Low voltage conductor's ampacity derating due to stationary disturbances

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***Abstract*—This paper presents a method to estimate the derating in Low Voltage (LV) conductors due to the presence of stationary power quality disturbances. The temporary increases in the rms-values of the voltages and currents caused by stationary disturbances, i.e. waveform distortion, unbalance and phase displacement, cause increases of power losses in the conductor and operation temperature. These power losses force to study the methods to calculate the cable ampacity due to stationary disturbances. Currently available models are employed; the expected power quality disturbance levels are extracted from power quality data bases. A discussion about the effects on insulation lifetime is presented.**

***Index Terms*—Power quality, insulation lifetime, Aging Factor, Phase displacement, Harmonic Derating Factor.**

I. Introduction

THE the massive usage of non-linear loads like Compact Fluorescent Lamps, LED based lamps, electric vehicles, electric appliances, computers, communication devices, etc., has led to an increase in harmonic distortion, voltage and current asymmetry and reactive power consumption. These disturbances cause many undesirable effects including thermal stresses, capable of accelerating the insulation's aging in electric power equipment. This condition is the main cause of lifetime's decrease and premature failures in the conductors' insulation.

This lifetime decrease lead to a re-calculation of the cable ampacity (derating) in order to mitigate aging issues due to the effect of stationary disturbances.

In this paper a method for estimating the derating for LV conductors due to the presence of stationary power quality disturbances is presented. The estimation of lifetime reduction is extracted from currently available procedures. These procedures are adapted to take into account the currents related to the considered power quality disturbances.

II. Derating in low voltage conductors

The increase of power losses in low voltage conductors is the main cause of temperature rise. These power losses due to harmonics currents may cause a derating in the conductor's Ampacity. To find the derating it's important to determine the power losses.

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A. Power losses due to harmonics currents in low voltage conductors

The power losses in the conductors are based on Joule effect losses due to current flow. The basic expression of the Joule Effect is the product between the resistance of the conductor and the square of the current (I^2R). If the power system contains nonlinear loads, the current contains a harmonic spectrum and the value of the conductor resistance becomes frequency-dependent. These changes affect and increase the result of the power losses. References [1]-[4] have raised a number of equations to determine the magnitude of power losses.

The first step is to determine the AC resistance in the cable (1)-(2).

$$R_{AC} = R_{DC}\left[1 + Y_S + Y_P\right] \tag{1}$$

$$R_{DC} = R_{20}\left[1 + \alpha_{20}(\Theta - 20)\right] \tag{2}$$

Where, R_{DC} is the DC resistance at maximum operating temperature in Ω/km, Y_S is the skin effect and Y_P is the proximity effect, R_{20} is the DC resistance at 20^{o}C, α_{20} is the temperature coefficient of resistance for conductor material at 20^{o}C per Kelvin and Θ is the maximum operating temperature in Celsius.

Two effects are added to the AC resistance. One is the Skin effect (Fig. 1) which cause a redistribution of the current within the conductor [9]. The other is the Proximity effect (Fig. 2) due to the arrangement of the conductors which provides a redistribution of the current in the adjacent conductors. Both effects are frequency-dependent [9].

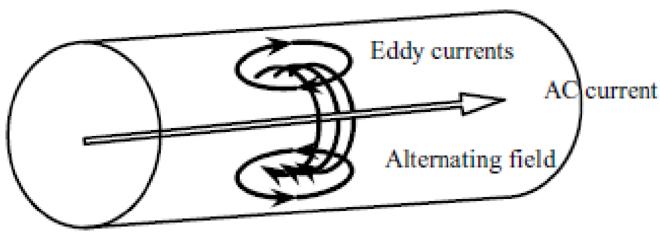

Fig. 1. Schematic representation of the skin effect [2]

