New Developments on the MAGLEV Long Stator Winding Cable

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ABSTRACT: The long stator winding (LSW) cable is part of the synchronous linear motor used for levitation and propulsion of MAGLEV train. This cable must fulfill a huge number of requirements related to frequency, rated voltage and current (ampacity), which are relevant parameters directly influencing the distance between adjacent feeder stations and thereby the costs of the power supply system. Moreover, environmental aspects, resistance against ozone, ultraviolet rays, moisture and other atmospheric conditions play an important role. As far as tunnels or stations are concerned, the fire behavior has also to be taken into account. Since each MAGLEV system will have its special inquiries, an effort is made to satisfy customer's needs at minimum costs (design to cost). Following the first generation of Nexans' LSW cables being installed in Shanghai, further development has been taken place. This paper will introduce the recent development of a halogen-free LSW cable. Beyond its benefit for humans and environment in case of fire, such a cable exhibits considerably improved ageing stability and as a consequence excellent reliability.

1 INTRODUCTION

The principle of propulsion and levitation of MAGLEV trains is well-known: magnetic forces between the train on the one hand – acting as a » long rotor « – and the track on the other hand – acting as a » long stator « – allow the whole train to lift-off and move [Jung 1988, Moon 1994].
For the *Transrapid* MAGLEV type, this long stator is fixed on both sides of the concrete girder, mounted on the bottom side, where the long rotor part (levitation magnet) of the MAGLEV train grasps around [Götzke 2002] (see Fig. 1).

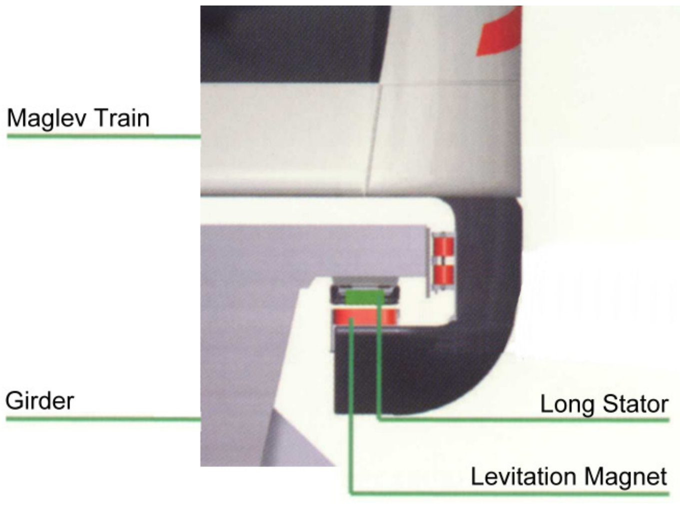

Figure 1: MAGLEV long stator

The long stator consists of a cable system with three cables, one for each electrical phase. These winding cables called » Long Stator Winding cables « (LSW cables) are fixed in compact cast resin blocks mounted parallel to the track. On the bottom side of the blocks, there are nuts (» stator grooves «) perpendicular to the track, which have a distance of 86 mm to each other. Inside each groove, one of the three LSW cables is fixed in a way, that along the track a three-phase order (1-2-3-1…) is obtained. So along the distance of three nuts (258 mm), each cable has to do a 180°-turn, that means, a strong bending of the cables has to be realized outside the resin blocks (see Fig. 2).

Figure 2: Bended LSW cable

Special stainless steel jackets, which are fixed inside the nuts, are used to clamp the LSW cables within the resin blocks. During installation of the long stator by an automated laying vehicle, the winding cables are pushed into these jackets, which are shaped in a way that the cable cannot plunge. Thus, it is obviously of high importance to realize very low tolerances regarding the outer diameter of the cables to secure safe operation for many years without a risk of moving and/or plunging of LSW cables. In this context, it should be mentioned that during operation the train rushes along the track with a gap of about 10 mm between stator and the train counterpart.

Additionally, the stainless steel jackets are important parts of the grounding system, since the contact of the LSW cable to the jacket is the only connection of the cable to the grounding system. The jackets themselves have a clamp at one of the ends, which carries a steel rope running along the track and being connected to earth (see Fig. 3).

Figure 3: Grounding steel jacket with clamp on the right side. In this picture, the earthing rope is sheathed with a semi-conductive material

2 THE LSW CABLE

As described, the LSW cable acts as a stator winding cable. That means that the magnetic field around the cable caused by an electrical current in the cable conductor induces the levitation and propulsion of the MAGLEV train. Thus, in contrast to most of the conventional motor winding cables, the LSW cable must withstand high voltages and carry large currents, i.e. it has to be designed as a medium voltage (MV) power cable.

