powerTRACE – a Novel Power Transmission and Actuator Entity

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ABSTRACT: Magnetically levitated vehicles without a physical contact to their guide rail require a contactless energy transmission system for a permanent supply of their on-board systems. This paper presents powerTRACE, an energy transmission system, which is integrated in the magnetic circuit of one or more of the vehicle's guiding actuators. Advantages of powerTRACE compared to already existing systems are the possibility to run at every vehicle speed and its fewer construction space requirement. Designated applications are slow magnetically levitated vehicles such as airport conveyor vehicles for baggage and elevator cars for very high buildings.

1 INTRODUCTION

Contactless power transmission from a fixed guideway to electromagnetically levitated vehicles is of particular interest, since sliding contacts or travelling cables negate all their benefits. Fast vehicles, such as the Transrapid™, for example, are able to consume power via harmonics induced by the propulsion device mounted to the guideway. However, this application is not feasible for slow vehicles. The alternative, an extra induction rail beneath the vehicle, yields further cost and requires additional construction space.

To minimize both, cost and space, an integrated solution of guiding and power transmission is recommended: powerTRACE (power **TR**ansmission and **AC**tuator **E**ntity), already in development at the Institute of Electrical Machines (IEM) at RWTH Aachen University, is an electromagnetic actuator, which possesses further coils on its guideway and on its moving part. The coil mounted on the guideway produces a high-frequency electromagnetic field, which superposes the levitating field. By means of this, a voltage is induced in the second coil mounted to the moving part and the power supply of the vehicle is established. Thereby, powerTRACE is an integrated solution for both, contactless guiding and contactless power transmission.

2 APPLICATION EXAMPLES

As aforementioned, powerTRACE is feasible for slow magnetically levitated vehicles. A first application example is a baggage conveyor vehicle for airports developed at the IEM (Van Goethem 2004). The vehicle test bench is shown in Figure 1. The frictionless operation guarantees lower maintenance costs and a longer hardware lifetime. The active part of the magnetic levitation actuators are mounted to the vehicle. Hence, a power supply is required for the moving part. It is also imaginable to prepare only a few sections of the track with powerTRACE and back up the power supply on the remaining track by an energy storage system.

Figure 1. Test bench of a conveyor vehicle for baggage

Figure 2. Elevator test benches

A further application example is a magnetically levitated elevator car (Schmülling et al. 2007). Figure 2 presents a ropeless elevator test bench (blue) and a contactless guiding test bench for elevator cars (grey) aside. The electromagnetically guided elevator car driven by electrical linear motors has no physical contact to the elevator shaft. Nevertheless, a power supply for the active magnetic guidings and the remaining electrical systems on-board is required.

The ongoing research activities about contactless guided elevator cars at the IEM gave the initial motivation to find an integral solution for both, guiding and power supply.

3 THE ELECTROMAGNETIC ENTITY

Basis of powerTRACE is a magnet module, which already is working at RWTH Aachen University (Schmidt et al. 2007). This actuator consists of two C-shaped iron yokes mounted side by side with a permanent magnet between them.

3.1 Guiding

The magnet module avoids the derailing of the vehicle. Usually, this is ensured by a combined deployment of several actuators mounted to the vehicle. The working principle of the actuator is the weakening and amplifying of its magnetic field. A cross-section of the actuator is presented in Figure 3. It can be seen that the actuator is a combination of an electromagnet and a permanent magnet.

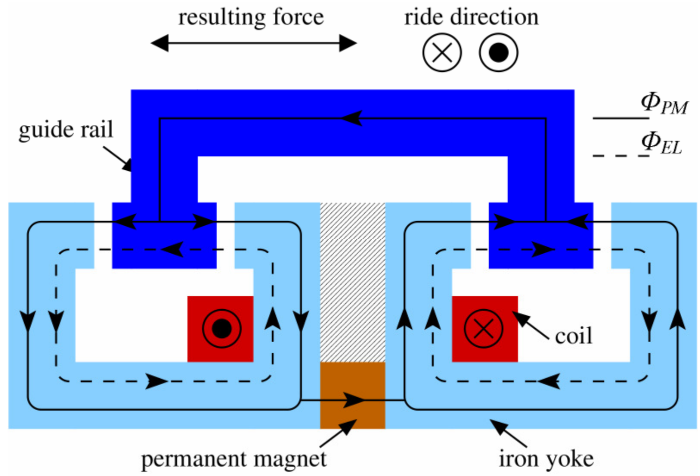

Figure 3. Cross-section of the magnet module

The return path of the flux is provided by the guide rail. The permanent magnet between the two laminated yoke parts closes its flux loops by crossing all four air gaps. The flux in the air gaps consist of a permanent magnet component Φ_{PM} and an electrically excited component Φ_{El}. By adjusting Φ_{EL} the permanent magnet flux can be increased in one air gap and decreased in the other one at the same time. Thus, positive and negative forces can be produced on the same action line depending on the current I_{EL}.

