Capacity of High-Voltage Cable Line with Tightly Mounted Shielding Loop

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***Abstract*—The paper deals with a high-voltage three-phase cable line with tightly mounted shielding loop used for magnetic field mitigation. The research is focused on the impact of the shielding loop on a cable line capacity. To calculate the cable line capacity in the non-shielded case, we use IEEE 835-1994 "IEEE Standard Power Cable Ampacity Tables". To study the case when the shielding loop is mounted tightly to the cable line, we carry out a numerical simulation of a thermal field. The simulation is carried out using a finite-element method. Then we solve an inverse problem and evaluate a current rating when the temperature of cable conductors does not exceed the allowable level of 90°C. This makes it possible to develop the technique to evaluate the capacity of the cable line with tightly mounted shielding loop. We use this technique to assess the reduction of cable line capacity caused by the shielding loop usage. To study the capacity reduction, we vary the cross-section of cable conductors and the soil thermal resistivity.**

***Keywords*—IEEE 835-1994, cable line, capacity, current rating, thermal field, shielding, passive loop**

I. INTRODUCTION

The modern urban power grids involve underground high-voltage cable lines. The right-of-way (ROW) of cable line is much smaller than the ROW of overhead line. For example, according to regulations [1] the ROW is 40 m for 110 kV overhead lines and 2 m for 110 kV cable lines in Ukraine. So the lack and the high price of urban lands make cable lines preferable when the power line route crosses the residential area.

Another advantage of the cable line is the ability to meet modern regulatory requirements concerning the level of power frequency magnetic field. The problem of the long-term effect of power frequency magnetic field on human health is studied for two last decades, particularly within "The International EMF Project" conducted by the World Health Organization. The values of maximum permissible levels (so-called reference levels) of the magnetic field are regulated by national standards. In different countries they vary from tenths to tens of microtesla [2]. For example, in Ukraine the reference level of power frequency magnetic field is 0.5 μT for living spaces and 10 μT for residential areas [1]. As opposed to 110 kV overhead lines, the high-voltage cable lines allow meeting the reference level 0.5 μT in all residential buildings nearby. At the same time, the reference level 10 μT for residential areas could be several times exceeded directly above the cable line.

Traditionally, electromagnetic [3]-[5] and magnetic shields [4]-[7] are used to mitigate the cable line magnetic field. The most technologically advanced is the so-called "High Magnetic Coupling Passive Loop" (HMCPL) proposed in [8]-[9]. It uses special ferromagnetic cores providing relatively high efficiency of magnetic field mitigation. A shielding loop similar to HMCPL is represented in the Ukrainian regulations "Design of cable lines with voltage up to 330 kV" [10]. Fig. 1 shows the sketch of this shielding loop. In contrast to HMCPL, it has only one loop and less number of ferromagnetic cores. However the efficiency of magnetic field mitigation by such shielding loop is close to the HMCPL efficiency.

The common disadvantage of HMCPL and the shielding loop from Fig. 1 is the close location of shield cables to the cable line. It leads to an extra heating of the cable line and to the reduction of its capacity. We focus on the study of capacity reduction caused by the shielding loop. To assess this reduction, two values are to be known. The first one is the cable line capacity in the non-shielded case, namely the capacity of the cable line with open-circuited shields of cables. We use IEEE 835-1994 "IEEE Standard Power Cable Ampacity Tables" [11] to calculate it. The second one is the capacity of the cable line with tightly mounted shielding loop. However there are no known quantitative assessments of capacity when the shielding loop is mounted. And neither of known standards allows evaluating it.

The goal of the paper is to develop the technique to evaluate the capacity of the cable line with tightly mounted shielding loop.

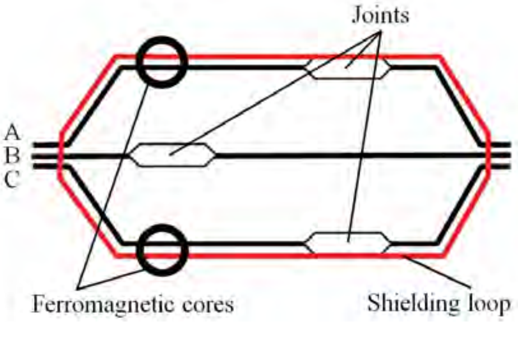

Fig. 1. Sketch of shielding loop with extra ferromagnetic cores mounted on cable line

II. IEEE STANDARD IMPLEMENTATION TO CALCULATE CABLE LINE CAPACITY

The modern high-voltage cable line consists of three single-core cross-linked polyethylene (XLPE) insulated power cables. Fig. 2 shows main structural elements of the power cable, namely conductor, insulation and shield (a.k.a. shield of cable). We analyze the following type of cable: 115-138 kV single aluminum conductor with concentric strand, unfilled, XLPE insulation. Using the classification provided by Intro-1 of IEEE 835-1994 [11], we find that the power cable under study has Type 4. The parameters of the cable are the following:

- cable insulation thickness is 800 mils (20.32 mm) according to Intro-6;
- cable insulation resistivity is 3.5 K·m/W according to Intro-4;
- cable shield resistance is 69 μΩ/ft (0.226 Ω/mm) according to Intro-5;
- jacket thickness is 140 mils (3.56 mm) according to Intro-8;
- jacket resistivity is 6.0 K·m/W according to Intro-4.

