Transrapid Operation Control System
Technical Prerequisites for Short Headways

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Following the decision by the German Federal Government not to implement Berlin-Hamburg Transrapid magnetic railway main-line route, a new field of application in regional traffic was sought. The Munich airport-city centre and Düsseldorf-Dortmund lines provided the solution. The Transrapid regional traffic variant was named Metrorapid. Because of the shorter distances between stations and the shorter headways in conurbations, regional traffic places different demands on the operating concept and technical equipment for Transrapid magnetic railway systems than does long-distance traffic. The preparation work that is being undertaken in parallel with the feasibility studies comprises the system-related analysis of the Metrorapid and the development of suitable control and safety procedures for regional traffic on magnetic levitation systems.

1. Introduction

Preparation for the application of magnetic levitation technology in Germany began in the late 1970s. This was aligned towards the "replacement of German domestic air traffic" and therefore considered the requirements of a main-line railway system. A vehicle, propulsion system, line equipment and operations control system were developed and optimised with this objective in mind. Another focal point was the high train speed of over 400 km/h, which presents considerable travelling time advantages in long-distance traffic. The estimated headways were aligned towards the customary levels for German Railways.

Long substation sections were derived from the specifications as an economically sound solution. The long-stator motor used meant that the developers of the operations control system could use a block system with block lengths of up to 50 km. At a train speed of 400 km/h, headways of 20 minutes were therefore easily attainable. The new "Metrorapid" field of application stipulated for Germany after the suspension of the Berlin-Hamburg Transrapid project is to be assigned to short-distance traffic. With reference to use in short-distance traffic, the advantages of the Transrapid magnetic railway system are lower noise emission, high acceleration capacity and the in-built prerequisites for automatic, driverless train operation. Short-distance traffic is characterised by short distances between stations, headways and passenger interchange times. The reduction in travelling times as a result of the maximum speed becomes a secondary factor. In the feasibility study for the North Rhine-Westphalia Metrorapid project, for example, eight stations are planned along a line of approx. 79 km. The maximum speed has been reduced to 300 km/h. In order to fulfil the requirements of Metrorapid, the solutions prepared for long-distance traffic are to be optimised for short-distance traffic application and supplemented or updated as required.

2. Special System-related Prerequisites

2.1 Long-stator Synchronous Propulsion System

The Transrapid magnetic railway system is characterised by electromagnetic levitation and a long-stator synchronous propulsion system. The long-stator travelling-field winding fitted on the guideway acts as a synchronous motor in combination with the levitation field of the vehicle.

Due to the special features of the long-stator synchronous propulsion system, its dimensioning can be individually adapted to the motion dynamics requirements of the line and of an operating concept.

However, the performance of the propulsion system is fixed by the dimensioning, and can only be changed with significant labour input.

This is because of the system-related integration of the propulsion system into the guideway and the technical data that is consequently fixed, such as stator section lengths, maximum permissible currents, insulation strength of the windings and propulsion segment lengths.

In addition to the guideway construction, the other crucial factor for the layout of the propulsion system and the power supply is the operating concept that can deal with the expected overall long-term passenger load. It is therefore necessary to clarify several boundary conditions at a very early planning stage.

As with wheels-on-rails vehicles, each train set on the Transrapid magnetic railway system also needs an integrated propulsion system throughout the duration of the run. In contrast with wheels-on-rails vehicles, the propulsion system is not permanently assigned to the vehicle, but is reconfigured during the run with the change of propulsion segments. The converter assembly assigned to the train set supplies the long-stator motor with three-phase AC voltage synchronised with the vehicle movement. The converter assembly is only available to other vehicles once a train set has left the propulsion segment or ended the run.

When changing a propulsion segment, therefore, there must be at least one free propulsion segment between the preceding vehicle and the following vehicle. The operations control equipment controls the propulsion function in the respective propulsion and vehicle configuration. The signalling and safety system monitors the train set for adherence to the permissible speed limits and secures the headway to the end of the guideway and to the preceding vehicles. In the event of a malfunction of the propulsion unit, this system shuts off the propulsion current safely. The specified braking action via the on-board supplementary brake is only available when the propulsion unit is shut off. As the propulsive power is fed in on the line, the safe propulsion shut-off facility is installed lineside.

