Drive Control and Position Measurement of RailCab Vehicles Driven by Linear Motors

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ABSTRACT

The novel railway system RailCab makes use of autonomous vehicles which are driven by an AC linear motor. Depending on the track-side motor part, long-stator or short-stator operations are possible. The paper deals with the operation of the doubly-fed induction motor which is used for motion control and for transferring the energy required on-board the vehicle. This type of linear motor synchronization of the traveling fields generated by the stationary primary and moving secondary windings is an important and demanding task because the instantaneous positions of the vehicle or the primary traveling wave must be determined with high accuracy. The paper shows how this task is solved at the moment and what improvements are under development.

Keywords: Linear motor, drive control, synchronization, position measurement

1. INTRODUCTION

In summer 2003 a test track was opened at University of Paderborn at which a novel railway system is investigated, see Fig. 1. The concept of the RailCab system and the features of test track have already been presented at ISICT'2003 [1, 2]. Meantime the first vehicles with all its basic functions - active steering of wheels, active tilting and suspension of carriage, driving and transferring energy to the vehicle by means of a long-stator linear motor – has been put into operation and is working well. Commissioning of a second vehicle is almost finished. Since the control is distributed to vehicle and track synchronization of the traveling waves is a demanding task for which the position of the vehicle or the stator's traveling wave must be measured.

Fig. 1. Test track. Left: total view with control center. Right: Vehicles with and without cover

2. CONTROL OF DOUBLY-FED LINEAR INDUCTION MOTOR

Up to now operation of long-stator motor has been investigated. The linear motor was realized as a doubly-fed induction motor with three-phase windings on the track (primary winding) as well as on board of the vehicle (secondary winding). When the secondary is fed with DC current, the machine behaves like a synchronous motor at which the speed of the vehicle matches the speed of the traveling magnetic field exactly. When sinusoidal three-phase current is applied to the secondary, the speed of the vehicle differs from the speed of the traveling magnetic field, voltage is induced to the secondary winding and energy can be transferred from the track-side to the power system on-board the vehicle.

Control of motion and energy transfer is performed by the drive control, see Fig. 2 and [3]. In accordance with commands for destination x_{Vd} and traveling speed v_{Vd} being sent from the central stationary control room to the vehicle by radio trans-mission the references for motion control are generated in the 'profile generator'. Depending on the situation reference for thrust force, speed or position is transferred to the block 'position and speed control' where further input signals, actual values of position and speed, are available for closed loop control. At the block 'operating point assignment' the references of primary and secondary current are generated under consideration of the force to be generated and the power to be transmitted. The reference for power transmission is delivered by an 'Energy Module operating strategy' [4] at which the requirements of the on-board power system [5, 6] is monitored and predicted continuously.

