Influence of the High Voltage Underground Cable Systems Design Parameters on Electrical Performances by Finite Element Method

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ABSTRACT

High voltage underground cables are commonly used because they do not cause visual pollution and provide a reliable operating condition for electrical distribution systems. However, the electrical performance of high voltage underground cable systems varies depending on their installation and operating characteristics. Current distribution, screen currents, screen voltages, and losses on conductors in cable systems vary according to the following parameters: number of parallel circuits, the distance between phases, and the distance between parallel circuits, formation, phase sequence, bonding system, harmonic distortion level and loading level of other cables. Those parameters have a crucial effect, especially on parallel cable systems used in the same cable gallery due to the increasing electrical power requirement. This study aims to examine the electrical performance of cable systems with two parallel circuits in flat and trefoil formation, solidly and single-point bonded in different phase sequences for different twelve cases. The influence of cable system design parameters should be evaluated during the design phase due to efficiency, safety, and sustainability performance. In this context, cable systems created according to different design parameters were modeled using the finite element method, and analyses were carried out. Within the scope of the analysis, the current distribution of the conductors, the screen currents, the screen voltages, and losses were calculated. According to the analysis results, the highest screen current in the flat formation is three times the trefoil formation for the solidly bonded and balanced current case. Similarly, for the single-point bonded case, the highest screen voltage in the flat formation is three times the trefoil formation. In this context, when analyzed parameters are evaluated, it is seen that the trefoil formation is superior in many aspects. In addition, different design cases were evaluated in this study.

***Keywords*:** High voltage underground cables, Current distribution in the conductor, Screen currents, Cable losses, Finite Element Method

INTRODUCTION

High voltage underground cables are frequently used in the distribution of electrical energy. The electrical performance of high voltage underground cables is highly affected by the design parameters of the distribution system. According to the design parameters of the cable system, current distributions pass through the cable cores, screen currents and screen voltages, voltage drops, and losses change. Various studies have been carried out regarding the cable system in the literature. These are generally about examining the current distributions in cable systems (Wu, 1984; Lee, 2010; Li et al., 2016), performing thermal investigations (Gouda et al., 2010), examining screen voltages (Ma et al., 2008; Kong et al., 2010; Gouramanis et al., 2011; Shaban et al., 2015), examining losses (Gouramanis et al., 2009; Gouda et al., 2011), examining grounding types (Garnacho et al., 2012; Czapp et al., 2016; M et al., 2017; Mahdipour et al., 2017; Candela et al., 2021), monitoring fault currents and voltages (Dong et al., 2017; Khamlichi et al., 2017; Czapp et al., 2020), examining screen voltage limiters (Khamlichi et al., 2016), examining many parallel cable systems and busbar systems in terms of current distribution and magnetic field (Demirol et al., 2021). In addition, studies evaluating electrical performance in high voltage cable systems depending on the design parameters are limited.

This study examines the electrical performance of cable systems with two parallel circuits in flat and trefoil formation, solidly and single-point bonded in different phase sequences for twelve cases.

Within the analysis's scope, the conductors' current distribution, screen currents, screen voltages, and losses were calculated. The analyses were carried out in the Ansys Electronics Suite program, which is one of the finite element software.

DESIGN PARAMETERS IN HIGH VOLTAGE UNDERGROUND CABLE SYSTEMS

In high voltage underground cable systems, the system design parameters during the installation phase of the cables are of critical importance in terms of efficiency, operational safety and operation quality. Especially in parallel cable systems, which carry the increasing power need, design parameters' importance becomes even more critical. In this context, understanding the effect of design parameters on electrical performance is crucial in the design phase. Therefore, the design parameters of high voltage underground cables can be listed as follows.

