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Estimation of Induced Overvoltage of Power Cables – A FEM Approach

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Abstract

Power cables are vital elements in the power system distribution network. The design of power cables with ratings above 6kV requires a metallic screen in their construction. The metallic screen represents the grounding element for the power cables. The metallic screen/sheath provides a path for the fault current to flow and be grounded. The method of bonding or grounding the metallic screen is important in the installation of power cables. Three types of bonding methods are popularly employed in the system. They are single-point, solid, and cross-bonding. The metallic screen experiences induced voltage due to the load current in the conductor in single-point bonding. The characteristics of the system determine the suitable bonding method, as each method has its own merits and demerits. The bonding and grounding method significantly affects power cable losses due to sheath-induced voltages and circulating currents. Sheath Voltage Limiters (SVL) are employed in single-point-bonded cables to limit transient overvoltages and protect the sheath. The design of the SVL also depends on the induced voltage in the system. The SVL is designed with a protective level higher than the normal induced voltage. Therefore, it does not conduct under normal load conditions. Hence, estimating the induced voltage during normal operation is essential for SVL design. This paper presents various methodologies, such as Analytical, Simulink, IEC 60287 and Finite Element Method (FEM), for estimating sheath-induced voltage, supported by a detailed case study of single-point bonding and a comparative analysis of the obtained results.

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1. INTRODUCTION

Power cables with ratings from 6kV to 400kV are already in use in the country. These screened cables are susceptible to induced sheath voltage due to electromagnetic induction caused by the load current in the conductor. The bonding methods employed for the metallic sheath of power cables are critical, as they play a significant role in minimising losses within the cable system. The current rating of the cable also depends on the cable losses[1]. In general, for shorter cable lengths, single-end bonding and solid bonding methods are adopted. In solid bonding, because both ends of the cable sheath are grounded, the induced current in the closed sheath loop increases system losses. Hence, the power cable needs to be derated and not utilised for its full capacity[2]. Single-point bonding is the only method suitable for short lengths of cable. In this method, as one end of the cable sheath is kept in an open condition, this metallic sheath is prone to inducing a voltage due to the load current flowing through the conductor during normal operating conditions[3]. In normal operation, the induced voltage may be within the safe limit for a short length of the cable and during a short circuit and transient conditions, the ungrounded end experience over voltage and, which may result in breakdown of the outer sheath insulation[2]. It necessitates the installation of SVL at the open end of the cable, which gets switched on only for abnormal conditions to limit overvoltage. In single-point bonding, during normal operation, as the length of the cable increases, the sheath-induced voltage also rises beyond the safe limit. Then, cross-bonding is adopted for long circuits to limit the sheath voltage. To ensure proper selection, the SVL should have a continuous operating voltage (Uc) greater than the calculated sheath voltage at the cable end. It makes the accurate calculation or estimation of the induced voltage is an essential step in selecting the rating of the SVL. The cross-bonding method offers significant advantages over single-point bonding; however, it requires the sheath to be divided into minor sections, resulting in higher installation costs and more complex maintenance. The SVL parameters must be selected based on the sheath bonding adopted and the estimated induced voltage to ensure reliable operation[4].

2. BONDING TECHNIQUES - LITERATURE REVIEW

The construction of High-Voltage Power cables with a rating above 6kV is with a concentric metallic sheath. The purpose of the metallic sheath is to provide a low-resistance path for the fault current during short-circuit conditions[3]. To limit the induced overvoltage within acceptable limits, various bonding techniques, including single-point bonding, both-end bonding, and cross bonding, are being adopted in practice. In the case of single-point bonding, there is a shock risk of open-circuit voltage at the ungrounded end. In both end bonding and cross bonding, even during normal steady-state operation, there is a risk of sheath circulating current[5]. The induced overvoltage causes the risk of shock to personnel involved, and also breaks the non-metallic outer sheath of cables[5]. Cross-bonding is a special type of bonding arrangement in which the metallic shields or sheaths of different-phase cables are interconnected across successive minor sections, in such a manner that the induced currents in the shields/sheaths are partially or fully cancelled[6]. Ground Continuity Conductor (GCC) is a parallel conductor laid close to single-bonded or cross-bonded cable to provide a continuous ground connection between the ends of the cable and along the route of the cable[6]. A surge protective device called SVL is connected between the metallic sheath and ground to limit shield/sheath overvoltages during system transients on bonded cables. Table 1 discusses the various aspects of bonding techniques adopted to reduce induced sheath voltage and losses in the cables.

