

Influence of metallic trays on the ac resistance and ampacity of low-voltage cables under non-sinusoidal currents

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Abstract

This paper investigates the influence of metallic trays on the ac resistance of PVC insulated, low-voltage (0.6/1.0 kV) cables made according to CENELEC standard HD603. The investigation is made with a validated finite element model for the fundamental and higher harmonic frequencies. It is shown that the cable's effective resistance is affected significantly by the relative magnetic permeability and specific conductivity of the tray, while the tray's dimensions do not affect it. The orientation of the cable with respect to the tray also influences the ac resistance of the phase and neutral conductors. An ampacity derating factor is defined and calculated for various cable cross-sections and harmonic loads. The presence of a metallic tray is shown to cause an additional derating of cable's ampacity which is relatively significant at large cable cross-sections. Working examples demonstrate the application of the results in calculating the ampacity of low-voltage cables and in assessing the energy savings that will result from the use of active harmonic filters.

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1. Introduction

Laying power cables on open metallic trays is a common practice in industrial and commercial electric networks. A metallic tray affects the ampacity of a cable in three ways: first by altering heat transfer conditions, second by increasing the resistance of the cable due to proximity effect and third by induced losses due to eddy currents in the tray. These factors are well documented and have been taken into account in various standards that deal with the derating of the ampacity of cables on metallic trays when currents of 50 or 60 Hz flow.

Thermal models, solving heat transfer equations, have already been developed for the calculation of cable ampacities when they are laid on trays [1–5]. In these models only 50–60 Hz currents are assumed to flow in the cable conductors. In these frequencies, the induced eddy currents in the cable tray and the increase of the cable's resistance due to proximity to the tray are insignificant and are therefore neglected.

The proliferation of power-electronic loads leads to ever increasing non-sinusoidal currents. When higher harmonic currents flow in the cables, their apparent resistance increases due to skin effect. At high harmonic frequencies eddy currents of significant magnitude are induced in metallic cable trays increasing both the cable losses due to proximity effect and the losses in the tray itself.

The accurate calculation of the derating of the ampacity of a cable in the presence of non-sinusoidal currents is important both for the estimation of its ageing and for the determination of its overcurrent protective device. Besides the calculation of a derating factor for the cable ampacity, knowledge of the increased losses due to harmonic currents is significant also for the economic evaluation of measures that deteriorate harmonic currents. Such measures can be, for example, passive or active harmonic filters [6,7].

The ampacity of low-voltage (<1 kV) power cables used in Europe is determined in [8] for various installation types including metallic trays. However, these ampacities are based only on 50 Hz currents.

The influence of harmonics on cable's ac resistance is mentioned in IEEE Std. 519-1992 [9], where ampacity derating factors are proposed for THHN and THWN cable types as they

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are specified in Article 310.13 and Table 310.13 of the National Electrical Code (NEC) of the USA [18]. These ampacity derating factors were extracted from [10], where the influence of metallic trays or conduits was not taken into account. The relative European Standard [8] mentions neither the increase of cable ac resistance due to the presence of higher harmonic currents, nor the influence of metallic trays on the ampacity of cables under non-sinusoidal currents.

The influence of circular metallic conduits on the ac resistance of 600 V cables (as specified in NEC) in the presence of harmonics was addressed by Sakis Meliopoulos and Martin [11] who proposed a refinement of the Neher and McGrath [12] analytical equations so that they reflect the additional cable losses. Their objective was to give simplified mathematical formulae for the evaluation of ohmic losses due to harmonics, and subsequently to compute an ampacity derating factor for the cable. To derive their formulae, they assumed balanced three phase loading of the cables. However, they mentioned that when the neutral conductor carries significant zero-sequence harmonic currents, the classic Neher–McGrath equation for ampacity should be used. This equation contains terms such as the ambient earth temperature and the effective thermal resistance between conductors and ambient, which are not readily available.

Palmer et al. [13] developed closed-form equations for calculating the ac/dc resistance of High Pressure Fluid Filled (HPFF) pipe-type power cables with metallic shield. Since these cables are used in transmission systems, there is no separate neutral conductor. The metallic shield carries only eddy currents or currents during faults, i.e., it does not serve as a neutral conductor. The results of the proposed closed-form equations were compared with a finite element analysis model that was developed for the specific cable type. The same equations were used to calculate a derating factor for HPFF cables in five cases of harmonic loading which are typical for transmission systems [14].

A finite element method was also used to evaluate the ampacity of high-voltage (110 kV) underground cables [19], without, however, considering the presence of metallic trays.

The effect of current harmonics on the losses in PVC insulated low-voltage (0.6/1.0 kV) power cables, as they are specified in CENELEC standard HD603 [15], was investigated in [17]. The cables were assumed to be in free air, i.e., the effect of metallic cable trays or conduits was not considered. Ampacity derating factors were calculated for representative cable cross-sections and for typical power-electronics loads met in industrial distribution networks.

This paper investigates the influence of metallic, open-top trays with solid bottom, on the losses in PVC insulated low-voltage (0.6/1.0 kV) power cables [15], when harmonic currents are present. This type of tray is frequently used for supporting cables in industrial or commercial power networks.

Four-core cables (three phases and neutral) are examined. Three cross-sections for the phase-conductor are considered, namely 16 mm², 120 mm² and 240 mm², which represent a relatively small, medium and large cable. Cases where the cross-section of the neutral conductor is equal to or less than that

of the phase conductors are examined. Multi-core cables with cross-sections larger than 240 mm² are hardly used, due to the difficulties they present in their installation. Instead, single-core cables are preferred in such cases. Therefore, four-core cables with cross-sections larger than 240 mm² are not examined.

The influence of the tray on the cable losses is a function of the dimensions of the tray, of the magnetic permeability and the electric conductivity of the tray's material and of the orientation of the cable with respect to the tray. The influence of each of the aforementioned parameters on the cable losses is investigated.

The cables and the trays are modeled using OPERA-2d which is a commercially available finite element analysis software made by Vector Fields Ltd. The validation of the model is extensively described in [17]. The trays were assumed to be solid, although in practical situations, perforated or ladder-type trays are also used. However, this assumption leads to more conservative calculations regarding the effective resistance and the derating of the ampacity of the cable. The cables are assumed to carry a balanced system of currents. A number of typical power-electronics loads are used to derive ampacity derating factors. The harmonic signature of these loads was measured in an industrial environment. Some of these symmetrical loads contain zero-sequence harmonics which cause significant currents in the neutral conductor and induce significant eddy currents on the tray. To emphasize the influence of the tray, the cable losses, their effective ac resistance and the ampacity derating factors calculated in the presence of a tray are compared to those obtained when the tray is absent or non-metallic [17]. The current in the neutral conductor and the fact that the zero-sequence harmonics are in phase, are properly modeled in order to derive the losses in the cable and in the tray at various frequencies. This is a main distinction between the present and the aforementioned works. Application examples show (a) how the new ampacity derating factors can be combined with the ampacity derating factors given in [8] in order to calculate an accurate cable ampacity and (b) how to estimate the savings in energy losses by the use of active harmonic filters.

2. Cable ampacities according to CENELEC Std. HD384

The ampacity of cables in [8] is listed according to their cross-section, insulation type, installation type and the number of active conductors. Derating factors are given for various ambient temperatures and cable groupings, including laying on trays. No distinction is made between metallic or non-metallic trays, since at 50 Hz, the cable losses associated to the tray material are insignificant. When 50 Hz currents are considered, the influence of the tray on the ampacity of a cable stems only from the fact that the tray reduces the heat transfer from the cable. The increase of the cable ac resistance due to proximity with the tray is insignificant at 50 Hz.