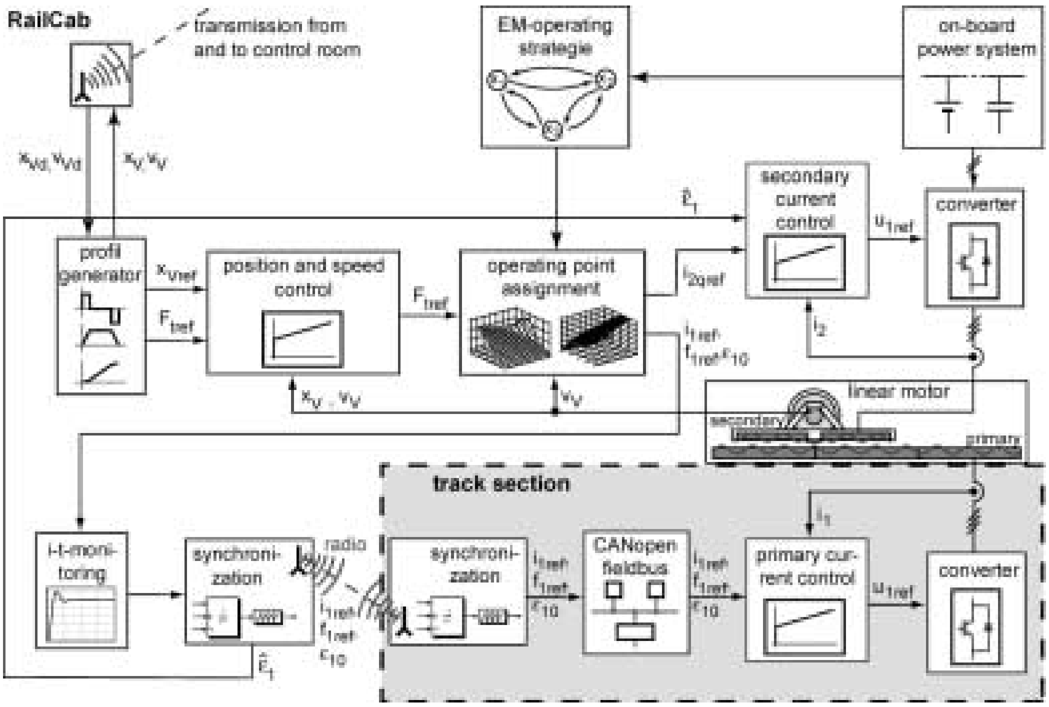

Fig. 2. Scheme of control distributed to vehicle and track

Generation of current references by the block 'operating point assignment' is discussed in the following subsections. Control of currents is performed by the track-side and vehicle-side power converters as usual.

2.1 Control of thrust force

The motion of the vehicle is determined by the thrust force which is realized by vector control of the primary and secondary current. Strategy for control of thrust force is based on (1) showing how the instantaneous value of thrust force F_t of a three-phase induction motor depends on the vectors $\underline{i}_1$, $\underline{i}_2$ of the primary and secondary current

$$F_t = \frac{3\pi}{2\tau_P} \cdot L_{12} \cdot \mathrm{Im}\{\underline{i}_1 \cdot \underline{i}_2^*\} = \frac{3\pi}{2\tau_P} \cdot L_{12} \cdot i_1 i_2 \cdot \sin \alpha_{1-2} \qquad (1)$$

(τ_P : pole pitch, L_{12} : mutual inductance). It is important to note that both current vectors must be inserted in the same coordinate system where α_{1-2} represents the phase shift between both current vectors. As proved in [7] α_{1-2} represents also the spatial displacement of the traveling waves generated by the primary and secondary current, see Fig. 3.

As can be seen from Fig. 3 α_1, α_2, and $\alpha_{1\text{-}2}$ represent the positions and the displacement of the traveling waves in a coordinate system which is oriented to the primary winding. Wave positions are β_1, β_2 when the coordinate system is oriented to the secondary winding. They differ from α_1, α_2 by the angular position α_V of the vehicle, which is x_V when measured in length units. ε_1, ε_2 are the phase angles of the current vectors in the coordinate frame of the respective winding. It are these variable by which the positions of the traveling waves are determined, $\alpha_1 = \varepsilon_1$, $\beta_2 = \varepsilon_2$, see [7].

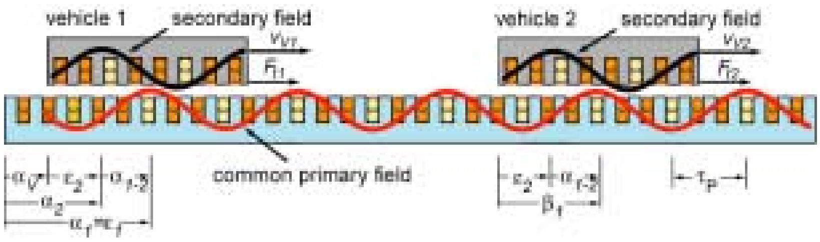

Fig. 3. Principle of long-stator linear motor with two vehicles on the same stator section, definition of symbols

Depending on the coordinate system two expressions for the wave displacement $\alpha_{1\text{-}2}$ can be obtained from Fig. 3:

$$\alpha_{1-2} = \alpha_1 - \alpha_2 = \varepsilon_1 - (\varepsilon_2 + \frac{\pi}{\tau_P} \cdot x_V), \qquad \alpha_{1-2} = \beta_1 - \beta_2 = \beta_1 - \varepsilon_2 \tag{2}$$

which can be used to establish this angle by control of current vectors, see section 3.

From (1) can be seen that minimum current and minimum losses are achieved when the reference of wave displacement is an odd multiple of $\pi/2$. Therefore its reference is set to $\alpha_{1-2ref} = \pm\pi/2$ where the sign depends on the direction of the force requested by the speed control.

