Preface

Knowing is not enough; we must apply. Willing is not enough; we must do.
Johann Wolfgang von Goethe in *Wilhelm Meister's Journeyman Years*.

This book took shape while working as Head of Electronics Development at Dr. Fritz Faulhaber GmbH & Co KG in Schönaich, at the suggestion of Dr. Bertolini, Managing Director. Both the drive controllers and the position controllers suitable for the miniature drives are developed there and combined to form systems for customers worldwide. The topic of Electromagnetic Compatibility (EMC) is usually discussed at the point when customers want to certify their products for market access.

When working with controlled electrical drives, it is essential to keep an eye on the EMC of various components. Ultimately in the 1920s, it was precisely the conflict between the emerging telecommunications and the already established electrical drive technology in urban transport that led to the development of the concept of EMC.

Today, electrical drives are controlled in many application areas, so in addition to the energy conversion and their switching operations, they also contain the telecommunications necessary for the sensors. Due to the interference emissions of the energy conversion process, it must be ensured that the sensors are therefore designed with the necessary interference immunity.

In the controlled electrical drive, power electronics, micro-controllers and sensors come together in a very small space. In miniature drives, marketable compromises must be found in tight spaces.

Due to these requirements, electromagnetic compatibility EMC is a constant challenge for the development of any electronics used in professional environments. Probably every electronics developer becomes painfully aware of this at one point or another, projects can fail due a lack of (or no) attention being given to EMC.

This makes it is all the more surprising that there is little introductory overview literature available on the subject. However, there are plenty of instructions for the correct design and installation in the form of assembly instructions, especially from drive manufacturers.

In this book, the knowledge from 30 years of professional practice is set out and arranged within a comprehensible structure. First, there is a brief overview of the development of the EMC topic and the current general boundary conditions for bringing electric drives onto the market.

After this, the effects, coupling paths and test methods for both the emitted interference and the interference immunity are presented. The sources of the different disturbances originating from a motor controller are named and linked to their effects. On this basis, the common EMC measures are then discussed step by step, and their effectiveness verified by means of the measurement result.

This information can help to ensure that the basic measures necessary for motor controllers for miniature drives are already taken into account at the development stage. However, users of electric miniature drives will also find crucial information to be able to set up their final application with a controlled small drive as an EMC-compatible component.

A team is needed for such a book project. I would like to thank all those who helped to make this book a reality. In addition to Dr. Bertolini, who repeatedly initiated the idea, Florian Jacobs and Thomas Scholl from electronics development must also be mentioned in particular. Mr. Jacobs took the main load of the setups and measurements, Mr. Scholl contributed to basic considerations for the interference immunity of the sensors, Mr. von der Pahlen evaluated the DC motors.

I would also like to thank the Vogel Communications Group for their professional implementation and especially Ms. Klein for her critical review.

Schönaich **Andreas Wagener**

Contents

1 Introduction: Electric miniature drives in everyday use

Electric miniature drives are now present in a wide range of applications. In addition to classic mains-operated kitchen appliances, a wide variety of battery-operated devices with built-in electric motors are used in a domestic setting, from robotic vacuum cleaners through motor-operated heating valves to milk frothers. Electric miniature drives are somewhat less visible in daily use in optical devices, in laboratory automation or in special machinery construction. Depending on the performance class, different motors and electronics are used [1].

