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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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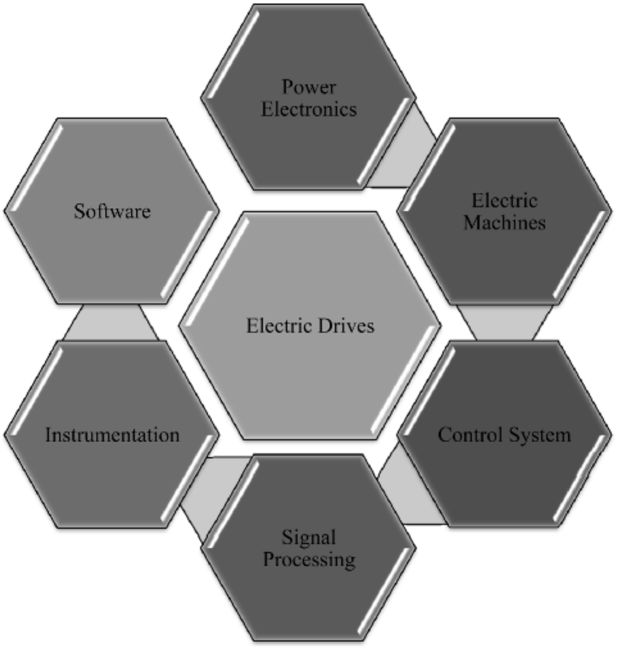

Figure 1.1 Electric drive system

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

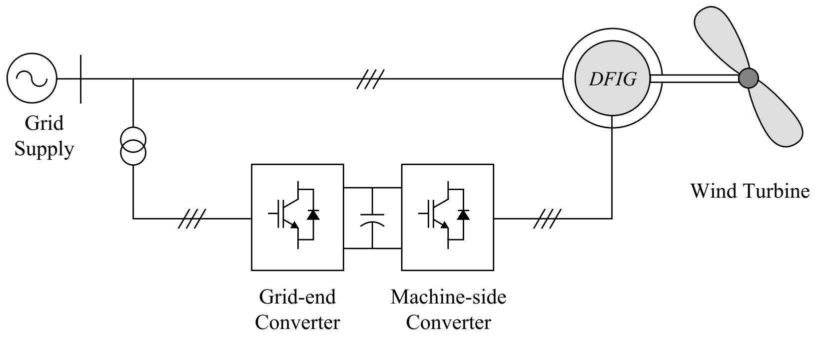

Figure 1.2 General view of a DFIG connected to wind system and utility grid

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 d*v*/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 micro-controller (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

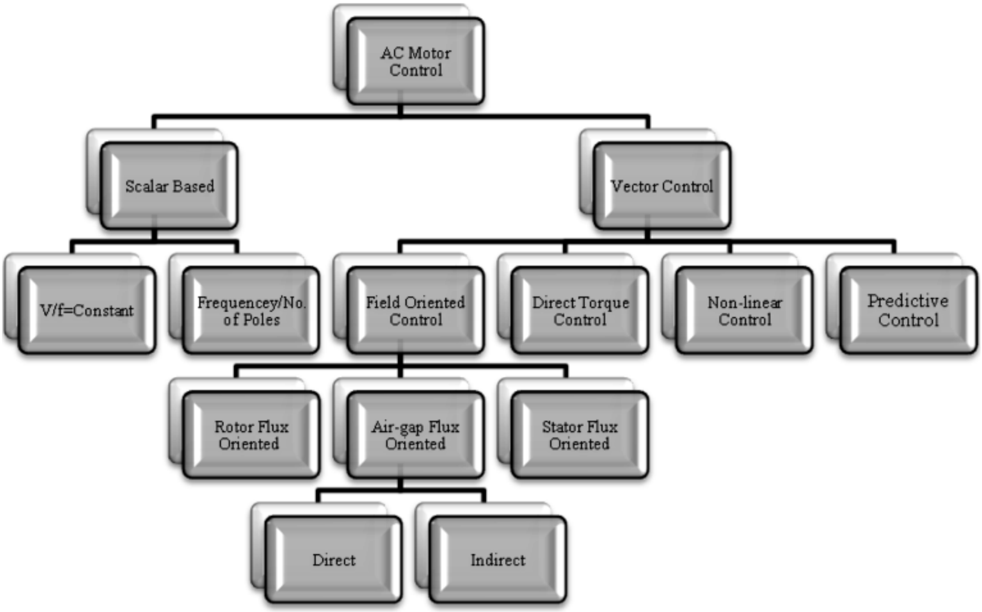

Figure 1.3 Motor control schemes

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

Modulation of inverter generates a common mode voltage on the motor side, which poses another challenge. The rating of the power semiconductor devices is also an important factor to be considered while designing an electric drive. High-quality voltage and current waveforms at the converter input and output is essential in all types of electric drive systems.

