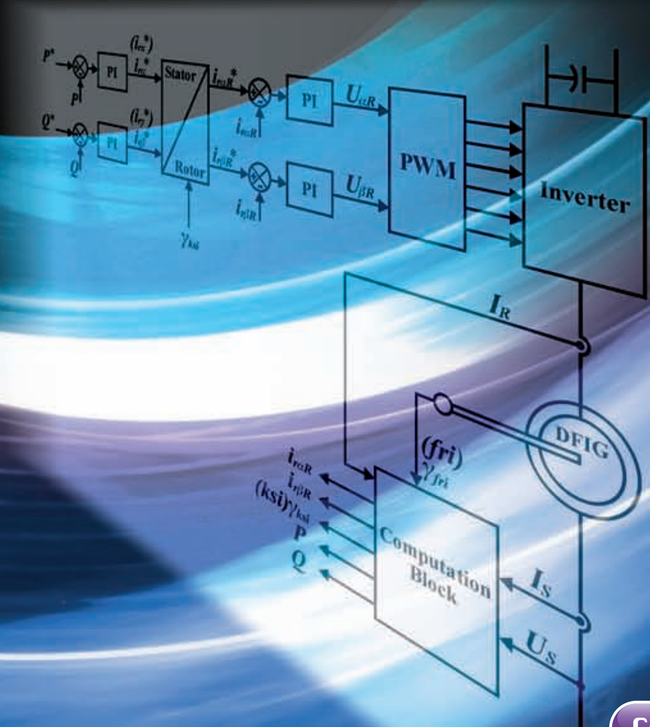
Haitham Abu-Rub | Atif Iqbal | Jaroslaw Guzinski

High Performance Control of AC Drives with MATLAB/Simulink Models



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Dedicated to my parents, my wife Beata, and my children Fatima,
Iman, Omar, and Muhammad.
—Haitham Abu-Rub

Dedicated to my parents, parents in-law, my wife Shadma, and my kids
Abuzar, Noorin, and Abu Baker who have inspired me to write this book.
—Atif Iqbal

Dedicated to my parents, my wife Anna, and my son Jurek.
—Jaroslaw Guzinski

Contents

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Haitham Abu-Rub, Atif Iqbal and Jaroslaw Guzinski

Biographies

Haitham Abu-Rub is an Associate Professor at Texas A&M University at Qatar. He holds two PhDs, from Gdansk University of Technology and from Gdansk University in Poland, received in 1995 and 2004, respectively. He was an Assistant Professor at the Gdansk University, and then at Birzeit University in Palestine, where he held the positions of Assistant Professor and Associate Professor for eight years. For four of those years, he was chair of the Electrical Engineering Department. His main research interests are electrical machine drives and power electronics. Dr Abu-Rub has earned many international, prestigious fellowships, such as the American Fulbright Scholarship (at Texas A&M University), the German Alexander von Humboldt Fellowship (at Wuppertal University), the German DAAD Scholarship (at Bochum University), and the British Royal Society Scholarship (at Southampton University).

Dr Abu-Rub is a senior IEEE member, with more than one hundred and thirty published journal and conference papers to his credit. He has also served as an Associate Editor with two journals, and has been on their editorial boards.

Atif Iqbal received his BS and MS of Electrical Engineering degrees in 1991 and 1996, respectively, from the Aligarh Muslim University (AMU), Aligarh, India, and PhD in 2006 from Liverpool John Moores University in the United Kingdom. He has been employed as a lecturer at AMU in India since 1991, where he is an Associate Professor. He has been on academic leave to work in a research position at Texas A&M University at Qatar from April 2009 and serve as a faculty member in the Department of Electrical Engineering at Qatar University, where he is working at present. He has published more than 150 research papers in the field of power electronics and drives, including 50 international journal papers. He has completed large R&D projects, and is the recipient of Maulana Tufail Ahmad Gold Medal for his BS Engineering exams in 1991 from AMU and EPSRC, a UK fellowship for his PhD.

Atif Iqbal is a senior IEEE member. He is an Associate Editor of the *Journal of Computer Science, Informatics and Electrical Engineering*. He also serves on the editorial board of the *International Journal of Science Engineering and Technology*, and is a manager for the *Journal of Electrical Engineering, the International Journal of Power Electronics Converter* (IJPEC), *International Journal of Power Electronics and Drive System* (IJPEDS) and the *International Journal of Power Electronics and Energy* (IJPEE).