Standard IEC-60287-1-1[1] defines the skin and the proximity effect as follows:

$$Y_S = \frac{x_s^4}{192 + 0.8x_s^4} \tag{3}$$

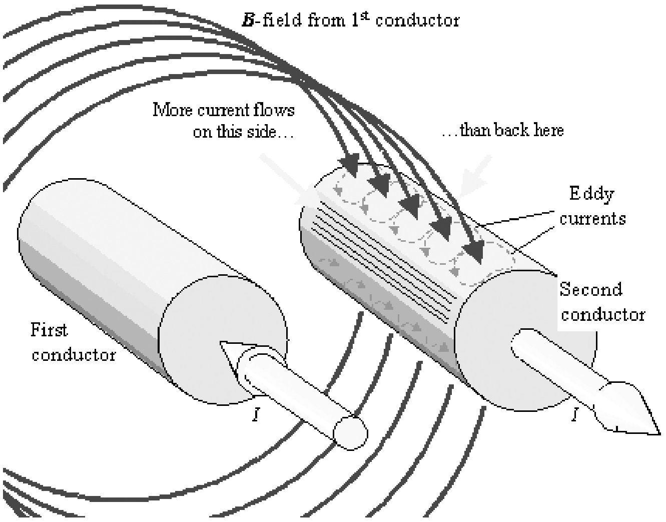

Fig. 2. Schematic representation of the Proximity effect [5]

$$Y_P = \frac{x_p^4}{192+0.8x_p^4}\left(\frac{d_c}{s}\right)^2 \times \left(0.312\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{x_p^4}{192+0.8x_p^4}+0.27}\right) \quad (4)$$

$$x_s^2 = \frac{8\pi f}{R_{DC}}10^{-7}k_s \quad (5)$$

$$x_p^2 = \frac{8\pi f}{R_{DC}}10^{-7}k_p \quad (6)$$

Where f is the frequency, d_c is the diameter of the conductor in millimeters (mm), s is the distance between conductor axes in mm and k_s and k_p are constant values given in table 2 of [1].

To simplify the AC resistance equation, [4] raises a fifth order solution for the skin and proximity effect which is frequency dependent.

$$Y_S = 10^{-3}(-1.04x^5 + 8.24x^4 - 3.24x^3 + 1.447x^2 - 0.2764x + 0.0166), \text{ if } x \le 2 \quad (7)$$

$$Y_S = 10^{-3}(-0.2x^5 + 6.616x^4 - 83.345x^3 + 500x^2 - 1061.9x + 769.63), \text{ if } 2 < x \le 10 \quad (8)$$

$$Y_P = Y_S\left(\frac{d_c}{s}\right)^2\left(\frac{1.18}{Y_S+0.27} + 0.312\left(\frac{d_c}{s}\right)^2\right) \quad (9)$$

$$x = 0.027678\sqrt{\frac{f\mu}{R_{DC}}} \quad (10)$$

Where x is the skin parameter and μ is the magnetic permeability. Some cable handbooks give the information of the resistance gain due to the skin effect.

With the resistance and the current harmonic spectrum, the power losses are calculated, but with some considerations. First, the current rms value of all conductors are the same (the system is balanced).Second, the neutral conductor carries triple order harmonics only [3],[10]. Third, the magnitude for the neutral harmonic current is three times the magnitude of the triple order phase harmonic current. With this, the power loss equation using Joule effect is:

$$P_{cable} = 3I_{(1)}^2 R_{AC,P(1)} + 3\sum_{h=2}^{h_{max}}(I_{(h)}^2 R_{AC,P(h)}) + \sum_{h=3n}^{h_{max}}((3I_{(h)})^2 R_{AC,N(h)}) \quad (11)$$

Where, P_{cable} is the power loss in non-sinusoidal conditions in Watts (W), $I_{(1)}$ is the current for the fundamental frequency in Amps (A), $R_{AC,P(1)}$ is the AC resistance for the fundamental frequency in Ohms (Ω), $I_{(h)}$ is the current for the harmonic order h in A, $R_{AC,P(h)}$ is the phase AC resistance for the harmonic order h in Ω, h_{max} is the maximum harmonic order and $R_{AC,N(h)}$ is the neutral AC resistance for the harmonic order h in Ω.

With the cable losses, the current derating can be calculated. Reference [3] proposes a derating factor k from (11) and assuming that the non-sinusoidal losses are equal to the sinusoidal losses.

