Method of Calculating the Correction Factors for Cable Dimensioning in Smart Grids

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Abstract. One of the main causes of overloading electrical equipment by currents of higher harmonics is the great increasing of a number of non-linear electricity power consumers. Non-sinusoidal voltages and currents affect the operation of electrical equipment, reducing its lifetime, increases the voltage and power losses in the network, reducing its capacity. There are standards that respects emissions amount of higher harmonics current that cannot provide interference limit for a safe level in power grid. The article presents a method for determining a correction factor to the long-term allowable current of the cable, which allows for this influence. Using mathematical models in the software Elcut, it was described thermal processes in the cable in case the flow of non-sinusoidal current. Developed in the article theoretical principles, methods, mathematical models allow us to calculate the correction factor to account for the effect of higher harmonics in the current spectrum for network equipment in any type of non-linear load.

1. Introduction
There are currents in neutral conductors for feeding non-linear consumers. The appearance of these currents due to the lack of phase shift at higher harmonics are multiples of the three and fundamental frequency. In some cases, the RMS current in the neutral conductor may reach 1.5-2 times higher than in the phase conductor [1]. Overloading of neutral cable conductor caused by higher harmonic currents leads to a further increase of temperature above the limit of provided by manufacturer, which accelerates the insulation aging of the cable and therefore reduces its lifetime [2, 3]. Current harmonics cause additional heating of the equipment; this should be taken into account for selection the conductor cross-section size and control allowable currents during operation [4-6].

2. Current Harmonic Spectra of Individual Power Consumers and Their Aggregation
To determine the possible effect of higher harmonics on cable lines it is necessary to assess the levels of interference caused by nonlinear electro receivers individually and collectively. For this purpose, there were performed experiments under certain types of power appliances with nonlinear voltage-current characteristics, which are most commonly used in residential and administrative buildings. The results show that these types of power appliances create high levels of distortion in the current...
waveform (third harmonic level reaches 80...90 [%], the fifth reaches 45 [%]), while all the above power-consuming equipment comply with the standard for emissions higher harmonic components of electro receivers with consumption current less than 16 [A] [7], and therefore can be freely used by consumers in the country. Thus, the requirements of the standard [7] can’t provide such levels of higher harmonics, which do not affect the electricity network. Measurements were performed on real objects (shopping center, specializing in the sale of computer equipment, office building and houses) to determine the possible values of current harmonic and spectra. The results are shown in Table 1. These spectra were used to calculate values for the correction factors for specific types of nonlinear consumers.

Table 1. Range of harmonics current to different types of consumers to the maximum load.

| Number of harmonic | Shopping center $I_{0n}$ [%] | Administrative building $I_{0n}$ [%] | Residential building $I_{0n}$ [%] |
|-------------------|-------------------------------|--------------------------------------|-------------------------------|
| 1                 | 100.0                         | 100.0                                | 100.0                         |
| 3                 | 31.2                          | 29.3                                 | 10.3                          |
| 5                 | 18.5                          | 13.9                                 | 6.3                           |
| 7                 | 12.7                          | 10.2                                 | 4.8                           |
| 9                 | 8.6                           | 15.2                                 | 5.5                           |
| 11                | 5.4                           | 9.5                                  | 4.6                           |
| 13                | 3.2                           | 8.2                                  | 3.2                           |
| 15                | 2.7                           | 3.9                                  | 1.9                           |
| 17                | 1.7                           | 4.6                                  | -                             |
| 19                | 1.1                           | 2.2                                  | -                             |
| 21                | 0.7                           | 1.4                                  | -                             |

The flowing of non-sinusoidal current through the phase conductor of cable generates heat; power is determined by the loss of active power at the fundamental frequency and high harmonics [8]:

$$ P_{\Sigma}^{ph} = I_1^2 \cdot R_1 + \sum_{n=2}^{40} I_n^2 \cdot R_n $$  \hspace{1cm} (1)

where $I_1$ and $I_n$ are currents of the fundamental frequency and high harmonics, $R_1$ and $R_n$ - resistance at the fundamental frequency and high harmonics.

