Development and Test of a High Force Tubular Linear Drive Concept with Discrete Wound Coils for Industrial Applications

Ralf Wegener¹ Member IEEE, Sebastian Gruber², Kilian Nötzold,² Florian Senicar,³ Christian Junge,⁴ Stefan Soter¹,⁴ Member IEEE

¹Institute of Electrical Drives and Mechatronics, Technical University Dortmund, Germany
²Electrical Machines and Drives Group, University of Wuppertal, Germany
³LTi DRiVES GmbH, Unna, Germany
⁴Retostronik GmbH, Gevelsberg, Germany
ralf.wegener@uni-dortmund.de; stefan.soter@ieee.org

Abstract—This paper deals with the development of a tubular permanent magnet linear drive with radial magnetized armature and discrete wound coils mounted on a star-shaped stator part. The rated force of the developed machine is 500 N per segment. This presented particular design results in a very economic product because all primary parts, except of the permanent magnets and coils, are made of standard not-laminated steel and are optimized for easy production and assembly. The control of this machine with a specially built low cost linear sensor based on the hall-effect is also presented. The suitability of the design is proven by the demonstration of a prototype with measurements of thrust and cogging force.

Keywords—Linear Machine, permanent-magnet machine, linear synchronous machine, electric drive

I. MOTIVATION

Linear electromagnetic machines become more and more important for industrial applications because in some cases they have numerous advantages compared to rotating counterparts. First of all, they are providing thrust force directly to the load without the need of mechanical gears. This results in a high efficiency, a more simple construction of the system and a high dynamic performance. Tubular linear machines are the best choice for industrial applications which have to produce a high thrust force like in squeezing machines or moulding presses, because the force density of this type of linear machine is excellent [1]. The focus of this paper deals with the development of this particular design of the linear drive. The speciality of the motor is the stator which is not slotted in the conventional way and build with discrete coils putted on poles in radial direction. The cooperation of two universities and two companies tries to reach the optimization goal of a simple manufacture due to an economic production.

II. DESIGN OF THE ARMATURE

The armature of a tubular linear permanent magnet actuator can be equipped with different orientated permanent magnets. Possible orientations are axial, radial or Halbach [4].

Axial: Axially magnetized magnets cause a higher force density than radial magnetized magnets but also require more material. The armature have to consist of nonmagnetic materials to avoid a magnetic short-circuit.

Radial: The cogging force can be reduced by the eliminated flux density, concentrated at the magnet edges which is caused by the radial flux. The induced voltage is higher with radial orientation, because of the better flux change characteristics compared to the axially magnetized permanent magnets.

Halbach: The configuration of the curved flux path through the magnets eliminates the force ripple/cogging, but the Halbach-oriented permanent magnets are relative expensive.

For this particular design the radial magnetization was chosen, because the high force demand results in a high armature radius which is not reasonable to fill completely with magnet material. Because of this, the armature consists of a steel pipe with magnets only on the surface. This can be done for example with plate-shape magnets or ring-shaped magnets having radial magnetization. Plate-shaped magnets have the advantage that they are inexpensive because of the mass production of this type. They can be attached to the magnetic carrier pipe in an integral manner by use of an adhesive. In comparison to the plate-shape magnets, the ring-shape magnets are more expensive but they have the advantage of a simple assembly. The ring-shape magnets can be slid on the outside of the pipe and fixed at both ends without the usage of any adhesive. For the design of the here presented armature the ring-shape magnets as shown in figure 1 (a) are used. The rings are assembled of 24 segments shown in figure 1 (b) in a non-magnetic casing. To achieve a high force density the rare-earth magnet material NdFeB is used for the
magnets. It has the advantage of a high coercive field strength and a low recoil permeability. Important for the electrical dimensioning is the demagnetization border in the environmental conditions, especially the temperature. The relevant linear part of the characteristic of the magnet material is shown in figure 2 (a). The nonlinear magnetization curve can be approximated by the equation

\[ B_{Mag} = B_{rem} + \frac{B_{rem}}{H_{cB}} H_{Mag} \]  

(1)

With the magnetic penetration of the stator flux and the approximation \( \mu_{Fe} \rightarrow \infty \) the flux density can be described as

\[ B_M = \mu_0 \left( \frac{\Theta}{\delta_{Luft}} - \frac{H_M \cdot d_{Mag}}{\delta_{Luft}} \right) \]  

(2)

The intersection point of the two lines has to be less than the coercive field strength.

Figure 2 (b) shows the short magnetic flux distance outside of the ferromagnetic material in the here presented motor construction. Only the short airgap and the magnet height must be overcome by the magnet flux which results in improved efficiency. Furthermore, the part of the magnetic flux through the magnet itself is minimized due to the radial magnetization of the permanent magnets.

### III. Design of the Stator

Figure 3 shows one half of the sectional drawing of one basic segment of the linear actuator. The rotation axis is below of the lower edge of the drawing. The basic segment of the stator is made out of steel without any laminations. It comprises a pipe which is the outer frame of the motor and an integer literal of three stars, composed of eight winding cores and a ring in the center of each star. The segments of three stars (one for each phase) may be arranged axially in succession in any desired manner, resulting in modularity with respect to the actuation path and/or actuating force. This design is ideally suited for implementing a modular system because most of the components may be used identically in all embodiments and this yields high potential savings.

For a better saturation of the winding volume the concentrated windings of the second phase can be shifted about 22.5 degrees concerning the position of the windings of the first and third phase. This is shown in figure 4. Additionally conical coils can be used instead of cylindric ones to fill the whole winding volume. The amount of copper in this design is smaller than the needed copper in known tubular linear motors, which results in an additional cost reduction.

