DESIGN OF THE POWER SUPPLY FOR THE DOUBLY-FED LINEAR MOTOR OF RAILCAB TEST TRACK

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Abstract. With RailCab a new railway system ha been suggested which makes use of autonomously travelling vehicles and linear motor technology. At the test track which was built at University of Paderborn in scale 1:2.5 a doubly-fed induction motor has been chosen for driving the vehicles and transferring all energy which is required on board the vehicles. In the paper the basic scheme of the stator's power supply, calculation of the voltage and power requirement and partitioning of the long-stator are discussed in detail.

Key Words. Doubly-fed linear motor, power supply of long-stator.

1. INTRODUCTION

At University of Paderborn a new railway system is being developed [1,2]. The RailCab system is characterised by autonomous vehicles which travel on demand instead of trains traveling in accordance with a fixed schedule. Furthermore the vehicles are driven by linear motors generating high thrust force without moving and wearing parts and independently from weather conditions. To make traffic cost-effective, vehicles can form convoys which is not possible with slowly reacting conventional switches. Therefore switches without moving parts are used and hydraulic steering mechanisms are introduced to the vehicles which are equipped with additional hydraulic pistons for active suspension and tilting.

For investigation of the complex mechatronic system a testing plant has been built at University of Paderborn in scale 1:2.5. The test track consists of a circuit with straight and curved stretches having a total length of 530 m, see Fig. 1. Furthermore the test track includes a switch at which composing and decomposing of convoys as well as the behavior of the steering system can be investigated.

When a vehicle shall enter or leave a convoy vehicles must be operated with different speeds. This is why two versions of the linear induction motor are used at the test track instead of a synchronous motor which is normally preferred for railway "applications" like the German Transrapid and the Japanese Linear Express. At the doubly-fed induction motor three-phase ac windings are installed at both parts of the motor, see Fig. 2a). Due to this fact the vehicle-side motor part, too, can produce a traveling wave making possible to operate a vehicle with its own speed which is not determined by the speed of the traveling waves.

Fig. 1: Test track with control and substations

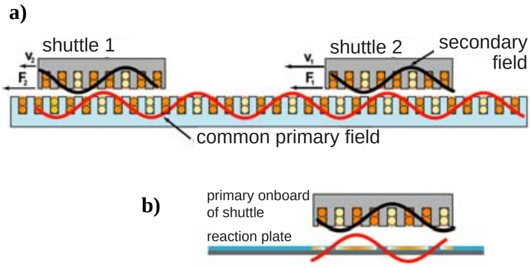


Fig. 2: Linear induction motor
a) doubly-fed motor with long-stator
b) short-stator induction motor

Thanks to having windings at both motor parts, like a three-phase transformer, two other features of the doubly-fed induction motor exist which are utilised at the test track.

First, during asynchronous operation energy can be transferred from the track-side to the vehicle-side winding. At the test track all energy required on-board the vehicle for supply of hydraulics and electronics is delivered via the linear motor and neither overhead wires nor contact rails have been installed. Consequently the long-stator motor is an important part of the power supply.

Second, when a simple reaction plate is installed on the track instead of the long-stator, the vehicle-side motor part can be used as a short-stator, see Fig. 2b). At the test track reaction plates are installed in front of the garage and in the surrounding of the switch. At the test track short-stator operation is investigated, too, but it is not considered in this paper [3].

In Section 2 of the paper the basic scheme of the power supply for the long-stator is shown, the equations for calculation of voltage requirement of the linear motor are derived and partitioning of long-stator in sections is discussed. The power supply

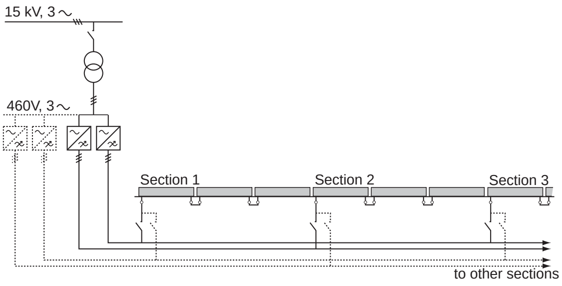


Fig. 3: Scheme of centralised power supply

system on-board the vehicles is presented briefly in Section 3. Finally features of the doubly-fed linear motor are discussed in Section 4.

2. POWER SUPPLY FOR THE LONG-STATOR

2.1 Basic Scheme of the Power Supply

As far as the construction of the long-stator is concerned no basic difference exists between synchronous motor and the doubly-fed induction motor. Hence, in accordance with the design of Transrapid or Linear Express, the long-stator is divided into sections which can be fed separately by DC link PWM converters. To save energy, current will be applied only to those sections at which a vehicle is present.