There are flowing harmonic currents of zero sequence in the neutral conductor under condition of balanced nonlinear load. This releases heat is power source, which is determined by the following formula:

$$ P_{\Sigma}^{ph} = 3 \sum_{n=3,9,15} I_n^2 \cdot R_n. $$  \hspace{1cm} (2)

Active resistance of the conductor on the n-th harmonic $(R_n)$ in (1) and (2) for $n \geq 3$ is defined by the formula [9]:

$$ R_n = R_1 \cdot (0.187 + 0.532 \cdot \sqrt{n}), $$  \hspace{1cm} (3)

where $R_1$ is the resistance of the conductor at the fundamental frequency currents, $n$ is number of the harmonic. The generated heat inside the cable, which is laid in the ground, is transmitted by the phenomenon of thermal conductivity into the surrounding space. The steady heat cable mode is described by Kirchhoff Law equation:

$$ \alpha \cdot \nabla^2 T = 0, $$  \hspace{1cm} (4)

where $\nabla$ is the Laplace operator. To develop a mathematical model for the study of the cable and thermal processes in it under the influence of harmonic currents that determine the capacity of cable lines, the most common types of cables were chosen and for each of them was composed mathematical model in the software Elcut [10]. Using this program we calculate the temperature field
of the cable according to the equation (4) for the stationary mode using finite element method.

4. Method for Determination of Ampacity Reducing due to Harmonics

General active power losses in the cable are the sum of tripled active power losses in the phase conductor and losses in the neutral conductor. Using the algebraic manipulation and formulas (1) - (3), we get the formula of general active power losses in the cable into a form which differs from the loss at the fundamental frequency, only the additional loss factor \( K_{\text{add}} \)

\[
P_\Sigma = 3 \cdot I_1^2 \cdot R_1 \cdot K_{\text{add}}
\]

\[
K_{\text{add}} = 1 + \sum_{n=2}^{40} (K_{I_n})^2 \cdot A_n + \frac{R_1^2}{R_1} \sum_{n=6k-3}^{40} (K_{I_n})^2 \cdot A_n,
\]

where \( K_n \) the current value of \( n \)-th harmonic component as a fraction of the current fundamental frequency, \( A_n = 0.187 + 0.532 \cdot \sqrt{n} \).

Then, we introduce the concept of equivalent current \( I_{eq} \). Equivalent current is the current of the fundamental frequency which flows through the three conductors and it generates the same amount of heat as through a non-sinusoidal current flowing in the three conductors and the neutral conductor. By their energy essence, the notion of an equivalent current is the transition from four sources of heat (three cores and neutral) to the three sources (three conductors), and it is assumed that all heat from power distorted currents is replaced by an equal value of active power losses created by the current at fundamental frequency, as in terms of energy no matter which of the current heats the conductor: 50 Hz sinusoidal or non-sinusoidal. Given entered term formula (5) can be written as

\[
P_\Sigma = 3 \cdot I_1^2 \cdot R_1 \cdot K_{\text{add}} = 3 \cdot I_{eq}^2 \cdot R_1
\]

where \( I_{eq} = I_1 \cdot \sqrt{K_{\text{add}}} \).

As a result, the desired correction factor to the permissible continuous current of the fundamental frequency \( K_{hh} \) is factor of higher harmonics), which recognizes the influence of harmonic currents flowing through the cable is

\[
K_{hh} = 1/\sqrt{K_{\text{add}}}
\]

This ratio is intended for selecting the power cable, as a correction value table of permissible continuous currents to prevent overheating of the cable insulation. For the RMS value of the current it is better to use other coefficient \( K_{n-l} \), which value is determined by the formula

\[
K_{n-l} = K_{hh} \cdot \sqrt{1 + \sum_{n=3}^{40} (K_{I_n})^2}
\]

