Abstract

Electrification of the vehicle sector has undoubtedly gained attention in the last decade, and almost all car manufacturers offer hybrid and fully electric drivetrain solutions in 2025. As traction motor, interior permanent magnet synchronous machines (IPMSMs) are used dominantly due to their superior performance including high efficiency and power density. This thesis aims to contribute to vehicle electrification by position sensorless control solutions to electric vehicle (EV) traction IPMSM drives that increases the reliability and safety of the drive system.

The objective of position sensorless control of electric drives is to regulate the torque, shaft speed, or rotor position of electric machines without installing a rotary position sensor on the machine shaft. A vast number of sensorless control solutions can be found in the literature for industrial applications such as pumps, blowers, and home appliances, where the main objective is to replace the position sensor with a position observer and therefore reduce the price of the product, but the requirement for control quality is moderate.

On the contrary, in EV traction drives, the position sensor is always installed to achieve the highest efficiency possible by accurate torque and current control. Being safety-critical systems, EV traction drives have to remain functional in harsh environment even in the event of a position sensor malfunctioning. Hence the focus of sensorless control of EV traction drives is on safety and reliability.

Even in sensorless control mode, the highest possible torque control quality should be aimed at, which is challenging due to the peculiarities of IPMSM traction motors. These motors are designed to have very high power density by fully utilizing the magnetic materials, thus they undergo heavy saturation and consequent strong parameter variation. Hence, using accurate flux and inductance maps in the fundamental current control and sensorless observer is highly advantageous over using constant nominal parameters. Besides the effect of magnetic nonlinearity, other aspects also have to be addressed, such as how to maintain high torque quality at low shaft speed in sensorless mode where saliency-based techniques apply high-frequency (HF) voltage injection to provide angle and speed estimation using the HF current response. Furthermore, activating the sensorless control when position sensor failure is detected can be highly challenging due to the initialization of multiple state variables in the observer. The transition from sensor-based to sensorless mode, or alternatively switching on-the-fly, is not analyzed for industrial applica-

tions since the position sensor is not installed. The sensorless control of EV traction drives is still under development due to their peculiarities, and novel solutions are needed, which is proven by the very low number of papers providing experimentally validated sensorless control of real EV traction motors.

In this thesis, three main contributions are elaborated in the field of sensorless control of EV traction IPMSM drives.

1) The HF torque ripple generated by the HF voltage injection is analyzed, and an optimal pulsating injection scheme is proposed that minimizes the HF torque ripple. The proposed approach is applicable to both sinusoidal and square-wave HF voltage injection, and the flux and incremental inductance maps are used to calculate the optimal HF voltage injection angle thus it does not hinge on the current reference vector. Hence, it allows more flexible application than alternative solutions in the literature, and the parameter sensitivity has also been analytically deducted and experimentally verified.

2) During the startup of the drive in sensorless mode, saliency-based observers converge either to the correct rotor position or to a misaligned position with 180° angle error due to the second spatial harmonic incremental inductance distribution. These two cases have to be differentiated by means of polarity detection methods and correct angle estimation has to be ensured before the start of the torque control. It has been proven that due to the locally inverse saturation characteristics of the direct flux map of EV traction IPMSMs, opposite polarity detection logic has to be applied than in the case of industrial motors. Two polarity detection methods have been optimized to obtain very fast and reliable polarity detection incorporating the opposite polarity detection logic. These methods have been seamlessly integrated into HF voltage injection-based sensorless control, hence they can be applied at any shaft speed and not only at standstill, which enables restarting the drive.

3) The switching on-the-fly transient at low shaft speed is particularly challenging because the observer relies on the HF current components, but HF voltage injection is not applied in sensor-based operation. Thus, the observer input signals are not available. In order to achieve accurate observer state initialization, a virtual HF voltage injection technique was proposed that runs the drive model with HF voltage injection virtually in the control code. With this solution, the observer states are always in a quasi-steady-state condition, and no limit is set on the demodulation complexity. The effectiveness of the proposed virtual HF voltage injection to obtain seamless switching on-the-fly transient was experimentally proven for both sinusoidal and square-wave injection in numerous operating scenarios.

Besides the main contributions, sensorless control has been developed and experimentally tested on a real EV traction motor over wide speed range using hybrid active flux observer at middle- and high-speed operation and a linear transition between HF voltage injection-based sensorless control and the hybrid active flux observer.