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Electrical equipment of the three-phase DB class E 120 universal mainline locomotive

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by Ernst Becker

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Data:

Year of delivery	1979
Track gauge	1435 mm
Length over buffers	19200 mm
Distance between pivots	10200 mm
Bogie wheel base	2800 mm
Wheel arrangement	BoBo
Maximum speed	160 km/h
Service weight	84 t
Max. tractive effort at starting	340 kN
Nominal rating	5600 kW
Resistor brake	
Continuous braking effort	3150 kW
Short time breaking effort	5600 kW
Max. braking effort	125 kN
Regenerative brake	
Continuous braking effort	3300 kW
Max. braking effort	150 kN
Applicable for following trains:	
700 t passenger train	v = 160 km/h
2700 t/5400 t* Ore trains	v = 80 km/h
(* in twin traction)	
2200 t Freight train	v = 80 km/h
1500 t Fast freight train	v = 100 km/h

Electrical equipment of the three-phase DB class E 120 universal mainline locomotive

by Ernst Becker

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One of the German Federal Railway (DB) three-phase prototype Class E 120 incorporating BBC (Mannheim) electrical equipment. This unit, 120-001 was built by Kraus-Maffei AG, the leader of the construction team, Nos 120 002 has been built by Thyssen-Henschel and No 120-003 by Friedr. Krupp GmbH

Four prototypes geared for 160 km/h make their appearance to be followed by a fifth for 200 km/h, as the first high power locomotives with three-phase induction motors in Germany. Extensive trial period to verify data and optimum performance: two independent traction main circuits embracing each bogie to maximise adhesion characteristics, transformers rated continuously to accommodate heavy freight train movements and electric heating of heavy expresses. Regenerative braking at 3·3 MW and rheostatic at 5·6 MW, frames-suspended motors with hollow cardan-drive shafts encircling the bogie axles.

The five locomotives of class E 120 which will be put into operation by the German Federal Railway (DB) during the next months, are the first high-power locomotives in Germany with three-phase induction motors. These locomotives are the result of many years of systematic development work carried out to disign a universal locomotive featuring good traction chracteristics, a high power factor, low maintenance costs and economical operation (1) (2) (3). Preliminary investigations have been performed to obtain the knowledge and experience required to realize an economical and technically reliable configuration of the electric equipment.

The requirements imposed on the locomotives of Class E 120 have been stated by the DB in a Specification. High starting tractive effort without any time limitations for freight service and maximum tractive effort permitting passenger trains to be accelerated to full speed are determined in the tractive effort curve of the locomotive (Fig 1). Traction motor and converter are rated in such a way that a hyperbolic TE/speed diagram is obtained. The tractive effort corresponding to this characteristics can be provided continuously and the full installed power of 5·6 MW can be applied continuously up to a maximum of 160 km/h.

At present, the installed power of a Bo-Bo three-phase locomotive with a total weight of 84 t is limited by the weight and volume of the electric equipment in the locomotive body. With a view to the relatively small traction motors which have no commutators, the bogies can be made light in weight with good running features. The electric equipment is subdivided into two independent circuits, each of which is feeding a bogie with two traction motors connected in parallel. This is a good compromise between a high degree of availability in the case of a fault and the advantages of induction motors working in parallel as proved in the three-phase locomotives already in operation.

The transformer being the heaviest part is rated so that the freight train-loads can be hauled continuously. Under due consideration of the power required for heating a 700 t passenger train, the temperature limits of the transformer will not be reached during passenger train operation.

Normally, the electric braking power is regeneration to a maximum of 3·3 MW which is returned to the overhead contact line. As an alternative, a rheostatic brake is available which is independent of the overhead supply. If the overhead contact line cannot absorb the energy, the rheostatic brake is automatically cut in with a maximum of 5·6 MW and a continuous rating of 3·15 MW.

Circuit diagram and mode of operation

Four secondary transformer windings of 1513 V each, feed four converters via the 'no-load' traction/braking change-over switches. The converters consist of four-quadrant controllers (4q-S) and motor inverters (WR) which are connected to the constant dc link with a voltage of 2·8 kV (Fig 2). Two converters each are connected on the dc side and at the three-phase output to supply one bogie. When starting operation the dc link is loaded via the loading position of the traction/braking change-over switch, the braking resistor and the free-wheel diodes of the four-quadrant controller 4q-S. The function of the four-quadrant controllers 4q-S is to keep the dc link voltage constant at its nominal value of 2·8 kV, and to set the input current in phase with the line voltage (4). Each four-quadrant controller 4q-S at its input terminals draws an almost sinusoidal current with a superimposed harmonic of 366 Hz. The pulsation of each of the four four-quadrant controllers is shifted by 90° each so that the resulting harmonic in the line current is less than 1 % of the rated current. In this way, low noise current values and a favourable line behaviour are obtained at a power factor of approx. 0·99. The output current of the four-quadrant controller 4q-S consists of a dc current which is superimposed by an alternating current of twice the line frequency. The ac portion is absorbed by a LC resonant circuit (5).

