Transrapid Motor Winding with Optimized Grounding System

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Abstract

ThyssenKrupp Transrapid developed a new motor winding for synchronous long stator propulsion with optimized grounding system. The motor winding using a cable without metallic screen is presented. The function as well as the mechanical and electrical design of the grounding system is illustrated. The new design guarantees a much lower electrical stress than the load capacity of the system. The main design parameters, simulation and testing results as well as calculations of the electrical stress of the grounding system are described.

The new motor winding with optimized grounding system further enhances the highly stable operation of the motor winding.

1 Introduction

The motor winding of the long stator motor is one of the crucial components of the Transrapid. The specific design of the electrical and mechanical components of the motor winding has to meet various requirements, e.g. high voltage insulation, high current loading capacity for high propulsion power, ground fault detection, capacitive charging and earth fault currents, and equalizing of voltages in the grounding system along the motor winding.

The experience ThyssenKrupp Transrapid gained with several types of motor windings was taken into account to develop a new motor winding with optimized grounding system.

2 Description of main components

2.1 Setup

Fig. 1 shows the motor winding of the Transrapid as it is presented in this paper. It is the stator of the long stator propulsion system. The alternating current in the cables generates a travelling magnetic field wave of variable frequency. The magnetic field interacts with the field of the levitation magnet of the Transrapid vehicle so that the vehicle can be accelerated (or decelerated). The cable is designed for a maximum voltage of 20 kV (phase to phase) corresponding to a Transrapid velocity of 500 km/h and a 200 m long Transrapid vehicle (8 sections). It consists of a highly flexible aluminum conductor to ensure that a bending radius of about one and a half times the cable diameter can be applied for the installation of the three phase long stator winding.

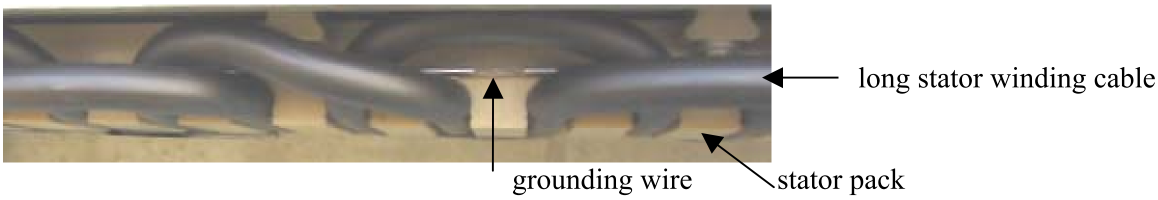
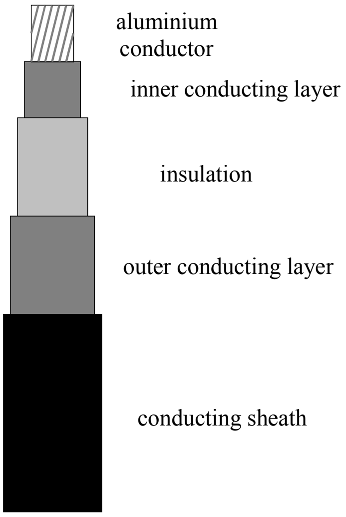


Fig. 1: Present design of the motor winding of the Transrapid

2.2 Grounding system

As the motor winding is open to environmental influences, insulation faults can not be excluded. For safety reasons as well as to avoid an expansion of the damaged area it is necessary that an insulation fault is detected immediately. This is realized by using a cable with a grounded screen. In this case an insulation fault always leads to grounding currents. These currents can be detected during operation so that the corresponding section of the long stator motor can be shut down immediately. This has no major influence on the performance of the system as motor sections are relatively short and only one of the two long stator motors on both sides of the track is affected. Therefore, regular operation can be continued and the fault can be removed after the operation hours of the Transrapid during normal maintenance.

Several setups for the screen of the cable are possible in principle: metallic screen and insulating sheath, metallic screen with conducting sheath and conducting sheath without metallic screen. The latter is used in our optimized system as shown in **Fig. 2**. To connect the conducting sheath a grounding system comprising of grounding sleeves and grounding wire as shown in **Fig. 3** is used.