The ampacity values given in [8] are valid for 50 Hz currents, and for two or three active conductors. This means that in four-conductor cables, where the fourth conductor is the neutral, only

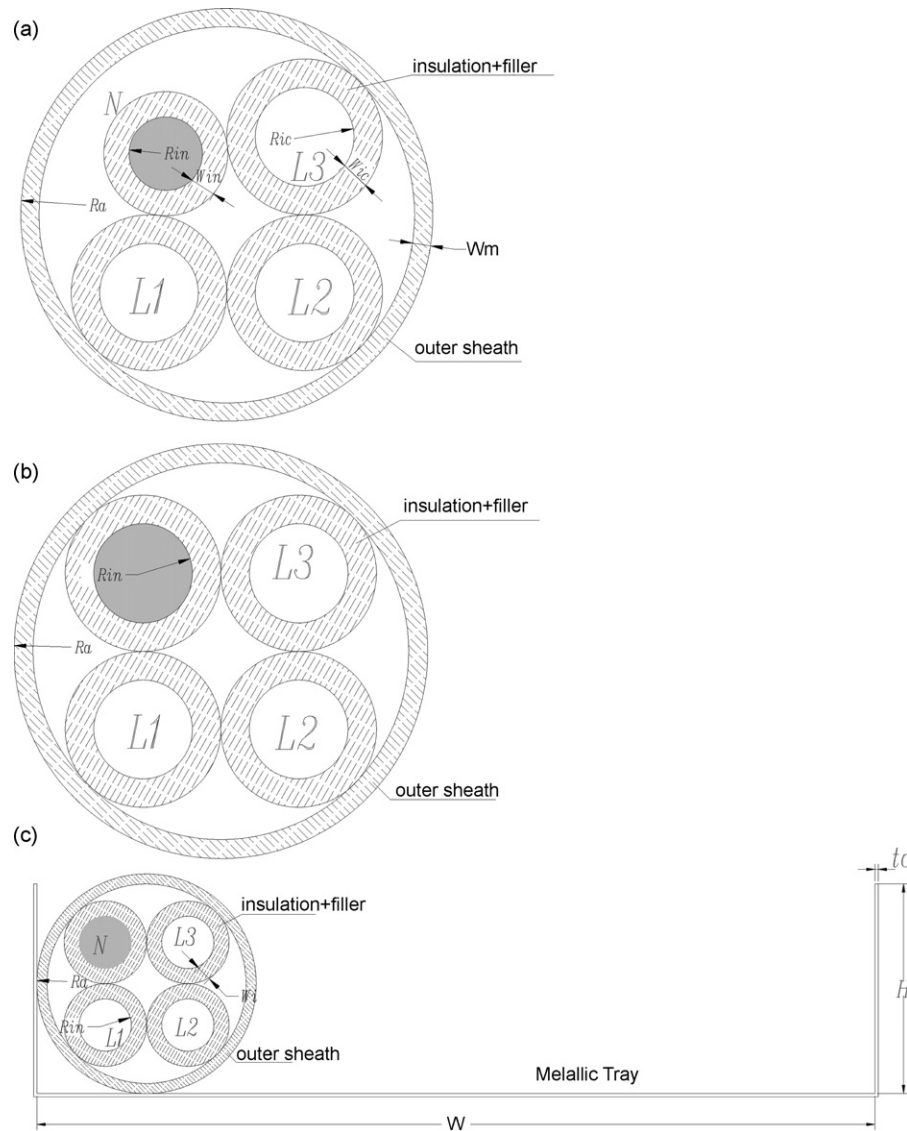


Fig. 1. Cable and tray geometry: L1, L2 and L3: phase conductors. N: neutral conductor. (a) Four-core cable with the neutral conductor having smaller cross-section than the phase conductors. (b) Four-core cable with the neutral conductor having the same cross-section as the phase conductors. Neutral conductor is shown shaded. Dimensions are shown in Table 1. (c) Geometry of metallic tray.

the three phase conductors are assumed to be active. It is also assumed in [8] that, when the neutral conductor is carrying current to the load, there is a respective reduction in the current of one or more phase conductors so that the total cable losses remain the same.

3. Cable types and trays

Fig. 1 and Table 1 show the geometry of the cables examined. The cables are rated for 0.6/1.0 kV and have PVC insulation both around the conductors and the outer sheath. These cables

Table 1
Dimensions of the examined cables

Dimensions (mm)	Nominal cable cross-section (mm ²)				
	4 × 16	3 × 120 + 70	4 × 120	3 × 240 + 120	4 × 240
Phase-conductor radius, R_{ic}	2.3	6.25	6.25	8.9	8.9
Neutral-conductor radius, R_{in}	2.3	4.65	6.25	6.25	8.9
Outer cable radius, R_a	12.8	26.18	26.18	34.43	34.43
Thickness of phase-conductor insulation, W_{ic}	2.0	3.6	3.6	4.2	4.2
Thickness of neutral-conductor insulation, W_{in}	2.0	3.4	3.6	3.6	4.2
Thickness of outer sheath, W_m	1.8	2.3	2.4	2.8	2.9

Table 2
Dimensions and material properties of the trays examined

Relative magnetic permeability, μ_r	1 to 1000
Electric conductivity, σ (S/m)	10^5 to 10^9
Tray width, W (mm)	100 and 600
Tray thickness, t_c (mm)	0.8 and 1.5

are commonly used for feeding individual loads and distribution switchboards.

The conductors in all cables were assumed solid. Although this is true only for the 16 mm^2 conductors, this assumption leads to results (cable losses, ac/dc resistance ratio, and ampacity derating) that are on the safe side.

Galvanized steel is the most common tray material. The magnetic and electric properties of the steel depend on its grade and on the galvanization type. Typical values for the relative permeability and electric conductivity are $\mu_r = 700$ and $\sigma = 6 \times 10^6 \text{ S/m}$, respectively, but the range of values of these parameters can be wide. For this reason, trays with relative permeabilities and electric conductivities that differ by an order of magnitude are examined in this paper. The geometry and the material properties of the trays examined are shown in Table 2. The tray height H , was kept in all cases equal to 50 mm.

4. Finite element analysis

The cables were modeled in two dimensions assuming that, at each harmonic frequency, balanced, three phase, sinusoidal currents flow through them. The metallic tray carries induced eddy currents which are calculated by the software. An example of the finite element analysis model is shown in Fig. 2.

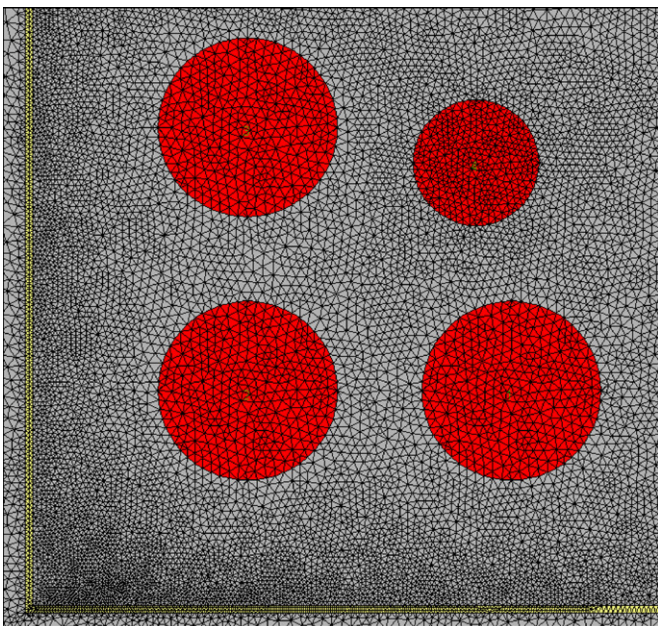


Fig. 2. Part of the finite element mesh as generated for cable type $3 \times 120 + 70 \text{ mm}^2$.

The cable was assumed to be placed at the corner of the tray, so that the proximity effect is maximized. This leads to results (losses and ampacity derating) that are conservative.

The finite element analysis is used to calculate the losses per unit length in each conductor when sinusoidal currents of various harmonic frequencies flow in the phase and neutral conductors. The losses caused by currents of a specific harmonic signature can be easily calculated when the losses at individual frequencies are known.

To calculate the losses, an ac steady-state harmonic analysis was employed. Only the odd-order harmonics, from the 1st up to the 31st, were considered. Higher order harmonic currents may exist in industrial or commercial power networks but their relative magnitude is so small that their influence on the cable losses is insignificant. In cases of harmonic resonance these higher harmonics may acquire large values but a cable is never selected on that basis.

