# Synchronous reluctance machines

The synchronous reluctance motor is a promising technology to achieve higher levels of efficiency. These higher efficiency levels are required by the European Commission for electric motors on the European Market. The research focusses on the detailed electromagnetic design in order to combine high efficiency with a low torque ripple and high power density. Moreover, the control of the machine is investigated in order to obtain a stable behavior and a fast dynamic response.

## Introduction

Recently, a growing interest in the efficiency and the cost of electrical machines has been observed. The efficiency of electric motors is important because electric motors consume about 40%-45% of the produced electricity worldwide and about 70% of the industrial electricity. Therefore, some types of electric motors have been classified in proposed standard classes based on their efficiency. By consequence, efficient and low cost electric motors are necessary on the market.

Several types of electric motors are used in industrial applications such as permanent magnet synchronous motors (PMSMs), induction motors (IMs) and reluctance motors (RMs). Due to the high cost of PMSMs and due to the rotor losses of the IMs, the RMs can be considered as promising and attractive candidates. Moreover, they have a robust and simple structure, and a low cost as there are no cage, windings and magnets in the rotor. There are two main types of RMs: switched reluctance motors (SRMs) and synchronous reluctance motors (SynRMs). However, there are some disadvantages of these types of machines. On the one hand, the SRMs have problems of torque ripple, vibrations and noise. In addition, their control is more complicated than that of three-phase conventional motor drives, a.o. because of the high non-linearity of the inductance. On the other hand, the SynRMs have a low power factor, so that an inverter with a high Volt-Ampère rating is required to produce a given motor output power. Therefore, adding a proper amount of low cost permanent magnet (PM) material - such as ferrite - may be a good option to boost the power factor. The PMs also increase the efficiency and torque density. These types of motors are called permanent magnet-assisted synchronous reluctance motors (PMaSynRMs).

In this project, both SynRMs and PMaSynRMs are investigated. The main focus is given to the rotor design, magnetic material grade and winding configuration. In addition, the modelling and control of SynRMs and PMaSynRMs are also studied.

## Modelling and control

First, parametrized models are made of the machines. The finite element method (FEM) is used to obtain the *dq*-axis flux-linkages $\lambda_d(i_d, i_q, \theta_r)$ and $\lambda_q(i_d, i_q, \theta_r)$ of the SynRM in static 2D simulations, as a function of *d*-axis current id, and *q*-axis current $i_q$ and rotor position $\theta_r$. As known, the performance (output torque, power factor and efficiency) of SynRMs depends mainly on the ratio between the direct (*d*) and quadrature (*q*) axis inductances ($L_d/L_q$). This ratio is well-known as the saliency ratio of the SynRM. As magnetic saturation causes significant changes in the inductances and by consequence in the saliency ratio during operation, a SynRM model based on constant inductances ($L_d$ and $L_q$) is not good enough. It can lead to large deviations in the prediction of the torque capability compared with the real motor. How large these deviations are, is clarified by comparing several models that do or do not take into account saturation, cross-saturation and rotor position effects. It is found that saturation and cross saturation must be included in the model for an accurate representation of the SynRM performance and control. This means the flux linkages should be function of $i_d$ and $i_q$. The rotor position needn't be included. Apart from the currents, the FEM contains many parameters for the flux barrier geometry, which have a strong influence on the torque and torque ripple of the machine. Next to static simulations, also dynamic simulations are done. In these simulations, the flux-linkages are stored in lookup tables, created a priori by FEM (see Figs. 1 and 2), to speed up the simulations.

