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IZBOR ODVODNIKA PRENAPONA ZA ELEKTRIČNU ZAŠTITU KABLA

SHEATH VOLTAGE LIMITERS (SVLS) SELECTION

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Kratak sadržaj: Kako bi se sprečile ili barem minimizirale cirkulacione struje u električnoj zaštiti kablovskog voda, duž trase se može primeniti uzemljenje električne zaštite na jednom kraju ili preplitanje električne zaštite. Otvorene krajeve kao i tačke preplitanja potrebno je zaštiti od sporih i brzih prenapona odgovarajućim odvodnicima prenapona za električnu zaštitu kabla (SVL). SVL se ugrađuju u *link-box* kutije, koje mogu biti instalirane ispod ili iznad nivoa tla, u zavisnosti od položaja kablovskih spojnica i završnica. Glavni kriterijum za odabir SVL-a je napon indukovan u električnoj zaštiti. U ovom radu je prikazano poređenje kriterijuma za odabir SVL-a prema sledećim dokumentima:

- IEC 60099-5: Surge arresters - Part 5: Selection and application recommendations
- Electra 128-2: Guide to the protection of specially bonded cable systems against sheath overvoltages
- CIGRE TB 283: Special bonding of high voltage power cables
- CIGRE TB 797: Sheath bonding systems of AC transmission cables - Design, testing, and maintenance
- ENA Engineering Recommendation C55 Insulated sheath power cable systems

Ključne reči: *SVL, uzemljenje električne zaštite, kabl*

Abstract: To prevent or at least minimize circulating currents in cable sheaths, single point bonding or cross bonding can be implemented along the cable route. The open ends as well as the cross-bonding points should be protected against slow- and fast-front overvoltages by suitable sheath voltage limiters (SVLs). SVLs are installed in link boxes at joint bays, either underground or above ground depending on the location of the cable joints, as well as at terminations. The main criteria for selecting SVLs is the sheath to earth voltage. This paper presents comparison of criteria for the selection of SVL in accordance with the following documents:

- IEC 60099-5: Surge arresters - Part 5: Selection and application recommendations [1]
- Electra 128-2: Guide to the protection of specially bonded cable systems against sheath overvoltages [2]
- CIGRE TB 283: Special bonding of high voltage power cables [3]

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- CIGRE TB 797: Sheath bonding systems of AC transmission cables - Design, testing, and maintenance [4]
- ENA Engineering Recommendation C55 Insulated sheath power cable systems [5]

Key words: *SVL, bonding arrangement, cable*

1 INTRODUCTION

The choice of bonding design will depend on the length of the cable circuit and the normal/short-time current rating.

If the cable sheath is grounded at both ends, any dielectric stress on the insulation can be avoided, but thermal losses occur due to circulating currents in the sheath. To minimise the sheath losses caused by these circulating currents and thus increase the circuit rating capability, specially bonded cable system needs to be considered. Depending on the cable route length, there are two types of specially bonded systems:

- Single point bonding, applied by connecting metallic sheaths together and earthing the sheaths at one point only along the cable route. Used for shorter route lengths (typically less than 1 *km*). Disadvantages of single-point bonding:
    1) there is voltage at the open end, especially in the case of fault
    2) the protection device operation is entirely dependent on a single earthing point.
    3) it is not possible to measure partial discharges online using a high-frequency current transformer (HFCT) at the open end of the sheath.

  The solution to the first two disadvantages is to use SVL at the open end of the sheath in the link box.
- Cross-bonding, applied by sectionalising the cable route into elementary sections and cross connecting sheaths at joint bays in order to neutralize the total circulating currents through sheaths in each group of three consecutive sections.

To mitigate the risk of failure of the sheath insulation, the open ends as well as the cross-bonding points can be protected against slow- and fast-front transient overvoltages by suitable sheath voltage limiters (SVLs). SVLs are installed in link boxes at joint bays either underground or above ground depending on the location of the cable joints as well as at terminations.