The magnet module offers more benefits than standard guidings for maglev applications such as U-shaped actuators (Schmülling et al. 2007). Firstly, it is not a hybrid actuator, since the permanent magnets are not permeated by the coil's flux, which results in a low reluctance (magnetic resistance) for flux Φ_{EL}. Furthermore the effective air gap has a constant size in each operation point i.e. actuator position. The advantage of a constant air gap is the easier system description, since there is no dependency of flux Φ_{EL} on the actuator's motion. A further advantage of the magnet module is the ability to produce an entire force in positive and negative direction. U-shaped actuators only produce a pulling force. Thus, the magnet module substitutes two of these standard actuators. Hence, the number of required actuators, rectifiers and the required construction space is reduced.

To control the entire guiding system, which is a combination of several magnet modules mounted to a vehicle, a multi variable state control is established. In principle, every single actuator can be controlled separately. For this purpose, the control algorithm calculates the local manipulated variable from the local air gaps. Due to large manufacturing tolerances in long tracks this method is unfavorable, since an independent control of solid-coupled actuators leads to unstable operation conditions. Therefore, a control of the degrees of freedom (DOF), i. e. global spatial variables, the so called DOF-control is applied (Wahner 2002). At this juncture, the decoupling of the actuators does not occur mechanically, but it occurs in the control loop system. Local measurement values are transformed into global values. This concept observes the absolute position of the vehicle. The global position vector is defined as

$$q = \begin{pmatrix} x & y & \alpha & \beta & \gamma \end{pmatrix}^T . \tag{1}$$

3.2 *Power Transmission*

Most contactless inductive power transmitters are based upon the transformer principle: A winding on the primary part contains a higher frequent current injection I_{PRIM} feeding the magnetic circuit. An electromotive force (EMF) U_{IND} is induced in a further winding on the secondary part, which supplies the load. powerTRACE is an extension of the magnet module described in 2.1 by transformer windings, whereas all actuator functions are still available. The magnetic circuit of the power transmission in a cross-section of powerTRACE is presented in Figure 4. The primary windings are wound around the four pole faces of the guide rail. They are in series connection and produce the magnetic flux Φ_{POWER} in the two iron yokes and in the end caps of the guide rail. During the dimensioning process it has to be regarded that flux Φ_{POWER} is much smaller than the actuator's working point flux Φ_{PM}, since Φ_{POWER} excites a disturbing force in each air gap. In Figure 5 can be seen that the addition of all disturbing forces yields zero at the same moment. One half of the entity forms a force in one direction unequal to zero and in the other half, the force points to the opposite direction. However, this force has to be regarded, since the actuator is excited by each single force with the transmission frequency, which can result in vibrations and acoustic noise. Therefore, it has to be avoided to operate the power supply system on a resonant frequency of the entity's body.

