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Modular transportation system with a three dimensional routeing

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Abstract: In intra-enterprise logistics and automation of manufacturing processes general a rising productivity by high flexibility is required. Existing transportation systems exclusively use two-dimensional track sections, because they can be served with standard drives. Because of these simple structures the transport speed is limited and thereby also the throughput. In this paper now a modular transportation system is presented which could reach higher speeds with a direct drive and the use of centrifugal force compensating curves. Simultaneously the system also can change the altitude. All this succeeds with the integration of three-dimensional track sections. Therefore a two piped guiding system with a long stator linear motor was designed. To combine the linear motor with the three dimensional track special stator elements were developed which allow a bending of the stator to follow the route course. The current work deals with the implementation of a mechanical passive switch, which is operated by the electromagnetic forces of the linear motor. So no additional mechanical actors or a separate electromagnetic system are necessary.

Key words: 3D-Linear Motor, passive switch, Steep turn, logistic, modular transportation system

1. Introduction

For intra-enterprise logistics and the linking of manufacturing processes always exists the desire for raising the productivity by higher transport speeds, easy changing of altitudes as well as achieving a flexible steering and distribution of the flow of goods by switchable junctions. In cooperation with ISR of the “Technische Universität Darmstadt” and the IfR of the “Technische Universität Braunschweig” the Institute of Electrical Machines, Traction and Drives (IMAB) developed a new transportation system to comply with this requirements. The linear drive test track investigated since 2010 represents an oval demonstrator with the main dimensions 3.5 × 4.5 m. The detailed specifications for this system were identified in the workshop “Geregelte Elektroantriebe” of the “Forschungsvereinigung Antriebstechnik e.V. (FVA)”, Germany and a project attendant committee of industrial representatives [1].

At IMAB a modular structured transport system with different function modules was designed for this duty. The input requirements to develop a robust drive, suitable for a long track without contact rails or trailing cables led to a system with a long stator linear drive and passive movers. As main systems a linear machine and one mover were developed, which are deformable in a three-dimensional way to follow the given bending of the track (Fig. 1). The system was built up as demonstrator in the laboratories of the IMAB and ISR and later at the IFR. The demonstrators consist of a mover and an oval with several track sections which have different functions. The different sections represent the capabilities and properties of the system. The curves are sloped to compensate centrifugal forces. The long stator is separated into modules of several stator elements with concentrated windings. Along with 10 magnet poles at the mover results a 12/10 synchronous motor topology. A possible double side arrangement in straight sections allows higher propulsion forces and therefore a higher acceleration. It is also a precondition for the later introduced switch function. With the 13 kg heavy mover, the system reached speeds up to 10 m/s at a thrust up to 900 N.

To reach the aims of low cost production by high-volume number of the single components, the segmentation and modularization together with such concepts as concentrated windings are indispensable. This also incorporates the implementation of inverters without intelligence for each module which allows a further cost reduction, while all control functionality is concentrated in one computer.

The development of the switch opens further applications with the possibility to realize parallel transportation lines and the distributing or merging of flows of goods. This e.g. is useful for a flexible linking of manufacturing stations.

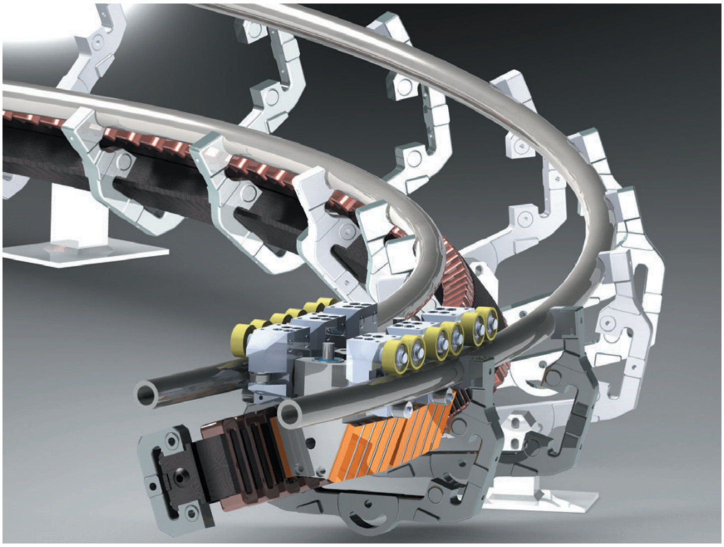

Fig. 1. Mover in the sloped curve

2. General structure of the system

2.1. Track modules

From the very first the development was focused on high modularized components. This should serve the user as an advantage to arrange the conveying machinery with a high flexibility. On the other side this minimizes the production costs with single parts which can be manufactured in a volume production. So the modularization starts with the separation of the track sections on the top and goes down to the single stator element.