2.2 Procedure for Train Spacing

According to the stopping point concept implemented for the Transrapid magnetic railway system (Figure 1), a passenger vehicle only comes to a halt in stations and at specially equipped stopping points.

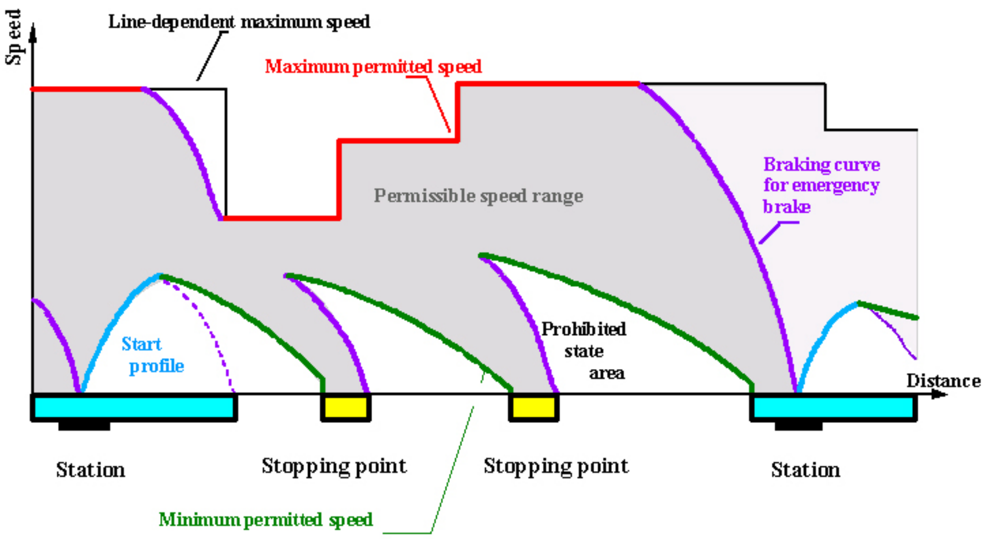

figure: 1 Permissible speed when using the stopping point concept

In stations, each platform is represented by a stopping point. A stopping point can only be occupied by one vehicle. In order for a travelling motion to take place, there must be a clear stopping point ahead of the vehicle. In addition, as per the route protection procedures used in wheels-on-rails systems, the run is exclusively permitted in the guideway segment that is reserved for the vehicle. The maglev-specific functions of the signalling and safety system include approaching the attainable stopping point after failure of the propulsion function. After a propulsion equipment failure, the vehicle continues its run using the available kinetic and potential energy. A controlled on-board supplementary brake is responsible for the stopping the vehicle correctly at the station in order to make use of the infrastructure installed at the stopping point.

In normal operation, the stopping point concept restricts the minimum headway of the vehicles to the spacing of the stopping points. The attainable headway is influenced by the permissible headway of the vehicles and therefore by the selection of the stopping point distance.

The Transrapid magnetic railway system has a significantly higher climbing ability compared with the wheels-on-rails system. Due to the direct magnetic coupling of the vehicle with the lineside long-stator motor, rising gradients of 10% can be overcome. However, there are restrictions with regard to the placing of stopping points. The skid brake that is used as a parking brake (delevitation of the vehicle on skids) is not able to hold the vehicle on rising areas in extreme weather conditions. For this reason, stopping points must not be positioned in the rising area. If rising sections are so long that they cannot be overcome using the kinetic energy available for continuing the run following a propulsion system failure, then “reverse levitation” is used. During reverse levitation, the vehicle first comes to a standstill in the rising area once the kinetic energy is exhausted. Then it is accelerated down the slope by means of the existing potential energy. The stopping point that is now to be reached is at the foot of the rise. For this reason, a following vehicle must only enter the rising area after the preceding vehicle has overcome the rise and thus no longer needs the “reverse levitation” function. However, as a result of reverse levitation, the minimum permissible headway on long rising sections is significantly higher than on the flat.

