Electrical Feed Drives for Machine Tools

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Preface

Due to the steadily increasing manufacturing and personnel costs, increasing productivity has recently become a stringent necessity. Electrical drives have considerably contributed to solving this problem in the area of the machine tool industry. They represent a cost-efficient engineering technique, which is economical even for use on feed units that were previously moved manually or with a central drive. Also, today's simple to operate, freely programmable numerical controls require independently controlled drives with a wide speed range.

Siemens has significantly contributed to this transition from mechanical and hydraulic systems to electrical ones, and has brought on the market highly dynamic converter-fed servo drives.

Due to their simple, robust construction, good dynamic properties, as well as their high durability, these drives are opened to a wide field of applications. The feed units of numerically controlled machine tools and tracing machines are positioned along programmed paths or with position control loops. The increasing automation puts ever stricter demands on these position control loops. The velocity and the accuracy of the feed movements can be significantly increased with the electrical drive.

For the further development of this engineering technique, Siemens AG sponsored special research studies centered on position control and feed drives at the University of Stuttgart, Institute of Control Theory for Machine Tools and Manufacturing Equipment. The theoretical technical basics for position control optimization have been worked out at this Institute, and procedures for practical measurements on applied position control loops have been developed. The long practical experience that Siemens has in this area was an important part of the project. The present volume summarizes the results of the scientific work at the University, and the practical experience of start-ups, design, development, and construction of these drives.

This book gives the basics necessary for the daily tasks and the procedures to be applied to make the right interpretations and decisions, for the staff in design and development offices, for sales and field engineers, and for service technicians.

Students of mechanical, electrical, and control engineering who would like to get aquainted with the area of feed drive technique, find here a comprehensive presentation of the different fields.

Erlangen/Stuttgart, April 1983

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Contents

1 Feed Drive and Position Control Loop 13
1.1 Basics of Control Theory 13
1.1.1 Open and Closed Loop Control 13
1.1.2 Stationary Systems Behavior 14
1.1.2.1 Characteristic Curves 14
1.1.2.2 Linearization 15
1.1.2.3 Normalized Values 16
1.1.2.4 Referenced Values 18
1.1.3 Dynamic Systems Behavior 18
1.1.3.1 Differential Equations 18
1.1.3.2 Transient Response 22
1.1.3.3 Frequency Response Curve 26
1.1.3.4 Bode Diagram 29
1.1.3.5 Linkage of Transfer Elements 32
1.1.3.6 Frequency Response Curve Symbol for Control Loops . . . 34
1.1.3.7 Experimental Determination of the Frequency Response Curve 35
1.2 Basics of the Position Control Loop 36
1.2.1 Construction and Functioning of the Position Control Loop 36
1.2.2 Localization 38
1.2.2.1 Measuring Value Detection 38
1.2.2.2 Measuring Procedures 39
1.2.2.3 Location of Measurement 39
1.2.3 Characteristic Values and Properties of Position Control Loops 40
1.2.3.1 Dynamic Systems Behavior of Single Control Loop Elements 41
1.2.3.2 Explanation of Terms 44
1.2.3.3 Behavior of Linear Position Control Loops 44
1.2.3.4 Non-linearities in the Position Control Loop 50
1.3 Position Loop Gain 52
1.3.1 Position Control Loop Model 52
1.3.2 Settling Time and Overshoot Width at Positioning 53
1.3.3 Ramp Distance for Thread Cutting 56
1.3.4 Contour Deviations on Corners 61
1.3.5 Contour Deviations on Circles 63
1.3.6 Disturbance Transient Response 66
1.3.7 Requirements for the Position Loop Gain 67
1.4 Bibliography 69

2 DC Motors for Feed Drives 70
2.1 Requirements for the Feed Drive 70
2.1.1 Requirements for Stationary Operation 70
2.1.2 Requirements for Non-stationary Operation 70

