electric vehicles. The main request is field-weakening possibility due to a converter voltage limitation. Therefore it is important to find the influence of parameters on the motor properties. Then a suitable combination of motor parameters can be determined. Synchronous motors are described by electrical and mechanical equations in direct-quadrature (d-q) reference frame. A whole problem is solved by computer simulations.

Keywords: electric traction drive, field-weakening, permanent magnet synchronous motor

1. INTRODUCTION

DC (Direct Current) motors were mainly used for electric traction drives due to simple control, in the past. Control of an AC (Alternating Current) brushless machine was difficult. Nowadays, usage of AC motors is simple, thanks to active power converters. Especially a synchronous motor with permanent magnets rotor (PMSM) and an asynchronous motor with squirrel cage rotor are often used. Both types have advantages and disadvantages. Specific application requirements determine which type of AC motor is chosen. Both types of motors can be used for a FW (field-weakening), but FW control of PMSM is easier. When voltage is maximal, the FW is used for increasing a motor speed (by decreasing direct current).

2. SYNCHRONOUS MOTORS

At beginning, a fundamental description and types of PMSM are mentioned, and then FW dependence on parameters can be shown.

2.1. MATHEMATICAL DESCRIPTION OF SYNCHRONOUS MOTOR

The mathematical model in d-q reference frame is often used for a synchronous motor description, which is tightly fixed with the rotor, as in [1] . Generally, synchronous motor equations are

$$v_{\mathrm{d}} = R_{\mathrm{s}}\left(\tau\right)\cdot i_{\mathrm{d}} + \frac{\mathrm{d}\psi_{\mathrm{d}}\left(i_{\mathrm{d}}, i_{\mathrm{q}}\right)}{\mathrm{d}t} - \omega_{\mathrm{e}}\cdot\psi_{\mathrm{q}}\left(i_{\mathrm{q}}, i_{\mathrm{d}}\right) \tag{1}$$

$$v_{\mathrm{q}} = R_{\mathrm{s}}\left(\tau\right)\cdot i_{\mathrm{q}} + \frac{\mathrm{d}\psi_{\mathrm{q}}\left(i_{\mathrm{q}}, i_{\mathrm{q}}\right)}{\mathrm{d}t} + \omega_{\mathrm{e}}\cdot\psi_{\mathrm{d}}\left(i_{\mathrm{d}}, i_{\mathrm{q}}\right) \tag{2}$$

$$T_{\mathrm{e}} = J\frac{\mathrm{d}\omega}{\mathrm{d}t} + T_{\mathrm{L}} \tag{3}$$

$$T_{\mathrm{e}} = p_{\mathrm{p}} \frac{3}{2} \left(\psi_{\mathrm{d}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) \cdot i_{\mathrm{q}} - \psi_{\mathrm{q}} \left(i_{\mathrm{q}}, i_{\mathrm{d}} \right) \cdot i_{\mathrm{d}} \right) \tag{4}$$

where flux linkages ψ_{d} and ψ_{q} are dependent on currents i_{d} and i_{q} and considerate cross-coupling saturation. The stator resistance R_{s} depends on winding temperature-rise τ , p_{p} is the pole pairs of rotor, J is the moment of inertia, ω_{e} is the electrical angular velocity, T_{e} is the electromagnetic torque, T_{L} is the load torque, v_{d} and v_{q} are components of the stator voltage vector. Above d-q voltages and currents are components of the voltage $\mathbf{V}_{\mathrm{s}}$ and the current $\mathbf{I}_{\mathrm{s}}$ vector

$$\mathbf{I}_{\mathrm{s}} = \sqrt{i_{\mathrm{d}}^2 + i_{\mathrm{q}}^2} \tag{5}$$

$$\mathbf{V}_{\mathrm{s}} = \sqrt{v_{\mathrm{d}}^2 + v_{\mathrm{q}}^2} \tag{6}$$

which have to satisfy conditions $|I_S| \le I_{MAX}$ and $|V_S| \le V_{MAX}$. Flux linkages in equations (1) to (4) are

$$\psi_{\mathrm{d}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) = L_{\mathrm{d}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) \cdot i_{\mathrm{d}} + \psi_{\mathrm{m}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) = L_{\mathrm{d}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) \cdot i_{\mathrm{d}} + L_{\mathrm{d}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) \cdot I_{\mathrm{m}} \tag{7}$$

$$\psi_{\mathrm{q}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) = L_{\mathrm{q}} \left(i_{\mathrm{d}}, i_{\mathrm{q}} \right) \cdot i_{\mathrm{q}} \tag{8}$$

specifically for PMSM motors, where L_{d} and L_{q} are d-q inductances, $\psi_{\mathrm{m}}(i_{\mathrm{d}},i_{\mathrm{q}})$ is PM flux linkage and I_{m} is PM “fictive” current ($I_{\mathrm{m}}= \psi_{\mathrm{m}}/ L_{\mathrm{d}}$), which is created for expression of PM FW under consideration in [2].

