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Electric Traction –
Motive Power and Energy Supply

Basics and Practical Experience | 2nd edition

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Elektrische
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im Verkehrswesen

Preface

Intention of this book and synopsis

This book has evolved from the lecture series "Elektrische Bahnen" ("Electric Railways") which has been held at Ruhr-Universität Bochum since 1996. Its primary audience are students of electrical energy technologies, control engineering and mechanical engineering as well as young engineers of electrical engineering, especially in the fields of power electronics, in railway industry and in railway-operating companies.

The book intends to convey mechanical fundamentals of electric railway propulsion, which includes rail-bound guidance, transmission of traction effort from wheel to rail under the influence of non-constant levels of adhesion and the transmission of motor torque to a spring-mounted and thus swaying drive wheelset.

The focal point of the book will be the disposition of electric traction units powered by three-phase induction motors. We shall discuss the stationary and dynamical behaviour of the squirrel-cage induction motors and the principle and construction features of pulse-controlled inverters, as well as scalar and field-oriented control systems and four-quadrant power converters, feeding the DC link of the inverters.

As is appropriate to the lesser importance these drive systems have nowadays, we will consider DC and AC commutator motors only in a cursory fashion, as well as their voltage control. By example, we will take a look at high-performance locomotives, high-speed trains, diesel-electrically powered locomotives and commuter passenger systems.

Since the specific railway energy supply network being either separate from or connected to the national power utility is a key factor in operating electric railway systems, chapter 13 will offer a detailed look at the various systems of railway power supply, under special consideration of converter technology in this field as, for example, the line interference of inverter-fed traction units (see chapter 14). Chapter 15 features an abridged overview of the most important systems of field-oriented control of induction motors and of an innovative speed-sensorless control approach for induction motor drives, having come into the commercial phase. Chapter 16 suggests further reading, while chapter 17 will provide lecture-oriented exercises (including sample solutions).

The Anglo-American reader may notice that the lion´s share of examples has been derived from central European (German, Swiss, Austrian and French) samples of Electric Traction. This is mainly due to the author´s personal experience as well as the fact that most fundamental research, design and construction of locomotives utilising power electronics took place in these countries, notably with ALSTOM, BBC/ABB/Bombardier and Siemens. We wish to apologise that British, American or Japanese locomotives or motor coaches only feature rarely; however, an approach based on personal experience appeared to be the most sensible way to tackle the subject.

The translation follows the International Electrotechnical vocabulary (IEV) of IEC [1] and the UIC Railway Dictionary [2]. The reader may excuse the use of German symbol standards in formulae and diagrams, since the vast number of variables involved would make a complete exchange a daunting task.

Basic knowledge

This book requires the following:

Basic knowledge of construction and operative behaviour of electric machines and transformers according e.g. to lecture "Basics of Electrical Power Engineering" [L1], basic knowledge of power electronics [L2] or textbooks as [3] [4] [5], basic knowledge of mechanics.

Preface to 2nd Edition

Following constant interest from practitioners' circles, now, six years after the initial publication of this book, the need has arisen to produce a 2nd, revised and extended edition under the same title. This enables both author and publishing house to include major developments which, by now, have become accepted practice in traction and railway industry.

In particular, these developments include the permanent-magnet synchronous motor technology as well as the inverter-fed medium-frequency transformer, which is aimed to replace the main transformer, proving too heavy for $16^2/_3$-Hz traction frequency. Furthermore, new dual-power and hybrid vehicles as well as the new Modular Multilevel Converter topology for $16^2/_3$-Hz traction power supply will be covered.

Words of thanks

Every industrial engineer stands on the shoulders of the colleagues before him. So I want to express my gratitude first to my father Karl Steimel, 1956−1967 head of R&D of AEG in Frankfurt/Germany, one of the indefatigable initiators of development in inverter-fed induction motors drives, and my academic teacher, R. Jötten at TU Darmstadt, departed 1990 and 2000, respectively. Then – only to mention very few – my elder colleagues at Brown, Boveri & Cie. in power electronics as L. Abraham (†), E. Futterlieb, W. Lienau (†), H. Stemmler and W. Runge, as well as in locomotive engineering W. Teich (†), J. Körber, M. Schulz and R. Gammert (†); R. Pfeiffer (†) from Technical University Darmstadt and W.-D. Weigel from Siemens Transportation Systems.