$$3I_{(1)}^2 R_{AC,P(1)} = 3I_{(1)}^2 R_{AC,P(1)} + 3\sum_{h=2}^{h_{max}}(I_{(h)}^2 R_{AC,P(h)}) + \sum_{h=3n}^{h_{max}}((3I_{(h)})^2 R_{AC,N(h)}) \quad (12)$$

$$k = \frac{I_{d,rms}}{I_{(1)}} \quad (13)$$

$$I_{d,rms}^2 = I_{(1)}^2 + \sum_{h=2}^{h_{max}} I_{(h)}^2 \quad (14)$$

$$k = \sqrt{\frac{\beta_1}{\alpha_1^2\beta_1 + \sum_{h=2}^{h_{max}}(\alpha_h^2\beta_{p,h}) + 3\sum_{h=3*n}^{h_{max}}(\alpha_h^2 * \beta_{n,h})}} \quad (15)$$

$$\beta_1 = \frac{R_{AC,P(1)}}{R_{DC}} \quad (16)$$

$$\alpha_1 = \frac{I_{(1)}}{I_{d,rms}} \quad (17)$$

$$\alpha_h = \frac{I_{(h)}}{I_{d,rms}} \quad (18)$$

$$\beta_{p,h} = \frac{R_{AC,P(h)}}{R_{DC}} \quad (19)$$

$$\beta_{n,h} = \frac{R_{AC,N(h)}}{R_{DC}} \quad (20)$$

Where $I_{d,rms}$ is the rms distorted current.

III. Derating of Low Voltage Conductors Due to Other Stationary Disturbances

The derating factor proposed above is based on the harmonic currents, but this is not the only stationary disturbance. Exist other stationary disturbances like phase displacements, which leads to study the contribution that may have these two perturbations in the ampacity derating.

Reference [6], made a current decomposition considering the following aspects. First if the voltage is approximately sinusoidal, the fundamental current, fundamental reactive current, the distorted current and the displacement power factor can be calculated. Third, the decomposition is made for 1-phase and 3-phase balanced systems.

$$I_{(1)} = \frac{I_{rms}}{\sqrt{1+THD_I^2}} \tag{21}$$

$$cos\phi_1 = TPF\sqrt{1+THD_I^2} \tag{22}$$

$$I_{rms} = \sqrt{I_{(1)}^2 + \sum_{h=2}^{h_{max}} I_{(h)}^2} \tag{23}$$

$$I_{rms} = \sqrt{I_{(1)}^2 + I_{(h)}^2} \tag{24}$$

$$\dot{I}_{(1)} = I_{(1p)} + jI_{(1q)} \tag{25}$$

$$\dot{I}_{(1)} = I_{(1)}(cos\phi_{(1)} + jsin\phi_{(1)}) \tag{26}$$

Where $I_{(1p)}$ is the fundamental active current, $I_{(1q)}$ is the fundamental reactive current (or phase displacement current [7],[8]), TPF is the true power factor and THD_I is total harmonic distortion.

With the magnitude of (26), (11) is rewritten to obtain a new power losses equation.

$$P_{cable} = P_a + P_q + P_h \tag{27}$$

$$P_a = 3R_1(I_{(1p)}^2) \tag{28}$$

$$P_q = 3R_1(I_{(1q)}^2) \tag{29}$$

$$P_{cable} = 3R_1(I_{(1p)}^2 + I_{(1q)}^2) + P_{h,ph} + P_{h,nt} \tag{30}$$

I_{1p} and I_{1q} are included in (14) to solve again the ampacity derating factor (13).

$$I_{d,rms}^2 = I_{(1p)}^2 + I_{(1q)}^2 + \sum_{h=2}^{h_{max}} I_{(h)}^2 = I_{(1p)}^2 + I_{(1q)}^2 + I_{(D)}^2 \tag{31}$$

$$k = \sqrt{\frac{\beta_1}{\alpha_1^2\beta_1 + \alpha_Q^2\beta_1 + \sum_{h=2}^{h_{max}}(\alpha_h^2\beta_{p,h}) + 3\sum_{h=3n}^{h_{max}}(\alpha_h^2\beta_{n,h})}} \tag{32}$$

$$\alpha_Q = \frac{I_{1q}}{I_{d,rms}} \tag{33}$$

IV. Simulation and Results

In order to compare (32) with (15) a simulation is performed in MATLAB with two cases. Case 1-Blue (with harmonics currents); Case 2-Red (with harmonics and phase displacements currents). The diagram showed in Fig 3, represents the flowchart implemented in an M-File.