For control of current vectors, a *d/q*-coordinate system was chosen which is oriented to the primary current. This choice proved to be suitable because if more than one vehicle is traveling on the same section of the long-stator all secondary windings have to interact with the traveling wave generated by this very current. Due to this choice of coordinate system, the primary current vector $\underline{i}_1$, has, by definition, no *q*-component in contrast with secondary current $\underline{i}_2$

$$\underline{i}_1 = i_{1d} + j\,0, \qquad \underline{i}_2 = i_{2d} + j\,i_{2q} \tag{3}$$

According to three current components $i_{1d} = i_1$, i_{2d}, i_{2q}, three degrees of freedom are available for control: Product $i_1 i_{2q}$ is determined by the demanded thrust force, ratio i_1/i_{2q} is available to realize any optimization goal and current i_{2d} is set to zero which means $\alpha_{1-2} = \pm\pi/2$.

Based on these conditions, force control is performed on-board of the vehicle by establishing the references for the primary and secondary current vector in two steps:

First, reference i_{1ref} of primary current's amplitude is established under consideration of voltage and current limitations. If these are not critical, losses can be minimized [7] or another optimization goal can be fulfilled. The current reference i_{1ref} together with other references (f_{1ref} , ε_{10}, see section 2.2) is transmitted to the track-side power converters by radio transmission every 20 ms [3]. Of course, the requirements of all vehicles must be considered when several vehicles are driving on the same primary section. In this case, one vehicle is declared as master and will make all decisions.

Second, control of secondary current vector is performed with high dynamics on-board of each vehicle under consideration of the own specific requirements. In particular, the reference for i_{2q} is established in accordance with the thrust force demanded by the own motion control. Orientation of the secondary current vector perpendicular to the primary current ($i_{2d} = 0$) is achieved by controlling the phase angle ε_2 properly. According to (2) two possibilities for determination of this angle exist and will be discussed in section 3.

Due to orientation of the secondary current to the primary current the well-known frequency requirement

$$f_1 = f_2 + \frac{1}{2\tau_P} \cdot v_V \tag{4}$$

which results when (2) is differentiated, is fulfilled automatically. Satisfying this condition is a must at any three-phase machine because otherwise traveling waves of primary and secondary winding would not be synchronized, displacement α_{1-2} in (1) would be oscillating and so would be thrust force F_t, too.

2.2 Control of energy transfer

Within any induction motor energy is exchanged between primary and secondary winding when the speed of the vehicle does not match the speed of the traveling waves ($v_V \neq 2\tau_P \cdot f_1$). For the power P_B transferred from the primary to the secondary winding the following equation holds [7]:

$$P_B = -P_2 = -3\pi \cdot f_2 \cdot L_{12} \cdot i_1 i_{2q} = 2\tau_P \cdot f_2 \cdot F_t \tag{5}$$

Obviously energy is transferred from the primary to the secondary winding when $f_2 \cdot i_{2q} > 0$. Hence energy transfer is possible not only at braking but also at accelerating and driving. Furthermore, control of energy can be performed as fast as control of secondary current because frequency can be changed without delay.

For control of energy transfer the reference f_{2ref} of the secondary frequency is calculated from the demanded power by use of (5) under consideration of the losses in the secondary winding [7]. Reference f_{1ref} of the primary frequency is then calculated from (4) and transmitted to the track-side power converters together with i_{1ref} as already mentioned in Section 2.1.

3. SYNCHRONIZATION OF PRIMARY AND SECONDARY FIELD

Synchronization of traveling waves, i e. orientation of secondary field perpendicular to primary field is an important task: It must be performed very accurately because if the error $\Delta\alpha_{1-2} = \alpha_{1-2} - \pi/2$ increases the following will occur:

- As long as $|\Delta\alpha_{1-2}| < \pi/2$ the force calculated from (1) decreases. Consequently the currents required to achieve the requested force must be increased which results in higher losses. E.g. in case of $|\Delta\alpha_{1-2}| = \pi/4$ or $|\Delta x_{1-2}| \leq \tau_P/4$, ($\tau_P$ = 100 mm), the force will be decreased to 70,7 %. For compensation the secondary current must be increased by 40 % which results in doubling of losses in the secondary winding.
- When $|\Delta\alpha_{1-2}| = \pi/2$ is reached, which corresponds to an error of 50 mm, no force will be generated at all.
- For $|\Delta\alpha_{1-2}| > \pi/2$ the force will change its sign. This causes the vehicle to move in the wrong direction and control to become instable because now feed back of the control loop has changed from negative to positive.

