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JOINTING OF HIGH VOLTAGE CABLE SYSTEMS

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Introduction

Premoulded slip-on cable accessories are nowadays the most common and most reliable technology for the jointing of polymeric high voltage cables up to voltages of 500kV.
The big advantages of this technology versus older technologies – like taping or field moulding - are the constant production quality, the easy and safe installation procedures and also their reliability during service. As this technology was already introduced in the early 70ties, the experience gathered in the meantime prove, that the lifetime of the premoulded accessories is adequate to the lifetime of high quality polymeric cables, which is more than 40 years.
In order to perform well during their whole service-life, the design of these premoulded accessories has to meet electrical, mechanical and thermal criterias. Further it must be insured that a constantly high quality of all the products installed in cable system can be achieved.
This paper gives some technical background information about the design and the quality control of premoulded high voltage joints and highlights some aspects for an appropriate earthing concept of the cable screen.

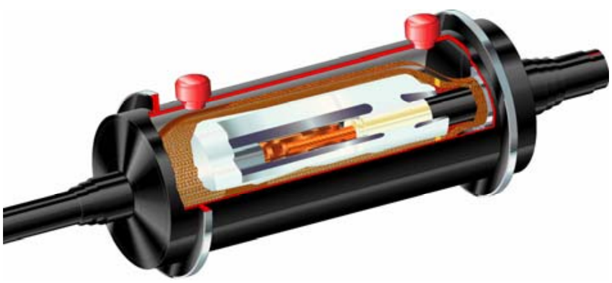
Design of High voltage cable joints

General

A premoulded cable joint consists normally of one elastomeric body, where all the stress control elements are integrated (see picture 1). For the stress control, basically the following methods are known:

- Geometrical, where the contour of conducting elements is controlling the electrical field at the end of a high voltage cable
- Resistive, where the resistance of a semiconducting material is used to reduce the electrical stress in high field regions
- Refractive, where material with a high permittivity is used for “pushing” away the field from high stress regions

While the resistive and refractive method is successfully used for medium voltage applications up to 72.5kV maximum, the geometrical field control method is the standard method for high voltage and extra high voltage applications. Controlling the field by a well defined contour still offers the best quality from design and production point of view.
To install a premoulded joint they are normally slipped-over the prepared cable on site by using grease and special push-on tools. Another technology, widely used in the medium voltage range, is the cold shrink technology. With this technique a premoulded joint body is pre-expanded on a support tube, which can be removed while being placed around the cable on site. It has the advantage that no push-on tools must be used. For high voltage application there is the disadvantage that the forces of a pre-expanded joint body are very high on this support-tube due to the required wall thickness and during the pre-expansion – which can be 1 year and more – there is a relaxation of the elastomeric joint body occurring resulting in a loss of contact pressure, which is a crucial factor for the reliability as will be explained later. Hence for high voltage application the slip-on procedure is still the preferred way to install the joint.



Picture 1: high voltage joint MSA123DO.G produced by Sefag ixosil Ltd.

Electrical Design

One basic function of every termination or joint is to control the electrical field at the end of a cable or between two cables.

As explained in the previous section for high voltage applications the common design is to use the geometrical field control method. This means that the electrical field is controlled by the contour of conducting elements integrated into the joint body. During design stage FEM (=Finite Element Method) calculation programs are an important tool as the latest versions of these programs offer a vast range of possibilities like

- Calculation of the electrical field in any direction of the joint body
- Optimisation tools for calculating the optimum shape of stress control elements
- Solving of coupled fields, like thermo-mechanical stresses
- Models for non-linear behaviour of materials, like stresses in polymeric materials
- Simulation of slip-on procedures

As nowadays aeroplanes and cars are fully designed and optimised with such powerful calculation and simulation programs, they are also the ideal tool for the design of high voltage cable accessories.

However all calculation and simulation programs need to be fed by reliable data. These data, which we call "design criterias", can be obtained from model investigations and also from the service experience.