At each harmonic frequency, $h \times 50 \text{ Hz}$, the software calculates the losses per unit length in each conductor using the integral

$$P_1(h) = \int_S \frac{J^2(h)}{\sigma} ds \quad (1)$$

where S is the surface of the conductor, $J(h)$ the current density, and σ is the conductivity of the conductor.

The model of the diffusion equation in two dimensions that is used by the FEM software is:

$$-\nabla \cdot \frac{1}{\mu} \nabla A_z = J_s - \sigma \frac{\partial A_z}{\partial t} \quad (2)$$

where A_z is the Magnetic Vector Potential (MVP) along the z axis, J_s the applied current density along the z axis, μ the conductor magnetic permeability and σ is the conductivity of the conductor.

Since the MVP and the currents were assumed to vary sinusoidally, they were expressed as the real parts of complex functions $A_c e^{j\omega t}$ and $J_c e^{j\omega t}$, respectively. Eq. (2) now becomes

$$-\nabla \cdot \frac{1}{\mu} \nabla A_c = J_c - j\omega\sigma A_c \quad (3)$$

and is solved using complex arithmetic.

When the total measurable conductor rms current is given, the software solves also the following equation:

$$-\int_S \sigma \left(\frac{\partial A}{\partial t} + \nabla V \right) dS = I \quad (4)$$

where S is the surface of the conductor, V the electric scalar potential and I is the total measurable conductor rms current.

5. Computation of the R_{AC}/R_{DC} ratio

To calculate an ampacity derating factor, the increased cable losses due to harmonics must be first calculated. Due to the absence of any symmetry in the cable–tray system (Fig. 1c) the losses in the phase conductors are not identical. This can be demonstrated, for example, by a $4 \times 120 \text{ mm}^2$ cable laid on

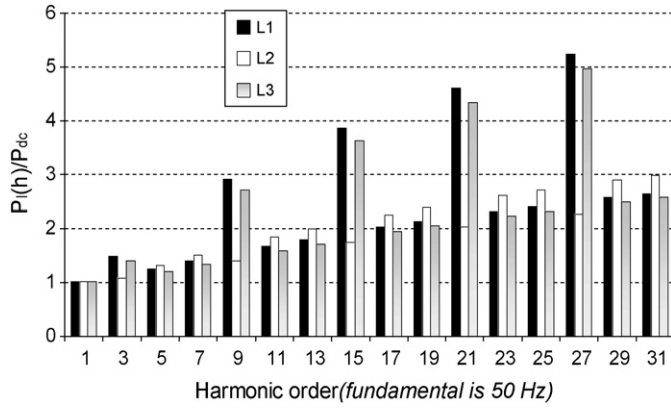


Fig. 3. $P_1(h)/P_{dc}$ ratio of conductors L1, L2, L3 of a $4 \times 120 \text{ mm}^2$ cable as a function of harmonic frequency. The cable is laid on a $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$ tray with $\mu_r = 1000$ and $\sigma = 10 \times 10^6 \text{ S/m}$.

a tray that is 200 mm wide, 50 mm high, 0.8 mm thick and its steel has relative permeability $\mu_r = 1000$ and electric conductivity $\sigma = 10 \times 10^6 \text{ S/m}$. The losses per unit length in the phase conductors, when a symmetrical current of rms value $I_{\text{rms}}(h)$ and of frequency $h \times 50 \text{ Hz}$ flows through them, can be defined as $P_{1(L1)}(h)$, $P_{1(L2)}(h)$, and $P_{1(L3)}(h)$. The losses in each of the phase conductors when carrying a dc current of amplitude I_{rms} can be defined as P_{dc} . The ratio $P_1(h)/P_{dc}$ for each phase conductor (L1, L2, L3) is shown in Fig. 3.

The asymmetry in conductor losses is easily noticed from Fig. 3. Moreover, the losses in conductor L2 (see Fig. 1c for its location) are larger than the losses in conductors L1 and L3 when currents of 1st, 5th, 7th, 11th, etc., harmonic order flow, whereas, when zero-sequence harmonics (3rd, 9th, 15th, etc.) flow, the losses in conductors L1 and L3 are significantly larger than those of conductor L2. This results from the cable geometry and the fact that zero-sequence harmonic currents are in phase to each other.

The uneven Joule losses inside the cable need to be considered when calculating the derating of the cable ampacity. According to [8], not only the average cable temperature but the temperature at any point of the cable insulation should not exceed the maximum permissible one. Therefore, for derating the cable ampacity, the maximum conductor losses should be considered and not the average of them. The maximum conductor losses can be represented by an equivalent conductor resistance per unit length $r_{eq}(h)$ for the harmonic order, h , that is defined by the following formula:

$$3P_1(h) + P_{1(N)}(h) = 3I_{\text{rms}}^2(h)r_{eq}(h), \quad h \neq 3n; n \in N \quad (5)$$

where,

$$P_1(h) = \max\{P_{1(L1)}(h), P_{1(L2)}(h), P_{1(L3)}(h)\} \quad (6)$$

and $P_{1(N)}(h)$ is the loss per unit length in the neutral conductor when a symmetrical current of rms value $I_{\text{rms}}(h)$ and frequency $h \times 50 \text{ Hz}$ flows in the phase conductors. In this case the neutral conductor carries only eddy currents. Resistance $r_{eq}(h)$ in (5) reflects the losses in the cable assuming that all the phase conductors have losses equal to the maximum conductor losses.

This definition of the conductor resistance will be later used in order to calculate a conservative derating of cable ampacity.

When zero-sequence harmonics are present, the neutral conductor picks up load. An equivalent resistance $r'_{eq}(h)$ that reflects the losses in the phase conductors and another equivalent resistance $r_{eq(N)}(h)$ that reflects the losses in the neutral conductor are now defined in (7) and (8), respectively:

$$3P_1(h) = 3I_{\text{rms}}^2(h)r'_{eq}(h) \quad (7)$$

$$P_{1(N)}(h) = I_{\text{rms}(N)}^2(h)r_{eq(N)}(h) \quad (8)$$

with $h = 3n$, and n an odd integer.

$P_1(h)$ is given again by (6) and

$$I_{\text{rms}(N)}(h) = 3I_{\text{rms}}(h) \quad (9)$$

is the rms value of the current of the neutral conductor for harmonic order h .

The ratios $r_{eq}(h)/R_{dc}$, $r'_{eq}(h)/R_{dc}$, and $r_{eq(N)}(h)/R_{dc}$ shall be referred to, from now on, as the R_{ac}/R_{dc} ratio.

Due to skin effect, the R_{ac}/R_{dc} ratio of a conductor depends on the current frequency. It also depends on its proximity to other conductors including the tray. The currents induced on the tray depend on the frequency, tray geometry, and the relative magnetic permeability and electric conductivity of its material. They also depend on the relative position of the cable conductors with respect to tray as shown in Fig. 4.

To investigate how the orientation of the cable and the tray parameters affect the cable losses and thus the R_{ac}/R_{dc} ratio, the $4 \times 120 \text{ mm}^2$ cable will be used as a basis. The results will then be extended to other cable types.

5.1. Influence of the orientation of the cable with respect to the tray

The R_{ac}/R_{dc} ratio of the phase and the neutral conductors were calculated for the four different cable orientations shown in Fig. 4. In all cases a $4 \times 120 \text{ mm}^2$ cable was assumed. The tray dimensions are $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$, its magnetic permeability equal to 1000, and its electric conductivity equal to $1 \times 10^6 \text{ S/m}$. The results are shown in Figs. 5 and 6. The R_{ac}/R_{dc} ratios were calculated using Eqs. (5)–(9).

It can be noticed that the R_{ac}/R_{dc} ratio of the phase conductors at non-zero-sequence harmonics is largest when Orientation-D is used. At zero-sequence harmonics the R_{ac}/R_{dc} ratio of the phase conductors is smallest at the same orientation. This is explained by the fact that at Orientation-D all the phase conductors are at close proximity to the tray, and by the fact that at zero-sequence harmonics the currents in the phase conductors are in phase while the neutral conductor carries the sum of the phase currents. At Orientation-B, the situation is reversed and the R_{ac}/R_{dc} ratio of the phase conductors is the smallest at non-zero-sequence harmonics and largest at zero-sequence harmonics because the neutral conductor is in closest proximity to the tray. The variation of the R_{ac}/R_{dc} ratio of the neutral conductor, as shown in Fig. 6, is explained in a similar manner.

