MŰEGYETEM 1782

PH.D. DISSERTATION
(THESES BOOKLET)

NONLINEAR PHENOMENA OF CONTROLLED THREE PHASE CONVERTERS

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Budapest, 2007

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I. PRELIMINARIES, MOTIVATION

At the end of 1980's, at the beginning of 90's, power electronics came to the front in the research of nonlinear dynamics. Nowadays, power electronic converters in some form are present almost everywhere in our life. Applications can be found in industrial, commercial and residential environments, ranging from gigawatt power systems to milliwatt battery management circuitry of portable systems. Power electronics exhibit a wide spectrum of nonlinearity increasing the chance of discovering new phenomena, bifurcation routes from regular states to chaos, thus providing the primary motivation to study power electronics in the context of nonlinear dynamics.

Earlier the scientific community has mainly concentrated on investigating various types of DC–DC converters. Depending on the kind of control and circuitry both generic types of bifurcations known from smooth systems and bifurcations due to the piecewise-smooth nature of these converters could be detected. The main outcome of the research on DC–DC conversion refers to the analysis of non-smooth Poincaré mapping functions and to the classification of their bifurcation routes, the various types of border-collision bifurcations.

Almost in parallel with the start of nonlinear study of DC–DC converters, the *strange* behaviors of an induction motor fed by a three-phase, two-level, full-bridge Voltage Source Converter (VSC) equipped with a novel adaptive hysteresis current controller have directed the developer's curiosity, and opened a new research. I could have joined to this work in a quite early phase. DC–DC converters are widely applied in the industry, this fact and the relative simplicity of their analytical descriptions are the main reasons why they have a distinguished role in the field of nonlinear dynamics. However, the other quite important segment of power processing performed by three-phase energy converters is studied much less from such point of view. The inherent complexity of the mathematical description of these systems in spite of their topological simplicity have turned the researchers' attention mainly to the simpler DC–DC and single-phase AC–DC or DC–AC conversion.

II. THE STUDIED SYSTEMS

The nonlinear characteristics of three, space vector based AC side control methods of the VSC is explored in the dissertation. Depending on the control strategy bidirectional power flow can be ensured in the VSC, it can be operated either as AC–DC or DC–AC converter. The range of applications is wide, numerous examples can be instanced from variable speed AC drives to active filtering or power quality conditioning. The main objectives of the research are

- to direct the attention of the engineers using in many applications such systems to their possible undesired states,

