Budapest University of Technology and Economics
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Booklet of PhD Thesis

Nonlinear Phenomena in Piecewise-Linear Nonlinear Mechatronic Systems

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Outline of Thesis Work

Many unexpected irregular behaviours caused by nonlinearities arise in mechanical and mechatronics engineering systems. The most common nonlinearities in the engineering practice are the friction, saturation, hysteresis, dead band and the backlash. Another source of nonlinearities caused by the controlled switching actions in power electronics converter. They play important role in up-do-date high-performance digitally controlled engineering systems, from milling machines via robotics through to the utilization of renewable energies, as they enable the efficient conversion of electric power to mechanical power and vice versa, furthermore to convert the electric power from one form to another.

In general, the power electronics converters are variable structure systems generated by a series of periodic switchings. Generally each structures can be modelled by linear time-invariant models therefore the systems are piecewise-linear. The overall systems are nonlinear as the switching times depend on one or more state variables or they are determined by nonlinear Pulse Width Modulation techniques.

One of the main goals of my research work was the comprehension and explanation of some unexpected phenomena caused in piecewise-linear systems, like the malfunction and breakdown of a high speed electro-mechanical drive including induction machine fed by voltage source converter or the large oscillations in the current signal of a Power Factor Correction (PFC) Converter. The analysis and understanding of nonlinear phenomena can help to improve the performance of the systems. The other goal of my work was to improve the reliability and extend the stability range of variable structure systems by novel auxiliary state vector technique. Its application is demonstrated for example in a PFC Converter.

The dissertation is divided into three chapters based on my three main research topics. Each chapter follows the same structure. After presenting the main motivation for the research a short review of the literature in the field is given. After that, the theoretic background required to understand the novel scientific contribution of the chapter is discussed. It is followed by the physical and mathematical description of the new contribution verified by simulation and experimental results supporting the theoretical predictions. At the end of each chapter the novel results and achievements are summarized in form of thesis. Furthermore, my related publications and the practical significance of the results are given.

Hereby I shortly summarize each of my research topics and introduce my theses.

DC Component and Subharmonics Generation of PWM Techniques in Ultrahigh Speed Drives

Failures of ultrahigh speed induction machines (USIM) experienced in the laboratory initiated my research work in the field of Pulse Width Modulation (PWM) techniques applied in threephase two-level Voltage Source Converters (VSC). The source of difficulties was the interaction of the Pulse Width Modulated (PWM) VSC and the USIM.

The basic feature of the PWM controlled VSC fed USIMs is the low frequency ratio $m_f = f_c/f_r$ ($m_f < 15$) owing to the necessarily high fundamental f_1 or reference f_r frequency and the carrier frequency f_c with limited maximum value leading to stator voltage and current harmonic spectra far more unfavorable as compared to those obtained at low fundamental frequencies. It should be noted, the problems encountered with the high speed drives appear also in high-pole count motor, used widely for hybrid and electric vehicles.

It is occasionally stated that the naturally sampled carrier-based PWM techniques do not generate DC components in the output phase voltage for synchronous PWM, when the frequency ratio is integer. The same results can be obtained by calculating the DC component using the double Fourier expansion method. I have proven just the opposite: when m_f is low and integer considerable DC components can be generated for natural sampled carrier-based PWM techniques when m_f is even and not multiple of 3. As it was shown the DC components can be avoided for even m_f if the number of samples during a carrier period is limited to be $n = 2$ (Doublesampled).

However, in most of the literature it is suggested to apply synchronous PWM and integer m_f if $m_f \leq 12 - 15$ even when f_1 varies, in most of the commercially available three-phase inverters the switching frequencies can be varied only in discrete steps (e.g. 3-6-12-16 kHz) resulting in asynchronous PWM. It gives the practical significance of investigation of the effect of low and non-integer m_f. Furthermore, as it was shown, subharmonic voltage component can results significant additional loss when $m_f \leq 15$. The presented results have to be evaluated in the light of many publications stating that the effect of subharmonics can be neglected.

