

1

Introduction to Electric Drives with LC Filters

1.1 Preliminary Remarks

The basic function of electric drives is to convert electrical energy to mechanical form (in motor mode operation) or from mechanical form to electrical energy (in generation mode). The electric drive is a multidisciplinary problem because of the complexity of the contained systems (Figure 1.1).

It is important to convert the energy in a controllable way and with high efficiency and robustness. If we look at the structure of global consumption of electrical energy the significance is plain. In industrialized countries, approximately two thirds of total industrial power demand is consumed by electrical drives [1, 2].

The high performance and high efficiency of electric drives can be obtained only in the case of using controllable variable speed drives with sophisticated control algorithms [3, 4].

In the industry, the widely used adjustable speed electrical drives are systems with an induction motor and voltage inverter (Figure 1.2). Their popularity results mainly from good control properties, good robustness, high efficiency, simple construction, and low cost of the machines [5].

Simple control algorithms for induction motors are based on the V/f principle. Because the reference frequency changes, the motor supply voltage has to be changed proportionally. In more sophisticated algorithms, systems such as field-oriented, direct torque, or multiscalar control have to be applied [6, 7]. Simultaneously, because of the estimation possibilities of selected controlled variables, for example, mechanical speed, it is possible to realize a sensorless control principle [7–10]. The sensorless speed drives are beneficial to maintain good robustness. Unfortunately, for sophisticated control methods, knowledge of motor parameters as well as high robustness of the drives against changes in motor parameters is required.

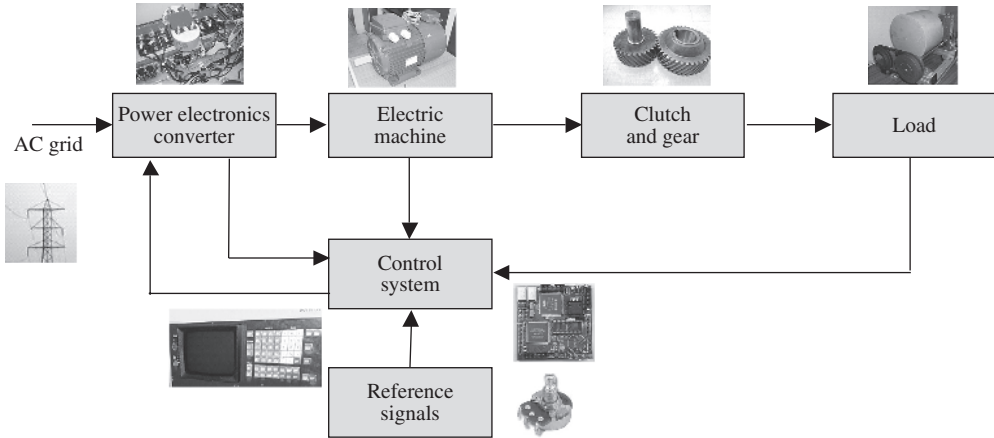


Figure 1.1 General structure of an electrical drive

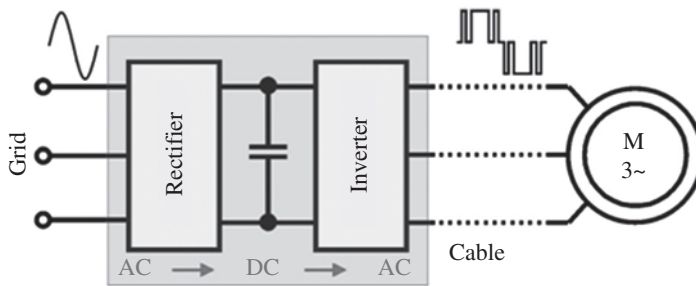


Figure 1.2 Electrical drive with voltage inverter and AC motor

1.2 General Overview of AC Drives with Inverter Output Filters

The inverter output voltage has a rectangular shape and is far from the sinusoidal one. Also, the use of semiconductor switches with short switching times causes high rates of rises of dV/dt voltages that initiate high levels of current and voltage disturbance [4, 11]. For this reason, it is necessary to apply filters between the inverter and the motor (Figure 1.3).