Jaroslaw Guzinski received his MS and PhD degrees from the Electrical Engineering Department at the Technical University of Gdansk, Poland, in 1994 and 2000, 2006 to 2009, he was involved in European Commission Project PREMAID Marie Curie, ‘Predictive Maintenance and Diagnostics of Railway Power Trains’, coordinated by Alstom Transport. He obtained scholarships in the Socrates/Erasmus programme, and headed two grants supported by the Polish government in the area of speed sensorless control and diagnostics for drives with LC filters. He has authored and coauthored more than 100 papers in journals and conferences.

He has patented solutions for speed sensorless drives with LC filters. His current interests include sensorless control of electrical motors, digital signal processors, and electric vehicles.

Truc Phamdinh received his BE degree in electrical engineering from the University of New South Wales (Australia) with first class honours. He then successfully completed his PhD studies, producing a dissertation entitled 'Direct Torque Control of Induction Machine Considering Iron Losses' at Liverpool John Moores University (UK). He is at present a lecturer with the Faculty of Electrical and Electronic Engineering, Ho Chi Minh City University of Technology, Vietnam National University, Ho Chi Minh. He is responsible for courses in advanced controls of electrical machines at both undergraduate and postgraduate levels. His research interests include high-performance drives of AC machines, such as field-oriented control and direct torque control, sensorless speed controls, and controls of doubly fed induction generator for wind power.

Zbigniew Krzeminski received his PhD degree from the Technical University of Lodz, Lodz, Poland, in 1983 and the DSc degree from Silesian Technical University, Gliwice, Poland, in 1991. He is a Professor with Gdansk University of Technology, Gdansk, Poland. His main areas of research are modeling and simulation of electric machines, control of electric drives, and DSP systems.

Preface

The book describes the concept of advanced control strategies of AC machine drives along with their complete simulation models using MATLAB/Simulink. Electrical Motors consume the most energy of the electricity generated worldwide. Thus, there exists a huge scope of saving energy by devising efficient operation schemes of these electrical machines. One approach could be the special design of motors with high-energy efficiency. Other approach lies in the proper control of the machines. The electrical motors employed in various applications run at fixed speed. However, it is found that by varying the speed of motors depending upon the load requirements, the efficiency can be improved significantly; thus, the variable speed operation is extremely important in obtaining highly efficient operations of the machines. As a result, the speed control of a machine for industrial and household applications is most vital for limiting greenhouse gas emission and offering an environment-friendly solution. Controlling the operation of an electrical machine by varying its speed, in literature, is called ‘variable speed drives’ or ‘adjustable speed drives’.

This book discusses the advanced technology used to obtain variable speed AC drives. This book also describes the basic modeling procedures of power electronic converters and AC machines. The mathematical model thus obtained will be used to develop a simulation model using MATLAB/Simulink. The Pulse Width Modulation (PWM) techniques for voltage source inverters and their simulation models are described in one chapter. The AC machines that are taken up for discussion are the most popular squirrel cage induction machine, permanent magnet synchronous machine, and the double-fed induction machine. The book illustrates the advance control techniques of electric drives such as ‘field-oriented control’, ‘direct torque control’, ‘feedback linearization control’, ‘sensorless operation’, and advances in ‘multi-phase (more than three-phase) drives’. A separate chapter is dedicated to a five-phase motor drive system. The effect of using an output LC filter at the inverter side on the motor drive control is elaborated on in another chapter.

These control techniques are in general called ‘high-performance drives’ as they offer extremely fast and precise dynamic and steady-state response of electric machines. Thus, this book describes the most important and industrially accepted advanced control technology of AC machines. The book encompasses these diverse topics in a single volume.

This book features exhaustive simulation models based on MATLAB/Simulink. MATLAB/Simulink is an integral part of taught courses at undergraduate and postgraduate programs and is also extensively used in industries. Thus, the simulation models will provide a handy tool to students, practicing engineers, and researchers to verify the algorithms, techniques, and models. Once familiar with the models presented in the book, students and practicing engineers can develop and verify their own algorithms and techniques.

The book is useful for students studying electric drives/motor control at UG/PG levels. The prerequisite will be the basic courses of electric machines, power electronics, and controls. Lecturers can find tutorial materials and Solutions to the problems set out in the book on the companion website: www.wiley.com/go/aburub_control. The contents of the book will also be useful to researchers and practicing engineers, as well as specialists.