In order to apply such design criterias we must distinguish different regions of the joint having different dielectric strengths. These regions are as follows:

1. Dielectric strength of the elastomeric material in combination with the semiconducting layers forming the electrodes
2. Dielectric strength of the interface between cable and joint body

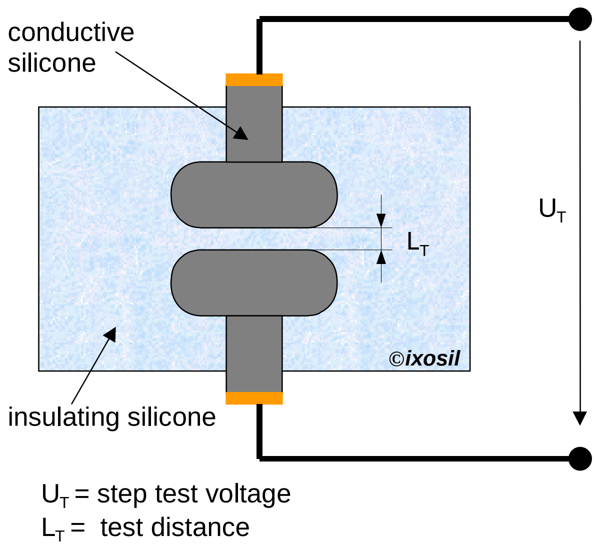
To 1: Dielectric strength of elastomeric material:

The breakdown voltage of a stress cone arrangement, consisting of a compound of con-ducting and insulating materials, does not only depend on the properties of the insulating material itself but also on the material of the electrodes, the compatibility of electrode and insulating material and the surface properties of the electrodes formed by the semiconducting elastomeric material. Therefore test arrangements for determining the breakdown field strength according IEC 60243 are not very useful in this case.

Further the dielectric breakdown field strength depends also on the volume (and surface) of the material involved due to statistical and physical volume effect. Practical experiments have shown, that the statistical effect is dominant, while the physical volume effect is normally neglectable [1].When results from small test arrangements are used for dielectric systems with bigger volume or surface, the dielectric strength has to be reduced according to the statistic distribution functions ([1] and [3]).

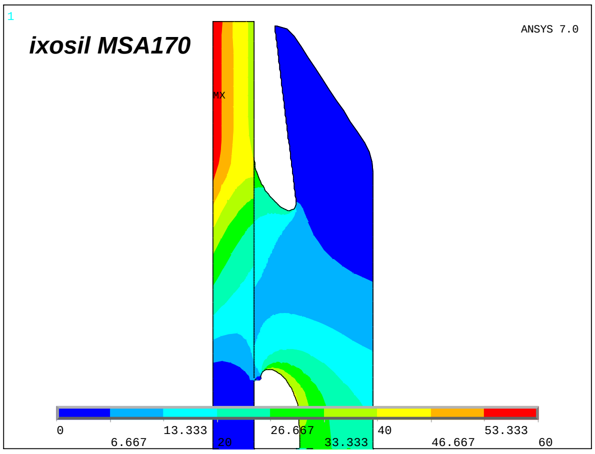
From a test arrangement, which design take into account the above mentioned aspects (see picture 2), the dielectric strength of the insulation can be determined (for example by step tests). This has to be done for AC and impulse voltage.

Further reductions for temperature, ageing and safety margins have to be applied



Picture2: Test arrangement to determine the dielectric strength of elastomeric material