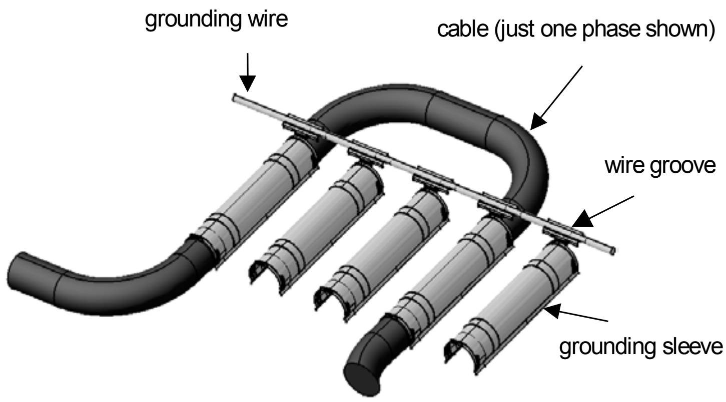


Fig. 2: Long stator winding cable

Fig. 3: Grounding system of the motor winding (without stator packs, just one phase is displayed)

The sheath is connected to the grounding system by the grounding sleeves which are connected to a grounding wire running along one side of each long stator. They are fixed in their position by form fit in slots of the stator packs. At both ends of the girder the grounding wire is connected to the grounding of the structure.

To avoid even slight contact corrosion, identical high grade stainless steel for grounding sleeve and grounding wire is used. Therefore, the whole setup is highly corrosion resistant.

3 Design parameters

The main design parameters for the grounding system are mechanical and electrical stress which affect the long stator cable during the passage of the Transrapid vehicle.

3.1 Mechanical design

The mechanical rigidity of the cable and the form fit in the grounding sleeves ensure that the cable stays in its correct position under all loading conditions. Nevertheless, the cable can be pulled out of the sleeves without damage for maintenance purpose.

The grounding wire is placed in the wire grooves of the grounding sleeves (**Fig. 3**). The contact force - needed to ensure a reliable contact with low resistance - is supplied by the spring force of the grooves which have a smaller diameter than the grounding wire. The spring force was calculated using the Finite Element method (FEM) as shown in **Fig. 4**. The result is that the design ensures sufficient forces even if the dimension of the wire grooves and the grounding wire diameters are at the high and low limit of the tolerance respectively.

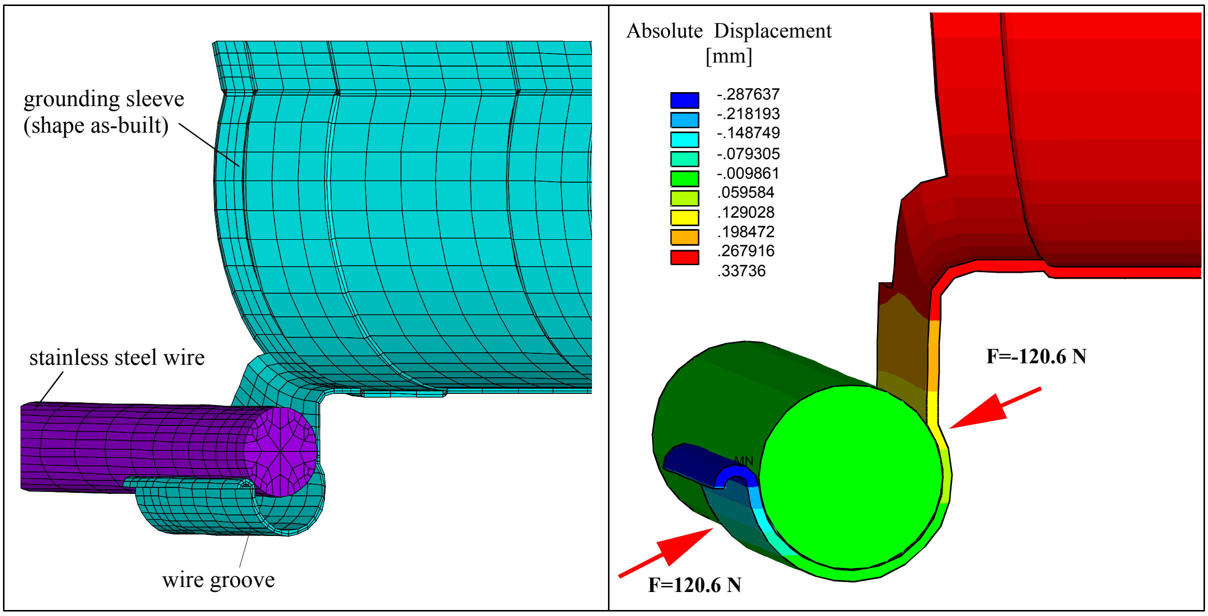


Fig. 4: Model for calculation of the contact force using FEM (left side) and example for result of calculation (right side)

The design of the sleeves avoids sharp edges in contact with the cable which may lead to high electrical fields and focussing of currents. Additionally, special contact beads as shown in Fig. 5 are used for a long-time stable contact with only small variation of the contact resistance between sheath and sleeve (s. chapter 3.2).

