Advanced converter and control components for TRANSRAPID

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Abstract

A new converter and control system for the TRANSRAPID was developed and successfully tested under realistic operating conditions, in particular in combination with double-end feeding, in the course of modernization of the TRANSRAPID test facility in Emsland. In this paper, prototypes incorporating new technologies are presented for the various subsystems and components. Above all, test results are reported. A new compact inverter module was developed and successfully equipped with 4.5 kV IGBTs and 4.5 kV hard-driven GTOs respectively.

1 Introduction

In preparation for commercial use, new propulsion components originating from Siemens in the course of the development programs - new GTO converters with a total output power of 45 MVA and an extended drive control system - were successfully tested under realistic operating conditions, in particular with double-end-feeding, at the TRANSRAPID test facility in Emsland. Project-independent approval of these components by the Eisenbahn-Bundesamt (EBA) has been obtained and this will considerably shorten the commissioning and approval times for reference lines. In this paper, the overall concept and prototypes incorporating new technologies are presented for various subsystems and components. Results of test runs at the TRANSRAPID test facility in Emsland are also reported.

Important components of the complex propulsion system used for the high-speed maglev TRANSRAPID are the converter units, located in substations next to the guideway. The converter itself consists of a thyristor rectifier, DC link, GTO-inverter and supplementary protection devices. The inverter is of the 3-level type using 3 compact modules equipped with 4.5 kV GTOs. Three of these modules form one inverter unit. Since maglev speed is determined by the fundamental frequency of the inverter, it is necessary that operation is possible over a wide frequency range.

In recent years, two alternative semiconductor devices have been available on the market with sufficient turn-on and turn-off capability. These are the 4.5 kV hard-driven GTO (HD-GTO) and the 4.5 kV press-pack IGBT (PPI). Both were tested in order to increase the efficiency of the inverter or the inverter modules. Two special factors should be mentioned:

- Increase of the maximum fundamental frequency from 270 Hz to 300 Hz without reduction of AC current and AC voltage
- Shift of operation with asynchronous modulation from 70 Hz to a frequency as high as possible (desirable frequency: 300 Hz) without reduction of AC current and AC voltage.

2 Structure of the Propulsion System

The structure of the propulsion system developed for revenue service comprises a number of components, which are located along the guideway. These drive components are temporarily switched together to form the drive control zones necessary to permit maglev operation over the guideway [1,2,3]. A drive control zone remains in its switched configuration as long as a vehicle is operating within the corresponding control range. It is capable of driving, accelerating and decelerating one maglev train. A drive control zone comprises the line section itself and, depending on the type of power supply selected, one or two drive units. The drive units are housed in substations, the latter being situated beside the guideway and spaced at a maximum distance of 50 kilometers. A substation for a single guideway contains one or two drive units, the necessary power supply and the decentralized operation control equipment as shown in Fig. 1. A substation for a dual guideway is simply composed of two single-guideway substations.

A line section consists of two long stators, each comprising approximately 50 stator sections, and also includes up to 50 switching stations, the feeder cable systems (two or three according to the selected mode of stator section switching) and the trackside switchgear. A drive unit is made up of the converter units as well as the drive-control/motor-control system, diagnostics, and components of the data transfer system. In turn, one converter unit comprises a converter power section, rectifier and output transformers, a closed-loop/open-loop converter control system, a converter cooling system and converter switchgear.

In a double-end feeding configuration, power is supplied to both ends of a line section from the two drive units of adjacent substations. If each substation has only one drive unit per guideway, there must be at least one clear drive control zone between two maglev vehicles running in the same direction. However, if each substation has two drive units per guideway, the second maglev vehicle may enter a zone just cleared by the first. Data exchange between the components of a drive control zone as well as between adjacent control zones and external subsystems is made possible by a powerful data transfer system.

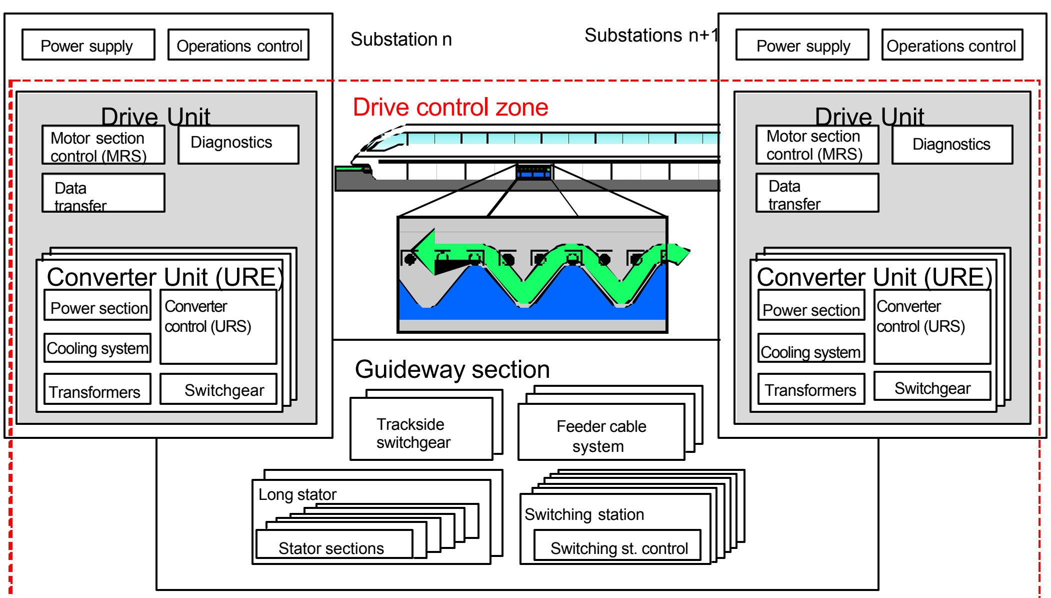

Fig. 1: Structure of the propulsion system

3 Control system

3.1 Architecture of the closed-loop/open-loop control system

In Fig. 2, the architecture of the TRANSRAPID's closed-loop/open-loop drive control system for a drive control zone of a guideway is shown in detail. The individual drive control zones each contain the following:

- Two motor section control systems (MRS) for closed-loop and open-loop control as well as guidance of a vehicle in the assigned drive control zone. The two MRS systems have an identical structure. The master function (active and passive roles) is passed on from one MRS to the other MRS in parallel to the vehicle's movement (master-slave changeover). For normal operation, only one MRS is needed for each drive control zone. The other MRS is a redundancy feature and, if a fault occurs, takes over the role of the master. The drive function is passed onto a subsequent drive control zone according to the same principle as the master-slave changeover within a drive control zone.
- Converter control systems (URS) for closed-loop and open-loop control of a converter. The number of URS systems within a drive control zone depends on the method of stator-section switching (two in the case of successive switching or three in the case of the three-step method) and on the type of converter (switchable type between two adjoining drive control zones or permanently assigned type for one drive control zone).
- Decentralized peripheral control components in the switching stations (for switching the stator sections on and off) and the trackside switchgear (for switching over the converters).
- Components of the operator control and visualization system and of decentralized drive diagnostics.

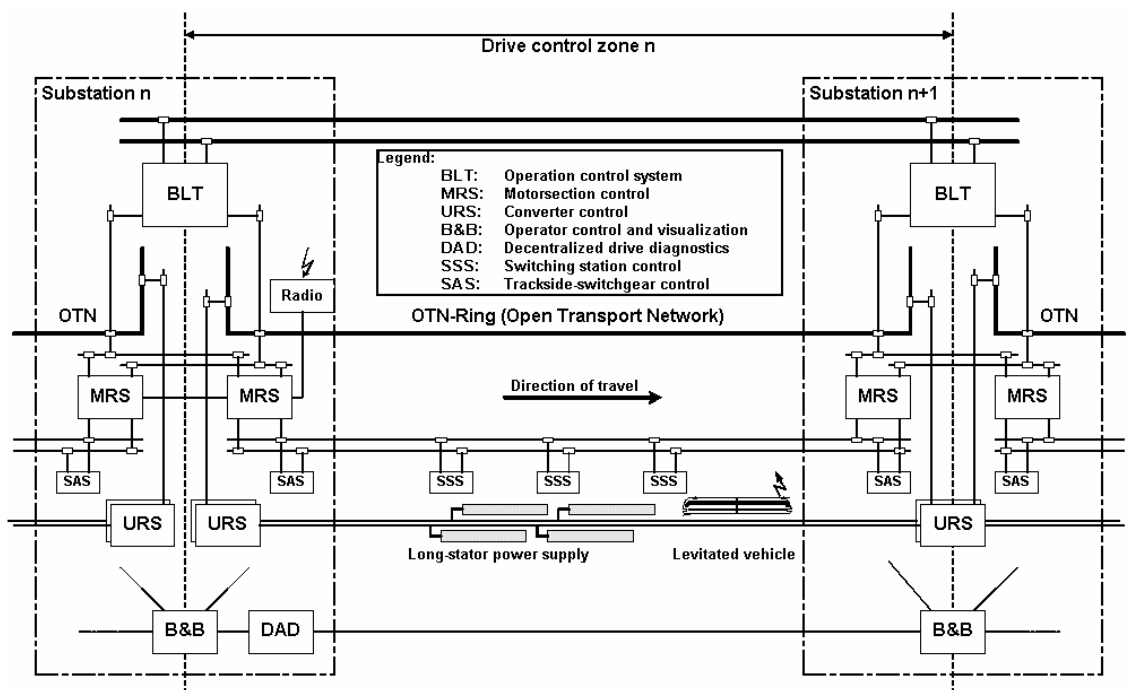

Fig. 2: Architecture of the TRANSRAPID drive control system

Data transfer between the motor-control and converter-control components takes place via a communication system, namely the Open Transport Network (OTN). This system is characterized by the following features:

- Two fiber-optic cable rings, one in each direction. Normally, data is transferred via one ring; the second ring is only used in the event of a fault (changeover or loop-back)
- Computer nodes: module racks and system modules for handling communications and for storing the configuration
- User or interface modules for special applications (Ethernet bus, closed-loop-control communication by means of time-division multiplexing),
- Network management system for managing the system (from configuration to diagnostics).

In each double drive control zone, the control system has an OTN ring for each of the two guideways, the reason being that data traffic in a transverse direction between the two guideways is also necessary due to the crossovers which exist. If the communication system was designed with only one OTN ring per drive control zone, data traffic would only be possible in a longitudinal direction.

The control computers of the decentralized operation control system are connected to the control bus of each OTN ring. In each drive control zone, data transfer between the adjoining drive blocks and the control components of the switching stations and trackside switchgear takes place via a redundant bus connection in order to increase availability.

The individual operator control and visualization stations are connected locally to the components of the control system via a special bus. The computers of the operator control and visualization system and the computers of the drive diagnostics system are globally networked to each other.

The data-transfer links via radio from the vehicle to the MRS (vehicle signals) are designed as redundant, synchronous, serial interfaces.

3.2 Functioning of the closed-loop/open-loop control system

Figure 3 shows the basic functional units of the TRANSRAPID drive control system and how they interact.