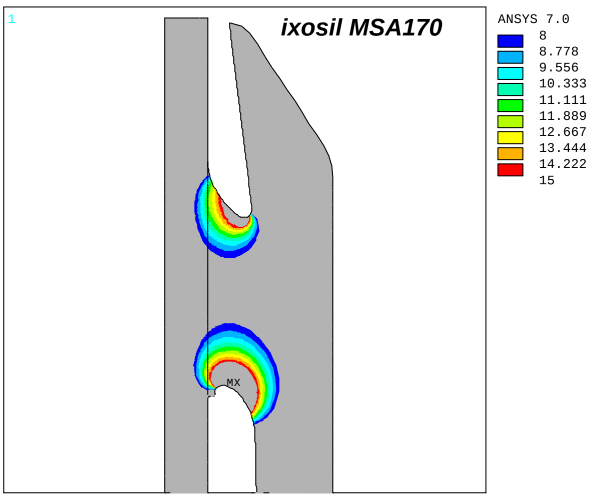
In the picture 3 the size of the total field is shown on the output of an electrical field calculation. The values indicate the electrical field at impulse voltage.



Picture 3: Value of total field at impulse voltage in joint body and cable.

To 2: Dielectric strength of interface

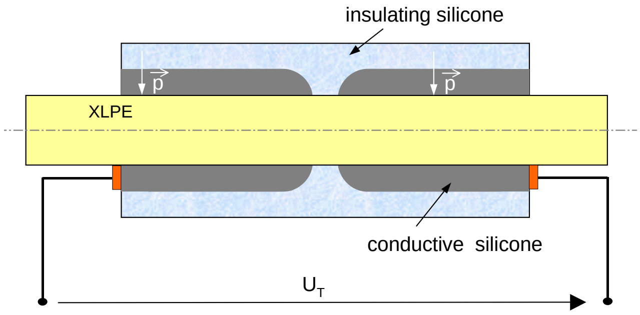
Special attention must be paid to the interface between cable and joint body. The electrical field along this interface (part of the field parallel to the interface) is always a critical issue as the dielectric strength of this interface is practically lower than the strength of an insulating body. Therefore the stress control elements must be designed that way, that the field along this interface stays within the permissible limits (picture 4).



Picture 4: Value of electrical field along interface at impulse voltage.

The electrical strength of this interface depends strongly on the mechanical design of the joint, which will be treated in the next chapter.

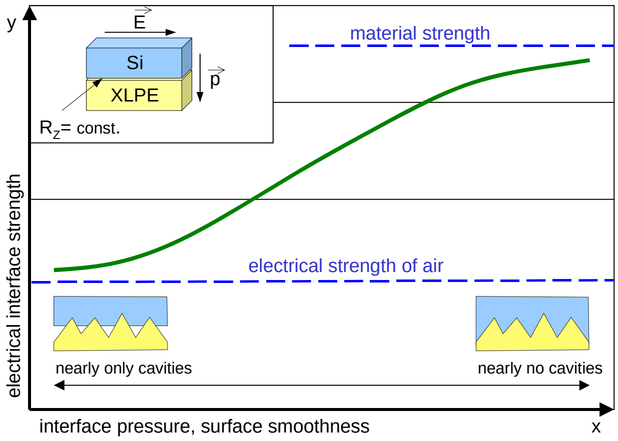
To determine the design criterias for the interface a special model arrangement was developed, where a high electrical field can be generated in the interface between cable and a polymeric sleeve. By inserting different cable sizes into the elastomeric sleeve, different expansions and contact pressures can be simulated (picture 5).



Picture 5: Test arrangement to determine the dielectric strength of the interface between cable and elastomeric sleeve for different contact pressures.

Mechanical Design

An important issue with respect to the mechanical design of a joint body is the interface between joint body and cable insulation. The dielectric strength of this interface depends strongly on the interface pressure and smoothness as shown in picture 6.