Consequently $|\Delta\alpha_{1-2}| << \pi/2$ is aimed and $|\Delta\alpha_{1-2}| < \pi/2$ must be fulfilled to ensure correct operation of the control.

Since the primary traveling wave can be common for more than one vehicle wave displacement α_{1-2} must be controlled onboard of each vehicle by proper control of the phase ε_2 of the secondary current vector, see Fig. 3. In accordance with (2) two possibilities exist for determination of ε_{2ref}. In the first case the position of the primary's traveling wave is determined from the primary current's phase and the vehicle's position. In the second case it is measured directly on-board the vehicle.

3.1 Synchronization of traveling waves by measurement of the vehicle's position

In accordance with (2) and Fig. 3 the required phase angle ε_{2ref} is determined on-board the vehicle from

$$\varepsilon_{2ref} = \hat{\varepsilon}_1 - \frac{\pi}{\tau_P} \cdot \hat{x}_V - \alpha_{1-2ref} \tag{6}$$

where $\hat{\varepsilon}_1$ is an estimated and $\hat{x}_V$ a measured variable.

Obviously the estimation of the primary current's phase angle as well as the measurement of the vehicle's position have to be performed with much better accuracy than demanded for $\Delta\alpha_{1-2}$. Considering that $\hat{\varepsilon}_1, \varepsilon_1, \hat{x}_V, x_V$ are varying continuously it is important to determine $\hat{\varepsilon}_1$ as well as $\hat{x}_V$ exactly for that instant for which ε_{2ref} shall be calculated. The power converters can be assumed to cause no phase error ($\varepsilon_2 = \varepsilon_{2ref}$, $\varepsilon_1 = \varepsilon_{1ref}$).

Estimation of the primary traveling wave's position

The angular speed of the primary traveling wave is determined by the frequency reference f_{1ref}. Based on this fact an estimate $\hat{\varepsilon}_1$ of the traveling wave's actual position is calculated in the block 'synchronization' of Fig. 2 by use of

$$\hat{\varepsilon}_1 = 2\pi f_{1ref} \cdot t + \varepsilon_{10} \tag{7}$$

As already mentioned, f_{1ref} is sent to the track-side power converters every 20 ms. At the same time the initial value ε_{10} is transmitted and updated, too, at the track-side to correct errors which might have occurred due to stochastic disturbances. At maximum speed of 10 m/s the vehicle moves 200 mm during one sampling period of 20 ms which corresponds to almost two times the pole pitch or more than three times the critical value of $\Delta\alpha_{1-2} = \pi/2$. Furthermore time for data transmission is of interest which at the moment is 44 ms. It is important to do the update of f_{1ref} and ε_{10} in (7) exactly at the same time at which i_{1ref}, f_{1ref} and ε_{10} are updated at the track-side current controllers.

Sampling time and transmission time are great and must be compensated exactly. But fortunately, these dead times do not cause severe problems because they do not affect the stability of closed control loops.

Measurement of the vehicle's position

Until now, the vehicle's position is measured by shaft encoders with high resolution of 0.31 mm which is required for determination of speed. 0.31 mm refers to an angular displacement of 0.55°. Hence accuracy of these sensors is very good but several effects can cause errors and must be considered.

First, slip has to be mentioned. Fortunately slip is very small and can be neglected because thrust force is not applied to wheels and rails. Second, by the steering mechanism a sinusoidal transverse movement can be applied to the vehicle's motion to distribute wear of the wheels to the whole width of the surface being in contact with the rail. Due to this effect the way of the wheels would be more than the distance which the vehicle has traveled. Third and most important, extremely great errors occur when the flange of a wheel strikes against the rail head. Normally this is prevented by the steering mechanism but it cannot be avoided during commissioning and must be handled later in case of a failure.

To reduce the influence of the mentioned disturbances several sensors and measures had been implemented, see Fig. 4.