The following track sections were implemented into the demonstrator oval:

- Acceleration / Brake
- Steady state operation
- Precise positioning
- Track branching (with passive switch)

The built up demonstrator oval first was configured as shown in Figure 2 on the left side. It consists of one straight acceleration section (1), two steep turns for steady state operation (2) and one straight precision section (3). The actual configuration is shown on the right side and includes the switch (4) instead of the precision section. Furthermore of course additional and more user specific modules are conceivable.

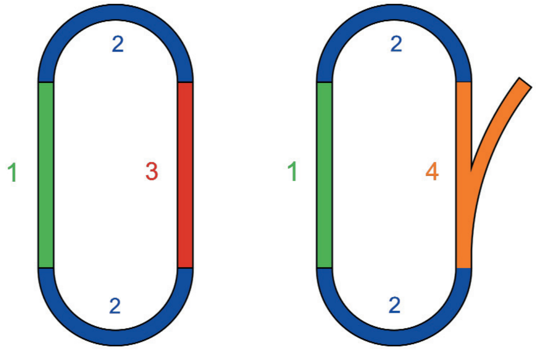

Fig. 2. Sections of the demonstrator ovals

2.2. Topology of the machine

The concept has to comply with the requirement for arbitrary track lengths and electrical passive movers. So the solely wise solution is a long stator principle. In this case it does not mean the whole track has to be covered by stator modules. Also bigger gaps of the drive along the track are possible where the vehicle is driven by its inertia. With the intention to build a switch function it was decided to use a permanent magnet synchronous machine. Therefore a topology of a $<6\text{-}1\text{-}2\text{-}10>_1$ poly phase machine PPSM was chosen with the magnetic circuit structure shown in fig. 3. In the mentioned code quadruple the basic type definition of the elementary machine is represented [2]. The arrangement allows relative large differences for the air gap at comparatively low variations of the propulsion force. Also the assembling of the stator coils is very simple and this means favourable to manufacture.

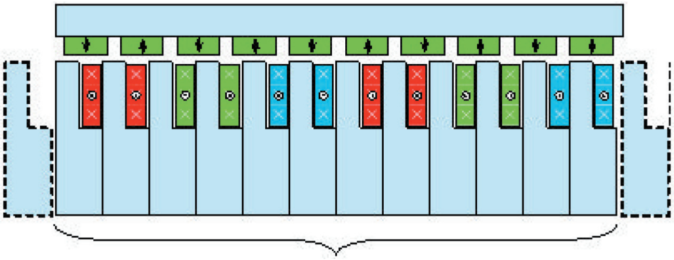

Fig. 3. Structure of the elementary machine

An elementary machine is to be understood as the smallest working unit. The fourth numeral of the code quadruple represents the count of poles and the first describes how many coils are implemented per elementary machine. The middle numerals determine in detail the structure of the winding by the count of coils per zone and a number of groups which consist of one or more zones respectively phases. The index at the end specifies if there are one or two coil sides in the slot [3].

3. Magnet circuit design

3.1. Stator

The length of an elementary machine of a 3d-linear motor is 240mm and is the same as the length of the actual mover. As the quadruple code shows, there are 12 slots made up of 12 stator elements and filled with 6 concentrated windings. The width of tooth amounts to 10 mm, the length 60 mm and the depth oft the slot is 30 mm. The open slot geometry shows a tooth to slot ratio of 1:1. The ratio varies slightly in dependency of the used track section. In a curve for example the slots spread a little bit because of the curvature. On the other side the two magnet poles in the middle of the mover shift closer together what results in a slightly reduced thrust. The coils split into two groups per elementary machine and each group consists of three phases. Several elementary machines are connected in series and combined to larger modules. Under consideration of the inverter link voltage and the desired maximum travelling field frequency a maximum size of a module is possible due to rising inductivity.

3.2. Translator (mover)

On the side of the translator there are 10 magnets with changing polarity according to the machine topology. The magnets are mounted on a massive iron yoke. Between the single poles are filled iron gaps, which are also necessary for the orientation during the assembly and serve as an inductive variance (saliency) too. For a better adaption to the track curvature the translator is divided in two halves linked by a ball joint. Apart from that the mover is passive which means that no energy supply on to the vehicle is required for the propulsion or any other additional equipment. The translator can be equipped with different payload platforms depending on the intended use. So a typically robust system results which can be deployed in stocking and production areas.