2.2. PMSM Parameters

Static and dynamic properties are given by parameters of PMSM. Parameters are shown in equations above, but only some parameters (especially their ratio) are important for FW like d-axis inductance L_{d}, q-axis inductance L_{q} and PM flux linkage ψ_{m} (for FW stator resistance R_{s} only changes voltage drop level). Some parameters are dependent on magnetic circuit saturation. Parameters are considered constant (it is sufficient in this case).

Parameters and values are expressed in per unit system (for better comparison).

2.3. Types of PMSM

Synchronous motors can be divided to motors with same d-q inductances $L_{\mathrm{d}}=L_{\mathrm{q}}$ (smooth rotor) and to motors with different d-q inductances $L_{\mathrm{d}}>L_{\mathrm{q}}$ or $L_{\mathrm{d}}<L_{\mathrm{q}}$ (salient pole rotor), as shown on figure 1.

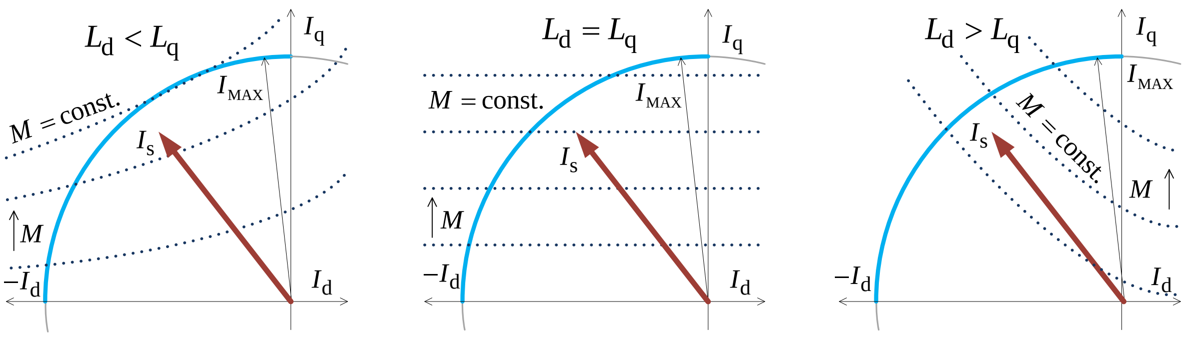

Figure 1: Differences between motor types of PMSM [3]

The suitable motor type for FW is determined from equation (4) with (7) and (8)

$$T_{\mathrm{e}} = p_{\mathrm{p}} \frac{3}{2} i_{\mathrm{q}} \left(i_{\mathrm{d}} \left(L_{\mathrm{d}} - L_{\mathrm{q}} \right) + \psi_{\mathrm{m}} \right) \approx i_{\mathrm{q}} \left(i_{\mathrm{d}} \left(L_{\mathrm{d}} - L_{\mathrm{q}} \right) + \psi_{\mathrm{m}} \right) \tag{9}$$

where differences between motor types are cleared. A suitable motor type for FW is motor with $L_d < L_q$, because at decreasing i_d is needed smaller i_q. The paper is focused on PMSM with $L_d < L_q$.

3. PARAMETERS VARIATION OF PMSM

How parameters affect FW is shown below. The torque is one of important values and from equation (9) is clear dependence on parameters.

