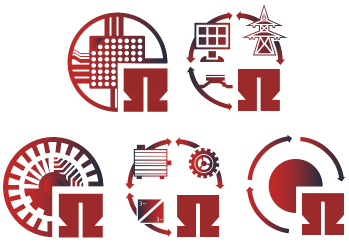
ELSYS Note



Precision Flux-Linkage Extraction

This note highlights the significance of the Finite Element Method (FEM) in accurately determining flux-linkage components for electrical machine design. By strategically setting the d-current to zero, the methodology efficiently extracts the synchronous inductance, offering precise insights into terminal behaviour amidst saturation and cross-coupling effects. The approach, reliant on FEM-calculated flux-linkages, enhances accuracy in predicting machine performance across varying current ranges.

Machine Design

A key step in designing electrical machines is to obtain the terminal parameters. In the simplest case, this is the flux-linkage as a function of the current, i.e., $\psi = f(i)$. In the case of an electrical machine, the flux linked by the stator coils is due to the current i. The flux-linkage is proportional to the current, i.e., $\psi = Li$. Thus the synchronous inductance L, defined as

$$L \equiv \frac{\psi}{i} \tag{1}$$

becomes a parameter that is only a function of geometric variables and μ_0. In this case, the terminal voltage from circuit theory is:

$$v = \frac{d\psi}{dt} = L\frac{di}{dt} \tag{2}$$

The materials used in electrical machines, especially the laminations, are saturable. Using analytical methods in machine design, it is clear that to obtain the terminal voltages, the focus is on calculating or estimating the inductance L. Furthermore, since the materials used are non-linear, this further complicates the procedure. In the case of machines with permanent magnets, this makes determining the inductance even more difficult. Therefore, a general method is needed to obtain the machine inductance.

Inductance not required

For asynchronous machines, design procedures are well-established, and in many cases, analytical tools are sufficient. When it comes to permanent magnet machines, this is not the case. However, since the increase in the use of the finite element method (FEM) in recent years [1], it is now possible to directly calculate the flux-linkage as a function of the current. **Therefore, there is no need to calculate the inductance to obtain the performance parameters in machine design**. However, a complete workflow to design an application is not limited to machine design only. In this not the focus is only on machine design.

Permanent magnets

The simplified equivalent circuits for the permanent magnet synchronous machine (PMSM) are shown in Fig. 1. Besides the non-linear material, the total flux-linkage in the d-axis has two components as shown in Fig. 1(b). In practice, determining the individual contributions of components, such as $L_\mathrm{d} I_\mathrm{d}$ and ψ_PM, to the total flux-linkage, $\psi_\mathrm{PM} + L_\mathrm{d} I_\mathrm{d}$, is not uniquely defined. Designers often need to make assumptions or employ specific methods to segregate the contributions of each component. Per definition ψ_PM does not contribute to L_d.

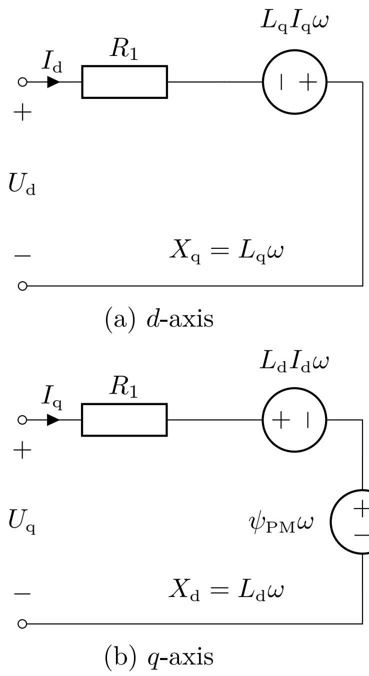
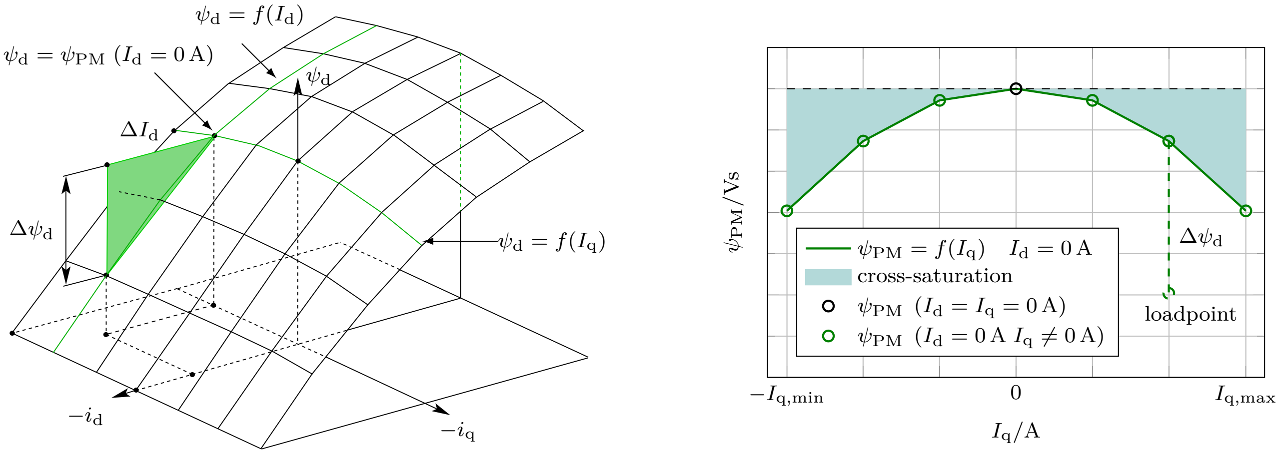