3. Initial Situation

The operations control and safety systems designed and developed for long-distance traffic with the magnetic levitation system are closely linked with the block structure that is predetermined by the propulsion system. The line-based equipment of the operations control system includes an operations centre and the decentralised protection and control equipment. These are adapted to the propulsion system in terms of their physical structure, and they are located in the substations. Further operations control equipment is located in the stations and maintenance centres, and wherever track-changing installations or equipment projecting into the clearance gauge (e.g. washing systems, depot doors or feed-in facilities for special vehicles) are to be protected. The line-conducted communication equipment and the base stations of the radio system are arranged along the line. Figure 2 shows an overview of the safety segments for a section of a revenue line. A decentralised safety segment is responsible for the control and monitoring of a propulsion segment in the substation section. Each track of the double-track guideway is assigned to a propulsion segment and equipped with a decentralised operations control system.

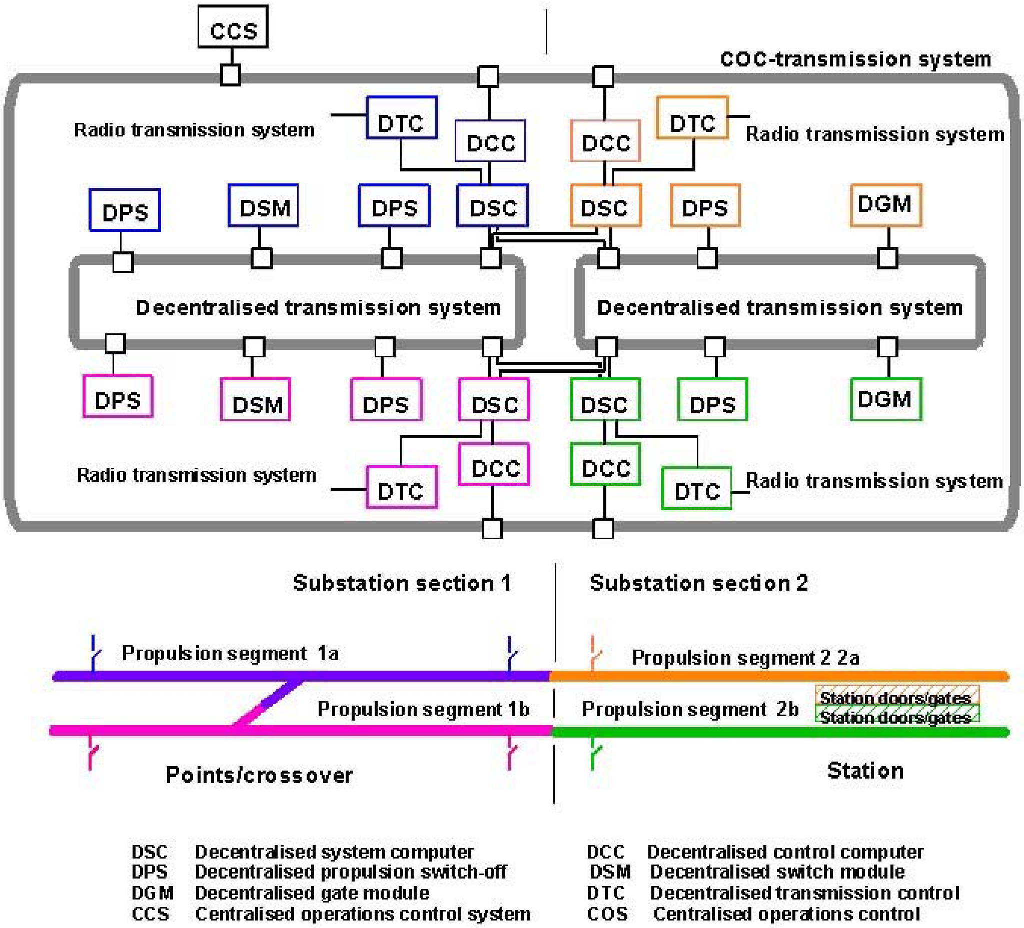

figure 2: Structur of the operations control system

The whole line is divided into substation sections in which only one magnetic levitation vehicle can be moved by the propulsion equipment on each track (propulsion segment). Entry into a propulsion segment is only permitted once the preceding vehicle has left the segment. The shortest headway is determined by the block length and the current braking distance of the following vehicle. The stopping and clearing times at stations are also to be considered in the calculation of the headway. If only trouble-free running in substation sections without station stopping is initially examined, when the selected structure and the adopted procedure are adhered to, a reduction of the interval between trains and therefore the headway can only be achieved by means of a shorter subsection spacing and an increased number of substations and converters. However, this requires greater outlay.