4. Example of Correction Coefficients Calculation

Power cable ASB 4x150 feeds nonlinear load (shopping center). It is necessary to determine the value of the allowable long-term current at the fundamental frequency. RMS value currents in phase and neutral conductor and the coefficient of higher harmonics in which the cable insulation does not overheat. Phase current harmonic spectrum is shown in Table 1. Resistance of cable conductor \( R_1 = 0.243 \Omega/km \) Manufacturer value of permissible continuous current is \( I_{perm} = 281 \text{ A} \) [11]. From the known spectrum of harmonics initially determined by the necessary formula (6), components: \( A_n, K_{I_n}^2 \), as well as their sum of the harmonics of zero sequence occurring at neutral, across the spectrum of the current phase in the conductors. These amounts equal to \( \sum_{n=2}^{40} (K_{I_n})^2 \cdot A_n = 0.2045; \sum_{n=6k-3}^{40} (K_{I_n})^2 \cdot A_n = 0.1229 \). Further the calculated \( K_{\text{add}} \) coefficient, using formula (6), is \( K_{\text{add}} = 1 + 0.2045 + 0.1229 = 1.573 \). With the known level of magnification of additional losses \( K_{\text{add}} \), determination of the correction factor \( K_{hh} \) does not make a lot of effort
Permissible continuous current is determined by the formula (9)

\[ K_{hh} = \frac{1}{\sqrt{K_{add}}} = \frac{1}{\sqrt{1.873}} = 0.797. \]

Allowable current value of long-term fundamental frequency corrected for harmonic currents power \( P_{perm}^{new} = P_{perm}^{old} \cdot K_{hh} = 281 \cdot 0.797 = 224.04 \) [A]. Table 2 shows results of calculation of coefficients for different cable design, supplying shopping center.

**Table 2.** Results of calculation of coefficients for different cable design, supplying shopping center.

| Cable brand          | 3x120       | 3x120+1x70 | 4x120      | 4x120  |
|----------------------|-------------|------------|------------|--------|
| \( K_{n-1} \)       | 0.695       | 0.771      | 0.875      | 0.875  |

On the picture of the thermal field (Figure 1) it is shown that the maximum temperature of the hottest point of the insulation is 78.5 °C. Thus, using the method described above can be relatively easy to obtain the correction values of the coefficients. However, this method introduces an error in determining the value of the correction coefficient. This is due to the fact that heat sources are separated by an insulation which is a thermal resistance. In fact, if the current RMS value in neutral conductor is commensurate to the phase current and a neutral conductor cross-section is less than the cross-section of the phase conductor, the heat power in neutral conductor exceeds the value of the phase heat power. As a result, the most heated point of core insulation will be near neutral conductor.

5. Use of the Described Method with Respect to the Measured Spectra of Harmonics

Relative to previously measured spectra of harmonics for three types of consumers (Table 1) were obtained the following correction factors to the current values of the long-term allowable currents of the fundamental frequency (Table 3).

**Table 3.** Values of the correction factor for power cables 380 [V], supply different types of non-linear load.

| Type of load          | Value of factor \( K_{n-1} \) |
|-----------------------|---------------------------------|
|                       | For cables with phase conductor cross section greater than neutral | For cables with the same cross section neutral and phase wires |
| Shopping center       | 0.77                           | 0.88                        |
| Administrative building| 0.76                           | 0.88                        |
| Residential building  | 0.96                           | 0.97                        |

After the calculations and the subsequent analysis of the results were made the following conclusions:

1) The value of the correction factor for the four-wire cable with smaller neutral cross-section size is less than for the cables with the same cross-section sizes of neutral and phases conductors. The wider range of harmonics generated by the nonlinear load, and the more the RMS value of current harmonics (especially harmonic multiples of three), the greater the difference of the above corrections for cable cross-sections for the same phase conductors.

2) Regardless of the phase conductor cross-section size, correction factor for all sections will have the same value.

3) An office building and shopping center have about the same impact on the cable in distribution.
network 380 V due to the proximity of non-linear power appliances that are located at the consumer.

Also it has been demonstrated using calculations if the any changes for the value of the coefficients for the different types of cable designs claimed for one cross-section. Calculation with similar ratios for other cable types is considered at the example of the cable with 120 mm² cross section size of the phase conductor. For comparison, previously selected three types of cables used for laying in trenches:

- ASB 4x120 cable with paper-oil insulation;
- ASB 3x120 +1x70 cable with paper-oil insulation;
- ASB 3x120 cable with paper-oil insulated neutral conductor, performed on the cable armature;
- APvBbShp 4x120 cable with XLPE insulation.