Fig. 1 PMSM equivalent circuits



(a) $\psi_d = f(i_d, i_q)$ (b) Function for permanent magnet flux-linkage

Fig. 2 Visualisation of the inductance extraction algorithm

Segregation

In recent years, the Finite Element Method (FEM) has become a common tool for obtaining the two flux-linkage functions [2] as functions of d and q currents, i.e.,

$$\begin{aligned}\psi_d &= f(I_d, I_q)\\ \psi_q &= f(I_d, I_q)\end{aligned} \tag{3}$$

as illustrated in Fig. 2(a) for ψ_d at a constant temperature. In the case of the q-axis flux-linkage, there is no offset due to the permanent magnets. However, in the d-axis, there is an offset. The green triangle in Fig. 2(a) shows that for a given ΔI_d the d-axis flux-linkage will change as well, i.e. $\Delta\psi_d$.

Setting $I_d = 0\,A$ simplifies the terminal voltage to $U_q = I_q R_1 + \psi_{PM}\omega$, where ψ_{PM} becomes the sole determinant. Crucially, I_q remains constant, accounting for cross-coupling effects. Extending this process across various operating points yields $\psi_{PM} = f(I_q)$ for $I_d = 0$, depicted as the green line in Fig. 2(a). Consequently, ψ_{PM} is reliably calculated for all operating points as shown in Fig. 2(b).

The change in voltage or flux linkage, initiated by $I_d = 0\,A$, unveils the synchronous inductance L_d,

$$L_d = \frac{\Delta\psi_d}{\Delta I_d} \tag{4}$$

which is distinctly termed synchronous inductance, differentiating it from a conventional differential inductance.

Discussion

There is no unique way to segregate flux-linkage components in the d-axis. While alternative methods exist, they are beyond the scope of this note. The presented method relies on two-dimensional FEM-calculated flux-linkages, as shown in Fig. 2(a) for ψ_d.

The extracted flux-linkages account for saturation and cross-coupling, describing the terminal behaviour of the machine over the given current range. The inductance extraction algorithm is a post-processing procedure and does not impact accuracy. If it doesn't meet design specifications, alternative algorithms can be considered, but this algorithm ensures the validity and positivity of inductance for all operating points.

Conclusion

In conclusion, the use of Finite Element Method (FEM) has revolutionized the extraction of flux-linkage components in electrical machine design. By setting the d-current to zero, the presented methodology accurately determines the synchronous inductance, crucial for understanding terminal behaviour. This approach, grounded in FEM-calculated flux-linkages, ensures accuracy in saturation and cross-coupling effects.

References

[1] J. Germishuizen and C. Adam. “Integrating FEM and existing traction motor design tools into an everyday engineering environment”. *e & i Elektrotechnik und Informationstechnik* 136.2 (2019), pp. 168–174. DOI: 10.1007/s00502-019-0719-7.

[2] J. Germishuizen and R. Tanner. “Calculating the PM motor inductances using the two-dimensional flux linkages”. *International Journal of Applied Electromagnetics and Mechanics* 57.S1 (2018), pp. 107–114. DOI: 10.3233/JAE-182300.