2.2 DC Shunt Motor 71
2.2.1 Construction Forms 71
2.2.1.1 Permanent Magnet-excited DC Servo Motors of the Series 1HU 71
2.2.1.2 Electrically Excited DC Servo Motors of the Series 1GS . . . 74
2.2.2 Drive Behavior 76
2.2.2.1 Differential Equation and Block Diagram 76
2.2.2.2 Stationary Behavior of the Uncontrolled Drive 80
2.2.2.3 Dynamic Behavior of the Uncontrolled Drive 82
2.2.2.4 Dynamic Behavior of the Speed-controlled Drive 84
2.2.2.5 Calculating the Drive Nominal Angular Frequency 86
2.2.2.6 External Inertia Effect 92
2.2.2.7 Dead Time Effect 94
2.3 Selection of DC Servo Motors 96
2.3.1 Methods of Calculation 96
2.3.2 Stationary Load 97
2.3.2.1 Friction and Losses 98
2.3.2.2 Machining Force 100
2.3.3 Dynamic Load 102
2.3.4 Heating Behavior 111
2.3.4.1 Periodic Load Changes 111
2.3.4.2 Overload Behavior 112
2.3.4.3 Thermal Time Constants 116
2.3.5 Additional Optimization Criteria 118
2.3.5.1 Energy Content of Moved Masses 118
2.3.5.2 Attainable Acceleration 119
2.3.5.3 Drive Comparisons 121
2.3.6 Calculation Scheme 123
2.3.7 Summary of Calculation Formulas 132
2.4 Bibliography 133

3 Current Converters for DC Servo Motors 134
3.1 Notions and General Overview 134
3.1.1 Requirements 134
3.1.2 Dead Time 136
3.1.3 Form Factor 137
3.1.4 Efficiency 139
3.1.5 Costs 140
3.2 Transistor DC Choppers 141
3.2.1 Applications 141
3.2.2 Principle of Operation 141
3.2.2.1 Driving, Clockwise, I. Quadrant 142
3.2.2.2 Driving, Counterclockwise, III. Quadrant 144
3.2.2.3 Braking, Clockwise, IV. Quadrant 144
3.2.2.4 Braking, Counterclockwise, II. Quadrant 145
3.2.3 DC Bus 145
3.3 Line Synchronized Thyristor Controllers 146

3.3.1 Generalities 146
3.3.2 Rectifier and Inverter Operation 147
3.3.3 Circulating Curent-free Connection 149
3.3.4 Circulating Current-conducting Connection 150
3.3.5 6-Pulse Circulating Current-conducting Cross Connection 151
3.3.6 3-Pulse Circulating Current-conducting Anti-parallel Connection 153
3.3.7 6-Pulse Circulating Current-free Anti-parallel Connection 157
3.3.8 2-Pulse Circulating Current-conducting Anti-parallel Connection 159
3.4 Controllers 163
3.4.1 Structure of the Control Loop 163
3.4.2 Overcurrent Limitation 164
3.4.3 Subordinated Current Control 165
3.4.4 Speed Control with Current Limit 166
3.4.5 Status Monitor 168
3.4.6 Adaptive Speed Control Influence 169
3.5 Selection Criteria 172
3.5.1 Characteristic Values of Converter Circuits 172
3.5.2 Applications for Converter Circuits 172
3.6 Bibliography 175

4 Design Versions of Mechanical Transmission Elements 177
4.1 Generalities 177
4.2 Requirements for the Mechanical Transmission System 178
4.2.1 Nominal Angular Frequency 180
4.2.2 Stiffness 184
4.2.3 Damping Gradient 185
4.2.4 Non-linearities 189
4.2.4.1 Reversing Errors 189
4.2.4.2 Friction 190
4.2.4.3 Effects of Reversing Errors and Frictional Reversing Errors 194
4.2.4.3.1 Indirect Position Control Measurement 195
4.2.4.3.2 Direct Position Control Measurement 198
4.2.5 Moment of Inertia 202
4.2.5.1 Cylindrical Bodies 202
4.2.5.2 Linearly Moved Masses 204
4.2.5.3 Gear Ratio 205
4.3 Calculating the Slide Elements of the Drive 205
4.3.1 Feed Screw Drives 205
4.3.1.1 Construction and Requirements 205
4.3.1.2 Feed Screw 208
4.3.1.2.1 Stiffness of the Feed Screw 209
4.3.1.2.2 Moment of Inertia of the Feed Screw 213
4.3.1.2.3 Efficiency 215
4.3.1.2.4 Feed Screw Lead 216
4.3.1.2.5 Lead Accuracy 216
4.3.1.2.6 Critical Speed 217