1

Introduction to High Performance Drives

1.1 Preliminary Remarks

The function of an electric drives system is the controlled conversion of electrical energy to a mechanical form, and vice versa, via a magnetic field. Electric drives is a multi-disciplinary field of study, requiring proper integration of knowledge of electrical machines, actuators, power electronic converters, sensors and instrumentation, control hardware and software, and communication links (Figure 1.1). There have been continued developments in the field of electric drives since the inception of the first principle of electrical motors by Michael Faraday in 1821 [1]. The world dramatically changed after the first induction machine was patented (US Patent 381968) by Nikola Tesla in 1888 [2]. Initial research focused on machine design with the aim of reducing the weight per unit power and increasing the efficiency of the motor. Constant efforts by researchers have led to the development of energy efficient industrial motors with reduced volume machines. The market is saturated with motors reaching a high efficiency of almost 95–96%, resulting in no more significant complaints from users [3]. AC motors are broadly classified into three groups: synchronous, asynchronous (induction), and electronically commutated motors. Asynchronous motors are induction motors with a field wound circuit or with squirrel cage rotors. Synchronous motors run at synchronous speeds decided by the supply frequency ($N_s = 120f/P$) and are classified into three major types: rotor excited, permanent magnets, and synchronous reluctance types. Electronic commutated machines use the principle of DC machines but replace the mechanical commutator with inverter-based commutations. There are two main types of motors that are classified under this category: brushless DC motors and switched reluctance motors. There are several other variations of these basic configurations of electric machines used for specific applications, such as stepper motors, hysteresis motors, permanent magnet assisted synchronous reluctance motors, hysteresis-reluctance motors, universal motors,

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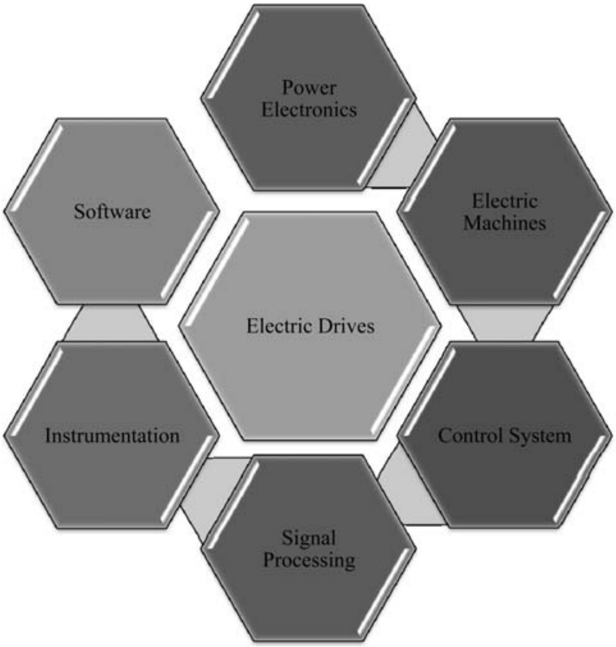

Figure 1.1 Electric drive system

claw pole motors, frictionless active bearing-based motors, linear induction motors, etc. Active magnetic bearing systems work on the principle of magnetic levitation and, therefore, do not require working fluid, such as grease or lubricating oils. This feature is highly desirable in special applications, such as artificial heart or blood pumps, as well as in the oil and gas industry.

Induction motors are called the workhorse of industry due to their widespread use in industrial drives. They are the most rugged and cheap motors available off the shelf. However, their dominance is challenged by permanent magnet synchronous motors (PMSM), because of their high power density and high efficiency due to reduced rotor losses. Nevertheless, the use of PMSMs is still restricted to the high performance application area, due to their moderate ratings and high cost. PMSMs were developed after the invention of Alnico, a permanent magnet material, in 1930. The desirable characteristics of permanent magnets are their large coercive force and high reminiscence. The former characteristics prevent demagnetization during start and short-conditions of motors and the latter maximizes the air gap flux density. The most used permanent magnet material is Neodymium-Boron-Iron (NdBFe), which has almost 50 times higher B-H energy compared to Alnico. The major shortcomings of permanent magnet machines are the non-adjustable flux, irreversible demagnetization, and expensive rare-earth magnet resources. Variable flux permanent magnet (VFPM) machines have been developed to incorporate the adjustable flux feature. This variable flux feature offers flexibility by optimizing efficiency over the whole machine operation range, enhancing torque at low speed, extending the high speed operating range, and reducing the likelihood of an excessively high back-EMF being induced at high speed

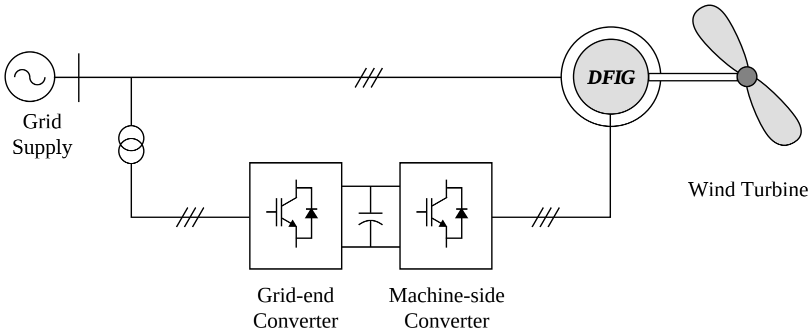

Figure 1.2 General view of a DFIG connected to wind system and utility grid

during inverter fault conditions. The VFPM are broadly classified into hybrid-excited machines (they have the field coils and the permanent magnets) and mechanically adjusted permanent magnet machines. Detailed reviews on the variable flux machines are given in [4]. The detailed reviews on the advances on electric motors are presented in [5–16].