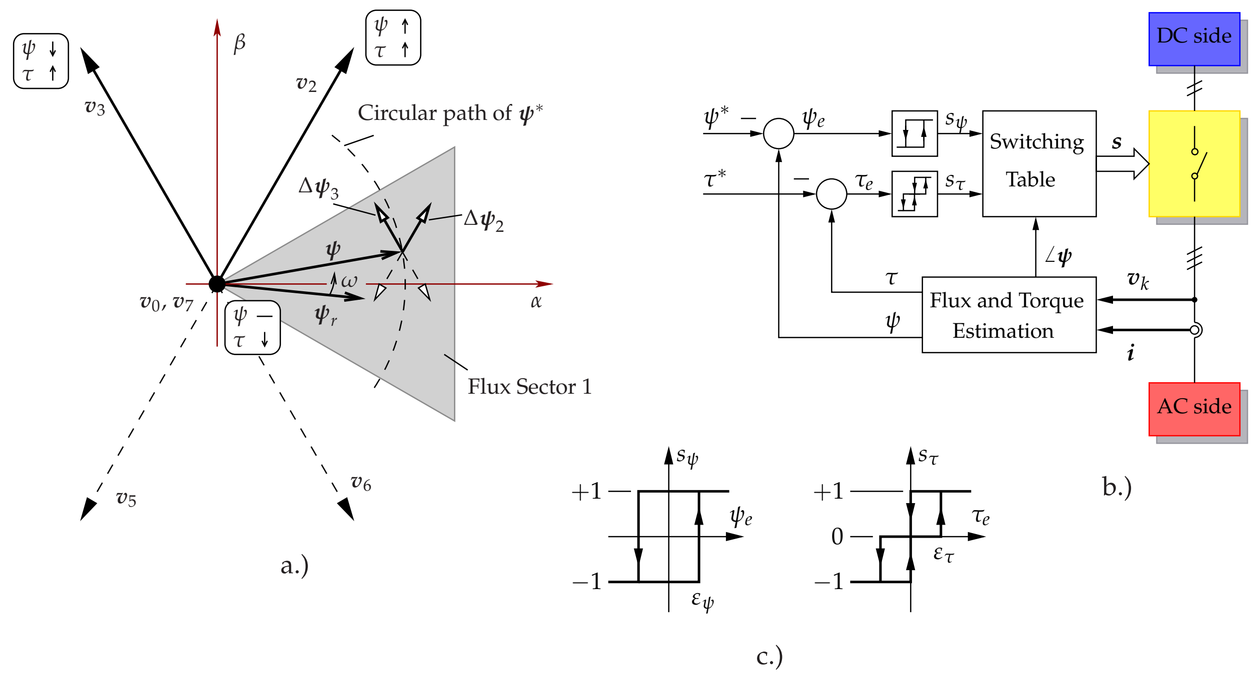

Figure 1. Direct Torque Control (DTC). (a) Selection of voltage vectors to increase/decrease the controlled variables. (b) Basic scheme of DTC. (c) Two and three-level hysteresis comparators of the flux and torque error.

- to develop the tools for describing their nonlinear behavior, for designing the controllers and
- to verify the considerations by numerical and simulation results.

The power stage of VSC is modeled by an ideal switching matrix connected to DC voltage source and AC three-phase, symmetrical, sinusoidal voltage source through series R–L circuit. The simple AC side circuit can model either the three-phase AC mains or various AC machines under certain conditions, and it can be applied for investigating wide parameter ranges. The space vector representation of this power stage model was used uniformly for all the controlled VSC systems studied in this work.

Most power electronic systems are equipped with multiple-embedded control loops. In order to achieve the aim of the control, the inner control loop keeps changing the converter configurations by means of the electronic switches. The desired waveforms are produced by varying the duty-cycles, the active and inactive times of converter states, so the control must include somehow a Pulse-Width Modulation (PWM) algorithm.

Practically, two main categories of modulation schemes can be distinguished, closed-loop and open-loop ones. In case of a closed-loop modulation, the control and the switching pattern generation is integrated into one unit. Usually hysteresis based controllers or other essentially nonlinear controllers belong to this category. *The source of nonlinear phenomena originates in the free-running nature of these systems* where the periodic use of circuit configurations is not guar-