- Layout: Flat or trefoil laying on the ground, or over cable trays.
- Phase sequencing: Layout sequencing of L1, L2 and L3 phases.
- Grounding system: Single-point bonding, solidly bonding, cross-bonding.
- Screen voltage limiters: Limitation of screen voltages in single-point bonded systems, usage distances and characteristic features of that equipment.
- Contact resistance between cable screens and earthing bus.
- Cable transposition: Transposing the cable cores in case of current distribution imbalance, how often this operation will be performed, the necessity of the operation, in which system this operation is required.
- Distance between cables: Horizontal or vertical distance between cables laid on the ground or installed in the cable tray.
- The number of parallel circuits used in the cable system: Presence of more than one parallel cable system in the same gallery in systems where high power is carried.
- The loading level of cables: The loading level of the cables in the system, the loading level of the parallel cables or the loading level of the independent cable systems in the same gallery.
- Harmonics: Presence of current or voltage harmonics in cable systems, the effect of harmonics on losses and screen currents.
- Length of cable system: Change of screen voltages and core current distribution according to the change of system length.

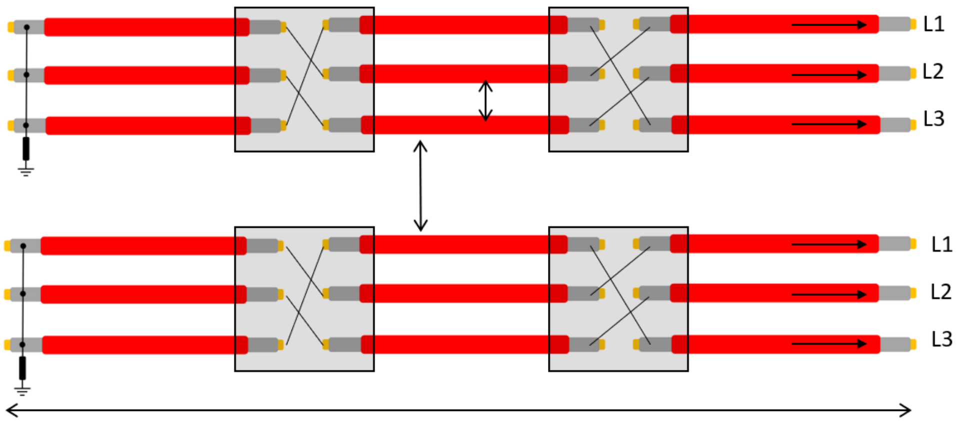

Figure 1. An example of a parallel high voltage cable system

The design parameters mentioned in the cable systems affect the following items in terms of electrical performance.

- Current carrying capacity of cables
- Current distribution imbalance in the cable cores
- Voltage drop and voltage drop imbalance
- Core currents, screen voltages and screen currents passing through the cables in case of a short circuit
- Screen currents and screen voltages

- Screen and core losses

All these parameters should be taken into consideration when designing cable systems. An example cable system is shown in Figure 1.

ANALYSIS METHOD

Theoretical methods are not always sufficient in calculating the electrical parameters of equipment and systems. In these cases, the finite element analysis method, which is one of the numerical calculation methods, can be used. With finite element analyses, simulations are carried out during the design phase of equipment and systems, and optimum design analyses, analyses to increase efficiency, and analyses to meet unique criteria can be carried out. The finite element method can obtain high accuracy and short-time solutions. In finite element analysis, a mesh structure is created on the model geometry, and Maxwell's equations (Eqs. (1) - (4) below) and auxiliary (structural) equations (Eqs. (5) – (7) below) are solved on this mesh structure.

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla . B = 0 \tag{3}$$

$$\nabla . D = \rho \tag{4}$$

$$\mathrm{J} = \sigma E \tag{5}$$

$$\mathrm{B} = \mu H \tag{6}$$

$$\mathrm{D} = \varepsilon E \tag{7}$$

Here, E: Electric field strength (V/m); B: Magnetic flux density (Wb/m^2); H: Magnetic field strength (A/m); J: Current density (A/m^2); D: Electric flux density (C/m^2); ρ: Volume charge density (C/m^3).

Finite element analysis steps are defined with the following items, respectively.

- Determination of analysis type and solver
- Geometric modeling
- Definition of boundary conditions
- Identification of material properties
- Material assignments
- Excitation assignments
- Parameter assignments
- Mesh definitions
- Running the analysis
- Performing calculations
- Examining the results

This study performed finite element analysis with Ansys Electronics Suite finite element analysis software. The analyzes were performed in the workstation with "128 Gb 1866 MHz" memory, "NVIDIA Quadro K2000" graphics card and two "Intel(R) Xenon(R) CPU E5-2683 v3 processors were used.