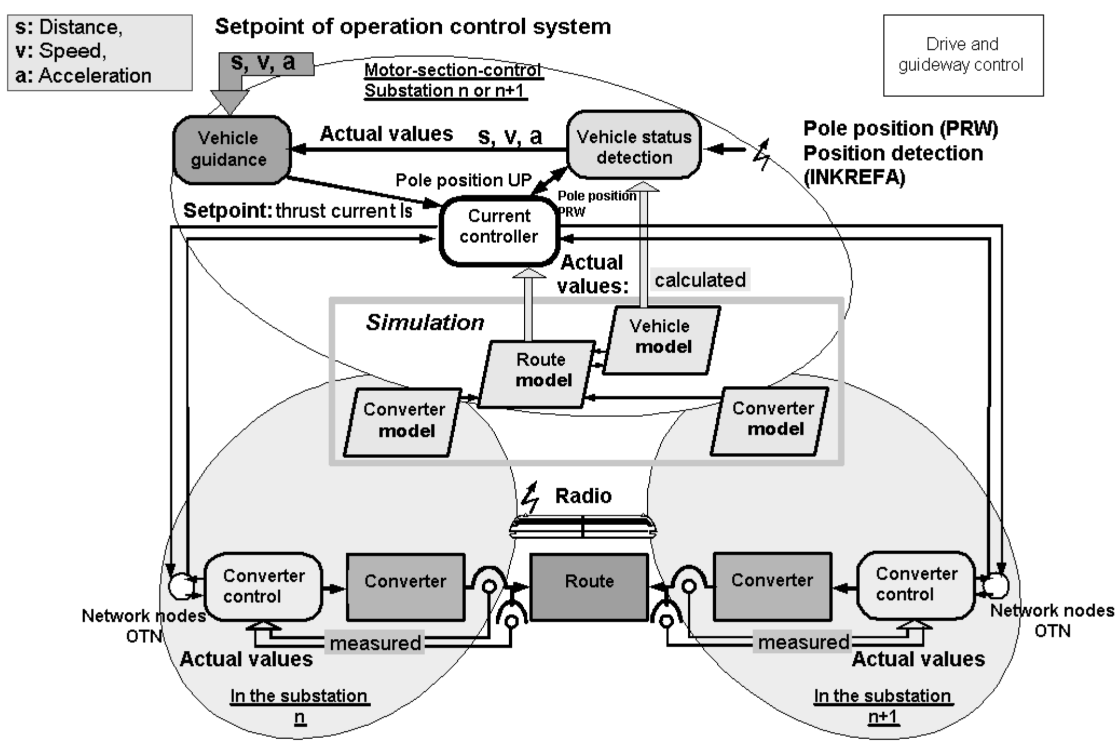

Fig. 3: Basic functional units of the TRANSRAPID drive control system and how they interact

In order to comply with the setpoints stipulated by the operation control system [4], the vehicle guidance system determines the appropriate thrust-current setpoint from the actual values registered and passes this setpoint on to the current controller. The current controller reports the corresponding setpoints to the converter control systems of neighboring substations via the OTN system. These setpoints then control the converters while taking into account the measured outgoing variables of voltage and current. The currently measured actual values are reported back to the current controller in the same way. The actual values of the process such as thrust currents and the vehicle's main field voltage are finally taken from a simulation model which runs parallel to the process. The purpose of the simulation is to exactly describe the controlled guideway dynamically at each working point so that - seen dynamically - the process is not subjected to closed-loop control but to open-loop control. Another function of the simulation model is to determine the vehicle's pole position (the position of stator flux relative to motor excitation). This is possible at speeds of approx. 20 km/h and above. Below this limit, the pole-position information has to be reported to the vehicle status detection system by sensors on the levitation vehicle via a radio channel.

The open-loop drive control system is responsible for coordinating all the events within a drive control zone and between drive control zones. These are events are primarily: the master/slave changeover within a drive control zone; the synchronization of neighboring drive units until final transfer of the master function from one drive unit to the next; the use of drive resources (converters) and activation of the corresponding, redundant components if an active unit fails.

The operating-mode control system is a higher-level control module which defines and passes on the modes for all lower-level components. Here, all the participating elements of a drive control zone are coordinated depending on their statuses and the current stipulations of the operation control system.

The communication interface to the operating control system is basically used for controlling the drive statuses and for complying with the stipulations for propulsion mode. The control system receives information regarding vehicle log-on and log-off, track data and the maximum route-speed profile. In turn, it sends current status information to the control computer in the operation control system. Subsequently, a route-speed profile is created which contains all the necessary information relating to the route to be driven on (points, stator sections, rising/falling-gradient parameters, locating markers etc.) and calculates braking curves leading up to the stipulated destinations.

The control-variable encoder continuously processes the data from the route-speed profile and from the calculated target braking curves. It selects the variables which are currently to have an effect and, taking into account passenger-comfort factors (acceleration/deceleration limits and jerk limit) and the limiting values specified by the drive system, determines time-optimal, harmonics-free control variables for distance and speed control and for acceleration precontrol.

The distance/speed controller is designed as a cascade controller. The distance controller has a proportional characteristic (P controller). The lower-level speed controller is also a P controller. The connected load-acceleration system compensates for the stationary control errors which occur in the case of proportional controllers. The acceleration pre-control system improves the control dynamics during acceleration and deceleration.

The current controller works according to the principle of closed-loop field-oriented control. In order to be able to break down the voltages and currents into components in and transversely (normal) to the field direction, knowledge of the angle between the stator winding and the rotor or pole-wheel excitation (= support-magnet field of the vehicle) is necessary. The vehicle synchronizing system (phase controller) determines this geometrically periodic load angle, using various measuring procedures and stipulates the vehicle's speed.

In the voltage model of the current controller, the components of the pole-wheel voltage induced by the vehicle are calculated from the components of the measured actual values of current and voltage and from the route parameters. The ratio of the components in and transversely to the field direction is a measure of the deviation of the vehicle's angular position in relation to the real position of the vehicle's excitation.

The load angle measured with the help of sensors is transmitted to the vehicle status detection system via the radio interface. After correction of the signal-return time, the difference between the load angle and the vehicle's angular position forms the phase-angle error of the load-angle procedure. This procedure is mainly used in the lower speed range where the induced voltage is very small.