Natural Sampled (NS) carrier-based PWM can be a favourable modulation for low m_f as no distortion or delayed response to the reference signal are introduced. Recently many researchers deal with the digital realization of NS utilizing the parallel computation properties of FPGA by increasing the number of samplings during one carrier period. In the dissertation a method for digital implementation of NS is presented which can be used even for low-cost microprocessor, where the registers of the PWM peripheral can be updated only twice during a carrier period. Contrary to other digital Natural Sampling techniques presented in the literature, the advantages of the method are that the multiple edge generation does not exist and it is enough to call the algorithm only twice per carrier period.

The results are detailed in Chapter 1 of the dissertation. The three novel scientific results are summarized in Thesis 1. The theoretical results were verified by computer simulations and laboratory measurements.

Stability Analysis using Auxiliary State Vector

Switching-mode power converters are probably the most commonly used devices as they can be found from simple domestic applications (like PFC converter) to different high performance drive systems (like DC or AC motor drive). The ever increasing need for producing more reliable, more effective and less expensive systems make the analysis, understanding and design of such switch-mode power converters important, interesting and even imperative.

It is common to analyse the stability and dynamical behaviour of these variable structure piecewise-linear nonlinear systems by discarding the switching details and retain only the average dynamics of the system. While this average model can be analysed easier using several tools available from linear control theory, it fails to capture the instabilities as the effect of the switching action. Furthermore in linear systems theory the loss of stability implies that the state diverges without limit. However, in nonlinear systems the outcome of a stability loss does not lead to an unlimited explosion of the variables. These devices may exhibit undesirable irregular behaviours such as bifurcations and chaotic motion.

The target of my research work was twofold. Firstly, to use and illustrate the application of the so-called auxiliary state vector to detect the subharmonic and chaotic dynamics of the state variables that could occur in systems applying switch-mode power converters. Secondly, to compensate the instabilities and expand the stable operation range of the studied systems. Two systems, a current controlled DC motor drive and a digitally controlled Power Factor Correction (PFC) with boost converter were analysed. Both systems are realized in the laboratory to verify the theoretic and simulation results.

It should be noted in the literature the Jacobian matrix of the PMF of the DC drive system was derived only for proportional controller. Furthermore, the results regarding to the PFC converter should be evaluated in the light of many publications in the field: On the one hand, the theory of nonlinear dynamics for stability analysis was applied mostly for PFC converters using only analog circuitry. On the other hand, mostly linear control theory was applied for the stability analysis of digitally controlled PFC converters.

I have shown that the novel method selected by me implying the so called auxiliary state vector inherently contains the feasibility to extend the stability range by adding a stabilizing signal into the control loop and the calculation of the parameters of the stabilizing signal. Furthermore I suggested a method to modulate the ramp signal for PFC converter according to the sinusoidal input voltage. I derived the equation of the stabilizing signal in the discrete time domain as well.

The results are detailed in Chapter 2 of the dissertation. The three novel scientific results are summarized in Thesis 2. The theoretical results of the stability analysis and the stability range extension were verified for both systems by computer simulations and laboratory measurements.

Effect of Sampling of Space Vector Modulation in Field Oriented Control Drives

Field Oriented Control technique is one of the mostly applied algorithm to control the speed and the flux of a three-phase electric drive thanks to its high performance and the advances in the semiconductors technology in both power and signal electronics. Due to its many advantage FOC driven electric machines are applied for drive systems of low-cost home appliances, like washing machine, to high performance and expensive systems, like transportation or manufacturing automation.

Furthermore as there is a strong trend to avoid mechanical motion (speed/ position) sensors because it reduces cost and improves reliability and functionality of the drive system my investigation is focused on a speed sensor-less FOC drive.

