Safety Certification and Approval of the Propulsion and Power Supply System of the Shanghai Transrapid

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Abstract

To ensure the safety of a technical system in public transport an approval by the competent Authority is needed. The approval requires the assessment of all aspects on the subsystem and overall system level relevant for safety. Considering the structure and the functionality of the Propulsion and Power Supply System (PPS) of the Shanghai Transrapid the paper describes the aspects relevant for safety, the course and the contents of the safety certification based on the methods of the European railway safety standard EN 50126.

1 Safety Assessment and Certification

One precondition for starting the commercial operation of the Transrapid in Shanghai was the approval of the technical system. The approval by a Chinese Authority required a safety certification with independent assessment of all safety relevant aspects of the system under the conditions of operation.

Because of the world-wide first commercial application of the Transrapid abroad first of all the contents, the responsibilities and the course of the approval process had to be specified and agreed by the participated project partners:

- the Shanghai Maglev Transportation Development Co., Ltd. (SMTDC),
- the Shanghai High-speed Transrapid Project Construction Headquarters (SHTPCH), entrusted with the approval as the competent Authority,
- the German suppliers consortium.

As defined in the contract between the Chinese Customer and the German Consortium the technical system of the Shanghai Transrapid was manufactured, delivered and built up according to the valid European or German standards. For the safety certification of the technical subsystems delivered by the German side as the vehicles, the Propulsion and Power Supply System (PPS) and the Operation Control System (OCS) the suppliers concerned had chosen independent third party experts authorized by the German Federal Railway Authority EBA for the Transrapid technology. Thus the experience of the former approval activities for the Transrapid in Germany could be contributed. This procedure was agreed with the Chinese project partners before.

To meet the requirements of the safety certification process a specific Safety Concept for the Shanghai Transrapid project has been developed by the supplier's consortium. Following the methods of the new European railway safety standard EN 50126 [1] the Safety Concept consists of

- Part 1: The Safety Procedure,
- Part 2: The Overall System Hazard Analysis,
- Part 3: The Proof of Safety Measures.

All safety relevant hazards are determined in the 'Overall System Hazard Analysis'. The hazards are subdivided into the responsible subsystems and the respective causes/ situations. The subsystem-related hazards are marked by a specific hazard sub-code. The protection measures against the hazard effects are described in the 'Proof of Safety Measures' and marked by a safety measure code. Thus these documents representing all causes, effects and measures relevant for safety were the basis for the safety certification of the overall system. For this reason the safety assessment of any subsystem had to refer strictly to the overall safety concept.

The Propulsion and Power Supply System (PPS) as one of the main technical subsystems of the Transrapid consists of a large number of components with a great extension alongside the track. As described in the following the PPS itself does not contain any safety relevant functions for the system's operation but it has a number of safety relevant interfaces to other subsystems. Based on the Overall System Hazard Analysis of the Safety Concept the safety relevant aspects related to the PPS can be subdivided in two types:

1. safety relevant aspects typical for Transrapid technology, such as maximum acceleration, Decentralized Propulsion Shut-off and earth fault protection (see chapt. 3) and
2. general safety aspects of electrical devices, such as touch protection, fire and explosion protection, electromagnetic compatibility.

For their safety certification a detailed "Concept for Preparation of Certification" was worked out by the supplier Siemens with the help of the independent third party expert. The concept was presented to the client SMTDC in an early project phase. Since an agreement was reached soon this concept became the manual for the realisation of the PPS safety assessment and the later approval by the Authority SHTPCH.

Based on the concept mentioned above the certification process for the PPS comprised

- the examination of the related technical documentation by the independent expert,
- the specification and realisation of special safety tests and inspections on site and
- the preparing of assessment reports by the independent expert.

To increase the understanding of the safety relevant aspects and the performed examinations and tests the structure and the functionality of the PPS of the Shanghai Transrapid shall be explained once more.

2 Principle structure of the Propulsion and Power Supply System (PPS)

The propulsion system of a Transrapid line is divided in several Propulsion Segments (PSE) driving the vehicle in the respective track section. The structure of a typical Propulsion Segment with Double Feeding and three-step Stator Section sequencing (see [2] for more details) as used for the main track of the Transrapid Shanghai is shown in Fig. 1. It is marked by existence of two Propulsion Blocks feeding-in the long-stator motor in parallel. The Propulsion Blocks are housed in the Power Substations located at each end of the Propulsion Segment. At the Shanghai Transrapid Project the length of such type of Propulsion Segment amounts of about 28 km.