The voltage between the sheath and the ground is the main factor in selection of SVLs. The analysis that relates to induced power frequency sheath voltages during normal, emergency, and through-fault conditions is more significant in selecting SVLs correctly compared to the analysis of transient voltages caused by lightning or switching impulses.

In order to correctly select a SVL the following parameters must be established:

- Induced sheath voltage under steady-state conditions (at maximum load current)
- Induced sheath voltage under through-fault conditions
- Impulse withstand level of sheath insulation, joint sectionalising insulation, bonding leads and link boxes.

2 INDUCED SHEATH VOLTAGE

The induced voltage in the cable metallic sheath is dependent on:

- Current passing through the cable conductor (either steady state or short circuit current)
- Installation arrangement
- Cable route length

While induced voltages due to steady state currents can be insignificant, induced voltages due to short circuit currents (faults), particularly ph-E faults in effectively earthed systems, play a crucial role for the SVL selection.

Estimating sheath overvoltages during system faults can be challenging and often requires specialized software. To address this, simplified formulas are used at the design stage of projects for calculating the maximum expected overvoltages. These formulas are based on detailed calculation analyses considering three types of faults (as per Appendix 2 of Electra 128-2):

- 3-phase symmetrical fault
- Phase to phase fault
- Single phase to earth fault

2.1 3-phase symmetrical fault (external to the cables) and steady state

Induced sheath voltages per meter for single point bonding and cross-bonding system during 3-phase symmetrical fault external to the cables are the same as during the steady state conditions [2], [3], [7]:

$$E_1 = j \cdot \omega \cdot I \cdot 2 \cdot 10^{-7}(-\frac{1}{2}\ln\left(\frac{2}{d}\frac{S_{12}^2}{S_{13}}\right) + j\frac{\sqrt{3}}{2}\ln\left(\frac{2S_{13}}{d}\right) \quad (2.1)$$

$$E_2 = j \cdot \omega \cdot I \cdot 2 \cdot 10^{-7}(+\frac{1}{2}\ln\left(\frac{4S_{12}S_{23}}{d^2}\right) + j\frac{\sqrt{3}}{2}\ln\left(\frac{S_{23}}{S_{12}}\right) \quad (2.2)$$

$$E_3 = j \cdot \omega \cdot I \cdot 2 \cdot 10^{-7}(-\frac{1}{2}\ln\left(\frac{2}{d}\frac{S_{23}^2}{S_{13}}\right) - j\frac{\sqrt{3}}{2}\ln\left(\frac{2S_{13}}{d}\right) \quad (2.3)$$

Where:

E : sheath voltage gradient for a particular phase [V/m]

d : geometric mean diameter of metallic sheath [mm]

S_{12}, S_{23}, S_{13} : are axial phase spacings [mm]

I : steady state / short circuit current [A]

ω : is angular frequence of the system [-]

In Electra 28 [6], it was considered that in the case of a phase-to-phase fault for cross bonded system, no sheath current flows due to balanced condition. However, in the normal case, sheath currents will flow, and use of computer calculations is required to obtain at an exact solution. It is not possible to derive a simple equation for the sheath voltages, but voltages between sheaths are less than those in formulas 2.1, 2.2 and 2.3 [2],[7].

2.2 Phase-to-phase and phase-to-earth fault

Induced sheath voltage gradients for single point bonding system during phase-to-phase fault between phases 1 and 2 for I_{12} fault current [2]:

$$E_1 = j \cdot \omega \cdot I_{12} \cdot 2 \cdot 10^{-7} \ln\left(\frac{2S_{12}}{d}\right) \tag{2.4}$$

$$E_2 = -j \cdot \omega \cdot I_{12} \cdot 2 \cdot 10^{-7} \ln\left(\frac{2S_{12}}{d}\right) \tag{2.5}$$

$$E_3 = -j \cdot \omega \cdot I_{12} \cdot 2 \cdot 10^{-7} \ln\left(\frac{S_{23}}{S_{13}}\right) \tag{2.6}$$

In case of single phase to earth fault for cross bonded system, the returning current divides between the metallic sheath / screen and the earth. The effect of the earth current is important, and to calculate these it is necessary to know the values of ground resistivity. Formulas for different installation arrangements are given in IEEE 575 [7].