The power quality is a factor of the converter topology used, and refers to the characteristic of the load, the size and type of the filter, the switching frequency, and the adopted control strategy. The switching losses of power converter devices contribute to the major portion of the drive losses; therefore, operation at a low switching frequency makes it possible to increase the maximum power of the inverter. However, an increase in the switching frequency of an inverter increases the harmonic distortion of the input and output waveforms. Another solution is to use multi-level inverters that deliver waveforms with better harmonic spectrum and lower d*v*/d*t*, which limits the insulation stress of the motor windings. However, increasing the number of switching devices in multi-level inverters tends to reduce the overall reliability and efficiency of the power converter. On the other hand, an inverter with a lower level of output voltage requires a large LC output filter to reduce the motor winding insulation stress. The challenge then is to reduce output voltage and current waveform distortions when low switching frequency is used to ensure high power quality and high efficiency.

The maximum voltage blocking capability of modern power semiconductor switching devices is nearly 6.5 kV. This sets the maximum voltage limit of the inverter and the motor in an electric drive system. Referring to the two-level voltage source inverter and the maximum conducting current (600 A) of available voltage IGBT switches, the obtained maximum apparent power is less than 1 MVA [45]. To overcome the limits of inverter ratings, series and/or parallel combinations of power devices are suggested. In such instances, extra measurements are required to balance the current between devices during turning on and turning off. Due to inherent differing device characteristics, more losses are generated, requiring a reduction in the de-rating of the inverter. There is a need to find a solution to increase the power range of inverter, while avoiding the problems associated with series/parallel connections of switches. One possible solution is using machines and converters with a high phase number (more than three). Drive systems using motors and converters of high phase orders have gained popularity in recent times, and extensive research efforts are being put into developing such commercially feasible drives.

Essential requirements for general purpose electric drives for industrial application include high efficiency, low cost, compact size, high reliability, fault protection features, easy installation, maintenance, and, in some applications, high dynamic performance, better power quality at the input side, precise position control, and regeneration capability.

1.3.1 Power Quality and LC Resonance Suppression

Unwanted harmonics are introduced in power grids due to the power electronic switching converters on the load side, which poses a serious problem that needs to be effectively solved. Uncontrolled diode based rectifiers at the source side of the inverter draw distorted currents from the grid and cause notches in voltage waveforms. This results in several problems, such as computer data loss, malfunction of communication equipment and protective equipment, and noise. Therefore, many standards define the limit of harmonics injected into the power grid, including IEEE 519-1999, IEC 1000-3-2 International Standard, 1995, and IEC 61000-3-2

International Standard, 2000. Current research and industrial applications tend to comply with these international standards.

The LC line side filter is used for current harmonic reduction or power factor compensation. Such LC filters may exhibit resonance phenomena. The supply system at the MV level has very low impedance, therefore lightly damped LC resonances may cause undesired oscillations or over-voltages. This may shorten the life of the switching devices or other components of the rectifier circuits. Effective solutions should guarantee low harmonics and low d*v*/d*t* using just a reactor instead of an LC filter, or using a small filter to solve the problem of LC resonance.

1.3.2 Inverter Switching Frequency

The use of high switching frequency devices in power converters causes rapid voltages and current transitions. This leads to serious problems in the drive system, such as the generation of unwanted common-mode (CM) currents, EMI, shaft voltage, with consequent generation of bearing currents, and deterioration of the winding insulation of motors and transformers.

Switching losses is a crucial issue that should be taken into account in designing electric drives, because they pose a limit on the switching frequency value and the output power level of the power converters. The switching losses of semiconductor devices contribute to a major portion of total device losses. A reduction of switching frequencies increases the maximum output power of the power converter. However, the reduction of switching frequency may cause an increase in harmonic distortion of the line and motor side. Hence, a trade-off exists between these two conflicting requirements.