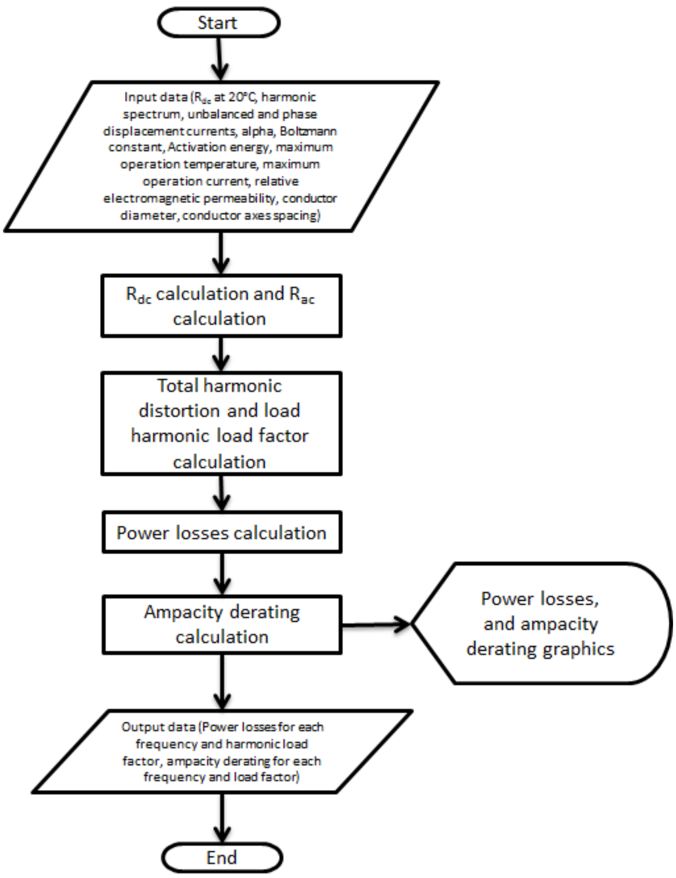

Fig. 3. Implementation flowchart

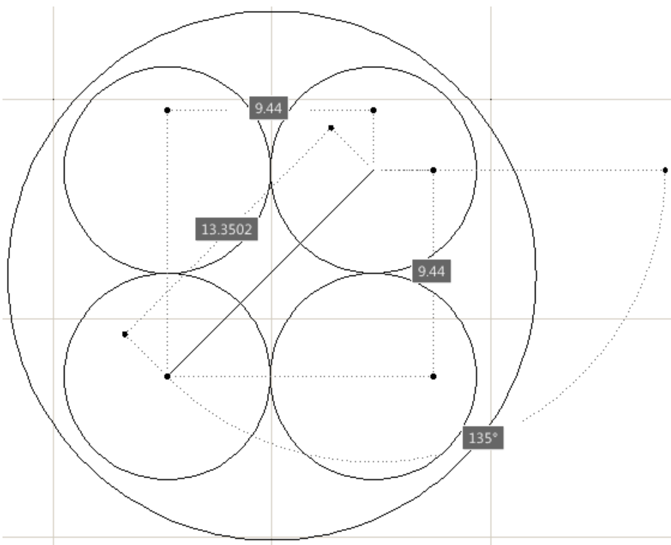

Fig. 4. Conductors physical distribution

A 4-core 2/0 cable with XLPE insulation is used to perform the simulation. Fig 4 shows the distribution inside the cable [3] and Table I are the physical and chemical parameters for the cable. The harmonic spectrum for the simulation is presented in Table II and Fig. 5. The blue bars correspond to the phase harmonic current and the red bars are the neutral harmonic current. The harmonic current in the neutral conductor is the sum of the zero sequence harmonics components in the phase conductor [10].

TABLE I
4-CORE 2/0 XLPE CABLE CHARACTERISTICS

Parameter	Value	Unit
Conductor size	4x2/0	
Dielectric activation energy	1.28	eV
Boltzmann constant	8.62×10^{-5}	eV/K
DC resistance at 20^{o}C	0.268	Ω/km
Maximum conductor temperature	90	^{o}
Fundamental frequency	60	Hz
Temperature coefficient α_{20}	3.93×10^{-3}	/K
Relative magnetic permeability	1	
Phase conductor diameter	9.44	mm
Neutral conductor diameter	9.44	mm
Axial spacing between conductors	10.6	mm
Rated current	280	A
Measured current	237	A
Current loading	85	%

TABLE II
PER-UNIT HARMONIC DISTRIBUTION

Harmonic order	Value	Harmonic order	Value
1	1.000	15	0.114
3	0.770	17	0.085
5	0.460	19	0.060
7	0.270	21	0.042
9	0.200	23	0.051
11	0.182	25	0.032
13	0.151		

The active, reactive and harmonics currents magnitudes are show in Table III. This decomposition is made in [4] from measurements of the current in the cable. The phase displacement current is the reactive current, as explained before. The program is simulated from 0% of Harmonic load factor or HLF (no harmonics) to 100% (full harmonic content).