The capacitors in the dc link serve for smoothing and for providing the commutating energy for the four-quadrant controller 4q-S and inverter (WR). The second section of the converter – the motor inverter – converts the dc voltage into three-phase of variable amplitude and frequency by pulse-width control (subharmonic method). The voltage is set proportional to the frequency up to the nominal value of the machines (about 60 Hz) which means that the induction motors are then excited at nominal flux. Above 60 Hz the voltage is kept constant with the machines working in the field weakening range. The frequency of the stator is set by the control system in such a way that depending on the required traction or braking effort, a corresponding rotor frequency reference value f_2 (slip frequency) is added to or subtracted from the actual rotor speed frequency f_n. At no-load the stator frequency – viz., the inverter output frequency – is equal to the rotor speed frequency.

The current harmonics of the traction motor are limited by the leakage inductance of the motor. In the lower speed range an additional external inductance is used. The two traction motors of a bogie are connected in parallel and are operated by a common control system.

During regenerative braking the mode of operation remains the same. By presetting a stator frequency which is lower

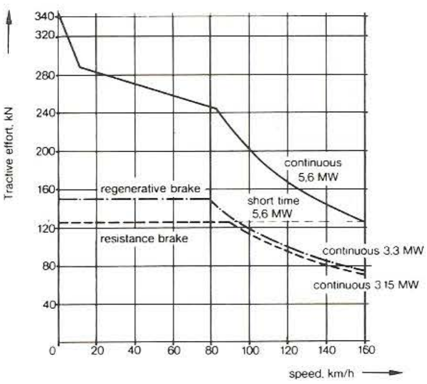

Fig 1. Tractive effort/speed characteristics of DB Class E 120 Bo-Bo locomotive

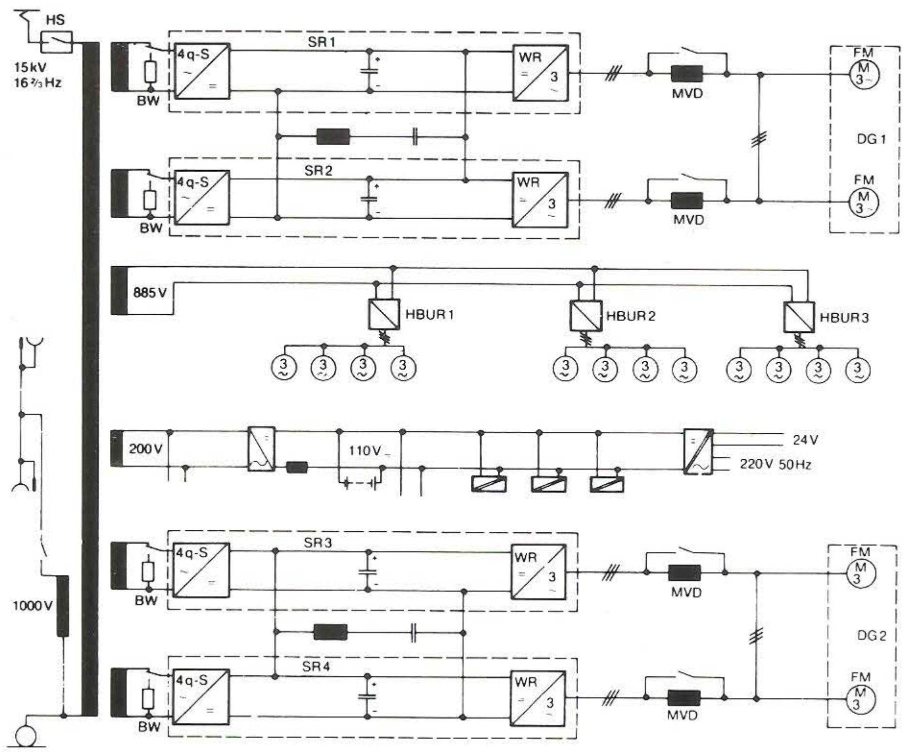

Fig 2. Basic circuit diagram of three-phase electric locomotive Class E 120

HS	High speed circuit breaker
BW	Braking resistance
4q-S	Four-quadrant controller
WR	Inverter (DC to 3-phase AC)
SR	Traction power converter
MVD	Traction motor chokes
FM	Traction motor
DG	Bogie
HBUR	Auxiliary inverter