From the review of technical articles, it is inferred that the selection of the optimal bonding and design of SVL needs calculation of sheath-induced voltage during steady-state operation.

Table 1. Aspects of bonding techniques

Stanislaw Czapp *et.al.*[3]	The induced sheath voltage reduces to over two times for a cross-bonded 110kV cable system during a fault than that of single point bonding. Two Earth Continuity Conductor (ECC) installations throughout the length of the cable at the same depth of burial as cross-bonded cables have a 5% reduction in the induced voltage compared to a single ECC installation.
Roberto Candela *et.al.*[5]	This study adopts a cost-effective single sheath bonding at both ends, eliminating the parallel ground conductor in a cross-bonded 30kV cable system to reduce the induced sheath current and the sheath losses.
M. Shaban *et.al.*[7]	It proposes an analytical method for the calculation of induced sheath voltage for single, double and triple circuit systems. It also concludes that the induced voltage is higher in triple-circuit lines than the other two.
Gouramanis *et.al.*[8]	This study calculates sheath voltage under steady-state and fault conditions for the real scenario of nine parallel cables. It also concludes that cross-bonding and grounding the cables at the ends with a low value of ground resistance reduces the sheath voltage significantly.
Stanislaw *et.al.*[9]	Computer modelling helps in finding the optimal earthing and bonding configuration of the system, and as equivalent to cross-bonding, single-point bonding with proper selection of the earthing reference point reduces the induced voltage.
Marina *et.al.*[10]	A new method is proposed to detect and localise four possible defects on the cable sheath that occur in the cross-bonding configuration based on the level of change of sheath current.
Mingzhen Li *et al.*[11]	The Fast Fourier Transform of the Sheath current will identify the fault current in cross-bonded systems. A set of fault localisation criteria is proposed based on the fact that the sheath current at the ends of the faulty section will be in the opposite direction.
Yong *et.al*[12]	It proposes the cross-bonding arrangement along with the Installation of a sheath connecting reactor in cross-bonding joints to reduce the sheath loss cost-effectively.
Prajakta *et al.*[13]	Positive Sequence impedance of transposed conductors is higher in the case of cross-bonded cables, and the losses are higher than in the non-transposed case. However, losses remain the same only for sheaths with longitudinal copper tapes.
Lulu Li *et al.*[14]	A new method wherein one of the sheaths is grounded at both ends and serves as the Ground Continuity Conductor (GCC) of the single-point bonding. Instead of grounding three sheaths at one location, one sheath is grounded at both ends, and the other two sheaths are connected with SVLs. It is an alternative to the cross-bonding method and increases the ampacity by 20-40% for heavy-loaded conditions.
Nikša *et al.*[15]	A correction factor to IEC 60287-1-1 to calculate the sheath loss factor for the middle cable of the flat formation, considering the proximity effect, is proposed.

3. COMPUTATIONAL METHODOLOGY

In this paper, four different approaches are adopted for the estimation of induced sheath voltage of a 19/33kV cable in trefoil mounting. These are analytical, International Electrotechnical Commission (IEC) 60287-based approach using Cyme Cable Ampacity Program (CYMECAP)[16], Simulink and FEM method. The constructional aspects of the cable are given in Table 2.

Table 2. Details of the 19/33kv, aluminium cable

Cable	1X630 Sq.mm, 19/33 kV Cable - Al
Conductor	Aluminium
Conductor screen	Semiconducting material
Insulation	XLPE
Conductor screen	Semiconducting material
Armour	Copper Wires
Outer Sheath	PVC

3.1 Estimation of Induced Voltage for Single-end Bonding

3.1.1 Analytical Method

The formulae used to calculate the sheath voltages for all phases under balanced three-phase current conditions are given below. The balanced three-phase currents in phases R, Y, and B are expressed as follows[6,17,18]. The three-phase balanced currents in phases R, Y and B are as below:

$I_R=I$; $I_Y=\alpha^2 I$; $I_B=\alpha I$; $\alpha= -\frac{1}{2}+j\frac{\sqrt{3}}{2}$

For Trefoil Configuration

$$E_R = j\omega I\ (2X10^{-7}) ln\frac{2S}{d}\ \text{V/m} \quad (1)$$

$$E_Y = j\omega I\ (2X10^{-7})(-\frac{1}{2}-j\frac{\sqrt{3}}{2}) ln\frac{2S}{d}\ \text{V/m} \quad (2)$$

$$E_Z = j\omega I\ (2X10^{-7})(-\frac{1}{2}+j\frac{\sqrt{3}}{2}) ln\frac{2S}{d}\ \text{V/m} \quad (3)$$

The parameters of the cable and installation considered for the analytical calculation are given in Table 3.