The vehicle-status monitor has the task of detecting the force (or the equivalent acceleration) which is acting (in a longitudinal direction) on the vehicle (running resistance such as air resistance, braking forces due to the linear generator and guideway system and force due to rising/falling gradients) in addition to the propulsion force and to provide it to the speed controller as a precontrol variable.

Knowledge of the vehicle's absolute position on the route is necessary for correctly switching the stator sections on and off, for stipulating the parameters of current control, for distance control and for master/slave switch-over in the drive control zone or during a changeover from one drive control zone to the next.

The current controller controls the (total) current beneath the vehicle and, in order to determine the vehicle's position, detects the pole-wheel voltage induced in the stator by the vehicle. The controller works according to the transvector method. The voltage and current components are determined parallel (d) and vertically (d) to the pole-wheel of the machine by transformation from the static coordinate system into the rotating dq system. Normally, the synchronous machine for propulsion of the Transrapid is operated near or at the stability limit. In order to increase utilization of the propulsion system, it can be advantageous to operate the machine with current components on the magnetizing axis as well.

The current controller is a complex controller for the two current components, magnetization and thrust, of the synchronous propulsion machine. From the given setpoint-current components of setpoint formation and the actual-value components calculated in the actual-value model, it calculates the manipulated variables for the setpoint model. The models work on the basis of cable equations and are each designed for a selected maximum route structure with double-end feeding. For the working point at a particular time, the models are configured with the model parameters from parameter processing and by means of control signals from the model control system. The current-splitting stipulator decides how the current is to be split between the two converters depending on the operating mode (single-end or double-end feeding) and on the operating status (normal, fault).

The guideway control system coordinates control and monitoring of the various switchgear equipment on the drive control route in relation to the stipulations of the successive switching method and the vehicle's location and speed. It supplies the control signals for opening and closing the stator-section contactors and for switching over the converters synchronously to vehicle movement and monitors the data of the guideway-cable and long-stator earth-fault protection devices.

The closed-loop/open-loop converter control system includes the DC link controller, the rectifier and inverter control sets and the sequence control system for internal statuses and the converter peripherals.

The DC link controller and the rectifier control set exist separately for each half of the DC link. The DC link voltage controller keeps the DC link voltage to a stipulated setpoint, irrespective of the load. In order to improve the dynamics, there is a lower-level current controller. This receives its positive setpoint from the voltage controller and is precontrolled with the active-power request of the inverter. The current-controller output stipulates the phase-control factor or firing angle for the rectifier control set. A negative current setpoint stipulates a phase-control factor for the brake chopper which reduces the DC link voltage via the brake resistor. The controller raises the DC link voltage if the braking power is too small due to minimum phase-control of the brake chopper. The rectifier control set generates the drive pulses for the thyristors. This is a comparator control set with a hardware basis. Synchronization takes place on an alpha/beta system of the three-phase 50 Hz system via a phase-control circuit. The brake-chopper temperature monitoring system uses a temperature model to find out the temperature of the brake resistors in both halves of the DC link. When the maximum temperature is reached, the converter is switched off.

The phase-control factor for direct-pulse operation or the limiting control angle and phase-shift angle for transformer operation is calculated from the setpoint for the inverter output voltage. The degree of freedom resulting from two control angles is used to avoid the excitation of certain resonance frequencies of the guideway cables. During direct pulse operation, the two inverters are connected in parallel via the primary winding of the output transformer. The output voltage is set by stipulation of a phase-control factor with optimized pulse patterns or space-vector procedures. During transformer operation at higher frequencies, the inverters are operated with fundamental-frequency pulsing. The voltage is set by means of the phase-control angle, the phase-shift angle of the two inverters. The phase angle of the output voltage is stipulated by the current controller in relation to a reference angle applicable across systems. In order to avoid transformer saturation resulting from asymmetry in the triggering of GTOs, any existing direct components in the inverter output currents are detected and switched to the control set of an inverter by means of a controller.

For complete and full testing, the closed-loop/open-loop drive control system contains simulations of the closed-loop-controlled and open-loop-controlled systems and simulations of the other subsystems (operation control system, vehicle sensors etc.).

The human-machine interface acts as an interface between the drive control system and the commissioning or maintenance personnel, on the one hand, and between the drive control system and the drive diagnostics system, on the other. The operator control and visualization system contains the core functions of providing graphic displays, recording measured values (archiving functions, data compression etc.), displaying, archiving and logging messages, documentation of process sequences and process communication.

The drive diagnostics system is model-based. The advantages compared to other variants of the system are the shorter time needed to instruct maintenance personnel, faster detection of faults, reliable localization of defective components and simpler configuration.

The system being used allows online diagnosis for permanent monitoring of the process as well as offline diagnosis. Offline diagnosis supports guided maintenance.

Given the comprehensiveness and uniformity of configuration - from parts-list importation and modeling to integration of documentation such as maintenance instructions and further documents - a complex, closed system is created which takes the user by the hand and even enables personnel who are not particularly well trained to maintain this complex system. The diagnostic system has a cascade structure so that it can be easily extended as required.

3.3 Platform of the closed-loop/open-loop control system

The heart of the closed-loop/open-loop control system is composed of components of the digital control system, SIMADYN D. For peripheral control components, the SIMATIC S7 automation system is used. Standard components such as processor and storage modules and communications modules (Ethernet, Profibus) are used. The special requirements for drive control (detection of voltages and currents, locking logic of the valve control system, processing of valve checkback signals, control sets for rectifiers, inverters, brake choppers, current control, vehicle status detection and modeling, control communication etc.) are satisfied by using signal processor modules. This type of module is a combination of a digital signal processor, a static program/data memory, a configurable logic module (FPGA) and interface modules for adaptation to the peripheral signals.

The basic control algorithms work with sampling times of 1.5 ms and are initiated synchronously with control-data transfer so that no beat effects due to asynchronous sampling times can occur within a drive control zone. The voltage and current levels detected are processed every 125 µs in order to avoid sampling effects due to the resonance frequencies of distributed networks (output transformers, guideway cables and stator-section windings).