The application of high precision shunt resistors to measure the stator currents is a popular solution in Field Oriented Controlled electric drives due to the low system cost and exact measurements. Mostly the resistors are placed in the bottom of the inverter leg limiting the sampling frequency to be the carrier frequency ($f_s = f_c$).

In the last decade increasing attention has been given to high speed and high pole count motor drives. Even with the up-to-date digital devices with clock frequency in the range of tens of MHz, the sampling frequency is limited due to the shunt resistor measurement technique. It results that not only the ratio of the carrier to the actual fundamental frequency $m_f = f_c/f_1$ but the ratio of the sampling to the actual fundamental frequency $F = f_s/f_1$ is low around the maximum speed of a high speed or high-pole count motor. It deteriorates the performance of the closed loop drive.

My research work demonstrated that the performance of the drive can be improved if F is low by applying Double Sampled Space Vector Modulation (DS SVM) technique instead of Regular Sampled one. The main advantages of using DS SVM is that the robustness of the drive can be improved and its stability can be extended without any additional hardware. Furthermore the extra calculation time required by the DS SVM is also very low so it requires very small time window in the precious processor time of the microcontroller or the DSP.

The results are detailed in Chapter 3 of the dissertation. The novel scientific result, verified by computer simulations and laboratory measurements, is summarized in Thesis 3.

Theses

Thesis 1

1.a

The exact value of the DC component generated by carrier-based PWM algorithms can be calculated by the summation of the value of the reference signal $v_{ref,x}$ at the switching instants α_i

$$V_{DC,x} = \frac{1}{4m_f}\left(\sum_{i=1}^{2m_f} v_{ref,x}(\alpha_i)\right)V_{DC}$$

where x denotes the particular PWM techniques.

In single phase system no DC component is generated for Natural Sampling carrier-based PWM, when the frequency ratio is odd. Furthermore DC component is generated using Oversampled carrier-based PWM techniques only when the number of samples during one carrier period $n \geq 4$. DC component is generated even both for Regular Sampled Third Harmonics Injection PWM and Regular Sampled Space Vector Modulation when the frequency ratio is $m_f = 3$ and $m_f = 3, 5, 7, 9, 15, 21...$, respectively. In three-phase system, when the frequency ratio m_f is multiple of 3 or Regular Sampled PWM techniques are applied the DC components are cancelled in each phase voltage and no adverse effect is done. The dead time reduces the DC component.

1.b

Even though the level of subharmonic voltage is low, the subharmonic stator flux and current can be surprisingly high due to the very low subharmonic frequency. It can cause serious detrimental effects as the subharmonic flux and current components results in considerable additional stator and rotor copper loss. The special parameters of ultra high speed machines further accentuate the detrimental effect of subharmonics.

1.c

A novel algorithm, which calculates the intersection points of the carrier and the reference signal in real-time, is developed in digital microcontroller realizing the carrier based PWM techniques applying Natural Sampling with high precision in open loop.

Related journal papers: [J1, J2, J4]
Related papers in conference proceedings: [P4, P5, P7, P8, P12]

Thesis 2

2.a

The Jacobian matrix of the Poincaré Map Function (PMF) of the peak current mode controlled permanent magnet dc drive system can be straightforward determined without the derivation of the PMF by using the auxiliary state vector when proportional-integrator type speed controller is applied.

2.b

The critical phase angle, where oscillations start in the inductor current, of the digitally implemented average current mode controlled Power Factor Correction (PFC) converter can be calculated using the auxiliary state vector, when the digital computation delay was approximated by using the second-order Padé approximation and the effects caused by the Zero-Order Hold and the non ideal circuit elements were taken into consideration.

2.c

The stable period-1 range can be extended both in the DC drive and in the PFC converter system by adding a stabilizing ramp signal to the control loop. The slope of the ramp signal can be calculated by using the auxiliary state vector. The ramp signal for PFC converter should be modulated according to the sinusoidal input voltage.