Table 3. Parameters considered for the analytical method

Parameters	Value
Current in phases (Ia, Ib, Ic) (A)	685
Frequency (Hz)	50
Geometric Mean diameter of sheath or Shield (d) (m)	0.0561
Axial Spacing between Phases for trefoil formation (S) (m)	0.0622

3.1.2 IEC 60287 Approach using CYMECAP

The ampacity and thermal performance of power cables can be evaluated using CYMECAP software. It adopts the IEC standard 60287 for steady-state analysis and IEC 60853 for transient analysis under various installation conditions. The software also calculates the conductor, insulation and screen losses of the cable, and the effect of induced current produced in the metallic sheath.

Table 4. Parameters considered for IEC 60287-based method

Diameter of the conductor D_{con} (mm)	31
Thickness of Insulation T_{ins} (mm)	8
Diameter over Insulation D_{ins} (mm)	49.1
Thickness of semiconducting screen T_{scc} (mm)	1
Armour Thickness T_{arm} (mm)	2.5
Cable diameter D_{cab} (mm)	62.3
Cross-section of the Conductor A_{con} (mm^2)	630
Length of the cable L_{cab} (mm)	10
Frequency f_0 (Hz)	50
Phase-to-ground voltage V_0 (V)	19.053
Rated RMS Current I_0 (A)	685
Thickness of outer sheath T_{pvc} (mm)	3

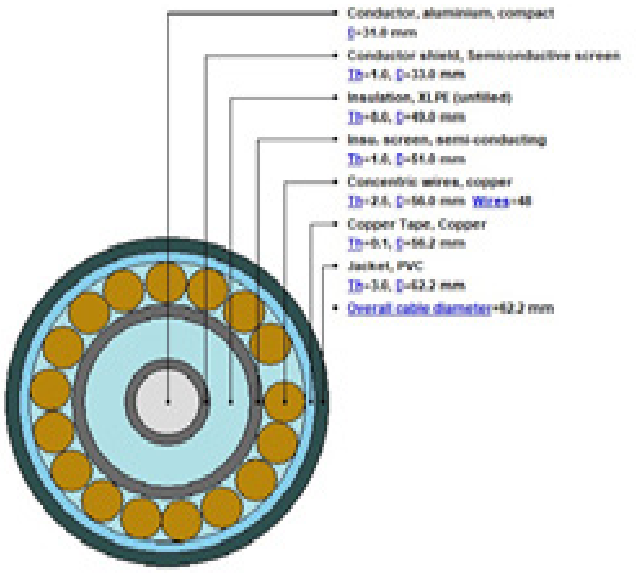


Figure 1. Geometry of the 19/33 kV cable in CYMECAP.

It can also model various types of metallic sheath bonding for flat and triangular arrangements of cables. The data considered for the steady-state analysis using CYMECAP are as shown in Table 4. By using the dimensions of various layers of the cable and selecting the respective material of the cable layer from the built-in library of the software, the induced voltage for the trefoil configuration and single-point bonding can be estimated. Figure 1 shows the geometry drawn in CYMECAP based on the provided inputs.

3.1.3 MATLAB Simulink Method

The built-in three-phase Alternating Current (AC) cable model in Simulink consists of a cylindrical phase conductor surrounded by a cylindrical conducting sheath. For medium- and long-length cables, the model accounts for frequency-dependent effects such as skin effect and proximity effect, which influence resistance and inductance. The cable parameters are defined per unit length and include conductor resistance, inductance, capacitance between conductor and sheath, sheath parameters, and earth return effects. These parameters can be entered directly or computed from geometric and material properties. This model, in its expanded three-phase ports, contains single-phase ports for each phase, a sheath, and an electrical reference node for establishing connections. The cable parameters considered for this model are as given in Table 5.

