FUNDAMENTALS OF ELECTRICAL DRIVE CONTROLS

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Keywords: Electrical drives, control, modeling, DC motor, permanent-magnet synchronous motor, cascade control, chopper, sensors, speed control, position control, pointing, tracking, friction, compliance, backlash, state control, nonlinear compensation.

Contents

Summary

Controlled electrical drives can be regarded as the most flexible and efficient source of controlled mechanical power. Understanding and developing the controlled electrical drive systems require a multi-disciplinary knowledge, starting from electrical machine theory, through electronic power converter technology to control system design techniques. This article gives a systematic overview of elements of a controlled electrical drive with emphasis on the control system design. The basic procedure of feedback and feedforward cascade control system design is presented for the separately-excited DC motor. It is then demonstrated that the basic principle of current/torque control can be applied to AC machines modeled in the rotational field coordinate frame, while the superimposed speed and position controller structure remains the same as with the DC motor. Finally, a notable attention is paid to analysis of transmission compliance, friction, and backlash effects, and their compensation by means of advanced control algorithms.

1. Introduction

Electrical drives represent a dominant source of mechanical power in various applications in production, material handling, and process industries. Applying the feedback control techniques to electrical drives substantially improves their performance in terms of achieving precise and fast motion control (servo-control) with a high efficiency. Traditionally, the controlled electrical drives were based on direct-current (DC) motors and analog controllers. However, the rapid development of power electronics and microprocessor technology in the last three decades has propelled application of servo-control to brush-less, alternating-current (AC) drives, and provided implementation of advanced motion control algorithms including compensation of transmission compliance, friction, and backlash effects. The overall control performance, efficiency, reliability, and availability of the controlled electrical drives have been substantially improved, thus accelerating their penetration into various engineering applications.

This article presents an overview of controlled electrical drive technology with emphasis on control system design. The presentation is based on the separately-excited DC motor, since control of this motor can be easily understood and readily extended to AC motors. First, the elements of a controlled electrical drive are described (Section 2), which include DC motor and its mathematical model, electronic power converters, sensors, and electronic control units including the basic control algorithms. Next, the steady-state form of DC motor model is used to describe the motor speed adjustment (or open-loop control) in the regions below and above the rated speed, as well as the controlled starting and regenerative braking of the motor (Section 3). This serves as a basis for presenting a cascade structure of motor feedback control, including optimal tuning of current, speed, and position controllers (Section 4). For tracking applications, the feedback system is extended by feedforward paths or a feedforward compensator, in order to reduce the dynamic tracking error (Section 5). Section 6 shows, on an example of permanent-magnet synchronous motor (PMSM), how the naturally decoupled armature and field control of DC motor can be applied to the coupled dynamics of three-phase AC motors. Finally, Section 7 analyzes influences of transmission insufficiencies related to compliance, friction and backlash effects on the static and dynamic behavior of a servodrive, and presents control algorithms for compensating these effects. The theoretical discussions are illustrated by a number of computer simulation results.

2. Elements of Controlled Electrical Drive

Figure 1 shows the structural block diagram of a controlled electrical drive. An electrical motor is coupled to a working mechanism in order to provide a transfer of mechanical power. The main additional features of controlled electrical drives compared to their conventional counterparts are: (i) the power transfer is made time variant/controllable using an electronic power converter , and (ii) the drive motion can be controlled in a precise manner based on the use of feedback paths containing sensors and electronic control unit.

The control tasks can be different, starting from current control (corresponding to open-loop torque/force control), through speed and position control, and towards force control. Normally, the controlled power flows from the electrical grid to the working mechanism. However, during transients or occasional continuous braking intervals, the motor switches to a generator mode and the power flows back to the grid. If the power converter does not support the regenerative braking feature (typically in low-power drives), the braking power is dissipated on a braking resistor.