Another popular class of electrical machine is the double-fed induction machine (DFIM) with a wound rotor. The DFIM is frequently used as an induction generator in wind energy systems. The double-fed induction generator (DFIG) is a rotor-wound, three-phase induction machine that is connected to the AC supply from both stator and rotor terminals (Figure 1.2). The stator windings of the machine are connected to the utility grid without using power converters, and the rotor windings are fed by an active front-end converter. Alternatively, the machine can be fed by current or voltage source inverters with controlled voltage magnitude and frequency [17–22].

In the control schemes of DFIM, two output variables on the stator side are generally defined. These variables could be electromagnetic torque and reactive power, active and reactive power, or voltage and frequency, with each pair of variables being controlled by different structures.

The machine is popular and widely adopted for high power wind generation systems and other types of generators with similar variable speed high power sources (e.g. hydro systems). The advantage of using this type of machine is that the required converter capacity is up to three times lower than those that connect the converter to the stator side. Hence, the costs and losses in the conversion system are drastically reduced [17].

A DFIG can be used either in an autonomous generation system (stand-alone) or, more commonly, in parallel with the grid. If the machine is working autonomously, the stator voltage and frequency are selected as the controlled signals. However, when the machine is connected to the infinite bus, the stator voltage and frequency are dictated by the grid system. In the grid-interactive system, the controlled variables are the active and reactive powers [23–25]. Indeed, there are different types of control strategies for this type of machine; however, the most widely used is vector control, which has different orientation frames similar to the squirrel cage induction motor, but the most popular of these is the stator orientation scheme.

Power electronics converters are used as an interface between the stiff voltage and frequency grid system and the electric motors to provide adjustable voltage and frequency.

This is the most vital part of a drive system that provides operational flexibility. The development in power electronic switches is steady and nowadays high frequency low loss power semiconductor devices are available for manufacturing efficient power electronic converters. The power electronic converter can be used as DC-DC (buck, buck-boost, boost converters), AC-DC (rectifiers), DC-AC (inverters), and AC-AC (cyclo-converters and matrix converters) modes. In AC drive systems, inverters are used with two-level output or multi-level output (particularly for higher power applications). The input side of the inverter system can consist of a diode-based, uncontrolled rectifier or controlled rectifier for regeneration capability called back-to-back or active front-end converter. The conventional two-level inverter has the disadvantages of the poor source side (grid side) power factor and distorted source current. The situation is improved by using back-to-back converters or matrix converters in drive systems.

The output side (AC) voltage/current waveforms are improved by employing the appropriate Pulse Width Modulation (PWM) technique, in addition to using a multi-level inverter system. In modern motor drives, the transistor-based (IGBT, IGCT, MOSFET) converters are most commonly used. The increase in transistors switching frequency and decrease in transistor switching times are a source of some serious problems. The high $\mathrm{d}v/\mathrm{d}t$ and the common mode voltage generated by the inverter PWM control results in undesirable bearing currents, shaft voltages, motor terminal over-voltages, reduced motor efficiency, acoustic noise, and electromagnetic interference (EMI) problems, which are aggravated by the long length of the cable between the converter and the motor. To alleviate such problems, generally the passive LC filters are installed on the converter output. However, the use of an LC filter introduces unwanted voltage drops and causes a phase shift between the filter input and output voltages and currents. These can negatively influence the operation of the whole drive system, especially when sophisticated speed, sensorless control methods are employed, requiring some estimation and control modifications for an electric drive system with an LC filter at its output. With the LC filter, the principal problem is that the motor input voltages and currents are not precisely known; hence, additional voltage and current sensors are employed. Since the filter is an external element of the converter, the requirement of additional voltage and current sensors poses technical and economical problems in converter design. The more affordable solution is to develop proper motor control and use estimation techniques in conjunction with LC filter-based drive [26–30].