3.3. FEM model

For the investigation of the drive behaviour and the layout of such a magnetic circuit like the one shown here a FEM analysis is very suitable. To get usable results a close to reality model for an elementary machine had to be build-up incorporating all stator elements and the parasitic gaps between them as well. This allows the understanding of the internal magnetic flux distribution while practical measurements are limited by the measurability of certain parameters during operation. With the FEM it is comparatively easy to observe dynamic effects while their measurements are very elaborate or nearly impracticable. Especially for the development of the switch (chapter 6.1.) it is important to investigate also secondary effects as thrust ripple and cogging. The model to be seen in Fig. 4 was created in "Vectorfields Opera" software. The Figure shows one side of the stator and translator with the magnetic fields arising if the motor is powered for maximum propulsion (exclusively q-current in dq-representation [4]). Here you can see in detail the divided structure of the vehicle with two separate plates as steel yoke for the magnets.

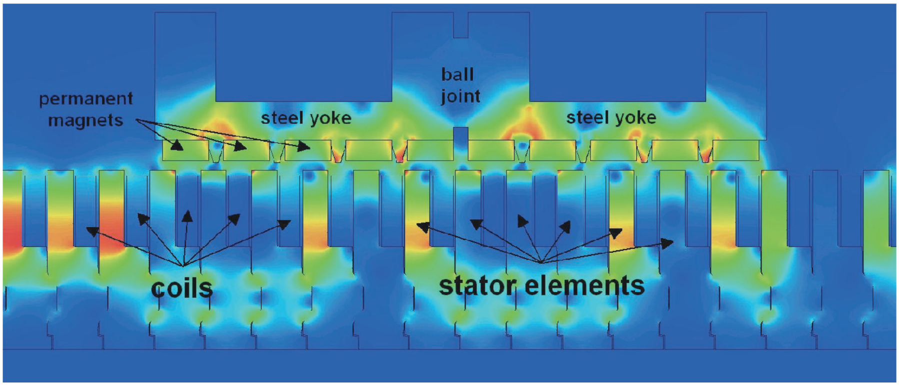

Fig. 4. B-field of single stator and translator

The ball joint in the middle also directs the magnetic flux and thus connects both halves of the vehicle magnetically. The air gap is adjusted to 4 mm. The Stator model is longer than an elementary machine by one hand to scan a minimum of a pole pitch during a movement of the vehicle and on the other hand to avoid undesirable end effects of the stator.

4. Construction of the system

4.1. Track

4.1.1. Stator

Due to the 3-d field distribution in the stator the SMC (**S**oft **M**agnetic **C**omposite) technology was chosen for the single stator elements. The production technology is based on the sintering process. This approach allows the design of complex element geometries as they are used in this case. The process is based on surface coated iron powder (Somaloy 500) [5], which could be pressed to a density of about 7,2 g/cm³, depending on the pressure of the compactor (general 600-800 MPa) and the complexity of the geometry. After the compaction step follows a precisely defined baking process in a powder specific atmosphere. The baking procedure produces an oxide binding and a mechanical stable structure. Because the coating is isolating each grain from the other, eddy currents also will be suppressed in each direction of space. Once the moulding tool for the SMC elements is produced, these could be fabricated in high quantities at low costs. For the implementation to the 3-d linear motor the constructive advantages of the SMC and the production costs had the highest rank. Because of the low frequencies the magnetic properties were not preferential.

Parallel to the development of the transportation system at the IMAB several SMC-powders were analysed concerning their mechanic and electromagnetic parameters. In comparison to electrical sheets or solid steel lower strengths as well as lower saturation were observed. This has to be considered during the design process of the construction and the magnetic layout.

The developed geometry of the stator elements consists of a stator tooth with a yoke section as back iron. On the front side is a positive and on the back side a negative ball joint surface. Both together allow a form fit with a possible rotation and tilt at once between two neighbouring elements without interrupt of the magnetic flux. So a very flexible three dimensional build-up of the stator is possible.

