Features of selection and application of solid insulation with integrated earthed shield for the complete switchgears at high voltage

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Abstract — **The article describes the requirements for medium-voltage switchgears. It shows the main advantages and drawbacks of the conventional air-insulated switchgears and the relevance of the switchgears with solid insulation and solid shielded insulation. The use of this insulation system allows to reduce significantly the size of switchgear and to improve considerably the safety of its operation. The analysis of above mentioned characteristics of insulating systems with solid insulation in switchgear with solid shielded insulation (SISS) was carried out and there were given recommendations for the use of solid insulation. There were considered the main features of the SISS solid insulation: weakly inhomogeneous electric fields; high working electric field intensity; large volume of solid dielectric; high operating temperatures; usage of compact connections of adjoining insulation systems with solid insulation. There were defined typical insulation clearances of SISS: coaxial cylinders; special connectors; cable adapters; current leads and the insulating cases in the switchgears. The analysis of the known characteristics of the cast epoxy insulation and EPDM shows that the thickness of the insulation at high voltage in different standard insulation clearances, as a rule, may differ. It was determined that in order to ensure reliable operation of the SISS it is necessary to take special measures to exclude the possibility of gas spaces presence in the solid insulation.**

Key words: switchgear, voltage, cell, solid shielded insulation.

I. INTRODUCTION

Currently, switchgears of cabinet type are widely used in the electricity distribution networks of 6 kV -110. Such switchgear consists of cabinets in which the switching units, protection equipment of automatics and telemechanics, measuring and auxiliary devices are installed. For voltages up to 35 kV switchgears most frequently have air isolation, but sometimes SF-gas isolation is also used, notably, that the efficiency of the SF-gas insulation increases with the voltage increase. In addition to the above-mentioned air and gas-filled devices, switchgears with solid insulation are also used (with an external earthing and without it). Sometimes combined devices can be used. The main advantages of the gas-filled switchgears are small size and independence from the influence of the atmosphere, and the main disadvantages are - high cost, necessity for sealing and, accordingly, the complication of their operating conditions, and - the lack of sustainability in the usage of sulfur hexafluoride (SF gas).

II. CONDUCTED RESEARCH

With the development of modern electric-power industry, the transition to a maintenance-free electric power facilities, improvement the reliability of electrical equipment, one of the most promising switchgears is the switchgear with solid insulation and earthed external shield - SISS (Figure 1).

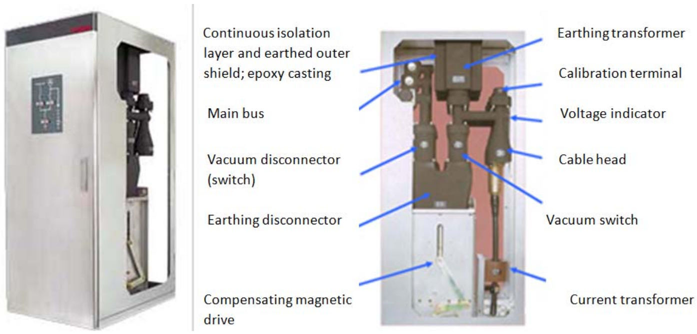

Fig. 1 Switchgear with solid insulation and built in earthed outer shield at rated voltage of 12 kV

SISS types of cells may be different, but their main common feature is the use of solid insulation and the presence of a zero potential on the surface of all elements of the cell.

The first development of SISS started up only 10-15 years ago.

The advantages of this type of switchgears are their compact size (the size of conventional cells is reduced by 2-3 times) and a high level of security as surface of all elements inside the cabinet is earthed.

Ensuring of safe operation of SISS largely depends on the electro-insulating characteristics of the solid insulation located between the current-carrying parts and the earthed outer shield.

Currently in SISS the most widely used cast epoxy insulation (LEI) and ethylene - propylene rubbers (EPDM).

However, the electro-insulating characteristics of SISS solid insulation - both epoxy compounds and ethylene - propylene rubbers in relation to working conditions in SISS are so far understudied, which makes it difficult to choose solid insulation and calculate its parameters.