A significant remark can be made from the results shown in Figs. 5 and 6: The actual cable losses depend on both the orien-

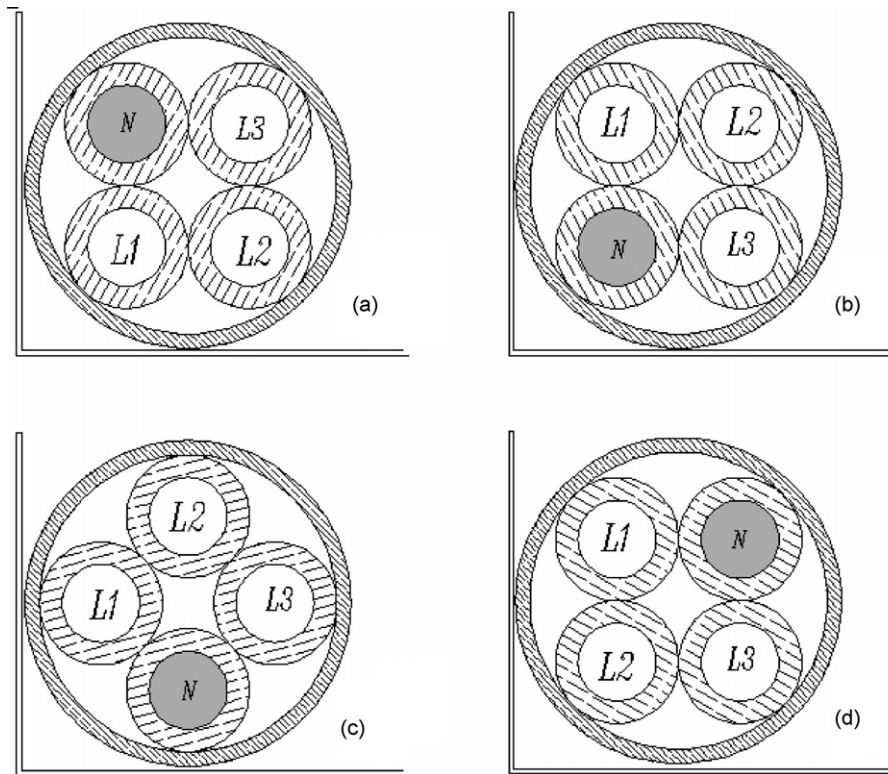


Fig. 4. Possible orientations of the cable with respect to the tray. (a) Orientation-A, (b) Orientation-B, (c) Orientation-C, and (d) Orientation-D.

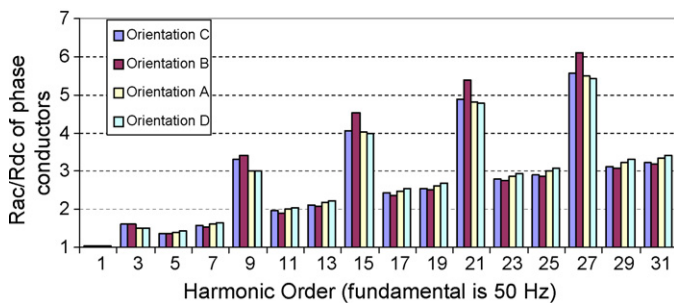


Fig. 5. Variation of R_{ac}/R_{dc} ratio of phase conductors with harmonic frequency for various cable orientations. A $4 \times 120 \text{ mm}^2$ cable and a $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$ tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6 \text{ S/m}$ is assumed.

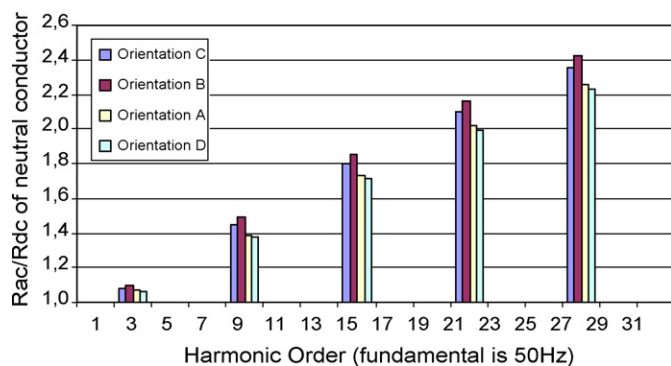


Fig. 6. Variation of R_{ac}/R_{dc} ratio of neutral conductor with harmonic frequency for various cable orientations. A $4 \times 120 \text{ mm}^2$ cable and a $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$ tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6 \text{ S/m}$ is assumed.

tation of the cable with respect to the tray and on the harmonic spectrum of the current in the phase and neutral conductors. Thus, a load current which is rich in zero-sequence harmonics (for example computer or fluorescent lighting loads) will induce the largest losses on the cable when Orientation-B is used. On the other hand, a load current which is rich in non-zero-sequence harmonics (for example an ac–dc–ac drive) will induce the largest losses on the cable when Orientation-D is used.

The cable losses and thus the cable orientation affect the ampacity of the cable. This issue will be discussed in Section 6.

5.2. Influence of tray's relative magnetic permeability and electric conductivity

A $4 \times 120 \text{ mm}^2$ cable is assumed to lay in the corner of a tray (see Fig. 4d) that is 200 mm wide, 50 mm high, 0.8 mm thick and its material has an electric conductivity that varies from 1 to $1 \times 10^9 \text{ S/m}$. Three values of the relative magnetic permeability of the tray were examined, $\mu_r = 1$ (i.e., a non-magnetic material), $\mu_r = 100$ and $\mu_r = 1000$. Fig. 7 shows the R_{ac}/R_{dc} ratio of the cable phase conductors as a function of tray's electric conductivity and relative magnetic permeability for various harmonic frequencies. R_{ac} is defined in (5) and (7).

It can be noticed that the effective ac resistance of the phase conductors of the cable increases with the increase of the relative magnetic permeability of the tray material. This was also shown in the mathematical approximations for pipe-type cables in [11]. On the other hand, as the tray's electric conductivity increases, the equivalent ac resistance of the phase conductors decreases. In