4.3.1.2.7 Buckling Strength . . . 218
4.3.1.3 Ball Screw Nut . . . 220
4.3.1.4 Feed Screw Bearings . . . 223
4.3.1.4.1 Stiffness and Preload . . . 224
4.3.1.4.2 Effect of the Bearing Mounting Elements . . . 226
4.3.1.4.3 Friction and Temperature Behavior . . . 227
4.3.2 Rack and Pinion Drives . . . 229
4.3.2.1 Range of Applications, Influencing Variables . . . 229
4.3.2.2 Stiffness . . . 230
4.3.2.2.1 Torsional Stiffness of Shafts . . . 230
4.3.2.2.2 Bending Strength of Shafts . . . 231
4.3.2.2.3 Radial Stiffness of Shaft Bearings . . . 231
4.3.2.2.4 Bending Strength of the Gear Wheel, Pinion, and Rack Teeth 233
4.3.2.2.5 Example . . . 233
4.3.2.3 Preload at the Pinion . . . 236
4.3.3 Machine Slide and Guides . . . 238
4.3.3.1 Machine Slide . . . 238
4.3.3.2 Table Guides . . . 239
4.3.3.2.1 Requirements . . . 239
4.3.3.2.2 Friction Guides . . . 240
4.3.3.2.3 Roller Guides . . . 241
4.3.3.2.4 Hydrostatic Guides . . . 243
4.3.3.2.5 Aerostatic Guides . . . 244
4.3.3.3 Damping . . . 245
4.4 Gears . . . 247
4.4.1 Overview of Applications . . . 247
4.4.2 Requirements . . . 251
4.4.2.1 Moment of Inertia . . . 251
4.4.2.2 Torsion and Bending . . . 253
4.4.2.3 Reversing Errors . . . 254
4.4.3 Toothed Belt Gear . . . 255
4.4.4 Advantage Limits of a Gear Ratio . . . 259
4.4.4.1 Motors of Equal Frame Size . . . 259
4.4.4.2 Motors of Different Frame Size . . . 261
4.4.4.3 Disturbance Transient Response . . . 264
4.4.4.4 Comparison of two Motors . . . 264
4.5 Couplings . . . 266
4.6 Bibliography . . . 268

5 Command Value Modification . . . 271
5.1 Purpose of the Command Value Modification . . . 271
5.2 Smoothing the Command Values . . . 271
5.3 Effects of Command Value Smoothing . . . 275
5.3.1 Stress and Contour Deviation Characteristics . . . 275
5.3.2 Contour Movements . . . 276
5.3.3 Diagrams for Contour Deviation and Stress Characteristics . . 279

5.4 Determining the Command Value for Acceleration 284
5.5 Conclusions 287
5.6 Bibliography 287

6 Measurements on Feed Drives 288
6.1 Substantiation, Aim 288
6.2 Measuring Procedures 289
6.2.1 Measurements on the Mechanical Transmission Elements . . 289
6.2.1.1 Reversing Error (Back Lash) 290
6.2.1.2 Total Stiffness, Nominal Angular Frequency 295
6.2.1.3 Friction Characteristics 296
6.2.2 Measurements on the Speed Control Loop 298
6.2.2.1 Step Response, Transient Response 299
6.2.2.2 Current Limit 301
6.2.2.3 Motor Heat 301
6.2.2.4 Nominal Angular Frequency of the Feed Drive 302
6.2.3 Measurements on the Position Control Loop 304
6.2.3.1 Contour Deviations 304
6.2.3.2 Measuring the Position Loop Gain 306
6.2.3.3 Measurements for the Smallest Position Increments 308
6.2.3.4 Positioning Response 309
6.3 Measuring Values of Machines in Use 310
6.3.1 Evaluation of Measured Frequency Response Curves 310
6.3.2 Measurements on a Timing Belt Gear 311
6.3.3 Effect of the Moment of Inertia 314
6.3.4 Motors in Short Version 314
6.3.5 Effects of Optimization of the Speed Control 316
6.3.6 Frequency Response Curve of a Shell Magnet Motor 316
6.3.7 Influence of the Converter Circuit 318
6.3.8 Frequency Response Curve of an Electrically Excited DC Servo Motor 320
6.3.9 Conclusions 321