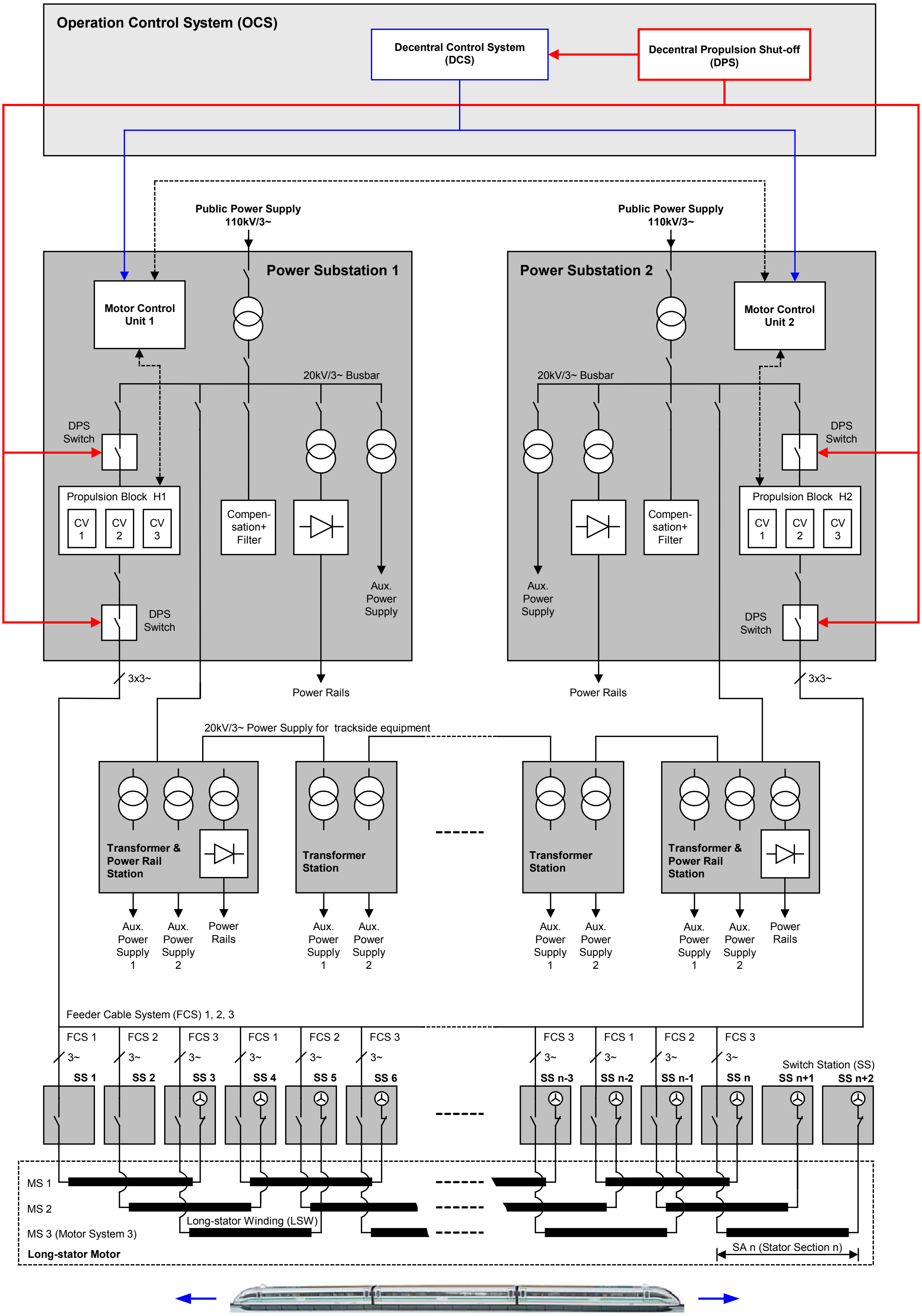


Fig. 1: Propulsion and Power Supply System of a typical Propulsion Segment used for the main track of the Transrapid Shanghai (principle overview)

A Propulsion Block for three-step stator section sequencing consists of three Converter Units (CV) supplying three separate Motor Systems (MS) with electrical power variable in voltage, current and frequency via separate Feeder Cable Systems (FCS). The Propulsion Blocks for the main track of the Transrapid Shanghai are equipped with high-power Converter Units (type H) achieving a maximum output power of 15 MVA each.