TABLE III
CURRENT DECOMPOSITION ACCORDING TO [4]

Cable segment	I_1 [A]	I_{1p} [A]	I_{1q} [A]	I_h [A]
Phase	168.42	163.53	40.31	166.74

Fig. 6 shows the comparison of power losses in both cases. The difference between both cases cannot be detailed, so a zoom-in is performed between 0% and 20% of Harmonic Load Factor (HLF) and other between 80% and 100% of HLF.

The power loss for HLF=2% in Case 1-Blue is 1.0012p.u., while the power losses in Case 2-Red is 1.0372p.u., which

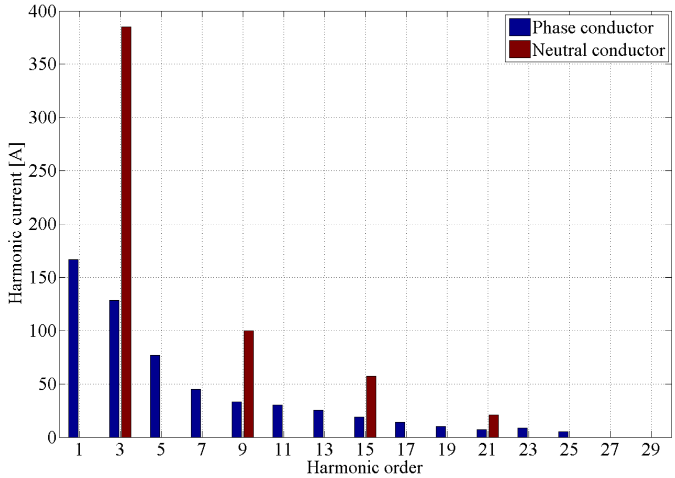

Fig. 5. Phase and neutral harmonic Spectrum

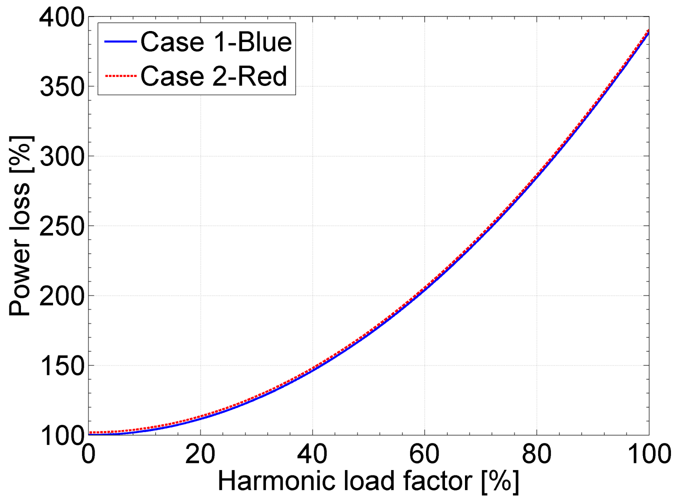

Fig. 6. Power losses for both simulations

means a difference of 3.60% (as seen in Fig. 7). Then with HLF=18%, the difference remains decreases slightly to 3.27%. Looking when the HLF=80% to HLF=100%, power loss for Case 1-Blue is 4.0632p.u., and power loss for Case 2-Red is 4.0992p.u., (Fig. 8). The difference between both cases decrease to 0.89%, showing the lower contribution of power loss due to phase displacement over harmonic currents. The summary of power losses results is shown Table IV.

TABLE IV
POWER LOSSES RESULTS

HLF [%]	Case 1-Blue [p.u.]	Case 2-Red [p.u.]	Difference [%]
2	1.0012	1.0372	3.60
18	1.0992	1.1352	3.27
50	1.7658	1.8018	2.04
80	2.9605	2.9964	1.21
100	4.0632	4.0992	0.89

Fig. 9 shows the change in the ampacity derating on the cable with increase of the Harmonic Load Factor. When the HLF is 0%, the derating in Case 1-Blue is 100%, while the

