DEVELOPMENT AND OPERATION RESULTS OF TRANSRAPID PROPULSION SYSTEM

(*) U. Henning, (**) D. Hoke, (***) J. Nothhaft

(*) Siemens AG, TS GT P, Werner-von-Siemens-Str. 67, 91052 Erlangen, Germany
Phone: +49 9131 727789, Fax: +49 9131 726534,
Email: uwe.dr.henning@siemens.com, http://www.siemens.com

(**) Siemens AG, TS LM TRA, Werner-von-Siemens-Str. 67, 91052 Erlangen, Germany
Phone: +49 9131 724991, Fax: +49 9131 724204,
Email: Dirk.Hoke@siemens.com, http://www.siemens.com

(***) Siemens AG, TS LM TRA, Werner-von-Siemens-Str. 67, 91052 Erlangen, Germany
Phone: +49 9131 728036, Fax: +49 9131 722526,
Email: Juergen.Nothhaft@siemens.com, http://www.siemens.com

Keywords

TRANSRAPID, propulsion system, power supply, Shanghai, operation results.

Abstract

For some time now, the synchronous long stator propulsion system of the TRANSRAPID has attained a level of maturity suitable for practical application. The world's first reference line for deployment of this system is located in Shanghai and connects Pudong International Airport with Long Yang Road station. Based on the well-proven, modular propulsion system structure, components of it have to be adapted according to the progressive technologies for future reference lines.

1 INTRODUCTION

The superhigh-speed TRANSRAPID magnetic levitation system is powered by a synchronous, iron-cored long stator linear motor which – in contrast to the classic railroad – is not installed on board the vehicle but in the guideway along the route. The special features of the long stator linear propulsion system enable its dimensions to be individually adapted to the running requirements of the route as well as to specific operating concepts.

A modular structured propulsion system has been developed for reference lines. Its interfaces are defined on the basis of system documents, which were mutually agreed on by the industrial companies involved and approved by the German Federal Railways Office (EBA) in the context of the TRANSRAPID certification program. Before using in commercial application the propulsion components were successfully tested under realistic conditions – particularly with double-end feeding – at the TRANSRAPID test facility in Emsland (TVE) in Northern Germany.

The world's first 30-km-long reference line making use of this technology connects Pudong International Airport and the financial district in the city area.

New concepts and prototypes for future applications both in long-distance and regional transportation applications are being developed on the basis of progressive technologies as part of a recently launched further development program.

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 propulsion units necessary to permit maglev operation over the guideway [1,2,3]. A propulsion unit remains in the switched configuration for as long as a vehicle is operating within the corresponding control range (drive control zone). It is capable of driving, accelerating and retarding one maglev train. A prolusion unit comprises the line section itself and, depending on the type of power supply selected, one or two propulsion blocks. The propulsion blocks 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 propulsion blocks, the necessary power supply and the decentralized operations control equipment (**Figure**). A substation for a dual guideway simply is composed of two single-guideway substations.