Induced sheath voltage gradients for single point bonding system during single phase to earth fault in phase 1 external to cables [2]:

$$E_1 = I_{1E}\left(R_c + j \cdot \omega \cdot 2 \cdot 10^{-7} \ln\left(\frac{2S_{1c}^2}{d\gamma_c}\right)\right) \tag{2.7}$$

$$E_2 = I_{1E}\left(R_c + j \cdot \omega \cdot 2 \cdot 10^{-7} \ln\left(\frac{S_{1c}S_{2c}}{S_{12}\gamma_c}\right)\right) \tag{2.8}$$

$$E_3 = I_{1E}\left(R_c + j \cdot \omega \cdot 2 \cdot 10^{-7} \ln\left(\frac{S_{1c}S_{3c}}{S_{13}\gamma_c}\right)\right) \tag{2.9}$$

where S_{1c}, S_{2c}, S_{3c} are the geometric mean spacings between cables 1, 2 and 3 respectively and the earth conductor, R_c resistance of earth conductor, γ_c geometric mean radius of earth conductor (for stranded conductors take 0.75 overall radius).

In a single-point bonded system, the highest induced sheath voltage typically occurs during a single phase-to-ground fault. Conversely, in a cross-bonded system, the highest induced sheath voltage is usually observed during a three-phase fault.

3 ENERGY ABSORPTION CAPACITY

The energy absorption capacity is determined as a function of the current duration and magnitude dissipated through the SVL. SVL shall have the sufficient energy absorption capability, which can be calculated as follows:

$$P_{SVL} = U_{RES} \cdot I_{SVL} \cdot T_{TAIL} \tag{3.1}$$

where, P_{SVL} energy absorption capability of SVL, U_{RES} residual voltage of SVL at a switching impulse, I_{SVL} discharge current of SVL, T_{TAIL} estimated duration of surge.

Discharge current of SVL [8], [9]:

$$I_{SVL} = \frac{2 \cdot \left(0.7 \cdot U \cdot \frac{\sqrt{2}}{\sqrt{3}} \frac{1.15}{1.1}\right) - e}{Z_s} \tag{3.2}$$

where U rated voltage, e discharge inception voltage of SVL, Z_s surge impedance of cable between conductor and sheath [10]:

$$Z_s = \frac{60}{\sqrt{\varepsilon_r}} \cdot \ln\left(\frac{D}{d}\right) \tag{3.3}$$

where ε_r relative permittivity of cable insulation, D outer diameter of cable insulation and d outer diameter of cable conductor shield.

The surge energy usually does not exceed the energy absorption capability, so this is not a major factor in choosing the SVL.

4 SVL PARAMETERS U_c, U_r AND U_{res}

The performance of a zinc oxide surge arrester during steady-state operation is determined by its maximum continuous operating voltage (U_c), rated voltage (U_r) and residual voltage during the passage of discharge current (U_{res}) [11].

The continuous operating voltage of an arrester U_c is the maximum power-frequency voltage between its terminals, which the SVL can withstand continually and under which the SVL can normally operate (rms. value of power-frequency voltage that may be applied continuously between the arrester terminals).

The rated voltage of an arrester U_r is maximum permissible rms. value of power frequency voltage between its terminals at which it is designed to operate correctly under temporary overvoltage (TOV) condition, defined as 10 s duration in [11], after being preheated to 60°C.

Residual voltage U_{res} is peak value of voltage that appears between the terminals of an arrester during the passage of discharge current [11]. The protective level of a SVL is the maximum residual voltage measured when carrying the nominal discharge current.