Next my senior colleague at Ruhr-University Bochum, M. Depenbrock, the inventor of the Four-Quadrant Converter and of Direct Self Control (DSC), and our Ph. D. students working on perfection of DSC and the line behaviour of traction converters and on the development of robust sensorless operation of induction motors. Last but not least thank is to be said to my son Christian for the translation, the secretary and the draughtswoman of our chair in Bochum and the critical readers of the first edition (in German), ferreting out its hidden errors.

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5 Induction traction motors and their control

Electric machines based on the principle of rotating fields are widely known to be free from the limitation of the product $P \cdot \sqrt{n}$, caused by the commutator. They can be built for highest power ratings (up to 1.7 GVA at 1.500 min^{-1}) as well as for highest speeds (10,000 min^{-1} in the multi-MW range). Rotating-field machines can be subdivided into synchronous and asynchronous or induction machines. Thanks to the higher speed they have distinctly less mass than the commutator motor at same rated power, and they are – especially in the form of squirrel-cage induction motors – extremely robust and nearly free of maintenance [85].

The asynchronous or induction motor – especially in the robust form with squirrel-cage rotor – has always been the "work-horse" of electric drive technology and thus the ideal traction means for railway technical engineers. Brought to practical applicability in 1888 by *M. Dolivo-Dobrowolski*, it was used by Brown, Boveri & Cie. (BBC) in locomotives and motor coaches for the first mainline electrified with three-phase voltage of 750 V and 40 Hz between Burgdorf and Thun in Switzerland already in 1899. In the year 1903 the motor coaches on the test track between Marienfelde and Zossen south of Berlin reached a maximum speed of 210 kph (131 mph), using squirrel-cage bogie-mounted motors and a three-wire catenary in vertical arrangement (Fig. 1.3). Subsequently several local lines in Upper Italy and then in 1908 the new Simplon Tunnel line were electrified with 3AC 3 kV/16$^2/_3$ Hz[11] conveyed by a horizontally arranged two-wire line (the third phase earthed with the rails). But, however, the clumsy three-phase systems, which offered only a small number of few economic speeds, were outclassed by the commutator-motor system, since it required only a single overhead wire and the speed could be controlled rather freely. With the exception of very few isolated local lines the last three-phase railways were retrofitted with AC or DC supply in the 1960s.

In the year 1971 the "second life" of the induction traction motor started, and with much more success. Following the unlucky Hawk diesel-electric locomotive on trial in Great Britain 1964 [86], the diesel-electric universal locomotive DE 2500, built by Henschel and BBC Mannheim (Fig. 1.8, [17] [87] [88]) could demonstrate the advantages of the frequency-variable operation of the induction motor by means of thyristor inverters. Since the mid-1990s all high-performance traction vehicles – high-power locomotives and high-speed trains – have employed induction motors, combining a high power-to-mass ratio (> 0.65 kW/kg) with robustness and low need for maintenance. The key factor has been the enormous increase of power of semiconductor devices and thus a corresponding decrease in inverter cost and bulk, achieved by the introduction of the self-turn-off devices Gate-Turn-Off (GTO) thyristor and the Insulated-Gate Bipolar Transistor (IGBT), which are described in subchapter 5.6 [83] [89] [90] [91] [92] [93] [94] [95].

5.1 Construction and stationary behaviour of the induction machine

5.1.1 Basics of induction machine

The stator of the induction machine (IM) carries a three-phase rotating-field winding. Fig. 5.1 exhibits – exemplarily for motors of big power rating – the winding zones of a two-pole dual-layer three-phase winding with two times six zones. Zones of top-coil and bottom-coil side bars belonging together are displaced not by an angle of π (a full pole pitch), but by $\pi - \varepsilon$ ("chording").