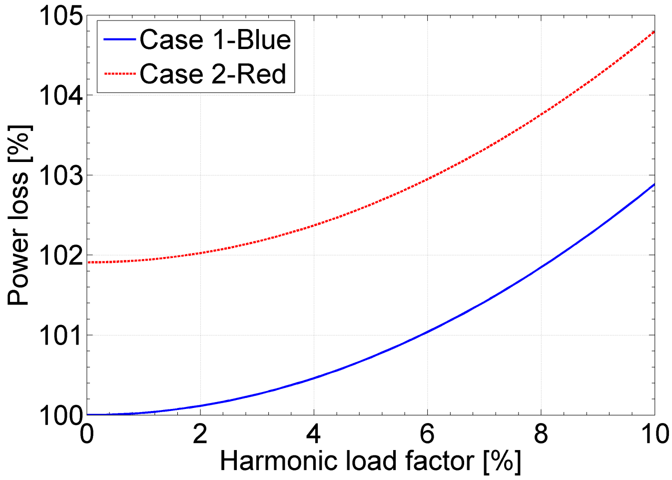

Fig. 7. Zoom-in of Power losses for HLF=0% to 20%

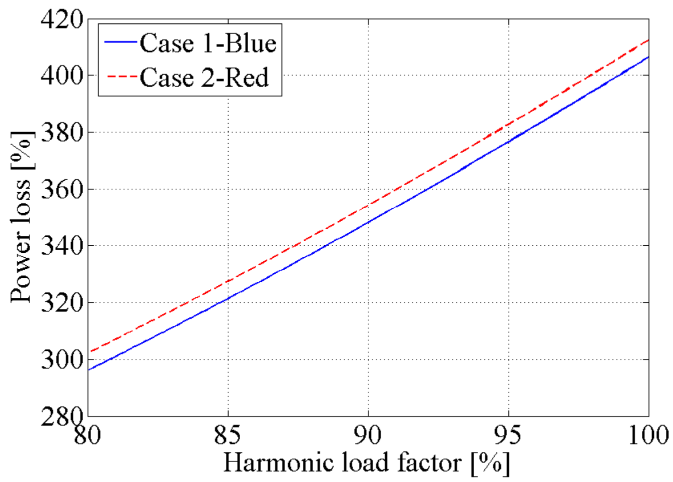

Fig. 8. Zoom-in of Power losses for HLF=80% to 100%

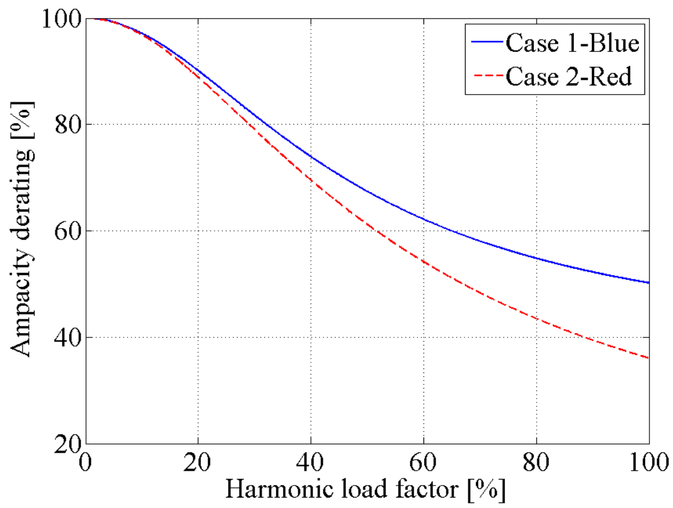

Fig. 9. Ampacity derating for both simulations

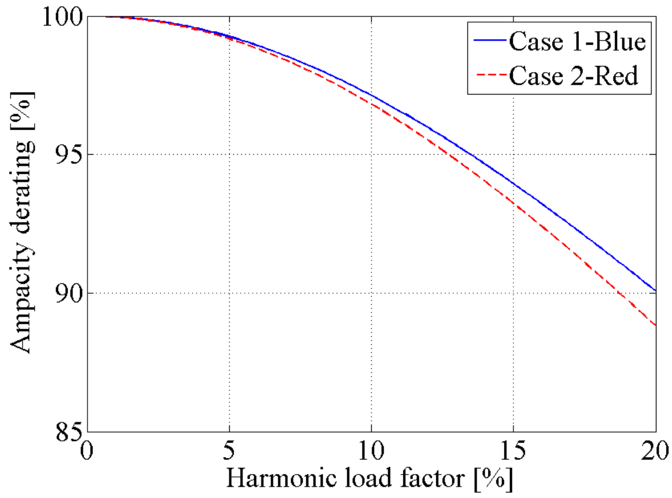

Fig. 10. Ampacity derating for HLF=0% to HLF=20%

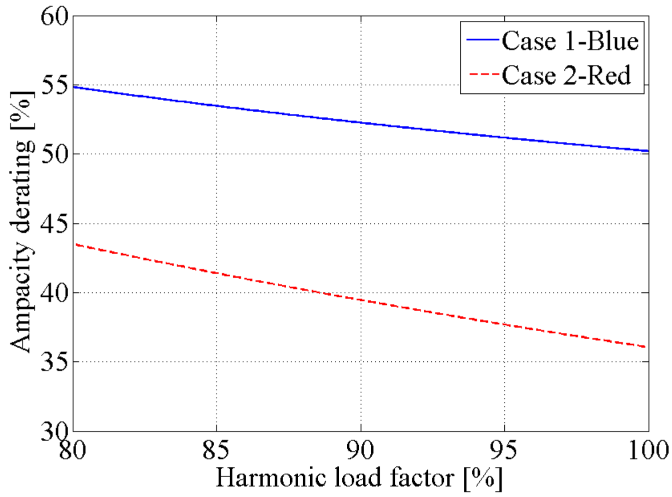

Fig. 11. Ampacity derating for HLF=80% to HLF=100%

derating in Case 2-Red down to 99.99%, a minimum decrease caused by other stationary disturbances than harmonics currents. After reaching a HLF=20%, the loss of life drops to 90.07% in Case 1-Blue and 88.81% in Case 2-Red, increasing the difference to 1.26%. At this point the phase displacement is the main cause of power losses. With increasing the HLF, the difference between the two cases increases, because the power losses due to harmonic currents start to be significant.

On the other hand, if the HLF=80%, the difference between both cases rise to 11.33%. This implies that the harmonic currents begin to take importance in the cables' power losses. Finally For a HLF=100% the new ampacity for the cable, with harmonic currents (Case 1-Blue) is 50.2% and with harmonic currents and phase displacements currents (Case 2-Red) is 36.04% (a difference of 14.16%). This progressive rise in the difference show the harmonic currents influence in the change in cable ampacity. The summary of Derating results is shown in Table V.

V. Discussion

The previous results show that current waveform distortion (current harmonics) is the main cause of accelerated degradation for insulation material and loss of ampacity in low-voltage

TABLE V
DERATING RESULTS

HLF [%]	Case 1-Blue [%]	Case 2-Red [%]	Difference [%]
0	100	99.99	0.001
20	90.07	88.81	1.26
50	67.39	61.15	6.24
80	54.82	43.49	11.13
100	50.2	36.04	14.16

conductors due to overheating. In this paper, voltage distortion was not taken into account, although they also degrade the insulating material.