1.3.3 Motor Side Challenges

Fast switching transients of the power semiconductors devices at high commutation voltages causes high switching losses and poor harmonic spectrum of the output voltages, generating additional losses in the machine. The problems are aggravated due to the long length of the cables between the converters and motors, as well as generating bearing currents due to switching transients.

1.3.4 High dv/dt and Wave Reflection

The high switching frequency of power devices causes high d*v*/d*t* at the rising and falling edges of the inverter output voltage waveform. This may cause failure of the motor winding insulation due to partial discharges and high stress. High d*v*/d*t* also produces rotor shaft voltages, which creates current flow into the shaft bearing through the stray coupling capacitors, ultimately leading to motor bearings failure. This is a common problem in adjustable speed drive systems in industry.

The wave reflections are caused by the mismatch between the cable, the inverter, and the motor wave impedance. Wave reflections can double the voltage on the motor terminals at each switching transient, if the cable length exceeds a certain limit. The critical cable length for 500 V/μs is in the 100-m range, while for 10,000 V/μs it is in the 5-m range [45]. The d*v*/d*t* also causes electromagnetic emission in the cables between the inverter and the motor. Expensive shielded cables are used to avoid these effects; nevertheless, the electromagnetic emission may affect the operation of nearby sensitive electronic equipment, which is called electromagnetic interference.

The design of the filters should achieve international standards (e.g. IEEE 519-1999). Filters also reduce the switching frequency. The widely used passive filters are designed to ensure very low total harmonic distortion (THD) in both motor and line sides. A large inductor in the LC filter must be used in most high power drive systems, resulting in undesirable voltage drops across the inductor. The increase in capacitor size reduces LC resonant frequency, which is then affected by the parallel connection of the filter capacitor and motor magnetizing inductance.

In an electric drive with an LC filter, instability could appear due to electric resonance between L and C parameters. Such phenomena are mostly observed in over-modulation regions when some inverter output voltage harmonics are close to LC filter resonant frequency. Active damping techniques could be then employed to resolve the problem of instability, while at the same time suppressing the LC resonance.

1.3.5 Use of Inverter Output Filters

The output voltage quality at the inverter side can be improved by using active and passive filters. Today, passive filtering is widely used at the output of the inverter to improve the voltage waveform. Such filters are hardware circuits that are installed on the output of the converter structure. The most common approach is the use of filters based on resistors, inductors, and capacitors (LC filters). In order to reduce the over-voltages that can occur, because of wave reflection at the motor terminals when long cables are used, differential mode LC filters are used. The cable length is important in determining the output performance of the drive system; however, the cable layout on the user end is generally unknown to the inverter manufacturer. Moreover, such filters components are decided according to the switching frequency of the inverter. When an inverter output filter is installed in the electric drive, the voltage drops and the phase shifts between the filter's input while output voltages and currents appear. This complicates the control system design, particularly for low speed conditions. The control systems are generally designed assuming the inverter's output voltages and currents are equal to the motor input values. In the case of a discrepancy between voltages and currents, the region of proper motor operation is limited. Therefore, in a control system of electric drives with an inverter output filter, it is essential to provide modification in the measurement circuits or in the control algorithms. A simple way to improve the performance of the electric drive with inverter output filter is to introduce additional sensors for motor voltages and current measurements. Such a solution is not practical because it requires changes in the inverter structure so, in this case, an accepted solution is to keep the inverter structure unchanged but to modify a control algorithm.

1.4 Organization of the Book

This book is comprised of nine different chapters dealing with different issues of High Performance AC Drives along with the MATLAB/Simulink models. Chapter 1 discusses the components of AC drive system and presents an overview on High Performance Drives.

The classification of electrical machines and their state-of-the-art control strategies, including field oriented control and direct torque control, are elaborated on. The persisting challenges for the industrial application of AC drives are further illustrated in Section 1.3. This chapter give an overall view of High Performance Drives.

Chapter 2 discusses the basic modeling procedures of different types of electrical machines. For the sake of completeness, DC machine modeling is presented in Section 2.2, followed by the modeling of the squirrel cage induction machine, which is presented based on the space vector approach. The obtained dynamic model is then converted into a per unit system for further simulation and generalization of this approach. This is followed by the modeling of double-fed induction machine and permanent magnet synchronous machine. The simulation using MATLAB/Simulink is also presented.