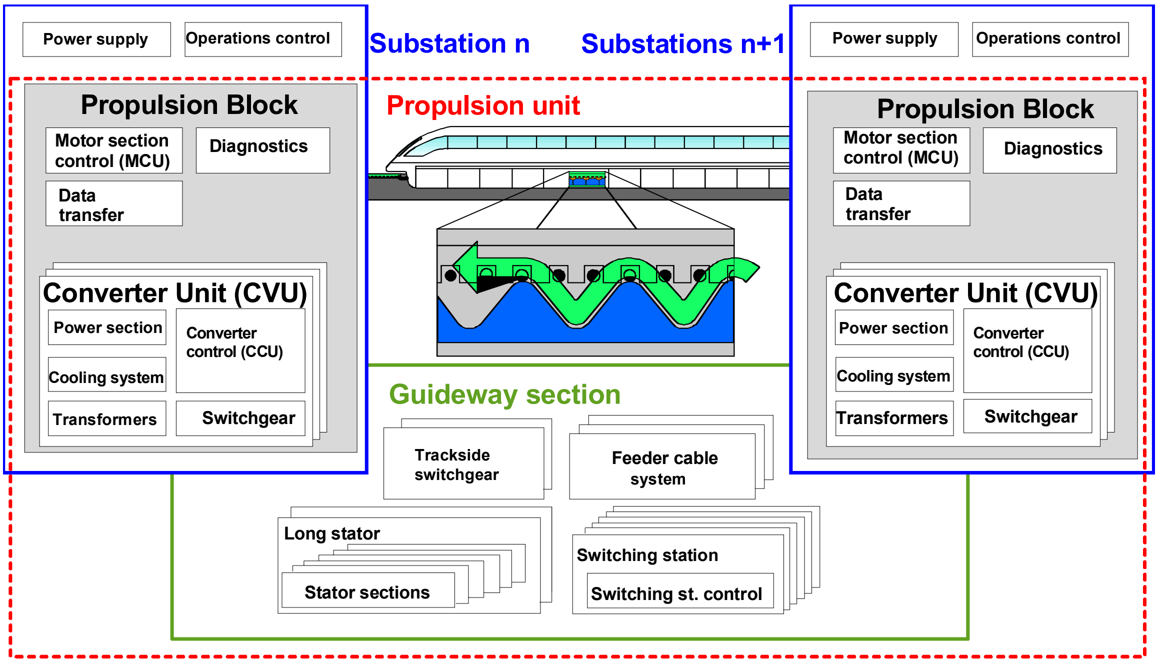

Figure 1: Structure of the propulsion system

A guideway section consists of two long stators, each comprising the necessary stator sections and switching stations to cover a distance of up to 50 km, the feeder cable systems (two or three according to the selected mode of stator section switching) and the trackside switchgear. A propulsion block is made up of the converter units as well as the motor section control, 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 guideway section from the two propulsion blocks of adjacent substations. If each substation has only one propulsion block 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 propulsion blocks 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.

2.1 Stator Section Switching

Main part of the synchronous long stator linear motor are its stator sections which are located on both sides of the track. Only the stator sections in which the vehicle is actually situated are connected to the feeding converter units by the respective feeder cable systems and switch stations. For commercial lines, two different types of changing from the actual stator section to the next one are designed: the step-by-step and the three step method (**Figure 1**). Both methods are characterized by locally displacing the right- and left-hand sides of the tracks' stator sections. When changing from one stator section to the next, the current of the feeding converter- and cable system has to be reduced to zero to ensure currentless switching of the vacuum contactors in the switching stations (because of life time reasons).

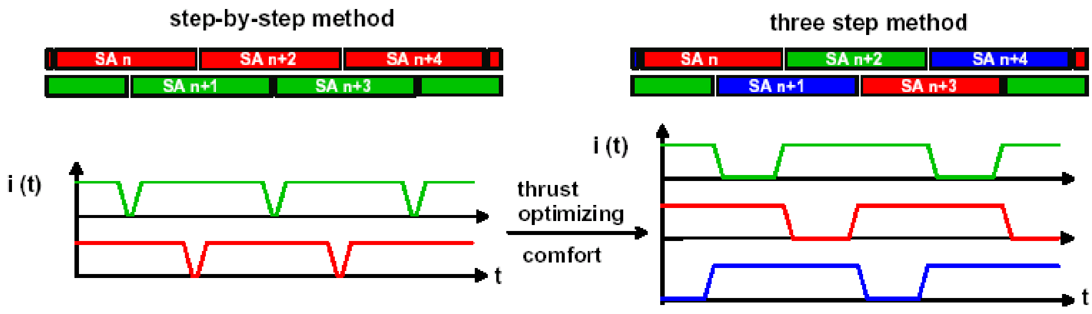

Figure 1: Methods for Stator Section Switching

In the step-by-step method only two different converter- and cable-systems are available. So reducing the stator current causes a drop in thrust for the vehicle which cannot be compensated by the other trackside in all cases. Because of this and the combined comfort aspects, in route areas with high thrust requirements (acceleration and maximum speed areas of the track) the three step method is used, which offers a third converter- and cable-system so that the "left" and the "entered" stator sections can be fed in the phase of stator section changing.
The step-by-step method is distinguished by its lower hardware requirements and is especially designed for steady-speed areas.

3 CONTROL SYSTEM

3.1 Architecture

In **Figure 2**, the architecture of the TRANSRAPID's closed-loop/open-loop drive control system for a drive control zone of a track is shown in detail [4]. The individual drive control zones contain each 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 role) is passed on from one MRS to the other MRS in parallel to the vehicle's movement (master-slave change-over). 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 on to 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 the step-by-step method 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.

Data transfer between the motor section 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 (change-over or loop-back)
- Computer nodes: module racks and system modules for handling communication 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).