The slot geometry allows in the next assembling steps a simple installation of the pre-fabricated single tooth windings and the subsequent connection (Fig. 5). With this given modularity it is possible to configure different long stator supply sections. The division of the track in several supply sections allows the reduction of the apparent power demand. Additionally multiple movers could operate independent in one track system because each section is then controlled by separate inverters. The longer a section is the bigger has to be the distance between two successive movers to control them individually. The other way around the amount of inverters increases if the sections are very short. So there has to be found a compromise between economic aspects and the required flexibility. Depending on the specific application this has to be considered separately for each application. For example on sections with steady propulsion or down-grade no full stator assembly is necessary. So several stator modules can be omitted in such sections where the mover has got enough speed to reach a next module. During the entry of a mover in a module the control systems gets back the electrical position and it is possible to accelerate or brake further.

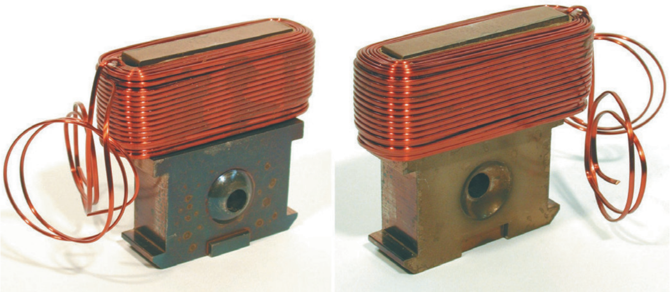

Fig. 5. SMC elements with concentrated windings

In the case of the demonstrator oval a full assembly was installed to present full functionality. The straight sections are equipped with modules of 4 elementary machines (48 stator elements, 24 coils) and in the curves with modules of 3 elementary machines. Altogether the oval consist of 18 modules

4.1.2. Guidance system

For the guidance of the mover the track consists of two pipe system with a track gauge of 170 mm. Both pipes are fixed every 30 to 40 cm by c-shaped retaining brackets of cast aluminium. Below the driving surface the brackets have fixations for the long stator on both sides. So the stator elements are also kept in position every 30 to 40 cm. To stabilise the stator in the free hanging zones between two brackets against the attractive forces of the permanent magnets glass fibre reinforcement was attached to the top and bottom side of the stator.

The two air gap plains are arranged in an angle of 70° to each other. So the angle of an air gap to the driving surface is 55°. This constellation generates a normal force component which pulls the mover constantly to the driving surface. The combination of two long stators on each side of the track allows moreover the integration of a mechanical passive switch.

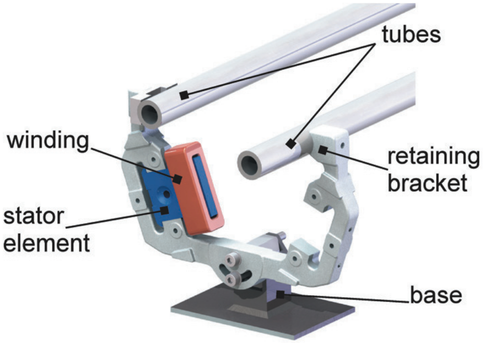

Fig. 6. Track/stator concept

The curves have got a radius of 1600 mm on average. Due to the superelevation of the track the pipes have a three dimensional geometry with a light variation of the radius over the whole curve progression. Thereby the projected curve spline has to comply precisely, also between two bracket bearing points. This requires accurate forming of the pipes within close tolerances. The more the tolerances are the bigger the air gap has to be to avoid jamming or collisions between mover and stator. With modern bending tools in a series production the necessary tolerances can be reduced to a certain extent.

4.2. Mover design

For the design and construction of the mover carriage the normal forces in the air gap are the biggest challenge. Both mover segments require at least three supporting points with appropriate degrees of freedom which is important on the one hand for an accurate positioning referenced to the stator and on the other hand to align the guide pulleys always parallel to the pipes. As you can see in Figure 7 there are pulleys on the top, bottom and sideways to guarantee the guidance. Because of the high speed of about 10 m/s the whole has to be sufficiently stiff with a minimal backlash. Otherwise a higher wear of the pulleys is possible or in the worst case a collision between mover and stator. A positive affect of attractive forces of the permanent magnets is that the bearing forces are reduced by the compensation of the mover weight if the whole system turns onto the side or overhead. Related to the track the mover gauge is slightly undersized to prevent higher friction and jamming due to changing tolerances in the distance of the pipes.

