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Saliency-Based Sensorless Vector Controls of Alternating Current Rotating Machines Using High-Frequency Voltage Injection Methods

PHD THESIS BOOKLET

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1. Introduction

In this dissertation I would like to present my scientific results in the field of sensorless vector control theories, especially the non-model based, high-frequency signal injection methods. My motivation during the research was to provide the full mathematical description of the selected methods, that were partitioned among many articles. Using the mathematical description as a basis, estimator structures can be defined. During the literature overview I discovered the estimator structures lacked of proper description. In the case of open-loop like estimators the required additional compensation methods, whilst in the case of closed-loop like estimators the dynamic equivalent model was missing. The proper modeling of the estimator structures is required to achieve the target precision and to be able to tune and investigate the stability of the estimators on the whole range of operation.

The structure of the dissertation is the following:

- in Chapter 2 I present the developed tools which were used during the research. It includes the development of the machine models and also the hardware and software design of the experimental inverter which was used during the measurements. **I detail the first thesis here, related to the modeling process**,
- in Chapter 3 I summarize the most common and successfully implemented sensorless vector control methods. The investigation of these methods pointed out the possible new scientific results in the injection-based approaches,

- in Chapter 4 I present the high-frequency stationary and synchronous voltage injection methods. Their mathematical description with proposed estimator structures is detailed on permanent magnet synchronous machines, synchronous reluctance machines and induction machines. Furthermore, simulation results and experimental measurement results are presented and compared. **In this chapter I present the main portion of the research and two theses related to high-frequency signal injection-based methods**,
- in Chapter 5 gives a summary and further development ideas related to the previously presented topics,
- in Chapter 6 I present all of the theses.

2. Developed Modeling and Measurement Tools

2.1. Motivation of Tools Development

In this chapter the developed machine models and the measurement system will be detailed. The target of the machine modeling process was to combine the space-vector-based models of the rotating machines with their FEM analyses' results. By doing this the inductance saturation and also the cogging torque effects of these machines can be modeled. Compared to coupled simulation, the execution times of the models are reduced, so they can provide accurate enough simulation results for control system development. It is worth to mention, that the precision of these extended machine models will not reach a true coupled simulation's one, but offer significantly better result than the static and concentrated parameter models.

The research involved the three most widely used AC machines in industrial and automotive applications:

- permanent magnet synchronous machine (PMSM),
- synchronous reluctance machine (SYNRM),
- squirrel-cage induction machine (IM).

These machines and their models were used during the simulations and experimental measurements. For the latter one, a single-phase input IGBT-based inverter was used, offering the possibility of implementing various control methods for the machines under test.

2.2. Modeling Process

In the AC machine modeling process, I combined the finite element method (FEM) approach with the space vector-based machine equations for all investigated machine types. The models were created using the following software:

- FEMM 4.2,
- MATLAB and Simulink 2019b.

This process could be considered as a two-way coupling between FEMM and MATLAB, and the process itself can be visualized as shown in Fig 2.1.

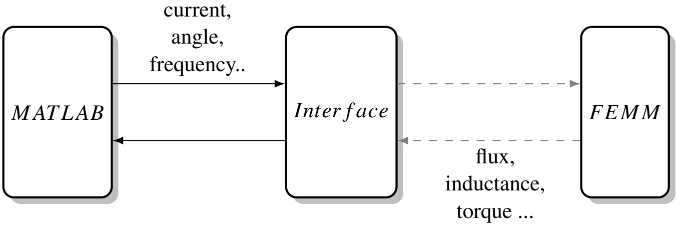


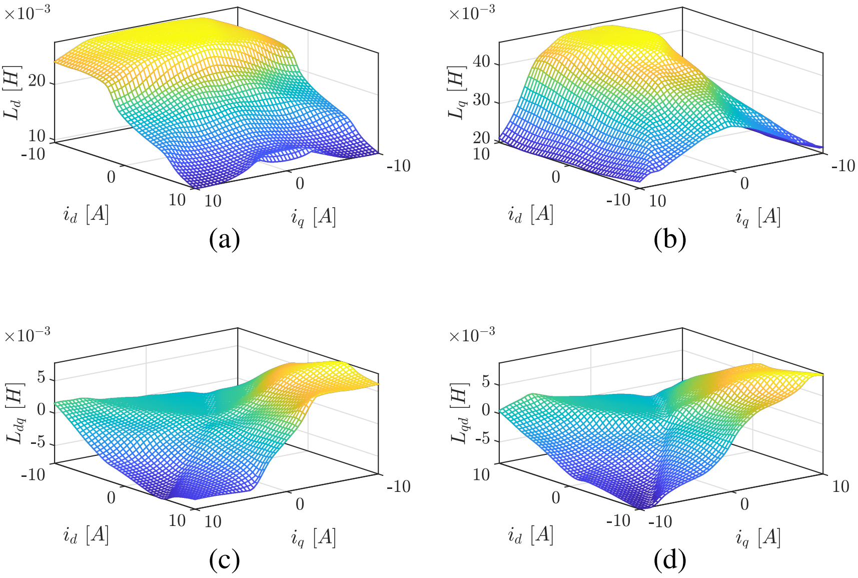
Figure 2.1 Combined modeling process of AC rotating machines using MATLAB and FEMM