The simulation tool is a significant step for performing advanced control for industry. However, for practical implementation, the control platform for the electric drive system is provided with microcontrollers (μCs), digital signal processors (DSPs), and/or field programmable gate arrays (FPGAs). These control platforms offer flexibility of control and make possible the implementation of complex control algorithms, such as field oriented control (FOC), direct torque control (DTC), non-linear control, and artificial intelligence-based control. The first microprocessor, the Intel 4004 (US Patent # 3821715), was invented by Intel engineers Federico Faggin, Ted Hoff, and Stan Mazor in November 1971 [31]. Since then, the development of faster and more capable microprocessors and μCs has grown tremendously. Microcontroller is a single IC containing the processor core, the memory, and the peripherals. Microprocessors are used for general-purpose applications, such as in PCs, laptops, and other electronic items, and are used in embedded applications for actions such as motor control. The first DSP was produced by Texas Instruments, TMS32010, in 1983 [32], followed by several DSPs being produced and used for several applications, ranging from motor control to multi-media applications to image processing. Texas Instruments has developed some specific DSPs for electric drive applications, such as the TMS320F2407, TMS320F2812, and TMS320F28335. These DSPs have dedicated pins for PWM signal generation that serve by controlling power converters. Nowadays, control algorithms implement more powerful programmable logic components called FPGAs, the first of which, XC2064, was invented by Xilinx co-founders Ross Freeman and Bernard Vonderschmitt in 1985. FPGAs have logic blocks with memory elements that can be reconfigured to obtain different logic gates. These reconfigurable logic gates can be configured to perform complex combinational functions. The first FPGA XC2064 had 64 configurable logic blocks, with two three-input lookup tables. In 2010, an extended processing platform was developed for FPGAs that combines the features of an Advanced Reduced Instruction Set Machine (ARM) high-end microcontroller (32-bit processor, memory, and I/O) with an FPGA fabric for easier use in embedded applications. Such configurations make it possible to implement a combination of serial and parallel processing to address the challenges in designing today’s embedded systems [33].

The primitive electric drive system uses a fixed-speed drive supplied from the grid, while mostly employing the DC motor. Adjustable speed drive systems offer more flexible control and increased drive efficiency when compared to the fixed speed drive. DC motors inherently offer decoupled flux and torque control, with fast dynamic response and simple control mechanism. However, the operating voltage of the DC machines is limited by the mechanical commutator’s withstand voltage; in addition, the maintenance requirement is high due to its brush and commutator arrangement. DC drives are now increasingly replaced by AC drives due to the advent of the high performance control of AC motors, such as vector control, Direct Torque Control (DTC), and predictive control, offering precise position control and an extremely fast dynamic response [34]. The major advantages of AC drives over DC drives include their robustness, compactness, economy, and low maintenance requirements.

Biologically inspired artificial intelligence techniques are now being increasingly used for electric drive control, and are based on artificial neural networks (ANN), fuzzy logic control (FLC), adaptive neuro-fuzzy inference system (ANFIS), and genetic algorithm (GA) [35,36]. A new class of electric drive controls, called brain emotional learning-based intelligent controller (BELBIC), is reported in the literature [37]. The control relies on the emotion processing mechanisms in the brain, with the decisions made on the basis of an emotional search. This emotional intelligence controller offers a simple structure with a high auto-learning feature that does not require any motor parameters for self performance. The high performance drive control requires some sort of parameter estimation of motors, in addition to the current, speed, and flux information for a feedback closed-loop control. Sensors are used to acquire the information and are subsequently used in the controller. The speed sensors are the most delicate part in the whole drive system, thus extensive research efforts are being made to eliminate the speed sensors from the drive system, with the resulting drive system becoming a ‘sensorless’ drive. In sensorless drive schemes, existing current and voltage sensors are used to compute the speed of the machine, and the computed speed is used for closed-loop control. The literature on sensorless drives is too vast to list, but a comprehensive review is available in [38–40]. A sensorless drive offers the advantages of a compact drive with reduced maintenance, reduced cost, and its ability to withstand harsh environmental conditions. Despite impressive progress in drive automation, there are still a number of persistent challenges, including a very low speed near to zero, operation at zero speed with full load condition, and an overly high-speed operation.

Network-based control and remote control of the drive systems are still in progress. Plug-and-play types of electric drives are an important area that can serve the applications that have a direct impact on the quality of life, such as renewable energy, automotive applications, and biomedical applications. Integrated converter-motor drive systems for compact design, as well as reduced EMI due to cabling wave reflection, are also in progress. More diversity in machine design with rare earth free motors is the subject of research, and high air gap flux density machines using superconductors are the direction of research in electric drive systems.