7 Technical Data 322
7.1 DC Servo Motors 322
7.1.1 General Data 322
7.1.2 Design Series 1 HU 325
7.1.3 Design Series 1GS 3 331
7.2 Current Converter Units 334
7.2.1 Transistor DC Choppers 334
7.2.2 Line-synchronized Thyristor Controllers 336

8 Technical Appendix 339
8.1 Symbols and Units Used 339
8.2 SI Units 350
8.3 Conversion Tables 353
8.4 Equations 356
Index 358

Introduction

In order to understand the characteristics of feed drives in position control loops on machine tools, a basic knowledge of control theory is necessary. The control technical procedures useful in explaining these characteristics in context are presented in the first chapter of this book. They represent a rapid refresher course for the expert and give the interested reader fast access to the subject. A comprehensive bibliography is also listed.

In the further chapters, sophisticated mathematical computations are purposefully omitted in favor of the methods and presentations commonly used in practice. These are based on the *frequency response curve* with the nominal angular frequency of a transfer element. It is presented with the *Bode diagram*, which can be easily determined with simple measurements by means of a frequency generator and a recorder or a storage oscilloscope. The advantage of the frequency response curve method is that algebraic calculation procedures can still be used for complex transfer control systems without mastering infinitesimal calculation; only knowledge of time differentials and integrals is necessary.

The inclusion of the newest standards (DIN) allows on one hand, the establishment of a consistent terminology, and on the other hand, comparisons between different drive concepts. The basis for the units is the SI-system. Relationships are shown by dimensional equation, supplemented in some cases with adjusted dimensional equations. The conversion tables presented in the technical appendix allow the engineer to make simple conversion from the formerly used units into SI-units.

1 Feed Drive and Position Control Loop

1.1 Basics of Control Theory

1.1.1 Open and Closed Loop Control

Open loop control is to be understood as the effect of information on an energy or material flow.

Here, *informations* mean instructions or statements subject to storage, transmission, and processing.

The *signals* are the carriers of informations. The information is presented as the value or the value sequence of the signal parameter (DIN 44300), e.g. of the amplitude.

The *closed loop control* differs from the open loop control in that the control variable x is measured, and the adjustment of the energy flow is dependent upon the control deviation between command value w and control parameter x. The principle presentation of the control loop is shown in fig. 1.1. The most important terms can be derived from it (DIN 19221 and DIN 19226).

The closed action loop is characteristic of the closed loop control. Sections of the control loop, like the *control device* and the *control system*, respectively their subdivisions, are designated as *control loop elements*, and are represented by rectangular blocks. The representation of connections between blocks results in the *block diagram*. The *input values u*, respectively the input signals, act upon the single elements of the control loop. The signals derived from them for further processing, also known as *output variables v*, are determined by the dynamic systems behavior of the single elements (see DIN 19229).

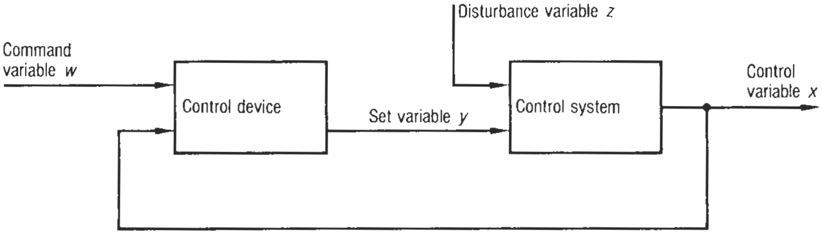


Fig. 1.1 Control loop elements

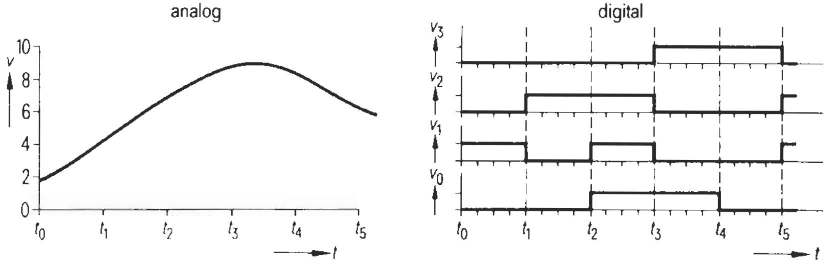


Fig. 1.2 Presentation of analog and digital signals

There is a distinction to be made here between static and dynamic systems behavior. The *static behavior* can be described, e.g. through characteristic curves. This marks the behavior in a stationary state, after all the transient responses have subsided. The *dynamic behavior* designates the time response of an element, and refers primarily to responses.