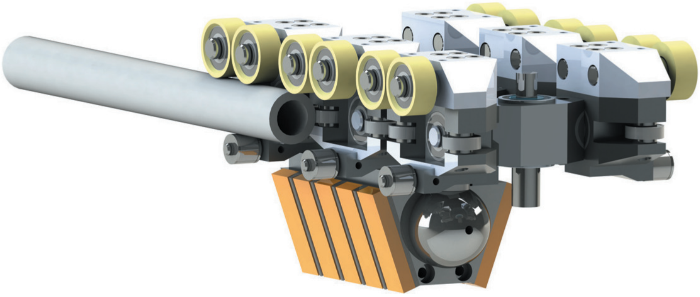

Fig. 7. Pulley guidance system at the mover

5. Drive control and power electronics

The control of the drive was developed in cooperation with the ISR at the TU Darmstadt and later the IfR of the TU Braunschweig. Here also a multiple mover operation mode was implemented. The three dimensional linear drive works in the general operation mode without extra sensors to get pole location of the mover. Therefore simply appropriate analysis of the stator terminal parameters are necessary. So the mover can be operated with maximum propulsion force and stopped and started at every position. Depending on the module length a coarse identification of the position is possible and during the operation with the assistance of the module transitions right on a few millimetres. For a precise positioning a straight section was equipped with a high resolution optical measurement system. An accuracy of 5 µm was reached. This shows that the system is suitable for work piece feeding at high precise processing stations.

The sections of the demonstration oval are energized by inverters of different rating according to there function. One straight section together with three adjoining curve modules serves as acceleration zone. The straight section is in this case equipped with two parallel stators (double stator arrangement) to generate more propulsion force. Therefore inverters with 25 A rating are installed in this zone. The remaining modules operate with 7.5 A inverters because lower accelerations are needed. All 18 inverters are assembled together in one switching cabinet with a supply module for 540 V intermediate circuit voltages out of the three-phase supply network. Additionally a standard personal computer with especially for this application developed bus circuit boards is required to control each inverter and the whole drive system.

6. Implementation of the switch

6.1. Design aspects and general function

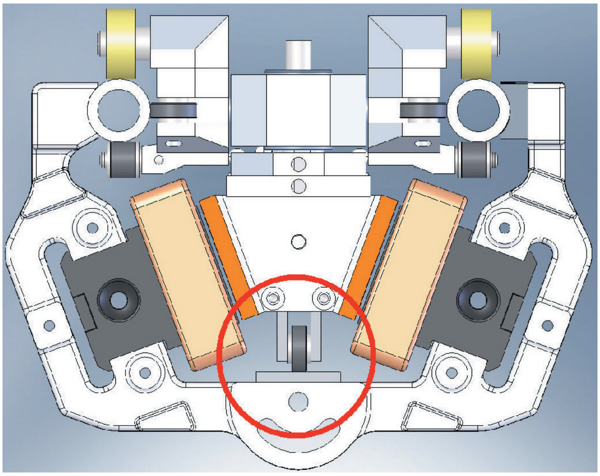

Fig. 8. Vehicle cross-section

For the realization of the passive switch the C-shaped (fig. 6 and 8) structure of the track is now beneficial. In this case the retaining brackets have to carry two stator modules in lateral arrangement for the electromagnetic operation of the switch. During the normal drive mode in the track the mover is carried by the two pipes. In the area of the switch where the pipes divide into different directions the mover loses one guiding side (Fig. 9, 10). To keep the mover in the right position additionally a new pulley system has to be introduced at the bottom side (Fig. 8, red circle) [1, 6]. A flat steel path serves as counter surface only in the switch zone (Fig. 8, 9).

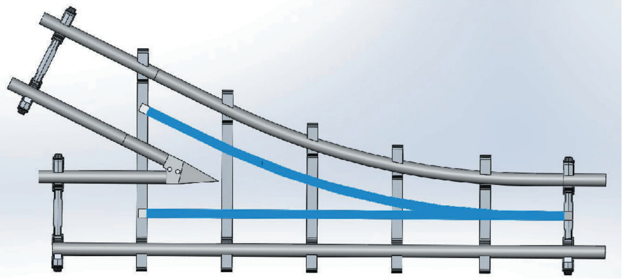

Fig. 9. Additional runway in the switch zone (blue)

Two operation modes have to be considered while passing the switch. The first mode describes the run-in from one of the tracks on the left side in Figure 9 (association mode). In this case no coordinated attraction force is necessary. Only a synchronization of the modulation has to be performed when the counterpart stator gets in reach.