Current, mechanical angle and frequency parameters were set in MATLAB script to achieve the desired operating point. Thereafter, using the provided interface [1] between the two software, these parameters were set in the FEM model. To speed up the overall analysis the calculations were run in parallel. The FEM results for the corresponding operating points were sent to MATLAB using the same interface. After the FEM analyses, their results were post-processed in MATLAB to obtain the inductance and torque profiles.

2.3. Permanent Magnet Synchronous Machine Model

The performed rotating machine analysis was the combination of measurement data evaluation and finite element method (FEM) analysis, so standard no-load and nominal load and short circuit measurements were performed on the custom-designed PMSM.

The inputs of the FEM analysis were the known motor topology including the applied materials and winding scheme. In the first step the $d-q$ axes fluxes and inductances were calculated as shown in Fig. 2.2, which are the functions of direct-axis i_d and quadrature-axis i_q currents, followed by the machine's torque profile calculation. As an enhancement the cogging torque was also taken into account as a look-up table, which is the function of current amplitude and actual electric rotor position.



(a) (b)

(c) (d)

Figure 2.2 (a)(b) Progression of PMSM inductances (in (a) and (c) the *d* axes were inverted)

2.4. Synchronous Reluctance Machine Model

The PMSM analysis can be fully adapted to the SYNRM machines too, with minor changes in the post process algorithms. Accordingly, in the first step, the machine's fluxes were calculated followed by the torque profile, which was calculated over only one pole pitch, because its double periodicity in angle.

2.5. Induction Machine Model

The analysis is based on a least squares method [2, 3], and its steps were the following:

1. Analyzing the machine at different slip frequencies and different stator current amplitudes. By doing this the torque profile of the machine and also the machine inductances can be calculated that are required for the next step,
2. Solving the linear parameter fitting problem, which is basically a least-square fitting problem for the machine parameters, that satisfies the FEM calculation's output.

2.6. Measurement System

The simulations were run in MATLAB Simulink [SzG1, SzG7] and the measurements were performed on an IGBT-based inverter, its functional diagram is shown in Fig 2.3. The power stage of the measurement system was a $2kW$ ST STGIPS20C60 single-phase input inverter and for its control I designed an isolated TMS320F28397D-based control module as shown in Fig. 2.4(a). The control card is able to handle many kinds of encoder, such as a SINCOS encoders as shown in Fig. 2.4(b)-(c).