4. Proposed Solutions for Reducing Headway

4.1 Separating the Train Spacing and Traction Control Functions

The selected long-distance transport solution was based on the principle that a premature entry of the following vehicle must be ruled out for the monitoring of the run in accordance with fail-safe signalling principles. A more in-depth analysis reveals the at least theoretical possibility of reducing the interval between trains by the service braking distance, as according to the safety requirements, the simultaneous movement of two vehicles in one substation section must not be ruled out. For the necessary train spacing, shorter block sections have already been installed using the stopping point concept applicable to the magnetic levitation system. However, regardless of this, the statement that the converter assembly can only be available for one vehicle remains valid. The function is therefore to control the operation in such a way that the following vehicle only enters the substation section after it has been cleared. In the event of a failure, if it is accepted that the following vehicle enters the propulsion section that is still occupied by the preceding vehicle without propulsion and if an effect of the propulsion unit that endangers the train is suppressed in a fail-safe manner, then the interval between trains can be reduced by the rate of the service braking distance. For the described disruption to be resolved as quickly as possible, it is then necessary to synchronise the long-stator motor with the coasting follow-up vehicle after the preceding vehicle has cleared the propulsion segment.

4.2 Monitored, Variable Assignment of the Propulsion Segments

4.2.1 Propulsion Segment Overlapping

If a propulsion segment contains a station and if a vehicle is to reach the same platform as the preceding vehicle with no intermediate stop, then the propulsion unit of the substation section is not available for the following vehicle until the station and the substation section have been cleared. If the propulsion segment in the station area is alternately assigned to the substation for the station area and to the following substation area (Figure 3), then the propulsion unit can be used by the following vehicle after the station stop of the preceding vehicle.

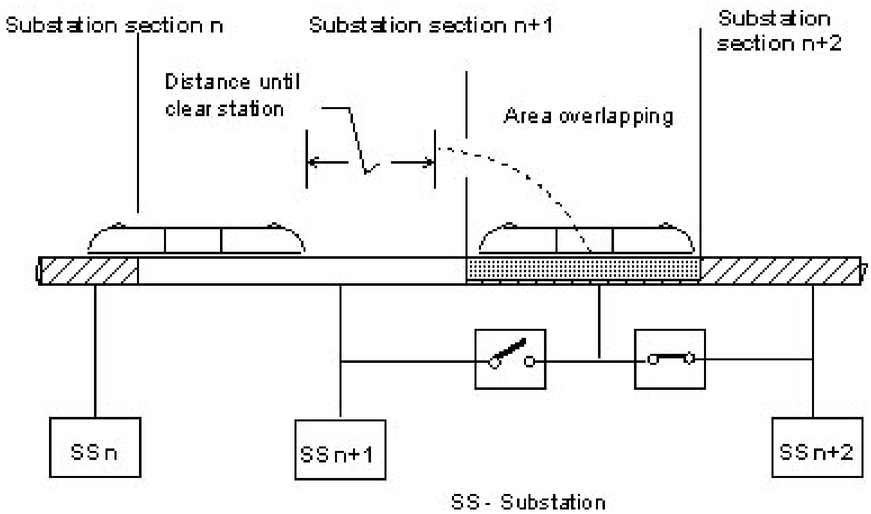

figure 3: Area overlapping

For the departure of the vehicle from the station, the station area is assigned to the substation that is adjacent in the direction of travel. This concept of variable assignment of propulsion feeding sections is called propulsion segment overlapping. With regard to the approach to a station, short intervals between trains are thus attainable that can be used advantageously to reconcile the stopping and clearing time of the preceding vehicle. Provided that the train spacing during the station occupancy by the preceding train permits running until just before the overlapping area and that braking when approaching the station is constant and uses the full operational braking power, the shortest headway can be determined from the time required for braking when approaching the station and the stopping and clearing time of the preceding train. If the times for the reconfiguring of the propulsion assignment and the route setting are considered, then the following applies:

$$t_{headway} = t_{stop} + t_{clear} + t_{control} + t_{entry}$$

where $t_{entry} = S_{clear}/V + V/a_{brake}$ and $t_{clear} = \sqrt{2S_{clear}/a_{accel}}$