MODELING STUDIES

It is assumed that the analyzed distribution system consists of two parallel systems at 36 kV operating voltage, and its length is one kilometer. The single-line diagram of the system is shown in Figure 2-a. First, a geometric model was created according to the cable dimensions in the finite element analysis program. The geometric model created and the cable sections on this model are shown in Figure 2-b. The real cable cross-section is shown in Figure 2-c. The cable model for the analysis was determined as A2XSY 1 × 400/35. A load resistor to pass 500 A is connected to the end of the distribution line. Each cable core and screen model is defined as a winding in the analysis program. Winding connections have been created with the external circuit for the models. The excitation circuit created for an example model is shown in Figure 3. The mesh structure created on an example model is shown in Figure 4. Approximately 9000 trihedral mesh elements were created for each analysis, and the analysis of each case took approximately two minutes. The mesh model was created with an energy error of 0.85%, and a total of 60 ms analysis was performed with 0.5 ms time steps.

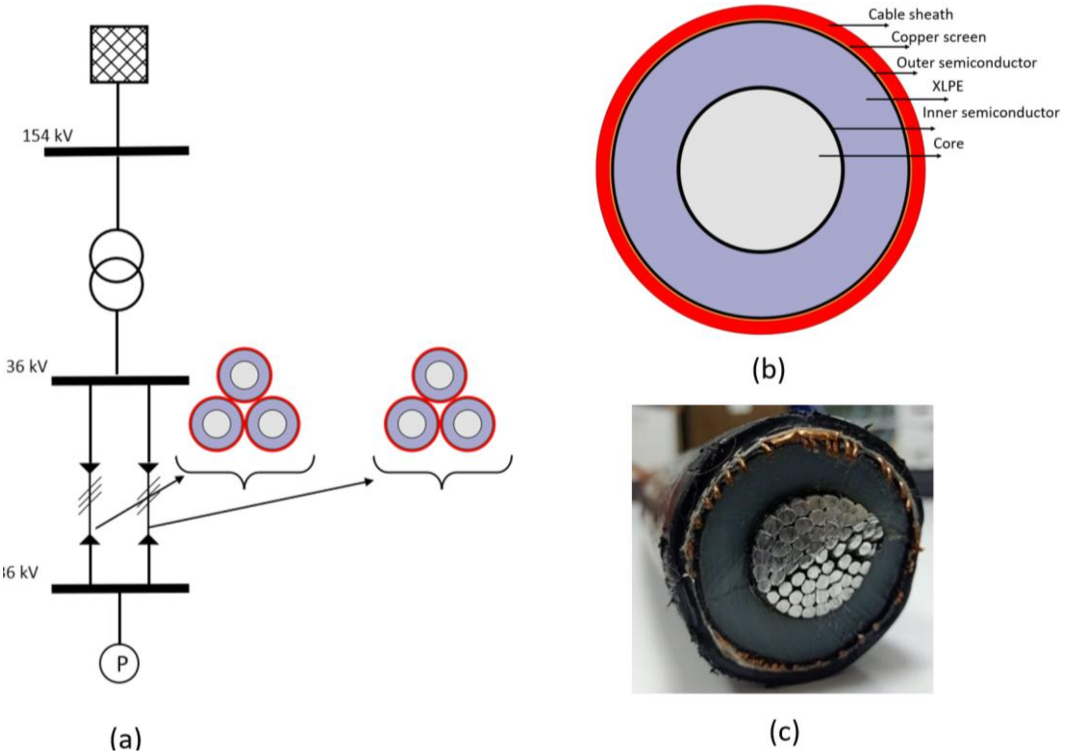

Figure 2. Single line diagram of the analyzed system (b) Cable model created in the finite element program (c) Real cable model

