Comparison of Finite Element Analysis to IEC-60287 for Predicting Underground Cable Ampacity

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***Abstract*—The ampacity of underground power cable lines is limited by the maximal allowable temperature of the conductor. Normally the IEC 60287 standard is used for steady state ampacity calculation. The standard employs the concept of thermal equivalent circuit. An alternative to the standard is the finite element (FEA) simulation of electromagnetic and thermal field around cables.**

This paper presents a systematic comparison of IEC calculation vs. FEA simulation for various cable line layout. The simulation includes coupled AC magnetic formulation with attached circuit and heat transfer formulation. The comparison shows that IEC and FEA gives almost same results with single-core cables laid in trefoil or flat formations. In case of cable duct bank with a number of lines, FEA shows a stronger electromagnetic and thermal interference than predicted by the IEC 60287 standard.

***Index Terms*-- Finite element analysis, multiphysics analysis, cable insulation, cable shielding, grounding.**

INTRODUCTION

The ampacity of underground power cable lines is limited by the maximal allowable temperature of the conductor. Normally the IEC 60287 standard [1] is used for static ampacity calculation. The standard employs the concept of thermal equivalent circuit [2].

When multiple cable lines are arranged close together, it is necessary to consider their electromagnetic and thermal interaction. The IEC standard evaluates the electromagnetic interaction of individual cable based on simplified models solved analytically [3]. The theoretical model is complemented by large amount of empirical data, mostly in a form of correction factors.

A promising alternative to the IEC 60287 standard is numerical simulation of two-dimensional electromagnetic and thermal fields. This approach is called perspective in the IEC report [5], and was developed by many authors, for example, [6] and [7], just to mention only a few recent papers. Some authors used FEA only for heat transfer simulation.

The more comprehensive approach is multiphysics simulation that combines at least two analyses: AC magnetics and thermal conductivity analysis [8], [9]. The former analysis evaluates the current density distribution over the cross section of conductor, shield and metallic armor taking into account the skin and proximity effects. The electromagnetic field model also includes an electric circuit to account bonding of shields and armor of individual cables. The found distribution of the Ohmic losses is then transferred to the heat transfer analysis for calculating the steady state or transient temperature field with the appropriate boundary conditions.

PROBLEM FORMULATION

The thermal model of IEC 60287 uses the ladder-type thermal equivalent circuit:

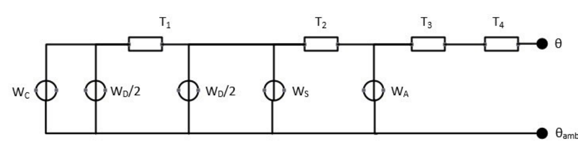

Fig. 1. Ladder-type thermal equivalent circuit

Where W_C, W_D, W_S, W_A – are losses per unit length in the conductor, insulation, shield and armor respectively, $T_1,\ldots,T_3$ – thermal resistances between metallic elements of the cable, and the T_4 is a thermal resistance between the cable surface and the ambient. Thermal resistances are assigned only to dielectric layers, these for the conductors assumed to be zero. The thermal model of IEC 60287 also considers the mutual thermal influence of cables to each other by superposition of temperature fields. To do that it is required for each pair of cables 1 and 2 to be able to calculate the temperature excess from cable 2 at the location of the cable 1, and vice versa.

The electromagnetic model implemented in the standard IEC 60287 is based in particular on A.H.M. Arnold's works [3]. He developed the closed form approximation of the exact solution, which was previously obtained in the form of an infinite series, whose members include Bessel functions of different orders.

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It can be assumed that the electromagnetic and thermal models of IEC 60287 accurately describe the single-circuit cable line, but may lead to insufficiently accurate result for a duct-bank with a number of closely spaced lines. To verify this hypothesis we performed a series of ampacity calculations with two methods: the IEC 60287 standard (implemented by the CymCap software [4]), and coupled AC magnetic and thermal FEA simulation (using the QuickField software [10]).