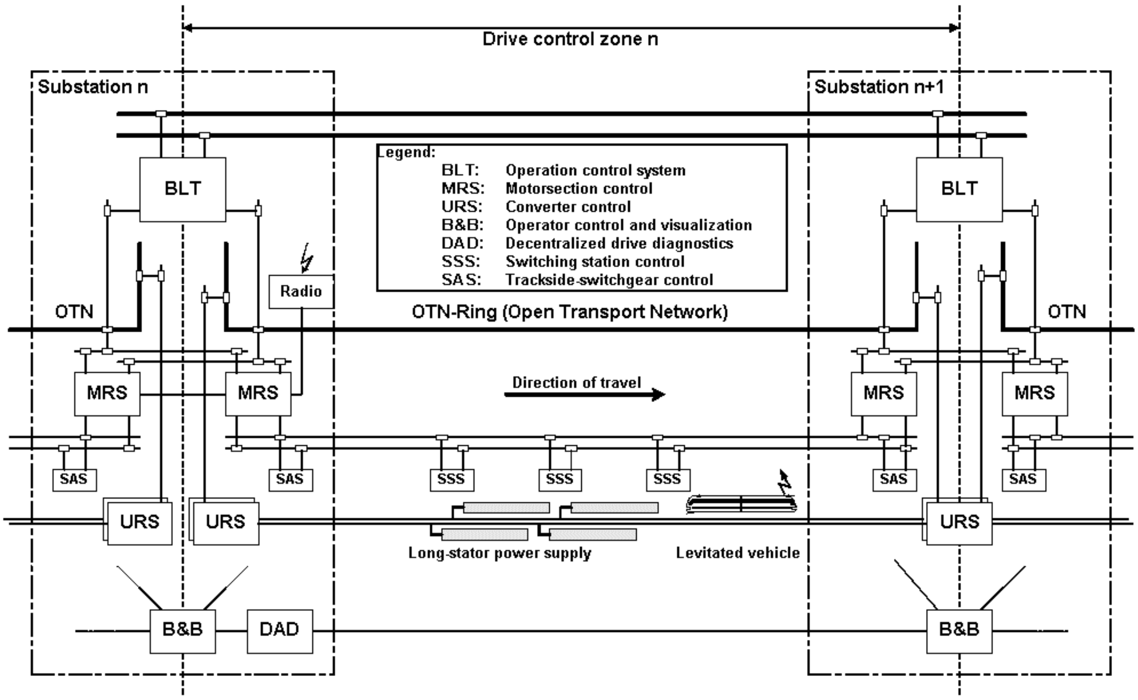

Figure 2: Architecture of the drive control system

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 control system

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

Motor section control. In order to comply with the set-points stipulated by the operation control system, 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 out-going 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 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.