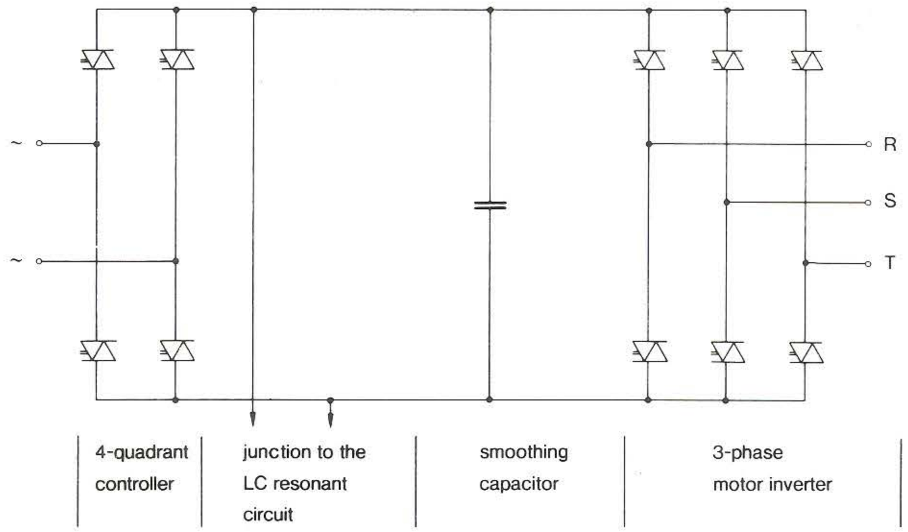

Fig 3. Basic circuit diagram of traction converter unit

than the rotor speed frequency, the motors work as generators. The converters operate in the same way as during traction, however with the energy flow is reversed. During rheostatic braking the braking energy is applied to the brake resistor via the inverters and four-quadrant controllers 4q-S. The four-quadrant controller then works as braking controller and produces a square wave alternating current. The block width is controlled depending on the braking power.
The auxiliaries of the locomotive E 120 are fed from separate three-phase power supplies. Three independent static frequency converters provide a three-phase voltage of variable frequency and amplitude up to max. 60 Hz and 440 V from the auxiliary winding of the transformer of 885 V, 16⅔ Hz. Each converter consists of a phase angle controlled rectifier and a thyristor converter with a transistor controlled turn-off circuit. Voltage and frequency are controlled in accordance with the required cooling air quantities. In this way, excessive ventilation is avoided. There after a short description of the main components:

The Transformer

On the low-voltage side the transformer has four secondary windings for traction and regenerative braking, one 1000 V winding for heating, one 885 V winding for the auxiliaries and an additional 220 V winding for battery charging. The maximum relative short-circuit impedance for the secondary and the primary winding is 30%. The secondary windings are effectively separated from each other.

The active part consists of two columns which are installed horizontally in the flat aluminium tank. Furthermore, the tank accommodates the smoothing circuit inductances. The insulation of the windings with the "Nomex", transposed individual conductors, non-magnetic core retainers and the aluminium tank made of extruded sections are some of the features incorporated in the design of this 16⅔ Hz transformer with a high specific rating.

Traction converter unit

Each of the four converters consists of a two-phase four-quadrant controller 4q-S and a three-phase motor inverter as well as the pertaining smoothing capacitors for the dc link (Fig 3). In such a converter unit a high power concentration is obtained by means of an oil cooling system for the components which generate (semi-conductors, resistors, commutating inductances). The semi-conductors are clamped-in between two oil-cooled copper heat sinks. The five phases of a converter are located in modules arranged above each other at the front.
Behind them are the smoothing and commutating capacitors and the commutation inductances. The phase module consists of positive, negative and commutation branches. The 2 x 4 hockey puck semi-conductor devices of each branch are arranged to form double stacks and are pressed together in the frame of the phase module to ensure an efficient contacting. The whole phase module can be exchanged by loosening a few connections. Individual semi-conductor elements can also be exchanged easily after the pressing devices have been unscrewed.

