FINAL RESEARCH REPORT

Investigation of control techniques applied in high speed electrical drives

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In the following, the research results carried out within the framework of the research project are presented by topics.

Optimized Pulse Width Modulation techniques for two-level inverters

To obtain the desired output voltage with variable frequency and magnitude the duration of the active and inactive switching states of the voltage source inverter (VSI) should be varied with a Pulse Width Modulation (PWM) technique. In the so-called linear modulation range only the 90.7% of the maximum available voltage can be achieved. Therefore, to improve the utilization of the inverter and to expand the output voltage to the maximum available voltage, the inverter should be operated in the overmodulation region. Very commonly the rated operational point and the flux weakening area of electric machines voltage are in the overmodulation region. Furthermore, for high-speed drives, the pulse ratio (ratio of the switching and fundamental frequency) in this range is a small number. Thus, the quality of the drive in this region is of great importance. The principle investigator deeply studied loss optimized PWM techniques in the overmodulation region. The optimization is elaborated for the lowest loss-factor, which is proportional to the square of rms value of current harmonics. Altogether four different PWM schemes are compared and analyzed deeply. It is determined, depending on the modulation index and the pulse ratio, which PWM scheme provides the optimal solution, the lowest harmonic loss. The calculation results are verified by simulations as well as laboratory test using a high-speed induction machine drive system. The results are published in a Q1 journal paper [J1] and in the proceedings of an international conference [P1]. The journal paper has received already 8 independent citations.

The PI investigated the application of the optimized PWM technique in closed-loop operation of high-speed induction machines as well. Applying optimal PWM technique in closed loop systems poses many challenges, like the proper timing of the current sampling. The PI proposed a method, which can express the fundamental current component from the measured distorted current signal. In this way the optimal PWM technique can be used in vector-controlled drives as well. The method is based on the estimation of the harmonic currents by using the transient equation of the induction machine. The harmonic currents are subtracted from the measured one to obtain the. The required sampling rate for the method is only three times higher than by applying synchronous sampling, which is a common method for non-optimal PWM techniques. Furthermore, a PLL (Phase Locked Loop) based method is introduced which can provide a synchronization between the controller and the look-up-table based optimal PWM algorithm The algorithm is demonstrated and validated by detailed simulation study for the overmodulation region of a high-speed induction machine fed by a two-level inverter. The results were published at an international conference [P2].

Within the framework of the research project the PI expanded the investigation of loss optimal PWM to the whole modulation range. Different possible voltage vector sequences are investigated as the function of modulation index and pulse ratio. Some rules are formulated, which can be used to find an optimal voltage vector sequence. It was demonstrated by the PI, that an optimal performance of a high-speed drive can achieved without exceeding a given maximum harmonic loss value or a maximum switching frequency constraint can be obtained.

The research work demonstrated that, lower switching frequencies/lower pulse ratios are enough if optimal PWM technique is applied, comparing to widely used carrier based PWM techniques. It is important from two aspects. On the one hand, the switching frequencies as well as pulse ratios are limited for high-speed drives. On the other hand, if the same harmonic performance can be obtained by lower switching frequency, the losses in the inverter can be reduced, which results in better efficiency of the drive system. The PI summarized the results in [P3]. The paper presents all the necessary equations, constraints and the numerical method used for the calculation. In this way the results can be reproduced and utilized by others. The calculation results are verified by laboratory experiments.

In summary the results obtained during the investigation of optimized PWM techniques demonstrate that, an acceptable drive condition can be obtained, even for very low frequency ratios both for overmodulation and linear modulation range. It makes the optimization technique applicable to operate not only high speed, but high pole-count drives or high-power drive systems as well.

Previously, one of the barriers for the spread of optimal PWM methods was their digital implementation. Nowadays, the high-performance digital devices allow the simpler implementation of optimal methods, which can cause their wider spread in practice. A simplified Look-up-table based implementation of optimal PWM technique is introduced by the PI in [J1].

Optimized Pulse Width Modulation techniques for multilevel inverters

Loss-optimized PWM techniques for two-level inverters are deeply studied both in the linear and in the overmodulation region for low pulse ratios, which is typical for high-speed drives. A feasible solution for the problems caused by low pulse ratio is to apply multilevel inverter topology. The most popular multilevel topologies are diode-clamped or neutral-point clamped (NPC), capacitor-clamped or flying capacitor (FC) and cascaded H-bridge converters (CHB). The method derived for two-level inverters are adopted by the PI to be used for multilevel inverter as well. Equations are derived which can be used practically for any number of voltage levels (like 3,5,7…).

In the literature for calculation of switching angles of optimal PWM techniques for multilevel inverters a quarter-wave symmetry is typically assumed, and the switching angles are calculated for the 0 – 90 electric degree range. Within the framework of the research project the PI used 60-degree vector symmetry (for voltage, current…) and the angles are calculated only the for 0-30 electric degree range. It results in considerably less computational effort at the same number of voltage level, pulse ratio and modulation index as the number of varying switching angles is less.