Fig. 2: Power Substation 2 (Pudong) of the Shanghai Transrapid

On track side the Propulsion Segment consists of the long-stator motor including the Long-stator Winding (LSW), the Switch Stations (SS) and the Feeder Cable Systems. The long-stator motor is subdivided in Stator Sections (SA) whose average length amounts of about 1.2 km at the Shanghai Transrapid. The Switch Station (SS) contains the Feeding Contactor connecting the LSW of the Stator Section to the respective Feeder Cable System and the Star-point Contactor shunting the ends of the LSW of the neighbouring Stator Section. The Stator Sections are staggered and arranged on the right and the left side of the track alternately. The Propulsion Control System (PCS) switches-on and -off the Feeder Contactors of the Stator Sections one after another following the movement of the vehicle.

Besides the Propulsion Blocks the Power Substations contain a number of equipment necessary for the main power supply and the auxiliary power supply of the Transrapid System i.e.

- the Filter and Compensation System for filtering of the harmonic currents and for compensation of the reactive power generated by the propulsion system on the side of feeding-in from the 110 kV public power supply grid,
- the DC power supply equipment supplying the electrical systems of the vehicle via power rails when it stops at the station or at an Auxiliary Stopping Area (ASA),
- the auxiliary power supply (440 V) supplying the power for the substation auxiliaries and for the equipment of other Transrapid subsystems if applicable.

A further function of the PPS is the supply of the auxiliaries spread over the length of the track e.g. Switch Stations, Radio Base Stations, etc.. The power supply system for the trackside equipment comprises the 20 kV power line powered from both substations of the PSE and the Transformer Stations (TS) providing low-voltage (440 V) auxiliary power circuits (Auxiliary Power Supply). Additionally the Transformer Station may contain the DC power supply equipment supplying the electrical systems of the vehicle via power rails when it stops at a neighboured Auxiliary Stopping Area.

3 Interfaces of the PPS with the other subsystems relevant for safety

As explained in chapt. 1 the Propulsion and Power Supply System is characterized by a large number of standard components with a great extension alongside the track. This circumstance requires an overall system concept that ensures a safe operation of the Transrapid system in any case e.g. in case of a component failure or a malfunction of the PPS. During the development phase of the basic concept of the Transrapid system the mentioned requirement has been considered consequently.

According to the concept the operation of the Transrapid system is safely monitored and protected against non-safe state by the Operation Control System (OCS). For that purpose the OCS comprises a number of safety functions working independent from the PPS and the other subsystems. The PPS itself doesn't contain any safety relevant functions but it has a number of safety relevant interfaces to the OCS and the vehicle as

- the maximum acceleration/ deceleration in case of malfunction,
- the switches of the Decentralized Propulsion Shut-Off function (DPS switches) and
- the short-circuit and earth fault protection of the Long-stator Winding and the Feeder Cable System.

3.1 Maximum acceleration/ deceleration

The maximum acceleration/ deceleration values in case of malfunction of a propulsion unit are input values for the design of the Transrapid guideway and also for determination of the speed limit curves which represent important parameters of the OCS's Speed Profile Monitoring function. The Speed Profile Monitoring function permanently monitors the actual speed of the vehicle and triggers a forced stop at the next stopping point using the safe brake (i.e. the eddy-current brake) when the vehicle's speed has violated the maximum speed limit curve [3]. Through this function it is ensured that any hazard point could not be driven through considering the most unfavourable fault scenario.

According to the physical principle of the synchronous long-stator motor of the Transrapid the thrust force and braking force (at operational braking) of the vehicle F_S depends proportionally from the fundamental wave current I_{1S} flowing in the stator winding

$$F_S \sim I_{1S} .$$

Therefore, in order to generate a high longitudinal acceleration or deceleration one or several faulty converter unit(s) must generate on the output a stationary or fluctuating over-current. Because of the inertia of the vehicle a faulty current should be applied for a sufficient long time to have an effect on to the acceleration or deceleration – more than a half period as a rule.