The results of calculation and simulation (Table 3) showed that the value of the correction coefficient is not affected by the type of insulation, but defined by cross-section only by the neutral conductor.

Developed method may calculate only coefficients for the ampacity reduction due to harmonic currents, but as the heat problem is not solved it is impossible to know the temperature of the cable. Thermal resistance between the conductor and the sheath (S1) for three core cables with sector conductors and core wrapping insulation is determined by the formula

$$S_1 = \frac{\rho T}{2\pi} \cdot 3 \cdot \left( 1 + \frac{3\tau}{2\pi (d_x + t)} \right) \cdot \ln \left( \frac{d_a}{r_1} \right);$$  \hspace{1cm} (11)

where \(\rho T\) is the thermal resistance of insulation, [K ∙ m / W]; \(d_o\) is core diameter, [mm]; \(r_1\) is the radius of the circle circumscribed around the cores, [mm]; \(dX\) is the diameter of a circular conductor with a cross sectional area and the degree of compaction, that the shaped conductor [mm]; \(t\) is thickness of insulation between core and metal wrapping, mm.

Thermal resistance between the sheath and armor

$$S_2 = \frac{\rho T}{2\pi} \cdot \ln \left( 1 + \frac{2t_2}{D_s} \right);$$  \hspace{1cm} (12)

where \(t_2\) is the thickness of the cushion under armor, [mm]; DS is outer diameter of surface, [mm].

Thermal resistance of the outer protective coating

$$S_3 = \frac{\rho T}{2\pi} \cdot \ln \left( 1 + \frac{2t_3}{D_a} \right);$$  \hspace{1cm} (13)

where \(t_3\) is the thickness of the protective coating, [mm]; \(D_o\) is outer diameter of armor (for unarmored take outer diameter element, usually located directly under the armor, i.e. shell, screen or pillows), [mm].

Thermal resistance of the environment for insulated cable laid in the ground is

$$S_4 = \frac{\rho T}{2\pi} \cdot \ln \left( \frac{2L}{D_e} + \sqrt{\left( \frac{2L}{D_e} \right)^2 - 1} \right);$$  \hspace{1cm} (14)

where \(L\) is distance from the surface of the ground to the cable, [mm]; \(D_i\) is cable outer diameter, [mm].

Temperature of core insulation for four-wire cable will be equal

$$\tau_c = P_c' \cdot S_1 + 3 \cdot P_c (S_2 + S_3 + S_4) + \tau_a,$$  \hspace{1cm} (15)

where \(\tau_a\) is ambient temperature, [K].

For three-core cable with neutral conductor formed on the sheath

$$\tau_c = P_c \cdot S_1 + 3 \cdot (P_c + P_n)(S_2 + S_3 + S_4) + \tau_a.$$  \hspace{1cm} (16)

Figure 1. Picture of the thermal field in the cable ASB 4x150.
Formulas (15) and (16) show that the temperature of core insulation is directly dependent on the heat with the constant component that is equal to the ambient temperature. Using these expressions does not introduce a large error in the final result, which was confirmed by the results of calculation and subsequent comparison with the results of mathematical simulation. Error was less than 2%. This is primarily due to the fact that the greatest resistance is the thermal resistance of the earth; it is about 60% of the total. Thus, the heat equivalent conversion from the conductors cannot make a significant error.

6. Summary
The proposed method of calculating the correction factors can be applied on the stage of cable selection which supplies residential areas, and during periodic monitoring of the current in distribution networks. The value of the correction factor depends on cross-section size of neutral and harmonic current spectrum. Regardless of the phase conductor cross-section size, correction factor for all cross-sections will have the same value. The approach can be used for three and four core cable lines for all types of insulation voltage up to 20 kV. Using of developed method in special software will protect distribution networks and gives opportunity for management electricity consumption and operating network ampacity.

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