The SVL shall not only be suitable for continuous operation with an applied voltage equal to the sheath induced voltage at full load or at the overload rating for the circuit, but TOV capability should also not be exceeded by induced voltages resulting from all kinds of external system faults.

The difference between the Maximum Continuous Operating Voltage, U_c, and the Rated Voltage, U_r is typically 15-25% (U_r is greater than U_c).

SVLs should be selected to provide protective levels below the impulse withstand voltages of any insulation between the cable sheath and earth (e.g. cable oversheath, joint protection etc.) arising from current impulses (i.e. current surges) in the primary conductor. Traditionally, the maximum value of U_{res} has been limited to 20 *kVp,* although EHV cables are typically tested at a much higher impulse voltage level and higher values of U_{res} can be considered.

The ratio between rated voltage (U_r) and U_c / U_{res} is generally linear for a specific design of SVL. Selection of a higher value of U_r therefore increases the protective level provided by the SVL, reducing the protective margin between U_{res} and the impulse withstand level of the cable sheath.

The relationship between the SVL parameters and the parameters of the cable system is illustrated in Figure 1.

This illustrates the selection of the SVL to provide a 'protective margin' (difference between U_{res} and the impulse withstand voltage of the cable and accessories) and TOV margin (difference between the TOV withstand capability of the SVL and the maximum induced voltage on the cable sheath during passage of fault current).

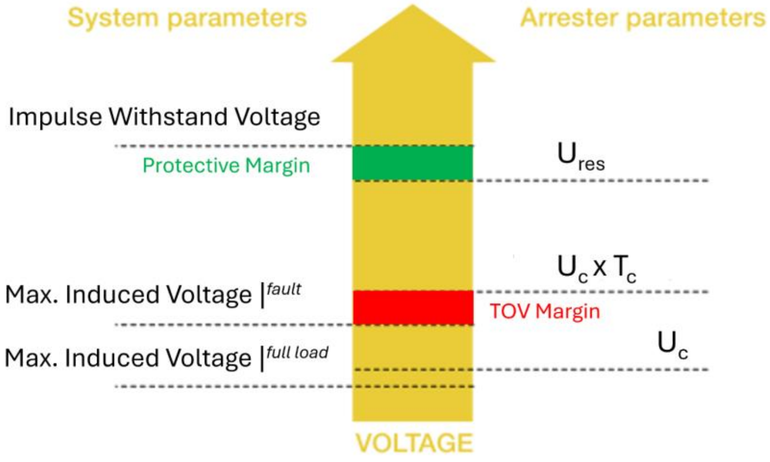

Figure 1: System parameters and SVL parameters

5 SVL SELECTION

5.1 SVL Selection as per IEC 60099-5

In IEC 60099-5: Surge arresters - Part 5: Selection and application recommendations [1], formula for determining the minimum continuous operating voltage of a SVL is given as follows:

$$U_c \geq \frac{U_i \cdot I_k \cdot L_k}{T_c} \tag{5.1}$$

where:

U_c : the continuous operating voltage of the surge arrester $[kV]$

I_k : the max. short circuit current of the cable (single phase) in $[kA]$

L_k : the length of the unearthed cable section [km]

U_i : the voltage induced in the per unit length of cable sheath in $[kV/(kA \times km)]$

T_c : the TOV (temporary overvoltage) factor corresponding to the continuous operating voltage U_c

IEC 60099-5 [1] defined U_r as a minimum TOV capability for 10 *s*. For other combinations of magnitude and duration of TOV the manufacturers give the TOV capability either in factors of the rated voltage, U_r, or in factors of the U_c. The U_r / U_c ratio is typically 1.25.

T_r is the temporary overvoltage factor corresponding to the rated voltage U_r (Figure 20a in [1]) and can be used as an alternative to T_c. SVL TOV capability can be determined either from $U_c \cdot T_c$ or $U_r \cdot T_r$.