1.2 General Overview of High Performance Drives

High performance drive refers to the drive system's ability to offer precise control, in addition to a rapid dynamic response and a good, steady state response. High performance drives are considered for safety critical applications due to their precision of control [41]. Since the inception of AC machines, several techniques have evolved to control their speed, torque, and flux. The basic controlling parameters are the voltage and frequency of the applied voltage/current to the motor. The grid supplies fixed magnitude and frequency voltages/currents, and are thus not suitable for obtaining controlled operation of machines. Hence, power electronic converters are used as an interface between the grid supply and the electric motors. These power electronic converters, in most cases, are AC-DC-AC converters for AC machine drives. Other alternatives are direct AC-AC converters, such as cyclo-converters and matrix converters. However, these direct AC-AC converters suffer from some serious drawbacks, including the limited output frequency, as low as one-third in cyclo-converters, and the limited output voltage magnitude, which is limited to 86% of the input voltage magnitude in matrix converters. Moreover, the control is extremely complex for direct AC-AC converters. Thus, invariably AC-DC-AC converters are more commonly called 'inverters,' and are used to feed the motors for adjustable speed applications. This book will describe the modeling procedures of the inverters, followed by the illustration of their existing control techniques. The basic energy processing technique in an inverter is called 'Pulse Width Modulation' (PWM); hence, PWM will be discussed at length.

The control of AC machines can be broadly classified into 'scalar' and 'vector' controls (Figure 1.3). Scalar controls are easy to implement and offer a relatively steady-state response, even though the dynamics are sluggish. To obtain high precision and good dynamics, as well as a steady-steady response, 'vector' control approaches are to be employed with closed-loop feedback control. Thus, this book focuses on the 'vector' based approaches, namely 'Field Oriented Control,' 'Direct Torque Control,' 'Non-linear Control,' and 'Predictive Control.'

It is well-known that the variable speed drive offers significant energy savings in an industrial set-up. Thus, by employing variable speed drives in industry, there exists huge scope for energy saving. The older installations relied on DC machines for variable speed applications, because of their inherent decoupled torque and flux control with minimum electronics involved; however, in the early 1970s, the principle of decoupled torque and flux control, more commonly called 'field oriented control' or 'vector control,' were achieved in more robust induction machines. Later, it was realized that such control was also possible in synchronous

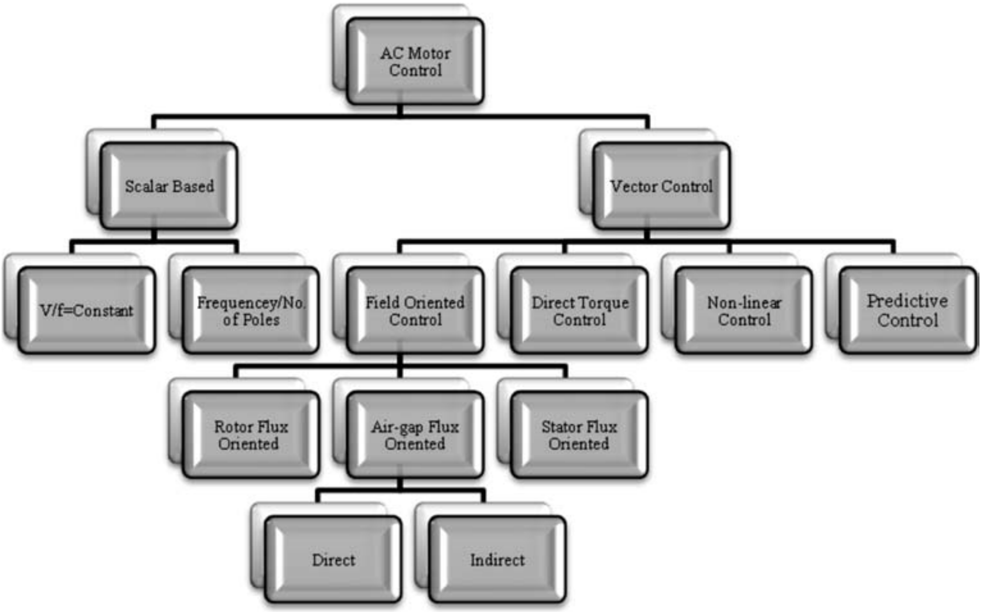

Figure 1.3 Motor control schemes

machines. However, the pace of development in variable speed AC machine drives was slow and steady until the early 1980s, when the microprocessor era began and the realization of complex control algorithms became feasible [34,35].

The FOC principle relies on the instantaneous control of stator current space vectors. The research on FOC is still active, with the idea of incorporating more advanced features for highly precise and accurate control, such as sensorless operation, and utilization of on-line parameter adaptations. The effect of parameter variations, magnetic saturation, and stray-load losses on the behavior of field oriented controlled drives are the subject of research in obtaining robust sensorless drives.