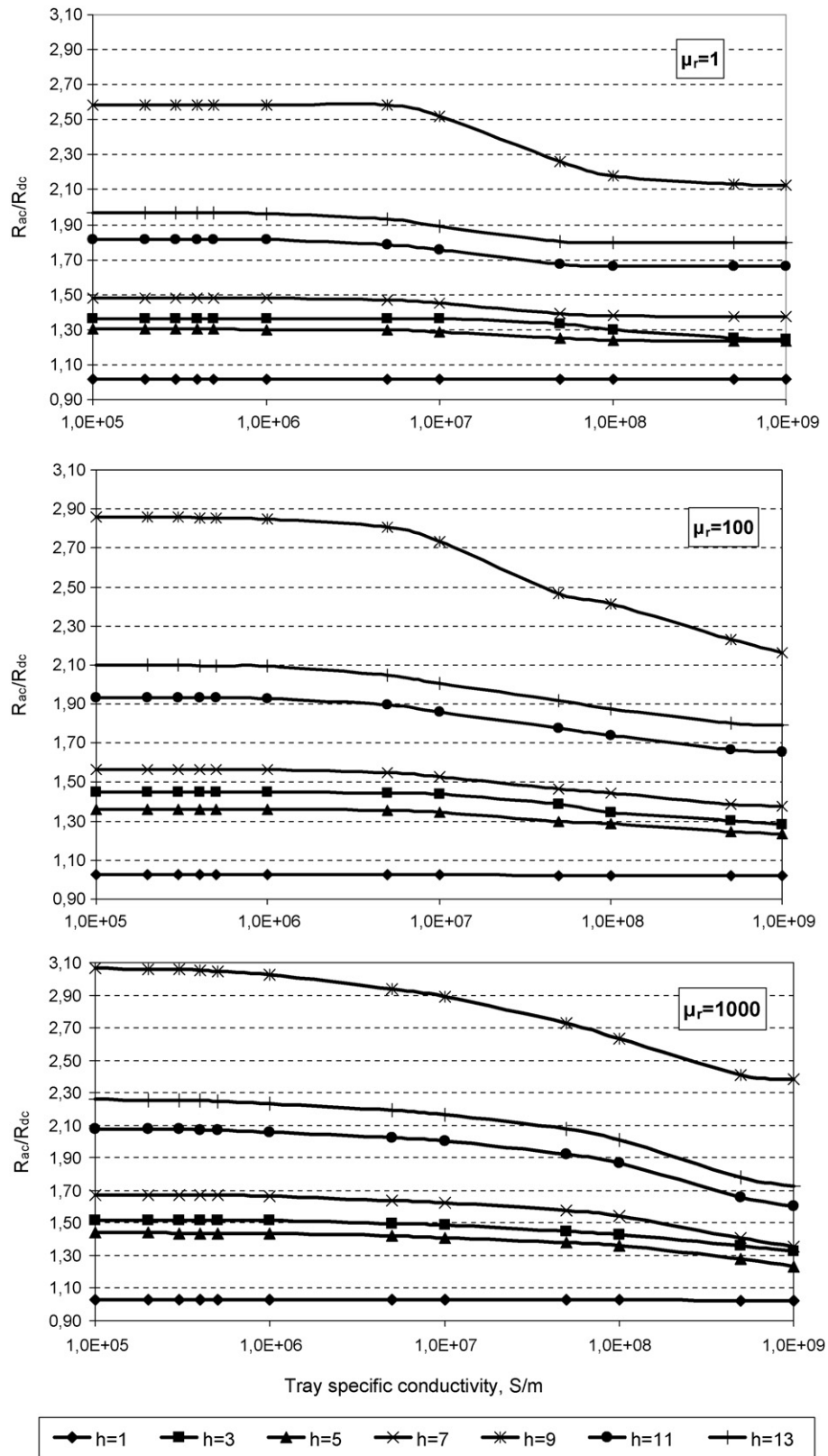


Fig. 7. Variation of the equivalent R_{ac}/R_{dc} ratio of the phase conductors of a $4 \times 120 \text{ mm}^2$ cable with tray's electric conductivity for three different values of tray's relative magnetic permeability and for various harmonic frequencies, $h \times 50 \text{ Hz}$. The cable is laid on a $200 \text{ mm} \times 50 \times 0.8 \text{ mm}$ tray.

every curve of Fig. 7, there is a point up to which the ac resistance is not sensitive to the variation of tray's electric conductivity. As the electric conductivity of the tray increases beyond this point, the ac resistance of the conductors decreases. This is the point where the thickness of the tray, t_c , becomes equal to the skin depth, δ , of the tray.

When $\delta < t_c$, the reflected permeability of the tray, i.e., the permeability as seen by an observer on the cable, is reduced [16]. Thus, as the tray's conductivity increases, the skin depth δ decreases to such a degree that $\delta < t_c$ and thus the reflected permeability of the tray also decreases. As mentioned previously, this will cause the ac resistance of the cable to decrease.

As can be noticed from Fig. 7, the influence of tray's magnetic permeability on the ac resistance of the cable's phase conductors is much larger than the influence of tray's electric conductivity.

In practical situations, trays made of galvanized steel have relative magnetic permeability within the range $100 \leq \mu_r \leq 1000$ and specific electric conductivity within the range $1 \times 10^6 \leq \sigma \leq 1 \times 10^7$ S/m. Thus, in order to calculate a conservative derating factor for the ampacity of a cable, a tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m will be assumed from now on. Fig. 8 shows the R_{ac}/R_{dc} ratio of the phase and neutral conductors for various cables laid on a $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$ tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m for various harmonic

frequencies. Each cable was assumed to be laid according to Orientation-D (Fig. 4d). For comparison, the R_{ac}/R_{dc} ratio of the same cable in free air is also shown.

It is evident from Fig. 8 that the existence of a metallic tray will increase significantly the effective resistance of the phase conductors of a cable. Thus, for a cable with medium cross-section such as $4 \times 120 \text{ mm}^2$, the tray will increase the effective ac resistance of the phase conductors by 1, 11, 10.3, 12.4, 17 and 13.6% at the 1st, 3rd, 5th, 7th, 9th and 11th harmonics, respectively, when the cable is laid according to Orientation-D. For a cable with large cross-section, such as $4 \times 240 \text{ mm}^2$, the influence of the tray is more significant since it increases the effective ac resistance of the phase conductors by 3.6, 17, 15, 15.2, 17.6, and 15% for the respective harmonic frequencies. For a cable with small cross-section ($4 \times 16 \text{ mm}^2$), the influence of the tray is much smaller since it increases the effective ac resistance of the phase conductors by 1.9% at the 9th harmonic and much less at lower-order harmonics. Thus, the influence of metallic trays on cables with cross-section smaller than 16 mm^2 is insignificant and is therefore not examined.

The R_{ac}/R_{dc} ratio of the neutral conductor is shown only for zero-sequence harmonics because only then a current, other than eddy currents, was assumed to exist in the neutral conductor. The ac resistance of the neutral conductor is defined in (8). It can be deduced from Fig. 8 that the specific tray increases the

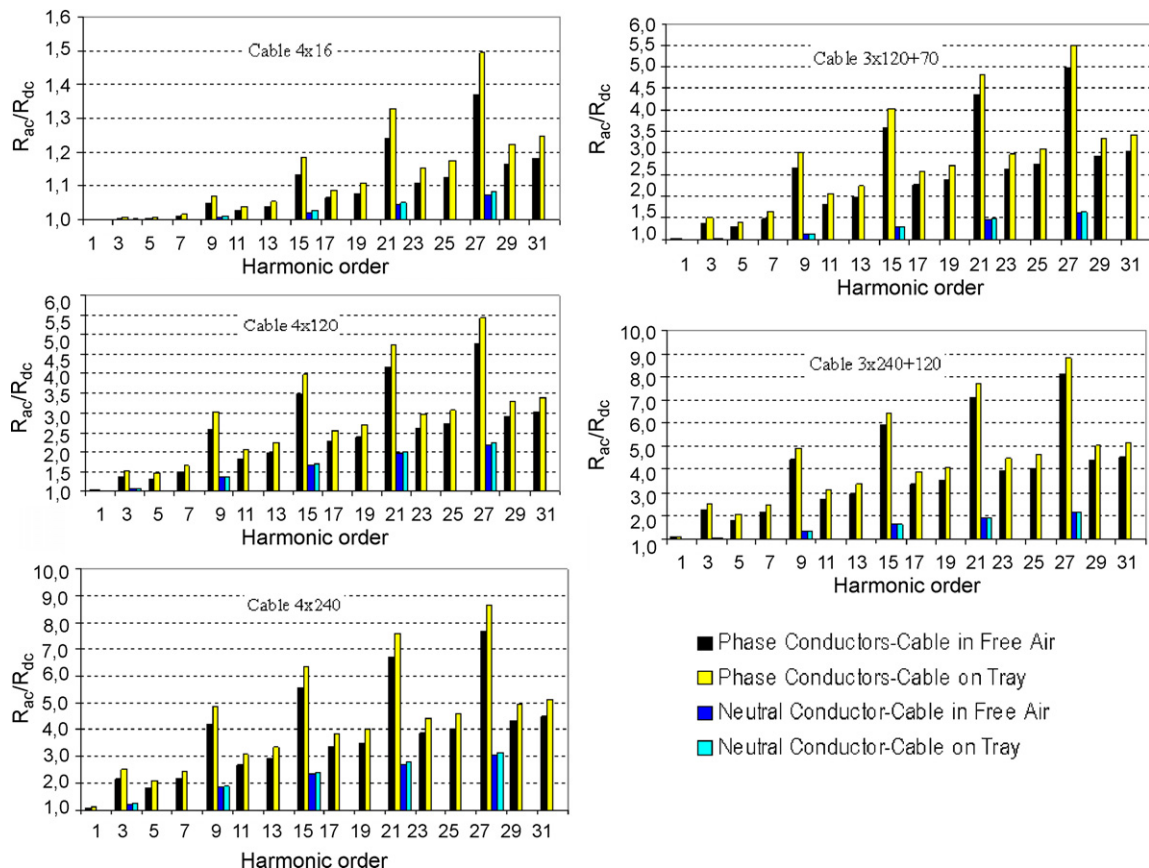


Fig. 8. Variation with the harmonic frequency of the equivalent R_{ac}/R_{dc} ratio of the phase and neutral conductors of various cables. The cables are laid according to Orientation-D on a $200 \text{ mm} \times 50 \text{ mm} \times 0.8 \text{ mm}$ trays with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m.