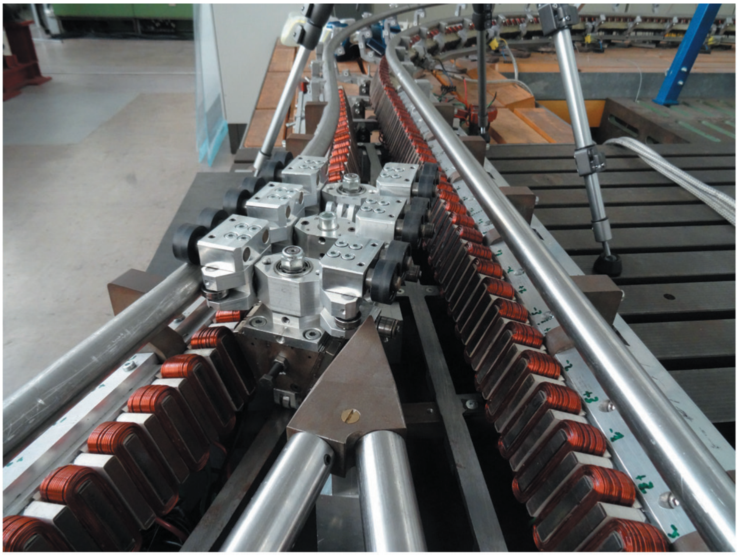

Fig. 10. Assembled switch with mover

A passing from the right side (splitting mode) requires a coordinated attraction force. Otherwise an instable state will be possible and a crash is inevitable. To assure a seamlessly threading of the wheel carriages onto the tubes again the flat steel path in the middle needs to be adjusted very precisely. After a successful "landing" the system can switch to normal driving operation.

The split mode represents the most challenging task for the electromagnetic function. The air gap has to be as symmetric as possible. The bigger the mechanical tolerances the more force reserves have to be provided at the disposal. In case of an unsymmetrical position immediately a passive attractive force arises, which is directed to the side of the smaller air-gap. According to (1) the magnitude of the normal force F_N has a quadratic characteristic. For changing the path the balance of the attractive forces has to be shifted to the intended side. This can be achieved by an appropriate field weakening or enhancement as known from classical control schemes at the respective stator side [4]. For this the control of the d-current component is used. The q-component producing the thrust stays untouched. Only if the current limit of the inverter is reached it has to be reduced.

$$F_N \approx \frac{1}{\delta^2}. \tag{1}$$

The superposition of the permanent magnet field with the armature field thus results in an increasing or decreasing of the normal forces. After subtracting the passive forces of the permanent magnets the controllable attractive forces can be illustrated like in Figure 11. The measurement shows the characteristics of two different currents for a single stator at 4mm air gap. In a static case it is possible to shift the resulting normal forces in the range of ±250 N with currents up to 10 A.

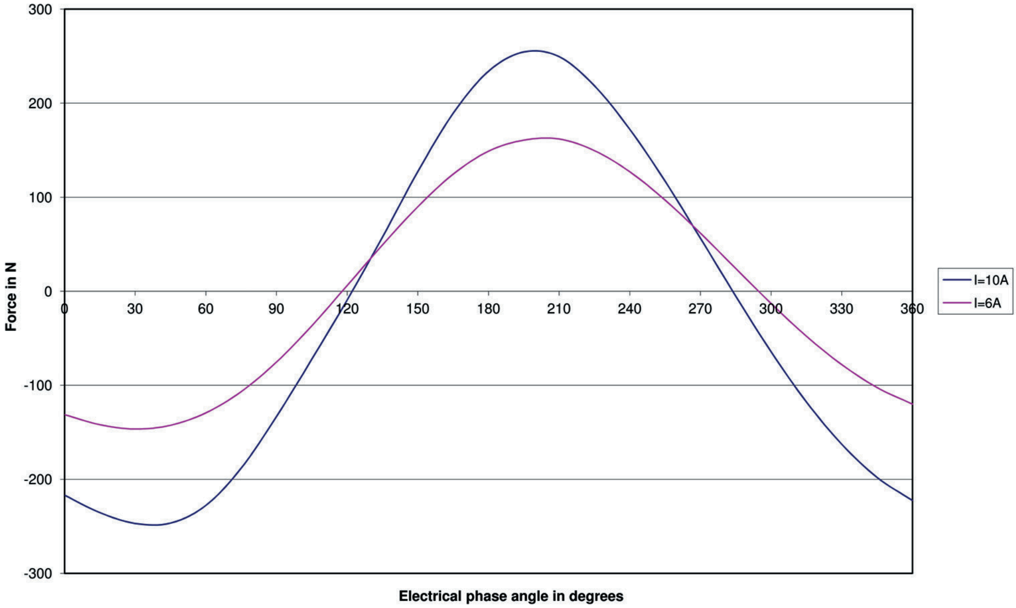

Fig. 11. Measured d-forces shifting at 4 mm air-gap, single stator

With the adjustment of a positive d-current and a negative one at two independent controllable stator modules the guiding force summarizes to about 500 N by 10 A current in each side. In the dynamical operation mode two failure effects may occur. A force ripple in the normal force vector would reduce directly the usable attractive force. Additional force fluctuations may be generated due to a force ripple in the propulsion vector. Because of the sensorless identification of the electrical phase angle a miscalculation of the actual electrical position can result. As consequence this generates a wrong phasing for the adjustment of the d-currents and finally wrong forces.