Chapter 3 describes the Pulse Width Modulation control of DC-AC converter system. The basic modeling of a two-level inverter based on the space vector approach is discussed, followed by different PWM approaches such as carrier-based sinusoidal PWM, harmonic injection schemes, offset addition methods, and space vector PWM techniques. This is followed by discussion on multi-level inverter operation and control. Three most popular topologies (Diode clamped, Flying capacitor, and Cascaded H-bridge) are illustrated. A new class of inverter, most popular in renewable energy application, called the Z-source inverter and its modified form called the quasi Z-source, are discussed in this chapter. The discussed techniques are further simulated using MATLAB/Simulink and the simulation models are presented.

Chapter 4 is dedicated to the field oriented control or vector control of AC machines, including the squirrel cage induction machine, the double-fed induction machine, and the permanent magnet synchronous machine. For consistency, scalar control (v/f = constant) is also presented. Different types of vector control are presented along with their simulation models. Wide speed control range from low to high (field weakening) is elaborated on. The field weakening region is discussed in detail, with the aim of producing high torque at high speed. Vector control of DFIG with grid interface is also described, as is the basic rotor flux estimation scheme using the Luenberger observer system.

Principles of DTC for High Performance Drives are introduced in Chapter 5. DTC takes a different look at the induction machine and the associated power electronic converter. First, it recognizes 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 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 it should not be possible to control flux and torque directly, without intermediate current control loops. This concept is discussed in Chapter 5. The main features, advantages, shortcomings, and implementation of d DTC are elaborated on. A simulation model for implementing d DTC is presented.

High Performance Drives are a solution intended to embed separately excited DC motor characteristics into AC machines. This goal has been almost achieved with the inception of vector control principle. 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. Although good results from vector control have been observed, attempts to obtain new control methods are still being made. Non-linear control of induction motors is another alternative to obtain decoupled dynamic control of torque and flux. This method of control to obtain High Performance Drive is presented in Chapter 6. Such a control technique introduces a novel mathematical model for induction motors, which makes it possible to avoid using sin/cos transformation of state variables. The model consists of two completely decoupled subsystems, mechanical and electromagnetic. It has been shown that in such a situation it is possible to have non-linear control and decoupling between electromagnetic torque and the rotor linkage flux. Non-linear control of induction machine based on multi-scalar model is discussed. Non-linear control of a separately excited DC motor is also presented. Non-linear control of non-linear induction machine and permanent magnet synchronous machine is illustrated. The discussed techniques are supported by their simulation model using MATLAB/Simulink.

Chapter 7 is devoted to a five-phase induction motor drive system. The advantages and applications of a multi-phase (more than three phases) system are described. The chapter discusses the dynamic modeling of a five-phase induction machine, followed by space vector model of a five-phase voltage source inverter. The pulse width modulation control of a five-phase voltage source inverter is elaborated on. The vector control principle of a five-phase induction motor in conjunction with the current control in the stationary reference frame and the synchronously rotating reference frame is presented. Finite state model predictive control applied to a five-phase voltage source inverter for current control is also presented. The simulation models of a five-phase induction motor and five-phase voltage source inverter are illustrated using MATLAB/Simulink.

Chapter 8 describes the speed sensorless operation of high performance drive systems. Speed sensors are the most delicate component of a drive system, which are susceptible to faults and malfunctioning. A more robust drive system is obtained by replacing the physical speed sensors with the observer system that compute the speed and use the information for the closed-loop control. Several observer systems and their tuning are elaborated on in this chapter. A model reference adaptive speed estimator system for a three-phase and a five-phase induction machine is described along with their simulation model. Sensorless control scheme of permanent magnet synchronous machine is also discussed. Model reference adaptive speed estimator system for a three-phase permanent magnet synchronous motor is also illustrated.

Nowadays, electric drives with induction motors and voltage source type inverters are commonly used as adjustable speed drives in industrial systems. The inverters are built with the insulated gate bipolar transistors, IGBT, whose dynamic parameters are high, i.e. the on- and off-switch times are extremely short. Fast switching of power devices causes high dv/dt at the rising and falling edges of the inverter output waveform. High dv/dt in modern inverters is the source of numerous disadvantageous effects in the drives systems. The main negative effects are faster motor bearings degradation, over-voltages on motor terminals, failure or degradation of the motor winding insulation due to partial discharges, increase of motor losses, and a higher EMI level. The prevention or limiting of the negative effects of dv/dt is possible if proper passive or active filers are installed in the drive. Particularly passive filters are preferable for industrial applications. This issue is described in detail in the Chapter 9. The problems due to use of passive LC filters at the output of the inverter and their solutions are discussed.