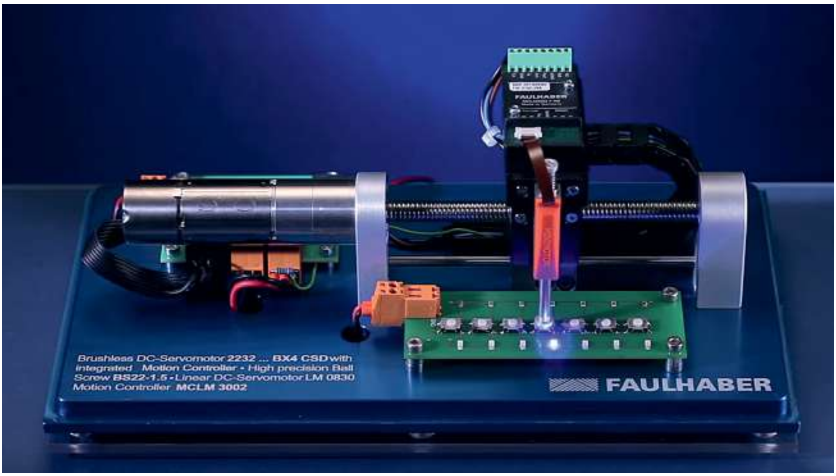

Fig. 1.1 FAULHABER demonstrator of a Pick & Place system with a compact linear unit and BLDC linear motor

Battery-operated devices typically use simple DC motors. The control ranges from simple switches to fully electronic positioning control, the operating voltage is usually below 30 V due to battery operation.

A similar development can also be observed with electric motors with an external power supply and outside the consumer sector. Compact actuators, some with directly integrated control electronics, have a wide range of applications in technology and industry. An example is shown in Fig. 1.1.

DC motors with and without control electronics are also used here. However, electronically commutated BLDC motors are now often used, especially for dynamic positioning tasks. Servo drives with outputs of up to several 100 W are typically operated on a low-voltage DC supply, i.e. with a maximum of 70 V DC.

In automation technology, several components can be operated on a common low-voltage supply, which then forms a DC network application with typical rated output voltages of either 24 V DC or – for higher power requirements – 48 V DC.

In addition to the motor, a control electronics, a position sensor and other filters are installed. Pure DC motors are sometimes also operated directly via the power supply without regulation.

2 Challenge of EMC

In systems with electric miniature drives in some cases the electrical energy is transformed multiple times. Alternating voltages and currents with very different frequencies will be observed. The possible sources of interference that may occur are explained in section 2.1. Fig. 2.1 shows the overall structure of a controlled drive system including the supply network. The faults referred to in section 2.1 which are attributable to this structure are shown by the reference numbers.

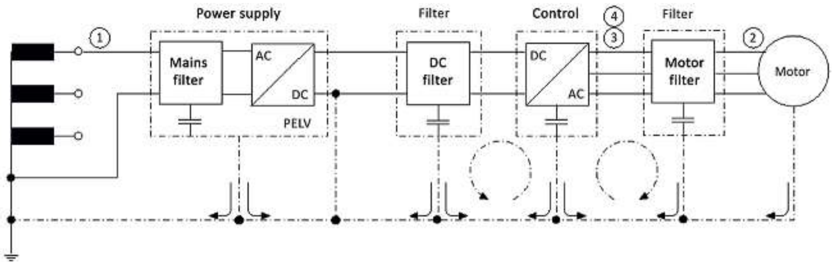

Fig. 2.1 Block diagram of a controlled motor and the interference paths, explanation of the numbering in the text

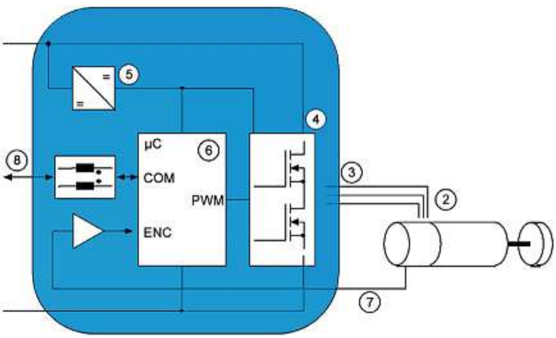

Fig. 2.2
Block diagram of a controlled drive with the identified interference sources, explanation of the numbering in the text

Fig. 2.2 shows the sources of interference in the drive controller itself, where you will find the other reference numbers for section 2.1.

2.1 Interference sources in electric drives

In Fig. 2.1 and 2.2, the sources of interference are marked with reference numbers, more detailed explanations follow here.