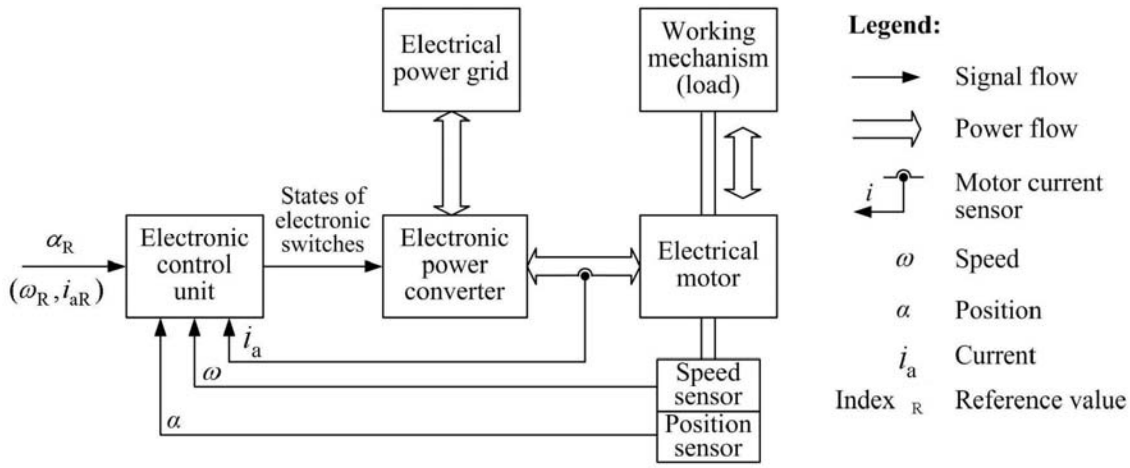

Figure 1. Structural block diagram of controlled electrical drive.

2.1. Separately-Excited DC Motor

Direct-current (DC) motor (see cross-section schematic in Fig. 2a) consists of a magnetic field flux (excitation) circuit (placed on the stator), armature circuit (placed on the rotor), and a commutator which inverts the current in an armature coil whenever it passes through the neutral zone that is perpendicular to the stator field axis. The power is transferred to the armature through brushes that are fixed in the neutral zone and leaned to the commutator.

The excitation and armature circuits can be connected separately from each other, or a series or parallel connection can be utilized instead. The separately-excited DC motors are mostly used in controlled drives, owing to the possibility of independent field and armature current control and related superior control features in a wide speed range.