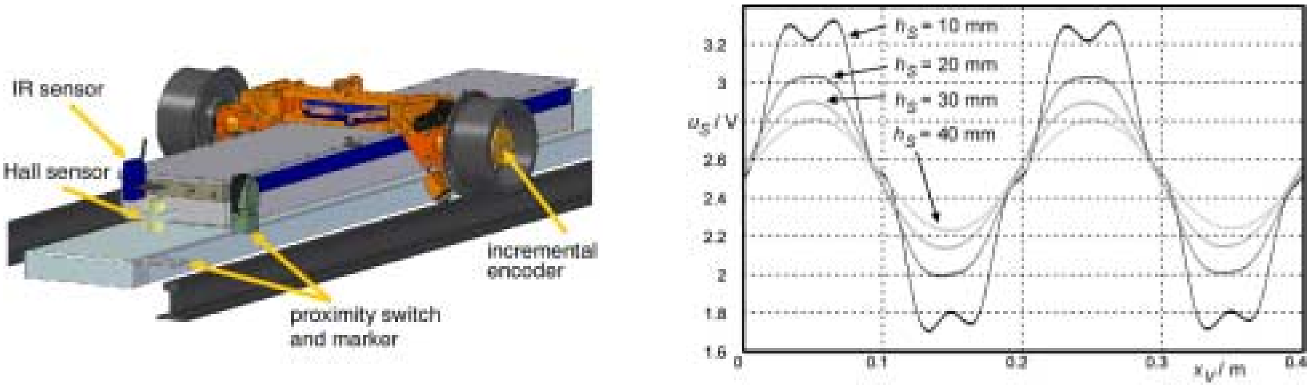

Fig. 4. Measuring for synchronization. Left: Sensors at the vehicle. Right: Signal of Hall sensor (h_S: height above stator)

First, the motion of each wheel is measured by a shaft encoder and the measured values are averaged before used as $\hat{x}_V$ for control. The quality of $\hat{x}_V$ is judged by means of the standard deviation calculated from the encoder signals.

In addition the incremental measuring system is calibrated periodically by updating the initial value ε_{10}. This is performed by evaluating the pulses delivered by a proximity switch which indicates markers installed at the front end of each stator segment i.e. every 1200 mm, see Fig. 4. Unfortunately the proximity switch features a dead time of 7 ms which cannot be neglected, because during this time the vehicle moves 70 mm (critical value 50 mm) when traveling at maximum speed of 10 m/s. Furthermore it is absolutely necessary to consider that, depending on the direction of the vehicle's motion, the leading edge of a pulse coming from the switch indicates the front end of a stator segment which is entered or the lagging edge of a impulse indicates the rear end of the stator segment which is left. Finally, erroneous impulses from the proximity switch can be caused by screw head and clamps used for fixing the stator segment. Such impulses are eliminated by evaluating the signal only in the close surrounding of markers where impulses are expected.

Periodical adjustment of position has proved to be important and must be performed with great reliability. Therefore a redundant measuring system has been introduced which is based on IR-sensors [8]. These sensors are used to scan the surface of the stator segments and to detect the gap between neighbored segments. An advantage of this sensors is the reaction within microseconds but attention must be paid to possibility of disturbance by stray light.

At very last, a measured position is rejected if is not compatible with an estimate calculated from the last position and the actual speed. In this case the former values are used for another sampling period of 20 ms.

3.2 Synchronization of traveling waves by measurement of the primary wave's position

With regard to robustness of sensors and reliability a second method for synchronization is under development which is based on measurement of the stator's traveling wave by Hall sensors, see Fig. 4 and [8]. Since the position is measured in the vehicle-oriented coordinate frame (angle β_1 in Fig. 3) calculation of ε_{2ref} is as simply as $\varepsilon_{2ref} = \hat{\beta}_1 - \alpha_{1-2ref}$.

Due to protection reasons, the Hall sensors are mounted in a distance from the stator which is larger than the air gap. Considering measured results, see Fig. 4, the distance was chosen great enough to avoid errors caused by harmonics.

For evaluation of sensor signals two methods are considered: First, a PLL is used to determine the angle $\hat{\alpha}_1$. As known, the phase discriminator of the PLL introduces 2nd-order harmonics, which have to be suppressed by a filter resulting in a phase lag in case of varying speed of vehicle or traveling wave. Additionally, the PLL cannot track the phase reliably during synchronous operation due to varying DC offsets of the sensor signal. The disadvantage can be avoided using a pair of sensors mounted with half pole pitch shift so that a coordinate transformation can directly be applied. It is also possible to extend the PLL approach with to phase-shifted input signals.

4. CONCLUSION

After commissioning the linear drive of the NBP test track and improving the reliability of the position measurement the test track is now ready for driving two vehicles at the same time and investigation of convoy operation. The challenge is to design strategies for dynamic generation and termination of virtually coupled convoys so that safety can be guaranteed under all operation and failure conditions. That makes high demands particularly on the communication system. Furthermore investigation of energy management will be continued which is also subject of a great faculty-comprehensive project.

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