① Mains voltage
Sinusoidal voltages with 50 Hz to 60 Hz or higher in special networks

② Motor currents
For BLDC motors with sinusoidal control, the fundamental components of the motor currents are up to 1 kHz for a 4-pole motor at 30,000 min^{-1}. Depending on the design of the control unit, high-energy harmonics also occur up to the 100 kHz range. In the case of DC motors and BLDC motors with block commutation, a pulsating motor current with a commutation frequency is also obtained, which is a multiple of the motor speed. For DC motors, the commutation frequency depends on the division of the collector, for BLDC motors, on the number of pole pairs of the motor.

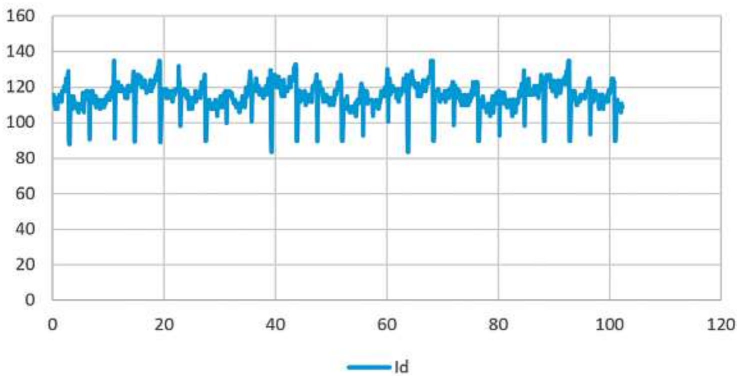

Fig. 2.3 Supply current I_d of a BLDC motor

For DC motors, mechanical commutation causes sparks on the commutator. The frequency spectrum of these motors is very wide and extends significantly into the MHz range. A typical supply current of a BLDC motor with block commutation is shown in Fig. 2.3. A DC motor would have a comparable profile, but with an odd division.

③ Switched output power stage

The motor voltage is generated from the DC supply via a power stage operated with pulse width modulation (PWM). The switching frequency of the PWM must be selected to be comparatively high for motors with non-ferrous windings, since their electrical time constants of approx. 50 µs to 200 µs are at least one order of magnitude lower than those of conventional ferrous windings. Typical PWM frequencies here are 50 kHz to 100 kHz to avoid producing unnecessary PWM-related losses in the motors. The relevant harmonics extend to the lower MHz range and decrease with 20 dB per decade of frequency.

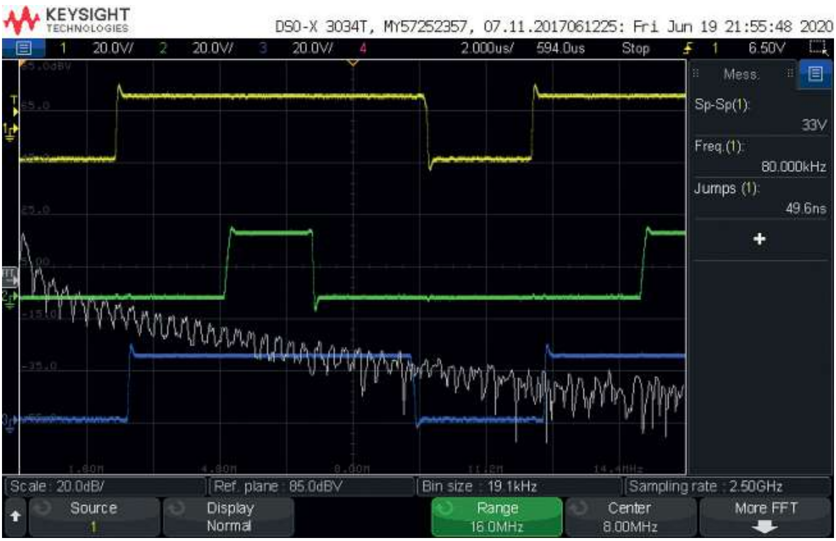

Fig. 2.4 Output voltage U_A ... U_C of a drive controller at 80 kHz switching frequency and FFT of the output signal over a frequency range of 16 MHz, attenuation scale 20 dB/division.