As the objects of the comparative study, we selected:

a. The single three-phase underground line of single-core cables in both flat and trefoil formations. Here we expect a good match of temperatures calculated by two techniques. At this stage, our goal is a fine-tuning of the FEA model.

b. The concrete cable duct bank with 4x10 plastic tubes for 10 high-voltage lines. The electromagnetic and thermal interaction of 30 individual cables is difficult to assess and significantly affects the temperature of individual cable.

Coupled FEA Technique

In this work, we use two successive 2D FEA analyses. The first one uses the AC magnetics formulation. Its goal is obtaining distribution of losses over cross section of all metallic parts of cables. The second analysis employs the steady-state heat transfer formulation. It consumes the losses calculated by previous step. Both electromagnetic and thermal analyses share the same finite element mesh, but the latest does not include an air above the earth surface. The modelled area includes the cross sections of all cables, the duct bank, other possible concrete and metallic parts, backfill, and a considerable part of surrounding area.

The AC magnetic analysis is performed at utility frequency with attached electric circuit of connected metallic sheaths (shield and armor). An example of grounding circuit is shown in Fig. 2. When needed, the model is able to support saturation of steel sheaths. We made all calculation with symmetric load of each line, but it is not due to limitation of the model: asymmetric load can be handled as well.

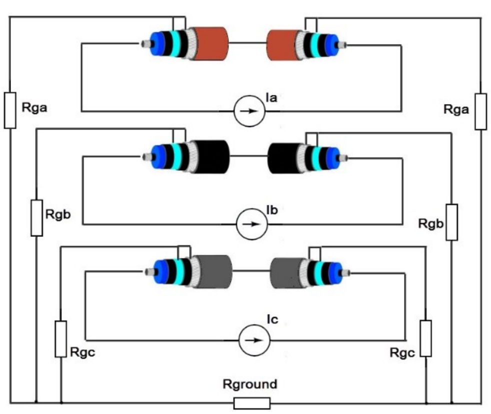

Fig. 2. Circuit of screen and armor bonding at two sides

The heat transfer model deals with heat conduction. The convective and radiative heat transfer can be only taken into account as a boundary condition. An important problem is correct modelling of the convective heat transfer from the cable in a pipe. In this paper we have substituted the convection between the outer surface of the cable and the inner surface of the pipe with thermal conduction in the medium with increased thermal conductivity. The question remains how to choose the correct equivalent thermal conductivity of the medium inside the pipe.

Single Underground Line

The underground three-phase line from single core cables 110 kV is considered. To be more general we choose a cable with two metal sheaths: a screen and an armor. Each cable (Fig. 3) has a round copper conductor of 630 mm^2, XPLE insulation, the copper wire screen 210 mm^2, and aluminum strip armor of 3.3 mm thick.

The screen bonding is encoded in the model by the coupled electrical circuit. Two variants of cable screen bonding are considered: at one end and at both ends of the line.

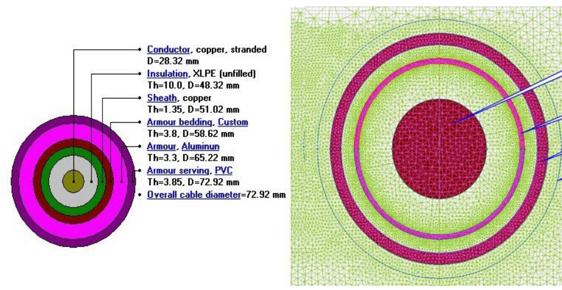

Fig. 3. Cable crosse-section and its FEA discretization

With both calculation methods were compared the final temperature of conductor, screen and armor as well as some intermediate data such as losses and thermal resistances. For example, in Fig. 4 the Joule heat density of the most loaded cable is shown (sheaths are bonded at two ends).