A calculation typical of the magnetic railway system results in headways of approx. 4 minutes. If it is permitted that the following vehicle initiates the braking procedure before the station is cleared, but the speed does not normally fall below approx. 50 km/h in this section, then significantly shorter times can be achieved. The vehicle applies the brakes in the last stopping point before the station area whilst the station entry has not yet been cleared. After the entry has been cleared, the vehicle changes to a run at constant speed and then slows down, approaching the station along the braking curve thus attained (Figure 4). The functional sequence, which is balanced in terms of the progress of the train, provides for an immediate change to a flatter curve running straight into the station after clearance of the station entry (Figure 5).

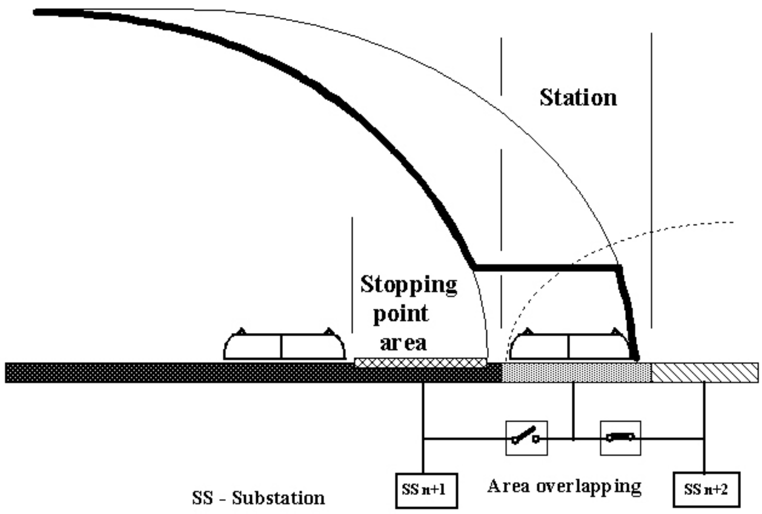

figure 4: Station approach with constant speed range

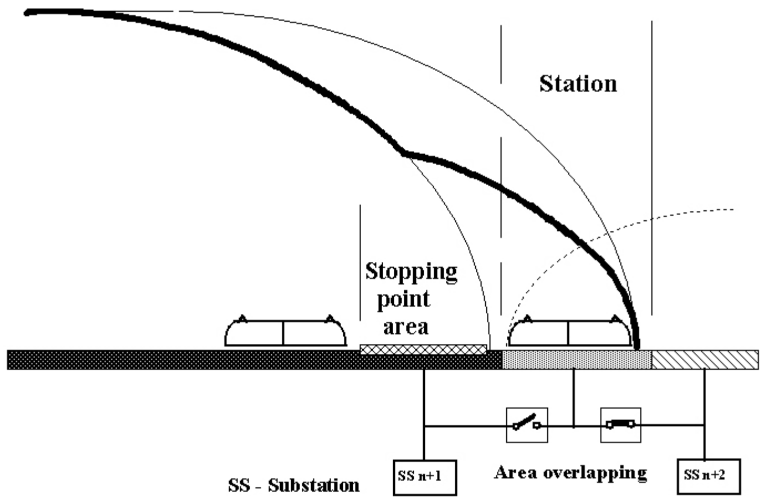

figure 5: Station approach with flat braking curve

Figure 6 shows that an increase in the headway of up to 10 seconds must be accepted as a result of this. It can also be seen from Figure 6 that in terms of the objective of achieving short headways, train sets consisting of few sections are beneficial due to the shorter station clearing and entry times. One factor to be considered deciding which functional sequence is preferable for the station entry is that the Transrapid magnetic railway system requires the guideway to be equipped with busbars on line sections where vehicle speeds are regularly less than 80 km/h. In individual cases, it is therefore necessary to weigh up equipment outlay against the advantage of shorter headways.