But one power converter is not enough to operate a vehicle satisfyingly: When a vehicle changes from one section to another a break-off of thrust force will occur which is caused by the reduced overlap of the vehicle-side motor part with the active stator section and by switch-over procedure of the converter. Consequently at least two power converters are required for operating a vehicle on the track.

For the layout of the power supply two suitable structures have been compared.

The scheme of centralised power supply, used by Transrapid and Linear Express for operation of one vehicle, is shown at Fig. 3 with solid lines. Dashed lines demonstrate how the scheme must be expanded if two vehicles shall be operated on the test track independently.

Obviously, in addition to one pair of power converters per vehicle, one mechanical or electronic switching unit per section is required. Additionally relatively long cables are required to connect the switching units to the power converters which conveniently are concentrated all near the control room while the switching units are distributed along the track.

At the scheme of distributed power supply each section is fed by a power converter of its own, see Fig. 4. This scheme is characterised by a great number of power converters but no switching units are required. When applying this scheme it is suitable to distribute the power converters along the track. By this measure total length of motor cables can be reduced which affect the impedance of the stator and are expensive (buying and installation) because shielding is a must. Finally the section control of the distributed structure is easier to implement and independent from the number of vehicles to be operated. Therefore the algorithm for section control can be easily expanded for more vehicles and can be transferred later to a real scale application.

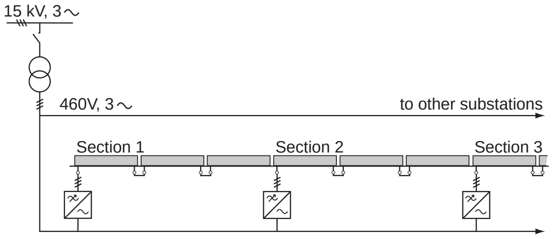


Fig. 4: Scheme of distributed power supply

When designing the power supply for the test track both schemes for power supply have been compared based on the requirement of operating three vehicles independently. Surprisingly the distributed power supply proved to be cheaper and therefore it was realised. Partitioning of the stator (see Section 2.2) resulted into 84 sections and the respective power converters were assigned to 4 substations which are distributed along the track, see Fig. 5.

2.2 Voltage and Current Requirement of the Long-Stator Linear Motor

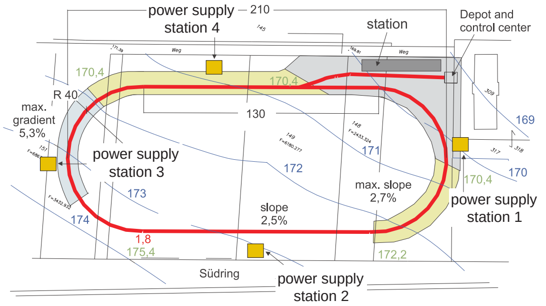
The voltages and currents required by the windings can be determined from the basic equations of the linear motor which are almost identical with those of a rotating doubly-fed induction motor. Since all energy required by the vehicles is applied to the stator winding the stator section will also be called primary and consequently the vehicle-side winding is called secondary.

In this paper all investigations are performed for steady-state conditions. Voltages and currents are assumed to be symmetrical and sinusoidal and will be represented by phasors with the amplitudes being rms-values.

Investigation is started from the voltage equation of the doubly-fed linear motor which are well-known from the slip-ring induction motor:

$$\begin{aligned} \underline{U}_1 &= (R_1 + j\omega_1 L_1)\underline{I}_1 + j\omega_1 L_{12}\underline{I}_2 \\ \underline{U}_2 &= (R_2 + j\omega_2 L_2)\underline{I}_2 + j\omega_2 L_{12}\underline{I}_1 \end{aligned} \qquad (1)$$

where



Fi. 5: Map of the test track

$\underline{U}_1, \underline{U}_2$: terminal voltage of primary/secondary,

$\underline{I}_1, \underline{I}_2$: current of primary/secondary,

R_1, R_2: resistance of primary/secondary,

L_1, L_2: self inductance of primary/secondary,

L_{12}: transfer inductance between primary and secondary,

ω_1, ω_2: angular frequency of primary/secondary,

τ_P: pole pitch.

Note that variables and parameters of the secondary winding are not referred to the primary side.

