1. Introduction

1.1 Motivation and Objectives

Today, the analysis and design of complex power electronic systems such as motor drives is usually done using a modern simulation software which can provide accurate predictions of the system's behavior in reality [16, 43]. Consequently, computer modeling of such systems at a desired level of accuracy becomes an essential part of the design process. A satisfying system model usually serves as a prototype for the system behavior simulations, as well as the small-signal analysis and control design.

A common approach to the modeling of power electronic systems is to develop several independent system models, on different complexity levels, which serve for the analysis of some particular stages of the design. The typical levels are: switching (detailed), average, and small signal (linear) levels. A small-signal model serves for the control design from the stability analysis perspective [4-6, 8-13, 18, 19, 33]. A large-signal average model usually includes ideal component models for the large-signal control design and system behavior simulations over long time periods. Several techniques are applied in order to narrow the trade-off gap between result accuracy and simulation speed [1-3, 10, 12]. Finally, a detailed model includes component models at a high level of accuracy [7, 14, 15] and it serves rather for the component behavior analysis than for the analysis of the whole system. It focuses on short time periods, usually several switching cycles, because of the necessity of an extensive simulation time.

A design, then, proceeds according to the results of independent analyses at each level. A problem with such an approach is that for the large system analysis, the model of the entire system must be developed at each level. The objective of the work presented in Chapter 2 is to develop a new, multilevel modular modeling approach wherein each module can be modeled at any level of complexity, while maintaining full compatibility of the modules.

One of the most popular control methods of three-phase motor drive systems, matured during the last decade, is field-oriented control [40, 54, 55], usually realized with a digital PWM controller in rotating, dq (or dq0 for unbalanced systems) coordinate space [11, 20, 28, 41, 61]. With the cost reduction of rare permanent magnet materials, permanent magnet (PM) motors became very popular in industry due to their simple structure, efficiency, robustness and high torque/size (or weight) ratio [27-29, 57, 61, 62]. Some issues of the permanent magnet (PM) motor drive control design in the application of the starter/generator for the aircraft auxiliary power unit (APU) initiated the control design analysis described in Chapter 3. An aircraft APU starting mechanism contains a three-phase (balanced) PM synchronous motor (PMSM) drive, which starts a gas (or interior combustion) turbine and gives it the support to accelerate the APU's synchronous generator to its synchronous speed [39]. A similar starting mechanism exists in an electrical vehicle propulsion system [67]. Since the turbine doesn't have enough power to run the generator by itself until a certain speed is reached, it presents an active load (the load torque changes dynamically with speed) on the PMSM shaft. A common power electronic circuit topology for running the PMSM contains a regulated three-phase voltage source inverter (VSI). Usually, only a current (or torque) control is provided, since the speed profile loses its importance against the acceleration time and energy consumption factors. A typical current regulator in this application is a digital proportional-integral (PI), or only proportional (P) regulator designed in d-q coordinates with decoupling loops for eliminating the cross-coupling terms from the motor dq state-space equations [11, 38, 50, 56-61]. Since the maximum current (torque) is the optimum current (torque) profile during the start-up out of the flux-weakening region, regarding the acceleration and the energy consumption, and it should follow its reference signal profile within the flux-weakening region, the current controller should be fast and robust at the same time. The issues of its accuracy and speed limits arise from the fact that it is a digital controller with a certain degree of delay due to the sampling and PWM effects [11, 20, 44, 57]. The sampling delay effects on the system stability are not negligible, and that fact gives the motif for a detailed small-signal analysis.

A speed control, if provided in this application, generally serves to establish and control the final motor speed, and to protect the system during a failure occurrence in its power stage. Otherwise, under normal operating conditions during the acceleration period, the speed controller is designed to be saturated, which leaves the speed control loop open [29, 39]. The question arises that when a speed control loop is already provided for mainly protective purposes, could it be also used for the speed tracking control, so that the speed profile could be also optimized, as it is in servo drive applications [48, 52, 71]. That raises the issue of the speed loop stability of the drive system with a dynamic load torque.