The SIMADYN D control system has a graphic configuration user-interface for standard and user function blocks. In accordance with the complexity of the closed-loop/open-loop drive control system, many special function blocks are used. C is mainly used as the programming language (C++-Compiler are, unfortunately, not sufficiently widespread for control applications) and sometimes UML is also used.

Originally, the configuration tool was designed for individual applications so that each individual function package had to be processed individually and manually or duplicated. Within the framework of control system development, this tool was developed further for the industrial use of regular closed-loop control structures. An important step here is the separation of functionality and parameterization. For the functionality, which is universally valid, there is a basic configuration. This configuration is adapted to locally-specific circumstances by suitably modifying the basic configuration automatically with the help of configuration files (generic configuration) and by supplementing the basic configuration by means of separate parameter files. Fig. 4 contains a schematic outline of how the software is created. As a result of these measures, it is now possible to handle software production for an application automatically and in a way which can be reproduced.

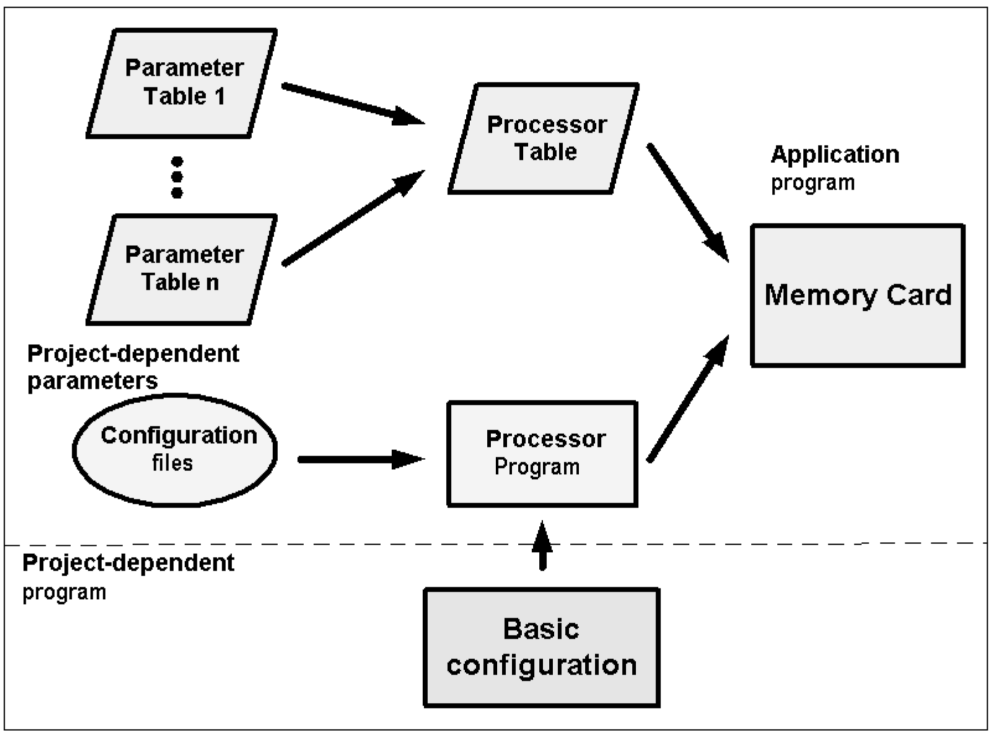

Fig. 4: How application-specific software is created

PC-based systems are used as the computers for the operator control and visualization system and for drive diagnostics.

4 Results of Trials at the TRANSRAPID Test Facility in Emsland

In order to achieve approval by the Eisenbahn-Bundesamt (EBA) for operation on reference lines, a new substation (UW 3) has been built in the north end of the TVE facility [5,6,7]. Fig. 5 shows this substation. The main reasons for the new substation are as follows: to enable testing of functions such as vehicle transfer between the drive-control/motor-control systems of neighboring substations within a drive control zone, to test vehicle transfers between two neighboring drive control zones with power supply to both ends of a line section from two drive units in adjacent substations (double-end feeding), to test stator section switching with the step-by-step method, to test decentralized methods of controlling and monitoring processes and to check diagnostics capability and a suitable concept for modules, redundancy and faults under realistic operating conditions.

Fig. 5: Substation UW 3 of the TRANSRAPID test facility in Emsland

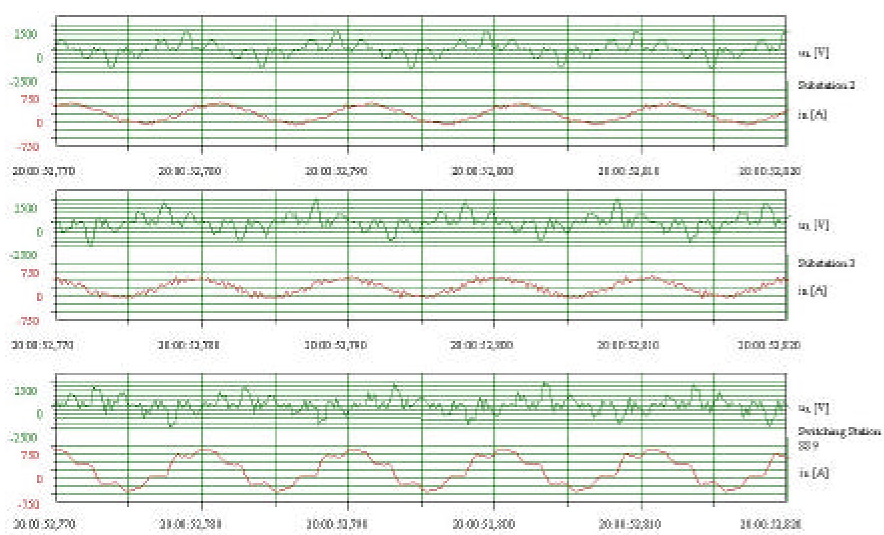

Fig. 6: Converter output voltage u_R and current i_R of substations UW 2 and UW 3 Stator section voltage u_{R_SA} and current i_{R_SA} (switch station SS9)