Furthermore, in order to generate thrust force or braking force the faulty Converter Unit(s) must keep the frequency and the phase angle of the output current in synchronism with the actual speed and location of the vehicle as condition.

The Propulsion Block is equipped with a protection system protecting the Converter Unit's output against over-current as well as the vehicle against high acceleration or deceleration values. It comprises two protection grades working independent from each other (see Fig. 3):

1st grade: Monitoring of the current (fundamental component) of each outgoing feeder of the Propulsion Block. If the current exceeds the limiting value the switching pulses for the respective converter power section are blocked and the contactors of the output switch gear are opened.

2nd grade: Monitoring of the output current of each inverter phase of the Converter Units. If the instantaneous value of the phase output current exceeds the limiting value, the switching pulses for the converter power section are blocked quickly and the contactors of the output switch gear are opened.

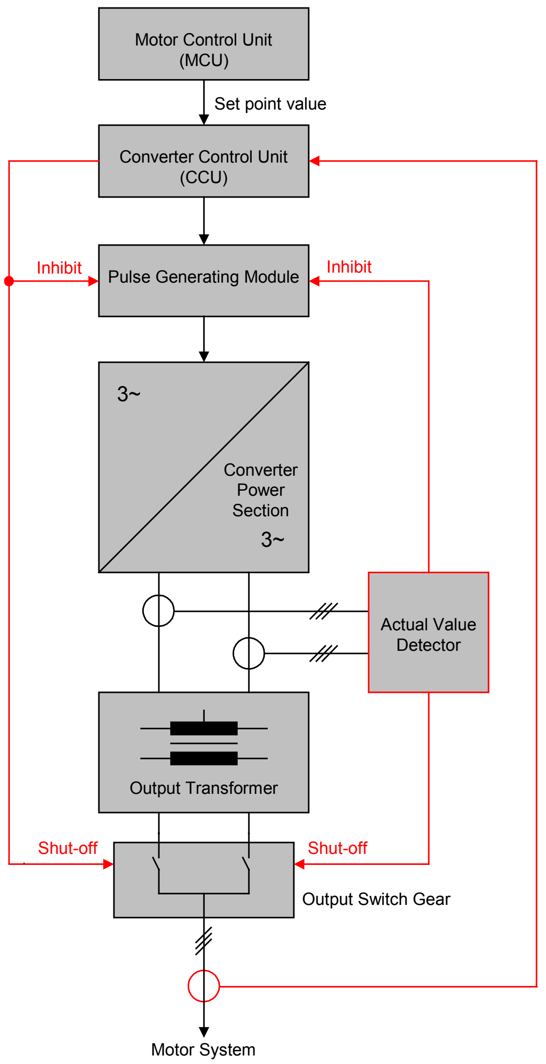


Fig. 3: Over-current protection concept of the Converter Units

3.2 Decentralized Propulsion Shut-off Switch (DPS Switch)

In order to prevent an influencing of the autonomous eddy-current brake through the long-stator motor, a further safety function of the OCS, the Decentralized Propulsion Shut-Off function (DPS function) ensures that the propulsion unit is shut-off safely before activating the eddy-current brake [3]. In the propulsion system the switching elements of the DPS function are installed, the so called 'DPS Switches'.

According to the Safety Concept of the Transrapid System the safe breaking of driving currents has high priority because a braking may not be influenced by any thrust forces generated from the propulsion system when the vehicle uses the safe brake (eddy-current brake).

The DPS function meets this requirement using vacuum circuit breakers (DPS Switches) arranged in the 20 kV power supply circuit as well as in each outgoing feeder of the Propulsion Block (see Fig. 4). The circuit breakers have a high reliability and they are safely controlled from the DPS computer of the Operation Control System, i.e. their control is fully independent from the Propulsion Control System (PCS).

If a Decentralized Propulsion Shut-off is requested by OCS's safety computer all DPS Switches of a Propulsion Segment are opened safely. The shut-off ensures that neither propulsion nor brake current will flow in the trackside feeder cables and thus in the long-stator winding in any operational situation.

