DISTRIBUTED CONTROL STRUCTURE OF THE NBP TEST TRACK WITH LINEAR MOTOR DRIVEN VEHICLES

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Abstract: This paper describes the drive control structure of the Railcab system realized at a test track at the University of Paderborn based on a distributed data processing system. The drive of this railway system, a doubly-fed linear motor, consists of two active parts distributed on the vehicles and along the track, which both have to be powered. Safe operation of the Railcabs is guaranteed by a mechanism synchronizing the current controllers via different communication channels (CANopen and radio). This measure makes possible to control the phase shift between the magnetic fields of primary and secondary which is a must for drive control. Finally measurement results are presented to prove the functionality of the described synchronization mechanism.

Key words: Railway system, Railcab, doubly-fed linear motor, drive control, distributed signal processing

1. INTRODUCTION

At University of Paderborn a new railway system called Railcab is under investigation. This system is characterized by the following features [1]:

- Instead of trains travelling in accordance with a fixed schedule autonomous shuttles travelling on request are used for transportation of passengers and cargo. By this change short time for transportation can be achieved without high-speed operation because passengers can travel any time and do not loose time by changing trains. On the other hand cargo does not spend most of transportation time on switch yards where trains are formed and split.

- On main routes all shuttles travel with approximately the same speed of about 160 km/h; neither passenger traffic and cargo traffic nor short distance traffic and long distance traffic are separated.
- Railcabs traveling on the same section of track can form convoys and save energy by reducing the wind resistance.
- When arriving at its destination a vehicle has to leave the main track for disembarking people or unloading cargo. With regard to long reaction time of conventional switches this causes a problem when a vehicle has to leave a convoy. Therefore the system makes use of passive switches in combination with active steering of the shuttle's axes.
- For driving the vehicles linear motor technology is used which allows to generate great force and to climb steep slopes. With linear motor generation of thrust force is performed without moving and wearing parts which results in high reliability of the drive system. Furthermore realization of active steering is simplified because wheels are not used for driving.
- With regard to size of Railcabs and great number of vehicles there is a great interest in transferring energy to the vehicles without using pantographs or contact rails.

The basic principles of Railcab system are under investigation at the test track of NBP project which was installed in scale 1:2.5 at University of Paderborn in 2003 (see figure 1). The track has a total length of 530 m and consists of a circle and a straight section which are connected by a switch.

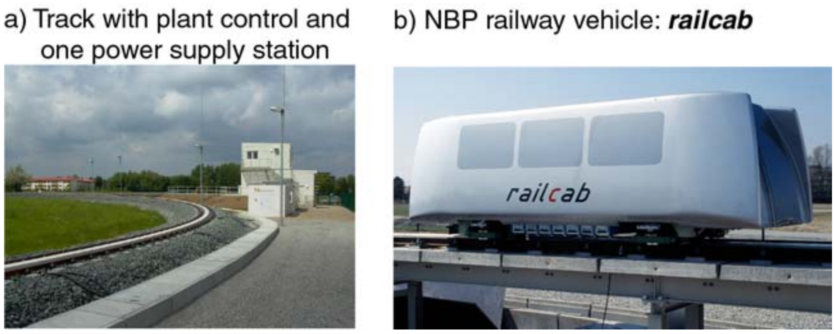

Figure 1: Test track and vehicle of Railcab system

The doubly-fed linear motor used for driving a Railcab consists of two parts. The primary is installed between the rails and two pairs of secondaries are fitted below the undercarriages. The primary generates a traveling magnetic field by means of a three-phase winding. The secondaries also have three-phase windings. By this means the magnetic field of the secondaries can be shifted with regard to the Railcab. Operating Railcabs in the asynchronous mode has two important advantages: First, vehicles travelling on the same primary segment are able to drive with different speeds, so relative motion between different Railcabs becomes possible which is required for forming convoys. Second, by asynchronous operation of the motor energy transmission from the primary to the secondary and to the on-board power supply system of a Railcab becomes possible [2] and neither overhead wires nor contact rails are required.

To realize this asynchronous operating mode of the motor with the advantages given above, a vehicle control structure based on along the track distributed systems becomes necessary, because the linear motor's thrust force depends on the current vectors in secondary and primary [3]. These currents (frequency and amplitude) are controlled by sterically separated systems.

2. SIGNAL PROCESSING AND COMMUNICATION SYSTEM OF THE TESTING PLANT

Signal processing and communication system of test track used for control of a single vehicle is shown at figure 2.