Considering the need to solve serious scientific and technological problems, the work to create SISS at voltage of 35 kV has been carrying out since 2016 with the financial support of The Ministry of Education and Science of The Russian Federation. Research and development (R&D) work is held in the National research university "MEI" with the participation of specialized factories. According to the results of R&D, the

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article presents the analysis of the insulating characteristics of the solid insulation and the main proposals on the use of solid insulation in SISS.

As the main advantage of SISS is its compactness associated with short distances between current-conducted and earthed elements, then on the one hand, it is reasonable to use insulation materials with a high electric strength, and on the other – to secure successful operation of isolation in weakly inhomogeneous electric fields, since the thickness of the insulation in the weakly inhomogeneous electric fields can be reduced in comparison with violently inhomogeneous fields.

The presence of the solid insulation on the entire surface of the current-carrying conductors, unfortunately impairs convective heat removal, thus reducing the thickness of insulation is also important for provision of the necessary thermal conditions.

A variety of different elements in SISS (circuit-breakers, disconnectors, earthing switches, measuring transformers, busbars, cables, arrestors, etc.) leads to the need for electrically strong connectors of adjacent insulation systems with a earthed outer shield.

Thus, the operating conditions of the solid insulation in SISS are usually characterized by the following features:

- Weakly inhomogeneous electric fields;
- The highest average operating stresses of the electric field in case of continuous impact of voltage (over 1kV \ mm)
- Sufficiently large volumes of solid dielectric, since all the elements of switchgears are covered with solid insulation;
- High operating temperatures because of flow of the operating current and short-circuit currents as well as complicated heat removal;
- Use of the compact connections of adjacent insulation systems with solid insulation.

Normally in SISS there are several types of insulating structures:

- Coaxial cylinders (e.g. busbar elements –Fig. 2);
- Special connectors - usually conical - Fig. 3;
- Cable adapters - Fig. 4
- Insulating constructions based on solid insulation of switchgears of various types (circuit-breakers, disconnectors, earthing switches, fuses), consisting mainly of cast polymer current leads to the switching device (Fig. 5) and directly insulating case (Rig. 5b.

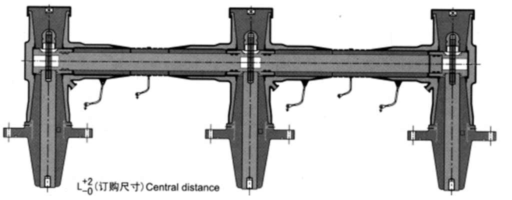

Fig. 2. Main typical insulation constructions of SISS for medium voltage classes - coaxial cylinders with conical connectors.

Coaxial cylinders of SISS are basically copper bars covered with a cast compound, and forming their cylindrical shell by an organic conductive material (usually - EPDM with special additives that allow high conductivity of rubber). The use of organic conductive shell is determined by the necessity of its good adhesion with compound and the partial discharges appearance suppression. For connection of SISS adjacent elements special standardized [1] Conical connectors are used – Fig. 3.

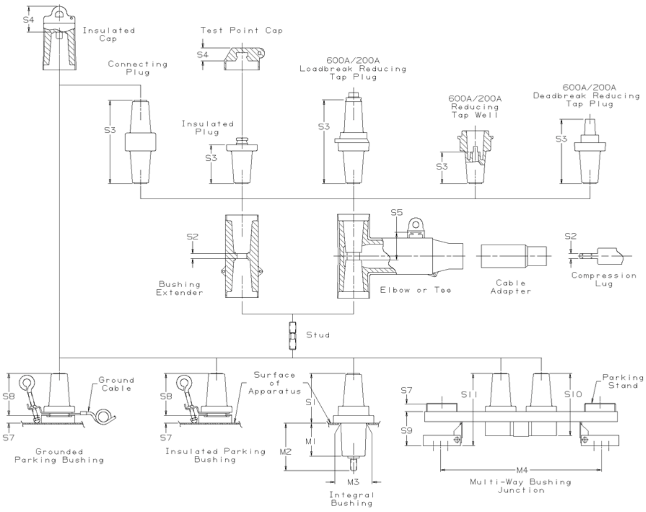

Fig. 3. Standard conical connectors for SISS [1]

Conical standardized connector is a cone of solid insulating material (usually - cast epoxy compound) with standardized dimensions and surface treatment [1-4], and the grommet of a more ductile insulating material (generally, of EPDM), fixed to the solid insulation cone. High precision during the cone production, grommet ductility and special lubricant applied to the surface of the cone during assembly provide exclusion of occurrence of air layers, and hence the partial discharges in the connector when applied to high voltage.

