THE MODEL OF PERMANENT MAGNET SYNCHRONOUS MACHINES

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Abstract – **This work shows the salient pole model of Permanent Magnet Synchronous Machines (PMSM). This type of modeling on used for several reasons: augmented understanding of the fundamentals of sensor less control, incorporate the combined effects of leakage and main inductance variations, incorporating the effects of loading of the machine.**

Keywords: *sensorless control, saliency modeling, permanent magnet, synchronous machines.*

1. INTRODUCTION

The objective for this work is to eliminate the need for a position sensor by using the machine as the position sensor. The position sensor, cabling and connectors have been a source of failure for motor control applications. For small drives the sensor contributes considerable to the overall cost. The basis for most low and zero speed sensors less control [1] is the presents of a difference in the d and q inductances. This difference is referred to as saliency.

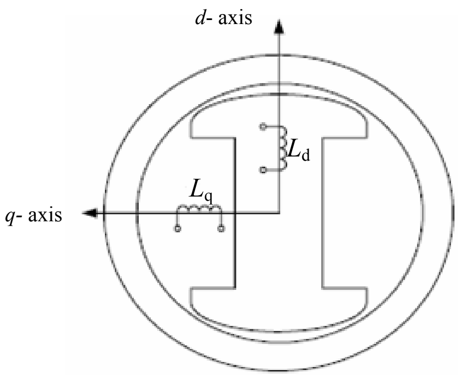

Figure 1: The Salient pole of synchronous machine.

There are several sources of saliencies in permanent magnet (PM) machines: rotor inherent saliency, saturation based saliency, rotor stator teeth harmonics [1], lamination direction based saliency [2], eddy current based saliency [3], and rotor eccentricity based saliency. The single saliency model is developed from the rotor inherent saliency and the saturation induced saliency. The term saliency can be understood when considering a salient pole synchronous machine structure (Figure 1). In this structure the rotor has an inherent saliency due to the shape of the rotor. In the *d*-axis the air-gap is small while there is a large air-gap in the *q*-axis. The *d*-axis inductance will in this case be larger then the inductance in the *q*-axis. The injection based sensor less control schemes [1], [4] extract rotor position information from the difference in the inductance.

2. SALIENCY MODELING

In Sensorless Control of PMSM the rotor inherent saliency or the saturation based saliency is usually used as the basis for the saliency. The used model (a 30 kW PMSM machine what is simulated in FEMLab) simplified as only these sources of saliency are included. The relative permeability function (from supplier) was included in the FEM simulation. First the machine is unloaded and only the flux from the permanent magnets contributes to the field. Three regions of the machine have low relative permeability values: the permanent magnet (in rotor), the stator teeth (in the main flux path) and the stator yoke (in the main flux path). The stator teeth are more saturated compared to the portions of the stator yoke that is saturated. The modeling of saliency is done by modeling the inductance in a *dq*-rotor oriented reference frame. The inductance is separated in two parts: the leakage inductance and the main inductance. In this work, the model can be used to incorporate the saliency sensed by carrier signals that is concentrated in the leakage flux paths or main flux path (or both). The sensor less schemes [1-4] will in general sense the resulting inductance but the high frequency carrier flux distribution determines the components of main- or leakage flux. In the first stage of the modeling the machine will be modeled at no load (only flux from the permanent magnets). The load dependency is included in the last section of the modeling. For to simplify the modeling, the some simplifications are made: only fundamental components are considered; the flux from the magnets and the windings are assumed sinusoidal distributed over the air gap; the distributed windings are simplified by representing them as a two axis model; saturation effects are assumed to be sinusoidal distributed (superposition applied); relative permeability assumed to wary linear with flux density. These simplifications may seem crude. Some lamination materials may have extremely non linear relation between relative permeability and flux density. The relative permeability is derived from the BH curves from the supplier. The non linearity in the lower region is related to the first magnetization curve of the material. When the machine model is considered this effect is neglected as the laminations have been exposed to a magnetic field and the time constant for the material to return to its original sate is very large.