The PI demonstrated the calculation procedure of optimal PWM for multilevel inverters for a three-level NPC type inverter in [P4]. The paper presents all the necessary equations and constraints for the calculation. In this way the results can be reproduced and utilized by others. It is demonstrated in the paper, by using optimal PWM a much better harmonic performance can be obtained at the same pulse ratio comparing to the widely used space vector modulation. Furthermore, not only the harmonic loss is smaller, but the switching loss of the transistors is also smaller for the same parameters.

Observer algorithms for high speed electric drives

The implementation of any high-performance three-phase drive system (e.g. applying Field oriented Control (FOC) or Direct Torque Control) requires a high accuracy estimation of the actual stator or/and rotor flux vector. Furthermore, in the case of high-speed drives, it is very hard and expensive to find a speed proper sensor, which provides good accuracy from zero speed up to rated speed. By using speed estimator algorithms, the value provided by the mechanical speed sensor can be made more accurate, or even the sensor itself can be avoided.

In the case of high-speed drives both the sampling over reference frequency ratio and the switching frequency over reference frequency is a low value. The latter one, the low pulse ratio, results voltage and current harmonic spectra far more unfavorable than at standard ratios. The low sampling over reference frequency ratio can result uncertainty and inaccuracy in the calculation of the magnitude and angle of stator or rotor flux vector or in the estimation of the actual value of the speed

Within the framework of the research project the PI investigated different open and closed loop flux estimators (like Gopinath method) and different speed estimators (like Model Reference Adaptive System (MRAS) or Phase Locked Loop type observers) The discrete form by using Tustin approximation of each algorithm by recursive equations were derived, which can be used for practical implementation. The performance of the algorithms both in open and closed loop is validated for low frequency ratios. It was presented, by applying some methods -like compensating the angle in rotor flux calculation - a much more robust and stable performance can be obtained at low sampling to reference frequency ratios. The results of the PI is summarized in a conference paper [P5]. The results obtained are utilized during the investigation of model predictive control of high-speed drives.

Model predictive control of high-speed induction and synchronous machines

Model predictive control (MPC) can be a feasible solution to control high-speed induction and synchronous machines. MPC uses a system model to predict the drive system response to a certain control action. Generally, control actions are evaluated via a cost function, which should be minimized in order to find an optimal performance.

MPC schemes for electrical drives can be classified according to several aspects. One aspect is whether MPC scheme is based on a single cost function with weighting factors or multiple cost functions without weighting factors. In the first case, the value of the weighting factors has a great impact on the performance of the drive and their tuning is a nontrivial process, which is generally based on heuristic trial and error procedures. The clear advantage of methods using cost functions for each control objective is that the previously mentioned problems and difficulties related to the selection of weighting factors are solved. Furthermore, it can result in an equal compromise of tracking for each control objective at the same time. Within the framework of this research project PI focused on MPC schemes relying multiple cost functions. For example, in the case of a high-speed induction machine it can be realized using separate cost functions for the torque and the stator flux. Although using multiple cost functions eliminates the problem of calculating any weighting factor, the selection of the final voltage vector requires an additional sorting algorithm. By increasing the number of voltage levels or the prediction horizon, the sorting algorithm becomes more and more time-intensive, which can severely impair the performance of the control algorithm. The PI with his student introduced a novel hybrid sorting algorithm consisting of two sorting networks and a merging step. The results are published in an Open Access Q1 ranking journal [J2]. The paper reviews a few possible solutions, for sorting for three-level inverters, where the number of possible voltage vector (control actions) is 19. The techniques are implemented, and a detailed benchmark is carried out. As it is shown the novel hybrid method using sorting networks can reduce the computational time compared to other widely applied methods for three-level inverters. It should be mentioned the novel algorithm would perform even better if parallelization is an option, for example by using a multicore DSP or an FPGA. The novel sorting method can be applied in essence for inverter fed electrical drives with less or more voltage levels or any other engineering systems where MPC algorithm is used and the number of control actions is finite. In the paper [J2] a high-speed drive system is used as a case study, which bought from the financial support of the research project. Furthermore, the estimation method for stator flux introduced by the PI in [P5] is used.

PI also introduced a novel MPC scheme, where the sampling frequency is synchronized to the fundamental frequency. The synchronized method can improve the performance of the control algorithm for very low sampling to fundamental frequency ratio, as it can eliminate the low order harmonics and the number of switching can be reduced comparing to unsynchronized case at the same sampling frequency. Furthermore, the ripple in the electric torque can be smaller. The results were published in an international conference paper [P6].

The PI started to apply this synchronized MPC scheme on a high-speed permanent magnet machine (PMSM). Here a Phase Locked Loop based method is developed to synchronize the sampling frequency to the synchronous frequency. Furthermore, a discrete model of PMSM is derived, which give more precise prediction at very low *s*ampling to fundamental frequency ratios. The method is tested by simulations and laboratory tests, it can be said that, the results are promising. Currently the PI work on the editing of the article [F2], which, as planned, would be submitted within a few months to a Q1 ranked Open Access journal.