The braking resistance is of modular design. It is suitable for high operating voltages and has a low specific weight and volume. The whole resistance block consists of 4 x 7 basic units. Each one of these units consists of a frame into which the meandering resistance ribbon is suspended elastically. The whole braking resistance is ventilated from bottom to top by an axial-flow fan.

Traction motor and drive

The traction motor is a sturdy four-pole induction motor with a squirrel-cage rotor with low maintenance (6). The stator winding is fitted with "Micadur" compact insulation. The slide-in stator is installed in a welded sheet-steel casing. The squirrel cage winding of the armature consists of rectangular copper bars which are inserted without insulation into the armature slots. The ends of the bars are hard-soldered to a short-circuit ring. The forced-ventilation cooling air passes the motor in axial direction through cooling bores in the armature, the air gap, the free part of the stator slots and between the casing and the laminations. The motor is dimensioned in such a way that the stalling torque will never be exceeded in operation according to the hyperbolic TE/speed diagram. The torque is applied to the larger coller flange of the hollow shaft drive by toggle-arms pivotted to herring-bone gear (Fig 4).

The driving-gear engaged by the traction-motor output-pinion is also mounted on

Traction motor
1 Stator core
2 Stator winding
3 Rotor core
4 Short-circuited winding
5 Shaft
6 Cylindrical roller bearing
7 Pulse disk
8 Casing
9 Air inlet
10 Connecting cable
11 Air outlets
12 Mounting eyes

Gear
13 Pinion
14 Gear-wheel
15 Gear-wheel bearing
16 Gear box

Rubber joint cardan drive
17 Linkage coupling
18 Hollow shaft spider
19 Hollow shaft
20 Fork spider
21 Linkage coupling
22 Hollow shaft casing
23 Supporting arm