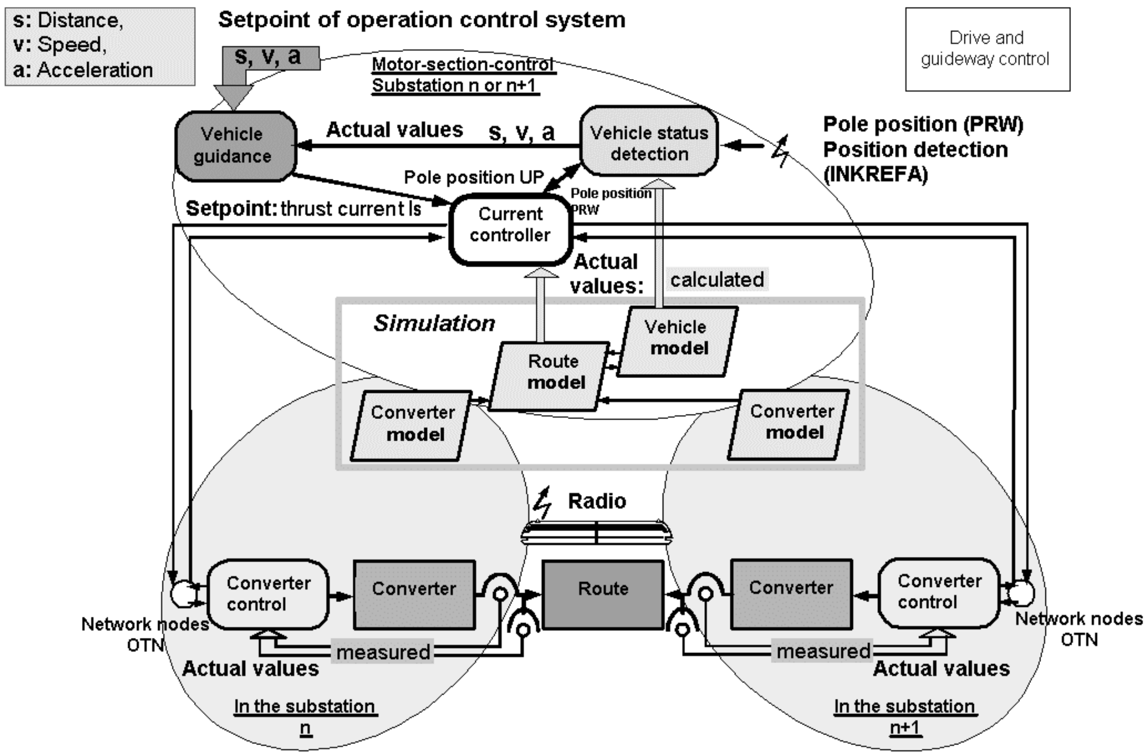

Figure 3: Basic functional units of the control system

The open-loop drive control system is responsible for coordinating all the events within a drive control zone and between drive control zones. These 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 communication interface to the operating control system is basically used for controlling the drive status 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 related 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.

Current control. 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 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. 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 set-point-current components of set-point 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.

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

Operator control, visualization, diagnostics. 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.

3.3 Platform of the 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) complete the platform. The special requirements for drive control (detection of voltages and currents, locking logic of the valve control system, processing of valve check back 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.
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 ms in order to avoid sampling effects due to the resonance frequencies of distributed networks.

4 THE SHANGHAI PROJECT

The contract to build the world's first TRANSRAPID reference line was signed in Shanghai on January 23, 2001. The line connects the new Pudong International Airport and Long Yang Road station, which is located in the Pudong financial center and is served by Metro Line 2. On December 31, 2002, only 23 months after the contract was signed, the VIP run with a promised speed of 430 km/h was completed successfully. Passenger service has been started December 29, 2003.

Figure 4: High-speed run, Nov. 2002

The propulsion system structure (**Figure**) meets all the requirements for commercial operation in Shanghai, such as a modular design, high reliability, high availability as well as low maintenance expenditure. The outstanding advantage of the modular structure introduced is that individual components can be replaced in accordance with project requirements without affecting the rest of the system. For example, three different converter power sections are being used in the Shanghai project in order to adapt the converter output to the route's particular requirements regarding acceleration and speed.
The double-track route is 30 km long. Consequently, at a maximum operating speed of 430 km/h, the travel time is only 7.5 minutes. Three 5-section maglev vehicles operate in round-trip mode at intervals of 10 minutes. The propulsion and power supply system has been specially configured for this service frequency.

Figure 5 shows a picture as displayed in the the operating and monitoring system: The main route with double tracks is divided into four propulsion segments, represented by the assigned motor section con-

trol systems (MCU). The average length of each stator section on the route is 1.2 km, with the three-step method being employed to implement stator section switching. To meet the high requirements regarding acceleration and speed, high-power propulsion blocks (CVU 111 – CVU 223) are used. These propulsion blocks are type I blocks, which means they can each feed the two adjacent propulsion segments in relation to the momentary position of the maglev vehicle. The propulsion blocks are located in two substations.
A medium-power propulsion block (CVU 321 and CVU 322) was chosen for vehicle shunting after the Pudong airport station because less power is needed in this particular instance. An additional propulsion segment is necessary for shunting purposes in the maintenance center area and is adequately served by a low-power propulsion block (CVU 9021 and CVU 9022). The current converter in this case is based on IGBT technology.
The moving vehicles are represented by the yellow dots near Pudong Int'l Airport and in the high speed part of the "lower" track.