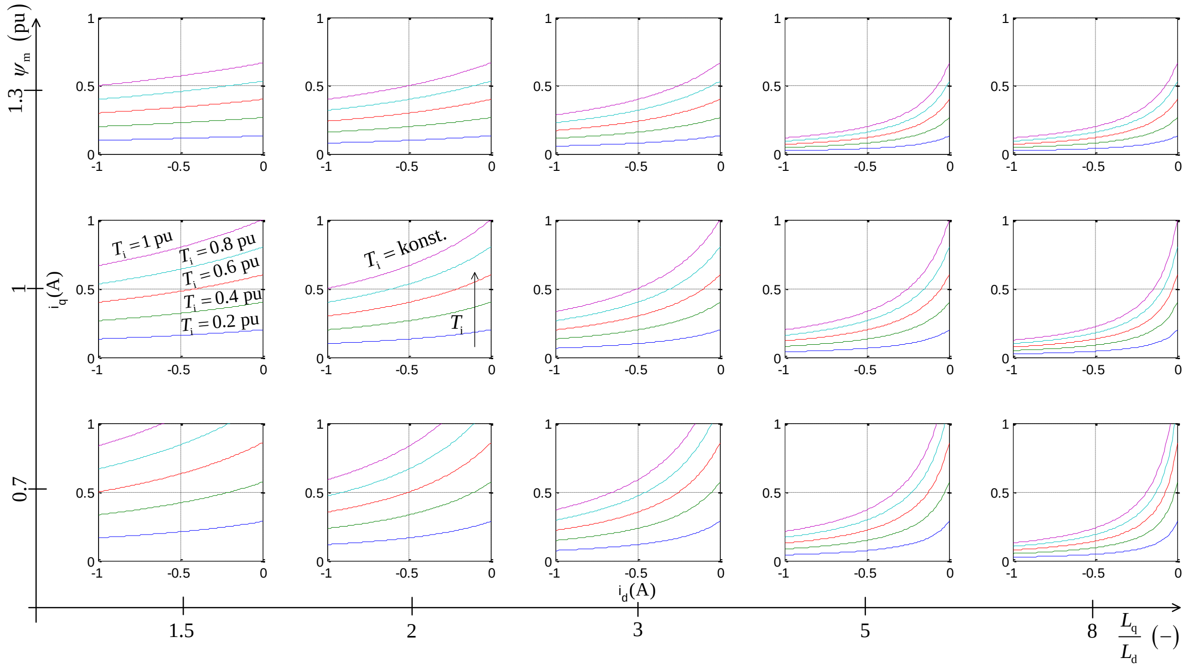

Figure 2: Dependences of quadrature current on direct current, inductances Ratio and PM flux linkage for different torques

The dependence of q-current on d-current for specific torque with PM flux-linkage and ratio of inductances variations is shown on figure 2. In this case, speed was constant.

For FW is seen, that for same torque is needed less current with increasing inductances ratio and PM flux-linkage. But on the other way, less current means higher stator voltage, as seen on figure 3, where is shown the dependence of stator voltage on d-current for specific torque with PM flux-linkage and ratio of inductances variations.

Generally, smaller stator current is suitable due to voltage drop on stator resistance, but high voltage level is not suitable for converter. Therefore, the MTPA (Maximum Torque Per Ampere) algorithm is used in many cases and field weakening algorithm is used for increasing speed with voltage condition $|V_S| \leq V_{MAX}$.

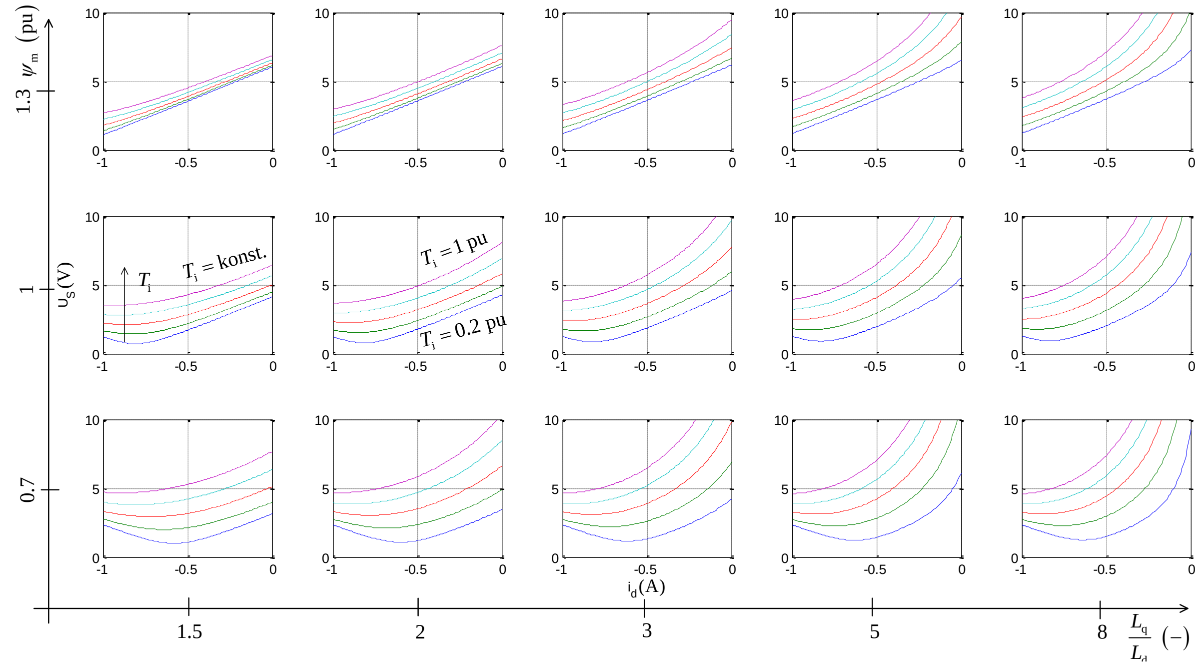

Figure 3: Dependences of stator voltage on direct current, inductances ratio and PM flux linkage for different torques