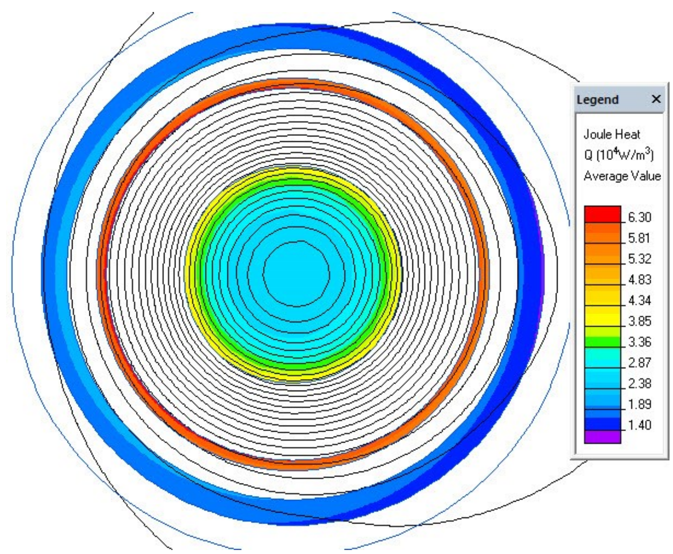

Fig. 4. Joule heat density map by bonding at two sides

A. Flat Formation

When the cables are bonded at one side, there is no circulating current in the screen, and the eddy currents are minimized. In case of bonding at both sides, the screen and armor form closed loops linked with the alternating magnetic flux, which is created by its own conductor and adjacent cables. The linked alternating flux induces EMF that cause circulating currents and eddy currents in all metallic parts. The analytical formulas in the IEC 60287 standard were developed for the case of single sheath (only screen or only armor). Extending it to include dual sheath is approximate.

The load current for each calculation was selected so that the maximum conductor temperature according IEC 60287 was 90°C.

The losses in metallic cable parts are shown in Table I.

Table I. The losses in the conducting elements of cable per 1m length, W/m

Phase	Conductor		Screen		Armor	
	Bonded at one side, Current=986 A					
	FEA	***IEC***	***FEA***	***IEC***	***FEA***	***IEC***
A	36.57	37.47	0.82	3.60	1.01	0
B	37.29	37.47	1.57	3.60	2.60	0
C	36.59	37.47	0.85	3.60	1.08	0
	Bonded at two sides, Current=791 A					
A	23.92	24.13	14.83	22.47	13.59	0
B	23.41	24.13	11.03	19.18	9.00	0
C	23.69	24.13	9.86	17.80	9.00	0

Note: The screen losses calculated by IEC are actually the sum screen and armor losses.

The comparison shows that the FEA gives somewhat lower losses in the screen and armor, which however leads to almost same temperature.

Table II shows the calculated the temperature of metal cable elements.

Table II. Temperature of metal cable elements, °C

Phase	Conductor		Screen		Armor	
	FEA	***IEC***	***FEA***	***IEC***	***FEA***	***IEC***
	Bonded at one side, Current=986 A					
A	82.6	86.3	71.8	no data	66.7	no data
B	86.9	90.9	75.9	no data	70.5	no data
C	82.6	86.3	71.8	no data	66.7	no data
	Bonded at two sides, Current=791 A					
A	89.29	89.6	82.25	82.4	79.30	78.8
B	90.63	90.0	83.56	82.8	80.89	79.5
C	85.60	83.4	78.63	76.2	76.07	73.0

As can be seen from the table, with screens bonded at one side the FEA calculation yields losses and temperatures by about 4 °C lower than the IEC 60287 calculation. We tend to believe that this small difference is due to a more accurate model of the electromagnetic interaction in the FEA model in comparison to the IEC model.

The thermal FEA model [5] does not use the concept of thermal resistance, since the latter is a simplified circuit equivalent of the temperature field. Nevertheless, it is interesting to compare the standard thermal resistances T_1, T_3, T_3, T_4 calculated by FEA and by IEC 60287. The comparison demonstrates almost 100-percent match.