Picture 6: Dielectric strength of interface versus interface pressure and surface smoothness
Source: Cigré Joint Task Force 21/15

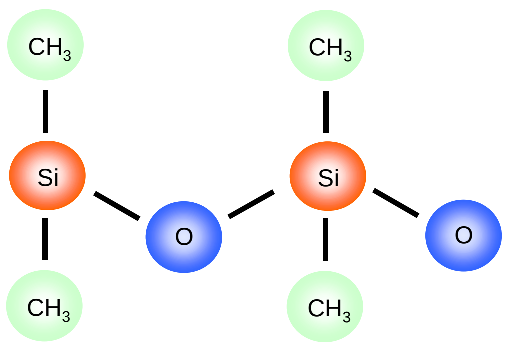
In this picture it can be seen that in case of a very small pressure the dielectric strength of the interface is going down to the strength of air as the interface consists to a large extend of enclosed air. For a very good interface – high pressure and perfect smoothness – the strength of the interface is theoretically reaching the strength of the material as in this case the remaining cavities in the interface will be theoretically of the same size as the distance between molecules in the bulk material.
When designing the interface between cable and joint body the real situation during the installation must be considered carefully as the cable insulation is prepared only on site. In order to have a sufficient safety margin even under non perfect conditions at site, the contact pressure must be chosen big enough to ensure a sufficient dielectric strength. This consideration leads finally to the minimum allowable expansion of the joint body in order a sufficient interface pressure is maintained, which has to be normally above 10%
The use of grease, which is necessary for the slip-on procedure is theoretically increasing the strength of the interface as the grease is filling-up the remaining small cavities in the interface. However it must be considered that the grease is normally dissipating into the elastomeric joint body or into the XLPE cable after a few weeks. Only with special greases it can be insured that the grease will stay in the interface for the whole service life. It is therefore recommendable to design the interface in this way that even without grease the dielectric strength is reaching sufficient values by taking care on the surface roughness of the cable surface and inner part of joint body. Practical experiments had shown, that due to the creeping of elastomeric materials small cavities in the interface will be filled out with polymeric material. Hence the effect of the dissipation of the grease can be counteracted at least partially by the creeping effect of the joint body.
The maximum expansion of the stress cone is mainly given by the feasibility for installation as the mechanical properties of the elastomeric materials used are normally much higher than the practical range of slip-on cable accessories. If the expansion is choosen too big, the force to slip-on the silicone sleeve will be very high, which can cause problems on site during installation. Therefore the maximum expansion should be in the range of 40%.
Special attention needs to be paid to load cycling conditions. During operation a cable system is subjected to heating and cooling processes. During the heating phase the diameter of the cable is enlarges and therefore the expansion of the stress cone is also increased, while during the cooling period the diameter is reduced. In order to maintain a sufficient contact pressure in the cooling phase of the load cycles, the tension set of the used materials must be taken into account for the calculation of the minimum required contact pressure. Further the relaxation of the elastomeric material must be considered as the elastomeric material is loosing its mechanical strength while being expanded over a long time period.
The above explanations show that the careful selection of the appropriate material is essential as electrical and mechanical properties are vital for the quality of the finished product.

Choice of Material

Nowadays the materials used for high voltage joints are silicone rubber and EPDM. The basic requirements for an elastomeric material are as follows:

- Sufficient mechanical properties in order being expandable in the required range
- Capability to withstand the required temperature range
- Availabilty of material with constant quality and constant purity
- Low ageing with respect to electrical and mechanical properties

According the requirements given above silicone rubber is an ideal and preferred material for cable joints.
Silicone rubber is a semi-inorganic material consisting of an inorganic backbone with organic sidegroupes as schematically shown in picture 7.



Picture 7: Basic chemical structure of silicone rubber

Due to this special chemical structure and the high bonding energy of the Si-O connection, which is 30% higher than the bonding energy of the C-C connection of organic molecules like EPDM, silicone rubber has the following outstanding properties:

- high thermal stability up to 200°C with respect to electrical and mechanical properties
- long life, very little ageing
  (life exponent N=70, see chapter below)
- low Shore A hardness in the range of 40 and excellent mechanical properties

Therefore it can be concluded that silicone rubber is an excellent material for the use in cable accessories as it can fully cope with the electrical, mechanical and thermal requirements given by nowadays polymeric cables.

