Convoy Operation of Linear Motor Driven Railway Vehicles

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Abstract: A test track of 530 m length for autonomously driven railway vehicles in scale of 1:2.5 was built at the University of Paderborn in 2002. The doubly-fed linear motor utilized for this plant enables convoy building on the track during drive operation as well as transferring power to the vehicle, so the need for pantographs or a third rail for supplying auxiliary power does not arise. In this contribution, the principle of driving several vehicles in a convoy is explained. The autonomous operation requires a complex communication structure and demands safety concepts, which are described here. A method for operating point assignment for convoy driving is presented together with simulation results of convoy building.

Keywords: Electrical vehicles, linear drives, convoy operation, motion control

1. Introduction

The NBP (Neue Bahntechnik Paderborn) project was founded at the University of Paderborn in 1998 (1). The novel system is characterized by autonomous vehicles traveling on demand instead of trains in accordance with a fixed schedule (2). A test track was built for investigations on railway vehicles, so-called railcabs.

The vehicles of the NBP represent a profound automated component of complex mechatronical system being designed modularly. The driving and breaking module is based on the doubly-fed linear motor, which was selected due to the reasons given in (3). For high riding comfort an active suspension and tilt module is implemented. Additionally the railcabs are equipped with an active guidance to get rid of active switches, maximize the comfort and improve the security.

For investigations on the complex mechatronic system, a test track in a scale of 1:2.5 was built in 2002 at the University of Paderborn. The track consists of an oval with a length of about 460 m. A straight track section is linked by a track switch. The gradients are up to 5.3% in order to demonstrate the enhanced climbing capability of linear motors (Fig. 1). Two railcabs (Fig. 2) can be operated at the same time with a maximum speed of 10 m/s. The length of a railcab is about 3.4 m. Height and width are both about 1.2m each. After investigations on operation with one vehicle a second railcab has been developed for testing convoy operation on the test track.

In this contribution first the required characteristic of the modules for convoy driving is described followed by communication and drive control structures and the safety concepts used.

Fig. 1: NBP test track

Fig. 2: Railcabs on the NBP test track

2. Doubly-Fed Linear Motor

For driving and regenerative breaking, a doubly-fed linear motor is used. The primary (stator) is mounted between the rails, whereas the secondary is fitted below the undercarriage of the vehicle. The doubly-fed linear motor enables contactless energy transfer from the primary into the railcab. Therefore, neither an overhead line nor third rail is needed (4). The secondary is fed by the battery buffered power supply, so that the secondary frequency and current amplitude can be regulated separately on each vehicle (Fig. 3). Therefore the propulsion concept allows a relative motion between different vehicles on the same stator, so that vehicles can align with others to convoys during drive operation (5). In order to decrease power consumption the track is divided into several sections with lengths of 6m. Only the currently needed stator section is activated. The propulsion force results from the exact adjustment of the electromagnetic fields of the primary and the secondary in consideration of the vehicle's position. The position is measured by a wheel-mounted encoder. Reference points are installed at the test track. In order to control the propulsion force as well as to enable convoy driving, information about absolute position of each vehicle is required and has to be exchanged between the primary and secondary controllers.

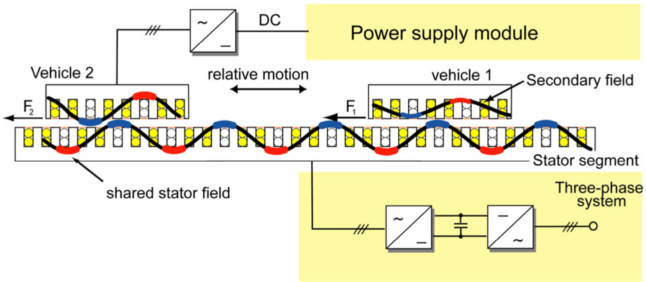

Fig. 3: Principle of a doubly-fed longstator linear motor

Propulsion force and energy transmission depend on stator and secondary current amplitudes and frequencies. The used doubly-fed linear motor provides on the one hand a maximum thrust of about 1300N and enables accelerations and decelerations of about 0.8m/s^2 on planar tracks, while on the other hand energy transmission up to 4kW has been realized so far.