Related journal paper: [J3]
Related papers in conference proceedings: [P1, P2, P9, P10, P11]

Thesis 3

3.

The stability range of a speed sensor-less Field Oriented Controlled induction machine can be extended by recalculating the reference signal of the Space Vector Modulation algorithm at the negative peak of the carrier signal by approximating the rotor flux angle change when shunt resistors, placed on the bottom of the three phase inverter legs, are applied to measure the stator currents and the current sampling, the estimation and the calculation of the controllers take place at and after the positive peak of the triangular carrier signal.

Related papers in conference proceedings: [P3, P6]

Other publications connected indirectly or loosely to the dissertation [R1, R2, R3, R4, R5, R6, R7, R8, R9]

Journal papers

[J1] **P. Stumpf**, R. K. Járdán, and I. Nagy, "Analysis of the impact of space vector modulation techniques on the operation of ultrahigh speed induction machines," *Mathematics and Computers in Simulation, Elsevier*, vol. 90, pp. 132–144, 2013.

[J2] **P. Stumpf**, R. K. Járdán, and I. Nagy, "Subharmonics generated by space vector modulation in ultrahigh speed drives," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 2, pp. 1029–1037, 2012.

[J3] **P. Stumpf** and I. Nagy, "Motor drive stabilization in its chaotic region," *Transactions on Electrical Engineering*, vol. 1, no. 1, pp. 19 – 25, 2012.

[J4] R. K. Járdán, **P. Stumpf**, P. Bartal, Z. Varga, and I. Nagy, "A novel approach in studying the effects of subharmonics on ultrahigh-speed ac motor drives," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1274–1281, 2011.

International Conference papers in Proceedings

11 papers in English, 1 paper in Hungarian

[P1] **P. Stumpf**, A. Lőrincz, and I. Nagy, "Stability of digitally controlled PFC boost converter with auxiliary state vector," in *2013 IEEE International Symposium on Industrial Electronics (ISIE), Taipei, Taiwan*, pp. 1–6, IEEE, 2013.

[P2] **P. Stumpf**, A. Lőrincz, and I. Nagy, "Analysis and compensation of oscillations in digitally controlled pfc converter," in *IECON 2013-39th Annual Conference on IEEE Industrial Electronics Society, Wien, Austria*, pp. 8348–8353, IEEE, 2013.

[P3] **P. Stumpf**, R. J. Kalman, and I. Nagy, "Digitally implemented naturally sampled svm applied in speed sensor-less field oriented controlled induction motor drive," in *Proceedings of the 12th Brazilian Power Electronics Conference (COBEP2013), Gramado, Brazil*, pp. 793–800, SOBRAEP, 2013.

[P4] **P. Stumpf**, R. K. Járdán, and I. Nagy, "Comparison of naturally sampled pwm techniques in ultrahigh speed drives," in *2012 IEEE International Symposium on Industrial Electronics (ISIE), Hangzhou, China*, pp. 246–251, IEEE, 2012.

[P5] **P. Stumpf**, R. K. Járdán, and I. Nagy, "DC components and subharmonics generated by naturally sampled pwm techniques," in *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, Montreal, Canada*, pp. 327–332, IEEE, 2012.

[P6] **P. Stumpf**, R. K. Jardan, and I. Nagy, "Effect of sampling space vector modulation in speed control loops of ultrahigh speed drives," in *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC), Novi Sad, Serbia*, pp. LS6a–3, IEEE, 2012.

[P7] **P. Stumpf**, Z. Varga, R. J. Kalman, and I. Nagy, "Analysis of space vector modulation techniques applied in voltage source converters of ultrahigh speed induction motor drives," in *Proceedings of the 2011-14th European Conference on Power Electronics and Applications (EPE 2011), Birmingham, UK*, pp. 1–10, IEEE, 2011.