Fixed cone sizes, size tolerances and processing of its surface also allow excluding the development of sliding discharges along the surface of the cone.

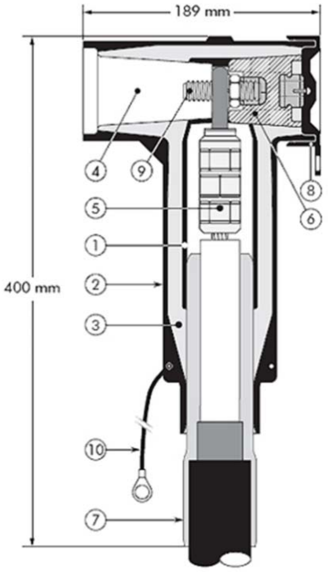

Fig. 4. The design of the cable adapter

(1-semiconductive screen on the basis of EPDM - electric field intensity alignment module, 2- outer conductive EPDM layer, 3 - main insulation of EPDM - insulating EPDM layer, filled between the grommet and the enclosure, 4 – cavity for epoxy cone, 5 - cable cap, 6 - epoxy plug - threaded rod insulation, 7 - cable, 8 - the plug cap of conductive EPDM, 9 – thread lock, 10 - earthing).

The outer surface of the grommet and insulation mated with a cone covered with a layer of conductive material (usually - EPDM), which after assembly provides a sole earthed conductive shield of a connector.

It should be noted that some companies have made efforts to improve the SISS connectors. For example, Schneider company has offered flat connectors [5] by using special technology. However, the positive experience of the operation of such connectors is only available for a rated voltage of 10 kV.

Cable adapters with earthed outer shield (Figure 4) are, although new, but the most mastered in the practice element of SISS, since they are connected with cables, which additionally have an external earth plane, and can be used not only in SISS.

Cable adapters are structurally close to the above-described connectors: for connection with an adjacent switchgear element the standardized conical connection on the basis of epoxy compound and EPDM is applied, and the outer earthed shield is made of conductive EPDM.

The difference from standard connectors and adapters is the appearance in the adapter the cable attaching by lug assembly and the inner semiconductive shield, leveling the inhomogeneous electric field of the attaching lug.

Current leads insulation construction in SISS switchgears is basically a wire holder of special shape, built-in in switching device and included a metal conductor cores, filled with epoxy compound.

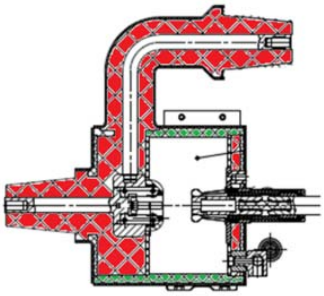

Fig. 5. Current leads (red) and the insulating case of switching devices (green) in SISS.

This wire holder secures the main function - voltage and current input into the switching devices.

To reduce the SISS size, the current leads are used for direct connection to other SISS elements - so their shape is standardized according to regulations for connectors [1-3].

These current leads have to work in conditions typical for switching devices, and to resist all relevant high-voltage, thermal and mechanical loads. This accords to the fact that the technical requirements for the current lead may be slightly different compared to standard connectors.

Insulating cases of switchgears have different shapes, but these insulation specific feature is that they have large built-in elements inside (vacuum chambers, contact units, etc.) – therefore they have the largest amount of insulation material and internal thermo-mechanical stresses in these constructions are highest possible.

As noted above SISS major insulating materials are cast epoxy compounds and ethylene-propylene rubbers (EPDM).

Known characteristics of cast epoxy compounds for use in SISS are shown in Table 1. The left bound of the given parameters range corresponds to the conventional epoxy compounds used in high-voltage equipment, and the right - epoxy compounds, specifically designed for SISS.