Optimized Pulse Width Modulation techniques for multiphase machines

As it is introduced PI studied optimized PWM techniques for high speed electric drives for three-phase two and multilevel inverters. To continue this research topic the PI started to focus on multi-phase machines. Advantages of multi-phase inverter-motor system, like better fault tolerance (it can operate even during phase open fault), lower motor torque ripples, smaller power rating of converter semiconductors and lower phase current for a given voltage rating, have been well evidenced in the past years. A space vector method for study harmonic losses of multiphase drives using optimized PWM techniques in the overmodulation region is introduced in a conference paper [P7]. The paper introduces the technique to calculate the switching angles and demonstrates that drawing vector paths in the different coordinate systems gives a very important information on magnitude of stator and rotor harmonic losses and show which harmonic order produce those losses. The calculations are verified by experimental results.

Resonant DC/DC converter for multilevel inverters

The PI participated in the study of a novel resonant DC/DC Boost converter, which has a possible application field for supplying multilevel inverters. The novel converter topology is capable of realizing the power flow amongst the two input and the four output channels in order to maintain the required equal or unequal output voltages. It offers the benefits of soft-switching capability, including zero voltage and zero current switching, resulting in high efficiency and reduced electromagnetic interference (EMI). A paper, which present the topology with a detailed steady-state analysis is sent to an Open Access Q1 ranked journal paper [F1]. The paper is currently under review.

Recent trends in electrical drives

The PI participated in the written of an educational, informative journal article about the current trends in the field of inverter fed electrical drives [J3]. The paper is published in Hungarian in the official journal of the Hungarian Electrotechnical Association. It is not indexed in international databases and it does not have any Q ranking or IF number. However, this journal has the highest number of copies among technical papers in Hungary.

Use of the financial support

With the help of the financial support of the research project the PI bought a high-speed drive system with a rated speed of 60 000 rpm. It consists of an induction machine connected to a permanent magnet synchronous machine. The fund covered also the cost of required additional auxiliary elements, like compressed air cooling, high speed clutch, holders, to run properly the machines at high speeds. A photo about the testbench can be found in [J2]. Furthermore, the financial support has made it possible to purchase digital development tools and to manufacture and build self-designed inverters, control and sensor cards. The financial budget made it possible to attend international conferences and cover the cost of Open Access publication.

It was already stated in the original research plan that PI would like to involve talented students in the research project. During the project PI worked successfully with many students. The financial support was used to provide adequate salary in return for their work. Some students were actively involved in the research, while other students did background work. PI published papers [J2], [P5], [P6] and [P7] with his students. Furthermore, one of the students (K. Bándy), who also involved in the research project, became the PhD student of the PI from February 2021.

Publication list

Journal papers:

[J1] P. Stumpf and S. Halász, "Optimization of PWM for Overmodulation Region of Two-level Inverters," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 54, no. 4, pp. 3393–3404, 2018. IF=3.488

[J2] K. Bandy and P. Stumpf, "Model Predictive Torque Control for Multilevel Inverter fed Induction Machines Using Sorting Networks," *IEEE ACCESS*, vol. 9, pp. 13800–13813, 2021., IF=3.745

[J3] S. Halász and P. P. Stumpf, "Az inverteres villamos hajtások fejlődési irányai," *ELEKTROTECHNIKA*, vol. 111, no. 12, p. 11, 2018. (in Hungarian)

Conference papers:

[P1] P. Stumpf and S. Halász, “Comparison of optimized PWM techniques for overmodulation region of two-level inverters,” in *International Ural Conference of Alternating Current Electric Drives (ACED 2018)*, 2018.

[P2] P. Stumpf and S. Halász, “Optimized PWM technique for Overmodulation Region in Vector Controlled High Speed Drives,” in *PCIM Europe Conference 2018*, 2018, pp. 1536–1543.

[P3] P. Stumpf and S. Halász, “Optimal PWM for Two-level Inverter fed High Speed Induction Machines,” in *2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC)*, 2018, p. 1.

[P4] P. Stumpf and S. Halász, “Optimal PWM for Three-Level Inverter fed High Speed Drives,” in *Proceedings of conference 13th IEEE International Conference on Power Electronics and Drive Systems*, 2019, p. 51.

[P5] P. Stumpf and L. Á. Váradi, “Investigation of Estimator Algorithms for High Speed Drive Systems,” in *Proceedings of the 2018 18th International Conference on Mechatronics – Mechatronika (ME)*, 2018, pp. 243–250.

[P6] P. Stumpf and I. Bara, “Model Predictive Torque Control with Synchronized Sampling Frequency for High Frequency Induction Machine Drives,” in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, 2020, pp. 332–338.

[P7] P. Stumpf, S. Halasz: Space Vector based Investigation of Overmodulation Region of Inverter Fed Multiphase AC Drives. In: *2020 IEEE 19th International Power Electronics and Motion Control Conference*

Papers under review:

[F1] J. Hamar, P. Stumpf: New Four-Channel Resonant Boost DC/DC Converter, IEEE Access (submitted: 21.03.2021)

Papers in preparation:

[F2] K. Bándy, P. Stumpf: Syncrhonized Model Predictive Torque Control scheme for High Frequency PMSM drives, Elsevire Mechatronics