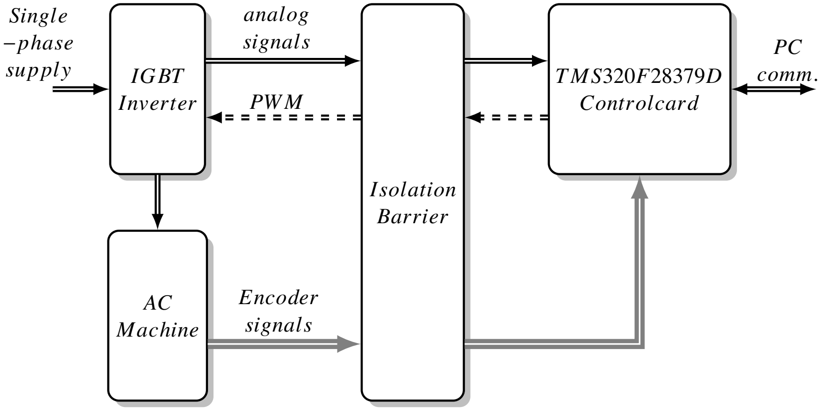


Figure 2.3 Functional overview of the measurement system

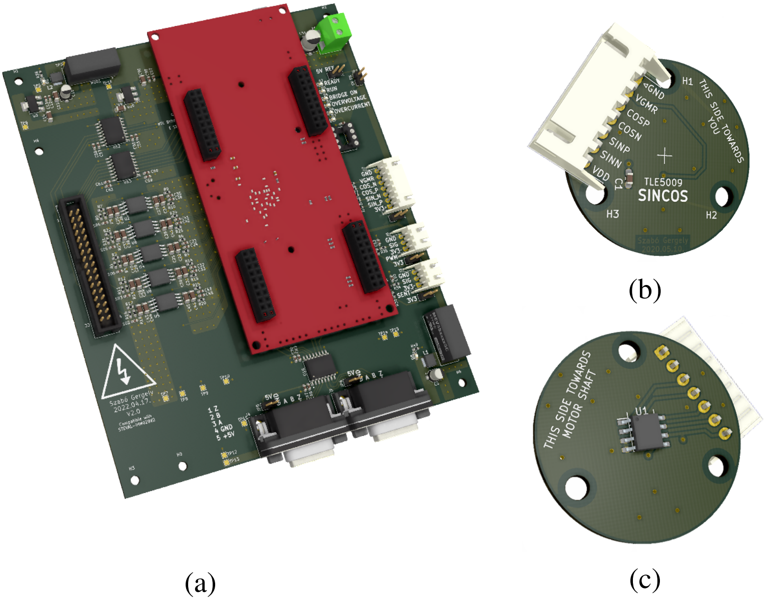


Figure 2.4 (a) Inverter control card, (b)(c) SINCOS encoder

3. Overview of Sensorless Motor Control Algorithms

3.1. Sensored and Sensorless Vector Controls

In this chapter I give an overview on some of the widely used sensorless vector control methods and it serves as a basis for the upcoming chapters.

The vector control algorithms of AC drives have an important common property; all of them require the common coordinate system's angle. This angle can be obtained using a shaft angle encoder, with machine model or with a sensorless algorithm. In case of shaft angle encoder, the property and the dynamics of the encoder highly influence the drive control method. The main differences are usually the sensing capabilities of the encoder, meaning whether it is able to provide absolute or relative angle. Another can be the sensing principle of the selected encoder which usually defines whether the encoder is shaft-mounted or contactless. Nevertheless, the communication interface of the encoder must be taken into account during the selection process.

The sensorless vector control methods [4] try to eliminate the speed encoder from the controlled electric drives, but in most cases, the shaft angle encoder cannot be omitted, because of the safety level of the application. In such drives, a sensorless vector control method can be used as backup algorithm, with which the drive system can be stopped without damaging the drive or the users. The sensorless term must be clarified depending on the machine to be controlled; in case of an induction machine, this term needs to be divided into at least two approaches, because the shaft angular position and the common coordinate system's angle, which is used to be rotor flux vector's position, are not the same and depends on the state of the machine. The simple sensorless term can be used for an algorithm, with which the common coordinate system can be estimated without using angle feedback from the shaft, but in this case, the closed-loop speed control still depends on the encoder attached on the rotor. On the other hand, a speed-sensorless method is capable to control the induction machine's angular speed too, without any encoder built in the system. In case of a synchronous machine the sensorless and speed-sensorless terms can be merged, since the pole-flux vector's angle is in direct relation with the shaft's mechanical angle.

From the algorithm point of view, the available methods could be categorized into two sections. The first one attempts to estimate the machine's signals based on its mathematical models and the combination of several filtering methods and controllers. Model Reference Adaptive System (MRAS) , Natural Field Orientation (NFO) or Sliding-Mode Observers are good examples in this section. This category also incorporates the well-known estimator structures; such as Kalman filtering method, which also uses the machine's model, combined with model of the system and the measurements disturbances.

Sensorless algorithms in the second category try to exploit the machine's magnetic properties, which are dependent on the rotor's position or the magnitude of the flux. A well know method of this category is the INFORM, Indirect Flux detection by On-line Reactance Measurement or the High-Frequency signal injection methods.

4. High-Frequency Signal Injection Methods

4.1. Overview of Injection-based Methods

In this chapter I summarize the main results thus the main theses of the dissertation. During the literature analysis I discovered that the description of the voltage injection methods in the literature was separated or segmented and in some cases not complete. Therefore, during the investigation one of my targets was to detail and logically present the voltage injection methods' mathematical description, which lead me to one of the theses. The investigation was carried out on the machines detailed in Chapter 2 during the research:

- permanent magnet synchronous machine,
- synchronous reluctance machine,
- squirrel-cage induction machine.