Fig. 5: Grounding sleeve with contact beads marked by arrows

3.2 Electrical design

The electrical design of the conducting sheath in combination with the mechanical design of the grounding sleeves ensure that the electrical stress during normal operation is much lower than the load capacity of the sheath material. This is achieved by using a conducting rubber with high resistance without losing the capability to equalize the induced voltage and to conduct a detectable ground current caused by an insulation fault.

The electrical stress of the grounding system during normal operation is described as follows.

3.2.1 Electrical stress of the grounding system as a result of the capacitive charging current

The inner conducting layer, the insulation and the outer conducting layer, shown in **Fig. 2**, form a capacitor. As the sheath is connected to ground in every sleeve, that means about every 0.6 m, the capacitive charging currents per grounding sleeve are very small and can be neglected.

3.2.2 Electrical stress of the grounding system as a result of the transformed current

The alternating current in the cables generates a travelling magnetic field wave of variable frequency. The magnetic field interacts with the stationary conductive material in stator packs of the guideway. This acts like a transformer with the result of an induced voltage in the cable. As the sheath is connected to ground in every sleeve, the voltage of the sheath is homogenized and very close to ground level. The corresponding transformed current along the grounding system is negligibly small due to the high resistance of the conducting rubber.

3.2.3 Electrical stress of the grounding system as a result of the induced pole wheel voltage

The largest electrical stress during normal operation is the pole wheel voltage induced during the passage of the Transrapid vehicle. This voltage is caused by the large and alternating magnetic field that is generated by the levitation magnet of the travelling Transrapid vehicle and the stationary ferromagnetic stator packs of the guideway. The induced pole wheel voltage leads to electrical stress of the grounding system which is determined by its electrical characteristic as follows.

The electrical characteristic of the grounding system is determined by the resistance per unit length of the conductive sheath of the long stator winding as well as by the grounding resistance. The grounding resistance is formed substantially by the electrical contact resistance between sheath of the long stator winding and sleeve.

To verify, that the electrical stress of the grounding system is much lower than the load capacity, several calculations and simulations were performed. They are based on complex electrically equivalent circuit diagrams of the grounding system, which describe accurately the electrical characteristic.

The pole wheel voltages are induced in the sleeves and along the conductive sheath in the area of the stator packs. The resistance R_{LSW} of the sheath of the long stator winding along one meander can be divided into the functional parts $R_{LSW,a}$ (resistance in the area of the sleeve), $R_{LSW,b}$ (resistance between the end of the sleeve and the crossing points) and $R_{LSW,c}$ (resistance between the crossing points).

The contact resistances between the sheath of the long stator winding and the sleeves are concentrated at the contact beads on both ends of the sleeves. The resistances vary in a small range of dispersion, which was taken into account in the calculation of the electrical stress of the grounding system.
The induced pole wheel voltages cause voltages between the crossing points (j = 1, 2, 3...) of the three phases of the long stator winding shown Fig. 6.

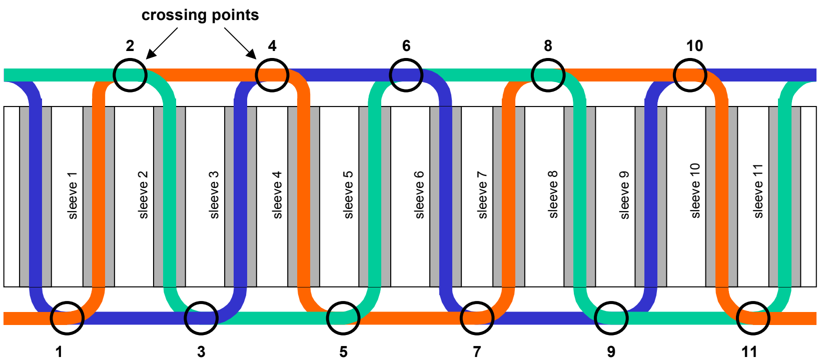


Fig. 6: The principle structure of the three phases of the motor winding by highlighting the contact points (crossing points) between the end windings of the different phases

At the crossing points the distance of the sheath of the crossing cables is small or they touch each other. Thus the resulting contact resistances vary along the long stator winding, which was taken into account in the calculation of the electrical stress of the grounding system.