Theoretical principles of ‘direct torque control’ for high performance drives were introduced in the mid- and second half of the 1980s. Compared with FOC which had its origin at the beginning of the 1970s, DTC is a significantly newer concept. It took almost 20 years for the vector control to gain acceptance by the industry. In contrast, the concept of DTC has been received by industry relatively quickly, in only ten years. While FOC predominantly relies on the mathematical modeling of an induction machine, DTC makes direct use of physical interactions that take place within the integrated system of the machine and its supply. The DTC scheme requires simple signal processing methods, relying entirely on the non-ideal nature of the power source that is used to supply an induction machine, within the variable speed drive system (two-level or three-level voltage source inverters, matrix converters, etc.). It can, therefore, be applied to power electronic converter-fed machines only. The on-off control of converter switches is used for the decoupling of the non-linear structure of the AC machines. The most frequently discussed and used power electronic converter in DTC drives is a voltage source inverter.

DTC takes a different look at the machine and the associated power electronic converter. First, it is recognized that, regardless of how the inverter is controlled, it is by default a voltage source rather than a current source. Next, it dispenses with one of the main characteristics of the vector control, indirect flux, and torque control by means of two stator current components. In essence, DTC recognizes that if flux and torque can be controlled indirectly by these two current components, then there is no reason why it should not be possible to control flux and torque directly, without intermediate current control loops.

DTC is inherently sensorless. Information about actual rotor speed is not necessary in the torque mode of operation, because of the absence of co-ordinate transformation. However, correct estimations of stator flux and torque is important for the accurate operation of hysteresis controllers. An accurate mathematical model of an induction machine is, therefore, essential in DTC. The accuracy of DTC is also independent of the rotor's parameters variations. Only the variation of stator resistance, due to a change in thermal operating conditions, causes problems for high performance DTC at low speeds [38].

In summary, the main features of DTC and its differences from the vector control are:

- direct control of flux and torque;
- indirect control of stator currents and voltages;
- absence of co-ordinate transformation;
- absence of separate voltage modulation block, usually required in vector drives;
- ability to know only the sector in which the stator flux linkage space vector is positioned, rather than the exact position of it (necessary in vector drives for co-ordinate transformation);
- absence of current controllers;
- inherently sensorless control since speed information is not required in the torque mode of operation;
- in its basic form, the DTC scheme is sensitive to only variation in stator resistance.

The research on the direct torque is still active and the effects of non-linearity in the machine models are being explored; the flexibility and simple implementation of the algorithms will be the focus of research in the near future. The use of artificial intelligence is another direction of research in this area. It is important to emphasize that many manufacturers offer variable speed drives based on the 'field oriented control' and 'DTC' principles and are readily available in the market.

The main disadvantage of vector control methods is the presence of non-linearity in the mechanical part of the equation during the changing of rotor flux linkage. Direct use of vector methods to control an induction machine fed by a current source inverter provides a machine model with high complexity, which is necessary to obtain precise control systems. Although positive results from field oriented/vector control have been observed, attempts to obtain new, beneficial, and more precise control methods are continuously made. One such development is the 'non-linear control' of an induction machine. There are a few methods that are encompassed in this general term of 'non-linear control,' such as 'feedback linearization control' or 'input-output decoupling control,' and 'multi-scalar model based non-linear control'. Multi-scalar-based non-linear control or MM control was presented for the first time in 1987 [38,39], and is discussed in the book. The multi-scalar model-based control relies on the choice of specific state variables and, thus, the model obtained completely decoupled mechanical and electromagnetic subsystems. It has been shown that it is possible to have non-linear control and decoupling between electromagnetic torque and the square of linear combination of a stator current vector and the vector of rotor linkage flux.

When a motor is fed by voltage source inverters, and when the rotor flux linkage magnitude is kept constant, the non-linear control system control is equivalent to the vector control method. In many other situations, the non-linear control gives more system structure simplicity and good overall drive response [35,38,39].

The use of variables transformation to obtain non-linear model variables makes the control strategy easy to perform, because only four state variables have been obtained with a relatively simple non-linearity form [38]. This makes it possible to use this method in the case of change flux vector, as well as to obtain simple system structures. In such systems, it is possible to change the rotor flux linkage with the operating point without affecting the dynamic of the system. The relations occurring between the new variables make it possible to obtain novel control structures that guarantee a good response of the drive system, which is convenient for the economical operation of drive systems in which this flux is reduced if the load is decreased.