Summarised steps in selection of SVL:

1. Calculate induced sheath voltage during fault
2. Determine the TOV factor from the TOV characteristic based on known fault clearance time.
3. Using formula (5.1), calculate SVL's U_c
4. Verify whether the maximum sheath overvoltage is lower than the $TOV = U_c \cdot T_c$.

It is recommended to select the residual voltage of SVL (protection voltage level) to be as low as possible since there is no clear definition or assurance of the oversheath's withstand strength during its service life. U_c / U_r should thus be minimised.

5.2 CIGRE

SVL units should be capable of withstanding continuously the sheath standing voltage applied to the metallic sheath during full load or emergency overload. In addition, the rated voltage of the SVL shall be at least equal to the highest 50 Hz voltage applied to it during system faults [2]. Formulas for calculation of these 50 Hz fault overvoltage are provided in Section 2.

When determining U_c and U_r it should be considered whether the SVL units are connected in star or in delta.

SVL protective level used to establish the necessary insulation levels for the system shall be taken as the highest of the maximum residual voltage during steep current impulse test or high current impulse test [2].

According to CIGRE 797 [4], the general procedure for selecting sheath voltage limiters involves following steps:

1. Calculation of the sheath power frequency (50 Hz) overvoltage during a fault at a specific fault duration.
2. Comparison of the calculated power frequency overvoltage (during a fault) with the TOV characteristics of a selected SVL. The calculated overvoltage shall be less than the temporary overvoltage value ($U_c \times T_c$) at a specific duration allowing for a typical 5% to 25% protection margin (indicated as TOV margin on Figure 1**Error! Reference source not found.**).
3. If the TOV characteristics of the SVL are not available, the SVL can be selected based on its U_c. U_c should be higher than the calculated power frequency overvoltage[1].
4. Select the Rated Voltage, U_r, from the manufacturer's SVL data sheet based on TOV comparison or selected U_c.
5. Consider the residual Voltage, U_{res}, of the selected SVL. The voltage is the maximum arrester voltage tested at, e.g., 8/20 μs and 10 kA current impulse. This value should be less than the transient overvoltage withstand level of the insulating components (cable

[1] An inherent safety margin is included by the difference between the Maximum Continuous Operating Voltage, U_c, and the Rated Voltage, U_r.

jacket, sheath/screen interrupts in joint bodies, etc.). The selection of SVLs is often done based on a 10 *kA* impulse current characteristic as this is often the nominal discharge current for a given surge pulse.

6. Verify the energy absorption capability of the SVL to withstand the maximum energy by the dissipated transient surge currents.

5.3 ENA Engineering Recommendation C55 Insulated Sheath Power Cable Systems

The following parameters of the SVL need to be specified [5]:

- Minimum continuous operating voltage (U_c)
- Rated voltage (U_r)
- Nominal discharge current (I_n)
- Protective level

According to ENA C55 [5], the minimum value of U_c shall exceed the maximum power frequency voltage (during a fault) calculated to arise between the cable sheath and earth with margin of at least 5% above the highest expected induced sheath voltage and rated voltage is selected by SVL manufacturer with a margin on top of U_c. U_r is generally between 1.15 × U_c and 1.25 × U_c.

The standard nominal 80 / 20 μs impulse discharge currents for surge arrestors, including SVLs are 20 *kA*, 10 *kA*, 5 *kA* and 2.5 *kA*. As per [5] unless otherwise agreed, SVLs should be chosen to have an I_n of not less than 10 *kA*, where 10 *kA* is a generally accepted value for system voltages up to and including 400 *kV*.

The protective level of a SVL equates to the peak residual voltage (U_{res}) that results from dissipating a particular current impulse waveform (e.g. lightning impulse, steep lightning impulse and switching impulse) with a particular current amplitude.

It is stated that SVLs should be chosen to provide protective levels below the impulse withstand voltages of any insulation between the cable sheath and earth.

