Sensorless Commissioning and Control of High Anisotropy Synchronous Motor Drives

Abstract:

This thesis contains the research developments achieved during three years of PhD program at Politecnico di Torino, where the main research topics have been automatic parameters identification, namely self-commissioning, and investigation of reliable encoderless control strategies for high anisotropy synchronous motor drives.

Synchronous motor drives are an attractive solution for replacing traditional Induction Motors (IMs) in a wide number of variable speed applications. This trend is pushed by the generally higher efficiency and competitive torque per volume ratio of the synchronous machines respect the IMs. Among the wide variety of synchronous machines, the interest in high anisotropy motor drives considerably grew in the last decade respect to the machines producing torque mainly from the permanent magnets.

In Synchronous Reluctance (SyR) motors, PMs are not adopted, and salient rotor structure is obtained with proper machine design aiming to achieve the highest possible anisotropy with limited torque ripple. SyR machines are robust and relatively cheap, presenting high efficiency and high transient overload capability. Moreover, the power losses in the rotor are almost null.

On the other hand, SyR motors usually present low power factor, so the power electronic converter must be oversized respect to the rated power of the machine. Moreover, under inverter voltage limitation, large constant power speed range cannot be achieved. These drawbacks are overcome using PM-assisted Synchronous Reluctance (PM-SyR) motors, presenting similar stator and rotor geometry, but with small amount of PM insert into the flux barriers. The power factor is greatly improved and a very large constant power speed range is reached, with slightly higher torque capability.

Advanced motor control of ac drives requires the knowledge of rotor position, but the use of position transducers such as encoders or resolvers brings additional cost to the drive, particularly significant in home appliances and low cost applications. In these cases, a sensorless control algorithm is usually preferred, where the rotor position is observed based on the electrical quantities. In other applications, e.g. electrical propulsion systems, a position transducer is commonly adopted but the safety constrains require a sensorless strategy to be adopted in case of fault conditions. Sensorless control of SyRM and PM-SyRM introduces relevant challenges and possible improvements, as discussed in this manuscript.

Sensorless control is often affected by parameters uncertainty. As in any motor control algorithm, the stator voltage is not measured but evaluated relying on the inverter commands, so the voltage drop across the inverter must be compensated. Moreover, the knowledge of stator resistance is often necessary, e.g. to evaluate the electromotive forces. Finally, the current-to-flux relationship is highly non-linear for SyR and PM-SyR motors, and it has to be accurately evaluated.

The most accurate method to offline evaluate these parameters requires adopting dedicated laboratory equipment and high human intervention. This solution is applicable only for small number of machines, while it is not feasible for large industrial series production, where the tolerances of the manufacturing process introduce relevant parameters discrepancy between the motors. Therefore, automatic parameters identification test not requiring additional hardware, commonly called self-commissioning, are often preferred. Despite most of the

self-identification techniques found in the scientific literature require an encoder, a full sensorless approach forces also the self-commissioning to be encoderless.

This PhD dissertation is organized as follow. At first, a summary of theoretical background principles is given to better understand the rest of the thesis. Then, the two main topics, i.e. self-commissioning and sensorless control, are treated in separate chapters. In both cases, a deep literature review of the already existing techniques is followed by personal achievements and contributions and experimental testing results. Then, the proposed sensorless and self-identification techniques are experimentally validated using a high power SyR prototype (250 kW), discussing the possible application of SyR and PM-SyR motors for aerospace applications. The main drawback of this machine, limiting its applicability, resulted the high current rating of the power electronic converter. Therefore, the thesis is concluded presenting an innovative technology, called Dual Winding (DW), which is capable of reducing the converter size. The main achievements are summarized in the following.

Dealing with self-commissioning, a feasible magnetic model self-identification test sequence was adopted and tested on several SyRM, resulting accurate in the most demanding conditions (i.e. standstill and free shaft). The test sequence was augmented for the first time with high frequency signal injection for online position tracking, considerably improving the measurement domain in the current plane and so the accuracy of the obtained flux characteristic. Accurate automatic calibration procedure was defined to make the algorithm self-tuned with negligible human intervention. Several post-processing methods for extracting the flux maps are proposed. An accurate algebraic magnetic model resulted well suited for every tested machine, and a proper data manipulation sequence is given for retrieving its parameters. Other solutions are also discussed. Then, the commissioning test sequence was extended to PM-SyR machines at free shaft, including two novel methods for retrieving the flux linkage contribution at standstill with promising results.

In the field of sensorless control, the peculiarities and critical issues of SyRM were analyzed, discussing different solutions. An appropriate saliency based position estimation technique was adopted at low speed, resulting immune from position error due to cross-saturation effect. This algorithm was merged with two different model based position observers at high speed, thus covering a wide speed range from standstill to flux weakening. At best of Author knowledge, MTPA trajectory was adopted for the first time for sensorless control of SyR motors. Additionally, fine analysis of local saliency characteristic in the *dq* plane was conducted, addressing the critical aspects of saliency tracking via HF injection and demodulation. This analysis demonstrates that a modified MTPA law is recommendable also for the sake of stability of saliency-based sensorless methods. Also in this case, automatic tuning criteria are proposed for control self-calibration. Combined with the automatic tuning of the self-commissioning technique, a completely plug-and-play strategy is reached. Finally, novel low speed injectionless position estimation algorithm is presented, based on FCS-MPC.

The self-commissioning test sequence was successfully applied to the 250 kW SyR machine, and the obtained flux maps, which resulted consistent with the reference characteristic measured at constant speed, were adopted in a feasible sensorless algorithm. Altogether, the magnetic model identification method proved to work properly independently by the size of the machine. Then, the DW technology is analyzed. A reduced size motor prototype was designed and successfully tested, proposing several solutions for its motor control. This prototype highlighted a relevant unbalance in the windings temperature distribution. Proper thermal model to analyze this effect is proposed, together with a test sequence able to accurately retrieve its parameters.