The introduction of a filter at the inverter output disables the proper operation of advanced drive control systems because doing this introduces more passive elements (inductances, capacitances, and resistances), which are not considered in the control algorithm [4, 12, 13]. This irregularity is caused by amplitude changes and phase shifts between the first current component and the motor supply voltage, compared to the currents and voltages on the inverter output. This causes the appearance in the motor control algorithm of inaccurate measured values of current and voltage at the standard measuring points of the inverter circuit. A possible solution to this issue is the implementation of current and voltage sensors at the filter output. However, this solution is not applied in



Figure 1.3 AC motor with voltage inverter and inverter output filter

industry drive systems because the filter is an element connected to the output of the inverter. The implementation of external sensors brings an additional cable network and that increases the susceptibility of the system to disturbances, reduces the system reliability, and increases the total cost of the drive.

A better solution is to consider the structure and parameters of the filter in the control and estimation algorithms. This makes it possible to use the measurement sensors that are already installed in the classical voltage inverter systems.

The addition of the filter at the voltage inverter output is beneficial because of the limitation of disturbances at the inverter output by obtaining sinusoidal voltage and current waveforms. Noises and vibrations are reduced and motor efficiency is increased. Furthermore, output filters reduce overvoltages on the motor terminals, which are generated through wave reflections in long lines and can result in accelerated aging of insulation. Several filter solutions are also used for limiting motor leakage currents, ensuring a longer failure-free operation time of the motor bearings.

The application of an inverter output filter and its consideration in the control algorithm is especially beneficial for various drive systems such as cranes and elevators. In that application, a long connection between motor and inverter is common.

The limitation of disturbances in inverter output circuits is an important issue that is discussed in numerous publications [14–18]. To limit such current and voltage disturbances, passive or active filters are used [4, 15]. The main reasons for preferring passive filters are especially the economic aspects and the possibility of limiting current and voltage disturbances in drive systems with high dV/dt voltage.

The control methods presented so far in the literature (e.g., [8–10, 19–27]) for an advanced sensorless control squirrel cage motor are designed for drives with the motor directly connected to the inverter. Not using filters in many drives is the result of control problems because of the difference between the instantaneous current and voltage values at the filter output and the current and voltage values at the filter input. Knowledge of this values is needed in the drive system control [28, 29]. A sensorless speed control in a drive system with an induction motor is most often based on the knowledge of the first component of the current and voltage. The filter can be designed in such a way that it will not significantly influence the fundamental components and will only limit the higher harmonics. However, most output filter systems introduce a voltage drop and a current and voltage phase shift for the first harmonic [4, 30]. This problem is important especially for sinusoidal filters, which ensure sinusoidal output voltage and current waveforms.

Another problem that has received attention in the literature [16, 30–37] is the common mode current that occurs in drive systems with a voltage inverter. The common mode current flow reduces the motor durability because of the accelerated wear of bearings. This current might also have an effect on the wrong operation of other drives included in the same electrical grid and can cause rising installation costs, which could lead to the need for an increase in the diameter of earth wire. Such problems come from both the system topology

and the applied pulse width modulation in the inverter, which are independent of the main control algorithms. Modifying the modulation method can cause a limitation of the common mode current [4, 30, 38].

This book presents the problems related to voltage-inverter-fed drive systems with a simultaneous output filter application. The authors have presented problems and searched for new solutions, which up to now, have not been presented in the literature. Therefore, this book introduces, among other topics, new state observer structures and control systems with LC filters.

The problem of drive systems with output filters, justifying the need for their application, is also explained. Moreover, the aim of this book is to present a way to control a squirrel cage induction motor and estimation of variables by considering the presence of the output filter, especially for drive systems without speed measurement.

Other discussed topics are several motor control structures that consider the motor filter as the control object. Such solutions are introduced for nonlinear-control drive systems and field-orientated control with load-angle control. Predictive current control with the presence of a motor choke is also analyzed. Solutions for systems with the estimation of state variables are presented, and the fault detection scheme for the mechanical part of the load torque transmission system is shown. Thus, for diagnostic purposes, state observer solutions were applied for drive systems with a motor filter.

The main points to be discussed are:

- A motor filter is an essential element in modern inverter drive systems.
- The introduction of a motor filter between the inverter and motor terminals changes the drive system structure in such a way that the drive system might operate incorrectly.
- The correct control of the induction motor, especially for sensorless drives, requires consideration of the filter in the control and state variable estimation process.

Some of the presented problems in the book also refer to drive systems without filters. Those problems are predictive current control using the state observer, fault diagnostics using a state observer in rotating frame systems, and decoupled field-orientated control with load-angle control.