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[11]   Rome-Sulmona in South Italy used 10 kV/45 Hz (1928)

Fig. 5.1: Winding zones of
a chorded dual-layer
three-phase stator winding

zone of
top-coil side bars

zone of
bottom-coil side bars

ε = chording
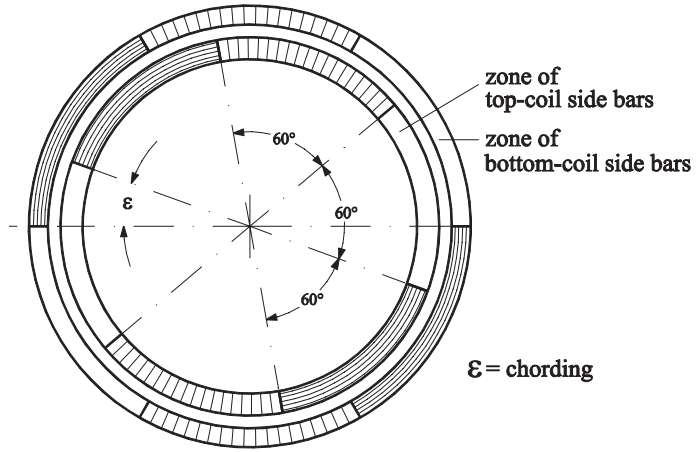
This attenuates the harmonics of the current coverage and the flux wave. Fig. 5.2 shows one (of three) phase windings with $q = 3$ slots per phase and pole, a so-called concentric lap winding. The axes of the three-phase windings are displaced by $\pm120°$ in the electric phase-angle reference (= $120°/p$ mechanically) against each other.

Zone of top-coil side
bars

Zone of bottom-coil
side bars

$2\tau_p$

$p = 1$
$q = 3$
$\varepsilon = 20°$

I = 1st double zone

II = 2nd double zone

x   U
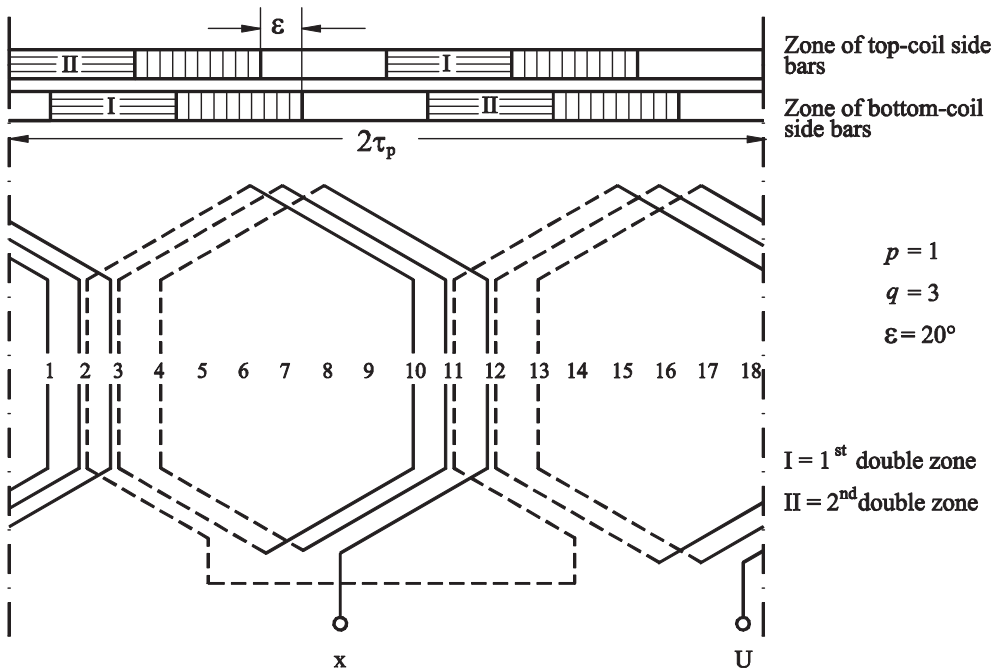
Fig. 5.2: One chord of a three-phase dual-layer concentric lap winding
($p = 1$, $q = 3$, $\varepsilon = 20°$)

Fig. 5.3 (left) shows the stator of the traction motor BQg4843 of Class 120 of DB (1400 kW, $p = 2$). The rotor may be equipped with a similar three-phase winding in star connection, with the three free terminals made accessible via slip rings and brushes ("slip-ring rotor"); but most widespread is the squirrel-cage "winding" made of copper bars, inserted in rotor-drum slots and connected at both ends over short-circuit rings, as visible in the right part of Fig. 5.3.

Fig. 5.4 compares this motor by its size and mass to the AC commutator motor of Class 110/140 of DB, of 1950s' vintage (cf. Fig. 2.14).