Geometries of cable line represented in Intro-9 of IEEE 835-1994 [11] are as follows: duct banks, direct buried, buried ducts, buried pipes, and cables in air. We deal with direct buried flat cable line. As well Intro-9 recommends the depth of buried cables that equals d=36 inches (914.4 mm). According to Intro-8 the cable spacing is s=12 inches (304.8 mm).

The earthing of shields of cables is required. An Intro-4 of IEEE 835-1994 [11] discusses two cases for spaced cables. And we examine both of them: short- and open-circuited shields. In open-circuited case the shields of cables are electrically bonded together and earthed at single point. So the cable line with open-circuited shields has maximum capacity. In short-circuited case the shields of cables are electrically bonded together and earthed at two points, at the beginning and at the end of cable line. The thermal effect of currents induced in short-circuited shields leads to the capacity reduction.

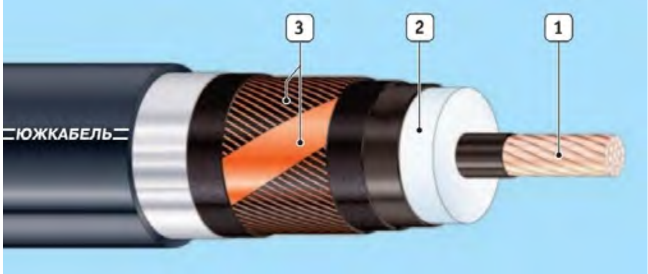

Fig. 2. Power cable
(1 – conductor, 2 – XLPE insulation, 3 – shield)

It is noted in Intro-3 of IEEE 835-1994 [11] that the correct knowledge of soil thermal resistivity is paramount in establishing the correct capacity for buried cable line. So we vary the soil thermal resistivity ρ_{Tg} from 0.6 K·m/W to 1.2 K·m/W with the step of 0.1 K·m/W. The ambient temperature is 25°C according to Intro-4.

We assume that load factor is 100% (see Intro-2) and the conductor temperature reaches the allowable level of 90°C (see Intro-5). And we examine the cable line capacity for different sizes of conductor cross-section.

Using data from page 1283 of IEEE 835-1994 [11], we find the cable line capacity when ρ_{Tg} takes on the values 0.6, 0.9, and 1.2 K·m/W. Table I shows the corresponding values for open-circuited and short-circuited cases. Based on them, we build Newton interpolation polynomials to find the capacity I for other ρ_{Tg} depending on the cross-section of cable conductor:

$$I = 1066 - 511.7 \cdot \rho_{Tg} + 138.9 \cdot \rho_{Tg}^2 \quad \text{for 1000 kcmil,} \tag{1}$$

$$I = 1211 - 591.7 \cdot \rho_{Tg} + 161.1 \cdot \rho_{Tg}^2 \quad \text{for 1250 kcmil,} \tag{2}$$

$$I = 1348 - 680 \cdot \rho_{Tg} + 188.9 \cdot \rho_{Tg}^2 \quad \text{for 1500 kcmil,} \tag{3}$$

when shields of cables are open-circuited;

$$I = 909 - 503.3 \cdot \rho_{Tg} + 144.4 \cdot \rho_{Tg}^2 \quad \text{for 1000 kcmil,} \tag{4}$$

$$I = 1002 - 581.7 \cdot \rho_{Tg} + 172.2 \cdot \rho_{Tg}^2 \quad \text{for 1250 kcmil,} \tag{5}$$

$$I = 1078 - 645 \cdot \rho_{Tg} + 194.4 \cdot \rho_{Tg}^2 \quad \text{for 1500 kcmil,} \tag{6}$$

when shields of cables are short-circuited.