Table 5. Parameters considered for Simulink

Parameters	**Value**
Current (RMS) (A)	685
Geometric Mean Radius of conductor (m)	0.01555
Sheath radius (m)	0.02805
Outer Cable radius (m)	0.03115
Line-to-line spacing between cables (centre-to-centre) (m)	0.0623
Line formation (Trefoil/Flat)	Trefoil
Conductor Resistance (Ω/km)	0.042103
Sheath Resistance (Ω/km)	0.08745
Insulation relative permittivity	2.5
Relative permittivity between lines and return path	1
Earth Resistivity (Ωm)	100

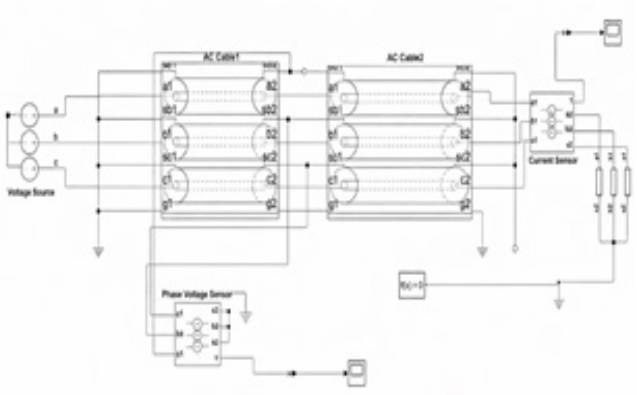


Figure 2. Simulink circuit with AC cable model.

By using cable models, an electrical circuit with a voltage source and a load is formed in such a way that the Root Mean Square (RMS) phase current in the circuit is 685 A. Figure 2 shows the Simulink circuit

with an AC cable model used for this study. The sheaths of the cable model are shorted and grounded at one end, and the other open-circuit end voltage is measured using the three-phase voltage sensor and scope. This simulates the single-end bonding of the cable. To preserve the overall cable length equal to the total required length, two AC cable model blocks are connected in series. The induced screen voltage of the first cable block is measured while varying the lengths of both blocks.

3.1.4 FEM Approach

The FEM software of COMSOL was used for this analysis. The cross-sectional cable geometry of the cable with the dimensions given in Table 3 is drawn. The other electrical parameters of the cable considered for the FEM study are given in Table 6.

Table 6. Cable parameters considered for FEM

Parameters	Value
Phase-to-ground voltage (V_0) (kV)	19.053
Rated Current (I_0)	685
Reference resistivity of conductor (Ω-m)	2.82e-8
Reference resistivity of screen (Ω-m)	1.724e-8
Relative permittivity of Insulation E_{xlpe}	2.5
Number of armour wires (N_{arm})	48
Aluminium conductivity at 20°C (S/m)	$5.96e^7$
Copper wire conductivity at 20°C (S/m)	$4.03e^6$
Relative permittivity of semiconducting compound	2.25
Relative permittivity of PVC Sheath	2.36

The FEM parameters considered for the study are as shown in Table 7. In the FEM simulation, the physics interface and magnetic field were considered for this 2D modelling study. Three cables of such geometry were placed in a trefoil configuration by choosing their x and y coordinates. The geometry of the trefoil cables is as shown in Figure 3. Then, the materials are assigned to the respective layers of the cable geometry.

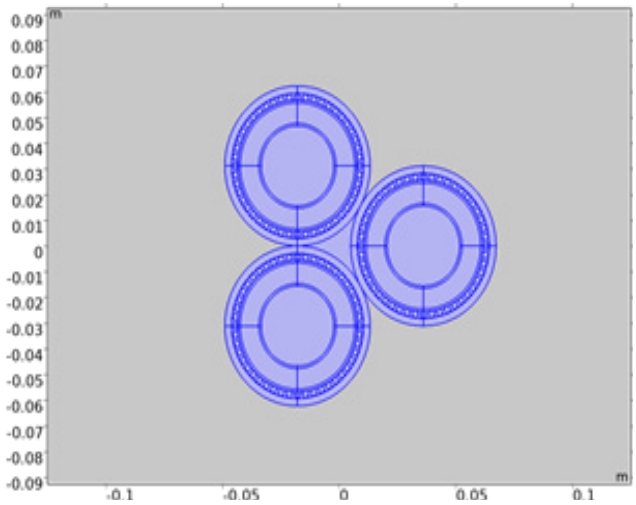


Figure 3. Cable geometry in Trefoil form.