In order to facilitate detailed description of these methods, in the first subsections I present the high-frequency methods, assuming the PMSM as a target machine. Thereafter, in case of the other machines I only point out and present the differences, since the core mathematics of the methods are similar.

In general, the high-frequency signal injection methods could be categorized into the saliency-based approaches, in which methods usually voltage signals are injected into the predefined points of the control structure. This leads us to two main approaches; the high frequency stationary injection modifies the phase voltages of the machine by adding a symmetric voltage system to the motor's terminal voltages [5]. In the second approach the test vectors are injected in the estimated common reference frame, hence these techniques are called synchronous injection methods [6]. Beside the point of the injections, the signal processing methods with which the common coordinate system can be estimated are different.

The stationary injections usually involve heterodyne filtering techniques, where the measured high frequency stationary currents are transformed into several coordinates systems in which they are filtered to obtain the required angle information [7]. In case of synchronous injection, the flux vector's position can be estimated with Phase-Locked-Loop (PLL) [8].

The properties of the selected sensorless method must be taken into account during system design. Since the injection-based methods are expected to be applied at low angular speed region, basically two main challenges must be solved. One of them is the initial angle estimation, which is necessary if the encoder, on which the vector control depends at higher angular speed regions, is not capable of providing absolute angle information. This can be achieved without rotating the motor, which usually requires the motor parameters, or during rotation, with a vibration method. The other challenge is the transition between the sensorless and sensored vector control.

Based on the work with my fellow engineers in [SzG4], [SzG5], the multiphysical approach provides optimal design of the drive system . The integration of the FEM analysis results in the drive control algorithm development provides more precise machine parameters, which can be taken into account in form of look-up tables depending on the actual current, temperature or frequency. On the other hand, these results allow seeking the limitation and boundaries of stability of the applied control method.

The mathematical description of methods made me recognize that high-frequency synchronous voltage injection method's PLL-based, closed-loop behavior estimator structure requires a dynamic model, allowing the tuning of its controller. During the research I developed this new dynamic model, for all the machine types under test, which resulted in a new thesis and its subtheses.

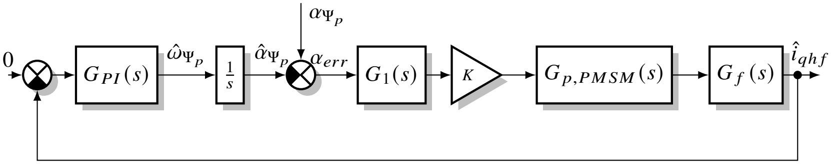


Figure 4.1 Example: Proposed dynamic model of the PLL for PMSM

With the help of the new dynamic model, and also the results from the FEM analyses I performed the stability analysis of this injection method. Furthermore, the integration of the FEM results provided more accurate limitations of the injection-based method, which resulted in a new subtheses too.

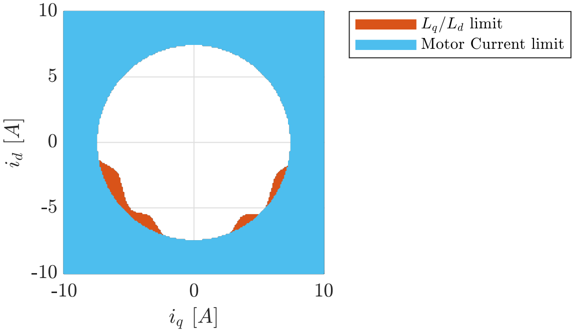


Figure 4.2 Example: Current limits for the PMSM under test with applied high-frequency voltage injection

In case of high-frequency stationary injection, I investigated the most common heterodyne filter-based approach, as shown in Fig. 4.3. Here I discovered that many times in the literature only the filter structure itself was presented but its intermediate signals and also the whole structure's effect on the output signal was completely missing or it was presented partially. The results of this investigation are also the part of one of the theses.

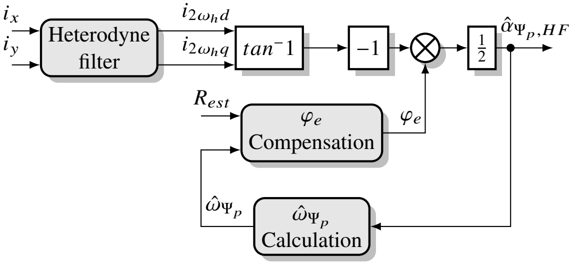


Figure 4.3 Heterodyne filter-based estimator

During research I discovered, that for certain reasons the synchronous injection method cannot be used for initial position estimation. To overcome these issues, I developed the combination of the injection-based methods, that solves the initial angle estimation problem and also the transition between them too. The performance of the proposed methods is demonstrated through simulation and experimental measurement results on the three examined machine types. This investigation led me to a new thesis too.