3. Convoy Driving

Operating vehicles in convoys offers different advantages. Because of the limited track system it is especially useful for railway applications to increase and maximize the track capacity. Furthermore the combination of vehicles to convoys decreases power consumption and offers the potential of energy optimization (6).

As described in the previous chapter the propulsion concept (doubly-fed linear motor) enables convoy building while driving on the track. Contrary to conventional railway systems the active steering of the railcabs enables building and dissolving of convoys even in the area of the track switch. The active steering of the railcabs enables in combination with passive track switches that vehicles driving back-to-back in a convoy may leave the convoy at the track switch, whereas other vehicles are still driving on the same rail track without mechanical coupling (7). This feature can be utilized especially for dissolving convoys.

For aligning of railcabs to convoys different strategies exist. A vehicle having low charged energy storage should drive in the slipstream of a forward vehicle to reduce its energy consumption. Furthermore, the operation point of vehicles driving in a convoy is generally different, whereas the stator settings have to be the same for all vehicles. Therefore, reference values for the primary has to be adjusted in consideration of the charge states of all vehicles involved and maximum desired propulsion force has to be provided (comp. chapter 6).

For building convoys knowledge about the other vehicle positions, operational profile and system status is imperative. Therefore, a complex communication structure is required for transmitting actual values and set points described in the following section.

Convoy operation requires handling of different velocities and small distances between two vehicles. If the distance between two shuttles is smaller than the break distance, various information is needed about the other vehicle for safe operation. In order to retain the safety in case of communication failures or emergencies, additional fallback safety concepts are required. Therefore, special systems for detecting distance and relative speed are advisable (comp. chapter 5).

4. Communication Structure

As the control of the drive and the other on-board components are running on the vehicle itself, the operational profile is transmitted from a control room via a radio communication by an operator. Each vehicle is equipped with a radio communication for transmitting its position and the requested set points of the primary current amplitude and frequency.

Because of the autonomous driving operation, the vehicles have to adjust the operational profile itself. Therefore each vehicle needs information about other vehicles driving on the same track. This information includes speed, position and information about the system status of the drive and break module and the energy storage. Furthermore, details about the operational profile are important so that another radio communication is provided for transmitting information between the two railcabs. The communication channels are realized by radio modems using bi-directional transmissions in 2.4 GHz ISM band. The structure of the communication system is shown in Fig. 4.

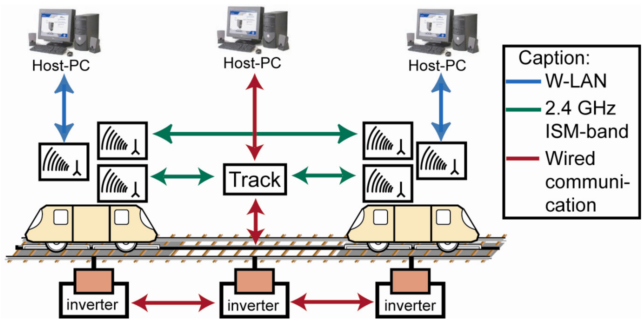

Fig. 4: Structure of communication system

For investigations on the communication between two railcabs and the distance controlled drive control, a HiL (hardware in the loop) test bed was built up. It realizes the communication in hardware, whereas the motion and drive control will be simulated. Therefore, two separate prototyping real-time systems, in each case with a Power-PC and a serial interface to a modem, have been installed in an industrial personal computer (Fig. 5). The used HiL test bed architecture enables running of drive control on separate processor boards and testing of data transfer between two vehicles in hardware.