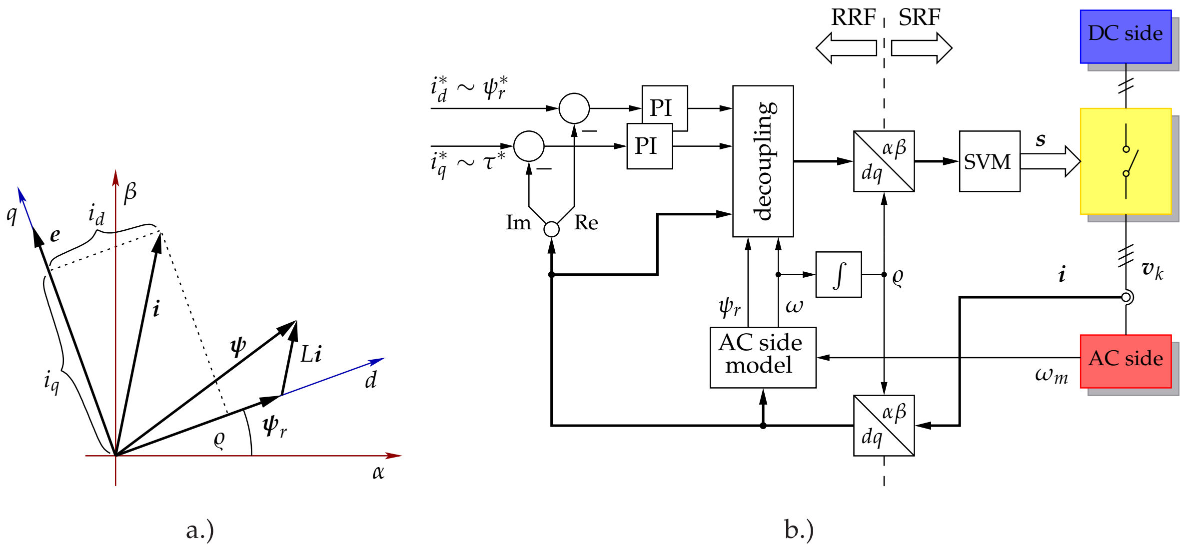

Figure 2. Field Oriented Control (FOC) of induction machine. (a) Space vectors in rotating d–q reference frame fixed to the rotor flux $\boldsymbol{\psi}_r$ of the machine. (b) Block diagram of FOC.

anteed. The non-periodic sequence of both the switching states and the switching time instants is typical. The switching frequency is varying here. A commonly used VSC system with closed-loop modulation is the Direct Torque Controlled (DTC) induction machine (Fig. 1).

In the second case, the control task and the switching pattern generation is decomposed. The switching pattern is provided applying some kind of open-loop PWM algorithm operated usually with a fixed switching frequency and fixed sequence of switching states, but *the switching time instants in a modulation period are varying and depend on the state variables*. The control task is fulfilled by additional linear (mostly PI) controllers. Assuming a sufficiently high switching frequency, systems equipped with open-loop modulation can be analyzed by averaged models. In this case the nonlinear phenomena will not relate to the switching operation but to various nonlinearity terms embedded into the control loop, e.g. to saturations applied to avoid *over-modulation* of the PWM block. Field Oriented Control (FOC) of induction machines is conventionally applies an open-loop PWM modulator which is usually implemented by Space Vector Modulation (SVM) (Fig. 2).

The control methods under consideration were the following:

ASP–HCC. Firstly, a Hysteresis Current Control (HCC) algorithm operated with Adaptive Switching Pattern (ASP) was investigated applying *brute-force techniques*, that is, system trajectories starting from different initial conditions are calculated for as many times necessary to locate steady-states in the state space. The ASP–HCC algorithm applies two concentric hysteresis circles around the peak of the reference current space vector. The aim of implementing double hysteresis limits is the reduction of undesired switching operations like *double commutation* and the sequences of *fast switchings*.

DCC–SVM. Secondly, a special complex Discrete-time Current Controller (DCC) equipped with a conventional Space Vector Modulation (SVM) was discussed. The *averaging approach* is applied to obtain approximate model of the system. The SVM controls the switching sequence and timing in VSC. Due to its inherently digital nature a discrete-time controller is applied to force the three-phase AC currents tracking the symmetrical sinusoidal reference signals. DCC applies a special PI controller with complex coefficients, and a complex saturation function ensures the avoidance of over-modulation in the SVM.

DTC–IM. Finally, again a hysteresis based control method, the classical Direct Torque Control (DTC) of Induction Machine (IM) was studied by constructing a *piecewise-defined iterated map* model. Since DTC is strongly nonlinear due to the hysteresis comparators, various nonlinear phenomena are expected. Note, that DTC is essentially an indirect way of current control, while the other two current control methods (ASP–HCC and DCC–SVM) are operated in rotating d–q reference frame, they can be considered as variants of FOC.

All studied control methods are discussed in single loop, the outer loops are supposed to be in steady-state.