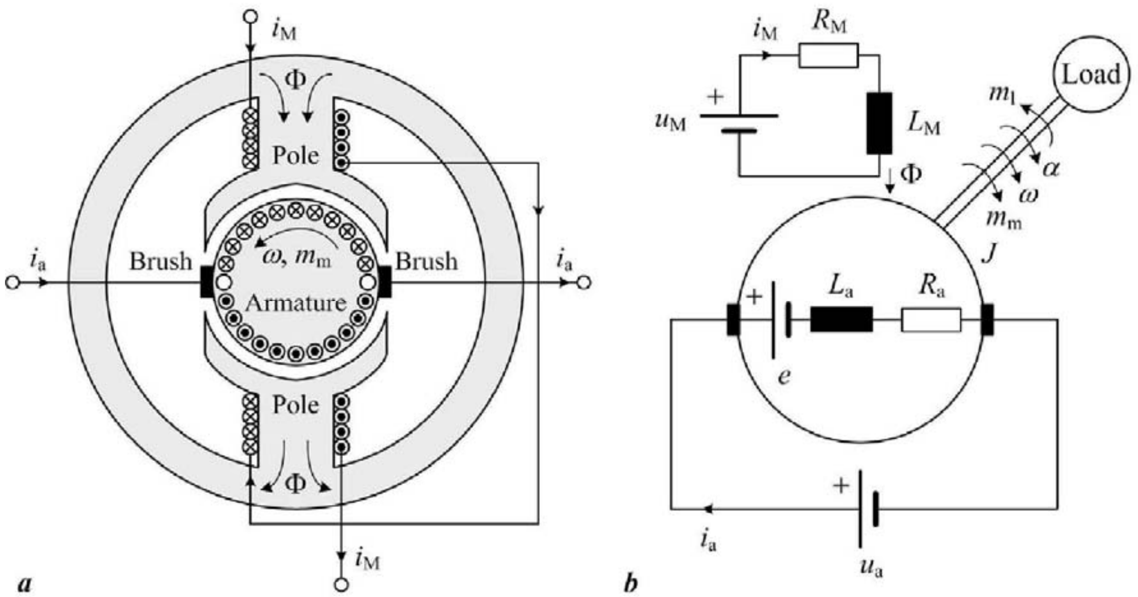

Figure 2. Simplified cross-section schematic (a) and equivalent scheme of separately-excited DC motor.

2.1.1. Dynamic Model

Figure 2b shows an equivalent scheme of the separately-excited DC motor. The stator magnetic flux Φ acts upon the armature current i_a, thus producing the motor torque. On the other hand, when the rotor rotates, the voltage e (back electromotive force, EMF) is induced in the armature winding. The motor dynamics are described by the following set of differential equations (see Nomenclature), given in both time (t) and Laplace (s) domain:

$$u_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e(t) \quad \Rightarrow \quad u_a(s) = R_a i_a(s) + L_a s i_a(s) + e(s) \tag{1a}$$

$$e(t) = K_e \Phi(t) \omega(t) \tag{1b}$$

$$J \frac{d\omega(t)}{dt} = m_m(t) - m_l(t) \quad \Rightarrow \quad Js\omega(s) = m_m(s) - m_l(s) \tag{1c}$$

$$m_m(t) = K_m \Phi(t) i_a(t) \tag{1d}$$

$$u_M(t) = R_M i_M(t) + N_M \frac{d\Phi(i_M(t))}{dt} \quad \Rightarrow \quad u_M(s) = R_M i_M(s) + N_M s\Phi(s) \tag{1e}$$

$$\frac{d\alpha(t)}{dt} = \omega(t) \quad \Rightarrow \quad s\alpha(s) = \omega(s) \tag{1f}$$

where $\Phi(i_M)$ is the nonlinear static magnetizing curve. The armature circuit, Eq. (1a), can be described by the following transfer function

$$\frac{i_a(s)}{u_a(s)-e(s)}=\frac{1}{L_a s+R_a}=\frac{K_a}{T_a s+1}, \tag{2}$$

where $K_a = 1/R_a$ and $T_a = L_a/R_a$ are the armature gain and armature time constant, respectively. Based on Eqs. (1) and (2), a block diagram of the motor model can be created, as shown in Figure 3a. In the basic case of constant excitation circuit voltage $(u_M = \text{const.} \Rightarrow \Phi = \text{const.})$ or permanent-magnet excitation, the block diagram reduces to the one shown in Figure 3b based on the following substitutions: $K_t = K_m\Phi$ and $K_v = K_e\Phi$.