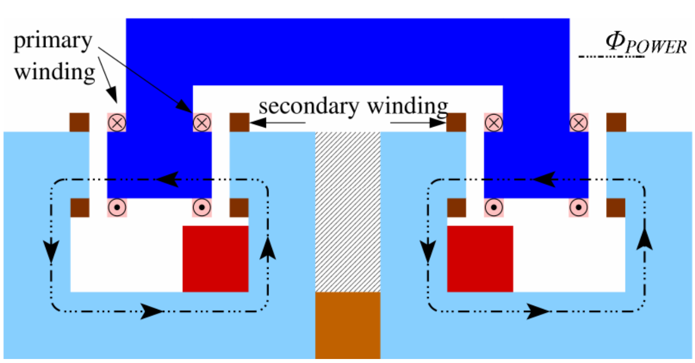

Figure 4. Cross-section of the powerTRACE entity

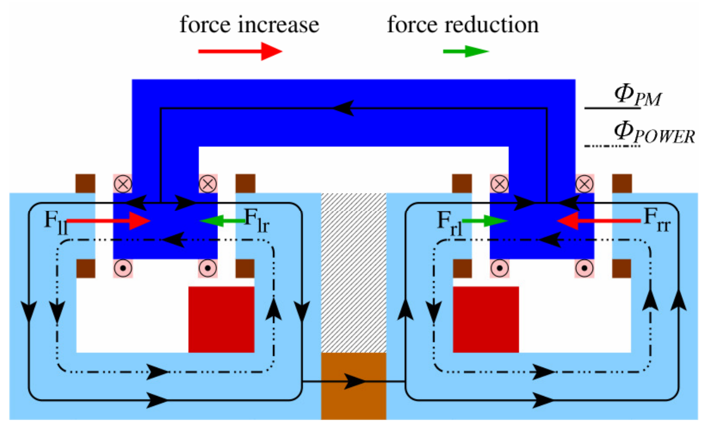

Figure 5. Disturbing forces due to power supply

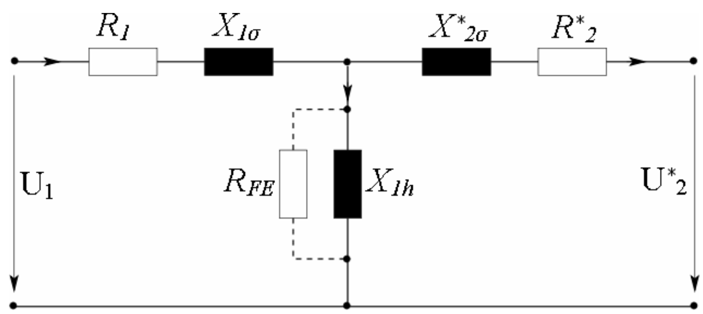

Figure 6. Equivalent circuit drawing of powerTRACE

The required EMF is induced in the opposite secondary windings, which are in series connection as well. The electrical transmission characteristic is described by a transformer equivalent circuit drawing, which can be seen in Figure 6. R_1 and R^*_2 are the winding resistances. In powerTRACE the flux leakage is quite high, when compared to standard transformers, due to the air gap reluctance and the long guide rail. This leads to a high leakage factor σ_1, and with it to a small value for mutual reactance X_{1h} in comparison to primary leakage reactance $X_{1\sigma}$. The secondary leakage reactance $X^*_{2\sigma}$ is smaller than X_{1h}, since secondary leakage factor σ_2 is smaller than 1. This is caused by the difference between actuator length and rail length. The primary winding is wound around a few meter long rail part. I. e. most of the secondary flux permeates the iron within the primary winding. The mathematically summarized coherencies can be seen below:

$$\sigma_1 = \frac{X_{1\sigma}}{X_{1h}} \qquad \sigma_2 = \frac{X^*_{2\sigma}}{X_{1h}} \tag{2}$$

R_{FE} is the eddy current resistance for an analytical description of the eddy current losses in the guide rail.

The values of the equivalent circuit quantities are determined by several transient Finite-Element (FE) computations using iMOOSE.tsa3d, which is an extension of iMOOSE.stat3d (van Riesen et al. 2004). This simulation also includes the assessment of the eddy current losses as well as the eddy currents' influence on the magnetic field.

To maximize the transformer's efficiency a power factor correction is performed. On both, primary side and secondary side, a capacitor is respectively implemented in series or parallel connection. Hereby, the power factor is adjusted for one defined frequency and one defined load. The system's requirement of reactive power is minimized.

3.3 Construction Space

The high advantage of powerTRACE, when compared to other inductive power transmitters, is the low demand for construction space. The guide rail has to be build in any event and other transmitters require additional rails for power supply systems. A power supply utilizing harmonics in the electrical linear drive is only possible for very fast vehicles. The linear generators, implemented in the Transrapid™, require a speed of more than 100 km/h to work (Zheng 2005). Therefore, additional power supply facilities are necessary in vicinity of a station.