Wheel set
24 Wheel set shaft
25 Disk wheel
26 Disk wheel with driving bolts

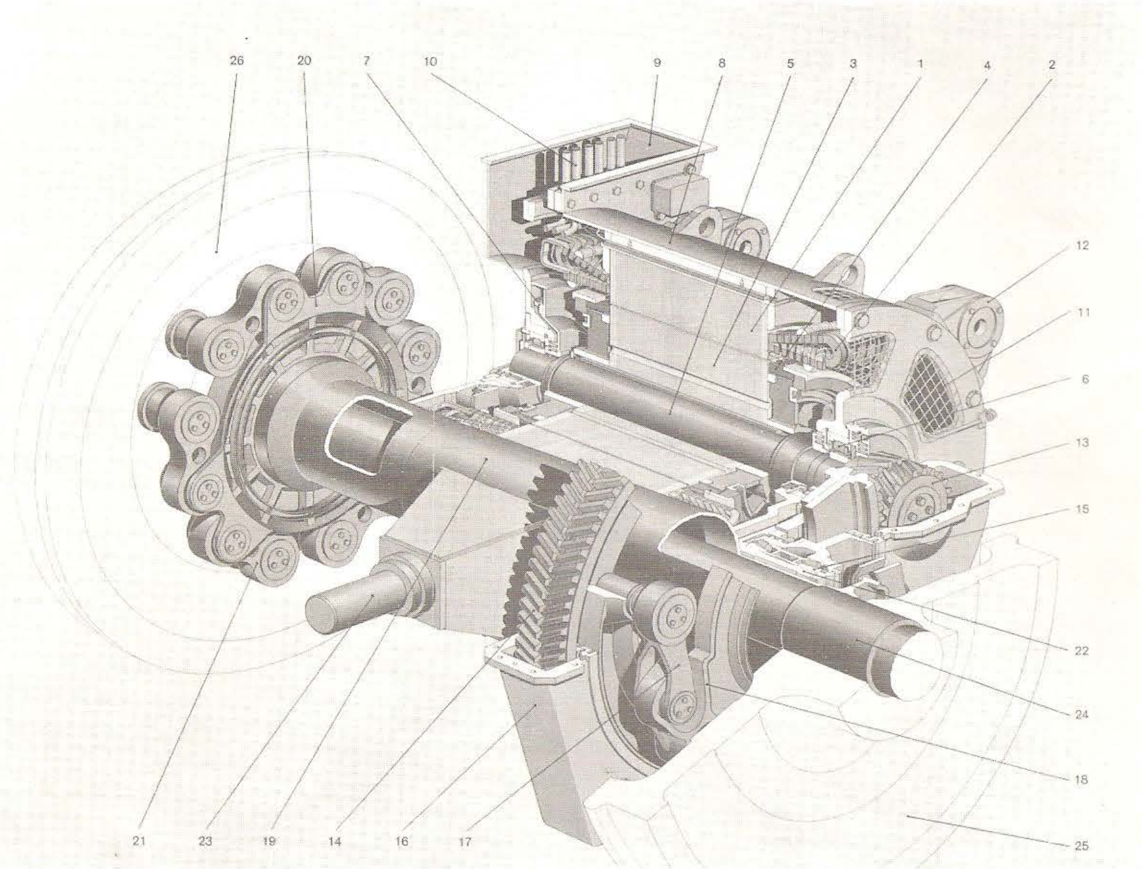

Fig 4. General arrangement of final drive, frame-suspended squirrel-cage motor and hollow cardan-shaft transmission group

the traction-motor casting assembly; the nose of the latter being extended forward of the axle to carry the locating pivot, the drive to the axle passing through it. The driving-gear is basically an annular herring-bone toothed rim carried on taper roller-bearings to which is pinned the toggle-arms, linked in turn to the collar-flange of the hollow cardan drive-shaft. Because of the continuous torque delivered by the three-phase motor, a wheel-face mounted torsion-elastic rubber ring jacket which would have the disadvantage of acting as a slip-accelerator, is no longer required on the E 120 wheel-sets. For this reason, link arms with spherical rubber-joints are mounted there, transmitting the torque. The six links each on the driven and the driving end of the hollow shaft are arranged in an opposite direction to obtain the required axial spring stiffness. The gear casing is cast of light metal and made tight by a thin-gap labyrinth packing.

Layout of equipment

The engine room has a straight central aisle. The converter, cubicles and apparatus racks are pre-assembled and are arranged on the right and the left of the central aisle (Fig 5). The transformer is located at the centre below the locomotive body. From there, the cables run over short distances via the supply cubicles (Nos 15 and 16 on the diagram) to the converters.
The smoothing-circuit capacitors are accommodated in the cubicles Nos 15 and 16; the smoothing circuit inductance is installed in the transformer tank. The traction motor ventilating towers with motor inductances are located above the bogies. The oil for the transformer and converters is cooled in two radiators. Further cubicles in the engine room include the resistance block, the compressed-air rack and the power supply for the auxiliaries. The electronic control equipment is installed in the driver's cabs. Control function groups for the four-quadrant controllers 4q-S, pulse generation, traction and braking control, etc., are combined in racks mounted in swing frames giving the access to the wiring side. The driver's control desks are of a standard design used also for the locomotive E 111 or for the driving trailer Bxf 796 of the German Federal Railway. After commissioning, the locomotives will be put through extended trials. Measurements to verify the calculated data and an optimization of the locomotive performances will be carried out to complete the development work of the first five of Class E 120, thus providing the conditions for series production of this class of locomotive.