III. New Scientific Results

Thesis 1 (ASP–HCC). *I have developed the novel ASP–HCC system applying vector approach and designed a numerical computing model to investigate on the system. I have shown that the time evolution of the state variables can move along periodic, subharmonic and chaotic orbits depending on the input variables, parameters and initial conditions. By means of numerical bifurcation analysis I have demonstrated three transitions between periodic and chaotic states: the period-doubling, the intermittency and a special period-adding phenomenon caused by discontinuity of the Poincaré mapping function (see chapter 4).*

The main goal of the research was to assist the application, design and optimization of the algorithm by exploring its nonlinear behaviors, characteristics. I have devised a numerical computation model suitable for investigating wide parameter ranges. The analytic solution of state equations between two sudden structure changes of the converter was applied. After determining the time instants of structure changes numerically, trajectories, stroboscopic Poincaré sections and bifurcation diagrams were caclulated by the numerical model. For the sake of better comprehension of the bifurcation phenomena I have calculated the averaged largest Lyapunov exponent based on the change of euclidean distance between trajectories.

I have shown that the state variables of the system can exhibit periodic, subharmonic and chaotic trajectories. Period-1 state is considered with the sixth of the period of AC side input voltage. I have experienced two types of chaotic states: (i) the trajectories move nearby the periodic track, the switching states are locked to periodic pattern, but the sequence of switching time instants is chaotic; (ii) both the switching pattern and the sequence of switching time instants change aperiodically. I have used as main control or rather bifurcation parameter the ratio of radii of the concentric hysteresis circles. Numerous nonlinear phenomena were observed: the system exhibits extremely complex operation, the abrupt, sudden changes are frequent, often multiple stable limit sets exist at the same parameter settings.

I have studied the following bifurcation routes to chaos: (i) the period-doubling cascade well known from many other research fields, (ii) the intermittency, and (iii) a special period-adding phenomenon. I have verified the validity of some characteristic features of the period-doubling cascade in our case, such as Feigenbaum constant, self similarity attribute, band splitting law and so on. The period-doubling cascade appears locally in quite narrow parameter regions. Changing the bifurcation parameter the system usually leaves the region by intermittent behavior, when two unstable states alternate, e.g. a periodic state is cyclically interrupted by chaotic bursts. Along the third studied bifurcation process, the system state becomes chaotic through successive period-adding scenario. A 1-dimensional (1D) piecewise-linear discontinuous iterated map was constructed in order to understand the background processes along the bifurcation route (see also this kind of iterated map in Thesis 3). The 1D iterated map approximate well the behavior of the system in the corresponding parameter area.

Thesis 2 (DCC–SVM). *I have developed an approximate and an accurate discrete-time model for both analytical and numerical study of a novel DCC–SVM system with complex PI parameters. The main nonlinearity stems from the complex saturation function resulting in two undesired fixed points. After determining the fixed points and their stability I have given design criteria for the controller parameters to avoid undesired fixed points. I have determined the basins of attractions for the fixed points. I have performed bifurcation analysis applying both analytical and numerical methods: saddle-node, saddle-saddle bifurcations of fixed points, saddle-node bifurcation of limit cycles, chaotic attractor and chaotic transient together with boundary crisis, furthermore homoclinic bifurcations of saddles are presented in chapter 5.*

The main goal was to develop a discrete-time model of the system in order to obtain more efficient tools for describing the nonlinear phenomena analytically, and for designing the discrete-time PI regulator. The system is approximated by averaging the fast switching operations caused by the modulation. After that, the approximate model contains only the complex saturation nonlinearity. I have applied both analytical and numerical methods to the study and interpretation of nonlinear phenomena. I have calculated the fixed points of the model and their eigenvalues based on the Jacobian matrix in order to: (i) perform further stability analysis, (ii) determine the dynamics of fixed points and (iii) design the controller. I have plotted bifurcation diagrams, phase portraits and Poincaré sections. Numerical results were presented to verify the theoretical consideration, to offer insight into the various nonlinear phenomena, bifurcations and to show the basin of attraction of the desired fixed point.