This substation operates with the substation (UW2) in the test center in a double-end feeding configuration. Although the converters were subjected to intensive stress during the test program under the severest contingent conditions, all tests were completed successfully [1,5].
Being one of the main aims of the modernization project for the Transrapid test center facility in Lathen, Germany (TVE), double-end feeding is demonstrated by feeding power to a stator section. As can be seen in Fig. 6. each of the two neighboring substations produces a phase-shifted output current with a fundamental frequency of 98 Hz. In the switching station, they superpose to form a nearly sinusoidal propulsion current. As the stator section is located nearly in the middle between the two participating substations, the amplitude of their output current is nearly the same. By adjusting the share of the substation output currents inversely in relation to the distance between the fed stator

section and the substations, power-transmission losses are reduced significantly compared to single-end feeding.

5 Characteristics and Test results of the New Inverter Module

Being the conventional module, the new one is of the three-level type with the same outer dimensions and with identical electrical and mechanical connections in order to make it completely compatible. Fig. 7 shows the main circuit of the inverter module including the components of the asymmetric snubber circuit. Important to the mechanical design of the new module was the demand to install both types of semiconductors, PPI and HD-GTO, in the same module.

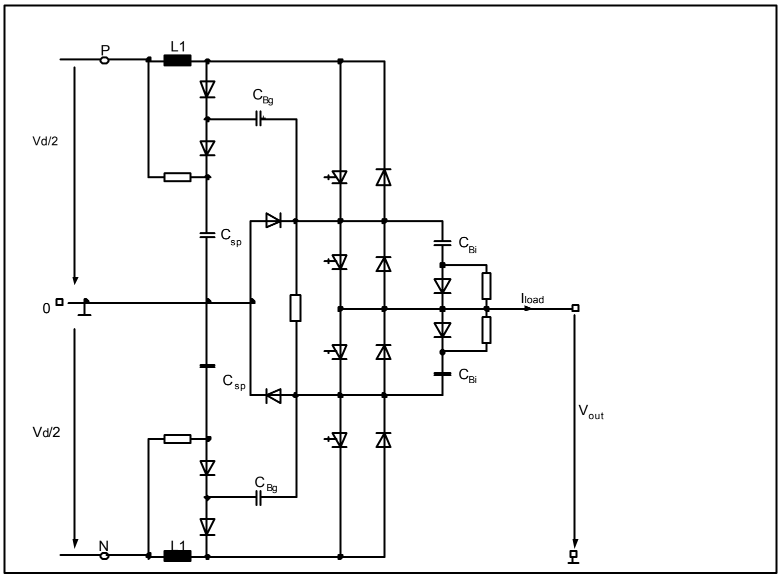

Fig. 7: Main circuit of the GTO-inverter phase including asymmetric snubber circuit

The installed HD-GTO corresponds to the ABB-type 5SHY 35L4503 (4.5 kV, 4 kA) and the PPI to the Toshiba-type 2991 (4.5 kV, 1.5 kA).For maximum utilization of the capabilities of the new semiconductor devices, the arrangement of the electrical and mechanical elements inside the new module is completely different. It was possible to decrease the installed capacity and inductivity by approximately half.

The new module was tested intensively in the high-voltage test laboratory [8,9]. In order to investigate the switching behavior of the PPI and HD-GTO and their ability to carry a DC-current and also in order to model the AC field conditions of the TRANSRAPID application, the new module was arranged in a single-phase inverter unit. The equivalent circuit is shown in Fig. 8.

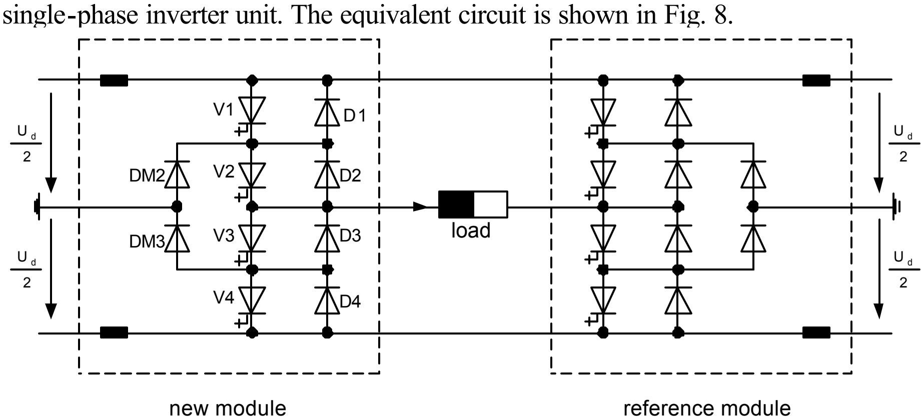

Fig. 8: Equivalent circuit during testing period

A conventional GTO-module was used as a reference. Because of its lower efficiency, it had to be cooled with water of a lower inlet temperature ($\vartheta_{in} \approx 20°C$) and switched with a lower pulse frequency than the new module (at least factor 3).
Fig. 9 shows the mechanical arrangement of the two modules in the laboratory during the testing procedure. The new module is seen on top.