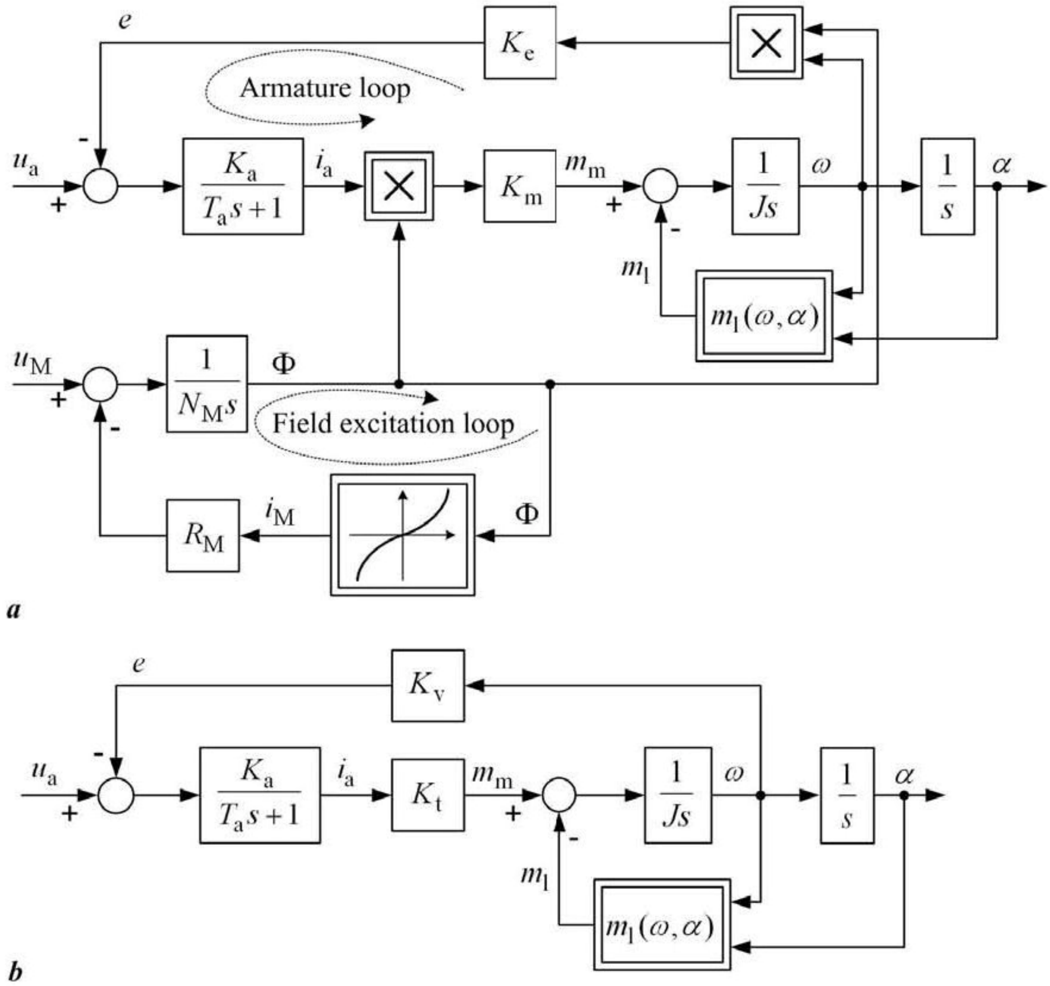

Figure 3. Block diagram of DC motor: (a) general case and (b) constant-flux case.

2.1.2. Steady-State Curve

Under the steady-state conditions, the time-derivatives of motor dynamic variables vanish (e.g. $di_a/dt = 0; s \equiv 0$). After rearranging the steady-state forms of motor equations (1), the following expression for the motor steady-state curve is obtained:

$$\omega = \underbrace{\frac{u_a}{K_e \Phi}}_{\omega_0} - \underbrace{\frac{R_a}{K_e K_m \Phi^2} m_m}_{\Delta\omega(m_m)} . \qquad (3)$$

The steady-state curve is shown in Figure 4. Since the armature resistance R_a is relatively small (particularly for high-power machines), the steady-state curve is rather stiff, i.e. the motor speed drop $\Delta\omega$ due to the increase of load $m_l = m_m$ is small compared with the idle speed ω_0. The drive operating point is determined as the cross-section point of the motor and load static curves (Fig. 4; note that $m_m = m_l$ is valid for the steady-state conditions according to Eq. (1c)). If the motor speed is lower than the idle speed: $\omega < \omega_0 \Rightarrow e < u_a \Rightarrow i_a > 0$, the motor operates in the driving mode (1st quadrant of the coordinate system in Fig. 4). Otherwise, for the case when $\omega > \omega_0$ ($e > u_a$ and $i_a < 0$), the machine operates in the generator braking mode, thereby producing the electric energy and transmitting it to the grid (2nd quadrant in Fig. 4). For the reverse motion ($\omega < 0$), the driving and braking modes relate to the 3rd and 4th quadrants, respectively (see also Section 3).