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References

1. http://www.sparkmuseum.com/MOTORS.HTM
2. http://www.google.com/patents?vid=381968
3. Mecrow, B. C. and Jack, A. G. (2008) Efficiency trends in electric machines and drives. *Energy Policy*, **36**, 4336–4341.
4. Zhu, Z. Q. (2011) Recent advances on Permanent Magnet machines including IPM technology. *Keynote Lect. IEEE IEMDC*, 15–18 May, Niagara Falls.
5. Jahns, T. M. and Owen, E. L. (2001) AC adjustable-speed drives at the millennium: How did we get here? *IEEE Trans. Power Elect.*, **6**(1), 17–25.
6. Rahman, M. A. (1993) *Modern Electric Motors in Electronic World.* 0-7803-0891-3/93, pp. 644–648.
7. Lorenz, R. D. (1999) Advances in electric drive control. *Proc. Int. Conf. on Elec. Mach. Drives IEMD*, pp. 9–16.
8. Rahman, M. A. (2005) Recent advances of IPM motor drives in power electronics world. *Proc. IEEE Int. Conf. Power Elect. Drives Syst., PEDES*, pp. 24–31.
9. De Doncker, R. W. (2006) Modern electrical drives: Design and future trends. *Proc. IPEMC-2006* 14–16 August, Shanghai, pp. 1–8.
10. Finch, J. W. and Giaouris, D. (2008) Controlled AC electrical drives. *IEEE Trans. Ind. Elect.*, **55**(2), 481–491.
11. Toliyat, H. A. (2008) Recent advances and applications of power electronics and motor drives: Electric machines and motor drives. *Proc. 34th IEEE Ind. Elect. Conf., IECON*, Orlando, FL, pp. 34–36.
12. Bose, B. K. (1998) Advances in power electronics and drives: Their impact on energy and environment. *Proc. Int. Conf. on Power Elect. Drives Ener. Syst. Ind. Growth, PEDES*, vol. 1.
13. Jahns, T. M. and Blasko, V. (2001) Recent advances in power electronics technology for industrial and traction machine drives. *Proc. of IEEE*, **89**(6), 963–975.
14. Bose, B. K. (2005) Power electronics and motor drives: Technology advances, trends and applications. *Proc. IEEE Int. Conf. on Ind. Tech., ICIT*, pp. 20–26.
15. Bose, B. K. (2008) Recent advances and applications of power electronics and motor drives: Introduction and perspective. *Proc. IEEE Ind. Elect. Conf.*, pp. 25–27.
16. Capilino, G. A. (2008) Recent advances and applications of power electronics and motor drives: Advanced and intelligent control techniques. *Proc. IEEE Ind. Elect. Conf., IECON*, pp. 37–39.
17. Lin, F-J., Hwang, J-C., Tan, K-H., Lu, Z-H., and Chang, Y-R. (2010) Control of double-fed induction generator system using PIDNNs. *9th Int. Conf. Mach. Learn. Appl.*, pp. 675–680.
18. Muller, S., Deicke, M., and De Doncker, R. W. (2002) Doubly-fed induction generator systems for wind turbines. *IEEE IAS Mag.*, **8**(3), 26–33.
19. Bogalecka, E. (1993) Power control of a non-linear induction generator without speed or position sensor. *Conf. Rec. EPE*, **377**(8), 224–228.
20. Jain, A. K. and Ranganathan, V. T. (2008) Wound rotor induction generator with sensorless control and integrated active filter for feeding non-linear loads in a stand-alone grid. *IEEE Trans. Ind. Elect.*, **55**(1), 218–228.
21. Iwanski, G. and Koczara, W. (2008) DFIG-based power generation system with UPS function for variable-speed applications. *IEEE Trans. Ind. Elect.*, **55**(8), 3047–3054.
22. Pena, R., J. Clare, J. C., and Asher, G. M. (1996) Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation. *IEEE Proc. Elect. Power Appl.*, **143**(3), 231–241.
23. Forchetti, D., Garcia, G., and Valla, M. I. (2002) Vector control strategy for a doubly-fed stand-alone induction generator. *Proc. 28th IEEE Int. Conf., IECON.*, **2**, 991–995.