1.3 Book Overview

Chapter 2 presents the problems of voltage and current common mode. The common mode is the result of voltage inverter operation with pulse width modulation in addition to the motor parasitic capacitances. The equivalent circuit of the common mode current flow is presented and explained extensively. Furthermore, attention is paid to the bearing current, whose types are characterized by a fundamental method. The main ways to limit the common mode current are mentioned, taking into consideration the application of common mode chokes. Additionally, a way of determining the motor parameters for common mode is shown. A considerable part of the chapter is dedicated to the active method of limiting the common mode through the modification of the pulse width modulation scheme. Some comments on synchronous sampling of inverter output current are also included in Appendix A.

Chapter 3 presents the motor model of a squirrel cage motor used for simulation research. The induction motor model dependencies are also used for analysis and presentation of the state estimators and control algorithms. The equations of transformations are given in Appendix C. The examples of data of the motors used in simulations and experiments are in Appendix D.

Chapter 4 contains selected output filter structures of the voltage inverter. The equivalent circuit of the output filter in the orthogonal frame is presented. The analysis of the obtained model makes it possible to conclude that only the sinusoidal filter has an influence on the motor control and variable estimation. Furthermore, this chapter contains a description of how to choose the filter elements for the complex filter structure, sinusoidal filter, common mode filter, and motor chokes. The examples of LC filter design are presented in Appendix B.

Chapter 5 demonstrates the problem of state variables estimation for drive systems with a sinusoidal filter. Several observers are presented, considering the installation of a sinusoidal filter. These include a state observer with a filter simulator, a speed observer in a less complicated version, an extended and full disturbance model, a speed observer in a rotating orthogonal frame, a speed observer based on a voltage model of the induction motor, and an adaptive speed observer. The presented systems make it possible to calculate the rotational motor speed, rotor and stator flux, and other required state variables of the control process. A supplement to chapter 5 is Appendix E in which the adaptive type backstepping observer [39] is presented.

Chapter 6 contains the control of an induction motor considering a sinusoidal filter. The problem is presented for the influence of the filter on an electric drive control operating in a closed loop without a speed sensor. Among the controls discussed, the following methods are included: classical field-orientated control, decoupled nonlinear field-orientated control, multiscalar nonlinear control, and nonlinear decoupled operation with load-angle control. Structures and dependencies are presented for further control methods, comparing the system operation for both situations, with and without consideration of the presence of the filter.

Chapter 7 presents a description of predictive motor current control for a drive system with a motor choke. To control the motor current, a controller was used in which the electromotive force of the motor was determined directly in the state observer dependencies.

Chapter 8 contains the diagnostic task of the chosen fault appearances in the drive system with an induction motor, voltage inverter, and motor choke. The fault diagnosis mainly concentrates on detection of failures in the mechanical torque transmission system and rotor bar faults. The diagnostic method in this chapter is based on the analysis of the calculated electromagnetic and load torques of the motor. Moreover, the chapter presents the fault diagnostic problem of a motor operating in a closed loop control structure, which is based on the analysis of chosen internal signals of the control system.

Chapter 9 presents a five-phase induction motor drive with an LC filter. The solutions presented in previous chapters for a three-phase system are adapted to a multiphase drive.

The last chapter, Chapter 10, contains a summary of the book.

1.4 Remarks on Simulation Examples

Generally, simulations of electric drives and power electronics converters could be done in universal simulation software with some standard models (e.g., MATLAB/Simulink, PSIM, TCAD, CASPOC, etc.) or in dedicated software written by researchers (e.g., in C or C++ language). Both solutions have advantages and disadvantages [40, 41]. The concept of simulation

in C language is attractive if one wants to keep good transfer of the models between different simulation software applications where all of them have the possibility of creating user-oriented blocks.

The simulation examples are an integral part of the book. The examples are prepared for a MATLAB/Simulink base without a requirement for any additional toolboxes. The principal part of each simulation is Simulink S-Functions for particular models written in C language. The complete C files of the simulation model are included in the book. With that approach, the examples used are not limited to MATLAB/Simulink. Because of the simple structure of the files and ANSI C standard, C files could be used in other simulation software that has the ability to define user blocks. The compilation of C files in MATLAB/Simulink requires the C compiler corresponding to the reader's particular version of MATLAB/Simulink. The book companion simulation examples were prepared in MATLAB/Simulink version 2014b and exported to previous version 2013a (files with the extension .slx) and simultaneously exported to version R2007b (files with the extension .mdl). The examples are described at the end of each chapter. The main structure and basic results are presented. The use of simulation examples requires basic knowledge of C language. With the knowledge given in the examples, it is possible to convert models to other simulation software. For each example, the particular results are presented.