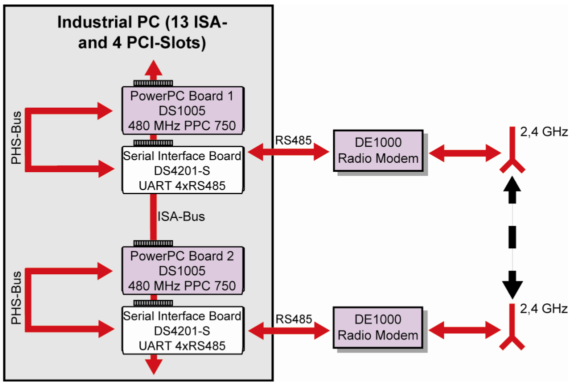

Fig. 5: HiL test bed for convoy operation

The basic information for driving with two vehicles on the same rail track is the arrangement about convoy building divided into three options for a railcab:

- No convoy
- Front convoy position
- Rear convoy position

In case of convoy building the arrangement of front or rear convoy will be performed after exchanging information about charge states of the energy storages. The vehicle with most energy reserve will drive in front. One vehicle becomes the convoy master, being solely responsible for transmitting reference values to the track. Status of the convoy master can be changed flexibly.

During the whole drive operation the following information will be exchanged continuously between the railcabs:

- Absolute position
- Velocity
- System status (linear motor, energy storage etc.)
- Emergency status
- Convoy status (master or slave) and stator settings

On the basis of the received information from the other railcab, the following vehicle will adjust its drive operation. If the radio communication fails and the distance between two vehicles is too small, fallback safety concepts have to be applied to avoid collisions described in the next section.

In case of operation with more than two vehicles it is not possible to realize a point-to-point connection between every vehicle. Therefore, a communication system can be built with a central station distributing only the desired information to the vehicles. This communication system will be developed within a project funded by the German Research Council, SFB614 (6).

5. Safety Concepts

A second redundant information system can be used retain safety in case of communication failures. In order to operate with all relevant distances, different sensors have to be applied for measuring distance and relative speed between vehicles.

For measuring long distances an ACC (Adaptive Cruise Control) sensor as used in the automotive industry can be applied. Thus, long range radar is used based on 77 GHz frequency. With an angle of beam spread of 16°, it facilitates measuring of distances of up to 35m in the area of curves und larger distances on straight track sections. Because this device is developed for measuring long distances, an infrared range finder can be used, detecting objects with shorter distances in the range up to 15m. For control of short-range distances of few centimetres, during back-to-back driving in a convoy, an ultrasonic control unit is used.

In order to maximize the retarding effort in case of emergencies a mechanical break exists, providing maximum deceleration. Tests on the track have shown a stopping distance of less than 25m at maximum speed of 10m/s. Minor distances between two railcabs are critical.

While driving with a large distance between two vehicles the data received by the radio communication is given the top priority. Not until the distance between the two vehicles is getting smaller than the critical value, distance control is performed using only the sensor signals. If communication failures occur, an emergency routine is applied using sensor data.

In case of system failures on the following vehicle, a systematic decelerating process is initiated, whereas handling of failures of the guiding railcab is more difficult. Before decelerating the guiding railcab the following vehicle has to reduce its velocity to increase the distance between the two railcabs.

6. Operating Point Assignment of the Linear Motor

Reference values for current amplitudes and frequencies of both motor parts are generated by each vehicle depending on demanded propulsion force and desired energy transmission (comp. chapter 2) and can be adjusted separately, if vehicles are driving on different track sections. However, if the vehicles are located on the same section, common stator reference values have to be determined, providing optimal conditions for each vehicle.
Fig. 6 shows the control structure of the test track with two vehicles operated on the same track section. In the depicted case, Railcab1 presents the convoy master being solely responsible for transmitting reference values to the track. Therefore the radio communication between Railcab2 and track is inactive. However, radio communication between both vehicles is active. Stator settings are transmitted from the convoy master to the slave.