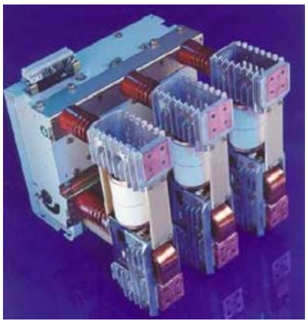


Fig. 4: Vacuum circuit breaker used for the Decentralized Propulsion Shut-off (DPS) function

3.3 Earth fault protection of the Long-stator Winding and the Feeder Cable System

The PPS comprises a large number of power cables laid along the entire length of the track. All power cables including the feeder cables and the cables of the Long-stator Winding are exclusively equipped with cable shields. In order to ensure a high availability and safety of the Transrapid system a comprehensive protection system against earth faults is necessary which is able to detect and to locate earth faults at any place of the equipment.

The most important requirement for the earth fault protection concept is the capability to detect an earth fault over the entire length of the long-stator winding. So the early detection of an earth fault in the winding and the immediate isolation of the respective stator section prevents that the fault could expand into a short-circuit causing a short-circuit current in the winding that could have influence on the magnetic levitation characteristics of the vehicle.

In the case of a short circuit in the Feeder Cable System secondary caused by an earth fault of a feeder cable the short circuit current flowing into direction of the Long-stator Winding is essentially lower than in the case mentioned above. So the risk of influencing the magnetic levitation system of the vehicle is not given. The earth fault protection of the Feeder Cable System is mainly designated to prevent a fire in the cable trench. Fig. 5 shows the principle concept of the trackside earth fault protection.

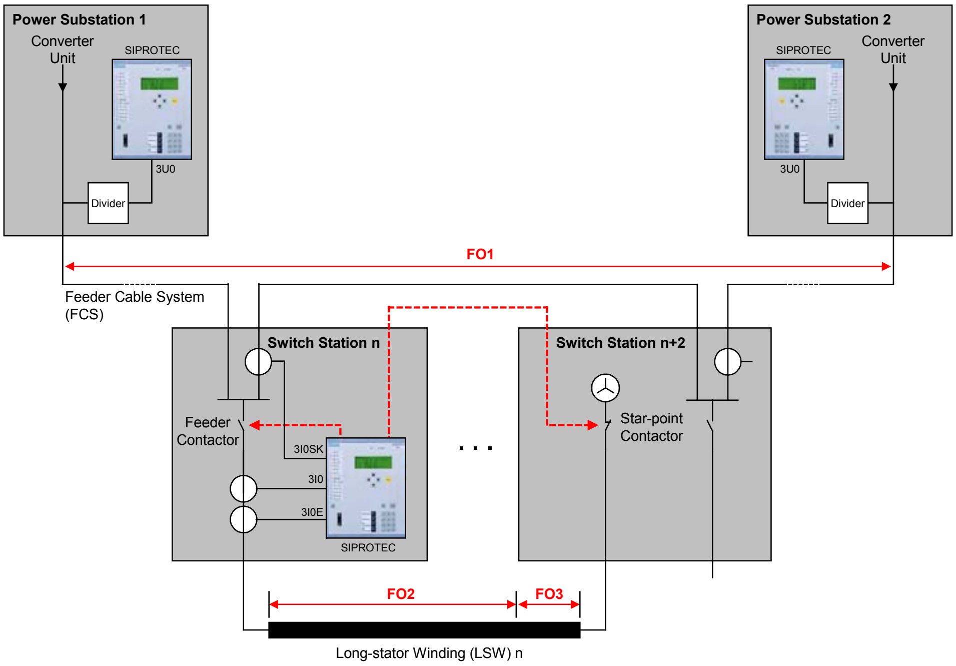


Fig. 5 Earth fault protection concept of the Transrapid propulsion system

The concept considers 3 different locations (FO) of an earth fault:

FO1: within the Feeder Cable System
FO2, FO3: within the Long-stator Winding (FO3: within the winding segment near the star-point).

An earth fault within the Long-stator winding (fault location FO2, FO3) is detected by the digital protection device (SIPROTEC) that is installed in the Switch Station feeding-in the respective stator section. The device monitors the zero current ($3I_0$, $3I_{0E}$) of the three-phase system. It ensures a reliable detection of earth faults within the entire operating and frequency area of the propulsion system.

If the zero current exceeds the limiting value the feeder contactor and the star-point contactor of the respective stator section are opened immediately and locked-out. The repair of the faulty winding takes place during the nightly operation pause. According to the Rules & Regulations the interlocking of the stator section may be overridden by the authorized operator only after the obligatory high voltage test (insulation test) has been carried out successfully.