2.1. No load model

In the no load model only the flux from the permanent magnets are considered. The inductance will be modeled in *dq*-rotor reference frame and the main and leakage inductance will be modeled separately.

2.1.1. Main inductance

In the first stage the machine is considered as a uniform structure with no magnets or saturation.

$$L_{d-main} = L_0 \tag{1}$$

$$L_{q-main} = L_0 \tag{2}$$

The effects sources of saliency for a no load condition is included in the model as:

$$L_{d-main} = L_0 - L_{0rd} - L_{0ts} - L_{0ys} \tag{3}$$

L_0 - Main inductance (symmetrical machine); L_{0rd} - rotor design (low relative permeability in magnets and induced currents in magnets); L_{0ts} - stator tooth saturation; L_{0ys} – yoke saturation. The yoke saturation is assumed to have minimal impact on the *q*-axis inductance. If high frequency carrier is used there may be induced currents in the magnets due to the carrier flux. The effect of induced currents in the magnets is reduced *d*-axis inductance. This effect is included in the model by the term L_{0rd} (combined effect of low permeability and induced currents). The induced current is highly dependent on the carrier frequency.

2.1.2. Leakage inductance

If on consider a flux vector (space vector) the leakage flux is located 90 electrical degrees spatially shifted compared to the main flux distribution. When the *dq*-inductances are modeled the reference system is referred to the main flux. The effects on the leakage inductance are there fore shifted 90 electrical degrees. The basis for the leakage inductance model is also a uniform structure with no saturation:

$$L_{d-leakage} = L_\sigma \tag{4}$$

$$L_{q-leakage} = L_\sigma \tag{5}$$

The leakage flux paths are illustrated in Figure 2. Three regions may lead to modeling of the inductance: stator teeth, stator yoke and rotor surface. Variations (or saturation) in the rotor surface is neglected in this model as the surface of the test machine is uniform and the saturation level is modest. If we consider a stator flux vector oriented in the magnet d-axis the leakage flux path for this main vector can be influenced by yoke saturation (saturation due to flux from the permanent magnets).

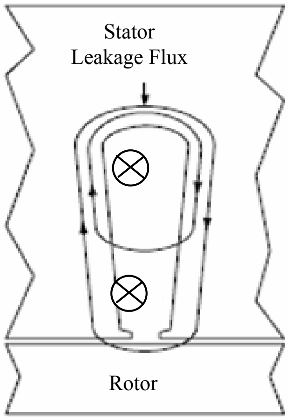

Figure 2: Leakage flux path.

This effect is included in the model as a reduction of the *d*-axis leakage inductance by a factor $L_{\sigma ys}$. If a stator current vector is oriented in the *q*-axis the leakage inductance may be influenced by tooth saturation (saturation due to flux from the permanent magnet). This effect is included in the model as a reduction of the *q*-axis leakage inductance by the factor $L_{\sigma ts}$:

$$L_{d-leakage} = L_\sigma - L_{\sigma ys} \tag{6}$$

$$L_{q-leakage} = L_\sigma - L_{\sigma ts} \tag{7}$$

L_σ - Leakage inductance (symmetrical machine); $L_{\sigma ys}$ - yoke saturation effect on leakage inductance rotor design; $L_{\sigma ts}$ - Teeth saturation effect on leakage inductance.