For assuring safety the priority has to be given to the desired thrust, which is proportional to the product of primary and secondary current amplitudes (3). Therefore, the stator current amplitude will be chosen, which provides the desired propulsion forces. After deciding on the stator current amplitude current frequencies of the primary and of both vehicles secondaries have to be determined. This will be done in dependence on major value of desired energy transmission.

For operating point assignment of the motor optimization methods for improvement of the efficiency are used (8). Secondary references of the linear motor demands actual information of adjusted stator settings, which are continuously transmitted via radio communication to the convoy slave.

7. Distance Controlled Drive Operation

Also convoy driving is to be realized at the test track. Therefore a distance control is essential, which enables the operation of two vehicles as a convoy and considering safety criteria. The design of the control is based upon a simplified dynamic model of a railcab. In combination with the speed control already installed the dynamic behavior of a vehicle can sufficiently be approximated by a first order lag element. By means of this simple linear model a position control for a following vehicle in the convoy was designed. The reference position $s_{2,\,ref}$ is calculated thereby from the current position of the leading vehicle and the reference distance given for vehicles driving in a convoy:

$$s_{2,ref} = s_1 - \Delta s_{ref} \tag{1}$$

Here s_1 represents the current position of the leading vehicle and Δs_{ref} the reference distance between the railcabs. The main problem for the controller design is that the vehicles are limited regarding their maximum velocities and driving forces - and thus accelerations and decelerations. A controller with integral action would provide for stationary accuracy of the process. However, in case of saturation of speed or thrust, an integrator windup has to be prevented by additional measures. For this case, a feed forward control was implemented, which essentially includes the inverse dynamics of the ahead-driving vehicle. Thus, the stationary accuracy of the control can be ensured, without running into problems of integrator overflow. The entire structure of the control for two vehicles is displayed in Fig. 7.

To avoid collisions, if the leading vehicle brakes during the approaching phase, the computation of the reference position is extended, in order to guarantee that the following vehicle is able to stop in time, even during an emergency braking of the leading vehicle. The necessary minimum distance depends thus on the current vehicle velocities.

Assuming a constant maximum deceleration a_{max}, a vehicle needs the braking distance

$$s_{i,hold} = \frac{1}{2}\frac{v_i^{\,2}}{a_{i,\max}} \tag{2}$$

to stop. Hence, the reference position for the following vehicle must consider the difference of the braking distances:

$$s_{2,ref} = s_1 - \Delta s_{ref} - \left(s_{2,hold} - s_{1,hold}\right) \tag{3}$$

Thereby, the distance of the vehicles never falls below the critical minimum distance, and in the case of an emergency breaking, the vehicles can be stopped without collision.

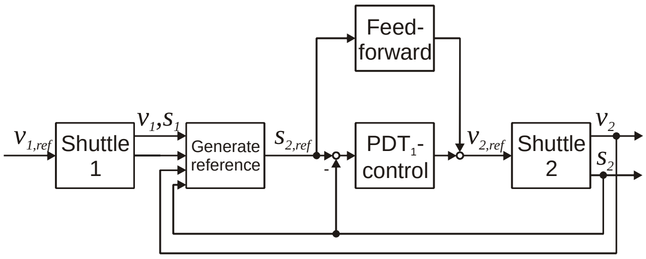

Fig. 7: Control Structure for convoy-driving

Fig. 8 shows simulation results of two vehicles with the described control structure implemented. By means of the presented control safe convoy-driving can be realized in principle. A precondition for this approach is the knowledge of the current position and velocity of the leading vehicle for the determination of the reference position for the following vehicle. However, it can be assumed that the required values are known because of the underlying drive and communication concept (see chapter 2, chapter 4). In order to ensure convoy stability the necessary communication structure can be used again. Changes of velocities in the convoy should not enlarge to the rear vehicle and should not oscillate by using the current position and velocity of the leading vehicle to generate the reference positions for all following vehicles. Into this concept the necessary monitoring and safety mechanisms especially for communication losses have to be integrated, so that the represented control strategy can be extended towards convoy driving with several vehicles.