An earth fault in a feeder cable (FO1) is detected by another protection device (SIPROTEC) that is installed in the Power Substations. The device monitors the zero voltage ($3U_0$) of the outgoing feeder. After an earth fault was detected the respective Feeder Cable System (Motor System) is automatically shut down and locked. The protection system allows the indication of the affected cable section and transmits this information to the diagnosis system. According to the Rules & Regulations the authorized operator may restart the Motor System after it was repaired and the obligatory high voltage test (insulation test) was performed successfully.

4 Examinations and safety tests

4.1 Examination of the project documentation

Based on the agreed ‘Concept for Preparation of Certification‘ (see chapt. 1) the first assessment step was the examination of the project documentation. It should guarantee, that all safety relevant aspects of the PPS are documented completely and factually correct. Therefore the technical documentation of the PPS had to consist of the following documents:

1. Equipment Manual and Equipment Identification Lists,
2. Operating Instructions, including a description of the main functionalities, but at least of the safety relevant aspects,
3. Circuitry documents,
4. Mounting Instructions (at least on the subsystem level),
5. Type and/or routine test reports of the components,
6. Instructions for Training of the operational stuff,
7. Instructions for Maintenance (if necessary).

The examination contained the following steps:

- Evaluation of logic and completeness of the documentation
- Examination of the type and routine test records and reports
    - Completeness of test reports
    - Fulfilment of the valid standards by the test specifications
    - Realization of the tests in accordance with the test specifications
    - Adequate test results

4.2 Theoretical certificates

For certain safety relevant interfaces theoretical certificates were required. This concerned e.g. the failure probabilities of the stator current protection function and of the Decentralized Propulsion Shut-off switches. The supplier was asked to submit these certificates for examination by the expert as described below.

4.2.1 Probability of maximum acceleration/ deceleration

In case of malfunction the propulsion system could produce a none regular stator current, which could lead to a non regular thrust force. The related maximum acceleration/ deceleration may not exceed defined maximum values with a certain probability. For the safety certification all failure scenarios which could lead to malfunctions of the propulsion equipment had to be proved. This comprised a fault tree analysis to get the corresponding probabilities as well as a calculation of the resulting acceleration/ deceleration values for all failure scenarios. Therefore the specific layout conditions of the PPS as well as the different protection limits of the converters had to be considered.

The supplier has realized these items with an internal process following the methods of the European Standard EN 50126. The calculation of the failure rates based on the fault tree analysis and reliability field data of all involved components was carried out with a standard software solution (ZUSIM – Reliability Assessment of Complex Technical Systems). The used methods, the considered technical data and the results of the calculations were examined by the independent expert. The correct setting of the current limits of the converters has been proven during the safety tests on site.

4.2.2 Failure probability of the DPS switches

The examination of the safety relevant Decentralized Propulsion Shut-Off function was actually a part of the OCS safety certification. But due to the location of the DPS switches (vacuum circuit breakers, see chapt. 3.2) in the input and output switchgear of the substation they have to fulfil interface requirements concerning their failure probability. This was proved by means of a theoretical certificate, too, considering the different failure scenarios and the special equipment of the Propulsion Shut-off devices. The calculations based on field data of the components and carried out with a standard software tool were proved by the independent expert.

4.3 Safety tests on site

A substantial part of the safety assessment was the realization of special safety tests on site in Shanghai. The tests were performed in order to prove the features and quality of the equipment with relevance for safety. The subjects of the safety tests concerning the PPS have been defined by the expert.

In preparation of the safety tests the supplier of the PPS has established detailed test specifications for all safety tests. The independent third party expert has assisted the preparing process. The examination work contained the following steps:

- Defining of the required tests,
- Evaluation of the test specifications,
- Performing the tests on site in attendance of the expert,
- Evaluation of the test reports.