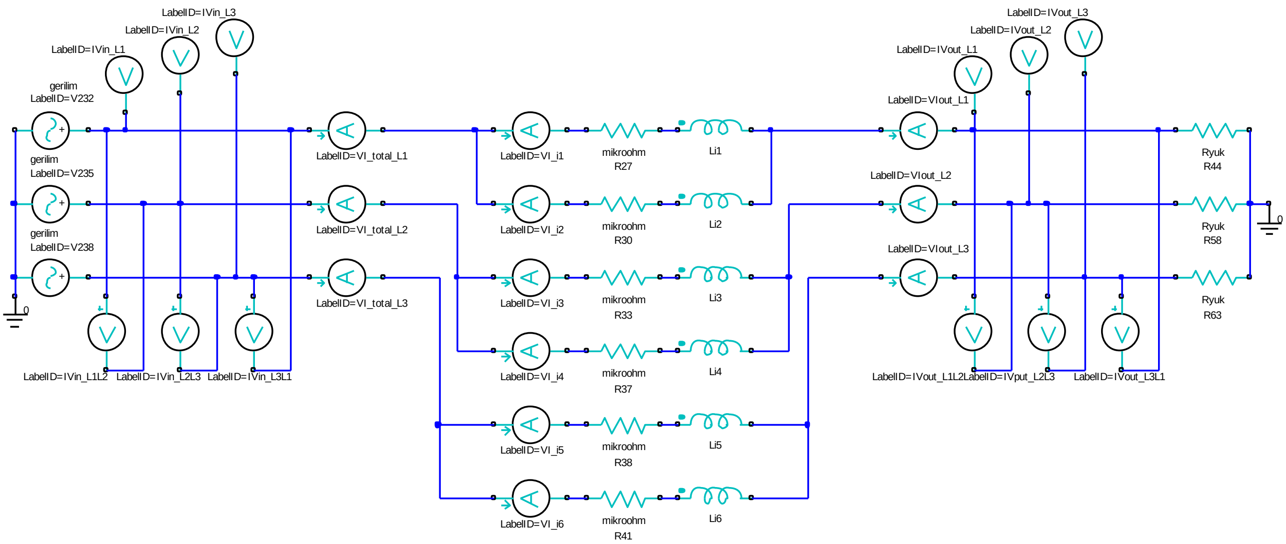

Figure 3. Excitation circuit for analysis

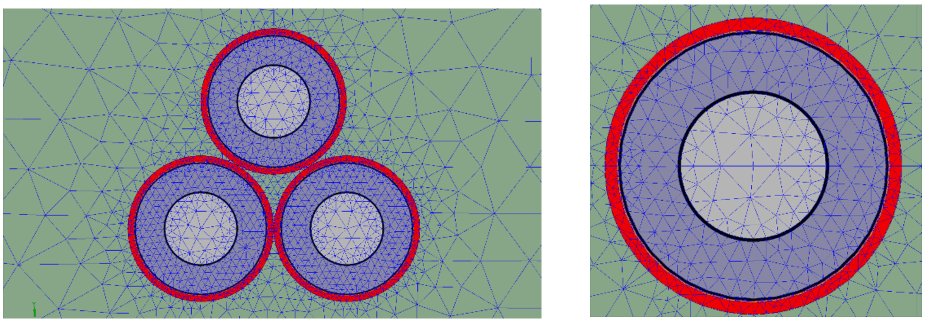

Figure 4. Finite element mesh structure created in the analysis

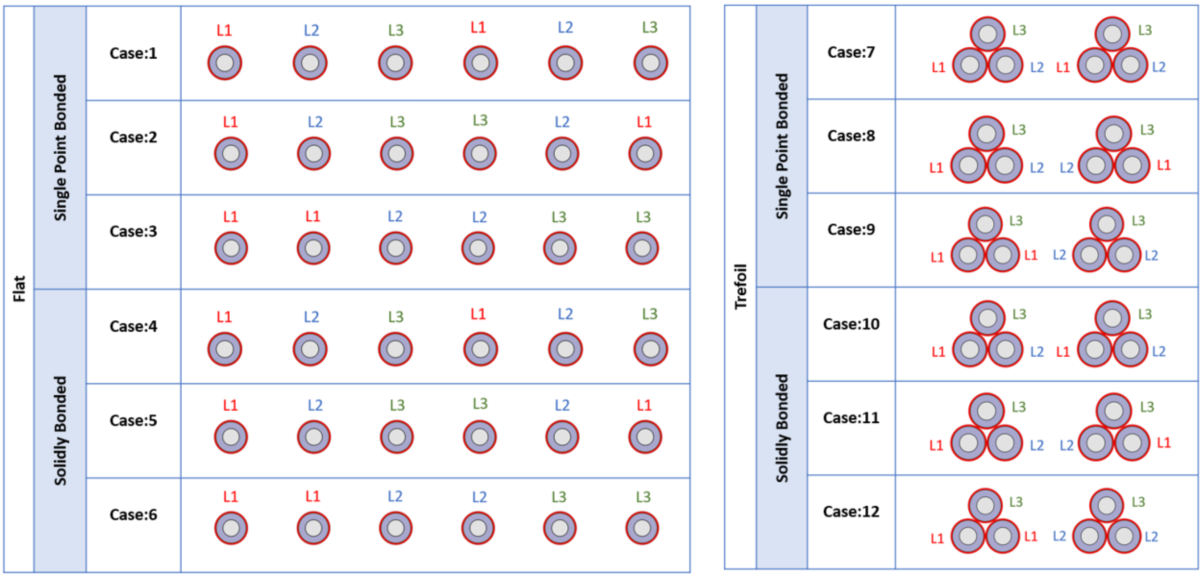

Figure 5. Analysis models

A total of 12 different analysis models were created. Six of these models are in flat layouts, and six of them are in trefoil layouts. Different phase sequences and grounding types have been evaluated in the models. All the models created are illustrated in Figure 5. Core and screen temperatures were determined as 20 degrees in the analysis. In this study, thermal analysis was not carried out. In this study, the effect of different design parameters on electrical performance was evaluated.

EXAMINATION OF ANAYSIS RESULTS

As a result of the analyzes carried out on the models examined, current distributions in the cable cores, screen currents, screen voltages, core losses, screen losses and total losses were examined.

Current Distributions

The current distributions found as a result of the analyses performed are shown in Figure 6. The first six cases represent flat layouts, and the last six cases represent trefoil layouts. In addition, the first three cases represent single-side bonded models, and the last three cases represent solidly bonded models. Model numbers are shown on the X-axis of the charts. The columns rising through each model number represent one cable from left to right. In these columns, the red-colored ones represent the L1 phase, the blue-colored ones represent the L2 phase, and the green-colored ones represent the L3 phase. The Y-axis of the graphs represents the current.