Fig. 5.3: *Three-phase traction motor BQg4843 of Class 120 DB (BBC)*
left: Stator with casing   *right: Rotor (A = pinion side)*
$P_N = 1400\ kW$ $U_{max} = 2200\ V$ $n_1 = 1778\ min^{-1}$ $n_{max} = 3600\ min^{-1}$
$I_N = 600\ A$ $M = 2380\ kg$ *(Bombardier Transportation)*

Fig. 5.4: *Comparison of size of three-phase traction motor to AC commutator traction motor*
left: QD 646 (prototype)
1400 kW / 2380 kg
right: WB 372-22
925 kW / 3500 kg
(Bombardier Transportation)

To describe the working behaviour, the squirrel-cage winding is replaced by an equivalent slip-ring-rotor three-phase winding with the same winding number (and winding factor) as the stator winding, so that the voltage ratio factor is unity (cf. [L1]). The machine is assumed symmetrical, only the fundamental-wave effects are taken into account. A balanced sinusoidal three-phase

13 Power supply of electric railways

13.1 AC railways operating at $16^2/_3$ (16.7) Hz

13.1.1 Central and decentral supply in Germany

With respect to the commutation of the AC commutator motor (cf. section 4.2.1), the "Central European" railway supply frequency was defined in the "Agreement on the implementation of electric traction" of the railway authorities of the German federal states Prussia (with Hessen), Bavaria and Baden [341] [342] of 1912 as one third of 50 Hz = $16^2/_3$ Hz (cf. also subchapter 1.2; from 1996 on, the operational set value value is 16.7 Hz, cf. section 13.1.2). Ensuing, the railways of Austria, Switzerland, Sweden and Norway fell into line, which had partly already begun with 15 Hz.

This decision required construction of a railway supply mains separate from the public mains. The generated/converted power of the railway mains nowadays is a mere 1.5% of the installed power of the German interconnected-operation mains. Fig. 13.1 illustrates the inclusion of the DB's so-called "central mains" in the public 50-Hz, three-phase AC power supply net. Simultaneously with the first isolated railway electrification schemes prior to the outbreak of the Great War [343], power plants operated and owned by the railway companies were built as well.
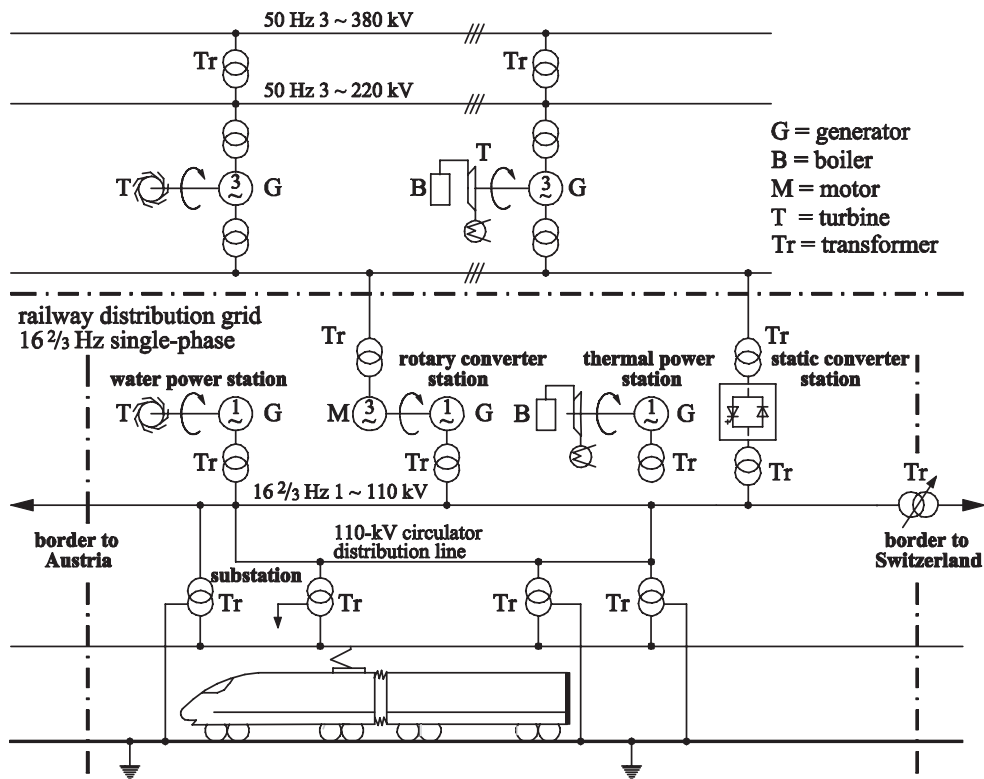