The presence of current waveform disturbances cause temperature rise in the cable. That is why studies are focused on power losses due to the Joule's effect, decreasing the nominal current capacity in the conductor. The effects of voltages waveform disturbances focused on studies of aging and failure of the dielectric materials.

Nevertheless, waveform disturbances are not the only stationary disturbance which can decrease the ampacity. Any disturbance that may increase RMS levels of voltage and current RMS for long time intervals can cause increased in power losses, reducing the cables' ampacity, as seen in the simulation.

Due to the low contribution of power losses of phase displacement currents, there are few studies of Ampacity derating considering all stationary disturbances.

VI. CONCLUSIONS

This paper presents a methodology for the estimation of ampacity derating due to stationary disturbances through the application of existing methods and the use of current decomposition techniques.

Two cases are simulated with this derating method. Case one with harmonic currents. Case two with harmonics currents and phase displacements currents.

The power losses are mainly caused by harmonic currents as well the cable ampacity, as seen in the reviewed methods.

In Case 2-Red, the phase displacement currents affects the cable ampacity from HLF=0%. Once the HLF reaches 40%, the contribution of the harmonic current is noted and Case 2-Red ampacity drops more than Case 1-blue.

These results are due to the magnitude in the phase displacement current. Also, this disturbance consider only the fundamental AC resistance because is not frequency-dependent.

Also, the results only consider phase displacement current. In other works [7],[8], unbalance currents are part of stationary disturbances in poly-phase systems. This type of disturbance can increase the power losses decreasing the cable ampacity.

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