A flux-weakening technique is usually applied when an extension of the motor rated speed is desired [18, 28, 50, 51, 63-66, 68-71]. The field-oriented control, with its flux/torque decoupling feature [11, 20, 50], finds no better alternative today in PMSM drive applications with flux-weakening control. Consequently, it is applied here to define the reference dq current components. Different flux-weakening strategies provide various results in various applications [50-52, 55, 63-71]. Establishing the basic criteria for choosing a flux-weakening strategy based on the analysis of its dynamics and application requirements was the final objective of this work. A comparative analysis of the three most promising flux-weakening control strategies today - constant power methods in versions with constant voltage and constant current (CVCP and CCCP), and optimum current vector control (OCV) method - served that purpose.

1.2 Review of Previous Research

"Let's make a model." It has been a motto of people working in various areas, from arts to engineering, throughout the history. From the famous ancient philosophers, artists and architects to today's computer design engineers, modeling has been a connection between the idea and its realization, with its purpose being to predict and help to understand the characteristics of the potential product. The beginning of mathematical modeling could be linked to the appearance of Decart's orthogonal coordinate system. Since then, a burst of mathematical models describing everything, from physical phenomena to the events related to the modern social and economics sciences, expands rapidly. The characteristics of the electromagnetic field has been also described using the same coordinate system, what was a basic point for today's knowledge and development of electrical engineering.

Computer modeling of power electronic systems has about a three decade history [12]. The development of computer machines and program languages has enabled users to translate their mathematical models to machine language relatively easily and to use the machine in various applications, from some extensive calculation work to the micro-controller design [1, 12, 67]. Since the early eighties, three major currents in the development of the modern simulation software packages used in electronics, have been:

1) SPICE-oriented electronic circuit simulator packages such as Saber [16], which are circuit node-equation matrix solvers initiated by the famous Dr. Pedersen's group SPICE simulator in the University of California in Berkeley [14],

2) signal- processing oriented software which evolved in a control design software with the modern control theory based models, such as Kalman filter, transfer function or state-space models in Laplace "s," and digital, "z," domains, such as Matlab [43], and

3) finite element analysis (FEA) oriented software packages, which are widely used in magnetic and IC designs.

With their user-friendly graphic interfaces, [17, 43], these software simulation packages made computer modeling very popular in the engineering population. In the field of power electronics, various models, from switching device models [1, 6, 7, 14, 15], to the system level models [4, 5, 10-13, 18] and PWM modulator models [5, 8, 25] have been developed, and have been serving their primary purpose in various control and circuit topology designs and analyses - helping to predict and understand the potential or existing product characteristics.

"Let's control the system" is a typical engineering motto. Since the development of simple breaking mechanisms, engineers have been trying to control the behavior of the devices they have invented. A development path, from the open loop regulators, through the feedback control loops, to the sophisticated adaptive, non-linear, usually observer-based, feedback/feed-forward or fuzzy-logic control systems [21, 22], evolved mainly during the last four decades of the twentieth century, enhanced by the appearance of the modern linear system theory and digital control [44] during the sixties. It was not a coincidence that this fast development in the area of the modern control theory happened at the same time of the rapid development of computers, which has enabled designers to model and simulate a considered system, as well as to implement and analyze new control methods incomparably faster than by building and testing real system prototypes. Also, digital controllers became faster and more reliable with the development of microchips, coming after the discovery of solid-state semiconductor switching devices during the fifties.

Following the same trend, mathematical modeling and control of power electronic systems has been developed mainly during this century. Since the discovery of electricity, electrical engineers have been dealing with power supply related problems of various systems, from distributed power systems and uninterruptible power supplies (UPS), to motor drives. Generally, the problems have been related to system efficiency, its stability, and signal distortions generated by the converters, such as recently emphasized electromagnetic interference (EMI).