2.1.3. Resulting no load model

In the resulting no load models the leakage and main inductance is summed up in each axis:

$$\begin{cases} L_d = L_{d-main} - L_{d-leakage} \\ L_d = L_0 - L_{0rd} - L_{0ts} - L_{0ys} + L_\sigma - L_{\sigma ys} \end{cases} \tag{8}$$

$$\begin{cases} L_q = L_{q-main} - L_{q-leakage} \\ L_q = L_0 + L_\sigma - L_{\sigma ts} \end{cases} \quad (9)$$

The difference between L_d and is the basis for saliency in the machine. The position dependent parts of the inductance can be illustrated by expressing the inductance on vector form:

$$\underline{L} = \sum L + \Delta_1 L e^{j2\theta} \quad (10)$$

where: θ - is rotor position

$$\begin{cases} \sum L = \dfrac{L_d + L_q}{2} \\ \sum L = \dfrac{2L_0 - L_{0rd} - L_{0ts} - L_{ys} +}{2} \\ \quad + \dfrac{2L_\sigma - L_{\sigma ts} - L_{\sigma ys}}{2} \end{cases} \quad (11)$$

$$\begin{cases} \Delta_1 L = \dfrac{L_q - L_d}{2} \\ \Delta_1 L = \dfrac{- L_{\sigma ts} + L_{\sigma ys} + L_{0rd} + L_{0ts} + L_{0ys}}{2} \end{cases} \quad (12)$$

If the main inductance variation is used as the reference the variation in the leakage inductance influence the magnitude of position dependent inductance. If the leakage yoke saturation term ($L_{\sigma ts}$) in (12) is larger than the leakage tooth saturation term ($L_{\sigma ys}$) the leakage terms adds to the main inductance saliency. If $L_{\sigma ts} > L_{\sigma ys}$ the leakage terms oppose the position dependent terms from the main inductance.

2.2 Load dependency

Several factors may change from an unloaded to a loaded machine: flux and saturation levels, flux and saturation orientation and saturation regions. In this model the orientation of the resulting stator flux is considered in the first stage. In the next stage saturation from the load current is included. In order to simplify the model the control optimal control of the PMSM is not considered. The control strategy of the machine is assumed when the current $i_d = 0$. The shift in the stator flux results in a shift of the stator yoke and teeth saturation regions. In addition to the main flux effects the leakage effects must also be included. Figure 3 illustrates typical saturation regions due to the leakage flux from the load current. This type of saturation will result in a load dependent term in the *q*-axis leakage inductance (L_{lds}):

$$L_{q-leakage} = L_\sigma - L_{\sigma ts} - L_{lds} \quad (13)$$

$$L_q = L_0 + L_\sigma - L_{\sigma ts} - L_{lds} \quad (14)$$

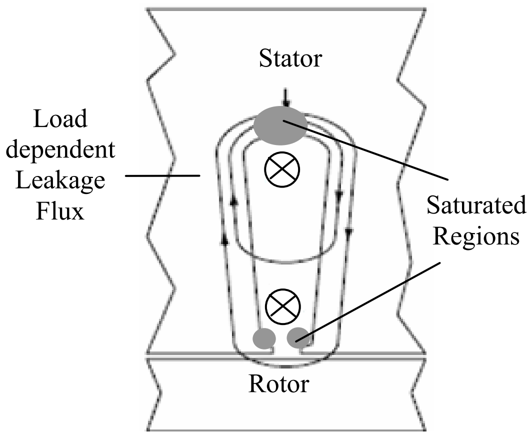

Figure 3: Saturation due to leakage flux from load current.

In this model the saturation is assumed sinusoidal distributed and linear. The different Terms may be combined to form resulting single saliency.

3. NUMERICAL ANALYSYS

For the numerical analysis on used a motor 30 kW (motor data in Table 1), motor was designed for high fundamental flux (500 - 600 Hz) operation during field weakening.

Parameter	Value
P_n	30 [kW]
U_n	110 [V]
I_n	181 [A]
n_n	2500 [rpm]
L_d	0.12 [mH]
L_q	0.4 [mH]
p	4

Table 1: Parameters and theirs values.