The electrical properties of the materials considered for the study are as shown in the table

Table 7. FEM Simulation Parameters

Physics Interface	Magnetic Fields (mf)
Mesh Type	Physics Controlled, Physics Controlled, unstructured triangular elements
Resolution of Mesh	Extremely fine (minimum element size of 2×10^{-4} m in the conductor and insulation regions)
Mesh Refinement	Applied at the Conductor–insulation, Insulation–sheath interfaces and Air gap/conduit boundaries
Study/Solver Type	Frequency Domain

Under the magnetic field (mf) physics, three terminals for the conductor domains and three for the sheath domains were added. The conductor domains were excited by the Coil current feature of a single conductor. The FEM study was run as a parametric sweep study under frequency-domain analysis by varying the length of the cable from 1km to 20km in 1km steps. The result of the screen voltage for each

parametric sweep is obtained under global evaluation as a derived variable of the results by selecting the respective sheath domain of the cable and using the expression as mf.VCoil.

4. RESULTS AND DISCUSSION

The observed sheath-induced voltage for the case of single-end bonding with all four methods is tabulated in Table 8.

Table 8. Sheath-induced voltage of 19/33kv cable

Sheath-induced Voltage per km (V)			
Analytical	Cymecap	Simulink	FEM
34.3	43.5988	44.51	33.315

From the table, it is observed that the analytical and FEM methods have shown almost the same results. The Simulink and FEM analyses have given similar results.

The results of the sheath-induced voltage by all four methods for the cable length of 1km to 20km are shown in Figure 4.

From Figure 5, it can be observed that the FEM and analytical method produce identical results. Cymecap and Simulink produce identical results.

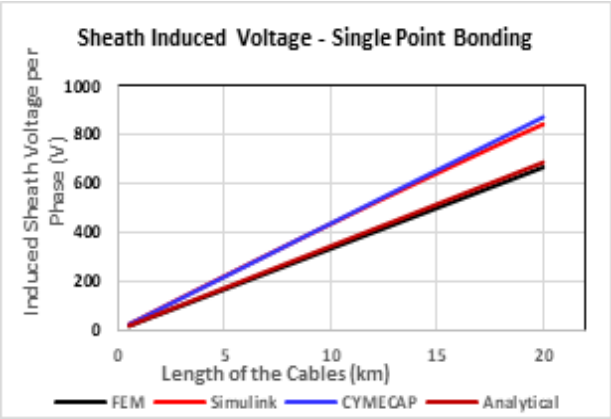


Figure 4. Sheath-induced voltage – Single point bonding.

Further, the other results, such as resistance, capacitance and various losses, obtained from the FEM study and Cymecap are indicated in Table 9.

Table 9. Results of 19/33kV cable by FEM and Cymecap

Measured Parameters		FEM	Cymecap
AC Resistance (Ω/km)		0.047155	0.06168
Phase Losses (W/km)		28692	28970
Cable Capacitance (μF/km)		0.3527	0.351
Dielectric Losses (W/km)		5.2826e-15	0.16027
Screen Losses (W/km)		4497.3	0.0
Charging Current per phase A/km		2.1111	2.10295

From Table 9, it is inferred that in both methods, the capacitance, charging current and conductor losses remain in the same range, indicating the comparability of both methods. However, there is a difference in the estimated sheath voltage between the two. This may be attributed to the various assumptions involved in the IEC 60287-based CYMECAP. This method overestimates the sheath voltage compared to the actual value. The difference in sheath voltage arises mainly due to differences in modelling approaches. The IEC and Simulink methods use simplified equations and lumped parameter representations, which may overestimate the sheath voltage. In contrast, the analytical and FEM approaches consider detailed cable geometry and distributed electromagnetic field effects, resulting in slightly lower values. However, the close agreement among the methods indicates good consistency and reliability of the results. This study also recommends, as a future scope of the study, to validate the applicable methods by assessing various voltage-rated cables and different bonding methods. The correctness of the computation methods can also be verified by some experimental measurements.

5. FAILURE ANALYSIS

The FEM analysis of sheath-induced voltage estimation is also employed for the failure analysis by simulating the power cable and its installation in FEM. One such case study is included in this study. The photograph of the failed cable is shown in Figure 5.

The failure of single-core 630mm

cables arranged in trefoil formation over a 6km route, operating at 440A per phase with single-point bonding, was investigated using FEM. At a length of 5.1km from the grounding point, the open-circuit voltage of the armour is 110V as shown in Figure 6.



Figure 5. View of the failed cable.