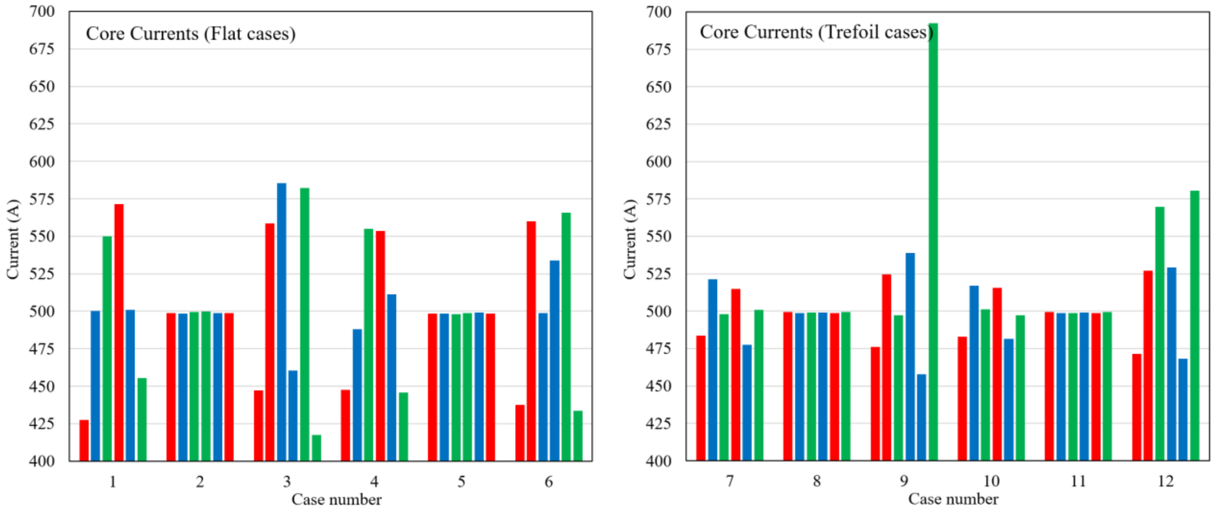

Figure 6. Core currents

The current distributions vary significantly according to the phase sequence in flat cases. It is seen that there is a current distribution imbalance that will cause problems in models other than the models that create a balanced current distribution. In the trefoil arrangement, it is seen that the current distributions are more uniform, except for one situation. In unbalanced loaded cables, overheating and related failures and fires may occur due to the current-carrying capacity being exceeded. This situation should not be ignored. Especially in systems with many parallel circuits, the phase sequences of the cables should not be mixed, and they should proceed in the same order throughout the gallery. It is seen that there is no need for transposition when the correct phase sequence is used.

Screen Currents and Screen Voltages

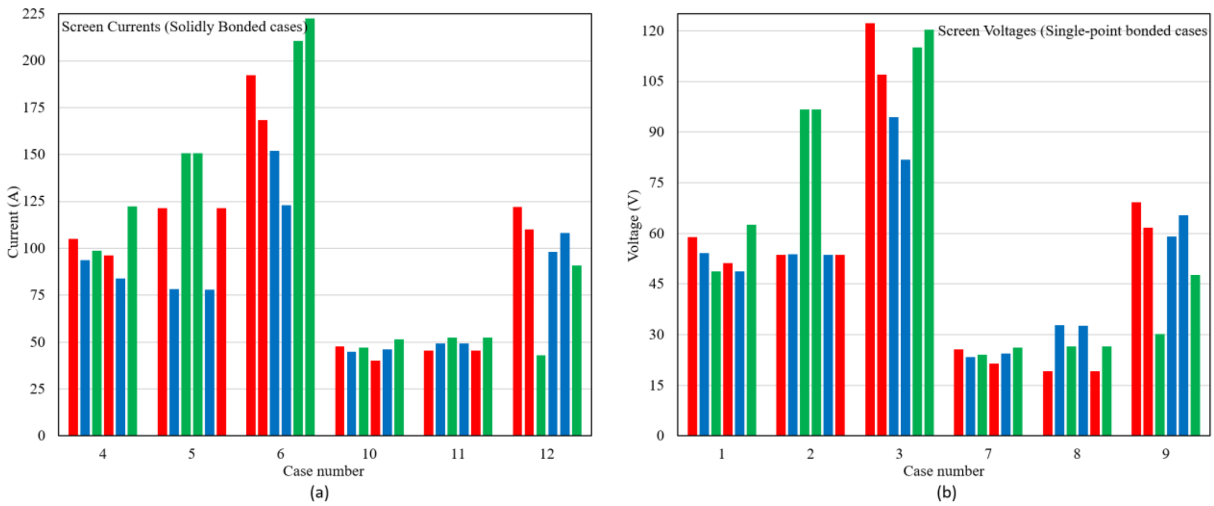

Figure 7. (a) Screen currents (b) voltages

Screen currents in single-side bonded systems are shown in Figure 7-a, and screen voltages in solidly bonded systems are shown in Figure 7-b. The maximum screen current is 150 A in balanced core currents case for flat layout and 52 A in trefoil layout. It is seen that the screen currents formed in the trefoil layout are significantly less. Screen currents are independent of cable length. In the worst case, the maximum screen current goes up to 225 A. The screen voltages that occur when single-point bonded cases are shown for all cables. The maximum screen voltage is 95 V in balanced core currents case for flat layout and 32 V in trefoil layout. Screen voltages are directly proportional to cable length and core current. In the worst setup, the maximum screen current goes up to 122 V. The limit value for the screen voltage can be accepted as 65 V for general applications. Instead of using a screen voltage limiter in flat layouts, trefoil layouts can be used to stay below the limit value.