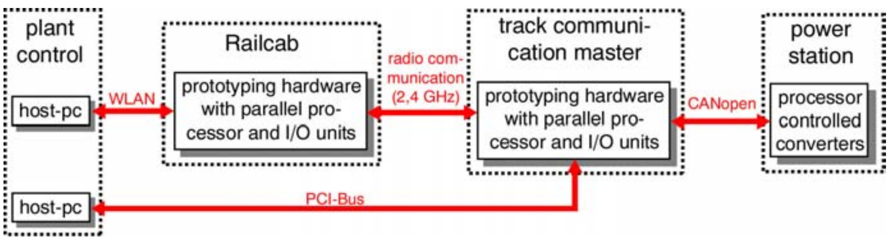

Figure 2: The Railcab system test track

In accordance with the procedures required for a fully automated operation of the testing plant the data and signal processing system is divided into three parts which are distributed to a central control room (plant control), the Railcab and the power stations distributed along the track which receive information from the vehicle via a track communication master.

Each motion of the shuttle is commanded and controlled at a central control room. By means of two host PCs the reference for the vehicle's position or destination, respectively, is set here as well as the maximum speed permitted during motion. This information is sent to the vehicle by WLAN radio transmission. In return data are received from the vehicle which are used for monitoring the experiment, measuring significant parameters and performing fault diagnostics.

On board the vehicles dSPACE prototyping hardware with parallel processors (power PCs) and several I/Os are used for controlling speed and position of the vehicle. In particular references for the frequencies, phase angles and amplitudes of the linear motor's currents are generated here with a sampling rate of 4 kHz. References of secondary currents are delivered directly to the signal processing units of the on-board power converters where closed loop control of currents is performed with a sampling rate of also 4 kHz. In addition to drive control, which is described in more detail afterwards, the prototyping hardware has also to control the charge of an on-board battery and operation of all hydraulic units used for steering of the undercarriages and for suspension and tilting of the carriage.

Closed loop control of primary currents is performed by the track-side power converters feeding the 84 primary sections. Therefore the references of primary currents are sent from the vehicle to a track communication master which is placed at one of four stationary power plants at which the power converters are installed. For this data transmission radio communication at 2.4 GHz is used. By the communication master references for amplitude, frequency and phase angle of primary current are transmitted to the power converters via CANopen and only those power converters are activated which are responsible for feeding the stator sections on which the vehicle is present. Primary current references are updated with a repetition rate of 50 Hz.

For operation of more than one vehicle radio communication between vehicles is also required when forming convoys and while driving in a convoy. Up to now this communication is not implemented at the track and not shown at figure 2, but tests have already been made at HIL test rigs.

3. SYNCHRONIZATION MECHANISM FOR VEHICLE-TO-TRACK COMMUNICATION

Magnitude and sign of the torque or force generated by an electric motor depend on the phase shift between magnetic fields of primary and secondary. Therefore synchronization of primary and secondary currents - which generate the traveling fields of both windings - is the most important control task at any drive. With doubly-fed linear motor this task is extremely difficult because primary and secondary and their power supplies are distributed to stationary track and moving vehicle. To perform force control reliably and as exactly as required a special synchronization mechanism has been implemented [4]. At figure 3 a communication diagram of this synchronization mechanism, which is based on radio links of the distributed control systems, is given.

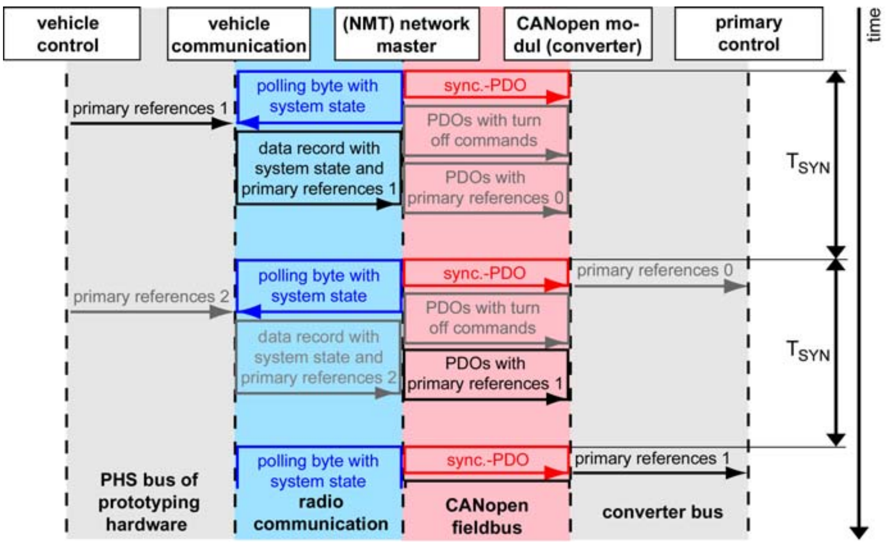

Figure 3: Diagram of communication sequences

Data transmission from vehicle-side motion control to track-side current controllers is performed within two sampling periods of the track-side network master (NMT). At the beginning of the first period data transmission of references ('references 1' in figure 3) is initiated by the NMT by sending a polling byte to the vehicle via radio communication. After receiving this polling byte, which is used to indicate error states of the communication channel or of primary sections, the primary references are sent from the vehicle's control to the NMT.