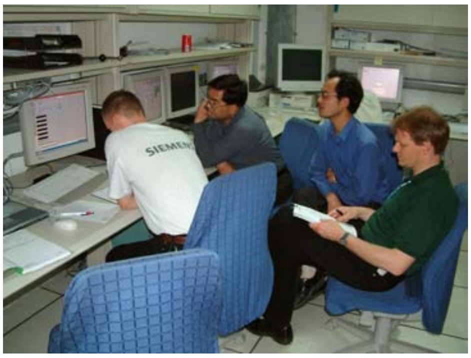


Fig. 6: Safety test on site

Because of the time schedule of the commissioning process of the PPS the tests had to be subdivided into two test phases. Phase 1 covered all tests which had to be done before the VIP run in 2002. Phase 2 contained the tests after finishing the commissioning of the entire system of the PPS in 2003.

The following tests had been required:

- Test of the over-current protection setup of the propulsion system (proof of the current limits, relevant for the determination of the maximum acceleration/ deceleration),

- Test of the long-stator and feeder cable earth fault protection (relevant for avoiding of short circuits in the long-stator windings),
- Visual inspection of the preventive fire and explosion protection measures,
- Visual inspection or rather measurement of all grounding connections (performed by the supplier, examination of the measurement records by the expert),
- EMC Test for the PPS subsystem (performed by the supplier in attendance of the expert, examination of the test report by the expert).

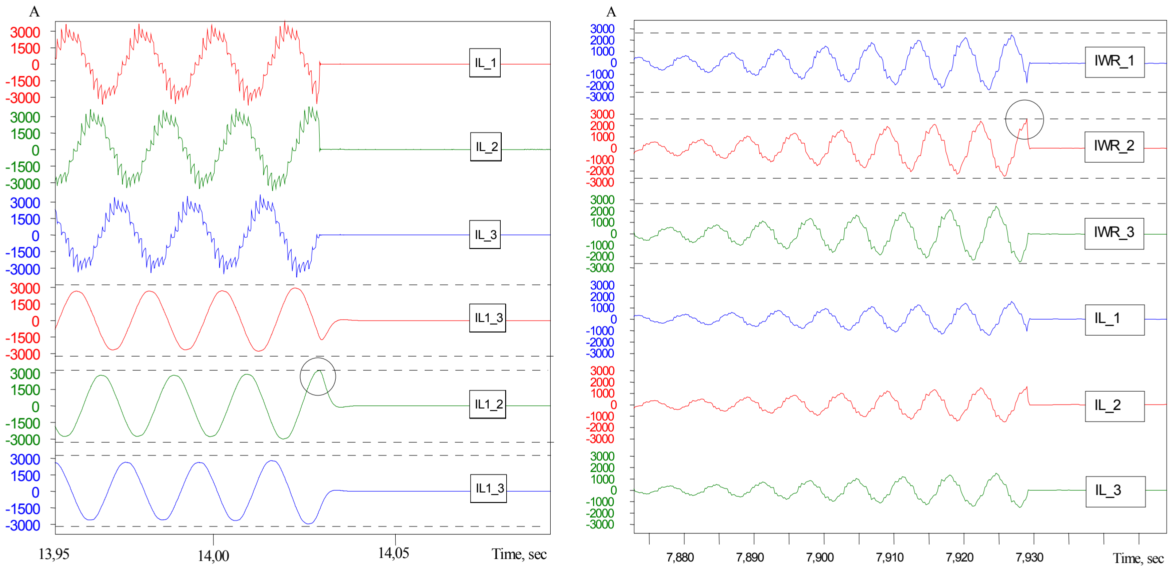
All tests had been sufficiently prepared by the commissioning team of the supplier or the Consortium respectively. Because of the tight schedule for the preparation of the VIP run all tests of Phase 1 had to be performed under consideration of the actual state of the commissioning process. The tests of Phase 2 have been performed after finishing the commissioning of the PPS during the running test operation with 2 vehicles (3 and 5 sections) within the maximum speed range on both tracks. Thus the test conditions were similar to the future operation conditions.

All tests were carried out after holding a preparation meeting with the client SMTDC in order to get the client's release. The client was invited to all tests, several employees of SMTDC took part in most of them. As a result of this procedure all tests could performed successfully as scheduled. Following some examples of special tests are explained with more details.

4.3.1 Over-current protection test

The correct setting and work of both protection functions of each Converter Unit (see chapt. 3.1) was proved within the safety test program after finishing of the commissioning of the entire propulsion system.