3.4 Eddy Currents

Using high-frequent magnetic fields in actuators, which partially consist of permanent magnet material, can be a particular problem. Magnet materials, such as NeFeB e. g., are conductive. Thus, eddy currents occur. This is prevented in the powerTRACE device. There is no flux exchange between the two yoke halves, since the transitional reluctance is quite high. Therefore, eddy current losses in the permanent magnets and with it heating and demagnetization are avoided. This is a major advantage of powerTRACE, when compared to a U-shaped hybrid actuator with power supply windings. As depicted in Figure 7, the power transmitting flux Φ_{POWER} can only be led to the yoke by permeating the magnets.

A further advantage of the powerTRACE setup is the neutralization of the flux Φ_{POWER} within the actuator coil area. In Figure 4 can be seen that the sum of this flux in the central actuator part is zero. Thus, no interference voltage is induced in the actuator coil. In a U-shaped actuator, as shown in Figure 7, an avoiding of the interferential voltage is not possible. Furthermore, the global entire disturbing force is not zero: Either Φ_{POWER} increases or it decreases all air gap forces in the working point.

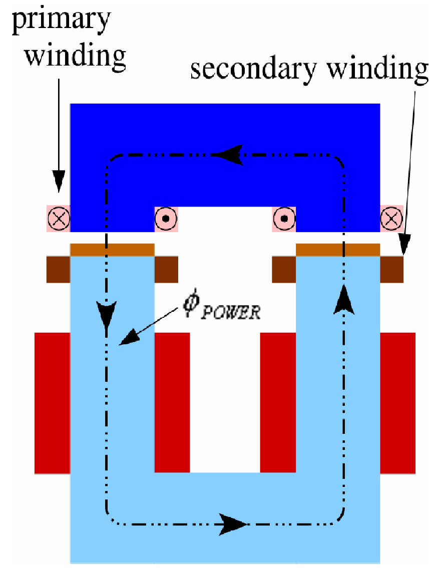

Figure 7. A possible power transmission in a U-shaped actuator

A challenge for powerTRACE is the reduction of eddy current losses within the guide rail. The rail is not laminated, since the construction of a laminated core of 100 meter length or more would be too complex and too expensive. The positive side effect is that the heat produced by the eddy current losses dissipates well. Nevertheless, the small skin depth at higher frequencies avoids a complete permeation of the rail. Therefore, the primary and secondary coils are directly placed opposite on two edges of one air gap. The coil positioning is the result of an intensive FE analysis, which obtained that the actual position (Figure 4) is the optimum. This is affirmed in literature (Ayano et al. 2002). In principle it is not necessary to use all four primary/secondary coil pairs. The more of these coil pairs are mounted to the rail/actuator the more power can be transmitted.

4 SIMULATION RESULTS

The application simulated is the guiding of an elevator car of a ropeless elevator system driven by linear motors. The validity of the DOF-control is verified by a dynamic simulation with Matlab™. Several real and extreme load cases are computed as well as the stiffness of the guiding system.

4.1 DOF-Control

Figure 8 shows the system response to force impacts in x direction, on a defined position lateral upside the barycenter of one wall. The force impact is displayed in the bottom left hand corner of the figure. It can be seen that only the position vector variables x, β, and γ are deflected in contrast to y and α. The displacement from the nominal position is compensated within *0.1ms*. To perform the simulation as realistic as possible the virtual position sensor signals are superposed by noise. Particularly, this can be seen in the characteristic of displacement variable *y*.

A couple of force impacts on different positions of the elevator car's walls and floor simulate the real load, i.e. walking and jumping individuals inside. The system response shows a robust guiding characteristic, even in extreme load cases.

The stiffness *k* of a guiding system is a commonly used comparison criterion. Hereby, quantifiable valuations about bearings and guidings can be performed, which are independent of the load cases. Stiffness *k* is the reciprocal of the maximum compliance, which is presented for variable *x* in Figure 9. It shows a maximum stiffness of $k=8N/\mu m$, which is a reasonable value for magnetically levitated systems.