The use of variables transformation to obtain MM makes the control strategy easier than the vector control method, because four variables are obtained within simple non-linearity form. This makes it possible to use this method in the field-weakening region (high speed applications) more easily when compared to the vector control methods. Extensive research has been done on the non-linear control theory of induction machines, leading to a number of suggested improvements. It is expected that more such control topology will evolve in time.

High performance control of AC machines requires the information of several electromagnetic and mechanical variables, including currents, voltages, fluxes, speed, and position. Currents and voltage sensors are robust and give sufficiently accurate measurements, and so are adopted for the closed-loop control. The speed sensors are more delicate and often pose serious threats to control issues, so speed sensorless operation is sought in many applications that require closed-loop control. Several schemes have been developed recently to extract speed and position information without using speed sensors. Similarly, rotor flux information is typically obtained using 'observer' systems. Much research efforts occurred throughout the 1990s to develop robust and precise observer systems. Improvements have been offered by the development of the methods, including the 'model reference adaptive system,' the 'Kalman filters,' and the 'Luenberger observers,' [40–42].

Initially, observers were designed based on the assumption of a linear magnetic circuit and were later improved by taking into account different non-linearities. The methods developed so far still suffer from stability problems around zero frequency. They fail to prove global stability for sensorless AC drives. This has led many researchers to conclude that globally asymptotically stable model-based systems for sensorless induction motor drives may not exist. Indeed, most investigations on sensorless induction motor drives today focus on providing sustained operation at high dynamic performance at very low speed, particularly at zero speed or at zero stator frequency. Two advanced methodologies are competing to reach this goal. The first category comprises the methods that model the induction motor by its state equations. A sinusoidal flux density distribution in the air gap is then assumed, neglecting space harmonics and other secondary effects. The approach defines the class of fundamental models. They are either implemented as open-loop structures, such as the stator model, or as closed-loop observers. The adaptive flux observer is a combination of the non-linear observer with a speed adaptation process. This structure is now receiving considerable attention and many new solutions follow a similar generic approach [41].

Three-phase electric power generation, transmission, distribution, and utilization have been well-known for over a century. It was realized that generation and transmission of power with more than three phases do not offer significant advantages in terms of power density (generation) and right-of-way and initial cost (transmission). A five-phase induction motor drive system was first tested for in 1969 [43]. The supply to a five-phase drive system was made possible by using a five-phase voltage source inverter, since simply adding an extra leg increases the output phases in an inverter. It was realized that the five-phase induction motor drive systems offered some distinct advantages over three-phase drive system counterparts, such as reduced torque pulsation and enhanced frequency of pulsation, reduced harmonic losses, reduced volume for the same power output, reduced DC link current harmonics, greater fault tolerance, and better noise characteristics.

In addition, there is a significant advantage on the power converter end, due to the reduced power per leg, the power semiconductor switch rating reduces, thus avoiding their series/parallel combination and eliminating the problem of static and dynamic voltage sharing. Furthermore, the stress on the power semiconductor switches reduces due to the reduced dv/dt. The attractive features of multi-phase drive systems means enormous research efforts have been made globally in the last decade to develop commercially feasible and economically viable solutions. Niche application areas are then identified for multi-phase drive systems, such as ship propulsion, traction, ‘more electric aircraft’ fuel pumps, and other safety critical applications. Due to their complex control structure, their widespread use in general purpose application is still not accepted. One of the commercial applications of a 15-phase induction motor drive system is in the British naval ship ‘Destroyer II.’ Similar drive systems are under preparation for US naval ships and will be commissioned soon. Nevertheless, there are many challenges still to be met before the widespread use of multi-phase drive systems, especially in general purpose electric drive systems [44].

1.3 Challenges and Requirements for Electric Drives for Industrial Applications

Industrial automation requires precisely controlled electric drive systems. The challenges and requirements for electric drive systems depend upon the specific applications being used. Among different classes of electric drives, medium voltage drives (0.2–40 MW at the voltage level of 2.3–13.8 kV) are more popular for use in industry, such as in the oil and gas sector, rolling and milling operations, production and process plants, petrochemical industry, cement industry, metal industry, marine drive, and traction drive. However, only 3% of the existing medium voltage (MV) motors are variable-speed drives, with the rest of these running at a fixed speed [45]. The installation of properly speed controlled MV drives will significantly reduce losses and total drive costs, as well as improve power quality in any industrial set-up. There are several challenges associated with the controlled MV drives that are related to the line/source side (e.g. power quality, resonance, and power factor), motor side (e.g. dv/dt, torsional vibration, and traveling wave reflections), and power semiconductor switching devices (e.g. switching losses and voltage and current handling capability). The power rectifier at the source side produces distorted currents at the source, in addition to poor power factors, thus posing a challenge to the designer of the controlled electric drive system. The Pulse Width