With this arrangement of eight discrete coils per phase a total of four operating voltages can be implemented by different types of wiring. There is the possibility to connect all stator windings in series or parallel or just four times two windings parallel or two times four windings parallel. With this possibility several different machines with varied electrical attributes can be build only by changing the connection, but with the same parts.

### IV. Position Control

In one main application field this linear drive is not used for precise positioning but to regulate pressure, flow or force of an industrial process, for example in squeezing machines. The position is only needed for lower control loops and the force is the higher ranking closed-loop control. The whole control of the presented linear actuator including the force control is done by a software modified standard inverter. The well known position control cascade is added by a precontrol dependant of the position of the armature. Details can be obtained in [3].
V. DEVELOPMENT OF A SPECIAL POSITION SENSOR

In this special application it is hardly possible to control the linear drive sensorless without any linear positioning sensor, but the usage of a standard sensor with accuracies from 50µm up to 10µm is very expensive. In the presented case a linear sensor with an accuracy of 200µm to 1mm is sufficient. A positioning sensor with this accuracy can be designed by two low-cost hall sensor elements, some surface mounted devices and a small pcb, already shown in [2],[3]. The permanent magnets provide a sinusoidal field in a certain distance as shown in figure 6 outside the winding area of the machine which can be used to measure the position. The sinusoidal field can be detected by placing the small positioning sensor in an optimal distance near the windings. The sensor needs no extra space in contrast to a conventional linear sensor.

It is necessary to measure the magnetic field with two hall sensors which are mounted in half of the distance of the effective length of one magnet. This produces two sinusoidal approximations of the magnetic field with a phase shift of 90°. The signals provide the possibility to determine the direction of the movement. An integrated sensor element is used for the measurement which is very easy to assemble. The amplifier and the output current source are already integrated in the sensor. Only the two measured signals from the Hall Elements (A- and B-Trace) have to be adapted to the inputs of the converter. This is done by two operational amplifiers with a differential output. The benefit of this differential transmission is the elimination of the electromagnetic interferences on the wires. In addition two other operational amplifiers correct the offset of the sensors. A final operational amplifier provides a constant voltage for the common mode input of the operational amplifiers A and B. The voltage corresponds with half of the power supply of the sensor. The complete circuit is shown in figure 7.

In order to test the built sensor it is mounted at a distance of approximately 20 mm in the above mentioned linear drive in orthogonal direction from the permanent magnets of the armature. This is moved with a fixed speed and the measured signals are recorded. The results are shown in figure 8.

The two sinusoidal signals are faulty at two positions. This is explainable with the near placement of the sensor to the coils which currents interferes with the signals. The measurement can be visualized in x-y diagram (figure 9) where the sine and cosine signals are plotted in both axis. With an optimal sensor the resulting diagram has to be a circle.

The resulted position signal is compared to the reference signal measured with a 10 µm optical linear sensor. The error of the
position is within a range about 1.6% during the whole measurement range and is absolutely sufficient for the described application.

VI. CONSTRUCTION OF THE PROTOTYPE

A prototype of the here presented linear motor is built based on 2D FEM-simulations. Therefore the design of the tubular linear drive can be easily transferred in a 2D rotationally symmetric model. Except of two parts, the drive is rotationally symmetric. The coils and the winding cores are discrete and have to be transformed for the model. Figure 3 shows the model with the coils and winding cores. To find an optimal design of a tubular linear drive with high thrust forces and low cogging forces the relevant geometrical parameters of the machine are varied in the simulations.

The stator of the prototype consists of three stars, each of them equipped with eight discrete coils. The stator is shown in figure 10. In this prototype each coil is connected outside of the machine in order to determine the influence of different connections like series and parallel and a mixture of both. In the finally produced drive each coil in one star is connected inside the machine and only one pair of cables for each phase will be sufficient. The coils in the prototype are also interchangeable to determine the effect of different windings.

The armature of the machine consists of one steel pipe which is supported by an axle inside of the pipe. At both ends linear bearings allow axial movements. The permanent magnets are slid on the outside of the pipe and fixed at both ends. Figure 11 shows the complete prototype with the stator and the armature inside. In this picture the coils are replaced by bigger ones to enhance the maximum force of the machine.

VII. MEASUREMENTS

The achieved thrust force of the built prototype is shown in figure 12. The red line shows the force produced by the machine with the large coils shown in figure 11. The force is not evenly distributed throughout the traversing range of the armature and varies from 475 to 615 N. This span is a result of the uneven polepairs and the overall construction of the armature and the stator and has to be minimized in future constructions. The green line shows the result of a simplified 2D-simulation of the built construction which matches the real measurements in the middle part of the movement. In particular at the right edge the precision of the simulation has room for improvement.

Not only the thrust force but the cogging forces are important for the efficiency of the whole drive. The cogging forces of the constructed prototype are shown in figure 13. The measured...
force, plotted in red, is pulsating with the effective length of the magnets and is changing the polarity within each magnet. The maximum amplitude is around 120 N which is a rated value of 20%. This high cogging forces can be minimized by changing details of the construction which is also part of the actual research work.

VIII. CONCLUSION

The presented innovative design of the tubular linear motor offers an optimized strategy of building a cost efficient motor. The properties with regard to the modularity of the actuating path, actuating force and power supply voltage are described. The motor has a high efficiency and is inexpensive in manufacturing due to the effective utilization of materials. An additional advantage is the possibility of using an integrated low cost positioning sensor for the regulation of the position of the armature. All these properties together allow an optimized modular system for many industrial application fields. The actual research work is focused on the optimization of thrust force by increasing the force per segment up to several thousand Newton and reducing the cogging force.

REFERENCES