The right side of the above given parameters shows the data range of the compound, developed by the Japanese company "Toshiba".

Table I

Characteristic	Unit measure	Parameter
Tg (glass transition temperature)	0 C	100 -146
Linear thermal expansion coefficient	K-1	36x10^{-6} -17x10^{-6}
Ultimate bending strength	N/m2	120-160
Ultimate tensile strength	N/m2	(7-85) -100
Dielectrical constant	-	3-4
Electric strength	kV\mm	20- 30

The glass transition temperature (Tg) the new compound becomes about 30°C higher in comparison to standard conventional epoxy compounds.

The glass transition temperature increases due to changes in the molecular structure of the epoxy resin, and this leads to an improvement in such parameters as strength, elasticity, electrical properties, and others.

It should be noted that the probability of cracks and delaminations at the interface of the epoxy compound and molded elements (for example, vacuum chambers) is greatly reduced due to the fact that the thermal expansion coefficient of the new material has a small value.

It is used in the new compound also another type of filler - a spherical silica (instead of the traditional - amorphous) and a small amount of rubber particles.

As a result overall mechanical characteristics get improved and the tensile strength as well as the bending strength are increased.

In the SISS design process it is desirable to use such special compounds with improved properties, as this may give an additional SISS reduction by 10-20% and increase its reliability. However it is possible to apply conventional compounds as well.

Production of epoxy insulation assemblies carried by APG technology – with set injection moulds treated with an antiadhesins, inside the frame by means of vacuum pumps connected to the process connectors, creates a vacuum atmosphere with a residual pressure of up to 0.5 mm of vacuum.

EPDM rubber is used primarily for the formation of an elastic connection with solid epoxy insulating cones in the most SISS isolation constructions. This material for its elasticity and other characteristics (Table 2) is the most suitable for use in SISS.

Table II

№	Description	Unit measure	Parameter
1	Electric strength	kV/mm	20
2	Volume resistance	O·m	6x10^{15}
3	Surface resistance	O	9x10^{15}
4	Tracking resistance	c	97
5	Breaking strength	kg/sm^{2}	317
6	Bending strength	kg/sm^{2}	483

Conductivity increase of EPDM external layer, and thus, the formation of outer-conductor layer in SISS elements is carried out by applying an appropriate filler during manufacture.

Such manufacturing technology of sequential application of EPDM rubber layers with different conductivity secures high-quality stitching the layers to one another and the absence of gas inclusions, which guarantees the absence of the partial discharge.

III. RESULTS

The decisive factor to selection the thickness of the cast epoxy insulation, located in weakly inhomogeneous electric field, is prolonged exposure of power-frequency voltage, as the electric strength of the insulation even in the absence of partial discharges can reduce over time by several times (Figure 6).

The dependence of the MER epoxy electrical strength of the dielectric strength exposure time in a log-log scale for the mean values is almost a straight line. However, for the small probability of breakdown (Figure 6) it is observed a breach of this linear dependence - the degree of dielectric strength reduction at low electric field intensity and long-time stress exposure decreases, which indicates the existence of a lower limit of dielectric strength.

In the absence of a partial discharges with intensity less than 5-10pC, considering the large "active" volume of dielectric (i.e. volume, where the electric field strength is not less than 85% of the maximum in the gap), the choice of the allowable electric field intensity range can be carried out by the following proportion presented in [6] for the cast epoxy insulation of large volume in weakly inhomogeneous electric field:

$$E_\tau = (\frac{\tau}{\tau_l})^{-\frac{1}{m}}\left\{E\frac{d}{v} + \left(E\frac{a}{sv} - E\frac{d}{v}\right)V^{-\frac{1}{\beta}}(\frac{ln1}{1-P}))^{\frac{1}{\beta}})\right\} \quad (1)$$

where:

E_τ - MER electric strength with "active" volume V in long-term (for a time τ) impact of voltage;

E^a_{su} - Electric strength MER with the single-unit "active" volume (over time τ_l) voltage exposure;

m - an indicator characterizing the degree of insulation aging rate (m = 10-12 for a slightly inhomogeneous electric fields);

E^d_{ll} - the lower limit of electric strength;

V – magnification rate of the "active" volume of the dielectric in the real insulation to the unit "active" volume;

β - measure of the dispersion of the distribution function of the electric strength by Weibull

P - probability of breakdown.