6.2. Simulation in FEM

The practical measurements can describe only the static behaviour of the drive regarding the d-forces. To provide more detailed information an electromagnetic FEM model was set up.

To evaluate the controllable force component, which is maximal at disposal, the q-current was set to zero. Figure 12 shows the attraction force consisting of passive magnet force and the force due to a d-current during the movement of the translator. An air gap variation is illustrated by the third axis. As supposed a basic ripple can be seen, which is rising to 50 N at an air gap of 1 mm. Additionally two peaks with a magnitude of 300 N appear.

The magnitude drops down to 100 N at an air gap of 4 mm (standard size). That is about 20% of the average d-force. The periodicity of the peaks measures an electrical angle of 300° and leads to the conclusion that it is produced by the mover. Several structural modifications in the model point to an end effect enhanced by the missing intermediate pole tooth at the joint and the

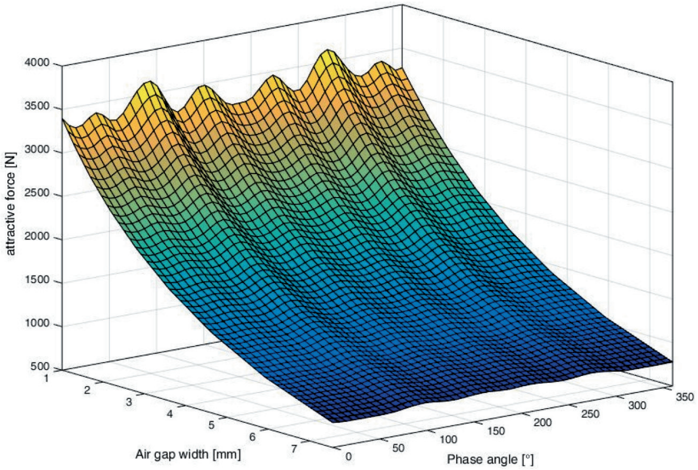

Fig. 12. Attractive force by magnets and d-current

ones at the end. Figure 13 shows the attractive force exclusively generated by the *d*-current. This is calculated by subtracting the passive magnet forces from the values in Figure 12. Thereby the peaks appear in the same angle distance but more amplified. The average values rise with reduced air gap to about 520 N. Figure 14 is showing a plot at a standard air gap of 4 mm. As already seen in Figure 12 with larger air gaps the basic ripple and the peaks are reduced too.

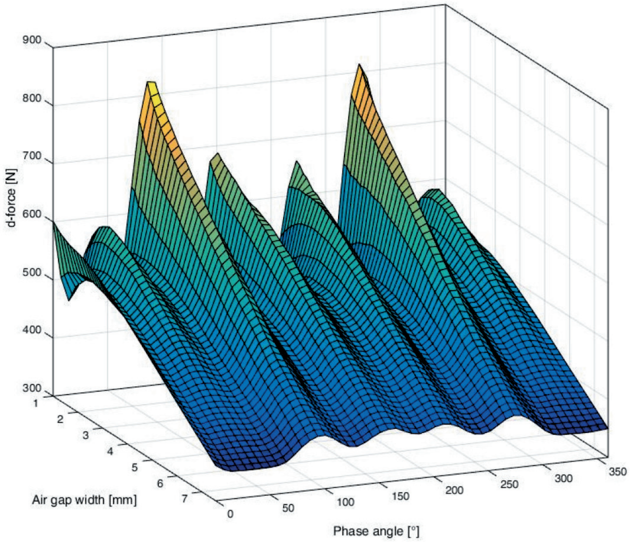

Fig. 13. Attractive force exclusively by d-current

Below 2.5 mm air gap the magnitudes of the average normal force drop down again (Fig. 11). A reluctance effect due to saturation may cause this and shifts the optimal phase angle of the d-current. This will be proved in future simulations.