3.1. Speed Range and Mechanical Power

Variation of PM flux linkage is important for speed range too (not only for torque). From known equation

$$\omega = \frac{U_i}{C \cdot \Phi} \approx \frac{U_S}{\psi_S} \tag{10}$$

where U_i is the induced voltage, C is the motor constant, Φ is the magnetic flux, U_S is the stator voltage vector magnitude and ψ_S is the stator flux linkage vector magnitude. From equations (10) is clear, that if $\psi_s = 0$, then speed range can be "infinite". There are three options, the motors with $I_m > I_{MAX}$, $I_m = I_{MAX}$ and $I_m < I_{MAX}$. For the maximum speed range and the highest possible torque is suitable the motor with $I_m = I_{MAX}$. The motor with $I_m > I_{MAX}$ cannot achieve infinite speed point. The all is seen on Figure 4.

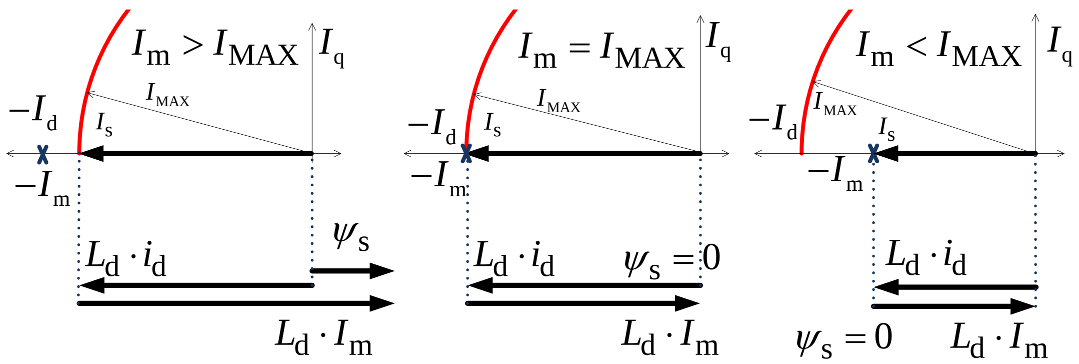

Figure 4: Speed range by PM flux linkage

From figure 5 is cleared, that for mechanical power is important saliency ratio and PM flux-linkage.

Motors with high PM flux linkage and saliency ratio have higher torque, but speed range is much smaller and power rapidly decreasing.

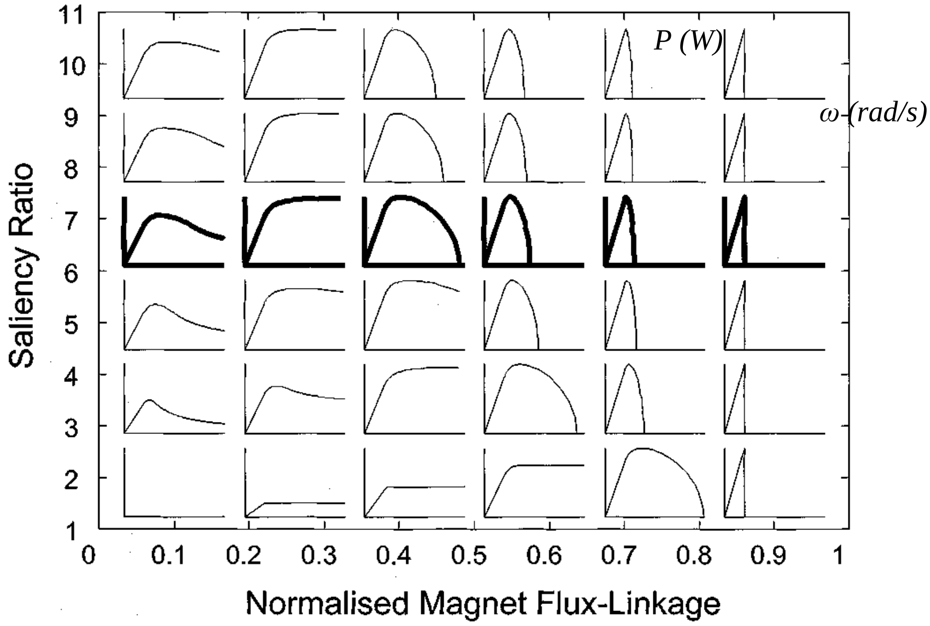

Figure 4: Power versus speed characteristic as a function of the saliency ratio and normalized magnet flux linkage [2]

4. CONCLUSION

The design of synchronous motor for FW is dependent on specific requirements. There is not universal solution. Motors with $L_d<L_q$ are suitable. For electric traction is need to know maximal speed and minimal power at this speed. Then the maximal torque can be determined by PM flux linkage value and saliency ratio value. Losses are increasing at FW.

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