This ratio is a mathematical description of the typical voltage-time dependencies of MER in weakly inhomogeneous electric field represented in Figure 6.

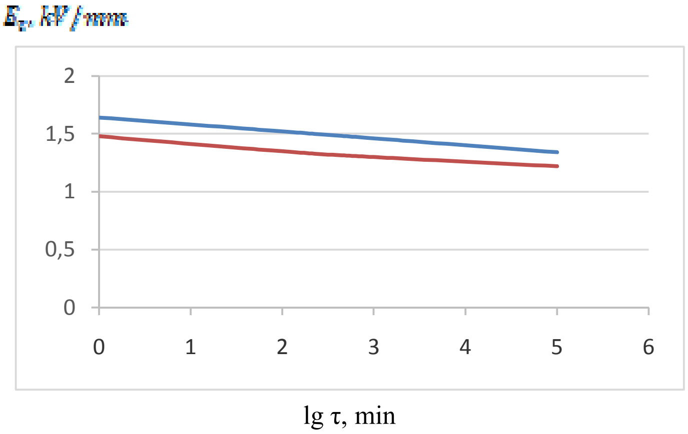

Fig. 6. Dependence of electric strength of cast epoxy insulation from the of voltage impact time in weakly inhomogeneous electric field, when exposed to power-frequency voltage in the double logarithmic scale (blue line - average values, orange - with a ten percent chance of breakdown - according to [6]).

Performed valuation by the ratio (1) of the parameters given in [6], show that the maximum allowable intensity of the electric field on the surface of current-conducting elements with a large "active" volume of MER is close to the lower limit value of electric strength and is about 4-6 kV / mm (peak value).

Using this value of permissible electric field strength for coaxial insulating gaps can estimate the required thickness of cast epoxy insulation «d» on the basis of the following known proportion for coaxials:

$$E_{add} = U_{op} / r * \ln(r + d)/r \qquad (2)$$

where:

E_{add} - the maximum allowable intensity of the electric field at continuous voltage exposure;

U_{op} - rated voltage;

r - radius of the inner conductor.

Normally for switchgears of distribution networks maximum operating current in the buses is usually about 1250 A.

This means that in accordance with the Rules of Electrical Facilities Maintenance (Chapter 3.1.) the minimum diameter of the copper buses of circular section under the continuous current of 1250 A should be at least 27 mm (in SISS according to the conditions on the temperature requirements can be selected bigger than the specified value of copper buses section). Thus, we can calculate the minimum thickness of the cast epoxy insulation in coaxial intervals of SISS at voltage of 10-35 kV (Fig. 7).

It should be pointed out that all this is true, if in the insulation there is no additional local field enhancement and delamination. For example, if there is delamination, for the avoidance of the partial discharges it is necessary to ensure the maximum intensity in the solid dielectric of about 4 times less than the minimum intensity of air discharge occurrence, i.e., about 0.7 kV/mm (instead of calculated 4kV/mm), i.e. it is needed to increase the thickness of the insulation by several times.

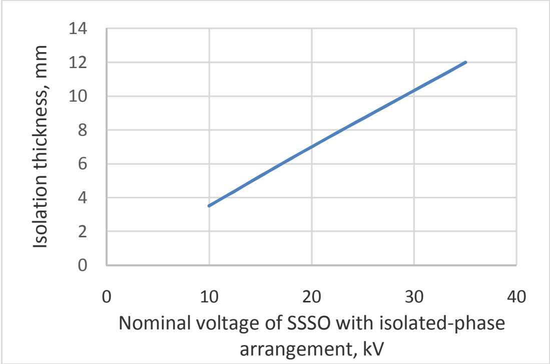

Fig. 7. Dependence of the minimum permissible MER thickness in coaxial intervals on nominal voltage.

It should be noted that in such standard insulation gaps as connectors and cable adapters, the polymer insulation has already been chosen by developers of these devices - but in the coaxial parts of these devices the thickness of the insulation is close to the above noted - for example, in cable adapters at a rated voltage of 35 kV the gap between earthed EPDM layer and inner semiconductive shield is about 15mm.