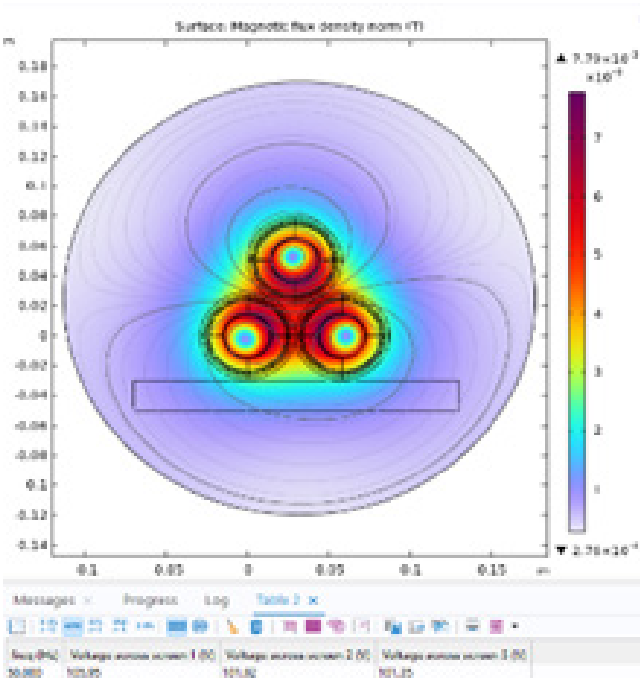


Figure 6. Voltage of armour at 5.1km.

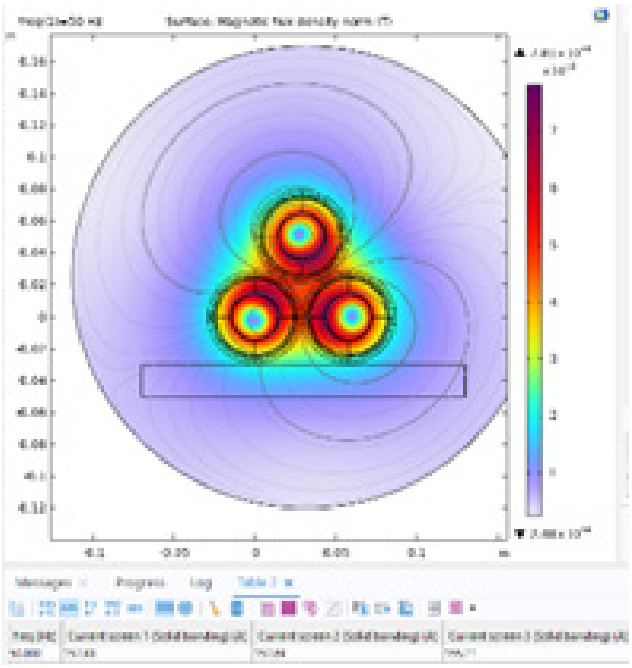


Figure 7. Magnetic field plot with computed armour current, when grounded.

Cable inspection revealed corrosion of the armour due to water ingress, leading to unintended grounding. Grounding of the complete armour would result in a circulating current of approximately 158A as shown in Figure 7. However, due to the standard 90% armour coverage, partial grounding of armour wires carrying elevated voltage led to arcing at water contact points, causing damage to the underlying semiconducting layer and ultimately resulting in cable failure due to partial discharge.

6. CONCLUSION

This study has discussed the importance of estimating the sheath-induced voltage and the various bonding methods adopted for the reduction of sheath-induced voltage. The various methods available for the calculation of sheath-induced voltage, such as analytical, Simulink, IEC 60287-based method and FEM, are elaborated. For one power cable of 19/33kV, the four methods are envisaged for the calculation of sheath-induced voltage. The results obtained are

compared, and the outcomes of the same are listed below:

- Analytical and FEM approaches have resulted in comparable sheath voltage.
- Sheath voltage calculated using Simulink and IEC-based methods is in a similar range. However, they are slightly on the higher side than the analytical and FEM approaches.

The other parameters, such as capacitance, conductor losses, charging current and dielectric losses, are comparable in both IEC and FEM methods.

The variation in sheath voltage arises from simplified assumptions in the IEC and Simulink methods, while analytical and FEM approaches consider the detailed electromagnetic effects. This study proposes a future scope of calculating the sheath voltage for various bonding methods and for different cable ratings in order to validate and arrive at the best method which accurately reflects the sheath-induced voltage. Further field measurements can also be explored in future to validate the calculation methods.

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AUTHOR CONTRIBUTION

Arunjothi: Conceptualization, Methodology and Simulation work, Data Collection, Writing- Original Draft Preparation; Himanshu Misra: Writing-Review and Editing, Supervision and Validation; Bhavani Shanker: Writing-Review and Editing, Supervision and Validation; Meena K P: Data Collection and Investigation, Writing-Review and Editing.