The phasors of voltages and currents are considered in a Cartesian d,q-coordinate frame which is oriented to the vector of the primary current because this quantity determines amplitude and phase of the stator's traveling wave with which all vehicle-side secondaries are interacting. Due to this definition the currents of the motor windings are

$$\underline{I}_1 = I_1 + j0, \quad \underline{I}_2 = I_{2d} + jI_{2q}\,. \tag{2}$$

As shown e. g. at [4] thrust force is determined by the currents,

$$F_M = -\frac{3\pi}{\tau_P} L_{12} \cdot I_1 I_{2q}\,, \tag{3}$$

and the power delivered from the secondary winding to the on-board power supply is calculated from

$$P_B = -P_2 = -3\omega_2 L_{12} \cdot I_1 I_{2q} - 3R_2 I_2^2 \tag{4}$$

Consequently $-\omega_2 L_{12} \cdot I_1 I_{2q} > R_2 I_2^2$ must hold for energy transfer to the battery which occurs if

$$-\omega_2 I_{2q} > \frac{R_2}{L_{12}} \cdot \frac{I_2{}^2}{I_1}\,. \tag{5}$$

In accordance with this result energy transfer to the battery occurs

- at driving thrust force ($F_M > 0$, $I_{2q} < 0$) if subsynchronous operation ($\omega_M < \omega_1$) is present,
- at breaking thrust force ($F_M < 0$, $I_{2q} < 0$) if hypersynchronous operation ($\omega_M > \omega_1$) is present.

From the above equations the voltages $\underline{U}_1$ and $\underline{U}_2$ can be calculated in dependence of thrust force F_M, speed v_M and transfer power P_B demanded by the motion control and on-board energy management [5].

For this purpose the secondary current and its components are expressed by the primary current by introducing two parameters n and q

$$I_2 = nI_1, \quad I_{2q} = -q \cdot nI_1, \quad I_{2d} = -\sqrt{1-q^2} \cdot nI_1\,. \tag{6}$$

Note that the ratio of current magnitudes must be positive ($n = I_2/I_1 > 0$). Parameter q with $0 < q \leq 1$ has been introduced in such a manner that $F_M / q > 0$ for driving force ($F_M > 0$). By this measure problems are avoided which can arise at eq.(7) from a square root with a negative argument. Finally only $I_{2d} \leq 0$ is considered because a d-component is not used but for flux weakening.

After the newly introduced parameters n and q have been used to replace the secondary current and its components, the primary current can be calculated from thrust force by means of eq. (3).

$$I_1 = \sqrt{\frac{\tau_P}{3\pi \cdot nL_{12}} \cdot \frac{F_M}{q}}\,. \tag{7}$$

Now the secondary frequency can be calculated from the required transfer power by means of eq. (4),

$$\omega_2 = \frac{\pi}{\tau_P} \cdot \frac{P_B}{F_M} + \frac{nR_2}{L_{12}} \cdot \frac{1}{q}\,, \tag{8}$$

and the primary frequency results as

$$\omega_1 = \frac{\pi}{\tau_P} \cdot v_M + \omega_2 = \frac{\pi}{\tau_P}(v_M + \frac{P_B}{F_M}) + \frac{nR_2}{L_{12}} \cdot \frac{1}{q}\,. \tag{9}$$

Finally the wanted expressions for voltages $\underline{U}_1$ and $\underline{U}_2$ are achieved, for better clearness, can be simplified by inserting $q = +1$. This value is suitable because the power supply should be designed in such a way that the maximum thrust force is achieved with minimum losses which is the case when $I_{2d} = 0$. After $q = 1$ has been introduced voltages for driving thrust force ($F_M > 0$ while $v_M > 0$) become

$$\begin{aligned} \underline{U}_1 = {} & \frac{\pi n L_{12} \cdot (P_B + v_M \cdot F_M) + (R_1 + n^2 R_2) \cdot \tau_P |F_M|}{\sqrt{3\pi \cdot L_{12} \cdot \tau_P |F_M|}} + \\ & \pm j \frac{L_1}{L_{12}} \frac{\pi L_{12} \cdot (P_B + v_M \cdot F_M) + nR_2 \cdot \tau_P |F_M|}{\sqrt{3\pi \cdot L_{12} \cdot \tau_P |F_M|}} \\ \underline{U}_2 = {} & \frac{\sqrt{n}\, L_2 \cdot (\pi L_{12} \cdot P_B + nR_2 \cdot \tau_P |F_M|)}{L_{12} \cdot \sqrt{3\pi \cdot L_{12} \cdot \tau_P |F_M|}} \pm j \frac{\sqrt{\pi \cdot L_{12}} \cdot P_B}{\sqrt{3n \cdot \tau_P |F_M|}} \end{aligned} \tag{10}$$

Note that voltages are given for braking thrust force, too, (use negative sign where indicated).