R_{ac}/R_{dc} ratio of the neutral conductor too, but to a smaller degree compared to the R_{ac}/R_{dc} ratio of the phase conductors.

5.3. Influence of tray's geometry

Although the dimensions of metallic trays do not follow any standard, the manufactures usually make them following more or less typical dimensions. Thus, the width is usually a multiple of 100 mm, the height is a multiple of 10 mm, and the thickness is a multiple of 0.1 mm.

The influence of tray geometry is investigated by examining two trays with considerable difference in their cross-section: the first tray has dimensions 200 mm × 50 mm × 0.8 mm (241.28 mm² cross-section) and the second tray has dimensions 600 mm × 50 mm × 1.5 mm (1054.5 mm² cross-section).

Fig. 9 shows the variation with harmonic order of the R_{ac}/R_{dc} ratio of the phase and neutral conductors of a 4 × 120 mm² cable laid on either of the two trays. In both cases the tray's material was assumed to have $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m since this material results in maximum conductor resistance as shown previously.

It is evident from Fig. 9 that the influence of the cross-section of the tray on the ac resistance of the phase and neutral conductors is insignificant. Actually the curves that correspond to the two different trays almost coincide.

It has been shown so far that the magnetic permeability and electric conductivity of a tray affect the ac resistance of the phase and neutral conductors of a cable laid on the tray. On the other hand, it has been shown that the cross-section of the tray does not influence significantly the ac resistance of the cable conductors. Of course, the dimensions of the tray determine to a large extent the losses in the tray due to eddy currents induced on it, but this issue will be examined later in this paper.

To calculate a conservative derating factor for the cable ampacity, a tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m will be assumed. A relative magnetic permeability of 1000 is close to the typical value for a galvanized steel tray, but an electric conductivity of 1×10^6 S/m is far from the typical value of 6×10^6 S/m for galvanized steel. However, $\sigma = 1 \times 10^6$ S/m will be used since it results in conservative ampacity derating factors.

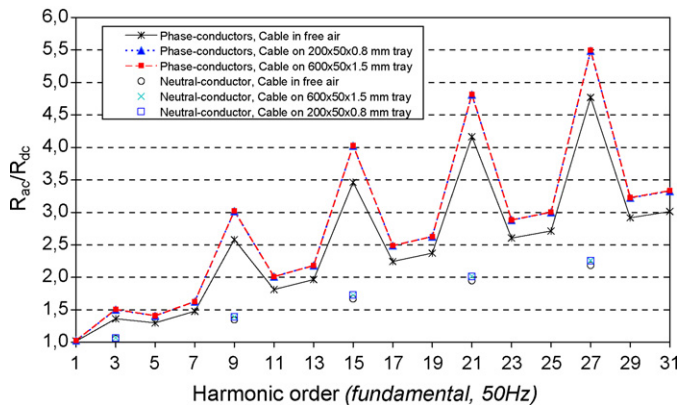


Fig. 9. Variation with harmonic frequency of the equivalent R_{ac}/R_{dc} ratio of the phase and neutral conductors of a 4 × 120 mm² cable. The cable is laid on trays with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m.

Since the tray dimensions are not significant, a typical tray with dimensions 200 mm × 50 mm × 0.8 mm will be used for the calculation of the ampacity derating factor of a cable.

6. Derating of ampacity due to harmonics

A derating factor can be calculated when the R_{ac}/R_{dc} ratios and the harmonic signature of the current are known. The derating factor is defined as the ratio of the rms value of a distorted current with a specific harmonic signature to the rms value of a current of fundamental frequency that produces the same losses in the cable as the distorted one.

Assuming that I_{c1} is the rms value of a current with a fundamental frequency that causes the same cable losses as a distorted current with $I_{d,rms}$ rms value, the derating factor is

$$k = \frac{I_{d,rms}}{I_{c1}} \quad (10)$$

If,

$$I_{d,rms}^2 = \sum_{h=1}^{\infty} I_h^2,$$

equating the losses yields

$$3I_{c1}^2 r_1 = 3 \sum_{h=1}^{\infty} I_h^2 r_{eq}(h) + \sum_{h=3n}^{\infty} (3I_h)^2 r_{eq(N)}(h) \quad (11)$$

where, r_1 is the equivalent resistance of the phase conductors in the fundamental frequency, i.e., $r_1 = r_{eq}(1)$. The first term on the right side of (11) represents the losses in the phase conductors, and the second term the losses in the neutral conductor. This second term is present only when triplen harmonics are considered, i.e., $r_{eq(N)}(h) = 0$, for $h \neq 3n$ with n an integer.

Defining

$$a_h = \frac{I_h}{I_{d,rms}} \quad (12)$$

and using (10) and (11), the derating factor k is calculated by

$$k = \sqrt{\frac{R_{ac}(1)/R_{dc}}{\sum_{h=1}^{\infty} a_h^2 (R_{ac}(h)/R_{dc}) + 3 \sum_{h=3n}^{\infty} a_h^2 (R_{ac(N)}(h)/R_{dc})}} \quad (13)$$

where, k is the ampacity derating factor of the cable and $R_{ac}(h)$ is the equivalent resistance of the phase conductors of the cable at harmonic frequency $h \times 50$ Hz. It is defined in (5) or (7) depending on whether zero-sequence harmonic currents are present or not. R_{dc} is the dc resistance of the conductors of the cable. $R_{ac(N)}(h)$ is the equivalent resistance of the neutral conductor of the cable. $R_{ac}(1)$ is the equivalent resistance of the phase conductors in the fundamental frequency.

The derating factor k , takes values between zero and unity. A unity derating factor means that no derating of the ampacity of the cable is needed.

The derating factor was calculated for four representative industrial loads and two office loads. The harmonic synthesis, the total rms value and the Total Harmonic Distortion (THD)

Table 3
Harmonic profiles, I_h , percent

Harmonic order	Load type					
	A	B	C	D	E	F
1	100.0	100.00	100.0	100.0	100.0	100.00
3	79.7	0.75	3.0	4.7	3.3	41.80
5	49.8	26.00	57.0	44.0	27.0	36.30
7	18.8	19.20	36.0	23.0	10.0	19.70
9	5.2	0.38	3.5	1.4	1.9	10.90
11	13.6	0.37	11.0	3.9	13.3	0.0
13	10.5	0.00	5.6	1.2	3.1	0.0
15	2.2	0.37	0.0	0.0	0.0	0.0
17	6.2	0.37	8.3	0.0	1.4	0.0
19	8.7	0.37	5.0	0.0	0.5	0.0
21	5.9	0.37	0.0	0.0	0.3	0.0
23	0.3	0.37	2.3	0.0	0.0	0.0
25	4.5	0.37	4.0	0.0	0.3	0.0
$I_{d,rms}$ (%)	140.3	105.1	121.8	111.8	105.0	116.49
THD (%)	98.39	32.35	69.53	50.06	32.13	59.76

of the load currents are given in Table 3 as percentages of the fundamental frequency current.

Load A is a computer load, load B is a typical ac–dc–ac drive with large inductance on the dc side, load C is a drive with capacitance on the dc side without a series choke, load D is a drive with capacitance on the dc side and a 5% series choke, load E is a drive with relatively high 11th harmonic and load F

is a typical office load consisting of computers and fluorescent lighting with magnetic ballasts. Loads A and F were measured in subdistribution boards in an office building at the Aristotle University of Thessaloniki, Greece, while the other loads were measured in distribution boards in the plants of a textile-spinning mill in Greece.

The current waveforms of the loads are shown in Fig. 10.