④ Switching operations in the power stage
Capacitive loads are transferred at each switching edge of the power stages. On the one hand, these are the gate charges of the MOSFETs, on the other hand, their parasitic drain source capacitors as well as the capacitive cable behavior of the motor cables. Very high peak currents can flow for a short time at the switching point. On output power stages based on Si-MOSFETs, the switching processes are completed after 5 ns to 50 ns. The high-energy components of these signals therefore extend into the 100 MHz range. The motor voltage is generated from the DC supply via an power stage operated with pulse width modulation (PWM)

In Fig. 2.4, the output voltages have a peak-to-peak value of 33 V, with a 24 V supply. The difference results from the transient oscillations at the switching edge. In Fig. 2.5 the transient oscillations mentioned in the phases can be seen easily.

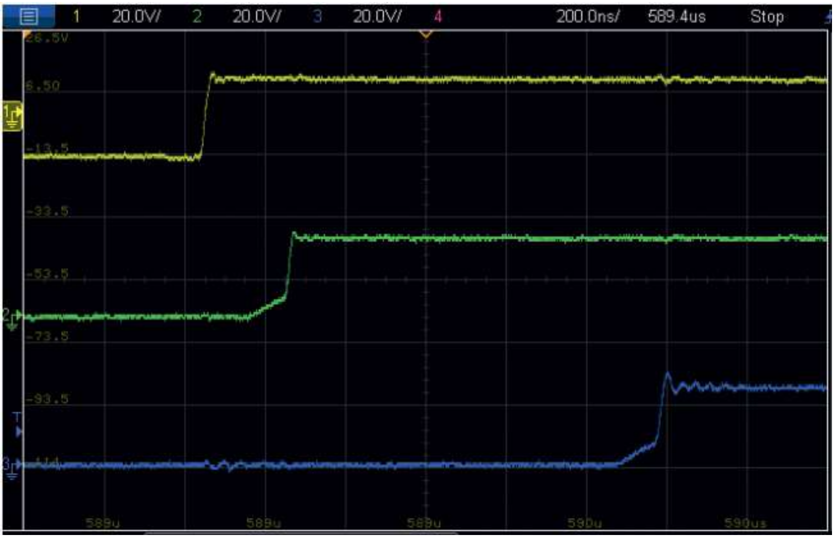

Fig. 2.5 Rising edges in the three phases of a drive controller with detectable transient oscillations in the 40 MHz range

⑤ Frequency of the internal DC/DC converters
The internal DC/DC converters of the control electronics are operated with switching frequencies between several 100 kHz and approx. 2 MHz. Here, too, the high-energy harmonics extend into the MHz range.

⑥ Processor clock speeds
Drive controllers for electric miniature drives are typically implemented using micro-controllers with an integrated flash memory for the program. Their clock frequencies range from 16 MHz to 200 MHz, due to the limited flash speed.

⑦ Frequency of position sensors
Position encoder systems with an incremental or absolute interface have signal frequencies in the range of approx. 500 kHz to approx. 5 MHz.

Hall signals, which are used for commutation of BLDC motors, are again exactly at the fundamental frequencies of the commutated motor currents. Due to the rectangular shape with steep edges, however, as with the PWM, high-energy harmonics occur here.

⑧ Clock frequencies of communication cables
The control electronics can be connected to a superordinate system via a communication cable. The resulting signal frequencies are between 10 kHz (RS232) and 100 MHz (Ethernet).

2.2 Summary of the frequency components

Fig. 2.6 summarizes the most important interference signals, their frequency ranges and a qualitative assessment of the interference power.