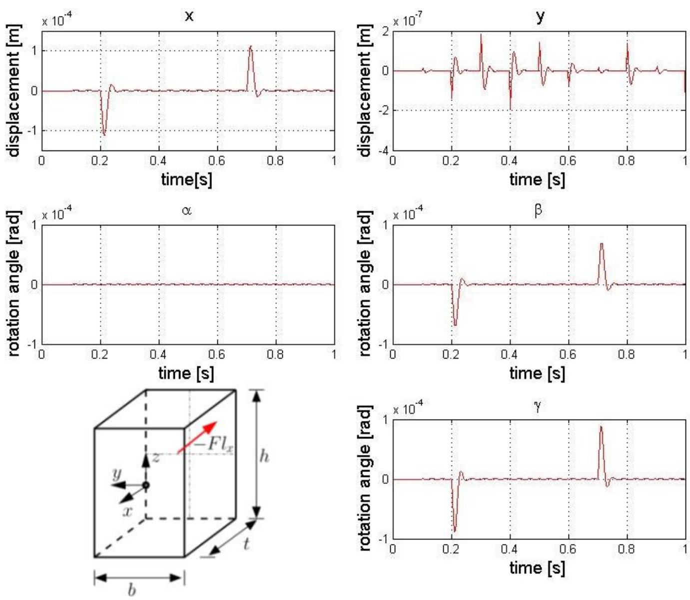

Figure 8. System response on a force impact

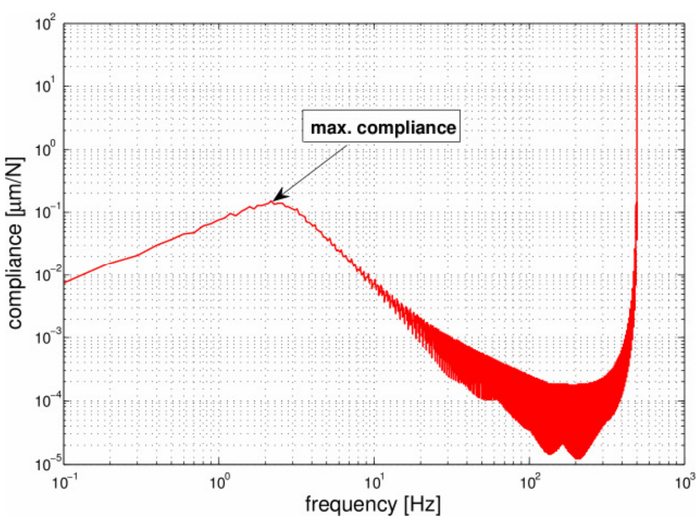

Figure 9. Compliance of displacement variable *x*

4.2 FE-computation of Power Supply

Main intention of the FE-simulation of the power supply is the determination of the eddy current losses. Therefore, transient computations of several working points are performed. For estimation as realistic as possible a simulation with field-circuit coupling is used (Lange et al. 2007). I. e., a coupled simulation of the magnetic circuit (transient FE-computation) and the electrical circuit (commercial circuit simulation software, Simplorer™) is accomplished. The electrical circuit simulation part includes load, power factor correction and voltage source. Hereby, it is possible to simulate the entire transformer characteristic with the accuracy of an FE-simulation.

A first simulation result is the dependence of the eddy current losses on time step and frequency for the same load for example. This characteristic is depicted in Figure 10.

For a load of $R_{LOAD}=100\Omega$ the resulting efficiency characteristic is presented in Figure 11. It can be seen that the maximum efficiency of $\eta=71\%$ approximately occurs at $f=7000Hz$.