5. Conclusion and Perspectives

During the research it was proven, that the integration of FEM analyses results into the classic space vector-based machine equations could provide more accurate results. The required inputs of the model development are motor topology and used materials and also a finite element software. Although the models provide more accurate results they could be improved further. One upgrade shall be the integration of eddy current and additional losses into the machine model combined with the heat transfer model of the machines. This improvement shall be in relation with the losses coming from the PWM methods and its impact on the machine under test. Furthermore, the calculated inductance and flux profiles could also be improved with the introduction of the frequency dependent effects. This inspection shall also include the integration of the skin effect into the machine models, which could be a big improvement in case of induction machines.

During the system design, in case of the encoders, many new questions were raised. Since many types of encoders are available on the market with many kinds of sensing principle and interface, their effect on the system should be investigated. Based on them, the signal processing and also the additional algorithms should be investigated.

The high-frequency stationary voltage injection method could be considered as an open-loop solution, since its estimator is just based on the mathematical model of the measured current response and the compensation of the effects coming from the machine parameters and several filters. This method was proposed as a solution for the initial angle estimation problem in case of combined methods, where it provided good results. Compared to this, the high-frequency synchronous voltage injection method can be considered as closed-loop method, since its estimator is based on PLL structure containing a PI type controller. It was shown that the estimator structure's performance depends on the machine's parameters, the injected voltage's amplitude and frequency. The further step of the investigation shall be the optimal choice of the parameters, so

- What shall be the optimal injected voltage's amplitude and frequency? In this case the machine parameters are considered to be given, so only the injection ones could be adjusted.
- What properties of the machine shall be prioritized during electromagnetic design, if the machine is intended to be used in a high-frequency voltage injection-based method?

Both approaches lead to a multi-objective optimization problem, with respect of the target application and the injection method.

During the measurements and simulations, the usability of the injection-based methods on the machines under test could be tracked. These results also give insights into the effect of the machines' construction on the injection-based methods. The best performance was provided by the permanent magnet synchronous machine, where the estimator's dynamics was the best in all of the cases.

In case of the synchronous reluctance machine, which is considered to be the second best performance machine, the L_d, L_q values were almost five time bigger compared to the permanent magnet machine's one. This is inevitable and logical, since such machine has only reluctance torque mainly governed by the L_d, L_q difference.

The worst performance was observed in the induction machine. This also could be explained by its construction, where the d and q axes impedances mainly differs in the additive presence of the rotor resistance. Therefore, the current difference which is the basis of the the estimation shows resistive properties making the phase detection relatively hard. Nevertheless, the bandwidth of the estimator was the worst among all of the cases.

Based on the research the injection-based methods should be used on permanent magnet synchronous machines or synchronous reluctance machines. In case of both machine types the combined algorithms are proven to be applicable and provide good results. In case of induction machines the injection-based methods are not recommenced, furthermore, the combined algorithms are not necessary.

The integration of the post processed FEM results into the stability analysis and also into the drive control algorithms are proven to be beneficial. A better picture of the system could be obtained and the system limits could be investigated more precisely. If the post processed data is available, then the injection method's stability can be simply maintained by keeping the current components below their predefined limits. The coupled analysis of the drive systems is promising regarding the optimal design. Along with my fellow research engineers, we started investigating joint rotating machine and drive design.

6. Theses

6.1. Thesis I. - Improved Modelling Process of AC Machines for Drive Control Development

Based on the published literature I examined and executed rotating electric machine analyses to use their results to extend simulation and model-based development approaches. Considering the benefits to be gained and the resource investment required, I developed and implemented an extended methodology, by involving the FEM analyses in the rotating machine modelling process, for permanent magnet synchronous machines, synchronous reluctance machines and squirrel-cage induction machines. The proposed extended models implement one-way coupling, compared to the usual two-way coupled co-simulation between a dynamic modelling software and a finite element software. With this extension, I can model the machines' cogging torque effects and saturating behavior. After runtime comparison test and also during the model-based software development process I found, that the usage of such one-way coupled, extended simulation is a sufficient improvement from an engineering point of view because the accuracy is significantly improved, while computational demand and simulation time are not significantly increased. Using this extended modelling process I can speed up the drive control software development iterations.