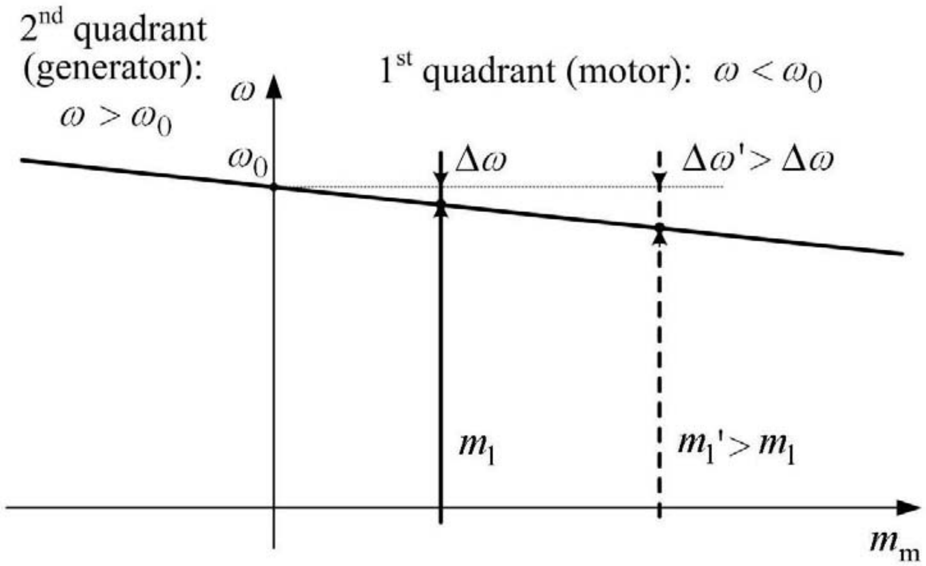

Figure 4. Steady-state curve of DC motor and construction of operating point.

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Biographical Sketches

Joško Deur (http://www.fsb.hr/acg/jdeur) received his B.Sc., M.Sc., and Ph.D. degrees in Electrical Engineering from the University of Zagreb, Croatia, in 1989, 1993, and 1999, respectively. He is an Associate Professor at the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb, where he teaches courses in electrical machines and drives, servodrive controls, digital control systems, and automotive mechatronics. The topic of his M.Sc. thesis was on vector control of permanent magnet synchronous motors, while the Ph.D. thesis dealt with compensation of compliance and friction effects in electrical servodrive transmissions. In 2000, he spent a year with Ford Research Laboratory in Dearborn, MI, working on different aspects of modeling and control of automotive power train systems. Prof. Deur has led about 20 projects supported by the Ministry of Science of the Republic of Croatia, the Ford Motor Company, the Jaguar Cars Ltd., and the CROSCO Integrated Drilling & Well Services Company. His main research interests include modeling, estimation, and control of automotive systems and servosystems. He has published about 20 journal papers and 70 conference papers. He received the Best Paper Award at the 19th IAVSD symposium in Milan, Italy, 2005, and the National Science Award in 2006.

Danijel Pavković received his B.Sc. and M.Sc. degrees in Electrical Engineering in 1998 and 2003, respectively, and his Ph.D. degree in Mechanical Engineering in 2007, all from the University of Zagreb, Croatia. He is an Assistant Professor at the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb, teaching subjects in the field of electrical machines, electrical servodrive controls, and digital control systems. He has participated on 13 research and technology projects supported by the Ministry of Science of the Republic of Croatia, the Ford Motor Company, and the CROSCO Integrated Drilling & Well Services Company. His research interests include estimation and control of electrical servodrive systems, including automotive applications. His research efforts were acknowledged by the National Science Award for young researchers in 2005.