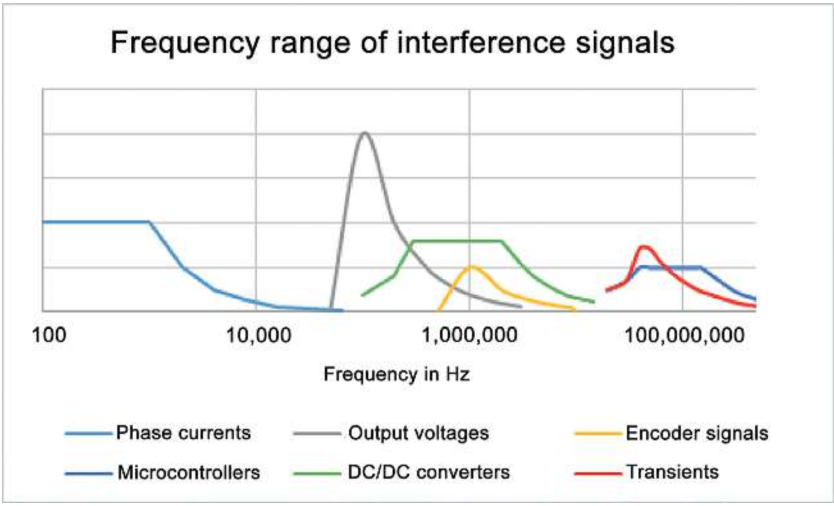

Fig. 2.6 Frequency ranges of the interference signals with qualitative interference power added

2.3 From radio interference suppression to EMC

All electric and magnetic alternating variables are coupled with corresponding alternating fields via Maxwell's equations. The law of induction and Ampère's law are the key elements here.

Ampère's law	$\operatorname{rot} \vec{B} = \mu_0 \left[\vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \right]$
Law of induction (integral form)	$\oint_{\partial A} \vec{E} \cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{A}$

Ampère's law specifies how currents $\vec{J}$ are surrounded by magnetic fields $\vec{B}$: The field strength is proportional to the current, the amplitudes are proportional to each other. In particular, alternating currents are surrounded by alternating fields of the same frequency.

The law of induction describes how magnetic alternating fields $\frac{\partial \vec{B}}{\partial t}$ induce voltages $U = \int_{\partial A} \vec{E} \cdot d\vec{s}$ in conductor loops: The level of the induced voltage is proportional to the area of the conductor loop and to the rate of change of the magnetic field [3].

In distributed structures, the fields of different signals are interconnected and influence or interfere with each other.

The interference caused by the use of energy were first noticed in the 1920s when the emerging radio networks were disturbed by electric trams [4]. In 1934, an international special committee was set up in the form of the CISPR (*Comité international spécial des perturbations radioélectriques*, International Special Committee on Radio interference), with the aim of developing internationally harmonized measuring methods and limit values, initially only for radio interference from devices.

Even though electric motors themselves were initially rather a source of interference, the increasing spread of microelectronic controls also meant that the interference affecting the electric drives had to be taken into account. This also meant that more attention had to be paid to the mutual influence of devices on each other. Instead of solely focusing on radio interference suppression, the electromagnetic compatibility of the devices is now considered. It is therefore no longer just about electric drives as a source of interference in the radio frequency range, but also about their own interference immunity.

EMC now looks at a variety of phenomena including the effects on the supply networks. The observed frequency range theoretically extends from 0 Hz to 400 GHz. The CISPR, now under the auspices of the IEC (International Electrotechnical Commission), continues to work on radio interference, in the case of IEC, directly on interference immunity. Their working results are published as an IEC standard.

The different ways of dealing with EMC can be easily traced to products from the respective periods. In in Tab. 2.1, the troubleshooting of a miniature drive in a model railway is used as an example.

	**Universal motor of a model railway locomotive, circa 1960** There are no interference suppression elements visible on the brush terminals. The locomotive itself does not contain any electronics, the direction control is achieved via a relay, the speed control via a control transformer.
	**Universal motor of a model railway locomotive, early 1980s** Interference suppression capacitors are installed at the brush connections. The motor supply cable is also filtered via a ferrite reactor. The original still contained no electronics.
	**Universal motor of a model railway locomotive, 2015** A capacitor is installed between the brushes. Both supply cables are protected against the electronics with one inductance each. The motor control is now completely electronic.

Tab. 2.1 Comparison of the suppression measures on different generations of a miniature drive application (model railway locomotive)