Operating Point Assignment of a Linear Motor Driven Vehicle Using Multiobjective Optimization Methods

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Abstract - A test track of 530 m length for linear motor driven railway vehicles in scale of 1:2.5 was built at the University of Paderborn in 2002. A doubly-fed long stator linear motor does not only drive the vehicles, but offers the opportunity of a contactless energy transmission into the vehicle's on-board supply system, too. In this pape, the motion control structure is presented comprising an operating point assignment of the linear motor optimized by a multiobjective optimization method.

I. INTRODUCTION

A novel railway system NBP (Neue Bahntechnik Paderborn) is under development at the University of Paderborn [1]. The novel system is characterized by autonomous vehicles travelling on demand instead of trains in accordance with a fixed schedule [2]. The vehicles, so-called railcabs, are driven by a doubly-fed linear motor, and comprise an active guidance and an active suspension for improved comfort.

Fig. 1: NBP Test Track

Fig. 2: Linear motor driven test vehicles

In order to investigate the complex mechatronic system, a test plant in scale of 1:2.5 was built in 2002 at the University of Paderborn. The test track consists of an oval with one switch and straight curved stretches having a total length of about 530 m. The gradients are up to 5.3% to demonstrate the enhanced climbing capability of linear motors (Figure 1).

Two railcabs (Figure 2) can be operated at the same time with a maximum speed of 36 km/h. The length of a railcab is approximately 3 m. The body's height and width are about 1.2 m. One railcab has a mass of nearly 1200 kg.

After giving a brief summary about the test plant the focus of this contribution is placed on the operating point assignment of the doubly-fed linear motor. The working principle of the latter is described in chapter II supplemented by an illustration of the energy flow. The operating point assignment is outlined in chapter III for optimizing the energy flow by the mathematical treatment as multiobjective optimization in chapter IV. The paper is closed by a discussion of simulation results in chapter V.

II. DOUBLY-FED LINEAR MOTOR WITH ENERGY TRANSFER

The primary of the linear motor is installed between the rails and the secondary is fitted below the undercarriage of the railcab. If the power is supplied to the primary and secondary independently implying independent alignment of the current vectors, the railcabs can be operated in asynchronous mode, which offers two additional advantages [3].

On the one hand, this operation mode allows a relative motion between several railcabs running on the same primary (Figure 3), while on the other hand, a contactless energy transfer into the railcabs becomes feasible. This, in combination with an on-board hybrid energy storage, makes overhead lines or third rails superfluous.

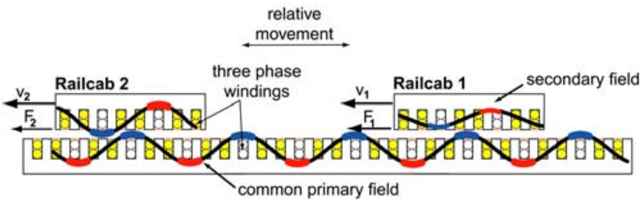

Fig. 3: Working principle of a doubly-fed linear drive

Studies have shown that the absolute value of the power transferred to the secondary depends on the operating point of the linear motor [4]. The transferred power depends on the motor currents and frequencies of primary and secondary. The energy flow between primary, secondary

and on-board power supply (Figure 4) can be controlled by variation of these values.
Less ohmic losses of secondary P_{dS} and less demanded mechanical power P_M yields increased charging power P_B, which is directed via bidirectional converters to either a battery or a supercap of the on-board storage. If the transferred power does not suffice to compensate the railcabs requirement of energy, the on-board energy storages are discharged.

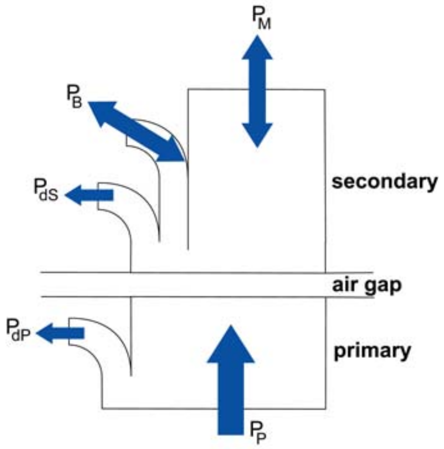

Fig. 4: Energy flow of linear motor

Thus an “intelligent” operating point assignment is required in order to minimize the losses of the linear motor and the on-board energy storage volume, weight and costs.

III. DRIVE CONTROL STRUCTURE AND METHODS OF OPERATING POINT ASSIGNMENT

The drive control structure of a railcab is shown in Figure 5. Depending on the target position of a railcab a jerk limited profile generator assigns the reference values of the current position x_M^* and speed v_M^*. By means of a cascaded structure of position and speed control the reference thrust force F_M^* of the linear motor is determined.