From these results the magnitudes of the voltages,

$$\begin{aligned} U_1 &= |\underline{U}_1| = \sqrt{\mathrm{Re}\{\underline{U}_1\} + \mathrm{Im}\{\underline{U}_1\}} \\ U_2 &= |\underline{U}_2| = \sqrt{\mathrm{Re}\{\underline{U}_2\} + \mathrm{Im}\{\underline{U}_2\}}\,, \end{aligned} \tag{11}$$

as well as the phasors of apparent powers,

$$\begin{aligned} \underline{S}_1 &= 3\underline{U}_1 \underline{I}_1^* = 3\underline{U}_1 I_1 \\ \underline{S}_2 &= 3\underline{U}_2 \underline{I}_2^* = 3\underline{U}_2 (-jI_{2q}) \end{aligned} \tag{12}$$

and the active power consumptions,

$$\begin{aligned} P_1 &= \mathrm{Re}\{\underline{S}_1\} = 3\,\mathrm{Re}\{\underline{U}_1\} \cdot I_1 \\ P_2 &= \mathrm{Re}\{\underline{S}_2\} = 3\,\mathrm{Im}\{\underline{U}_2\} \cdot I_{2q} \end{aligned} \tag{13}$$

can be calculated easily (note: $P_2 = -P_B$ must hold).

The results achieved up to now are used for partitioning of the long-stator which is discussed in the following section.

2.3 Partitioning of the Long-Stator

Partitioning of the long-stator means dividing the stator in sections and determining the lengths of sections in such a way that the power converters are able to apply the currents which are required to achieve the demanded values of thrust force, speed and transfer power.

At partitioning the following features of the linear motor have to be considered. First, the parameters of the primary winding (stator section) depend on the length of the stator section which shall be determined. Second, the transfer inductance and consequently the self inductance of the primary winding depend on the position of the vehicle: Obviously the transfer inductance L_{12} increases from zero to a maximum when a vehicle enters the section. At the same time self inductance L_1 is increased from a minimum to maximum.

Therefore it is suitable to subdivide the total length x_1 of the stator section in an active part (length x_{1act}), which is determined by the overlap of the stator section and the secondary, and a passive part (length $x_{1pass} = x_1 - x_{1act}$), which is not covered by a secondary, see Fig. 6.

The parameters for an active and a passive part having well-defined length can be calculated or measured, and from the result length-related parameters $R_1', L_{1act}', L_{1pass}'$ and L_{12}' can be achieved.

At partitioning of the long-stator the length of stator section x_1 has to be established in such a way that the maximum voltage requirement of the stator section does not exceed the rated voltage of the feeding power converter. Consequently the maximum voltage requirement has to be taken into account which appears when the vehicle or vehicles, respectively, are completely inside the section. In this case the active length of the section is determined by the total length x_2 of the vehicle-side secondary which is a multiple of secondary devices. Hence $x_{1act} = x_2$ is established, see Fig.6, and so are all parameters R_2, L_2, L_{12} of the active motor part being determined by the number of secondary devices overlapping the stator section.

The remaining parameters depend on the wanted length of the section according to

$$\begin{aligned} R_1 &= R_1' \cdot x_1, \\ L_1 &= L_{1act}' \cdot x_2 + L_{1passt}' \cdot (x_1 - x_2) \end{aligned} \tag{14}$$

With these parameters the magnitude of the stator voltage given by eq. (11) becomes a function of the section's length which, considered for $x_1 \geq x_2$, is almost linear. When depicted at a figure the value of x_1 can be read off simply for which the required voltage agrees with the rated voltage of the available power converter. The final value of x_1 must be established in such a way that it matches a multiple of the length of the stator devices from which the stator section is composed.