The appearance of Park's matrix transformation [11, 53] can be counted as a beginning of the modern control theory of AC motor drives. It enabled control designers to make steady-state state-space mathematical models of AC motor drives, and perform small-signal analysis on them. Although during the first half of this century the control designers were rather limited with the existing technology, some modern solutions in power electronic circuit topologies and PWM modulation schemes can find their predecessors, regarding the basic principles, from that period [34]. With the development of solid-state semiconductor switching devices during the fifties, the technological obstacles were significantly reduced and a tight race between the power device sophistication and the power electronic circuit design began.

The next break-through was the development of field-oriented control, which implemented field-torque decoupling, and enabled control designers to reduce the models of the AC machines down to the models of their equivalent DC counterparts [40, 54]. This has been the light-motif of control designs of AC machines and 3-phase converters during last two decades. Finally, the development of power electronics (converter topologies and control) and PWM control during the last three decades wraps up the modern control of motor drives in today's boundaries.

Over the last fifteen years, major breakthroughs in motor drive stability and efficiency improvements (sometimes above 90%) were made thanks to significant progress in all relevant sectors:

1) development of highly efficient and fully controllable power semiconductor switches (MOSFET and IGBT technologies) [7, 15],

2) appearance of new topologies such as four-leg, resonant and soft-switching converters [24, 31, 32, 36, 37],

3) development of new AC machine control theories such as field-oriented control and spiral vector theories [41, 46, 48, 49, 55, 57, 61, 62], and

4) new, or optimized existing, control solutions and analyses, such as hysteresis, classical and observer-based feedback, adaptive and fuzzy control methods [20-22, 26-30, 33, 38-42, 50-54, 58, 61, 79, 80], which include the optimization of the pulse-width modulation (PWM), which has evolved into space vector modulation (SVM) switching schemes [25, 59, 72-78].

Although observers and nonlinear controllers have found their application in high technology and high power motor drives, a traditional cascade PWM controller is still the most favorable solution in industry due to its low cost and high robustness.

Signal-distortion issues have been answered by power factor correction converters and, more often, EMI filter designs [23, 47]. It has raised the interaction issue between subsequent drive modules. A new control theory of module interactions was developed and some design guidelines have been published during the nineties [35, 47].

The evolution of the control design of PM motor drives begins with the cost reduction of permanent magnet materials and follows the progress of control theory of AC electric machinery [18, 20, 28, 29, 48, 50, 52, 56-58, 62]. The main difference between PM motor drives and their earlier developed counterparts (DC and synchronous motors) lies in the removal of the excitation field circuitry with troublesome brushes from the motor, and its replacement with permanent magnets [18, 62]. But the application of permanent magnets disables classical field-weakening control, because the magnets produce a constant magnetic field intensity. As a substitute a several variations of a new technique for the implementation of the field-oriented control in PM motor drives were proposed during the eighties [65-71]. The idea was to provide the speed extension through the regulation of the stator voltage-to-current phase angle, by controlling the stator current d-q components. A drawback of stressing the magnets and risking their permanent demagnetization was minimized by the discovery of very qualitative magnetic materials, and a detailed stress analysis, which revealed the tolerance limits of the current vector dislocation [63]. The technique has been called “flux-weakening” because of the fact that the excitation (magnetic) field wasn’t changed, but, instead, the flux-producing stator current vector was rotated out of its rotating q-axis [65]. The theory of the flux-weakening control and operating limit extensions of the PMSM was elaborated on during the late eighties and early nineties [65-71].

Although the inherently unstable systems, with right half-plane poles in their small-signal transfer functions, are nothing new in control theory and practice (constant power supplies, for example), the studies of electric motor drives with active loads, which can change the drive stability characteristics, are relatively rare. The author hasn’t found any such analysis with PM motors in his research, although similar applications were found [39, 67]. Usually, the analyses were limited to cases of four quadrant motor drive operations and passing from one quadrant to another [52, 57] through the generic breaking, or the stabilization of torque estimation in sensorless motor drives [39]. These studies did not include the decreasing load torque dynamics in the first quadrant of the motor torque/speed diagram, characteristic for engine starter applications. The studies related to electric accelerators, although a limited number have been included in this research, also seem to pay little attention to the open-speed-loop stability issues related to these applications [39, 67]. Although constant power converter control deals with the voltage loop instability, the solution for that control loop was not found in the open-loop stabilization. The research was concentrated in IEEE publications related to electric motor drives and power electronics.