Losses

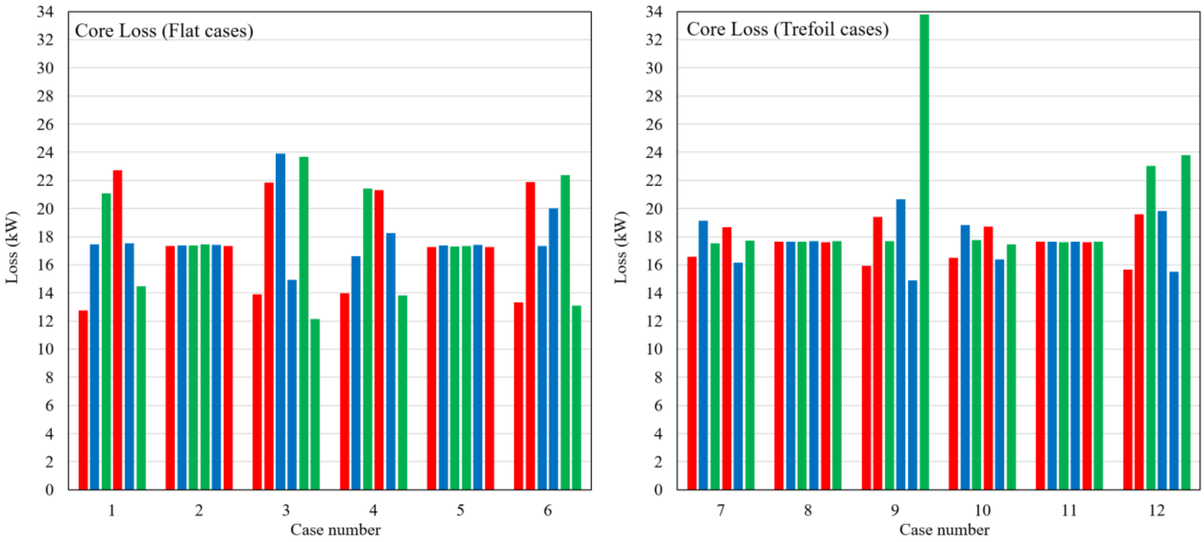

Figure 8. Core losses

Core losses for all cases are shown in Figure 8. It is seen that the losses are different in cases where the current distribution is unbalanced. Cores with high losses will overheat, and cable life will be reduced. In addition, the risk of structural defects in cable terminals and cable joints will increase due to heating, and accordingly, partial discharge and, ultimately, failure may occur (Alboyacı et al., 2022). This situation should be taken into consideration in system design.

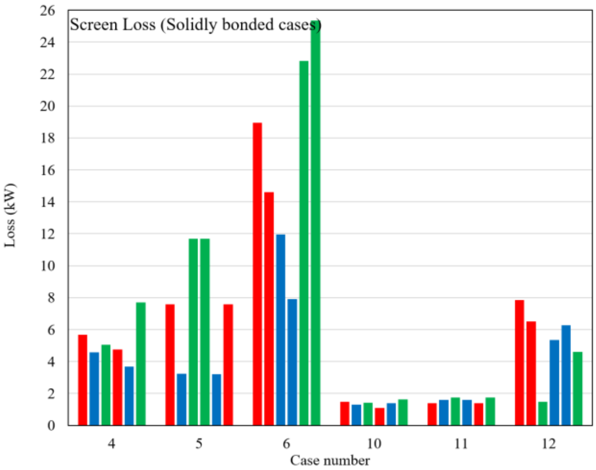

Figure 9. Screen losses

The screen losses for solidly-bonded cases are shown in Figure 9. It is seen that the screen losses in trefoil layouts are much less than in flat layouts. Maximum screen loss is 11.8 kW in balanced core currents case for flat layout and 1.8 kW in trefoil layout. In the worst setup, the maximum screen loss is up to 25 kW. High screen losses will cause overheating on the cable surface and reduce the cable life, and problems will occur in the joints and cable terminals.