During the second period the references are transmitted from the NMT to all power converters placed along the track. At the beginning of the third period - exactly when sending the polling byte to the vehicle - the NMT sends a synchronization process data object (PDO) to the respective power converters via CANopen causing the power converters to replace the previous references (references 0) by the new values. By demanding for new reference values from the motion control and activating already transmitted values at the power converters at exactly the same time a well-defined transmission time and a deterministic behavior of the control system is achieved as necessary for adjusting the magnetic fields of primary and secondary with sufficient accuracy.

4. STRUCTURE OF DRIVE CONTROL

Basic task of the drive control is to control the linear motor's primary and secondary current in such a way that

1. the magnitudes of currents do not exceed the permitted limits,
2. speed and position are in accordance with the references delivered from the plant control and
3. the energy transferred to the on-board power system via the motor matches the requirement.

The structure of the control solving these tasks is shown at figure 4.

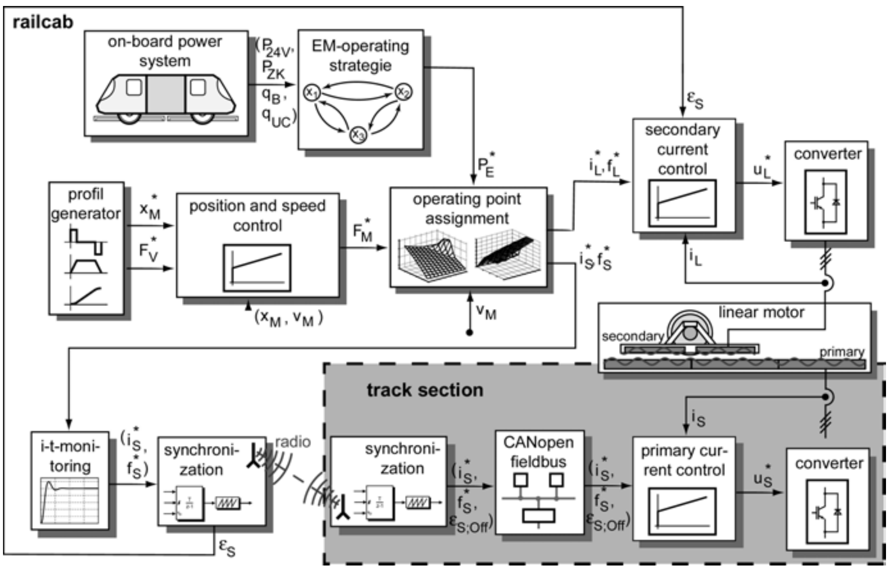

Figure 4: Linear drive control structure

The first requirement, limitation of currents, is fulfilled as usual by closed loop control which is performed by microprocessors on the power converters with a sampling rate of 4 kHz.

For motion control profiles for position, speed and force are determined onboard the shuttle from the information delivered from the central control room. Under consideration of actual conditions the force reference is calculated. Thrust force depends on primary current I_1 and secondary current I_2 and on the special phase shift α between the magnetic traveling fields produced by these currents.

$$F_M = -\frac{3\pi}{\tau_P} L_{12} \cdot I_1 I_2 \sin\alpha$$

where τ_P and L_{12} are the pole pitch and the coupling inductance of linear motor, respectively.

Obviously torque is generated with minimum current and minimum losses when the secondary magnetizes perpendicularly to the magnetic field of the primary winding or when angle $\alpha = \pm\pi/2$, respectively. Furthermore it is important to notice that the angle must not leave the range $0 < |\alpha| < \pi/2$ because otherwise thrust force will change its direction and motion control will become unstable. Phase shift α between traveling waves depends not only on the phases of primary and secondary but also on the vehicle's position where an angle of $\alpha = \pi/2$ refers to a length of a half pole pitch ore $\tau_P /2 =$ 60 mm, respectively. Consequently the position of the vehicle must measured with a relatively high accuracy.