The flow of signals, respectively variables, is shown by means of lines with directional arrows. These lines represent the connections between individual blocks in a block diagram. The signals themselves can be either analog or digital. Examples are shown in fig. 1.2.

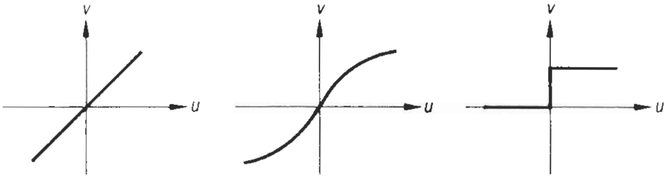
Analog signals can have steady or non-steady courses. An analog acting element or system is characterized by the fact that it reconstructs an analog output signal out of an analog input signal. No linear dependency is necessary between the two signals. Examples of analog systems are potentiometers with linear, logarithmic, cosine-, or sinusoidal characteristic curves.

Digital signals consist of characters, which can only assume discrete states. Examples of such characters are numbers. The *binary signal* belongs to this category; it is a signal with only two states. A digital acting system assigns digital output signals to corresponding digital input signals.

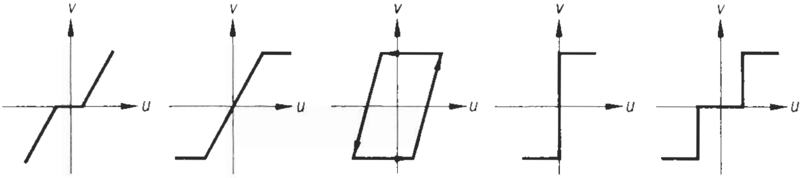
1.1.2 Stationary Systems Behavior

1.1.2.1 Characteristic Curves

The transfer elements of a system can be sorted according to their behavior in the stationary state. Fig. 1.3 shows stationary characteristic curves of transfer elements. If the relationship between the input and the output value of an element is a steady function, the total element is designated as steady; if the relationship is not steady, the total element is considered unsteady.



Linear, steady Non-linear steady Non-linear, non steady



Dead territory Limitation Hysteresis Two-point behavior Three-point behavior

Fig. 1.3 Stationary characteristic curves of transfer elements

A special case of the steady characteristic curve is the linear characteristic curve. For systems consisting of transfer elements with linear characteristic curves, there is an extensive theory which describes the transient response completely. The mathematical treatment of systems containing transfer elements with non-linear characteristic curves is very difficult, and is presented mostly with approximating procedures.

1.1.2.2 Linearization

The theory of linear systems can also be used in connection with non-linear systems with steady characteristic curve. The prerequisite for this is that the proposed work-range should be small, i.e. only small deviations from a fixed operating point would be allowed. The steady but non-linear characteristic curve will be replaced by the tangent, at the operating point; hereby the operating point-dependent gain as an operating point-dependent relation value between the input and the output value is derived. Fig. 1.4 shows as an example the determining of the operating point-dependent gain for a DC generator, and presents it graphically, together with the time behavior, in a block diagram.

The starting point for the determination of the gain is the excitation characteristic curve $U_G = U_G(U_E)$ for the DC generator (fig. 1.4a).

The individual steps are:

1. Establishing the *operating point* on the characteristic curve, with coordinates $U_{0\,G}$ and $U_{0\,E}$.
2. Introducing a new coordinates system whose zero point is located in the operating point, and which is valid only for the deviation in question. In the example, it is the coordinate system with axes ΔU_E and ΔU_G (fig. 1.4b).
3. Linearizing in the operating point, i.e. approximating the characteristic curve through the tangent. The slope of the tangent indicates the operating point-dependent gain

$$K=\frac{\Delta U_G}{\Delta U_E}=\frac{U_{0\,G}}{U_{HE}} \tag{1.1}$$

U_{HE} is an auxiliary variable determined by the intersection point of the tangent with the abscissa.