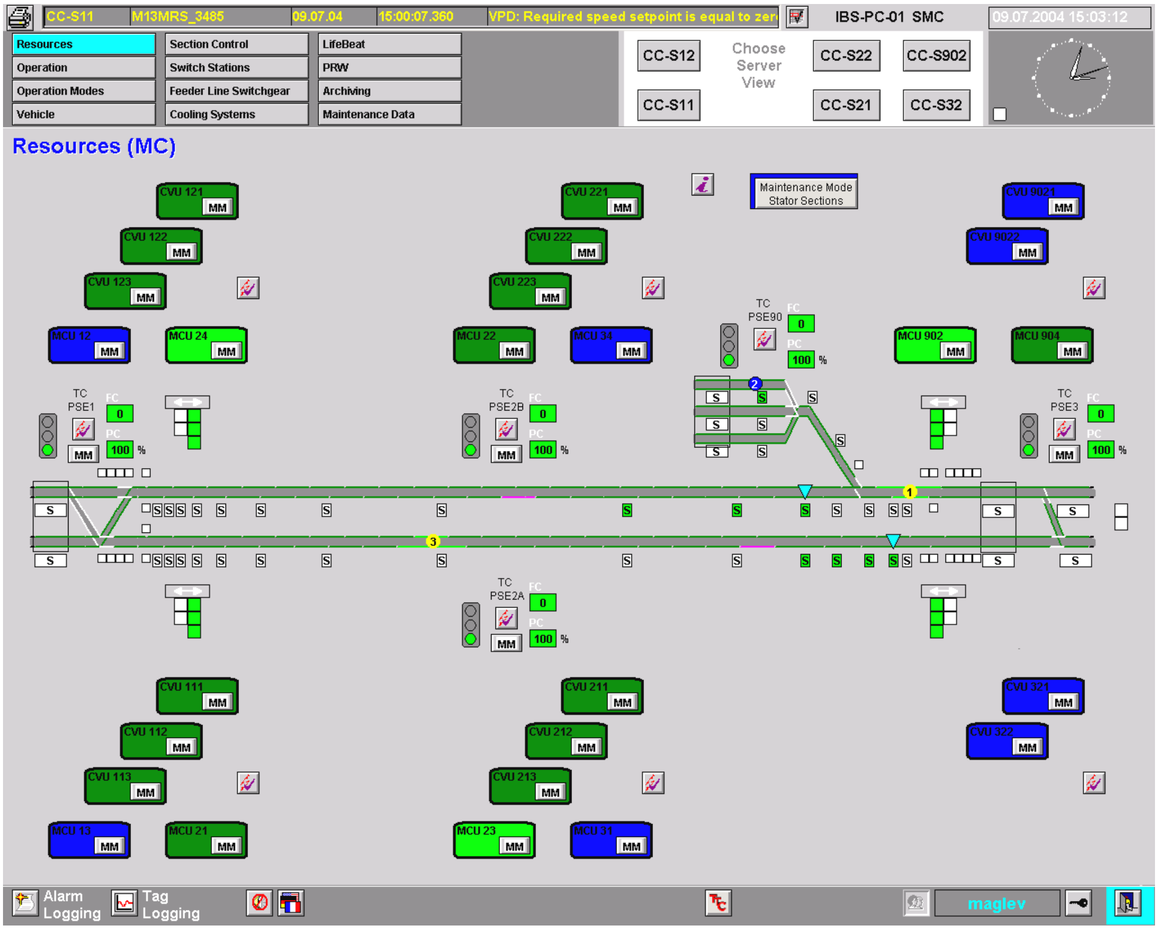

Figure 5: Propulsion layout of the Shanghai project as displayed in the operating and monitoring system

4.1 Component Testing

Before using in commercial application the components of the propulsion system resulting from the development programs of the past years were all tried and tested under realistic conditions at the TRANSRAPID test facility in Emsland (TVE) and proved successfully [5,6,7]. Above all, the following functions were tested:

- Multiple-substation operation
- Vehicle transfer/takeover between adjacent substations

- Double-end feeding from adjacent drive units
- Different stator section changeover methods
- Diagnostics capability
- Possibility of decentralized operator control and visualization
- Module concept, redundancy and the fault strategy.

Due to the fundamental preparation at the TVE it was possible to reduce the time for commissioning of the propulsion components in the Shanghai project significantly. This was a key success factor for the first TRANSRAPID application.

4.2 Operation Results of the Shanghai Project

In Figure 6 you can see the ride of a vehicle with five sections as it is performed several times each day. In the chart presented below, the vehicle is travelling from Long Yang Road Station (LYR) to Pudong International Airport (PIA): After leaving LYR the vehicle is speeding up with an almost constant average acceleration of 0,6 m/s^2 (except the velocity restriction due to a curve near LYR) until it reaches the maximum speed of 430 km/h. When traveling with 430 km/h for about one minute, a distance of about 7 km is covered. Then braking starts to meet the next velocity restrictions for the right turn in front of PIA. And finally the vehicle is decelerated to arrive in PIA station only 7.5 minutes after leaving in LYR.