Fig. 13.1: *Railway power supply in the central $16^2/_3$-Hz mains of the DB (acc. to [348]).*

These include the hydroelectric plant at Kochel (Walchensee, finished 1924) for the Bavarian mains, the thermal power station Muldenstein for the central Prussian mains [344] [345] and the hydroelectric plant at Porjus for the Kiruna railway in North Sweden (1915).

When, during the 1920s, electrification of railways could resume, it was resolved – analogous to the national 50-Hz supply – to construct a (2 x 55)-kV transmission mains in Southern Germany which would link power plants and substations. In 1942, the Bavarian and the Central German railway mains joined up at Saalfeld in Thuringia.

After the Second World War, the DB quickly re-established electrical operation in Bavaria and Württemberg, as well as re-initiating the electrification of new tracks. In the early fifties, a heated debate arose with respect to the Ruhr-area rapid transit "Ruhrschnellverkehr" whether to operate the railways with the general 50-Hz, which had been proven to be technically feasible by trials on the Höllental line and in Northern France. Yet DB decided, for continuity reasons and to maintain the option for a power-frequency-control system of its own, to keep to the $16^2/_3$ Hz supply system [346], and determinedly expanded the 110-kV transmission and interconnection mains. Furthermore, the electrification of the new high-speed line Cologne-Rhine/Main with $16^2/_3$ Hz underlined this decision [347] [348].

Following the complete dismantling of the electric railway equipment in the Soviet Occupation Zone, later GDR, in 1946 [344], locomotives, power plants and substation equipment where returned to the DR, successor of the Reichsbahn in the former GDR, only until 1956. The Soviet railway organisation SZD had run trials of the technology on the Workuta railway in Siberia, but found the system unsuitable for Soviet-Russian requirements. In 1958, the SZD started a program of 50-Hz electrification using French and (new) German technology.

In the Weimar–Leipzig–Chemnitz–Dresden region, the original central mains was refurbished [349]. The further extension of the supply grid was stopped by the decision of Comecon, to procure only diesel-electric locomotives of Soviet-Russian and Romanian provenance in the GDR. When electrification was resumed after the first oil crisis 1973, DR decided for the northern lines to Berlin and to the Baltic Sea in favour of a decentral power supply system with fixed-frequency synchronous-synchronous rotary converters (cf. section 13.1.2), due to the lower initial cost [350] [351] [352]. In the 1930s, Norway and Sweden had also chosen decentral supply for sparsely-populated areas. To avoid circulating current flow, the feeding sections must not be longitudinally coupled; thus, to make the system fault-tolerant, it is necessary to have a high converter spare and thus total rating, which results in the decentral supply system becoming economically inefficient in the long run.

Following German reunification in 1990, it was therefore decided to abandon the decentral supply step by step. Initially, the Berlin area was tied up to the central mains at Wolfsburg and at Dessau; subsequently, the formerly separate mains were joined at Bebra and Saalfeld. The Prenzlau-Anklam line was converted to the autotransformer system (cf. section 13.2.3) in 2000, in order to replace cost-efficiently old decentral converters [353]. Increasingly, static intertie converters are applied.

Fig. 13.2 shows the current state of the DB Energie interconnected mains, together with the own power plants and the converter plants. A 150-MW pumped-storage plant has been built in 1975 in Langenprozelten near Würzburg [354]. The 110-kV circuit length is about 7,650 km (4,743 miles). The transmission mains operate as a resonantly-earthed system with step-switched Petersen coils, at 15 substations distributed all over the mains. In 2003, a converter for neutral-voltage displacement and residual earth-current control due to detuning of the resonant circuit made up from the circuit capacities and the Petersen coils and due to harmonic currents produced by vehicles with power-electronic control, respectively, took up service in the converter plant Borken/Hessia [355]. Ties to the other $16^2/_3$-Hz mains were established in Zirl and Salzburg towards Austria and at Etzwilen to Switzerland.