1.1.2.3 Normalized Values

To normalize, means to refer a value to a certain characteristical value of the same magnitude, in order to render that value dimensionless and thus obtain manageable numerical values. This procedure significantly simplifies the mathematical treatment of control technical problems. The generator voltage U_G, for instance, can be derived dependently on the speed n, at constant excitation, as $U_G=c_E\cdot n$ where c_E is the excitation constant, depending on the type of generator.

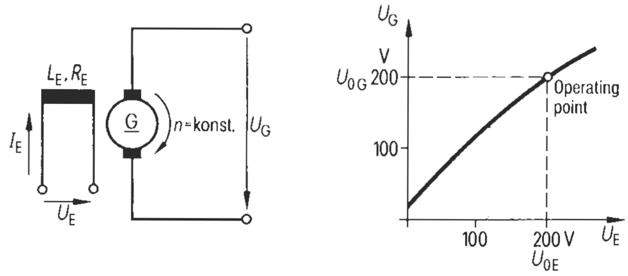
If the reference value selected for the speed n is the nominal speed n_0, and with $U_{0\,G}=c_E\cdot n_0$ for the normalized generator voltage dependent on the normalized speed, we will get

$$\frac{U_G}{U_{0\,G}}=\frac{n}{n_0} \tag{1.2}$$

The machine-specific constant c_E is thus eliminated.

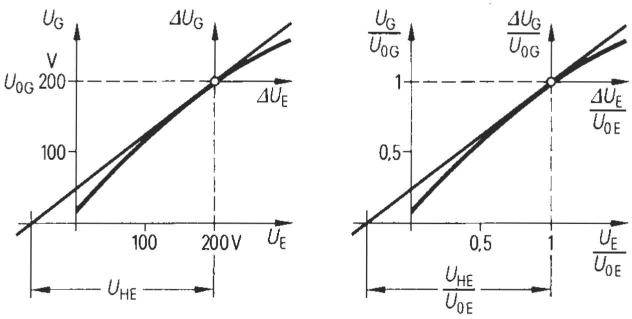
The normalization can also be used for systems which are linearized. One example of this might be the DC generator with its corresponding non-linear characteristic curve, presented in fig. 1.4. In order to normalize the operating point-dependent gain, the auxiliary coordinates ΔU_E and ΔU_G as well as the original coordinates U_G and U_E must be normalized. The reference values are the rated voltages $U_{0\,E}$ and $U_{0\,G}$ of the operating point. Thus, one obtains the normalized auxiliary coordinate system with the axes $\frac{\Delta U_E}{U_{0\,E}}$ and $\frac{\Delta U_G}{U_{0\,G}}$. From the original coordinate system one obtains the normalized coordinate system with the normalized coordinate axes $\frac{U_E}{U_{0\,E}}$ and $\frac{U_G}{U_{0\,G}}$ (fig. 1.4c). The normalized gain at the operating point, derived, is:

$$K_N=\frac{\Delta U_G/U_{0\,G}}{\Delta U_E/U_{0\,E}}=K\frac{U_{0\,E}}{U_{0\,G}} \tag{1.3}$$



Physical equivalent diagram

a
Excitation curve



b
Linearization

c
Normalization

Block diagram

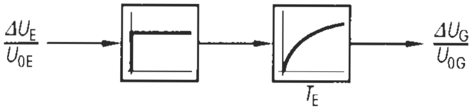


Fig. 1.4
Linearization and normalization in reference to the DC generator example

1.1.2.4 Referenced Values

Referenced values are quotients of values of different types belonging to tangible matter or bodies (DIN 5490). Examples are the referenced corner deviation $\frac{60 \cdot e_{\max F}}{v_B/\omega_{0\,A}}$ and the referenced position loop gain $K_v/\omega_{0\,A}$ (see fig. 1.32). The referenced values are used in diagrams, to reduce the number of parameters.

1.1.3 Dynamic Systems Behavior

The time behavior of a system shows the way the output signal follows a variable input signal over time. The time behavior can be deduced by different methods:

- ▷ as described by differential equations
- ▷ as described by the transient response
- ▷ as described by the frequency response curve equations, respectively their graphic presentation, e.g. in the Bode diagram or Nyquist plots.

1.1.3.1 Differential Equations

Differential equations are the mathematical models of physical transfer elements and systems. With given input values and boundries, the corresponding output values can be calculated with their help, by solving the differential equation or the system of differential equations involved.