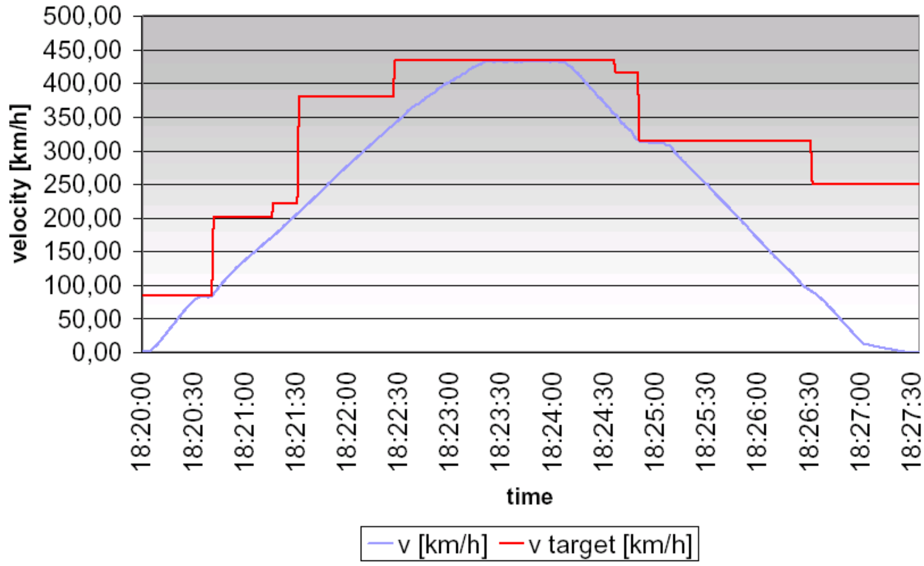

Figure 6: Speed profile

The upper part of Figure 7 shows the corresponding output currents of the three converters in LYR-substation: When starting in LYR, the vehicle is traveling in drive control zone #1 (represented by MCU 12 and MCU 13). There, on each side of the track only one stator section is installed. So only two converter units are in operation (I_{out} 21 of CVU 151 and CVU 152). They run in direct mode (refer to [12]) using single end feeding with an output current of up to 1485 A in this example. After changing in drive control zone #3 (MCU 21 and MCU 23 standing in for it), double end feeding is used, i.e. almost the same currents are fed to the stator sections by the converters in PIA-substation. The converters are operated in transformer mode with an maximum output current of the single inverters of 1200 A: in each converter, two inverters are connected in series via an output transformer with a projected ratio of 1 / 2.0. So the shown output currents of 600 A in the acceleration phase of the ride correspond to the maximum output current of the converters. When traveling with 430 km/h, only an average current of 220 A is necessary to guarantee this high speed.