The resistance per unit length of the sheath of the long stator winding is specified and covers the range from $R'_{LSW,min}$ and $R'_{LSW,max}$. Its value primarily depends on the charge of the long stator winding. Thus its variation within the phase of a long stator section is negligible. The boundaries of the long stator section are given by the boundaries of the motor section and the junction points.

Electrical stress of sheath and of contact points between sheath and sleeves

If the phases do not touch at the crossing points, the contact resistances between the crossing points can be considered as infinitely high. Thus there is only one path of current along the phase. The maximum value $I_{LSW,max}$ of this current was evaluated for the worst case. An easy worst case calculation is possible for the unrealistic assumption that all contact resistances between sheath and sleeves have the theoretical value zero.

The long stator winding with the lowest resistance per unit length, i.e. $R'_{LSW,min}$, results in the maximum current $I_{LSW,max}$. In practice, the contact resistances between sheath and sleeves are much higher than zero. Therefore, the actual current is always much lower than the evaluated one.

If some or all phases touch each other at the crossing points, there are additional paths of current between the phases. The small contact surface at the crossing points lead to a high contact resistance and thus only small currents between the touching phases. Regardless of this fact an easy worst case calculation is possible for the unrealistic assumption that both the contact resistances between sheath and sleeves and the contact resistances between the contact points have the theoretical value zero. Hence simplified equivalent circuit diagrams for the three phases of the propulsion motor winding were used for investigation of the electrical stress of the sheath and of the contact points between sheath and sleeves.

The sheath and the contact points between sheath and sleeves are only stressed by currents during the passage of the Transrapid vehicle. The calculation of the maximum current shows that the largest value $I_{LSW,max,th}$ results from the long stator winding with the minimum resistance per unit length $R'_{LSW,min}$. The theoretical value of this worst case calculation is larger than $I_{LSW,max}$.
In practice the contact resistances between sheath and sleeves and the contact resistances between the contact points amount to much higher values than zero, thus reducing the actual currents to values far below the theoretical maximum value $I_{LSW,max,th}$. Tests of a sample cable and a sample long stator motor winding have shown that both the sheath and the contact points between sheath and sleeves are able to carry permanently a multiple of the current $I_{LSW,max,th}$. A sufficient reserve is thereby provided.

Electrical stress of crossing points

Tests have shown that the maximum electrical stress of the crossing points is determined by the voltage $U_{c,cross,max}$ between the contact surfaces at the crossing points. The tests show that by a permanent voltage $U_{c,cross,max}$ the resistances between the contact points are allowed to vary freely within reasonable physical boundaries without ever causing critical stress to the long stator winding.

Therefore it had to be verified, that the induced pole wheel voltages result in voltages $U_{c,cross}(j)$ between the contact surfaces of the crossing points smaller than $U_{c,cross,max}$ ($j = 1, 2, 3 ...$). Simulations have shown, that the voltages $U_{c,cross}(j)$ amount to the highest values, when there is no contact of the phases. Therefore it is possible for the worst case calculation to assume the contact resistances between the crossing points to be infinitely high. In that case the equivalent circuit diagram is simplified by the omission of the resistances between the crossing points.

The maximum value of the voltage $U_{c,cross}(j)$ was analytically determined for some hundred poles. The statistical variation of the contact resistances between long stator winding sheath and sleeves has been considered. The variation of the resistances was determined by series of tests of several sample windings. The results show that the maximum value of the voltage $U_{c,cross}(j)$ is far below the limit value $U_{c,cross,max}$. Thus the electrical stress of the crossing points is considerably low and a sufficient reserve is provided.

4 Outlook

The long stator motor winding with optimized grounding setup was developed for the existing Transrapid routes as well as future application for short, medium and long distance routes and can be mounted with automatic mounting equipment [1]. The robust design guarantees a highly stable operation of the motor winding.

References

1. X. Liu, J. Braun. *Transrapid Motor Cable Mounting Technology*. 18th International Conference on Magnetically Levitated Systems and Linear Drivers, Shanghai, 2004.