1.3 Thesis Outline and Major Results

The overall idea of this work was to develop a user-friendly system simulation modeling tool, using a modern simulation software, which can be easily modified at different desired complexity levels according to design and analysis requirements, and to perform a detailed analysis of an interesting application of VSI-fed PMSM drive systems.

A new multilevel modeling approach for creating the simulation models of power electronic circuits is developed for easier analysis and faster simulations. It is based on a modular approach wherein each module can be modeled at any level of complexity, while maintaining full compatibility of the modules. Besides the obvious advantages of modular modeling, the main benefits of this method are that it allows:

1) change in the system model complexity by simply modifying module models without the need to change the system description, and

2) mixed level modeling using the interface modules, where only a critical module is modeled at a higher complexity level, while the rest of the system is modeled at a lower level.

The new approach is applied to modeling of the three-phase VSI-fed PMSM drive system. The developed module models, as well as a generative system level model are described in Chapter 2. Several modeling issues and simulation results, obtained with an example of the system mixed-level modeling, are discussed. Saber/DesignStar and Matlab/Simulink simulation packages were used as the simulation and modeling platforms. The developed models are mutually compatible. The simulations performed on mixed levels and commonly used levels give comparable results. Detailed models, which include magnetic saturation, temperature dependence etc. are not considered in this work. However, such effects can be easily included by replacing any of the models presented with more detailed ones, still using the same approach. The experimental verification of the model of a three-phase VSI-fed permanent magnet synchronous motor (PMSM) drive system and module compatibility at several modeling levels are presented in the last section of Chapter 2 and its simulation results in Chapter 4.

The experimentally verified system model is used to simulate and analyze the application of the PMSM drive system as a starter/generator for an aircraft APU, where the load changes dynamically with the motor speed. As a result of the analysis, a new, detailed procedure for the field-oriented control design of a two-stage cascade digital controller is presented in Chapter 3. The main characteristics of this PMSM drive application is that the load torque on the rotor shaft changes dynamically with speed. Moreover, it changes its nature - from breaking to generative. Hence, it should be considered an active load. Special attention is given to the part of the starting cycle where the starter accelerates an already started engine, until it develops enough power to continue to operate independently. In that case, the load torque still has the breaking characteristic, but with a negative slope referring to speed (equivalent to the electrical load with negative resistance), which destabilizes the speed control loop. Assuming the accuracy of the PMSM drive model from Chapter 2, the model is used for a two stage cascade digital controller design in the dq coordinate frame with the new speed loop stabilization method. Matlab/Simulink simulation software is used for the simulations of the small-signal and large-signal system behavior. A comparison of several controller design approaches is included. Special attention was given to the analysis of the sampling delay influence on the system stability using these approaches.

After the introduction to the large-signal characteristics of the applied interior permanent magnet (IPM) motor, an optimum reference torque profile is proposed for this application (regarding the chosen motor and the load torque profile). The controller's highly non-linear elements, such as the integrator reset loops of the VLPI compensators and voltage and current limiters are parts of the large-signal design, as well as the switching from the motor series (series stator winding connections) to parallel (parallel stator winding connections) operating mode as an idea for reaching higher motor speed. Finally, the large- and small-signal analyses of several flux-weakening strategies are presented as a separate section of Chapter 3. The result of these analyses is a clear path to choosing the appropriate strategy for the considered application.

The new stabilization method of the speed loop using the load torque estimation, analysis of the sampling delay effects on the system stability, large-signal and small-signal analyses of several flux-weakening strategies, besides the new modeling approach, are the major contributions of this work.