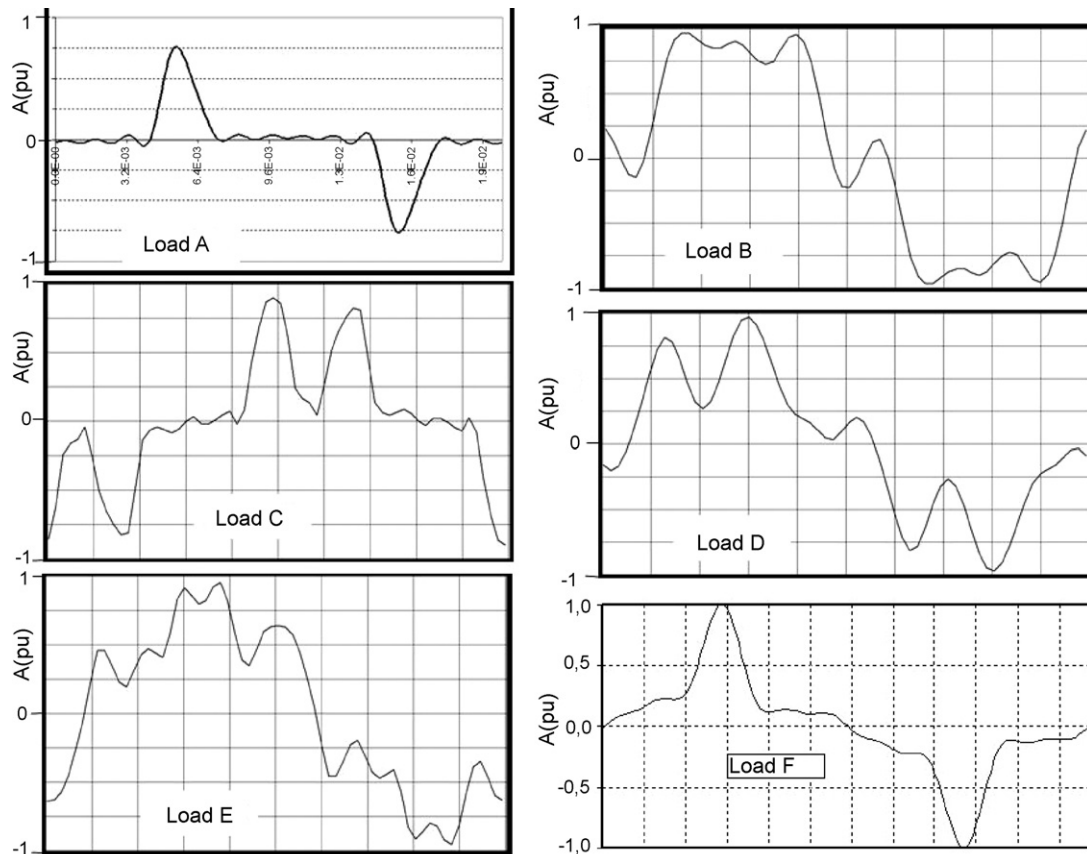


Fig. 10. Waveforms of the loads shown in Table 3. Each waveform represents one period of the fundamental frequency (20 ms).

Table 4

Calculated ampacity derating factor of cables shown in Fig. 1 and Table 1 for various loads

Cable Type	Load Type											
	A		B		C		D		E		F	
4x16 mm ²	0,709	-0,14%	0,999	0,00%	0,995	-0,10%	0,996	0,00%	0,997	0,00%	0,84	0,00%
	0,710		0,999		0,996		0,996		0,997		0,84	
3x120+70 mm ²	0,573	-1,38%	0,979	-0,51%	0,925	-1,80%	0,955	-1,04%	0,973	-0,51%	0,727	-1,09%
	0,581		0,984		0,942		0,965		0,978		0,735	
4x120 mm ²	0,654	-2,82%	0,978	-0,61%	0,924	-1,91%	0,955	-1,14%	0,974	-0,51%	0,791	-2,10%
	0,673		0,984		0,942		0,966		0,979		0,808	
3x240+120 mm ²	0,523	-2,43%	0,955	-0,83%	0,859	-2,50%	0,911	-1,62%	0,948	-0,84%	0,676	-2,03%
	0,536		0,963		0,881		0,926		0,956		0,69	
4x240 mm ²	0,588	-5,31%	0,956	-0,83%	0,862	-2,38%	0,913	-1,62%	0,950	-0,84%	0,732	-3,81%
	0,621		0,964		0,883		0,928		0,958		0,761	

The derating factors for the same cables in free air are shown in italics.

Factors a_h of Eq. (12) can be calculated by dividing an I_h value given in Table 3 with the respective $I_{d,rms}$ value.

Table 4 shows the ampacity derating factors for the cables shown in Table 1 and for the loads shown in Table 3. For comparison reasons, the derating factors in the absence of trays are also included. The cables were assumed to be laid in the corner of a 200 mm × 50 mm × 0.8 mm tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m. For the load types A and F, the cables were assumed to be laid according to Orientation-B (Fig. 4b) while for the rest of the loads Orientation-D was assumed so that a conservative derating factor is obtained. The shaded cells of Table 4 show the relative decrease of the ampacity derating factor that is caused by the presence of a metallic tray, with respect to the case where the cable is in free air.

The following remarks can be made from the results given in Table 4:

- The influence of the metallic tray on the ampacity derating factor increases with the cable cross-section. For example, for a load of type A, the metallic tray will decrease the derating factor from 0.710 to 0.709 or by 0.14% in a 4 × 16 mm² cable, while for the same load but for a 4 × 240 mm² cable the decrease will be from 0.621 to 0.588 or by 5.3%. The same trend is followed with the other load types, too.
- The metallic tray influences more the cables in which the neutral conductor has the same cross-section as the phase conductors than the cables with reduced neutral cross-section provided that the load is rich in zero-sequence harmonics (load types A and F). If the load is not rich in zero-sequence harmonics, the influence of the tray is approximately the same in cables with reduced neutral and cables where the neutral conductor has the same cross-section with the phase conductors. For example, let us compare the influence of the tray on the 4 × 120 mm² and 3 × 120 + 70 mm² cables. For a load of type A (rich in zero-sequence harmonics) the tray will reduce the ampacity derating factor from 0.673 to 0.654, or by 2.82%,

in the 4 × 120 mm² cable and from 0.581 to 0.573 or by 1.38% in the 3 × 120 + 70 mm² cable. In this case the influence of the tray is significantly larger on the cable with neutral conductor of equal cross-section. For a load of type D (which is not rich in zero-sequence harmonics) the tray will reduce the ampacity derating factor from 0.966 to 0.955, or by 1.14%, in the 4 × 120 mm² cable and from 0.965 to 0.955, or by 1.04%, in the 3 × 120 + 70 mm² cable, i.e., the influence of the tray is approximately the same.

- The influence of the tray on the ampacity of a given cable varies significantly with the harmonic signature of the load.

The eddy currents induced on the tray produce heat that is transferred to the surrounding air. However, the tray losses are very small compared to the losses in the conductors for trays with $\mu_r < 1000$ and $\sigma < 1 \times 10^8$ S/m. This can be demonstrated by the following example: a 3 × 240 + 120 mm² cable lies according to Orientation-D on a 200 mm × 100 mm × 0.8 mm tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6$ S/m and a symmetrical current with rms value equal to 435 A (this is the ampacity of the cable at 50 Hz according to [8]) flows through it. The losses in the conductors and in the tray are shown in Fig. 11 for various frequencies of the current. It is evident from Fig. 11 that even at high frequencies the tray losses are small compared to the losses in the conductors.

The tray losses do not affect the cable temperature if it is assumed that they are entirely transferred to the surrounding air. The validity of this assumption increases with the increase of tray's surface. Thus, the influence of the tray losses on the cable ampacity could be neglected.

7. Application examples

The following examples demonstrate the application of the results obtained in this paper.