Related own publications: [SzG2] [SzG3] [SzG4] [SzG5] [SzG6]

6.2. Thesis II. - Mathematical Description and Modelling of High-Frequency Voltage Injection Methods

I developed and presented a complete mathematical description and modelling of the high-frequency synchronous voltage injection and high-frequency stationary voltage injection methods for the most common AC machine types, such as permanent magnet synchronous machines, synchronous reluctance machines and induction machines, not yet available in the literature. This allowed me to develop estimator structures, and algorithms for both injection methods, optimize, tune, test and adapt them to different types of machines, highlighting the differences between them .

Subthesis II. / A - New Dynamic Model for Permanent Magnet Synchronous Machines in the PLL-based Pole Flux Position Estimator

I developed and presented a new dynamic model, missing from the literature, for the high-frequency synchronous voltage injections method's PLL-based pole flux vector's angle estimator, applied on a permanent magnet synchronous machine. The presented dynamic model depends on the machine parameters and the injected voltage's amplitude and frequency and makes possible the tuning of the PLL's controller.

Subthesis II. / B - New Dynamic Model for Synchronous Reluctance Machines in the PLL-based Pole Flux Position Estimator

I developed and presented a new dynamic model, missing from the literature, for the high-frequency synchronous voltage injections *method's PLL-based pole flux vector's angle estimator, applied on a synchronous reluctance machine. The presented dynamic model depends on the machine parameters and the injected voltage's amplitude and frequency and makes possible the tuning of the PLL's controller.* ***I adapted the estimator structure, based on the different machine construction compared to the permanent magnet synchronous machine. I showed , that based on the different direct and quadratic impedance ratio, compared to the permanent magnet synchronous machine, the sign of the estimator's PI controller's feedback signal must be inverted.***

Subthesis II. / C - New Dynamic Model for Induction Machines in the PLL-based Rotor Flux Position Estimator

I developed a new dynamic model for the high-frequency synchronous voltage injections method's PLL-based rotor flux vector's angle estimator, applied on a squirrel-cage induction machine. ***I showed, that the new dynamic model is third order polynomial, compared to the permanent magnet synchronous machines and synchronous reluctance machines second-order polynomials. This higher degree polynomial comes from the inverse-Γ equivalent circuit that I used for the modelling.*** *The presented dynamic model depends on the machine parameters and the injected voltage's amplitude and frequency and makes possible the tuning of the PLL's controller.* ***I adapted the estimator structure, based on the different machine construction compared to the permanent magnet synchronous machine. I showed, that based on the different direct and quadratic impedance ratios, compared***

to the permanent magnet synchronous machine, the sign of the estimator's PI controller's feedback signal must be inverted.

Subthesis II. / D - Integration of FEM Results for the High-Frequency Voltage Injection-based Methods' Stability Analyses and Limitations

I developed a new method and principle for the motor current limits calculation, that maintains the usability of the high-frequency voltage injection methods. As a new approach, I combined my complete mathematical description of the high-frequency injection-based methods and the proposed new estimator structures with the post-processed FEM results. A good indication of its effectiveness and usefulness is that I applied these newly proposed current limits on the high-frequency voltage injection methods stability and parameter sensitivity analyses and I pointed out, that the integration of the post-processed FEM data extends the precision of these analyses.

Related own publications: [SzG8] [SzG2] [SzG3] [SzG9] [SzG10] [SzG11] [SzG12]

6.3. Thesis III. - Usability of Combined High-Frequency Voltage Injection Methods

Based on my previously detailed and presented new results, going beyond the methods found in the literature, I presented the initial angle estimation properties of the high-frequency synchronous voltage injection method in case of permanent magnet synchronous machines, synchronous reluctance machines and squirrel-cage induction machines. I *proposed, adapted and successfully combined the high-frequency stationary and synchronous injection methods as a solution for the initial angle estimation problem in case of permanent magnet synchronous machines and synchronous reluctance machines, where the precise knowledge of the common coordinate system's initial angle is required, since it is bound to the machine's designated mechanical points. I showed, that the combined algorithm is not necessary in case of induction machines, because the common coordinate system's angle is bound to the rotor flux vector's position, that can be commanded to any initial angle by the user.*

Related own publications: [SzG8] [SzG2] [SzG3] [SzG9]

Own Publications

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