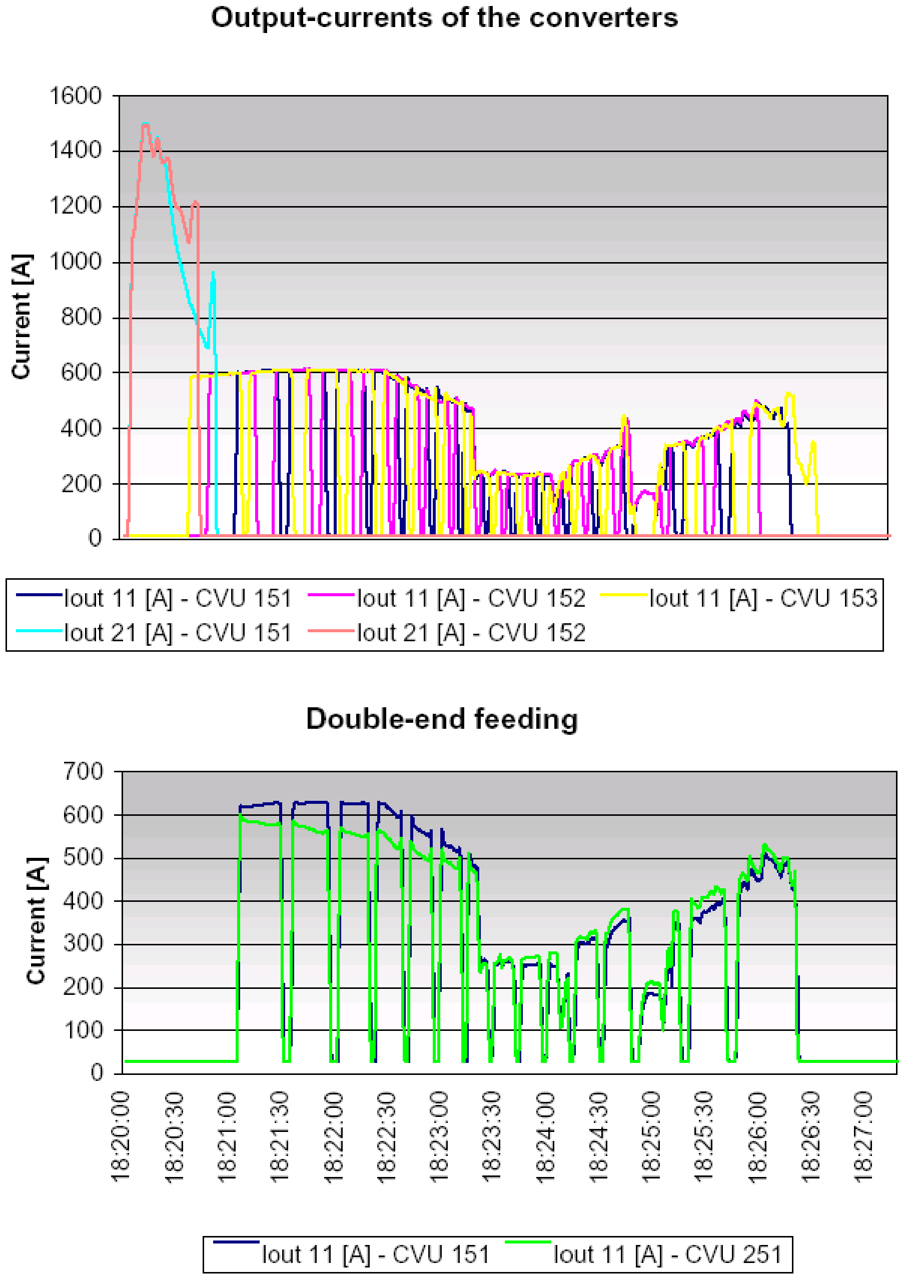

Figure 7: Output-currents of the converters

Double end feeding in drive control zone #3 is illustrated in the lower part of Figure 7, using the examples of converter unit 151 in LYR-substation and converter unit 251 in PIA-substation: An average division of nearly 50 : 50 is used. Nevertheless, the converter unit which is closer to the vehicle feeds the main share of the propulsion current to the respective stator section, i.e. the more stressed converter unit changes when the vehicle is traveling from LYR to PIA.

The shapes of the currents also show the use of the three step method for stator section switching. To illustrate this, a detail of Figure 7 is zoomed out in Figure 8: The shapes correspond to those, presented in **Figure 1** for the three step method.

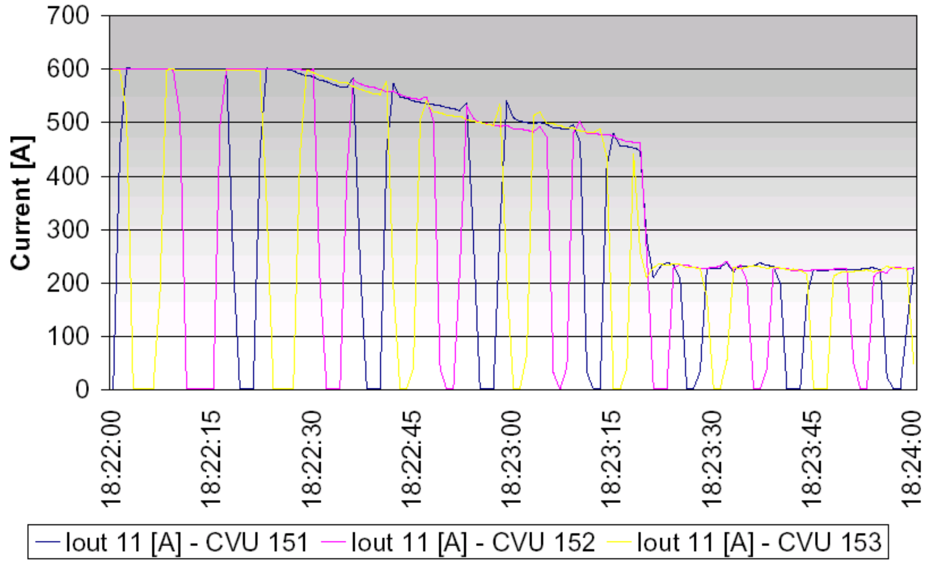

Figure 8: Output-currents of the converters - three step method

5 FURTHER DEVELOPMENT OF THE PROPULSION COMPONENTS

New concepts and prototypes for future applications both in long-distance and regional transportation are being developed on the basis of progressive technologies as part of a recently launched further development program. This applies to the converter power section and to the control system as well.