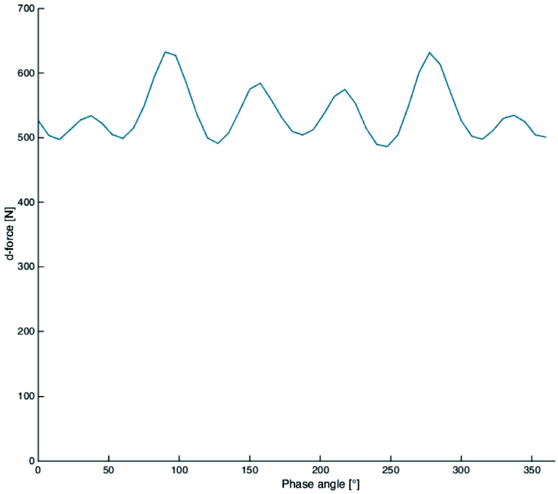

Fig. 14. Attractive force of d-current (without magnets), 4 mm air gap

For the mechanical adjustment of the guiding system in the switch and thereby the position of the vehicle relative to the stator it is important to identify the ratio of the asymmetric forces to the controllable d-forces. The asymmetric forces are associated directly to the position of the vehicle and the resulting air gaps on both stator sides. As the vehicle cannot be centred perfectly in the track, in the next step the relevant tolerances have to be reduced as much as possible.

In Figure 15 the passive attractive force as a function of the air gap is shown. Assuming an air gap of 4 mm and a position tolerance of 0.5 mm (Fig. 15 black cursor), an unbalanced force

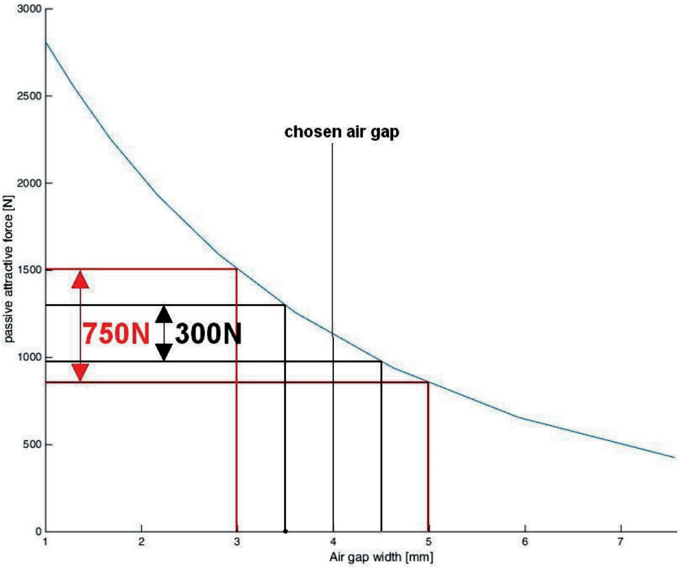

Fig. 15. Asymmetric forces due to tolerances by 4 mm

of about 300 N will occur. By 1 mm tolerance this increases to approximately 750 N (Fig. 15 red cursor). To compensate this force an appropriate d-current is necessary. But the *d*-current is limited by the maximum inverter current and the actual adjusted q-current. So the *q*-current has to be reduced for safe passing of the switch.

At first view this will lead to a speed reduction to increase the d-current reserve and thereby the d-current force. But it is also possible and easy to upgrade the inverters. Previous experiences with this drive show no perceptible warm up of the coils. Thus, the phase currents may be raised without further ado. A second option is to extend the air gaps. The curve in Figure 15 shows that the sensitivity to the tolerances drops with basically higher air gaps. But this alternative is limited as the d- current force and the thrust are reduced as well. Finally as an optimal basic air gap the value of 4..4.5 mm was chosen as a compromise between both effects [6].

7. Conclusions

A versatile modular linear motor based transport system able to adopt 3D routeing is presented. Applications may be intra logistics and flexible linking of production stations. On the basis of the results obtained by thoroughly testing of an experimental track, a passive switch operated by the difference in the normal force components was constructed and is actually being built up at the IMAB. The electromagnetic FEM model shows the influence of the ripple of the normal forces on the operation of the switch and helps to implement the right strategy into the control software. Furthermore a compromise between the possible switch passing speed and the adjustable air gap and its tolerances has to be found. This leads to an increase of the current rating of the inverters or the aspired speed has to be reduced. After completion, the switch will be thoroughly tested and compared with the simulated data.

Acknowledgements

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