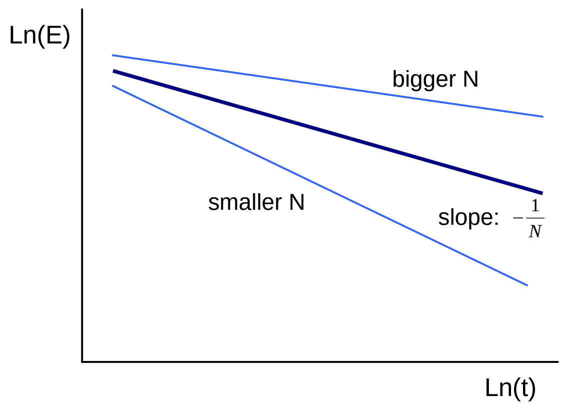
Ageing

In important aspect, which we still have to consider is the ageing factor of insulating material and interface. The ageing can be described by the life time law as follows

$$E^N * t = const.$$

Where as : E = Electrical field in the insulation
t = Time, where the electric field is applied
N = Lifetime coefficient

If the above equation is ploted in a diagram with the logarithm scale, it will lead to the following graph:



Picture 8: Graph showing life time law

The bigger the N value, the smaller is the ageing of the material. Silicone rubber with a life time coefficient of N=70 ([1] and [3]). is one of the best polymeric materials available. For XLPE for example lifetime coefficients of only 15 to 20 are achievable.
For the interface the ageing is faster than in a perfectly produced joint body. In the interface the mean distance between molecules is generally bigger than in the bulk material. Hence the mean free path of the electrodes is bigger, resulting in higher energies and faster decomposition of molecule chains. According Kunze [1] and Österheld [2] the life time coefficient is in the range of 40, which is

significantly lower than in the silicone rubber materiel but still much higher than the XLPE material.

Example

If we assume that the remaining withstand voltage of a cable joint has to be 1.7 Uo in order no failure occurs, already the passing of a typetest, where 2.0 Uo is applied for 30 days gives a theoretical lifetime of few thousand years.

The above stipulated lifetime law is only applicable if there are no severe contaminations in the insulation material used. A contamination in an insulating system will increase the local electrical fields drastically, thus accelerating the ageing. Due to this increase of the local electrical field the considerations made during the design stage by applying the design criterias are not any more valid. Therefore a clean raw material of constant quality is essential to guarantee a constant quality of the finished product. This is another advantage of silicone rubber versus EPDM as the production process and basic materials of silicone rubber are better controllable than with EPDM

Quality Assurance

General

A new product has to undergo different tests before it can used in real applications. After internal design tests are passed successfully an important part to check the integrity of the design and to get the acceptance by customers are typetests as specified in IEC60840 (60kV up to 170kV), IEC62067 (for voltages ≥ 170kV) or alternatively in IEEE404. However all the type tests specified above give only information about the design and the quality of a limited amount of samples. When a typetest is passed it does not automatically mean that all the products produced afterwards in series are of sufficient quality

In order to guarantee a constant and outstanding quality of high voltage cable joints, the following measures should be taken

1. Regular check of dielectric strength of raw material by destructive step-tests In these tests samples of silicone rubber are subjected to a dielectric test, where the voltage is increased step by step until the samples fail. This test is up to now the only reliable test to determine the quality of an insulating system
2. Clean room environment for entire production
3. Optical check of products during different stages of the production
4. Electrical routine tests according IEC60840 or IEEE404 regulations
5. Installation of the products only by trained and certified fitters

Picture 9: Sample test of stress cone in Sefag ixosil high voltage laboratory

Production

The production of the complete silicone joint should be fully integrated in a clean room environment of class 1000 or better as it is also state of the art for the production of high voltage cables.
In addition it must be insured that the production of the insulating and conducting elements are fully separated as any conducting contaminants in the insulating body would be fatal for the quality of the silicone sleeve.