The first column of fig. 1.5 shows the differential equations of the so-called basic transfer elements.

Along with the differential equations, this figure also shows the further description possibilities given by the transient response (see section 1.1.3.2) and the frequency response curve $F(j\omega)$ (see section 1.1.3.3).

Examples for the basic transfer elements described in fig. 1.5.

Electrical Proportional Element

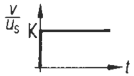
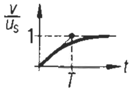
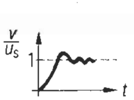
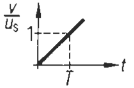
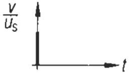
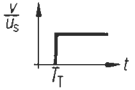
Ideal amplifier with resistor circuit (see fig. 1.6).

The output voltage is

$$U_2 = -\frac{R_2}{R_1} U_1 = -K \cdot U_1 \tag{1.4}$$

with the gain

$$K = \frac{R_2}{R_1} \tag{1.5}$$

Type of behavior	Differential equation	Transient response for the step function as an input value		Freq. response curve equation $F(j\omega)$	Type of element
	System equation	Solution equation	Graph		
Proportional	$v = K \cdot u$	$v = K \cdot u_s$		K	P-element
Proportional with 1st order delay	$T\frac{dv}{dt} + v = u$	$v = u_s(1 - e^{-\frac{t}{T}})$		$\frac{1}{1 + j\omega T}$	PT_1-element
Proportional with 2nd order delay	$T^2\frac{d^2v}{dt^2} + 2DT\frac{dv}{dt} + v = u$ $D < 1$	$v = u_s\left\{1 - e^{-D\frac{t}{T}}\left[\cos\left(\frac{t}{T}\sqrt{1-D^2}\right) + \frac{D}{\sqrt{1-D^2}}\sin\left(\frac{t}{T}\sqrt{1-D^2}\right)\right]\right\}$		$\frac{1}{1 + j\omega 2DT + (j\omega)^2 T^2}$	PT_2-element
Integral	$T\frac{dv}{dt} = u$	$v = \frac{t}{T} \cdot u_s$		$\frac{1}{j\omega T}$	I-element
Differential	$v = T\frac{du}{dt}$	$v = T\frac{du_s}{dt}$		$j\omega T$	D-element
Dead time	$v = u(t - T_T)$	$v = u_s(t - T_T)$		$e^{-j\omega T_T}$	Dead time element

v = output value u = input value u_s = input step

Fig. 1.5 Summary of the basic transfer elements

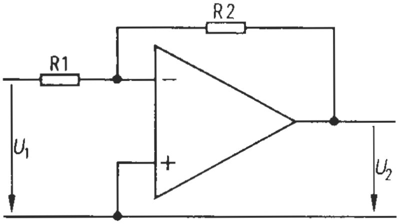


Fig. 1.6
Ideal amplifier with resistor network in input and feedback

At a stepwise change in the input voltage U_1, the output voltage U_2 also executes a stepwise change.

Electrical Proportional Element with 1st Order Delay

The DC generator of fig. 1.4, with an operating point-dependent gain $K=\frac{U_{0\mathrm{G}}}{U_{\mathrm{HE}}}$ and excitation time constant $T_{\mathrm{E}}=\frac{L_{\mathrm{E}}}{R_{\mathrm{E}}}$. Following applies:

$$\Delta U_{\mathrm{G}}=K\cdot\Delta U_{\mathrm{E}}(1-\mathrm{e}^{-\frac{t}{T_{\mathrm{E}}}}) \tag{1.6}$$

At a step change in the excitation voltage U_{E} by ΔU_{E}, the output voltage follows according to an exponential function to the value $U_{\mathrm{G}}+\Delta U_{\mathrm{G}}$ (see fig. 1.10).

Mechanical Proportional Element with 2nd Order Delay

Spring-mass system on a feed drive, according to fig. 1.7.

For an impulse-type deflection due to force F, the slide position shows a transient response.