I have carried out bifurcation analysis by changing the eigenvalues of the desired fixed point, that is, indirectly the complex coefficients of the PI regulator, both in the stable and in the unstable region. I have shown that in some regions of the controller parameters, even when the "linear" system designed without the saturation function is stable, different steady-states, fixed points or limit cycle (quasi-periodic state in the stationary reference frame) can develop by switching on the saturation. The system can meet the basic requirement, to generate approximately sinusoidal AC currents only by arriving into one fixed point out of the three ones obtained analytically. Usually large steps in the reference signals are required to jump over the boundary of basin of attraction belonging to the desired fixed point. The coexisting fixed points and limit cycles generate extreme large current magnitudes so these states must be avoided in practice. Design conditions were given to avoid the undesired operations of the system. One of the undesired fixed points is always a saddle point in the state space, while the other one can be node, spiral node or saddle point. This pair of points appear/disappear by a saddle-node or saddle-saddle bifurcation at the boundary of the existence region of the fixed points as the bifurcation parameter is changing. The limit cycles can appear by saddle-node bifurcations, when a stable and an unstable limit cycles develop. I have observed also homoclinic bifurcations. After the homoclinic connection of the stable and unstable manifolds of the saddle point, limit cycle appears/disappears. In unstable condition undesired fixed point, chaotic state and limit cycle can come about, but the results obtained in this region have mainly theoretical value rather than practical one. Although chaotic states stay nearby the sinusoidal reference, but the harmonic distortion is large. When the chaotic attractor collides with a saddle fixed point, or with an unstable limit cycle by changing the bifurcation parameter, the attractor disappear by a boundary crisis, and a chaotic transient develops.

Thesis 3 (DTC–IM). *I have derived a piecewise-defined, non-stroboscopic, discrete-time Poincaré map for the DTC–IM system which takes into account the fast switching operations. For this end the movement of the two controlled state variables, the stator flux linkage and the electric torque, within the hysteresis loop had to be determined. I have calculated the Jacobian matrix of the mapping function in order to determine the spectrum of the Lyapunov exponents. Periodic, subharmonic, chaotic and intermittent chaotic states along a bifurcation route caused by discontinuity of the Poincaré mapping function were detected. I have constructed a one-dimensional piecewise-linear discontinuous iterated map which provides analogous characteristics with the above bifurcation route (see chapter 6 and section 4.10).*

I have developed a Poincaré map in order to describe the variable structure processes of the classical DTC–IM. The main goal was twofold: (i) on the one hand, the design of control parameters (width of hysteresis bands) can be supported by obtaining a deeper insight into the operation of DTC–IM, (ii) on the other hand, the sudden changes of system states or bifurcations expected due to the strong nonlinearities can be detected and studied.

The developed Poincaré map calculates samples from the magnitude of the flux space vector and the electromagnetic torque, when the fictitious voltage vector perpendicular to the stator flux reaches a predefined position in the 60° width control sector between two adjacent active voltage vectors of the VSC. I have obtained the overall mapping function by cascading the switch-to-switch mappings between two consequtive structure changes of the system. The time instants of structure changes are given implicitly at the switch-to-switch maps, those are calculated numerically by a modified Newton-Raphson gradient method combined with interval bisection. The Jacobian matrix of the Poincaré map were determined simultaneously. I have calculated the spectrum of Lyapunov exponents from the Jacobian matrix applying the Gram-Schmidt orthonormalization method. Beside calculating and drawing bifurcation diagrams, trajectories, frequency spectra, Recurrence Plots were also presented based on the state vector reconstructed from the delayed Poincaré samples of a single selected state variable, from the samples of the torque error to reveal the possible states and bifurcation routes.