TABLE I. CABLE LINE CAPACITY CALCULETED BY IEEE 835-1994

Conductor size, kcmil (mm^2)	**Type of cable line**	***I*, A**						
		ρ_{Tg}=0.6 K·m/W	***ρ_{Tg}=0.7 K·m/W***	***ρ_{Tg}=0.8 K·m/W***	***ρ_{Tg}=0.9 K·m/W***	***ρ_{Tg}=1.0 K·m/W***	***ρ_{Tg}=1.1 K·m/W***	***ρ_{Tg}=1.2 K·m/W***
1000 (506.7)	open-circuited	809	775	745	718	693	671	652
	short-circuited	659	627	598	573	550	530	513
1250 (633.4)	open-circuited	914	875	840	809	780	755	733
	short-circuited	715	679	646	618	592	570	552
1500 (760.1)	open-circuited	1008	964	924	889	856	828	804
	short-circuited	761	721	686	655	627	603	584

Using the polynomials, we tabulate the cable line capacity when ρ_{Tg} takes on the values 0.7, 0.8, 1.0, 1.1 K·m/W and supplement Table I.

As expected the cable line with open-circuited shields has higher capacity compared to a short-circuited case, since there is no thermal effect caused by shield currents. As well Table I shows the monotonic capacity decrease with the increase in soil thermal resistivity ρ_{Tg} regardless of the type of cable line.

III. CAPACITY EVALUATION VIA CABLE LINE THERMAL FIELD SIMULATION

To evaluate the capacity of the cable line with tightly mounted shielding loop, we conventionally divide the procedure into two steps. At first, we take some value of the cable line current rating and find a thermal field distribution around the cable line and the shielding loop using the finite element model. This gives the temperature of cable conductor. If it is bigger than the allowable level of 90°C, we repeat the numerical simulation with less current rating. Otherwise we increase the current rating for the next simulation. Repeating the cycle, we find the cable line capacity by successive approximations.

We assume the thermal field to be plane-parallel in the shielding region. Therefore we solve the problem in a two-dimensional formulation. Fig. 3 shows the computational domain that includes cross-sections of the cable line and the shielding loop, and the soil.

Since the cable line runs in a steady-state, the temperature θ does not change over time and it is a function of coordinates. Its distribution $\theta=\theta(x,y)$ obeys the stationary heat equation:

$$\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}=-\rho\cdot q\,, \tag{7}$$

where ρ is the thermal resistivity of the subdomain for which the equation is written, K·m/W; q is the thermal energy density, W/m^3.

The released thermal energy in the current-conducting subdomain (the conductor and the shield of power cable, the conductor of shielding loop) is $q_k=(I_k/S_k)^2/\sigma_k$, where k is the index of subdomain; I_k is the RMS current in the corresponding conductor, A; S_k is the conductor cross-section, m^2; σ_k is the electrical conductivity, S/m.

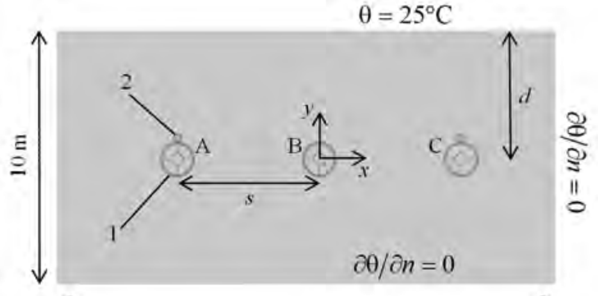

Fig. 3. Computational domain of cable line thermal field (1 – power cable, 2 – shielding loop)

When we simulate the thermal field of the cable line with open-circuited shields, the conductors of power cables are the only thermal sources. The currents in cable shields provide an extra heating in the short-circuited case. These currents are coupled with conductor currents and calculated according to [12]. By analogy the current in the shielding loop provide an extra heating of the cable line. We assume that the loop current is equal to the β-component obtained as a result of the Clarke transformation of currents of short-circuited cable shields. This allows equalizing the magnetic field shielding efficiencies in the short-circuited case and when the shielding loop is used.

The shield of cable is made of copper. Using the value of the cable shield resistance from Intro-5 [11], we find that the cross-section of the shield is 77.7 mm^2. Evaluating the thermal effect of the shielding loop, we assume that it is made from the same material and it has the same cross-section. The thickness of loop insulation is 3.5 mm.

Equation (7) is written for each subdomain of the computational domain shown in Fig. 3: conductor, insulation, and protective coating of power cables, conductor and insulation of shield cable, as well as the soil.

At boundaries of subdomains with different thermophysical properties, the distribution $\theta=\theta(x,y)$ meets the condition of continuity of temperature

$$\theta_l=\theta_r\,, \tag{8}$$

and the condition of continuity of heat flux

$$\frac{1}{\rho_l}\frac{\partial\theta_l}{\partial n}=\frac{1}{\rho_r}\frac{\partial\theta_r}{\partial n}, \tag{9}$$

where θ_l and θ_r are the temperatures “to the left” and “to the right” of the boundary, respectively; ρ_l and ρ_r are the thermal resistivities of the corresponding subdomains; n is the normal vector.