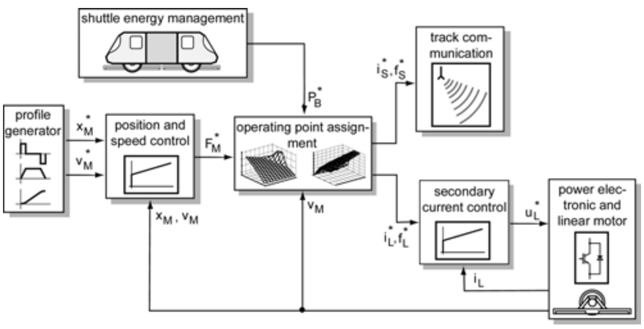

Fig. 5: Drive Control structure of the test track

A railcab energy management calculates the demanded power P_B^*, which has to be transferred via the drive. Considering these two values and the measured speed v_M of the railcab the operating point assignment determines the reference values for frequencies and currents of both motor parts. The stator references have to be transmitted to the primary power supply via radio, whereas the references of the secondary have to be processed by the secondary current control. Both current controls are based on a primary current oriented reference frame [5].
The operating point assignment consists of a *multiobjective optimization* method considering two objectives:

- the maximum degree of efficiency η
- the maximum converter utilization factor η_{SN}, taking in consideration the ratio of real output power to apparent power of the linear motor

For comparing both optimization objectives one operation point of a railcab on the test track characterized by a thrust force F_M^* of 200 N, a speed v_M of 36 km/h and a transferred power P_B of 2 kW is considered. Typical characteristics of these objectives are summarized in table1.

TABLE 1
CHARACTERISTICS OF OPTIMIZATION OBJECTIVES

	η - optimization	η_{SN} - optimization
secondary reactive power [kVAr]	7.72	2.97
primary real power [kW]	6.63	9.36
secondary copper losses [kW]	0.69	0.31

By definition an optimization considering a high efficiency the needed primary real power becomes minimal. But copper losses and the apparent power of the secondary are still higher than using an optimization based on the converter utilization factor. Hence, if the temperature in secondary rises and the cooling of this motor part is not sufficient, an η_{SN}-optimization should be preferred. If the energy storage of the railcab is discharged and the batteries state of charge is low, the optimization based on η_{SN} should be favoured, because in this case the reactive power oscillating between secondary and battery (flicker-effect) generates an extra load to the battery.
For a *multiobjective optimization method* based on η and η_{SN}, the temperature of the secondary ϑ_S und the state of charge of the battery q should be considered, too.

IV. TREATMENT OF THE MULTIOBJECTIVE OPTIMIZATION PROBLEM

As described above, the goal is to optimize the two objectives η and η_{SN} simultaneously. Since these two objectives are contradictory this leads, mathematically speaking, to solving a corresponding *multiobjective optimization problem (MOP)*. It becomes necessary to find those points in parameter space which describe the optimal compromises with respect to the given objectives: a point *x* in parameter space is called optimal – or a *Pareto point* – if there is no other point which is at least as good as x in all the objectives and strictly better in at least one objective. The corresponding set of optimal solutions is called the *Pareto set*.

Recently a new set oriented numerical approach has been proposed for the numerical treatment of MOPs ([6] [7]): starting with the entire set of possible parameter values of the MOP this set is permanently subdivided and refined producing increasingly finer coverings of the Pareto set. The algorithm stops if the desired granularity of the resulting covering is reached (see e.g. Figure 6). Since this method has proved to be very efficient, it is also the method of choice in the present context.

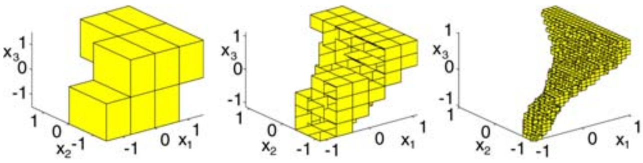

Fig. 6: Working principle of the subdivision techniques: the set of possible parameter values is permanently subdivided and refined. The pictures show a resulting box collection of a MOP consisting of three objectives in 3-dimensional parameter space for 10, 15 and 21 iteration steps. For details see [6] and [7].

Once the entire Pareto set for a given working point (v_M , F_M , P_B) has been computed, one has to determine "the ideal" point within this set for the given problem. Thus, an appropriate so-called "decision maker" is needed.