Picture 10: View of a production station for insulating material in clean room environment

Installation

The very compact design of premoulded joints offer shortest installation times, while increasing the safety of the installation procedure on site.
Due to the soft material silicone rubber the installation of the joint body can be achieved by simple handcrancks. Therefore very little special tools are required for the installation of silicone rubber joints.

Picture 11: Installation of a 245kV joint supervised by instructor

Although the installation of premoulded high voltage joint is very simple, all fitters, who install high voltage cable joints, should be thoroughly trained in order they understand the correct preparation of a high voltage cable and know about the sensitive and critical steps. Before certification of any installation staff it must be verified by tests that the fitters having attended the training understood the basic issues. Only certified fitters should be allowed to work on high voltage cable equipment.

Earthing concepts

General

Fundamentally the screen of a high voltage cable can be treated in the following way:

- Sheath bonded at one side only
- Sheath bonded at both sides
- Application of a cross bonding system

The practical implications of the choice of a specific earthing system are manifold and must be taken into account when a cable system is designed. The following aspects are influenced by the earthing concept of a cable system

- Current rating of a cable circuit
- Overvoltages in the cable screen
- Magnitude of the zero and positive sequence impedance
- Appearance of stray currents in the earth
- Earthing impedance of (remote) substations

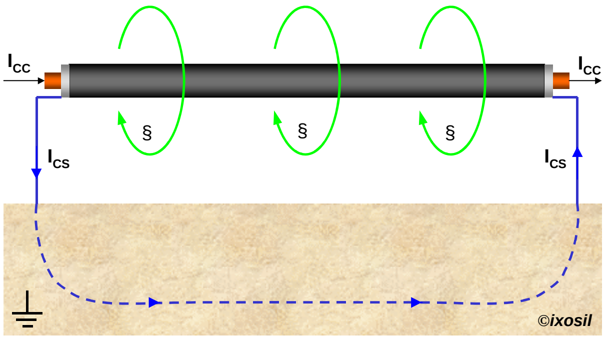
Both sides bonding

If the screen of a cable is bonded at both sides, the following effects will appear (see also picture 12)

- Due to the magnetic field of the main cable and the closed loop of the cable screen, a circulating current is flowing in the screen. This circulating current is causing additional losses. The losses are increasing strongly with increasing spacing between cables.
- The ampacity of the cable system is changed due to these extra losses in the screen. The best ampacities are reached

with a touching trefoil formation as this arrangements gives the lowest losses in the cable screen.

- There is no induced voltage appearing in the cable screen (as it is compensated by the circulating current) nevertheless of the length of the section (as section we understand the cable circuit between two earthing points of the cable screen)
- The earthing impedance of (remote) substations can be improved by the screen of the cable.
- The zero-sequence impedance has normally lower values than with one side bonding and can be calculated more accurately



Picture 12: Both sides bonding

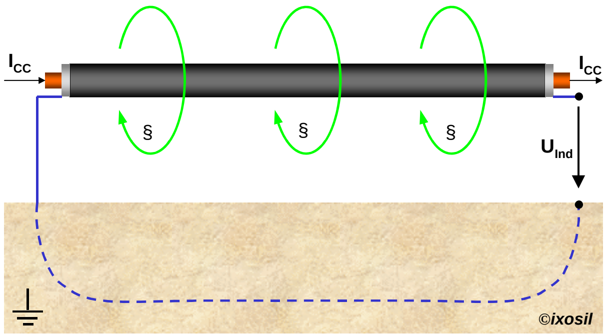
I_{CC} : current in conductor
I_{CS} : current in cable screen
§ : Magnetic field

One Side bonding

If the cable screen is bonded at one side only, the following effects are appearing (see also picture 13):

