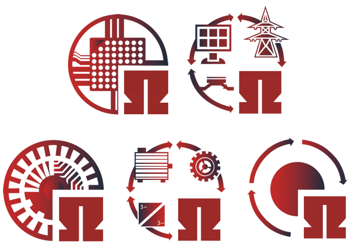
ELSYS Note



With or without rotation

This ELSYS Note presents a practical conceptual-design procedure for electrical machines in engineer-to-order environments. Three compact machine topologies (IPM-DDW, RSM-DDW, IPM-NOW) are analysed using flux-linkage maps obtained from fixed- and stepped-position FE simulations. The method achieves reliable performance estimation with less than 5 % *deviation while reducing computation time by a factor of up to* 50.

Conceptual design

The conceptual design of an electrical machine starts with selecting the main geometrical dimensions. In this step, the goal is to determine the volume that encloses the air gap, i.e., the bore diameter and the effective stack length. A simple and widely used approach is based on the torque per unit rotor volume (TRV) and the Esson coefficient C. Although computing power today is inexpensive and FEA has become a standard engineering tool, there remains a strong need to avoid time-consuming time-stepped simulations while still obtaining reliable performance estimates.

When developing a conceptual-design procedure, it is essential to consider the specific production context. The method presented in this note is tailored for an engineer-to-order production environment, where machines are not produced in series but are drafted, quoted, ordered, and only then fully designed. Consequently, accurate and robust performance-estimation procedures are required during the lead time.

Case Studies

Compact designs imply that the laminated parts operate deep in saturation, which makes the approximation of material behaviour a key design aspect. Examples of such compact machines are shown in Fig. 2 [1]. The machines considered are:

- an interior permanent-magnet synchronous machine with a double-layer distributed winding (**IPM-DDW**),
- a reluctance synchronous machine with a double-layer distributed winding (**RSM-DDW**),
- and an IPM with a single-layer non-overlapping winding (**IPM-NOW**).

The selection of these prototype machines covers a broad range of effects: highly saturated magnetic parts, spatial harmonics, reluctance torque, permanent-magnet torque, and combinations thereof.

Flux linkage maps

Flux-linkage maps can be obtained either from fixed-rotor-position FE solutions or from stepped-rotor-position simulations, as illustrated in Fig. 1. In the stepped approach, the rotor is advanced over several electrical degrees and an FE solution is computed at each step, which captures spatial harmonics and position-dependent saturation effects. However, this procedure leads to long computation times.

An alternative is the fixed-position approach, where the full flux-linkage surface is generated from a single, suitably chosen rotor position by applying the required dq-current excitations. This drastically reduces the computational effort while still representing the magnetic state of the machine.

The main question is whether such a single-position FE solution provides sufficient accuracy during the conceptual and lead-design phases, where quick but reliable performance estimates are essential.

This note investigates this question quantitatively by comparing fixed- and stepped-position FE results for three different machine topologies.

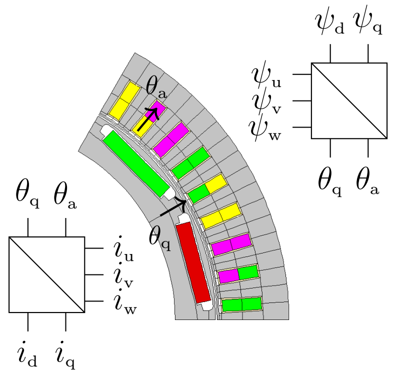
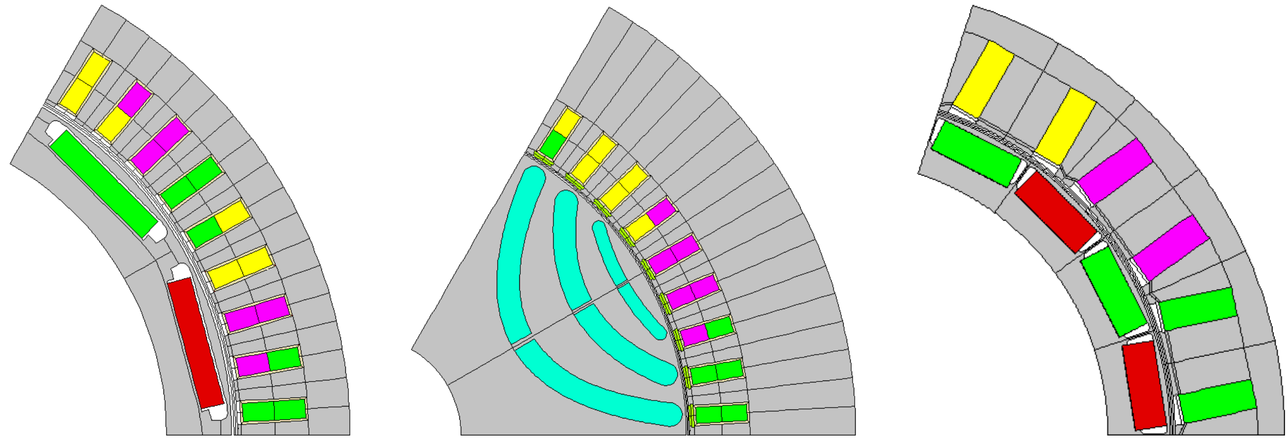