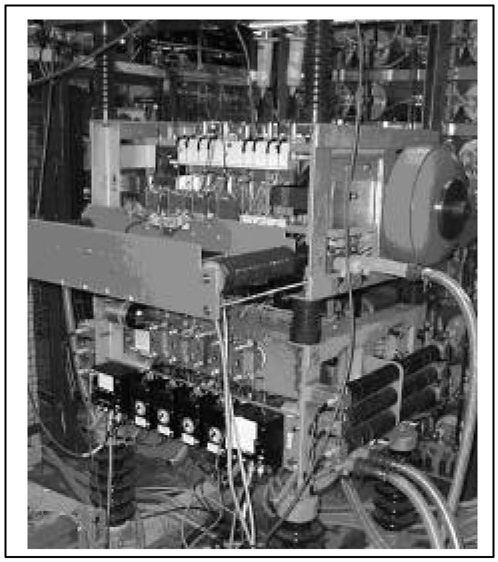

Fig. 9: New module (on top) during testing procedure

The switching capability was tested at least with 5 successive single shots. That means there were no stationary current flows via the switched semiconductor. An example of switching the PPIs can be seen in Fig. 10. The load current increases linearly (flowing via V2 and DM2, see Fig. 8). Then, V1 is switched on at 3.4 kA and it carries the load current for approximately 100 µs, before it is switched off at an instant current of approximately 3.6 kA.

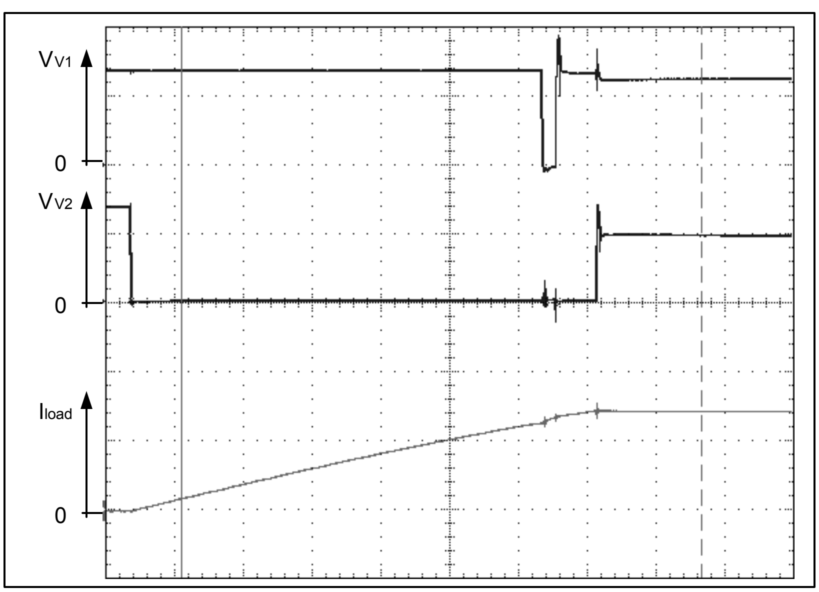

Fig. 10: Measurement of the switching capability (new module equipped with PPIs)
Voltage : 2kV/div Current : 2.5kA/div Time: 500µs/div

During the heat-run test, the switching frequency of the modules is very low. The load current has a DC shape, and current is only applied to the semiconductor switches V1 and V2 (or V3 and V4 for reversibility of the DC-current). An example is shown in Fig. 11. Here, the HD-GTOs were installed in the new module. Whereas the semiconductor V1 carried DC current of more than 2 kA during a period of 100 ms for less than one millisecond (recognizable from the voltage breakdowns of V_{V1}), the conductor V2 is subjected to a DC-current of about 2.1 kA for 70 ms.

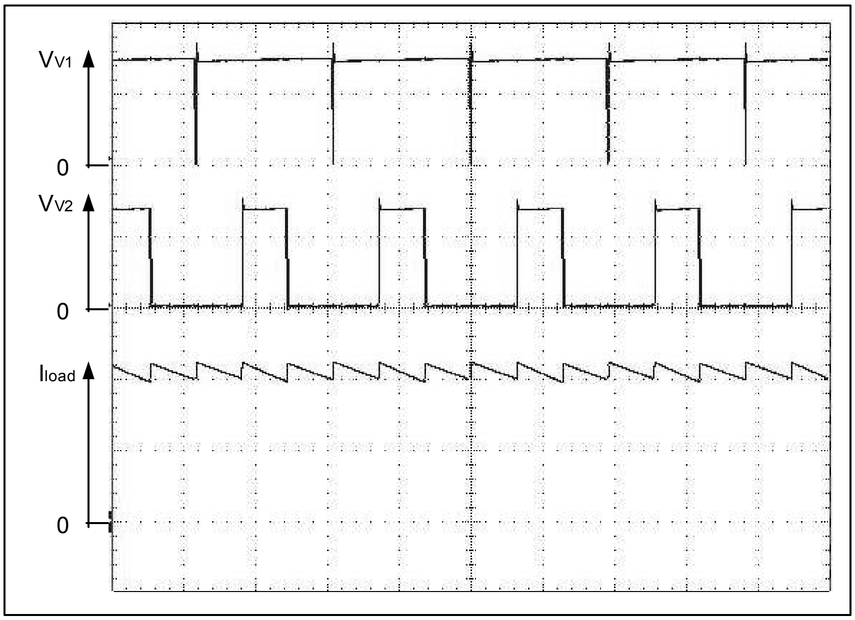

Fig. 11: Heat run test (new module equipped with HD-GTOs)
Voltage : 2kV/div Current : 1.0kA/div Time: 50ms/div

6 Results of Calculations regarding Field Behavior of the New Module

Because the AC-tests in the high-voltage laboratory could not exactly reflect the field conditions of TRANSRAPID operation (e.g. because of the pulse pattern applied during the AC measurements), the max. permissible AC currents of the module equipped with HD-GTO or PPI were calculated with account being taken of these field conditions.

The results of the calculations are shown in Fig. 12 and Fig. 13. They differ because in Fig. 12 the pulsing is according to the fundamental frequency whereas in Fig. 13 an asynchronous pulse modulation three times higher than fundamental frequency is assumed (according to the laboratory tests). For better understanding, the principal load current (assumed to have a sinusoidal shape) and load voltage of the calculations are sketched on top of the line diagrams.