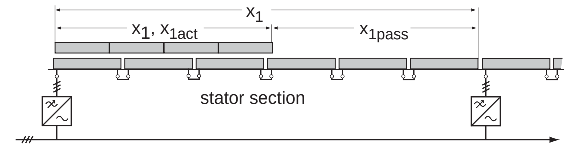


Fig. 6: Definition of active and passive length

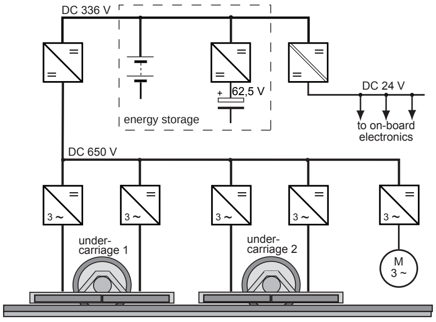


Figure 7: On-board power supply

2.4 Result of Partitioning

For the test track power converters have been chosen from an industrial type series for which a digital interface had been developed in the past. This interface makes possible to access the converters' control hardware directly from the rapid prototyping hardware used for all overlaid control tasks and for communication [6]. In addition these power converters can be fed with an increased three-phase AC voltage of 460 V, see Fig. 2. In accordance with the rated output voltage maximum section length was calculated and finally section length was established to 6 m consisting of 5 stator devices each being 1.2 m long.

3. POWER SUPPLY OF THE VEHICLE

On-board the vehicle energy has to be delivered to the pump motor of the hydraulic system and to the electronics for analog and digital signal processing, see Fig. 7. Furthermore all energy required by the linear motor must be delivered when driving in areas where no long-stator is present. Therefore energy must be stored on-board the vehicle which is performed by means of a battery having great storage capability and Ultra-capacitors which can handle high peaks of power occurring e. g. at braking [7]. To ensure a safe on-board energy supply a dedicated energy management is under development [8] which determines the reference of the power to be delivered by the linear motor and its distribution to the battery and capacitors.

As can be seen from Fig. 7 the secondary winding is composed of four sub-windings which are distributed to the undercarriages of the vehicle (required for investigation of a pitching control [9]). The sub-windings are fed separately with current $\underline{I}_2$ and their voltages are one fourth of voltage $\underline{U}_2$ which was calculated in Section 2. Due to shunt connection of the power converters at the DC-side the level of the DC link voltage is determined by $\underline{U}_2 / 4$ and the total current delivered by the linear motor to the DC link is related to $4\underline{I}_2$.

4. FEATURES OF DOUBLY-FED MOTOR

After three years of commissioning and operating the testing plant all expectations concerning the behaviour of the doubly-fed linear motor have been fulfilled. The vehicles can be driven continuously with all power delivered to the vehicle via the motor.

Power transfer does not influence the currents which are determined by force generation. But it is determined by slip frequency ω_2: With increasing transfer power slip frequency and primary frequency are increased which causes an increase of primary voltage. As a result the rated power of the primary power converters must be increased, too. The increase of primary voltage is caused by the inductance of the primary winding which depends on the length of the stator section. Therefore it is suitable not only to design the motor with low inductance but also to have short sections which is also advantageous with regard to losses.

For comparison of different designs or operating conditions two ratios are of special interest,

- the well-know efficiency η_P at which the useful power is related to the used power and
- a new ratio called "converter utilisation" η_S at which the useful power is related to the apparent power delivered by the converters.

Calculation of useful power depends on operation condition. Normally energy will be applied to the primary winding ($P_1 > 0$) and it will be converted to mechanical energy for driving ($P_M = v_M F_M > 0$) and transferred to the vehicle ($P_B > 0$). In this case the characteristics of interest are

$$\eta_P = \frac{P_M + P_B}{P_1}, \quad \eta_S = \frac{P_M + P_B}{S_1 + S_2}. \tag{15}$$

For linear motors these values are low compared with rotating machines due to the great air gap. For the test track they are even lower and not representative (and therefore not presented here) because a large air gap (10 mm, as much as at Transrapid) was chosen to ensure safe operation and the power of converters have been installed with unusual margins which allows to investigate the behaviour of the whole RailCab system under any conditions.

5. CONCLUSION

Up to now investigations of the linear drive were mainly devoted to improve the performance of motion control e. g. by investigation of different methods used for synchronisation of the traveling waves and by improving the communication between the vehicle-side and track-side control units. Furthermore methods for optimum control of the drive under consideration of power transfer has been investigated [8].

An important task still to be solved is optimization of the linear motor and its power supply. Basic equations have been presented for the motor at [4] and for the power supply in this paper. In these investigation the ratio $n = I_2 / I_1$ will play an important role because it influences many important data like efficiency, converter utilization and normal force of the motor considerably. Also the question, if it is cost-effective to use the linear motor for power supply of the vehicle instead of overhead wires or contact rails, must be answered before the system can be used for a real application.

ACKNOWLEDGEMENTS

The authors thank the Federal State of Nordrhein-Westfalen, the City of Paderborn and the University of Paderborn for financing the testing plant and supporting our research.

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