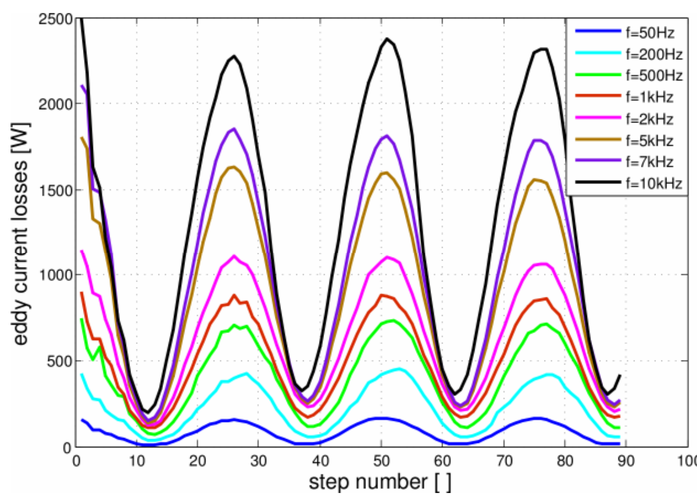

Figure 10. Eddy current losses

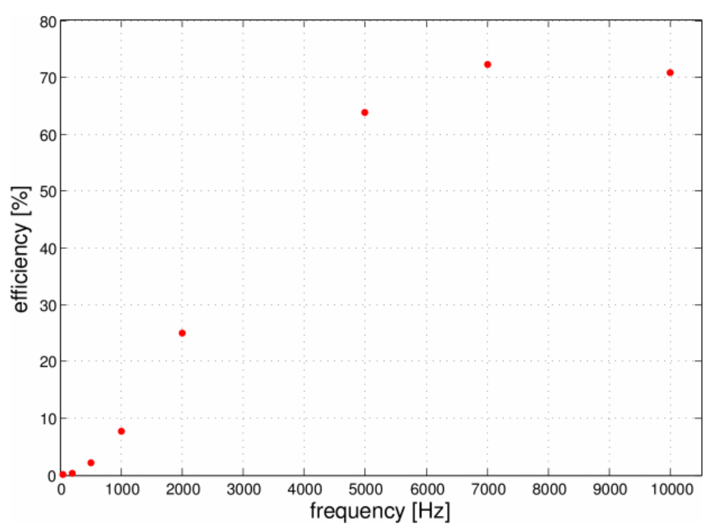

Figure 11. Efficiency characteristic for $R_{LOAD}=100\Omega$

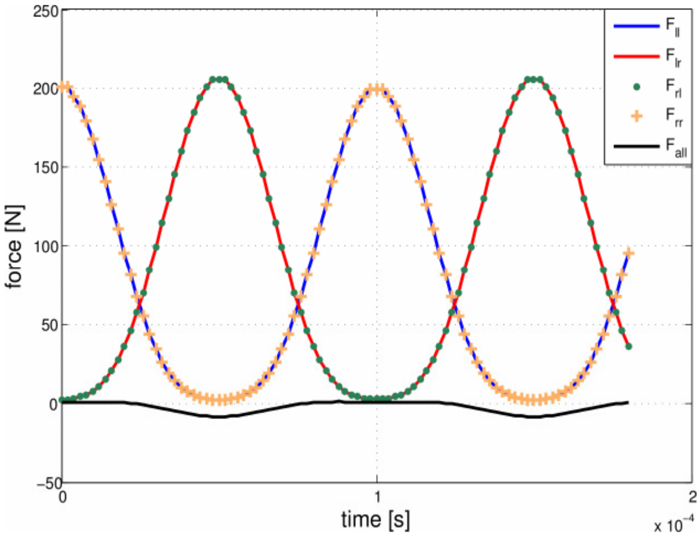

Figure 12. Disturbing forces in each air gap and cumulated force

These values are only benchmarks and not final results, since powerTRACE is still in development and changes in the electrical indicators as well as in the dimensioning are still possible.

4.3 Transformer's Influence on Guiding

As aforementioned, the vectorial sum of all disturbing forces is assumed to be zero, when the actuator is in its center position. This condition is investigated by the FE-simulation as well. The result is depicted in Figure 12. The amount of each single air gap force, i. e. F_{ll}, F_{lr}, F_{rl}, and F_{rr} (as displayed in Figure 5), is deduced from the numerical solution for the entity's flux. The figure presents a solution for a frequency of $f=10000Hz$. It can be seen that the cumulated force $F_{all}=|F_{ll}|-|F_{lr}|+|F_{rl}|-|F_{rr}|$ is nearly zero over the entire period. Taking these results into account, it is assumed that the guiding operation of the actuator is not affected. However, an operation of the transformer at the entity's resonant frequencies has to be avoided.

5 CONCLUSION

An integrated system for both, contactless guiding of a vehicle and the energy transfer to this vehicle, is presented. The actuating partition of powerTRACE is working properly, which is accounted by a system simulation of an elevator. The functioning of this magnetically levitated elevator system is explained and illustrated.

Simulation results of the integrated power supply system are presented as well. The disturbing influence on the guiding system is small, due to the high mass inertia of the guided vehicle, the high transformer frequency, and the compensation of the disturbing forces. A challenge of the continuative research on the entity is the increase of efficiency. This must be possible, since similar power supply systems are able to reach a high efficiency (Mecke 2001) by use of modern power electronics. However, due to the good dissipation of heat in the guide rail, the deployment of powerTRACE is already feasible.

The next research steps contain an optimization of the guide rail's topology to decrease construction costs and the development of an efficient and adequate rectifier for the supply of an electrical load.

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