The list of most used variables and functions is given in Appendix F.

References

- [1] Mirchevski S. Energy efficiency in electric drives. *Electronics Journal*. 2012; **16** (1): 46–49.
- [2] Siemens AG. Energy-efficient drives: Answers for industry. 2009. Germany. Available from: https://w3.siemens.com/mcms/water-industry/en/Documents/Energy-Efficient_Drives.pdf.
- [3] Bose BK. *Power electronics and motor drives—Advances and trends*. San Diego: Elsevier/Academic Press; 2006.
- [4] Abu-Rub H, Iqbal A, Guzinski J. *High performance control of AC drives with MATLAB/Simulink models*. Chichester, UK: John Wiley & Sons, Ltd; 2012.
- [5] Bose BK. Power electronics and motor drives recent progress and perspective. *IEEE Transactions on Industrial Electronics*. 2009; **56** (2): 581–588.
- [6] Kaźmierkowski MP, Krishnan R, Blaabjerg F. *Control in power electronics*. San Diego: Academic Press; 2002.
- [7] Krzeminski Z, Lewicki A, Wlas M. Properties of sensorless control systems based on multiscalar models of the induction motor. *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*. 2006; **25** (1): 195–206.
- [8] Rajashekara K, Kawamura A, Matsuse K. *Sensorless control of AC motor drives*. New York: IEEE Industrial Electronics Society, IEEE Press; 1996.
- [9] Orłowska-Kowalska T, Wojsznis P, Kowalski Cz. Comparative study of different flux estimators for sensorless induction motor drive. *Archives of Electrical Engineering*. 2000; **49** (1): 49–63.
- [10] Orłowska-Kowalska T, Wojsznis P, Kowalski Cz. Dynamical performances of sensorless induction motor drive with different flux and speed observers. Ninth European Conference on Power Electronics and Applications (EPE'2001). Graz, Austria. August 27–29, 2001.
- [11] Enlayson P. Output filters for PWM drives with induction motors. *IEEE Industry Applications Magazine*. 1998 (Jan/Feb); **4** (1): 46–52.
- [12] Guzinski J. Closed loop control of AC drive with LC filter. Thirteenth International Power Electronics and Motion Conference EPE-PEMC, 2008, Poznań, Poland. September 1–3, 2008.
- [13] Salomaki J, Hikkaniemi M, Luomi J. Sensorless control of induction motor drives equipped with inverter output filter. IEEE International Conference on Electric Machines and Drives, IEMDC'05, San Antonio, TX. May 15–18, 2005.
- [14] Hanigovszki N, Poulsen J, Blaabjerg F. Performance comparison of different output filter topologies for ASD. European Conference on Power Electronics and Applications, EPE'03, Toulouse, France. September 2–4, 2003.