The test was carried out by the following simplified procedure: a neighbouring to the Converter Unit feeder line section was shorted in a suitable distance from the Power Substation. Then the output current of the Converter Unit was increased step-by-step up to the releasing of the over-current protection function. The releasing value of the output current was recorded by measurement system (see Fig. 7). The same procedure was done for all Converter Units and all feeding modes. The test results completely met the requirements.



a) **b)**

IL_1…3: Feeder line current (phase 1…3), IWR_1…3: Inverter output current (phase 1…3)
IL1_1…3: Feeder line current, fundamental wave (phase 1…3, the visible phase shift is caused by the low pass filter used for evaluation)

Fig. 7: Feeder Line current waveforms recorded during the test of the over-current protection functions: a) Test of the 1st grade, b) Test of the 2nd grade

4.3.2 Earth fault protection test

During the commissioning phase of the Transrapid system the correct setting and function of the earth fault protection for the Long-stator Winding has been tested for each stator section. According to the test procedure a test current has been injected in the Zero Current Transformer and the correct releasing and interlocking of the respective stator section has been checked.

In the safety test phase the protection function of the Long-stator Winding has been tested with a running vehicle in powering and braking mode. The tests carried out as spot checks representing the entire speed range and the entire track length. According to the safety test procedure a real earth fault near the star-point was simulated by switching-on an earthing contactor in the moment when the vehicle was passing the respective stator section. Fig. 9 shows the trace record (sample) of the protection device (SIPROTEC) detecting a simulated earth fault in the long-stator winding.

Fig. 8: Earth fault protection test at the Shanghai Transrapid Project

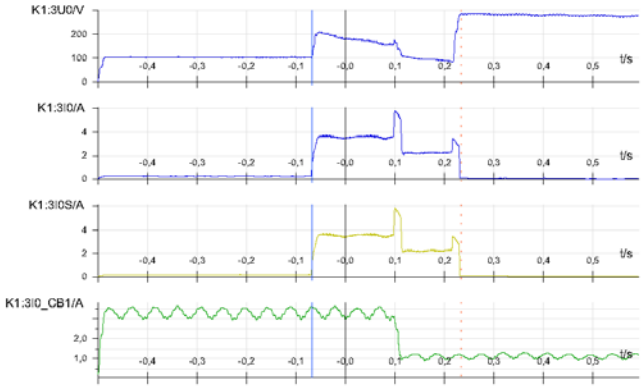


Fig. 9: Trace record of the SIPROTEC protection device detecting an earth fault in a long-stator winding

4.3.3 EMC tests

As the basic standard for the EMC tests the new European standard EN 50121 [4] was used. For the PPS of the Transrapid the specific standard EN 50121-5 (fixed installations) is relevant. The railway standard EN 50121 refers to basic industrial EMC standards. For the safety items of pacemakers the German standard DIN V VDE V 0848-4/A3 [5] was applied. The standards mentioned above contain the valid EMC limits as well as the measurement methods. They were strictly used also for the Transrapid Propulsion System.

The EMC tests were carried out by the Consortium internally in attendance of the expert. For the EMC tests a separate test specification based on the EMC test standard was prepared.

The EMC tests contained several emission and immunity tests for the system and the devices (apparatus). Under consideration of the similar equipment and the identical arrangement in the sub-stations, switch stations, transformer stations and power rail stations the immunity tests and the apparatus emission tests were planned as type tests for the respective subsystems and devices because of the exclusive use of type tested or routine tested components for the PPS.

5 Conclusions

The Safety Certification of the Propulsion and Power Supply System of the Shanghai Transrapid was finished successfully. Because of the first application of the Transrapid technology abroad both the supplier and the client could not fall back on experience of other projects.

A solid foundation for the success was the existence of a specific Certification Concept based on the overall Safety Concept, which was presented and agreed with the client SMTDC in an early project phase. The examination work for the PPS was done with the help of an independent third party expert, approved by the German Federal Railway Authority EBA.

The realisation of the safety assessment work was characterized by a maximum of frankness in order to reach comprehension and confidence on both sides. Beside the technical work the expert also played the role of a mediator between the client and the Authority on the one hand and the supplier on the other hand.

The Safety Certification of the Propulsion and Power Supply System of the Transrapid in Shanghai has shown that it is possible to find a successful way for the approval of a new railway system even under the conditions of a very short realization time. Therefore the close and trustful co-operation of the client, the supplier, the expert and the Authority was an essential precondition.

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