In the insulation constructions of the current leads and switchgear cases electric field generally differs from coaxial one and the degree of enhancement of the electric field may be higher. Therefore, the thickness of the insulation must be adjusted taking into account the maximum permissible value of the electric field - 4 kV / mm (usually upward). The estimates show that the degree of the electric field enhancement in the typical spaces may be about 2 two times higher than in coaxial. As a result, the insulation thickness can also be increased about two times compared to the data presented in Figure 7.

As an example, Figure 6 shows the pattern of the electric field in SISS fuse unit at 35kV voltage with insulation thickness of 25 mm, which is twice the permissible thickness in coaxial intervals.

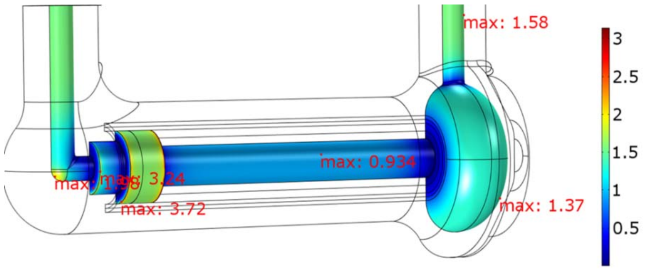

Fig. 8. The picture of the electric field and the peak value of the field intensity in case of 20 percent increase of the maximum operating voltage at SISS fuse unit at voltage of 35kV.

Electrical-isolation characteristics of the EPDM with continuous exposure of power-frequency voltage is less studied. However, there is no physical earth to assume that the dependence of the EPDM electrical resistance on voltage exposure time in weakly inhomogeneous electric field is significantly different from the voltage -time characteristics of epoxy compounds.

As the short-term electric strength of epoxy compounds and EPDM are close to each other (see presented Table 1 and Table 2) it can be assumed that the permissible field strength at voltage continuous exposure will also be close.
Furthermore, it should be noted that in contrast to EPDM epoxy compounds is placed in SISS construction, typically on the periphery of the insulation system where the electric field intensity is less.

Therefore, assumptions made about the possibility of the same approach for the EPDM seems reasoned.

As noted above, it is highly important to secure absence of cracking and delaminations of polymeric insulation during manufacturing and operation. Air gaps in the cast insulation may lead to partial discharges with intensity of more than 10 pC already at a thickness of 0.2-0.3 mm – i.e. they are unallowable.

The absence of partial discharges should be secured by high adhesion characteristics of compound to metal through activating the surface of poured metal fittings, as well as the lack of mating surfaces with a small radius of curvature.

Prevention of partial discharges on the connecting cone surface should be achieved via strict abidance by the requirements for these cones in accordance with IEC standards [1-3].

IV. CONCLUSIONS

1. In the last 10-15 years there has been appearance at electrically-powered equipment market of a new type of switchgears with cast solid insulation and a earthed outer shield (SISS) for distribution networks at rated voltage of 10-110 kV.
2. In the function of basic insulation the cast epoxy compounds and ethylene-propylene rubbers are typically used - but their characteristics in relation to the working conditions in SISS are not sufficiently studied yet.
3. Operation conditions of SISS solid insulation are characterized by weakly inhomogeneous electric fields; high operating intensities of the electric field; large amounts of solid dielectric; high operating temperatures; using compact connections of adjacent insulation systems with solid insulation.
4. The following typical SISS insulating gaps can be pointed out: coaxial cylinders; special connectors; cable adapters; current leads and the insulating cases in the switching devices.
5. Characteristics of existing epoxy compounds and ethylene - propylene rubbers allow them to be used in SISS - but to further improve the SISS dimension and weight parameters - it is expedient to create special materials.
6. The analysis of known characteristics of the cast epoxy insulation and EPDM shows that the thickness of the insulation at rated voltage of 10-35kV in various standard insulation clearances, as a rule, may be from 3.5 to 25 mm (depending on the voltage level and the degree of electric field inhomogeneity).
7. To ensure reliable operation of SISS it is necessary to take special measures to exclude the possibility of appearance of gas layers in the solid insulation.

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