[P8] **P. Stumpf**, D. T. Sepsi, R. K. Jardan, and I. Nagy, "Space vector modulation techniques applied in voltage source converters of ultrahigh speed induction machines," in *2011 IEEE International Symposium on Industrial Electronics (ISIE), Gdansk, Poland*, pp. 402–407, IEEE, 2011.

[P9] **P. Stumpf**, Z. Sütő, and I. Nagy, "Unexpected test results with variable structure nonlinear systems and their theoretical background," in *PEIA 2011 Workshop on Power Electronics in Industrial Applications and Renewable Energy, Doha, Qatar*, pp. 39 – 44, IEEE, 2011.

[P10] **P. Stumpf** and I. Nagy, "Állandó mágneses egyenáramú hajtás kaotikus viselkedése (in Hungarian)," in *OGÉT XIX. Nemzetközi Gépészeti Találkozó, Csíksomlyó, Románia*, pp. 335 – 338, 2011.

[P11] **P. Stumpf**, A. Lorincz, and I. Nagy, "Analysis and compensation of chaotic response in DC motor drive," in *3rd International Students Conference on Electrodynamics and Mechatronics, Opole, Poland*, pp. 83 – 88, 2011.

[P12] **P. Stumpf**, Z. Varga, T. Sepsi, R. K. Járdán, and I. Nagy, "Ultrahigh speed induction machine overheated by subharmonics of pwm inverter," in *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, Glendale, USA*, pp. 1754–1759, IEEE, 2010.

Other publications connected indirectly or loosely to the dissertation

[R1] **P. Stumpf** and I. Nagy, "Study of doubly fed induction generator for wind power application," in *International Conference on Clean Electrical Power (ICCEP), Alghero, Italy*, pp. 403–410, 2013.

[R2] Z. Varga, **P. Stumpf**, R. K. Járdán, and I. Nagy, "Application of ultrahigh speed induction machine for waste or renewable energy recovery," *International Journal of Renewable Energy Research (IJRER)*, vol. 1, no. 4, pp. 200–211, 2012.

[R3] **P. Stumpf**, Z. Sütő, and I. Nagy, "Phenomena discovered in development phase in variable structure systems and their explanations, keynote speak," in *The 3rd Power Electronics, Drive systems and Technologies Conference (PEDSTC), Tehran, Iran*, 2012.

[R4] **P. Stumpf**, D. T. Sepsi, R. K. Jardan, and I. Nagy, "Comparative analysis of ICEVs and different types of EVs," in *ELECTRIMACS, Paris, France*, pp. 1–6, 2011.

[R5] Z. Varga and **P. Stumpf**, "Villamos hajtások (in Hungarian)," *ElektroNet*, vol. 20, no. 2, pp. 12–15, 2011.

[R6] **P. Stumpf**, "Multimedia material for teaching and e-learning in nonlinear dynamics and power electronics," in *2010 IEEE International Symposium on Industrial Electronics (ISIE), Bari, Italy*, pp. 3906–3911, IEEE, 2010.

[R7] **P. Stumpf**, R. K. Jardan, and I. Nagy, "Dynamics of different speed controls of ultra high speed induction generator using approximate and accurate model," in *2010 International Symposium on Power Electronics Electrical Drives Automation and Motion (SPEEDAM), Pisa, Italy*, pp. 1024–1029, IEEE, 2010.

[R8] **P. Stumpf**, R. K. Járdán, and I. Nagy, "Speed control of ultrahigh-speed turbine-generator set with nonlinear control–loop applied for waste and renewable energy recovery," in *European Control Conference ECC, Budapest, Hungary*, pp. 4193–4198, 2009.

[R9] G. Sziebig, P. Korondi, Z. Sütő, **P. Stumpf**, R. Jardan, and I. Nagy, "Integrated e-learning projects in the european union," in *IECON 2008. 34th Annual Conference of IEEE Industrial Electronics, Orlando, Florida*, pp. 3524–3529, IEEE, 2008.