The self and the mutual inductance were estimated by applying a transient excitation to the machine connected through inverter. Figure 4 shows the difference in the position dependent part of the self and the mutual inductance. In classical machine modeling the self and mutual inductance are modeled as:

$$L_a(\theta) = L_{a\sigma} + L_{a0} - L_g \cos(2\theta) \quad (15)$$

$$L_{ab}(\theta) = -L_{a\sigma}/2 - L_g \cos(2\theta - 120) \quad (16)$$

Where: $L_{a\sigma}$ - leakage inductance phase *a*; L_{a0} - average inductance (minus leakage) phase *a* and L_g - position dependent inductance phase *a*.

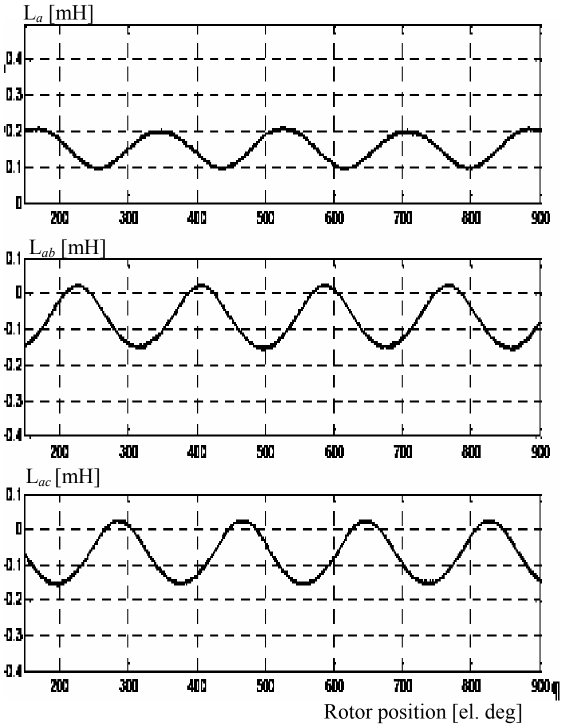

Figure 4: Self and mutual inductance with transient excitation.

In the saliency modeling in the previous section variations in the leakage inductance where assumed. If these variations are included in the model, the self inductance can be expressed as:

$$L_{a\sigma}(\theta) = L_{a\sigma 0} - \left(L_{a\sigma ts} - L_{a\sigma ys}\right)\cos(2\theta) \quad (17)$$

$$L_{a}(\theta) = L_{a\sigma 0} - \left(L_{a\sigma ts} - L_{a\sigma ys}\right)\cos(2\theta) - L_{g}\cos(2\theta) \quad (18)$$

where: $L_{a\sigma 0}$ - is the average leakage inductance phase *a*; $L_{a\sigma ts}$ - tooth saturation dependent term phase *a* and $L_{a\sigma ys}$ - yoke saturation dependent term phase *a*. The *b* and *c* – phase did not conduct any current and the leakage inductance. The expression in (16) is therefore assumed to be correct for the mutual inductance term. The classical modeling uses the average inductance as the basis for the model. In this work a maximum inductance was used. In order to relate the two models (18) was used in the stationary inductance matrix and transformed to the *dq* – representation. The magnitude of the position dependent terms in the mutual and self inductance indicates that there is a position dependency in the leakage inductance. The term $(L_{a\sigma ts} - L_{a\sigma yt})$ describes the position dependent term in the leakage inductance. In classical modeling this term will equal zero.

4. CONCLUSIONS

A new saliency model is presented in this work. The model incorporates the combined saturation effect in the stator teeth/yoke, induced currents in the magnets and load dependency. The model suggests that the leakage inductance should be modeled with a position dependent part. Simulations on a PMSM show that there can be a difference in the position dependent term in the self and mutual inductance when transient excitation is used to estimate the inductance. This difference can be incorporated in the machine model by adding position dependent part to the leakage inductance.
The model describes: the different sources of saliency, the combined effect of saliency in main and leakage inductance, saliency due to induced currents in magnets and the load dependency in the machine.

References

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