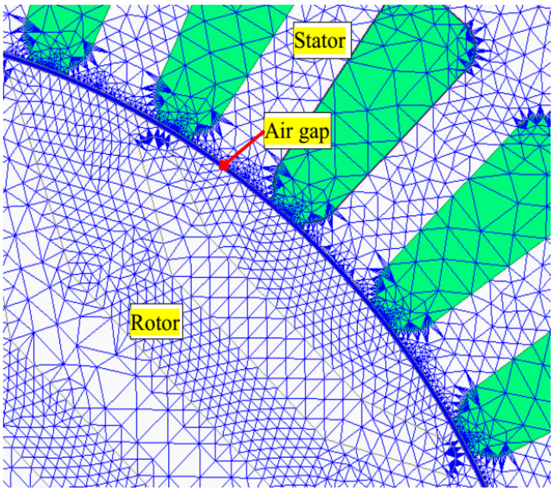


Figure 1. Mesh of a part of the SynRM geometry

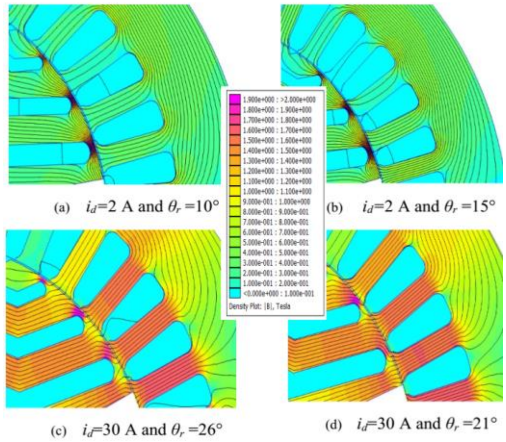


Figure 2. Flux paths of the SynRM for *iq*=10 A and different values for *id* and *ϑr*. The flux density scale ranges from 0 T (cyan colour) to 2 T (magenta colour)

## Design of SynRM

Based on the SynRM FEM model, the design of the SynRM rotor is investigated. Choosing the flux-barrier geometry parameters is very complex because there are many parameters that play a role. Therefore, an optimization technique is always necessary to select the flux-barrier parameters that optimize the SynRM performance indicators (maximize the saliency ratio and output torque and minimize the torque ripple). To gain insight in the relevant parameters, first a sensitivity analysis is done: the influence of the flux-barrier parameters is studied on the SynRM performance indicators. These indicators are again saliency ratio, output torque and torque ripple. In addition, easy-to-use parametrized equations are proposed to select the value of the two most crucial parameters of the rotor i.e. the flux-barrier angle and width. The proposed equations are compared with three existing literature equations. At the end, an optimal rotor design is obtained based on an optimized technique coupled with FEM. The optimal rotor is checked mechanically for the robustness against mechanical stresses and deformations.

## Improving SynRM Performance

### I. Electrical steel grade

Apart from the geometry, the electric steel grade plays a major role in the losses and efficiency of an electric machine. Therefore, several steel grades are compared with respect to the SynRM performance i.e. output torque, power factor, torque ripple, iron losses and efficiency. Four different steel grades NO20, M330P-50A, M400-50A and M600-100A are considered. The steel grades differ in thickness and in the losses they produce. It was found that the "best" grade NO20 had in the rated operating point of the considered SynRM 9.0% point more efficiency than the "worst" grade M600-100A.

### II. Combined star-delta configurations

Next to energy-efficiency, a large interest in recent research is dedicated to obtain a high torque density. One of the main techniques to improve the machine torque density is to increase the fundamental winding factor through an innovative winding layout. Among several configurations, the so-called combined star-delta winding layout was proposed in literature several years ago. In the PhD, the combined star-delta winding is compared with the conventional star winding in terms of output torque, torque ripple and efficiency. A simple method to calculate the equivalent winding factor of the different winding connections is proposed. In addition, the modelling of a SynRM with combined star-delta winding is given. Furthermore, the effect of different winding layouts on the performance of the SynRM is presented. To compare both windings experimentally, two stators are made, one with combined star-delta windings and one with conventional star windings, having the same copper volume. Simulations revealed a 0.26 % point higher efficiency and a 5.2% higher output torque of the first machine at rated current and speed.

### III. Adding Ferrite PMs in the rotor

In order to further improve the power factor and the output torque of the SynRM, ferrite PMs are inserted in the center of the rotor flux-barriers. The rotor geometry of the resulting PMaSynRM is the same as the conventional SynRM. Hence, two rotors with identical iron lamination stack were built: one with PMs and a second one without magnets. Having the two stators and two rotors, a comparison of four prototype SynRMs is done in the PhD, each of 5.5 kW. Several validation measurements have been obtained. The combined-star delta SynRM with PMs in the rotor had up to 1.5 % point more efficiency than the SynRM with star winding and rotor without magnets at the rated current and speed.