Fig. 1: Flux linkage maps workflow



(a) IPM-DDW 260 kW (b) RSM-DDW 110 kW (c) IPM-NOW 150 kW

Fig. 2: Selected topologies to cover a broad range of modelling characteristics.

Topologies

Depending on the specific application requirements, several motor topologies are available. PM machines offer high power density due to the remanent flux of the magnets and are particularly suitable for high pole-number designs. The RSM features no rotor copper losses and can exceed the performance of an induction machine, as shown in [2]. PM machines with non-overlapping windings are also widely used, especially in automation. Whether implemented as single- or double-layer windings, the resulting winding harmonics must be analysed carefully to ensure acceptable torque ripple and efficiency.

Comparison

The properties of the three prototype machines are listed in the table. For a selected operating point on the torque–speed characteristic, the corresponding stator current and terminal voltage are calculated. These quantities allow an assessment of whether a conceptual design can meet customer requirements.

The selected prototypes represent different modelling characteristics, including magnetic saturation, spatial harmonics, and distinct torque-production mechanisms. With respect to the research question, the deviation between fixed- and stepped-position FE results remains below 5 % for all topologies.

A central finding of this study is the significant reduction in computation time. For the same number of grid points, fixed-position FEAs are typically around 50 times faster than stepped-position simulations while maintaining an error level that is acceptable for conceptual and early-stage design calculations.

	IPM	**RSM**	**IPM**
P/kW	260	110	150
n/rpm	830	1500	255
T/Nm	2990	700	5600
D_o/mm	420	485	370
l_s/mm	400	340	786
p	6	3	10
$\theta_a/°$	50	96.67	30
$\theta_q/°$	30	30	18
Stepped FEA			
I_1/A	420.8	226.6	360.6
$\alpha/°$	128.2	53.5	103.1
U_1/V	454.1	486.5	430.8
Steps	29	31	37
t_s/s	2143	1461	1459
Fixed position FEA			
I_1/A	422.5	217.1	351.4
$\alpha/°$	128.9	54.4	97.6
U_1/V	450.2	495.2	440.1
t_f/s	46	25	26
Deviation			
ΔI_1/%	-0.4	4.2	2.6
$\Delta\alpha$/%	-0.5	-1.7	5.3
ΔU_1/%	0.9	-1.8	-2.2
Time-saving factor			
t_s/t_f	46	58	56

References

[1] J. Germishuizen and R. Tanner. "Stepped versus Fixed Rotor Position FEA Solutions for 2D Flux Linkage Maps in Machine Design". *Proceedings of the International Conference on Electrical Machines.* 2018. DOI: 10.1109/ICELMACH.2018.8507203.

[2] M.J. Kamper, F.S. van der Merwe, and S. Williamson. "Direct finite element design optimisation of the cageless reluctance synchronous machine". *IEEE Transactions on Energy Conversion* 11.3 (1996), pp. 547–553. DOI: 10.1109/60.537006.