Equipped with the HD-GTO, a higher rms-current capability is available in the low frequency range. Here, the theoretically permissible AC current and therefore the power output is nearly 40% higher than that of the same module equipped with PPI. The main reason is the higher on-state voltage of the PPI compared to the HD-GTO.

The situation changes at higher frequencies. Here, the PPI is able to feed higher currents because of its lower switching losses. The cross-over takes place around 250 Hz in Fig. 12 and 120 Hz in Fig. 13 respectively.

With reference to the requirements and characteristics of the operational ranges of the TRANSRAPID system as indicated in Table I, the following conclusions can be drawn [9,10]:

- According to Fig. 12, a current of 1200 A (rms) is gained with both elements, HD-GTO and PPI, at a fundamental frequency of 300 Hz
- According to Fig. 13, the asynchronous modulation with pulse frequency three times higher than fundamental frequency could be extended up to fundamental frequencies of 150 Hz for the HD-GTO and 180 Hz for the PPI (both at rms-current of 1200 A)

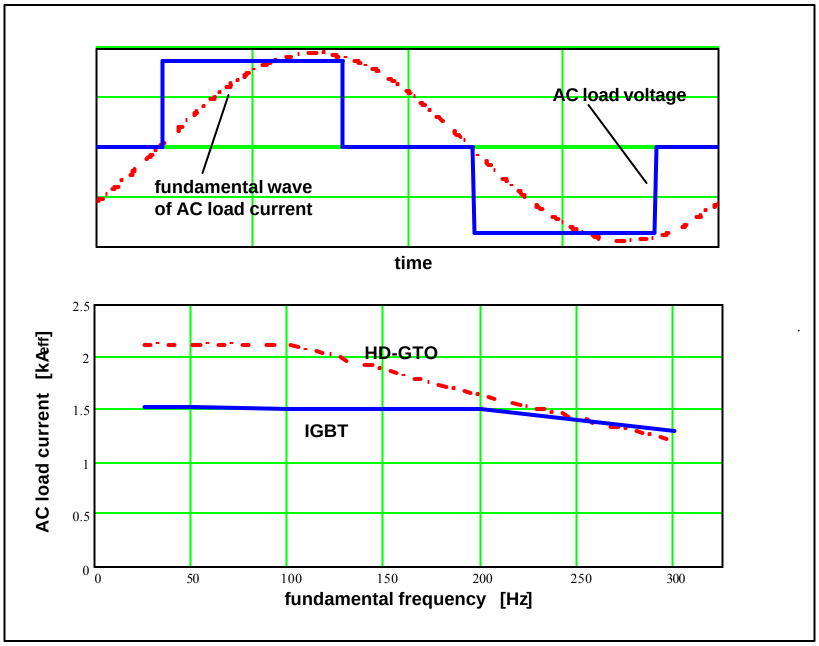

Fig. 12: Max. permissible AC rms-current of the module equipped with HD-GTO or PPI in dependence on fundamental frequency
(assumption: pulse frequency according fundamental frequency)

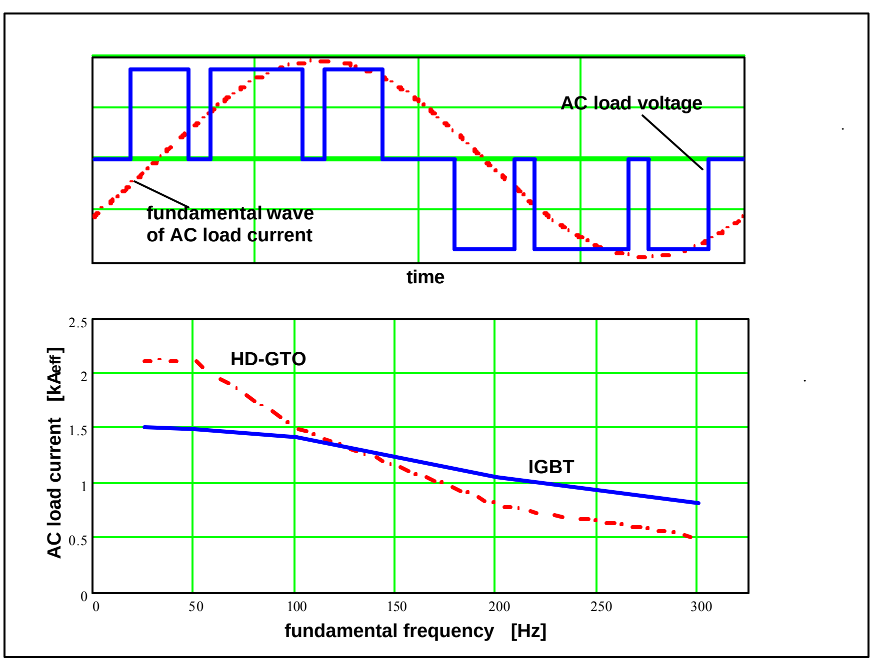

Fig. 13: Max. permissible AC rms-current of the module equipped with HD-GTO or PPI in dependence on fundamental frequency
(assumption: pulse frequency three times higher than fundamental frequency)

7 Conclusion

The drive components resulting from the system development program have been tested under realistic operating conditions in the course of modernizing the TVE test facility. Especially the ability of the converter to withstand the stresses due to harmonics, which are a special feature of the long-stator synchronous motor, and the new, successfully tested functions of the extended drive control system confirm the excellent performance capability as well as verify the suitability of the concept for use in revenue service.

The comparison between PPI and HD-GTO shows that both semiconductor elements are able to increase the efficiency of the inverter modules compared with the conventional GTO. The time has come to replace GTOs for the Transrapid propulsion converters. After this, further detailed development will have to be carried out to finalize the inverter design for field application.

8 References

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