5.1 IGCT Converter

The next converter generation for TRANSRAPID will be based on hard–driven GTO (HD-GTO or IGCT - Integrated Gate Commutated Thyristor). This converter type will be the standard converter also for industrial applications as steel and rolling mills. The first prototype converter for TRANSRAPID will be tested in 2005 and is expected to have significant advantages to the actual GTO converter generation:

- Investment cost reduction for converter units
- Increased output performance
- Increased reliability
- Increased efficiency
- Regeneration of braking energy with AFE (Active-Front-End)

5.2 Propulsion control system

To meet requirements of future applications, Siemens is already today investigating alternatives to the existing SIMADYN D platform for the control system. The main parameters for the analysis are the following:

- Standardization (economy of scales, long-term availability, reduction of maintenance costs)
- Open technology (autarky, long-term availability, flexibility)
- Communication performance (remote diagnostic and maintenance, adaptable to new track layouts)

There are three hardware platforms that meet the above mentioned requirements to a big extent and therefore have been short-listed for future applications:

- SIMATIC TDC: Successor system to Simadyn D, special hardware components with related real-time Operating System
- SICOMP IMC: Industrial microcomputers (PC based) for automation systems with hardware-independent real-time Operating System
- SIMOTION: standard platform optimized for automation solutions for motion control of machine tools.

For realization SICOMP has been chosen as it allows flexible, modern (UML, C++) programming for design-to-customer applications based on standard components.

6 CONCLUSION

The modular structure of the propulsion and power supply system for TRANSRAPID reference lines makes it possible to create custom-made solutions for each individual project. The layout of the first TRANSRAPID project in Shanghai is derived from this structure. This project marks the international breakthrough for the TRANSRAPID system. Apart from its task of transporting passengers, this reference line has also been a touch-stone for the technical performance of the overall maglev system as well as for the ability of the participating companies to create a complex transportation project with a new technology in a very short time. The passenger operation starting December 29, 2003 and the signing of the Overall Acceptance Certificate by the customer on April 13, 2004 prove the success of the reference line in Shanghai.

References

[1] Henning, U.; Hellinger, R.; Nothhaft, J.: The TRANSRAPID Propulsion System – Results of Operation. *Proc. the 16th Intern. Conf. on Magn. Levitated Systems*, Rio de Janeiro 2000, pp. 269-274.

[2] Henning, U.; Kamp, P.G.: Static Frequency Converter of the TRANSRAPID Propulsion System – results of operation. *Proc. the 8th European Conf. on Power Electronics and Applications*, Lausanne 1999.

[3] Henning, U.; Hochleitner, J.; Kamp, P.G.: Langstator – Synchronmotorantrieb des TRANSRAPID. *Elektrische Bahnen* 93(1995) H.7, pp. 230-235.

[4] Henning, U.; Hoffmann, R.; Hochleitner, J.: Advanced Converter and Control components for TRANSRAPID. *Proc. the 17th Intern. Conf. on Magn Levitated System and Linear drives*, Lausanne 2002.

[5] Nothhaft, J.; Henning, U.: Propulsion System for the Magnetic Railway Line Shanghai Pudong Airport – Long Yang Road Station. *Proc. the 3d Intern. Symposium on Linear Drives for Industry Applications*, Nagano 2001, pp. 389-394.

[6] Henning, U.; Hellinger, R.: Magnetbahnantriebstechnik für die Anwendung. *Elektrische Bahnen* 97(1999) H.3, S. 93 – 99.

[7] Henning, U.; Hellinger, R.: Antriebsausrüstung des Transrapid. *Elektrische Bahnen,* 101(2003), pp.81-90

[8] Helmer, J.; Henning, U.; Kamp, P.G.; Nothhaft, J.: Advanced converter module for high speed maglev system TRANSRAPID. *Proc. the 9th European Conf. on Power Electronics and Applications*, Graz 2001.

[9] Kamp, P.G.; Helmer, J.; Henning, U.; Nothhaft, J.: Advanced Converter Module for High Speed Maglev System TRANSRAPID. *Proc. the Intern. Conference Power Electronics*, Shanghai 2002, pp. 196-201.

[10] Henning, U.; Hoffmann, R.; Hochleitner, J.: Advanced static power converter and control components for TRANSRAPID maglev system. *Proc. the Power Conversion Conf.*, Osaka 2002, pp.1045-1049.

[11] Engel M., Hellinger R., Nothhaft J.: Power Supply and Propulsion System for Transrapid Commercial Lines, *Proc. the 17th International Conference on Magnetically Levitated Systems and Linear Drives*, Lausanne 2002.

[12] Blank K., Engel M., Hellinger R, Hoke D., Nothhaft J.: Antrieb und Energieversorgung des Transrapid, *ZEVrail* 10/03, pp. 70 – 87.