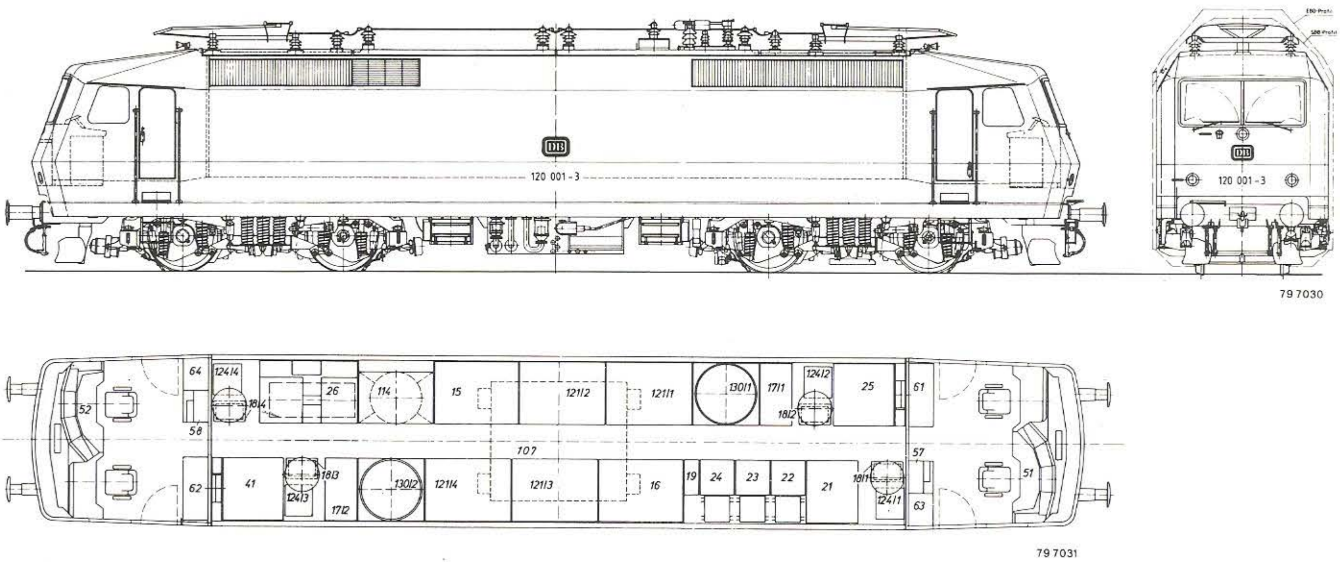

Fig 5. General equipment layout and arrangement diagram of DB Class E 120 Bo-Bo locomotive of 5600 kW

General Particulars

Length over buffers 19200 mm
Total wheelbase 10200 mm
Bogie wheelbase 2800 mm
Bogie wheel dia 1250 mm
Mass 84 t, service speed 160 km/h
Max tractive effort 340 kN
Minimum curve 100-m rad

15, 16	Switchgear and capacitators
18	Traction motor blower
21	Switchgear and auxiliaries
22, 23, 24	Converter for three-phase auxiliaries
25	Compressed air and braking equipment
26	Compressor
41	Control equipment
51, 52	Control desk
61, 62	Electronics module
107	Main transformer
114	Braking resistances
121	Traction power converters
124	Traction motor cokes
130	Transformer oil cooler

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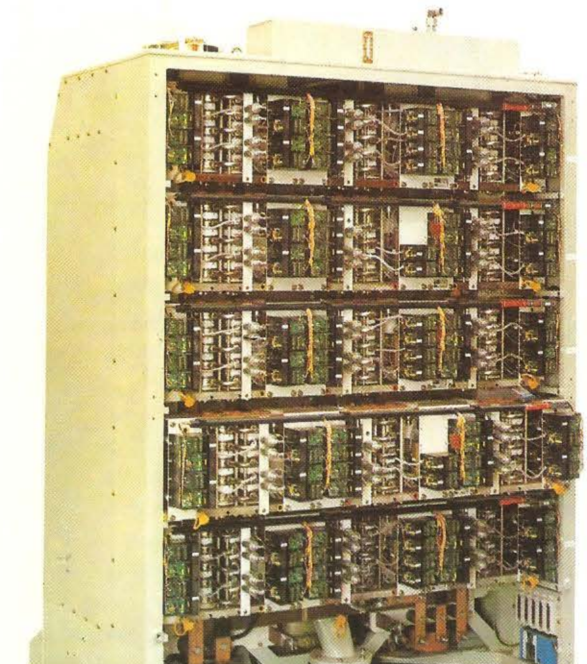
Transformer with pumps for cooling oil

Power:	5525 kVA
weight:	11000 kg

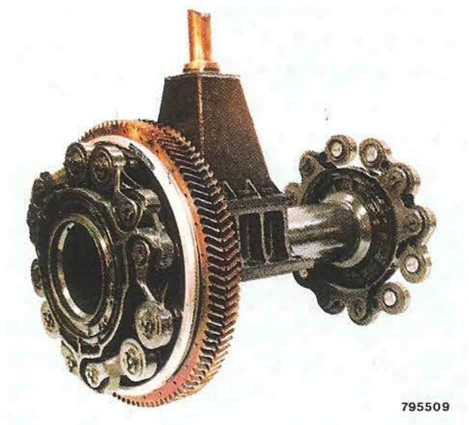
The three-phase-traction-motor of the E 120

Type:	BQg 4843
Continuous rating:	1400 kW
max. speed:	3600 min^{-1}
max. voltage:	2200 V
max. current:	600 A
max. torque:	10,5 kNm
weight:	2400 kg



Traction-converter unit with five modules for four-quadrant controller and three-phase inverter.

Data
Input: 1513 V 16⅔ Hz
Output: 0 to 2200 V
0 to 600 A
0 to 200 Hz
Mass: 1950 kg



Hollow cardan drive-shaft group viewed from the input end. The motor pinion meshes with the annular toothed-wheel which is carried on roller-bearings located on the traction motor nose extension through which the driving-axle passes. The toother-wheel drive is transmissed to the hollow drive shaft by six bell-cranks which in turn is transmitted to the far driving wheel in a similar way. These links are clearly shown at the right end of this illustration.

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