- [15] Moreira A, Lipo T. Modeling and evolution of dv/dt filters for AC drivers with high switching speed. Ninth European Conference on Power Electronics and Applications, EPE'2001, Graz, Austria. August 27–29, 2001.
- [16] Muetze A, Binder A. High frequency stator ground currents of inverter-fed squirrel-cage induction motors up to 500 kW. Tenth European Conference on Power Electronics and Applications EPE'03, Toulouse, France. September 2–4, 2003.
- [17] Popescu M, Bitoleanu A. The influence of certain PWM methods on the quality of input energy of the asynchronous motor and frequency converters driving system. Tenth International Power Electronics and Motion Control Conference, EPE–PEMC 2002, Dubrovnik, Croatia. September 9–11, 2002.
- [18] Akagi H. New trends in active filters for power conditioning. *IEEE Transactions on Industry Applications*. 1996; **32** (6): 1312–1322.
- [19] Abu-Rub H, Guzinski J, Krzeminski Z, Toliyat HA. Speed observer system for advanced sensorless control of induction motor. *IEEE Transactions on Energy Conversion*. 2003; **18** (2): 219–224.
- [20] Abu-Rub H, Guzinski J, Toliyat HA. An advanced low-cost sensorless induction motor drive. *IEEE Transactions on Industry Applications*. 2003; **39** (6): 1757–1764.
- [21] Abu-Rub H, Oikonomou N. Sensorless observer system for induction motor control. Thirty-ninth IEEE Power Electronics Specialists Conference, PESC'08, Rodos, Greece. June 15–19, 2008.
- [22] Adamowicz M, Guzinski J. Control of sensorless electric drive with inverter output filter. Fourth International Symposium on Automatic Control AUTSYM 2005, Wismar, Germany. September 22–23, 2005.
- [23] Holtz J. Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification. *IEEE Transactions on Industry Applications*. 2002; **38** (4): 1087–1095.
- [24] Holtz J. Sensorless control of induction motor drive. *Proceedings of the IEEE*. 2002; **90** (8): 1358–1394.
- [25] Holtz J. Sensorless control of induction machines—with or without signal injection? *IEEE Transactions on Industrial Electronics*. 2006; **53** (1): 7–30.
- [26] Kubota H, Sato I, Tamura Y, Matsuse K, Ohta H, Hori Y. Regenerating-mode low-speed operation of sensorless induction motor drive with adaptive observer. *IEEE Transactions on Industry Applications*. 2002; **38** (4): 1081–1086.
- [27] Tsuji M, Chen S, Izumi K, Ohta T, Yamada E. A speed sensorless vector-controlled method for induction motor using q-axis flux. Second International Power Electronics and Motion Control Conference, IPESC'97, Hangzhou, China. November 3–6, 1997.
- [28] Seliga R, Koczara W. Multiloop feedback control strategy in sine-wave voltage inverter for an adjustable speed cage induction motor drive system. Tenth European Conference on Power Electronics and Applications, EPE'2001, Graz, Austria. August 27–29, 2001.
- [29] Seliga R, Koczara W. High quality sinusoidal voltage inverter for variable speed ac drive systems. Tenth International Power Electronics and Motion Control Conference, EPE–PEMC 2002, Dubrovnik, Croatia. September 9–11, 2002.
- [30] Guzinski J. *Selected problems of induction motor driver with inverter output filters. Monograph No. 115*. Gdansk, Poland: Gdansk University of Technology; 2011.
- [31] Akagi H. Prospects and expectations of power electronics in the 21st century. Power Conversion Conference, PCC'02, Osaka, Japan. April 2–5, 2002.
- [32] Akagi H, Hasegawa H, Doumoto T. Design and performance of a passive EMI filter for use with a voltage-source PWM inverter having sinusoidal output voltage and zero common-mode voltage. *IEEE Transactions on Power Electronics*. 2004; **19** (4): 1069–1076.
- [33] Busse DF, Erdman J, Kerkman R, Schlegel D, Skibinski G. The effects of PWM voltage source inverters on the mechanical performance of rolling bearings. Eleventh Annual Applied Power Electronics Conference, APEC'96, San Jose, CA. March 3–7, 1996.
- [34] Busse DF, Erdman JM, Kerkman RJ, Schlegel DW, Skibinski J. An evaluation of the electrostatic shielded induction motor: a solution for rotor shaft voltage buildup and bearing current. *IEEE Transactions on Industry Applications* 1997; **33** (6): 1563–1570.
- [35] Cacciato M, Consoli A, Scarcella G, Testa A. Reduction of common-mode currents in PWM inverter motor drives. *IEEE Transactions on Industry Applications*. 1999; **35** (2): 469–476.
- [36] Kikuchi M, Kubota H. A novel approach to eliminating common-mode voltages of PWM inverter with a small capacity auxiliary inverter. Thirteenth European Conference on Power Electronics and Applications EPE'09, Barcelona, Spain. September 8–10, 2009.
- [37] Muetze A, Binder A. Practical rules for assessment of inverter-induced bearing currents in inverter-fed ac motors up to 500 kW. *IEEE Transactions on Industrial Electronics*. 2007; **54** (3): 1614–1622.

- [38] Choi HS, Cho BH Power factor pre-regulator (PFP) with an improved zero-current-switching (ZCS) PWM switch cell. PCC'02, Osaka, Japan. April 2–5, 2002.
- [39] Morawiec M, Guzinski J. Sensorless control system of an induction machine with the Z-type backstepping observer. IEEE Twenty-third International Symposium on Industrial Electronics, ISIE 2014, Istanbul, Turkey. June 1–4, 2014.
- [40] Yusivar F, Wakao S. Minimum requirements of motor vector control modeling and simulation utilizing C MEX S-function in MATLAB/Simulink. Fourth IEEE International Conference on Power Electronics and Drive Systems, PEDS 2001, Indonesia. October 22–25, 2001.
- [41] Ji Y-H, Kim JG, Park SH, Kim J-H, Won C-Y. C-language based PV array simulation technique considering effects of partial shading. IEEE International Conference on Industrial Technology, ICIT 2009, Gippsland, Australia. February 10–13, 2009