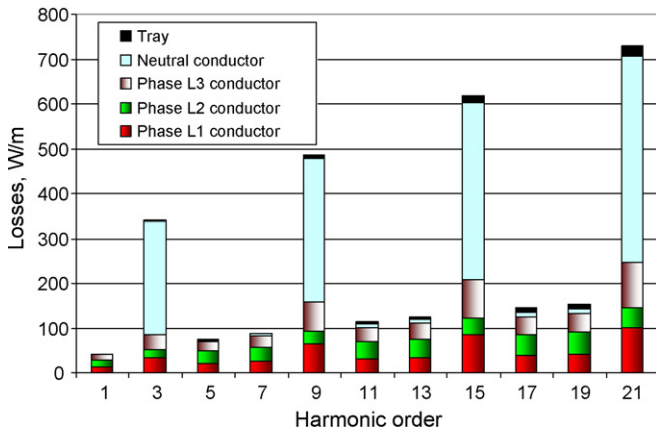


Fig. 11. Losses in the conductors and in the tray for a $3 \times 240 + 120 \text{ mm}^2$ cable laid on a $200 \text{ mm} \times 100 \text{ mm} \times 0.8 \text{ mm}$ tray in the way shown in Fig. 4d. The material of the tray has $\mu_r = 1000$ and $\sigma = 1 \times 10^6 \text{ S/m}$. At each harmonic frequency a symmetrical current of an rms value of 435 A is assumed to flow.

7.1. Derating of the cable ampacity

Assume a J1VV $3 \times 120 + 70 \text{ mm}^2$ cable which is laid on a metallic tray. No other cables are on the tray. The ambient temperature is assumed to be 35°C . According to [8], the ampacity, I_n , of the cable is calculated by

$$I_n = I_0 f_t f_n \quad (14)$$

where, I_0 is the reference ampacity of the cable at 30°C ambient temperature, f_t a coefficient for derating the ampacity according to the ambient temperature, and f_n is a coefficient for derating the ampacity according to the proximity of the cable to other cables or to cable trays. For the examined cable, $I_0 = 276 \text{ A}$, $f_t = 0.94$ and $f_n = 1$. Thus, $I_n = 276 \times 0.94 \times 1 = 259 \text{ A}$.

According to [8], this is the ampacity of the cable irrespective of the type of load current. The only assumption made is that the load is more or less symmetric. If the load is symmetric and the neutral conductor carries harmonic currents, then [8] mentions (in paragraph 523.5.2) that the current in the neutral conductor should be taken into account when determining the cable ampacity but does not mention how.

According to this paper, the ampacity of the cable is given by,

$$I_n = I_0 f_t f_n f_h \quad (15)$$

where f_h is the ampacity derating due to harmonics given in Table 4 according to the load type. Thus, if the cables is intended to feed an office load (type F), $f_h = 0.727$ and the ampacity of the cable is $I_n = 276 \times 0.94 \times 1 \times 0.727 = 189 \text{ A}$.

7.2. Calculation of cable losses

Assume a J1VV $4 \times 240 \text{ mm}^2$ cable feeding a symmetrical office load (type F). The cable is assumed to lay on a metallic tray with $\mu_r = 1000$ and $\sigma = 1 \times 10^6 \text{ S/m}$ according to Orientation-D. Let the rms value of the line current be equal to its ampacity which is calculated from (15) with $I_0 = 430 \text{ A}$, $f_t = 1$, $f_n = 1$ and $f_h = 0.732$ (from Table 4). Thus, $I_n = 315 \text{ A}$. In this case the neutral conductor carries the sum of the 3rd and 9th harmonic phase currents. According to manufacturer's data, the dc resistance of the phase and neutral conductors at 20°C is $0.07 \text{ m}\Omega/\text{m}$. Assuming that the temperature of the conductors is 50°C , the final dc resistance is $0.08 \text{ m}\Omega/\text{m}$. Table 5 shows the calculation of the cable losses per unit length. The harmonic currents are calculated from Table 3 with $I_{d,\text{rms}} = 315 \text{ A}$. The R_{ac}/R_{dc} ratios are given in Fig. 8.

It can be noticed from Table 5 that the largest part of the total losses are due to harmonic currents. Thus, the application of an active harmonic filter would reduce the losses to 19.5 W/m , i.e., by 59%. If the same cable were in free air (i.e., the influence of the tray is neglected) then, the R_{ac}/R_{dc} ratio of the phase conductors would be 1.072, 2.163, 1.809, 2.139 and 4.204 for the 1st, 3rd, 5th, 7th and 9th harmonic, respectively, while the R_{ac}/R_{dc} ratio of the neutral conductor would be 1.2, and 1.851 for the 3rd and 9th harmonic, respectively. The total losses of the cable would be 44.2 W/m and the application of an active harmonic filter would reduce the losses to 18.8 W/m .

It is evident that such calculations can help in the economic evaluation of the application of active harmonic filters in an industrial or office network.

8. Model validation

The finite element analysis model and the methodology for calculating the ac resistances of the cable conductors at various harmonic frequencies were validated in [17] by comparison with data given in [9] and measurements of losses in a real cable installation.

Table 5
Example on the calculation of cable losses per unit length

Harmonic order	R_{ac}/R_{dc} of phase conductor	R_{ac}/R_{dc} of neutral conductor	R_{ac} , of phase conductor ($\text{m}\Omega$)	R_{ac} , of neutral conductor ($\text{m}\Omega$)	Current in phase conductor, A (rms)	Current in neutral conductor, A (rms)	Cable losses (W)
1	1.111		0.089		270		19.5
3	2.531	1.224	0.203	0.098	113	339	19.0
5	2.081		0.166		98		4.8
7	2.464		0.197		53		1.7
9	4.858	1.898	0.389	0.152	29	88	2.2
Total					315	350	47.2

9. Conclusions

The effective ac resistance of four-conductor, PVC insulated low-voltage (0.6/1.0 kV) power distribution cables increases with the relative magnetic permeability and electric resistivity of the metallic tray on which they are laid. The increase is larger at higher harmonic frequencies. In situations met in practice, trays made of galvanized steel have $1 \leq \mu_r \leq 1000$ and $10^6 \leq \sigma \leq 10^7$ S/m. It was shown that the effective ac resistance of the phase-conductors of the cable is maximized when the tray has $\mu_r = 1000$ and $\sigma = 10^6$ S/m. The ac resistance of the neutral conductor increases also with the relative permeability and electric resistivity of the tray, but not as much as that of the phase conductors. The influence of tray's dimensions on the effective ac resistance of the cable was shown to be negligible.

The orientation of a four-core cable with respect to the tray also affects the ac effective resistance of the phase and neutral conductors. It was shown that the ac resistance of the cable is maximized when Orientation-B is combined with loads that are rich in zero-sequence harmonics while when the load is rich in non-zero-sequence harmonics, the ac resistance of the cable is maximized if Orientation-D is employed.

The influence of the tray on the effective ac resistance of a four-core cable was shown to depend also on the cross-section of the cable. At small cross-sections the influence was shown to be insignificant while at large cross-sections the presence of a metallic tray increased the effective ac resistance of the cable by as much as 18% at the 9th harmonic.

The influence of the tray on the ampacity of a four-core cable was shown to depend on the harmonic signature of the load current, on the cross-section of phase-conductors and on the cross-section of the neutral conductor. Ampacity derating factors in the presence of a metallic tray were calculated for five representative cables and seven load types. The calculated derating factors are on the conservative side since they were calculated assuming that the cables are placed at the corner of the metallic tray where its influence is maximized. The following general conclusions can be drawn:

- The influence of the metallic tray on the ampacity derating factor increases with the cable cross-section.
- The metallic tray influences more the ampacity of the cables in which the neutral and the phase conductors have the same cross-section than the cables with reduced neutral cross-section provided that the load is rich in zero-sequence harmonics (load types A and F). If the load is not rich in zero-sequence harmonics, the tray influences approximately equally cables with the same or reduced cross-section of the neutral conductor.
- The influence of the tray on the ampacity of a given cable varies significantly with the harmonic signature of the load. Generally a metallic tray will reduce the ampacity derating factor from 0 to 0.14% of a cable with small cross-section (16 mm^2), 0.5–2.8% of a cable with medium cross-section (120 mm^2) and 0.83–5.3% of a cable with large cross-section

(240 mm^2) with respect to the case where the tray is absent or non-metallic.

- The losses in the tray itself due to induced eddy currents were shown to be very small compared to the losses in the conductors of the cable. Therefore, their effect upon the ampacity of the cable is negligible.

The results obtained in this paper can be used for the evaluation of the additional losses caused by harmonic currents in four-core cables laid on metallic trays in an industrial or office network and for the establishment of additional correction factors regarding the ampacity of such cables.

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