6 EXAMPLE OF SELECTION SVL

Table 1 presents the estimated sheath standing voltage for the circuit under steady state and for three phase (LLL) and phase to earth (LG) faults. ECC is assumed located equidistant from the centre and outside phase in flat formation and transposed at the midpoint of the cable route.

Table 1: Cable sheath induced voltages

Circuit arrangement	Rated Voltage	Circuit Length	Rated Current	Fault current (LLL and LG) for 1 *s*	Cable spacing	Sheath Standing Voltage		
						Rated Load	LLL Fault	LG Fault
	(*kV*)	(*m*)	(*A*)	(*kA*)	(*mm*)	(*V*)	(*kV*)	(*kV*)
Flat formation	400	300	1372	63	300	51	2.34	5.73

Table 2 presents differences in the SVL's continuous operating voltage (U_c) and rated voltage (U_r) according to the documents described in the paper for the example cable circuit in Table 1.

Table 2: Continuous operating voltage (Uc) and rated voltage (Ur)

Document	U_c (*kV*)	U_r (*kV*)
IEC 60099-5	≥5.73/T_c=4.41 (for *Tc* value, refer to the example in Figure 20b of IEC 6099-5 with prior energy).	≥5.73/T_r=5.46 (for *Tr* value, refer to the example in Figure 20b of IEC 6099-5 with prior energy).
ELECTRA 128-2	>0.051	≥5.7
CIGRE TB 797	≥5.73	according to the SVL datasheet and selected U_c, typically ≥7.17
ENA C55	≥6.02	≥7.52

Table 2 indicates that using a different document may result in the selection of a different SVL.

7 CONCLUSION

Various documents (standards, recommendations, brochures) provide similar recommendations for the selection of SVLs for cable circuits. However, some of these documents include safety margins between calculated maximum induced sheath voltage and capability of SVL (either as U_c or U_r), whereas others do not:

- IEC 60099-5: no additional margins are considered in the selection methodology. Users may wish to add a TOV margin (on top of highest expected induced sheath voltage under fault conditions) and a protective margin when using this Standard to select SVL characteristics
- CIGRE TB 797: this recommends leaving a 5% to 25% margin (the TOV margin) between the maximum induced voltage under fault conditions and the SVL TOV capability. If the TOV characteristics of the SVL are not available, U_c should be selected to be higher than the calculated power frequency overvoltage, which includes an inherent safety margin through the difference between the maximum continuous operating voltage U_c and the rated voltage U_r (typically 25%).
  Cigre also recommends allowing a protective margin. Although no figure is given, it is noted that IEC 60071-2 [12] suggests using a safety factor of K_s = 1.15 for 'internal' insulation (a protective margin of 15%).
- ENA ER C55: this suggests leaving a margin of at least 5% on top of highest expected induced sheath voltage when selecting the continuous operating voltage U_c. As U_c includes an inherent margin from the actual TOV (defined by the rated voltage U_r) this methodology typically gives a minimum TOV margin of $1.05 \times 1.25 = 1.3125$.
  It is recommended that a protective margin is allowed between U_{res} and the withstand level of the cable serving and accessories, although no figure is specified

It is considered by the authors that, where possible, SVL selection should be based on a manufacturers TOV characteristic. The TOV factor T_c should be determined using the maximum fault clearance time specified for the network and the minimum value of U_c x T_c should be selected considering a TOV margin of at least 5%.

If the TOV characteristic of the SVL is not available and T_c is unknown, the SVL should be selected based on the minimum value of U_c. This includes an inherent margin between the maximum continuous operating voltage U_c and the rated voltage U_r, which defines the SVL TOV withstand properties.

The peak residual voltage U_{res} of the selected SVL shall be no greater than the oversheath dielectric strength. If IEC 60071-2 recommendations are followed then a minimum protective margin of 15% should be allowed between U_{res} and the impulse withstand level of the cable serving and accessories.

In most cases, the energy absorption capability of the SVL is not a determining factor in the selection of the SVL as this capability often exceeds the surge energy released during emergency and through-fault conditions.

8 REFERENCES

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