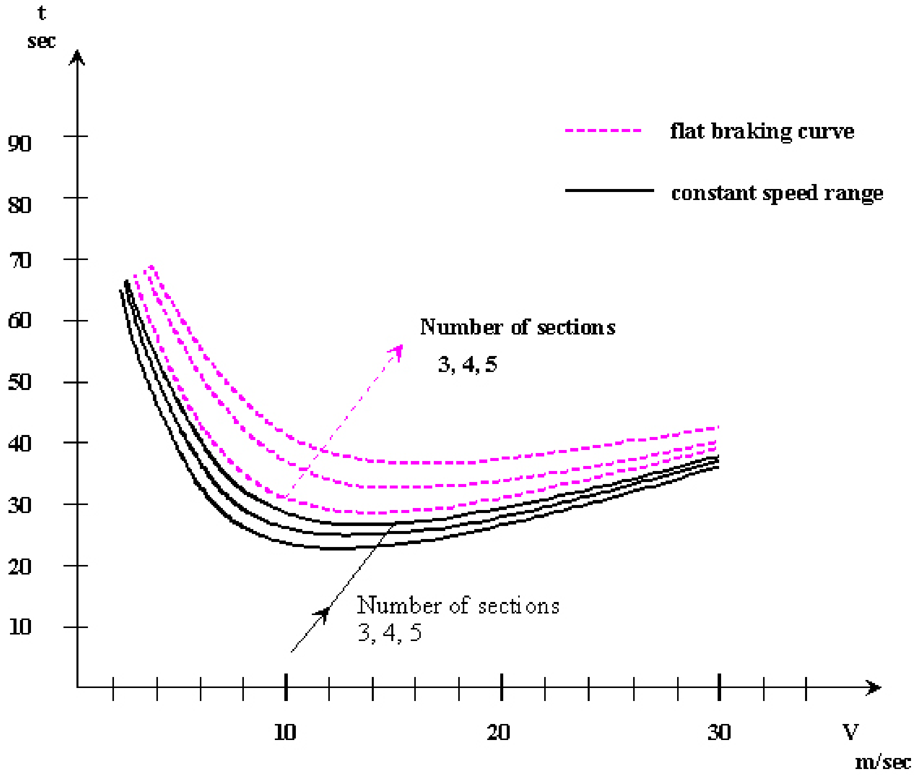

figure 6: Entry time as a function of the control technique and the number of sections

4.2.2 Variable Propulsion Segment Assignment

Propulsion segment overlapping is proving to be an effective method of significantly reducing the amount of time required for entering and exiting a station without increasing the number of converters. However, the usefulness for the entire system only becomes apparent if sufficiently short substation sections are available outside the stations. As described above, for fault-free operation, a propulsion segment must have been cleared by the preceding vehicle before it is entered by another vehicle. If a converter assembly is assigned to each propulsion segment and all vehicles run at constant speed, then half of the converters are only needed during the segment changeover phase. If the assignment of the converters to the propulsion segments is variable, the number of converters can be reduced to 1 1/3 per vehicle or the interval between trains can be shortened accordingly with the same number of converters (Figure 7).