The installation of MV power cables has to come along with a detailed concept for grounding of the cable system. So these kinds of cables usually have a metallic screen underneath the outer sheath to carry fault and capacitive load currents which may occur during service. The grounding of the screen is carried out in joints and terminations according to the grounding philosophy of the electric grid, in which the cable system is implemented.

The use of a compact metallic screen is not advisable for LSW cables, since according to Lenz's law such screen would generate a magnetic field being antipodal to the one of the conductor and therefore weakening the overall magnetic field outside the cable. Therefore the grounding is realized by using a semi-conductive material for the outer sheath, which obviously leads to specific requirements on the used material.

Taking the place of installation of the LSW cable into account, it can be guessed, that a huge amount of further properties of the cable is required, for example:

- Outer diameter with narrow two sided tolerances
- High radial elastic properties
- Smooth surface for automated processing
- Homogeneous mechanical properties
- Extremely low bending radius (1.5 D)
- Long term stability of shaping
- Long term electrical stability after installation
- Unique screen and sheathing design

Figure 4 shows the LSW cable which was designed to fit these requirements and which is installed on the *Transrapid* MAGLEV system in Shanghai [Büthe 2003a,b,c].

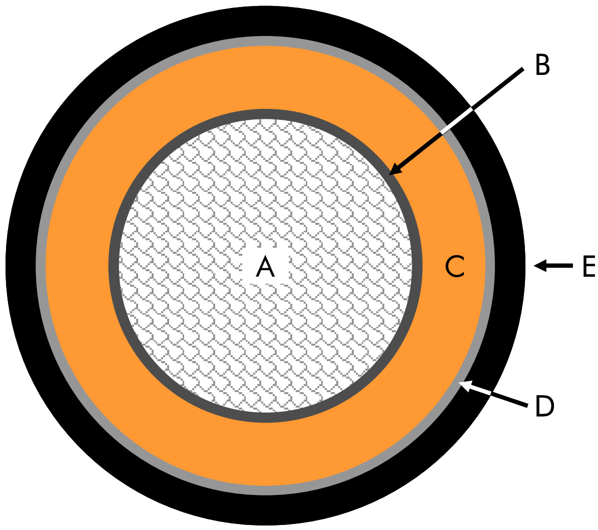

Figure 4: LSW cable

A: Conductor
A class 2 stranded, compacted and annealed aluminium conductor with 300 mm² gauge size is used. It is specially designed for superior homogeneous bending behavior and long term stability. Nevertheless, a diameter of 20.3 mm can be realized, giving enough additional space for the insulation, which is necessary for a high operating voltage.

B/D: Inner / outer semi-conductive layer
Ethylene propylene copolymer rubber (EPR) is the basic material of the compounds used for inner and outer semi-conductive layer of the MV power cable triple insulation system. The compounds are produced according to recipes designed by Nexans.

C: Insulation
As insulation, a low loss (dissipation factor below 0.003) EPR compound is used, which has high elastic properties to support the mounting in the stator grooves. At least, it acts as an elastic corset for the shaped aluminium conductor.
For the insulation, a continuous vulcanization (CV) line with triple extrusion head for inner / outer semi-conductive layer and insulation using a state of the art diameter control is used.

E: Outer sheath
Since high elastic properties are necessary, a rubber based, semi-conductive chloroprene rubber (PCP) sheathing compound was chosen for the *Transrapid* MAGLEV in Shanghai. As the grounding of the LSW cable has to be ensured by the outer sheath, a focus is put on the electrical properties, especially conductivity. Additionally, due to the possible exposition to heat, oil, UV, ozone and other environmental and chemical media, the accordant resistances are important features of the sheathing material. Furthermore, the product is flame retardant according to the IEC 60332-1.
Since a gliding coating is applied on the surface of the cable for easy mounting into the steel grooves, a sufficient adhesive surface of the outer sheath has to be assured.
For the sheathing, a double head CV line is used (see Fig. 5). A laser driven diameter control took care of the outer diameter tolerance, which is an important property of the whole cable, as mentioned in section 1.