Based on [13], we use a rectangular computational domain with sides of 10 m and 20 m. The top boundary of computational domain corresponds to the ground level. According to [11] and [14], we set the constant temperature condition θ=25°C at the top boundary. We use the thermal insulation condition $\partial\theta/\partial n=0$ on the bottom and side boundaries, where n is the normal vector to the boundary.

We apply a mapped meshing in subdomains of insulation and protective coating of power cables, and triangular meshing in remaining subdomains. The minimum mesh size is 2.5 mm.

All simulations we perform using *Heat Transfer in Solids* computation module of the *COMSOL Multiphysics* software.

The accuracy of the numerical solution was tested by comparison with solutions obtained at the double increase of computational domain and by using denser mesh. During these tests the change of temperature in control points, particularly the temperature of the cable conductor, lay within 0.5%.

The developed finite-element model gives the thermal field for the preassigned currents in cable conductors. To solve the inverse problem and to find the capacity when the cable conductor temperature is 90°C, we carry out a number of simulations. The method of successive approximations allows evaluating the capacity of the cable line with tightly mounted shielding loop. We evaluate the capacity for different values of the conductor size and the soil thermal resistivity. Table II shows the results in lines titled “with shielding loop”. As well we use the same technique to examine the cable lines with short- and open-circuited shields of cables.

IV. RESULTS AND DISCUSSION

This paper presents the technique of evaluation of the capacity of the cable line with tightly mounted shielding loop. It is based on the finite-element model of the cable line thermal field and on the method of successive approximations. We tabulate the capacity for the soil thermal resistivity ρ_{Tg} from 0.6 K·m/W to 1.2 K·m/W with the step of 0.1 K·m/W and for three sizes of cable conductor (see Table II). The capacity for other values of soil thermal resistivity and conductor size can be found by linear interpolation.

Table I shows the capacity of cable lines with short- and open-circuited shields of cables calculated by IEEE 835-1994 standard. Table II shows the results for the same ones evaluated by the developed technique. The difference between results lies within 0.8÷1.6% in case of 1000 kcmil (506.7 mm^2) conductor size, within 1.2÷2.3% in case of 1250 kcmil (633.4 mm^2) conductor, and within 1.7÷3.3% in case of 1500 kcmil (760.1 mm^2) conductor. We attribute this with the finiteness of the computational domain used in the numerical simulation.

So the developed technique allows evaluating the capacity of the high-voltage cable line with tightly mounted shielding loop with 0.8÷3.3% error.

The tightly mounted shielding loop mitigates the cable line magnetic field, but causes the reduction of the cable line capacity. Table II shows the following capacity reduction:

- by 10.7÷13.7% in case of 1000 kcmil (506.7 mm^2) conductor size;
- by 16.4÷19.4% in case of 1250 kcmil (633.4 mm^2) conductor size;
- by 22.0÷24.0% in case of 1500 kcmil (760.1 mm^2) conductor size.

However Table II shows that the capacity reduction caused by the tightly mounted shielding loop is less as compared with short-circuited shields of cables. Namely, the capacity is 6.2÷11.6% higher when the magnetic field is mitigated by the shielding loop comparably to the capacity of cable line with short-circuited shields of cables.

Further research involves the development of analytical expressions for evaluating the capacity of the cable line with tightly mounted shielding loop.

ACKNOWLEDGMENT

This work was supported by IEEE Standards Education Student Grant.

TABLE II. CABLE LINE CAPACITY EVALUATED VIA NUMERICAL SIMULATION

Conductor size, kcmil (mm^2)	**Type of cable line**	***I*, A**						
		ρ_{Tg}=0.6 K·m/W	ρ_{Tg}=0.7 K·m/W	ρ_{Tg}=0.8 K·m/W	ρ_{Tg}=0.9 K·m/W	ρ_{Tg}=1.0 K·m/W	ρ_{Tg}=1.1 K·m/W	ρ_{Tg}=1.2 K·m/W
1000 (506.7)	open-circuited	820	785	755	729	704	682	662
	short-circuited	665	632	605	579	557	538	520
	with shielding loop	732	696	665	638	614	591	571
1250 (633.4)	open-circuited	932	892	857	826	798	772	749
	short-circuited	725	688	656	628	603	581	562
	with shielding loop	779	739	704	674	648	625	604
1500 (760.1)	open-circuited	1036	990	950	915	883	855	829
	short-circuited	774	733	698	668	641	617	596
	with shielding loop	808	767	732	702	675	651	630

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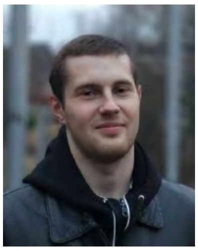

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