As can be seen from the above equation the product of primary and secondary current is determined by the demand on thrust force. The final setting of the current references is performed at the module Operating Point Assignment where the current ratio is established under consideration of different aspects: On the one hand, limitations of voltages and currents as well as the influence of the current ratio on efficiency have to be considered. On the other hand frequency of primary current is calculated from the actual speed and the frequency required in the secondary winding for energy transfer [2].

Closed loop control of stator current is performed at the track-side in accordance with magnitude and frequency reference delivered by the on-board drive control which are updated every 20 ms. With regard to delay time caused by radio communication, it is impossible to perform the most important task - synchronization of primary and secondary field of linear motor - by control of the primary current. With regard to operation of several vehicles on the same stator section it is also suitable to adjust each vehicle's magnetic field to the traveling wave of the primary.

As can be seen from the figure the actual position of the primary field is calculated from the frequency reference being sent to the track. At this calculation it is essential to consider the delay time caused by data transmission (44 ms) and the motion of the traveling field during the sampling period. If error of position angle is not considered safe operation of the Railcab is not possible and control can become instable.

5. MEASUREMENT RESULTS

At figure 5 measured response of speed control to a step of speed reference from 0 to 5 m/s are presented. During all the process shown reference of power to be transferred from the primary into the on-board supply system of the Railcab is 4 kW (1 kW for each secondary winding).

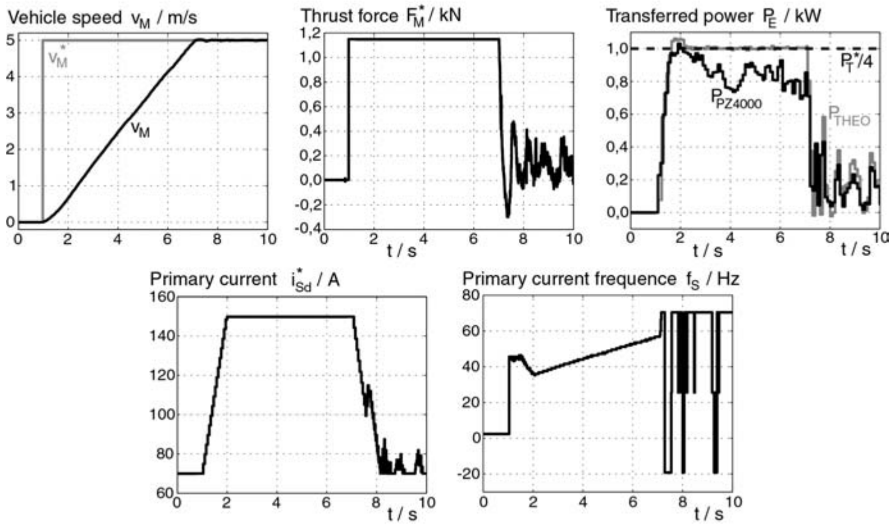

Figure 5: Step response of speed control with control of energy transfer

As can be seen from the plots measured thrust force and speed match the references determined by the profile generator very well. In contrast the transferred power which was measured with a power analyzer (PZ4000) shows an aberration from its reference. The error becomes extremely high after acceleration is terminated which confirms that noteworthy energy transfer is only possible while a relevant amount of thrust force is generated by the linear motor.

While high thrust force is present during acceleration error of transferred power rises up to 20 %. This has different reasons: First, when speed and frequencies increase voltages of power converters reach their limits. Second, in contrast with position and speed the transferred power is not subject of a closed loop control which compensates parameter variations and edge effects of the linear motor [5].Third, errors of measured vehicle position and remaining dead time effects of data transfer from Railcab to track (dead time is not an integer literal multiple of the Railcabs controller sampling time) cause an error of phase shift between magnetic fields of primary and secondary which cannot be compensated.

Strong disturbances of thrust force can be observed after acceleration. They are caused by the rims of wheels touching the rails which happens because at time of measuring steering mechanism was not in operation.

Finally the measurements in figure 5 document the functionality of the synchronization mechanism of the drive control based on a distributed hardware structure works. In spite of continuous changes of primary current and frequency a safe operation of the linear motor driven Railcab with energy transfer in the required dimension becomes possible.

6. CONCLUSION

After one year of commissioning the drive of test track with its distributed control, signal processing and communication system was fully in operation. Due to energy transfer via the linear motor the vehicles can be driving for unlimited time without any stop for charging the onboard battery.

Present and future work is devoted to improve the onboard power management and implement a set of capacitors (power caps) [6] which are capable of higher currents than the NiCd battery used onboard the vehicle for energy storing and make possible to store all energy delivered by the drive at braking.

Last not least, another system for communication is under development [7]. The system is based on a distributed active network with a dynamic changing number of communication units which will increase the data rate and so fasten up the control dynamic of this railway system.

7. REFERENCES

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