## Experimental setup

Several SynRM prototypes are manufactured and available at EELAB. Two stators with different winding layouts (conventional star connected winding and combined star-delta connection) and two rotors with and without ferrite PMs are manufactured. Figure 3 shows a photograph of the porotypes.

The complete experimental setup is shown in Fig. 4. It consists of a 9.3 kW induction motor that is used as a braking load for the prototype SynRM. A torque sensor is mounted between the two motors to measure the output torque of the SynRM. In addition, the motor speed is measured by an incremental encoder of 1024 sample/revolution. A Semikron IGBT module inverter is used to drive the SynRM while a commercial inverter is employed to control the induction motor. The electrical variables i.e. voltage, current and power are measured using a power analyzer. For the control purposes, DS1103 platform is used to implement the control system that drive the SynRM properly.

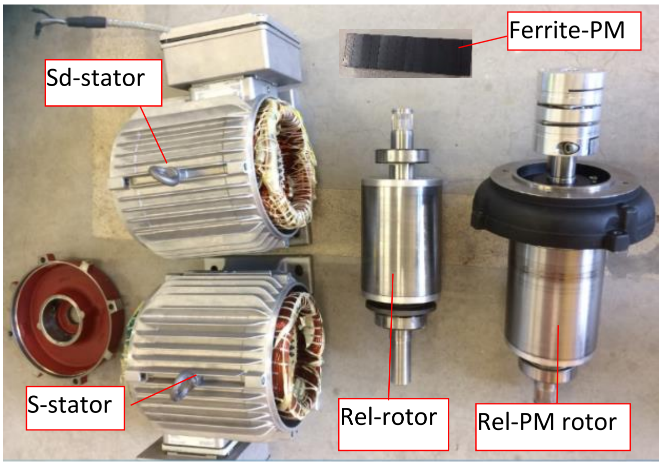


Figure 3. A photograph of the prototypes, where S is a conventional star connected stator, Sd is a combined star-delta connected stator, Rel is a conventional rotor without PMs and Rel-PM is a rotor with PMs.

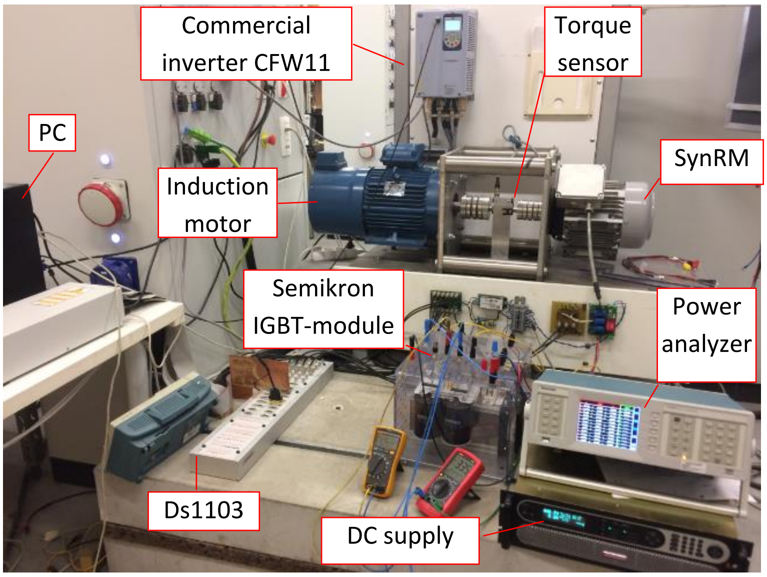


Figure 4. A photograph of the complete experimental setup.

## Application case: PV pumping system employing SynRM

As an application of SynRM, an efficient and low cost photovoltaic (PV) pumping system employing a SynRM is studied. The proposed system doesn't have a DC-DC converter that is often used to maximize the PV output power, nor has it storage (battery). Instead, the system is controlled in such a way that both the PV output power is maximized and the SynRM works at the maximum torque per Ampère, using a conventional three phase pulse width modulated inverter. The design and the modelling of all the system components are given. The performance of the proposed PV pumping system is presented, showing the effectiveness of the system.

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