Table III. Thermal resistances T_1,…T_4

	A		B		C	
	FEA	***IEC***	***FEA***	***IEC***	***FEA***	***IEC***
T_1	0.298	0.306	0.298	0.305	0.298	0.305
T_2	0.076	0.076	0.076	0.078	0.076	0.077
T_3	0.061	0.064	0.061	0.067	0.061	0.064
T_4	1.180	1.189	1.271	1.193	1.180	1.186

The increased value of the thermal resistance between the surface of the middle cable and the ambient (the T_4 for cable B) according the IEC standard is due to workaround made in the standard in order to take into account the heating of the middle cable by two adjacent ones. The FEA model takes into account the mutual thermal (and electromagnetic) influence of cables on each other in a natural way, without the need for artificial adjustment of thermal resistance.

B. Trefoil formation

Calculations similar to the above were also performed for the single-core cables laid in trefoil formation. The temperature and losses table are omitted here for sake of brevity. The temperature of metal parts and losses exhibit the same high degree of coincidence between the two compared calculation techniques as for the flat formation. Remarkable exception is the cables bounded at two sides. In the last case, the FEA calculation yields the total losses 4% lower than the CymCap calculation, mainly due to lower losses in screen and armor. As result, the conductor temperature is 6-7 degrees lower than according CymCap.

Cable duct-bank

When designing a 110/330 kV substation in the central part of St. Petersburg turned out that the entry of eight lines of 110 kV and, in the near future, the two lines of 330 kV, must be organized in the limited space between a developed system of urban underground utilities.

We used one of design options of cable arrangement and estimated daily load of each line to perform comparative cable ampacity calculations by IEC 60287 (using CymCap) and by 2D FEA (using QuickField).

The cable duct bank () of 1750 mm width and 4250 mm height contains 10 rows of ducts (4 ducts per row). The horizontal and vertical distance between ducts is 400 mm. Each three-phase line occupies one row of three adjacent ducts; the fourth duct in row remains reserved. Each duct is a polyethylene tube of outer diameter 225 mm and a wall thickness of 20.5 mm. The top of the duct-bank is located at a depth of 4.5 m for decoupling with the existing underground utilities.

Each cable has an XPLE insulation with a thickness of 16 mm for 100 kV and 27 mm for 330 kV. The cross section of copper wire screen is 185 mm^2 for 110 kV and 240 mm^2 for 330 kV. All cables have the plastic sheath with a thickness of 3.4 mm.

The magnetic field pattern in the duct-bank by the load given in the Table IV is shown on Fig. 6.