To prove that this type of cable is able to meet all necessary demands, a comprehensive specification is agreed on between customer and cable supplier [ThyssenKrupp 2003]. Subsequently a huge number of different tests was performed on the cable. For example, the behavior during weathering is tested to obtain information about the performance of the cable – especially the sheath – concerning the simultaneous impact of radiation, temperature and humidity. Other examples are tests of the electrical properties like electrical strength, load capacity, earth fault resistance, loss factor and so on. Most of the tests are carried out on samples of the whole cable system, which are a few meters of a long stator consisting of resin block and three bended, crimped and fixed LSW cables.

Even though the existing specifications are very comprehensive, they are nevertheless only dedicated to the accordant MAGLEV project. For other, future projects, additional or changed requirements will presumably come up, which the cable has to meet.

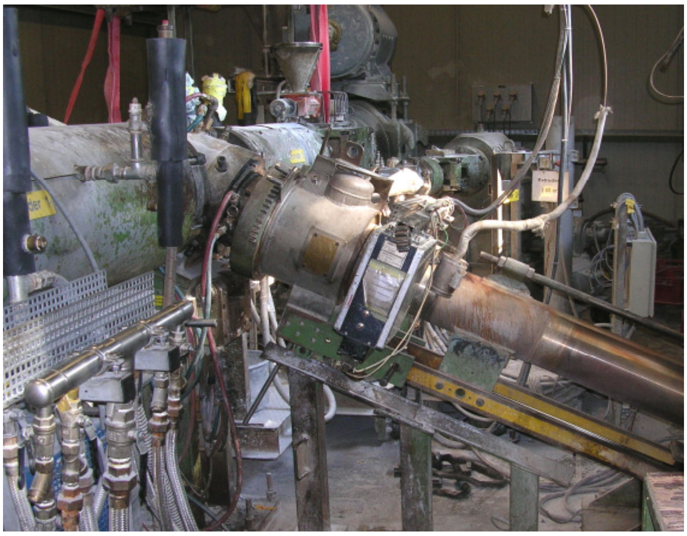

Figure 5: CV line used for manufacturing the outer sheath

3 DESIGN TO NEED / DESIGN TO COST

There are a lot of possible reasons, why the specifications for the LSW cable may differ from one MAGLEV project to the next. Examples for varying ancillary conditions of such projects and possible impacts on the LSW cable are:

- Further development of the MAGLEV system
  ⇒ Cable dimensions
  Electrical features
  Mechanical properties (changed installation technique)
- Legal rules concerning safety, environmental aspects etc. of the country the project is realized
  ⇒ Materials
- Local climatic conditions (temperature, humidity, UV, ozone etc.)
  ⇒ Materials
- Size of the MAGLEV system (track length, number of tracks etc.) and related (electro-) technical aspects (voltage level, distance between feeder stations etc.)
  ⇒ Electrical features
- Project budget
  ⇒ Design

Obviously, a single type LSW cable solution will be not satisfactory for upcoming projects. In the contrary, the manufacturer of a MAGLEV system needs a cable design made to fit his special needs within the project and also made to fit the existing budget. Based on the existing experience and knowledge concerning conductive, semi-conductive and insulating materials as well as cable designs, this idea to satisfy customer's needs at minimum costs can be followed by Nexans.

One example of this approach is given by the so-called AERO-Z® conductor [Büthe 2004]. This stranded conductor type has originally been developed for overhead power lines and consists of Z-like profiled wires used for the first and sometimes second outer layer. These layers are considered as fully-locked, i.e. they form a firmly fitted circular belt around the core (see Fig. 6).

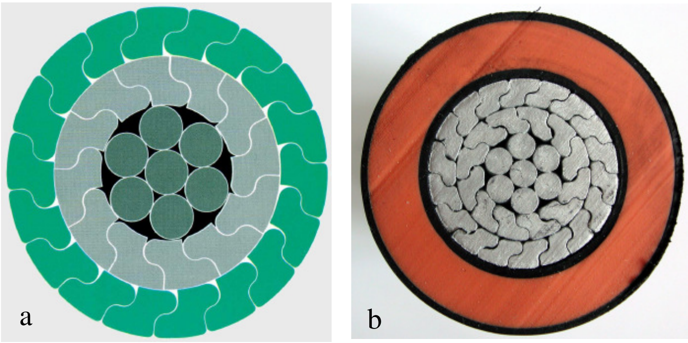

Figure 6: Schematic diagram of an AERO-Z® conductor (a) and LSW cable with AERO-Z® conductor (b)

There were some good reasons to study in detail, whether this conductor type could also be used for LSW cables: As can easily been evaluated, an AERO-Z® conductor has a higher ampacity in comparison to a conventional conductor with same outer diameter. Furthermore it turned out that the bending and crimping behavior is improved. This means that the AERO-Z® conductor requires significant less bending force and exhibits a superior shaping performance.