As shown in section 1.1.3.4 for the 2nd order delay, and in section 4.2 for the mechanical transmission elements, the transient response of this transfer element is characterized by

the nominal angular frequency $\omega_0=\frac{1}{T}=\sqrt{\frac{k}{m}}$

and the damping gradient $D=\frac{1}{2}c_{\mathrm{v}}\sqrt{\frac{1}{k\cdot m}}$

k spring constant
m mass
c_{v} damping coefficient

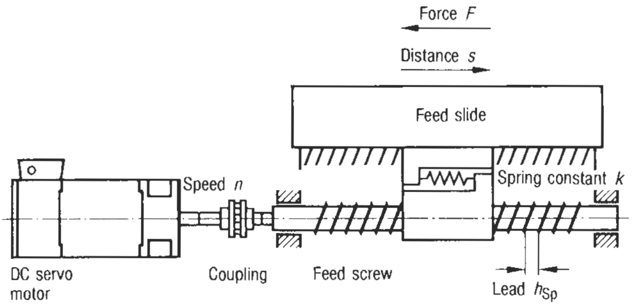


Fig. 1.7 Feed unit

Mechanical Integral Element

The transformation of a feed screw speed n, into the slide movement s, on a feed unit (see fig. 1.7).

The output value for the slide movement s is

$$s = h_{Sp} \cdot \int n \cdot \mathrm{d}t \tag{1.7}$$

At constant input value, feed screw speed n, the distance is

$$s = s_0 + h_{Sp} \cdot n \cdot t \tag{1.7.1}$$

i.e. the slide movement increases linearly from the start value s_0, over time t.

Electrical Differential Element

Approximation: the charging current i_C of a capacitor with capacitance C dependent on the voltage U_C.

$$i_C = C \cdot \frac{\mathrm{d}U_C}{\mathrm{d}t} \tag{1.8}$$

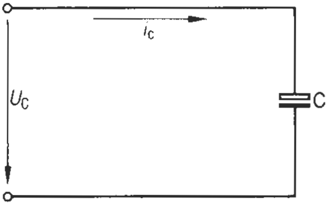


Fig. 1.8
Ideal capacitor on DC voltage

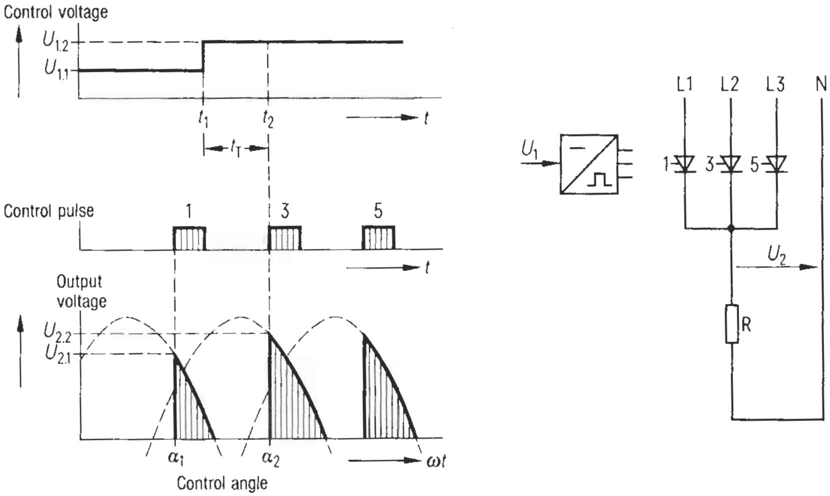


Fig. 1.9 Thyristor control of a 3-pulse current converter circuit

At a stepwise voltage change, charging current i_C for an ideal capacitor is theoretically infinite. In practice, it results in an impulse of limited amplitude and exponentially declining edge.

Electrical Dead Time Element

Approximation: a current converter with line synchronized gate control.

A control pulse on the thyristor can result in current flow only when the voltage is positive relative to the direction of conduction. For instance, according to fig. 1.9, if a control voltage change from $U_{1.1}$ to $U_{1.2}$ occurs at time t_1, the output voltage U_2 will change only at time t_2. The control angle shift from α_1 to α_2 becomes effective only with the control of the following thyristor 3. The dead time is $t_T = t_2 - t_1$. (For dead times of current converter circuits, see table 2.3 on page 95.) The following proportionally applies for the course of the output voltage over time:

$$U_2(t) \sim U_1(t + t_T) \tag{1.9}$$

1.1.3.2 Transient Response

The *transient response* indicates the evolution over time of the output value of a system, in response to random over time changes in the input value. It is a specific solution to the differential equation, used to describe the system.