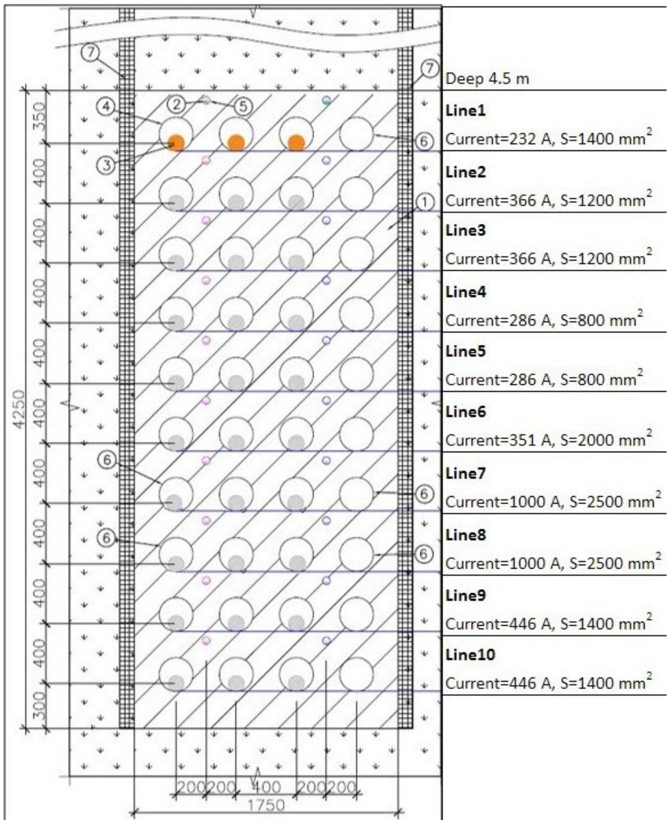

Fig. 5. The cable duct-bank with dimensions and loads

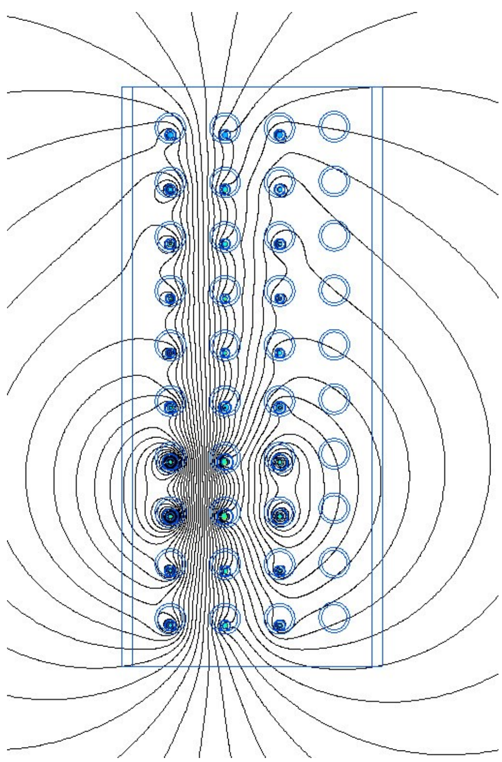

Fig. 6. Magnetic field pattern arrond the duct-bank under load condition

The calculated conductor temperature is shown in Table IV.

Table IV. Conductor's temperature calculated by FEM and by IEC.

#	Cur-rent	CymCap			FEM		
		A	*B*	*C*	*A*	*B*	*C*
1	232	77.4	78.1	77.4	79.8	80.9	79.7
2	366	84.3	85.2	84.3	90.3	92.2	90.3
3	366	89.1	90.3	89.1	97.4	99.8	97.5
4	286	93.5	94.9	93.5	103.8	106.5	104.0
5	286	98.3	100.0	98.3	111.0	114.4	111.2
6	351	102.8	105.1	102.8	118.2	123.0	118.5
7	1000	118.0	121.2	118.0	140.5	148.5	140.8
8	1000	118.4	121.7	118.4	140.2	148.4	140.4
9	446	105.6	108.0	105.6	119.1	124.0	119.2
10	446	99.6	101.2	99.6	107.5	110.3	107.4

The color coding in Table IV helps us to understand that the pattern of temperature distribution is the same for both calculations, but the figures differs significantly. For better understanding have a look at Table V, shows the difference between temperatures calculated by FEA and by IEC 60287 (CymCap).

Table V. Conductor temperature difference calculated by two methods

№	Current	Difference, Fem - CymCap		
		A	*B*	*C*
1	232	`	2.8	2.3
2	366	6.0	7.0	6.0
3	366	8.3	9.5	8.4
4	286	10.3	11.6	10.5
5	286	12.7	14.4	12.9
6	351	15.4	17.9	15.7
7	1000	22.5	27.3	22.8
8	1000	21.8	26.7	22.0
9	446	13.5	16.0	13.6
10	446	7.9	9.1	7.8

The Table V shows that the FEA calculation yields the higher conductor temperature than the IEC calculation. The greater the conductor temperature, the higher is the difference between FEA and IEC.

The reasons for this discrepancy to be found in the difference in eddy current losses, i.e. evaluation of skin effect and proximity effect. Let us compare the conductor and screen losses calculated by two methods (Table VI).