I have identified periodic, subharmonic, chaotic and intermittent chaotic states. The observed nonlinear phenomena evolve usually due to the complex discontinuous type of Poincaré map where the continuous sections are mostly linear. Sometimes trajectories are locked into smaller segments of the mapping functions where only a single discontinuity determines the operation of the system. I have analyzed a bifurcation route between periodic and chaotic states under such circumstances. In order to simplify the study I have constructed a one-dimensional (1D) piecewise-linear iterated map. The 1D map provides analogue behaviors with the system and it is able to explain some phenomena. Changing the iterated map parameters the special period-adding phenomenon observed in ASP–HCC can be explained (see Thesis 1 and section 4.10). The fixed point of the period-1 orbit moves on the stable region of the mapping function by the bifurcation parameter, the reference torque of DTC–IM, while it collides with the discontinuity, the border between two linear segments of the mapping function. At this border-collision bifurcation the fixed point disappears and high-order subharmonic state develops, which becomes chaotic after subsequent period-adding scenarios. The chaotic attractor collides with an unstable fixed point of the mapping function and loses its stability. After that, a new intermittent chaotic attractor evolves wandering in a wider segment of the state space.

IV. Further Research Plans

Up to now the work mainly focused on exploring nonlinear phenomena of controlled VSC systems. The primarily goal of the research was the comprehension and explanation of strange phenomena, the systematic treatment of the numerous bifurcation routes by means of the theory of nonlinear dynamics. The three example systems have served as excellent practice in the application of some sophisticated investigation and modeling techniques in power electronics.

Future research should move toward much more practical exploitation of the know-how accumulated during this work. From practical points of view, the throughout mapping of the parameter space where undesired system states might occur is important, it can help us to avoid those states. if we understand additionally by theoretical investigations the background processes which are responsible for the phenomena we can design more effective control strategies. The studied systems have exhibited strange phenomena related to almost all areas of nonlinear dynamics, this kind of richness implies again further theoretical investigations.

In the hope of exploring new phenomena, new bifurcation processes, an obvious extension of the studied systems would be the application of more energy storages, the increase of degree of freedom. It can be accomplished by applying more sophisticated models at either the DC and/or at the AC side of VSC. The studies can be extended to the full model of induction machines or other AC machines e.g. the Permanent Magnet Synchronous Machine (PMSM). There is again an open question how sensitive the system behaviors to the estimation of motor parameters, the back-EMF voltage and so on. More operating regions like generating mode can be compared in the light of nonlinear dynamics. Further algorithms and other three-phase multi-level converters with more circuit structures can be tested. For example, in the case of ASP–HCC and DCC-SVM systems, being the AC current transformed to d–q reference frame, it implies the possibility to extend the study toward the application of field orientation. Of course, the above refinements of the models would give a better view to the physical systems, but at the same time might make the theoretical investigations more difficult, so a careful balancing between realistic and more abstracted models is crucial.

One of the disadvantages of hysteresis based control algorithms, like the ASP–HCC or the DTC–IM systems, is the variable switching frequency and the mostly aperiodic movement of system trajectories. From engineering point of view, usually the periodic state is preferred because here the system behaviors becomes predictable, the stress of switching components can be calculated, optimized. We have seen that the system state under hysteresis control can be even periodic. It gives ground for hope and encourages further research to find techniques locking the system trajectory into periodic states. Beside the periodic states subharmonic states are also detected. These states could cause problem if the frequency of the subharmonic variables comes close either to the mechanical resonance of the machine or the resonance of some electric circuit.

Another research can be opened to the application of the chaotic states. Some steps have been taken into the direction of comparing the various system states detected in the ASP–HCC system from the points of view of the number of switchings and harmonic content. Usually there is a relevant difference between the number of switchings of different system states developed at near parameter settings, but either the periodic or the chaotic state might be better from this point of view. Furthermore, the chaotic state might offer some benefits in Electromagnetic Compatibility (EMC) with its dispersed, broad-band spectrum. According to some of our observations the spectrum spikes are degreased in case of a chaotic trajectory, but the full energy contents is practically unchanged, chaos just rearrange the overall power in the spectrum. Further work is still needed to give convincing answers to the above questions.

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