24. Pena, R., Clare, J. C., and Asher, G. M (1996) A doubly fed induction generator using back-to-back PWM converters supplying an isolated load from a variable speed wind turbine. *IEEE Proc. Elect. Power Appl.*, **143**(5), 380–387.
25. *The Industrial Electronics Handbook* (2011) CRC Press, Taylor & Francis Group, New York.
26. Forest, F., Labourı, E., Meynard, T. A., and Smet, V. A. (2009) Design and comparison of inductors and inter cell transformers for filtering of PWM inverter output. *IEEE Trans. on Power Elect.*, **24**(3), 812–821.
27. Shen, G., Xu, D., Cao, L., and Zhu, X. (2008) An improved control strategy for grid-connected voltage source inverters with an LCL filter. *IEEE Trans. on Power Elect.*, **23**(4), 1899–1906.
28. Gabe, I. J., Montagner, V. F., and Pinheiro, H. (2009) Design and implementation of a robust current controller for VSI connected to the grid through an LCL filter. *IEEE Trans. on Power Elect.*, **24**(6), 1444–1452.
29. Kojima, M., Hirabayashi, K., Kawabata, Y., Ejiogu, E. C., and Kawabata, T. (2004) Novel vector control system using deadbeat-controlled PWM inverter with output LC filter. *IEEE Trans. on Ind. Appl.*, **40**(1), 162–169.
30. Pasterczyk, R. J., Guichon, J-M., Schanen, J-L., and Atienza, E. (2009) PWM inverter output filter cost-to-losses trade off and optimal design. *IEEE Trans. on Ind. Appl.*, **45**(2), 887–897.
31. Bhattacharya, S. S., Deprettere, F., Leupers, R., and Takala, J. (2010) *Handbook of Signal Processing Systems*. Springer.
32. www.ti.com
33. Rich, N. (2010) 'Xilinx puts ARM core into its FPGAs.' EE times. Available from, http://www.eetimes.com/electronics-products/processors/4115523/Xilinx-puts-ARM-core-into-its-FPGAs (accessed April 27 2010).
34. Leonhard, W. (1996) *Control of Electrical Drives*, 2nd edn. Springer-Verlag.
35. Vas, P. (1998) *Sensorless Vector and Direct Torque Control*. London, Oxford University Press.
36. Vas, P. (1999) *Artificial Intelligence Based Electric Machine and Drives: Application of Fuzzy, Neural, Fuzzy-Neural and Genetic Algorithm Based Techniques*. Oxford, Oxford University Press.
37. Daryabeigi, E., Markadeh, G. R. A., and Lucas. C. (2010) Emotional controller (BELBIC) for electric drives: A review. *Proc. IEEE IECON-2010* pp. 2901–2907.
38. Krzeminski, Z. (1987). Non-linear control of induction motor. *IFAC 10th World Congr. Auto. Cont.*, Munich, pp. 349–354.
39. Abu-Rub, H., Krzemisnki, Z., and Guzinski, J. (2000) Non-linear control of induction motor: Idea and application. *EPE–PEMC (9th Int. Power Elect. Mot. Cont. Conf.)* Kosice/Slovac Republic, **6**, 213–218.
40. Holtz, J. (2006) Sensorless control of induction machines: With or without signal injection? *IEEE Trans. Ind. Elect.*, **53**(1), 7–30.
41. Holtz, J. (2002) Sensorless control of induction motor drives. *Proc. IEEE*, **90**(8), 1359–1394.
42. Acarnley, P. P. and Watson, J. F. (2006) Review of position-sensorless operation of brushless permanent-magnet machines. *IEEE Trans. Ind. Elect.*, **53**(2), 352–362.
43. Ward, E. E. and Harer, H. (1969) Preliminary investigation of an inverter-fed 5-phase induction motor. *Proc. IEEE*, **116**(6), 980–984.
44. Levi, E. (2008) Multiphase electric machines for variable-speed applications. *IEEE Trans on Ind. Elect.*, **55**(5), 1893–1909.
45. Abu-Rub, H., Iqbal, A., and Guzinski, J. (2010) Medium voltage drives: Challenges and requirements. *IEEE Int. Symp. on Ind. Elect., ISIE 2010* 4–7 July, Bari, Italy, pp. 1372–1376.