Table VI. Losses per 1 m calculated by FEA and by IEC (using CymCap).

#	Cur-rent	CymCap			FEA		
		A	*B*	*C*	*A*	*B*	*C*
1	232	0.90	0.90	0.90	1.09	1.13	1.09
2	366	2.64	2.65	2.64	3.05	3.14	3.05
3	366	2.68	2.69	2.68	3.10	3.21	3.10

4	286	2.37	2.38	2.37	2.63	2.71	2.63
5	286	2.41	2.42	2.41	2.68	2.77	2.68
6	351	1.62	1.63	1.62	2.25	2.56	2.25
7	1000	11.22	11.30	11.22	15.72	16.64	15.72
8	1000	11.23	11.31	11.23	15.71	16.65	15.71
9	446	3.61	3.63	3.61	4.36	4.64	4.36
10	446	3.55	3.56	3.55	4.22	4.35	4.22

The Table VI shows the qualitative agreement in loss distribution between two methods. It is also clear that the cables located on the edges of the duct-bank demonstrate lower discrepancy. With the cables located in the middle of the block, where induced eddy currents are higher, the FEA calculation shows significantly higher losses, somewhere up to 50%. The ratio of conductor losses calculated by FEA and by IEC for each cable is shown in Table VII.

Table VII. The percentage ratio of conductor losses calculated by FEA and by IEC.

#	Current	A	B	C
1	232	21.6%	26.0%	21.6%
2	366	15.5%	18.3%	15.5%
3	366	15.5%	19.2%	15.6%
4	286	11.1%	13.8%	11.1%
5	286	11.3%	14.6%	11.4%
6	351	38.7%	57.0%	38.8%
7	1000	40.1%	47.3%	40.1%
8	1000	39.9%	47.3%	39.9%
9	446	20.7%	27.9%	20.7%
10	446	18.8%	22.2%	18.8%

Table VII shows the clear tendency: the closer a cable to the center of the duct-bank, the higher loss ratio. It should be noted that the FEA calculation might lead to some excess of losses because we did not find a proper way of accounting the segmental (Milliken) conductor design. Nevertheless, the FEA clearly predicts more intensive electromagnetic coupling of adjacent cables, than the calculation according to IEC 60287.

LOSSES VS. CABLE DISTANCE

Apparently, a substantial part of the discrepancy is due to different mechanisms account of skin effect and proximity effect for cables lying in the center of the duct-bank. If so, the degree of divergence between the methods should increase with decreasing distance between the cables.

To investigate this phenomenon, we performed a series of comparative electromagnetic and thermal calculations of the duct-bank with variation of the distance between the cables in the range of 250...450 mm.

The degree of electromagnetic coupling can be measured by the ratio of AC resistance to DC resistance $k_R = R_{AC} / R_{DC}$. Fig. 7 and Fig. 8 shows k_R vs. row number (from top to bottom). The ratio k_R is calculated for the middle cable in each row because the middle cable is most loaded. Each curve corresponds to the given distance between adjacent cables (the duct pitch). Fig. 7 demonstrates AC/DC resistance ratio calculated by FEA, and Fig. 8 shows the same quantities calculated according to IEC 60287.