- As the screen is open, there are no circulating currents, but there is an induced voltage appearing at the open cable screen, where sheath voltage limiters must be installed in order to protect the cable outer jacket against transient overvoltages
- The ampacity is higher compared with both sides bonding, as there are practically no losses in the screen
- The length of one section is limited as the magnitude of the induced voltage is increasing with length.
- The zero-sequence impedance is bigger than for both sides bonding. This is due to the fact, that the mean return distance of the current in earth, which depends on the conductivity of the ground, is normally in the range of 1000m, which gives high values for the inductivity of the zero-sequence impedance. Practical measurements, which we have performed in the past for a Swiss power utility, showed, that the effective zero-sequence impedance differs a lot from the theoretical value, as the ground is normally “disturbed” by additional conductors like water and drainage pipes, railway lines, gas pipelines etc. Hence if single side bonding us used, the zero-sequence impedance needs to be measured for each cable system in order to have accurate values.
- Stray currents in the ground from earth faults can cause disturbances to neighbouring low voltage and data cables.

In order to improve zero-sequence impedance and the general earthing situation it is recommendable to install a parallel conductor along the cable route. The losses in this additional can be prevented by transposing it along the cable route ([2]).



Picture 13: Both sides bonding

I_{CC} : current in conductor
U_{ind} : induced voltage at the open side
§ : Magnetic field

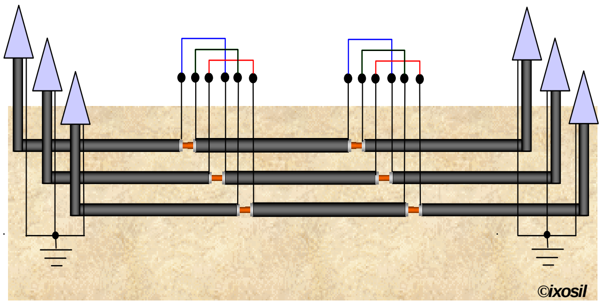
Cross Bonding

In a cross bonding system (see picture 14) the whole cable circuit should be divided in three sections with the same length. After every section the screen of the cable is cross bonded to a different phase. This is preferably done in positions, where joints (with screen interruption) are placed. Like this the connected screen will see the same amount of induced voltage from every phase, hence the induced voltage is becoming zero. If the cables are laid in plain, the cables itself need to be transposed at every joint bay, as the screen impedance is different for the inner cable and the outer cables. In order the sum of the induced voltage is really becoming zero, the connected screen must run always on the same position of the cable circuit (for more details see [2])

A cross bonding system can be considered as combining the advantages of single- and one side bonding, which are as follows:

- In a cross bonding system the cable screen can be earthed on both sides without having circulating currents and additional losses (as long as every section has the same length).
- Earthing impedances and zero-sequence impedances are improved due to both sides bonding.

However the disadvantage of the induced voltage appearing on every cross bonding point - similar to one side bonding - is still remaining. Hence the length of one section is limited. Further there is additional equipment needed like cross bonding boxes, earthing cable, cross bonding joints.



Picture 14: Crossbonding bonding system

Recommendations

Earthing concept in or near a substation, where an earthing grid is in the ground

- single side bonding in order to reduce the losses in the cable screen.

Earthing concept outside of a substation

1. For short cable lengths , where less than three sections of cables are needed, we recommend single side bonding together with an additional earth conductor to improve the zero-sequence impedance and the earthing impedance
2. For long cable lengths, consisting at least of three cable sections, we recommend implementing a cross bonding system as it increases the ampacity and improves the zero-sequence impedance
3. For cable circuits, where the number of cable sections is unequal to three or unequal to a multiple of three, the recommendations one and two can be combined.

If for any reason both sides bonding (without cross bonding) is applied, the spacing between cables should be minimised and trefoil formation should be chosen in order to reduce the losses in the screen and to maximise the ampacity of the cable.

Conclusion

If a premoulded joint is designed in a proper way, it is a very reliable component of a complete cable system. An important aspect is however to insure an integral quality of every joint from raw material to installation.

The proper engineering of the earthing concept is an important aspect in the design of a complete cable system and has to be made carefully for every project.

References

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