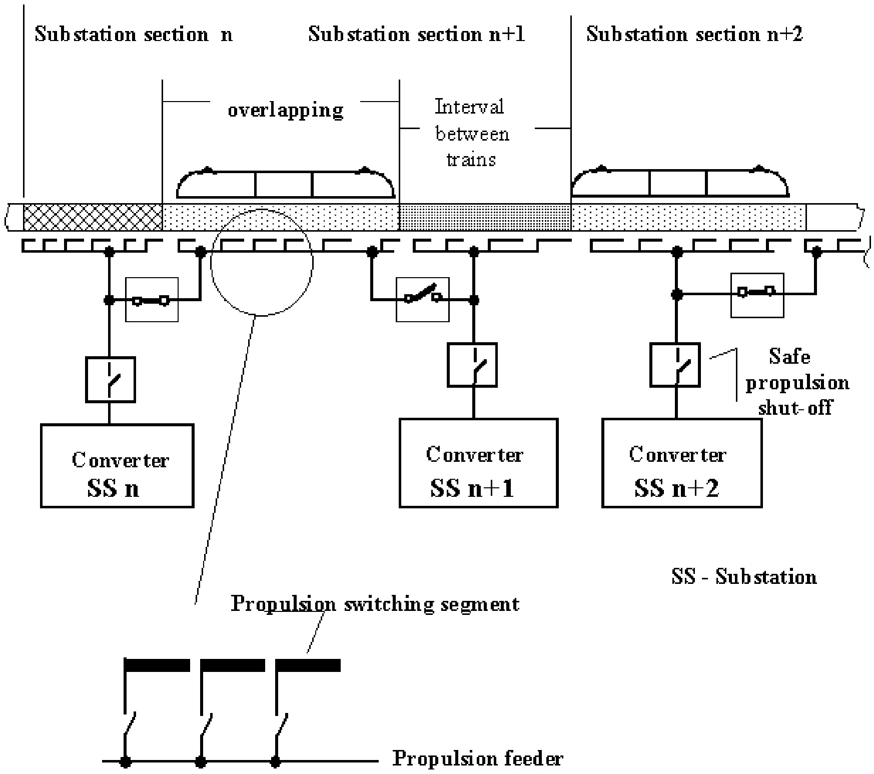

figure 7: Variable propulsion segment assignment

In order to reduce the propulsion losses, the substation section is divided into propulsion switching sections, which are continuously switched by the traction controls in step with the movement of the vehicle. The propulsion switching sections are permanently assigned to propulsion feeding sections with the relevant feeders. The fail-safe propulsion shut-off operates at the output of the converter system. With regard to the fail-safe propulsion shut-off, all propulsion switching sections of a propulsion feeding section form one unit. The purpose of variable assignment of the propulsion feeding sections is to separate the propulsion feeding sections of the substation sections and, if necessary, assign one of them to one of the adjacent substations. The fail-safe propulsion shut-off to be carried out by the signalling and safety system if necessary remains possible on a vehicle-selective basis, as in the case of a permanent converter assignment, if it can be ruled out for the adjacent propulsion feeding section to be conductively connected with the newly configured feeding section. A fail-safe switchover of the converter assignment is required for this purpose.

During a run, the vehicle is supplied via the currently active converter, provided that it can be reached via the propulsion unit structure. For the changeover to the adjacent converter, the participating converters must be frequency-synchronised and temporarily operate simultaneously on the vehicle. The vacant converter is then available to the following vehicle.

5. Subsequent Procedure

The German Federal Ministry of Transport, Building and Housing has set up a programme to secure the future of German magnetic railway systems and to establish high-speed maglev traffic. In addition to the implementation of feasibility studies for the Metrorapid/Transrapid revenue lines in North Rhine-Westphalia and Bavaria, this encompasses a refinement programme to adapt and optimise magnetic railway systems for use in regional traffic.

For the selected line layouts of the planned Metrorapid applications, it is necessary to find a cost-effective system configuration that corresponds to the planned transport capacity.

The effect of the selected configuration and control procedures with regard to the attainable headway and the susceptibility to operational disturbances is to be investigated in detail in operation simulations. Using the results of the simulation the refinement of the propulsion and operation control system is to process.

The technological expertise gained by the employees of Siemens AG (Transportation Systems) in basic development up to the readiness for application of the Transrapid influences the optimisation of the maglev technology and adaptation to the requirements of the Metrorapid installation. In the planning permission process, Siemens employees are working alongside the planners, providing guidance and support.

6. Summary

The analyses carried out in preparation for the forthcoming planning and development work show that the Transrapid magnetic railway system has the potential to fulfil the headway criteria that are necessary for the Metrorapid application. However, headways in the range of 1 to 2 minutes, which are attainable in modern underground and urban railway systems, require the refinement of the equipment that is already implemented for control and, when the defined safety level is adhered to, for protection of the long-stator propulsion system. When planning the Metrorapid lines, it must be borne in mind that although a layout geared exclusively towards short headways allows a high line throughput, this is at the expense of travelling time. Here the interactions that are known for the wheels-on-rails system apply accordingly.

7. References

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