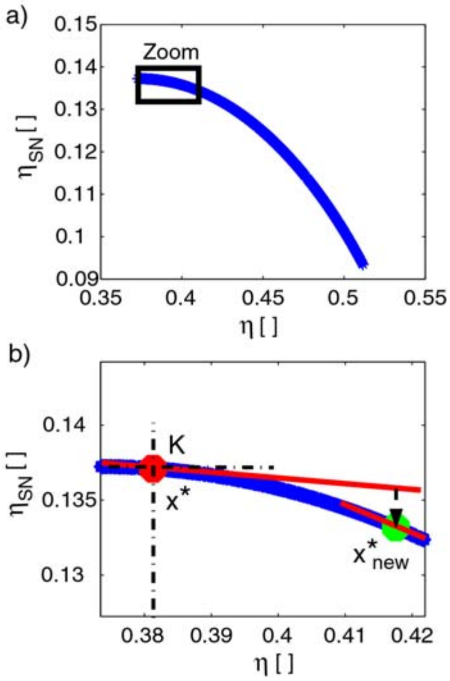

Fig. 7 a): Entire Pareto set for one simulated working point
b): Zoom - Illustration how the Decision Maker works on a selected interval of the Pareto set

Based on the relations summarized in Table 1, a decision-making algorithm was developed, which takes into account two variables as mentioned above, namely the charging state of the battery q and the temperature of the secondary motor part, ϑ_S. If the battery is being charged, then only the temperature ϑ_S is regarded.

To be more precise, the decision maker works as follows: The function values of a point of the Pareto set are considered. A point x^* is accepted as a good point, if the ratio of the two objective values of x^* is equal to a specified value K, which depends on ϑ_S and q.

Furthermore the neighborhood of x^* is taken into account. If a small decrease of one objective causes large benefits of the other one, the working point x^* is adapted, until a prescribed slope of the tangent at x^* is exceeded. Figure 7 shows a typical Pareto set during the run of a railcab and illustrates the principle of the decision maker.

V. SIMULATION RESULTS

A simulation model of the linear motor and the load cycle of the test track was used to obtain first results and impressions by using *multiobjective optimization* methods.

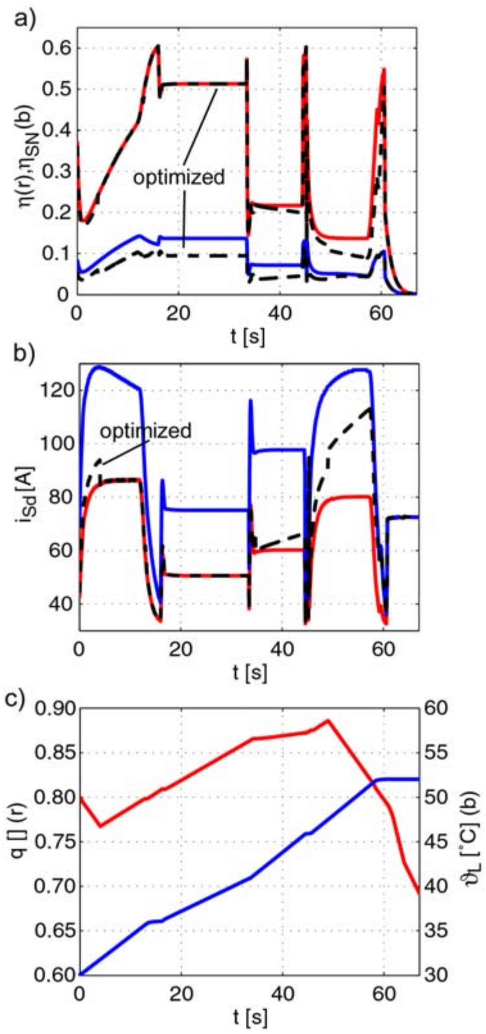

Fig. 8a): max. possible efficiency (red), max. possible converter utilization factor (blue) and values of multiobjective optimization (black)
b): primary current references: degree of efficiency (red), converter utilization factor (blue), multiobjective optimization (black)
c): temperature of secondary (red) and railcab battery load value (blue)

The plots presented in Figure 8a to c belong to a simulated drive of a railcab around the 450 m long track oval with an acceleration up to a speed of 36 km/h and at the end a brake process down to 0 m/s. In order to get more demonstrative changes of the operation point assignment the increase of the weighting factors of the decision maker ϑ_L and q are augmented above common rated values. For visualization the same changes without an augmentation the simulation period would have to be raised extremely.
Following the lapse of the battery charging state depending on the battery current (Figure 8c), the time sequence of the two step decision maker is split into three time intervals and so two switches happen during the simulation time.
Considering the optimized primary current in Figure 8b, the first switching action is visible after 4s. The battery is no longer discharged and so the charging state rises and q has no longer an influence on the decision maker and in case of the low temperature of the secondary the operating point of the drives follows solely objective functions maximizing the efficiency (Figure 8a). If the temperature increases, the efficiency deviates from its maximal value and objective functions, maximizing the converter utilization factor, are focused on. Because the ohmic losses of this motor part are reduced, the rise of temperature in the secondary goes down.

CONCLUSIONS

Doubly-fed linear motors driving railway vehicles can be used for energy transmission into the vehicles, if a special operating point of the motor is assigned by the control structure. In consequence of their design and the large air gap linear motors do not reach high efficiencies. A *multiobjective optimization* method can be used to optimize the operating point assignment. In this case possible optimization objectives could be the efficiency and the converter utilization factor of the linear drive.
The advantages using such a *multiobjective optimization* are based on the consideration and evaluation of the entire Pareto set in contrast to classical optimization methods.

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