The AERO-Z® conductor was shown to be fully compatible to the LSW specifications. Thus, a new option for cable construction has been realized, supporting the ability to offer LSW cables with specific design for specific needs.

The recent step in the development of cable technologies deals with safety and environmental aspects: the Halogen-Free Fire-Retardant (HFFR) LSW cable solution.

4 HFFR LSW CABLE

Since in the meantime first drafts of MAGLEV systems exist with large parts of the track running through tunnels, the fire behavior of the different system components becomes more and more important. Of course, also stations are concerned in this context. Thus, a halogen-free cable solution would bring benefit for humans and environment in case of fire. Since insulation and semi-conductive layers are already halogen-free, the focus is put on the outer sheath which is up to now made of chloroprene rubber. In case of fire, a PCP-based sheath would release hydrogen chlorides. So the development of an HFFR sheathing compound fulfilling all the actual requirements of the LSW cable looked necessary to support future projects.

It turns out that promising results can be achieved with a new EVA-based compound. To evaluate the properties in detail, the material is first extruded and cross-linked on a small-size laboratory extruder. Different types of test samples are made to obtain a first estimation about e.g. mechanical properties, ageing behavior and ozone resistance.

Thereafter, the new compound has been used for sheathing a LSW cable length. The industrial tools (extruder, CV line) described in section 2 are used. Some of the tests performed on the cable sample are presented subsequent.

4.1 *Mechanical properties / ageing behavior*

Mechanical properties are measured on the new HFFR sheathing compound and the cable produced therewith. Tensile strength and elongation at break of unaged test samples clearly suit the requirements given in the specification. After thermal ageing in an oven according to IEC 60811-1-1/2 only minor changes are detectable in comparison to the values before ageing.

It turned out that the shore A of the new compound is significantly higher than for the original PCP compound. On one hand, this supports good form stability; on the other hand, the necessary forces for deformation are increased, which has to be taken into account for (automated) mounting of the cable. However, also the creation of a version with reduced hardness is under consideration.

4.2 *Electrical resistance of the outer sheath*

To prove whether the electrical resistance of the outer sheath is compliant with the range given in the specifications (e.g. 0.25-0.75 kΩ/m), the test set-up shown in figure 7 is used. Two inner ring-electrodes made of conductive silver are connected to a voltmeter, two outer electrodes are connected to a constant current source, which embosses a current of 200 mA. By measuring the voltage and the distance between the inner electrodes, the sheath resistance can be evaluated.

The resistance of the HFFR sheathing material is 0.346 kΩ/m, which is in the mentioned range and differs only slightly from the value measured on the former PCP-based sheath (0.337 kΩ/m).

Figure 7: Test set-up for electrical resistance measurement

4.3 Ozone resistance

The ozone resistance is tested according to VDE standard 0472 part 805, method B: An elongation of 40% is applied to the sample that is exposed for 72 h inside an ozone chamber (Fig. 8). The ambient temperature in the chamber is 40 °C and the relative humidity is 55%. The measurement takes place under an ozone concentration of 2.0 ppm. After testing, the surface of the HFFR sheathing compound shows no cracks and therefore passes the test.

Figure 8: Ozone chamber

5 CONCLUSIONS

The long stator winding (LSW) cable is an essential part of the propulsion and levitation system of MAGLEV trains. There exists a huge number of interactions between this cable and the overall system, such as voltage level, frequency, current, environmental impacts, security aspects, dimensions, grounding system etc.

Future MAGLEV projects will presumably have changed ancillary conditions; therefore the focus is put on conceivable customers' needs. As an important feature, a halogen-free solution for LSW cable is now developed. Beside benefit for humans and environment in case of fire, this cable exhibits considerably improved ageing stability and as a consequence excellent reliability.

The LSW cable produced with the new HFFR-sheath has been successfully tested regarding corrosivity, electrical properties, ozone and abrasion resistance, mechanical and ageing behavior and much more. The results clearly show the ability of this new material to satisfy the future expectations.

Nevertheless, the development on the LSW cable technology will be continued to be further on prepared for upcoming projects and their needs.

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