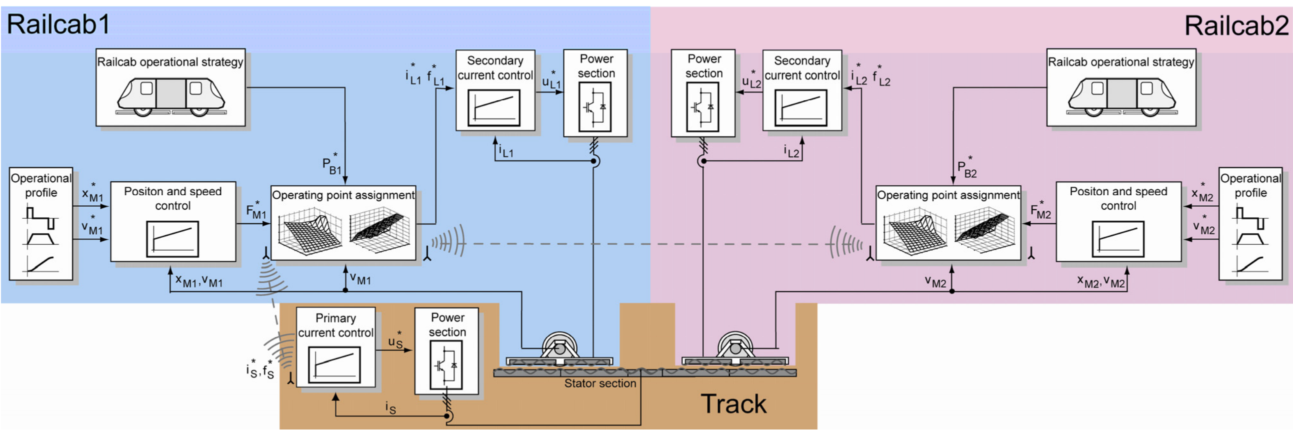

Fig. 6: Control structure of the test track

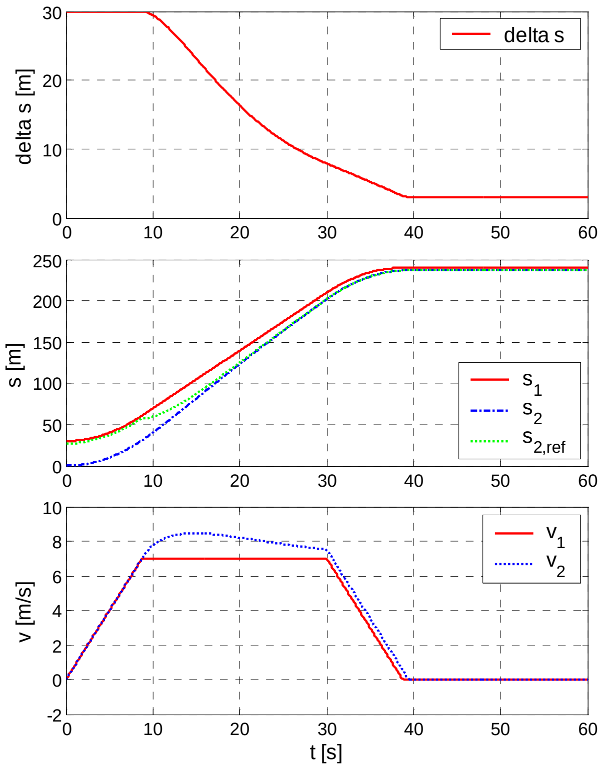

Fig. 8: Simulation results for approaching process

8. Conclusions

Doubly-fed linear motors driving railway vehicles enable convoy building during driving operation. Because of the autonomous actuating, a complex communication structure and extensive safety concepts are imperative. While operating in convoys, a common operating point of the primary part of the motor has to be assigned. Therefore, a method is used for ensuring primarily desired thrust for each vehicle. Due to the detailed information about position and velocity, which are required for the linear motor, convoy control ensuring convoy stability, can be realized easily.

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