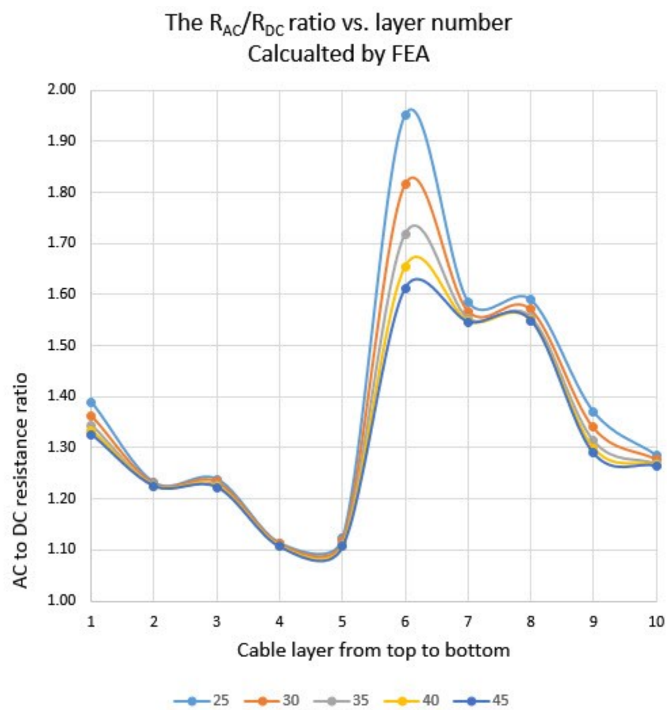

Fig. 7. R_{AC} / R_{DC} ratio calculated by FEA

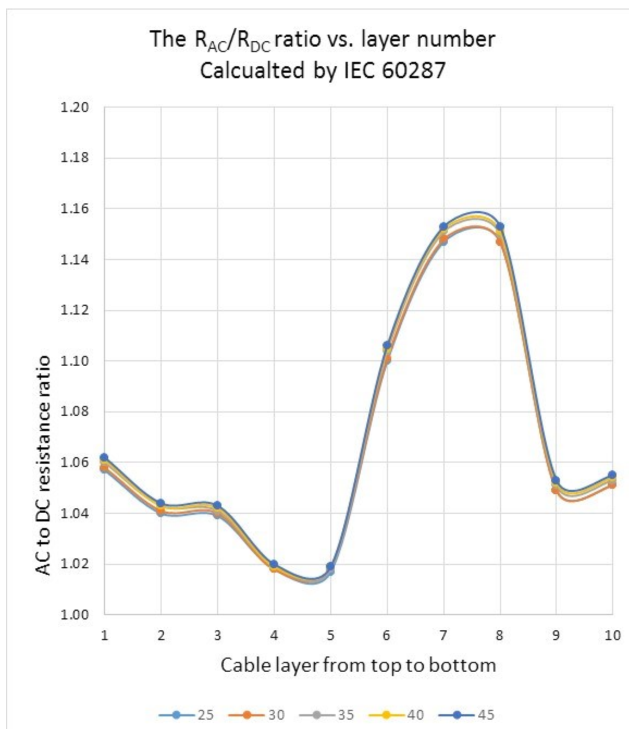

Fig. 8. R_{AC} / R_{DC} ratio calculated by IEC 60287

As we have seen above, the closer the cable to the middle of the duct-bank, the higher AC/DC ratio. The news is that the IEC calculation do not predict any increasing of AC losses with decreasing of duct pitch, whereas the FEA calculation does.

Comparing curves in Fig. 7 and Fig. 8 we note that FEA predicts the AC/DC loss ratio in the middle 70% higher than IEC 60287.

CONCLUSION

Having the results of using of the two different calculation methods it is hardly possible to conclude which one is closer to the truth. The best criterion can be an experiment, for example, the comparison of the calculation results with the distribute temperature sensing (DTS) data, which the authors do not yet have.

However, referring to the above-mentioned facts, namely:

- Almost exact match of IEC 60287 and FEA results for simple cable lines, and
- Monotonous discrepancy between the IEC and FEA results for complicated duct-bank where the standard cannot completely take into account the electromagnetic coupling between all cables.

We can assume that FEA reveals the higher degree of electromagnetic coupling than that calculated using the extrapolation of simple models. This means that the multiphysic FEA simulation of electromagnetic and thermal interaction of multiple cables capable to providing for engineer more comprehensive data than the IEC 60287 standard. The specially tailored software interface to a common FEA software could made FEA as simple as the using of traditional ampacity calculators.

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