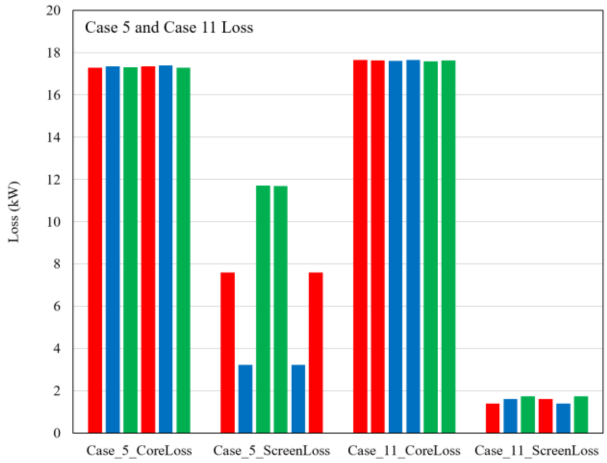

Figure 20. Losses for Case-5 and Case-11

For solidly-bonded bonded cases, the flat layout with the most uniform current distribution is case-5, and the trefoil layout is case-11. Figure 10 shows the core and screen losses that occur in these situations. The maximum screen loss in cables in flat layout is 70% of the core loss. The maximum screen loss in cables in trefoil layout is 10% of the core loss. It is seen that the screen losses are significantly higher even in the balanced current case for flat layout.

Total losses for all cases are shown in Figure 11. There is a 33.75 kW difference between flat and trefoil models, which are solidly-bonded cases and have the most uniform current distribution (case-5 and case-11). This difference corresponds to annual energy of 295650 kWh. Considering that this value occurs on a line only one km long and the number of energy distribution lines is considered, it is seen that there is a severe loss value. Instead of a solidly-bonded system, a single-side bonded system can also be used, but in this case, the costs of the screen voltage limiters must also be taken into account.

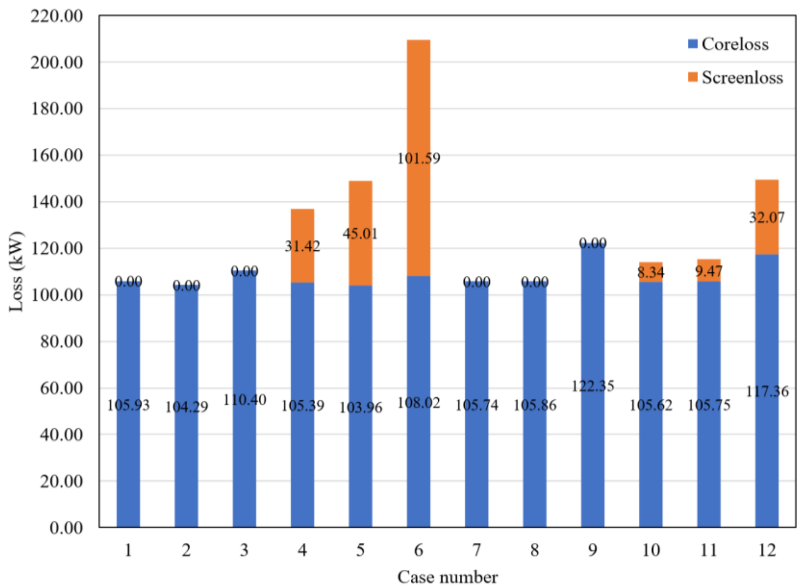

Figure 31. Total losses

CONCLUSION

This study investigated the electrical performance of 12 different cable systems using by finite element analysis method. It is seen that trefoil systems are better regarding screen losses and current distribution in solidly bonded systems. It is seen that trefoil systems are better in screen voltages in systems single-point bonded cases. In a single-point bonded flat system, it is possible to stay below the screen voltage limit values by using a trefoil system instead of cross-bonding or using SVL. In a solidly bonded flat system, screen losses, costs, and possible failure points can be reduced by using a trefoil system instead of screen crossing. The soil channel area can be reduced by using a trefoil system instead of a flat system. Future studies are aimed at making coupling thermal analyses, examining harmonic loading situations, and examining screen voltage limiters. The results of that study are essential for high voltage underground cable system designers.

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