Effects of stationary power quality disturbances on lifetime of low voltage conductors

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***Abstract*—This paper presents a method to estimate the effects over the expected lifetime in Low Voltage (LV) conductors due to the presence of stationary power quality disturbances. The cable insulation aging can be accelerated by temporary increases of rms values of voltages and currents caused by stationary disturbances, i.e. waveform distortion, unbalance and phase displacement. A short duration increase of rms values cannot cause a significant reduction of insulation's lifetime, but its recurrent presence during long time periods will produce a cumulative effect. Currently available models for insulation aging 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, Harmonics, Unbalance, Phase displacement, Arrhenius equation, Aging Factor.**

I. Introduction

THE increased use of nonlinear loads in Colombian residences have led to the presence of stationary disturbances that deteriorates the power quality in the distribution system. These disturbances cause overheating in the dielectric material, increasing the aging rate. This overheating is the main cause of loss of life and premature failure in the LV cables.

Previous studies made by the Universidad Nacional de Colombia and CODENSA have revealed that the increase of harmonics distortion is one of the majors problems in power quality. It was also found that only certain frequency values are more common harmful for power equipment and the electric network.

These results have led to the study of the impact, not only of wave distortions, but stationary disturbances and their contributions in overheating and aging of the conductor's insulation. The non-linear loads that impact the power quality are electronic devices (computers, TV sets, communication devices, chargers), compact fluorescent and LED based lamps, among others.

This paper presents a method for the estimation of LV conductors overheating and aging due to harmonic distortions and how can include other stationary disturbances. Methodologies for estimating the aging and loss of life included are extracted from currently available methods.

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II. Aging in low voltage conductors

Aging in electrical equipment such as low voltage conductors are given by different factors, but the most important is overheating, because this is the main cause of degradation in dielectric material. There are several phenomena that can cause an increase in the internal temperature, so it's important to review these factors and how they relate to aging and premature loss of life.

A. Aging in low voltage conductors due to temperature rise

Different studies about aging in conductors have shown that temperature rise is the main cause of accelerate aging in the dielectric material in electrical equipment. Some works are based on the results of the study of the Arrhenius thermal reaction theory or Arrhenius equation [1]. This equation relates a specific rate of chemical reaction in the material and the temperature, as shown in (1). This equation led to the formulation of an aging factor (2) to estimate loss of life in the conductors.

$$K_0 = Ae^{\frac{-E_a}{k\Theta}} \tag{1}$$

$$F_A = e^{\frac{E_a}{k}\left(\frac{1}{\Theta_H+273} - \frac{1}{\Theta_{H,R}+273}\right)} \tag{2}$$

Where K_0 is the reaction rate constant, A is a constant that depends in part on chemical concentrations in the reaction, E_a is the activation energy of the degradation process, Θ is the absolute reaction temperature in Kelvin, k is the Boltzmann constant, F_A is the Aging Factor, $\Theta_{H,R}$ is the maximum allowable temperature in Celsius and Θ_H is the conductor temperature in Celsius.

With F_A can calculated the loss of life for constant temperature, but the issue is when there are different temperature values during different time intervals. Therefore is necessary to determine a cumulative aging factor or F_{EQA} (3). With the F_A or F_{EQA} the Loss of life (ΔL)(4) [2] can be calculated.

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{A,n} \times \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{3}$$

$$\Delta L = \frac{F_{EQA} \times t \times 100}{NIL} \tag{4}$$

Where N is the total number of time intervals, $F_{A,n}$ is the aging factor for the time interval n, Δt_n is the time interval n in hours, t is the study time in hours and NIL the standard dielectric (insulator) lifetime in hours.

B. Aging in low voltage conductors due to harmonic currents

Different studies about aging have shown that electrical stresses is the main cause of temperature rise and accelerated aging in conductors. References [3]-[7] show that harmonics currents are the main cause of overheating in electric conductors, degrading the dielectric material and reducing its lifetime.

A series of equations has been proposed in [3]-[7] to estimated temperature rise and lifetime reduction in low voltage cables based on the I^2R power losses in phase and neutral conductors due to the harmonic currents. These equations consider the change in the AC resistance due to the different frequency value in the harmonic spectrum. Also considers two important effects such as the skin effect and proximity effect, also frequency-dependent.

References [3] to [5] defines the AC (5) resistance as a value dependent of the DC resistance, the skin and proximity effect. Also it defines the DC resistance (6) as temperature dependent value.

$$R_{AC} = R_{DC}\left[1 + Y_S + Y_P\right] \tag{5}$$

$$R_{DC} = R_{20}\left[1 + \alpha_{20}(\Theta - 20)\right] \tag{6}$$

Where R_{DC} is the DC resistance at maximum operating temperature in ohms per distance, Y_S is the skin effect and Y_P is the proximity effect, R_{20} is the DC resistance at 20^{o}C in ohms per kilometer, 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.

From the definitions of [3] to [5], [8] defines the skin effect (7), (8) and the proximity effect (9) as follows.

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

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

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

$$x = 0.027678\sqrt{\frac{f * \mu}{R_{DC}}} \tag{10}$$

$$x = 0.015281\sqrt{\frac{f * \mu}{R_{DC}}} \tag{11}$$

Where x is the skin effect parameter, d_c is the diameter of the conductor in millimeters (mm), s is the distance between conductor axes in mm, f is the harmonic frequency component in hertz (Hz) and μ is the magnetic permeability (one for nonmagnetic material). If R_{DC} is in $[\Omega/1000ft]$, (10) should be used and if is $[\Omega/km]$, (11) should be used.

After obtaining the resistance for each frequency component, the next step is the calculation of the power losses (13)-(16) due to the harmonic current and the AC resistance. It's important to note that the phases have the same value for harmonic current and resistance, the neutral conductor only carries triple harmonics currents [7] and the magnitude is three times the phase current harmonic magnitude.

$$\Delta P_{cable} = \Delta P_a + \Delta P_h \tag{12}$$

$$\Delta P_h = \Delta P_{h_{ph}} + \Delta P_{h_{nt}} \tag{13}$$

$$\Delta P_a = \sum_{p=1}^{3} I^2_{(1,p)} * R_{AC(1,p)} \tag{14}$$

$$\Delta P_{h_{ph}} = \sum_{p=1}^{3}\sum_{h=2}^{h_{max}} I^2_{(p,h)} * R_{AC(p,h)} \tag{15}$$

$$\Delta P_{h_{nt}} = \sum_{h=3*n}^{h_{max}} (3 * I_{(h)})^2 * R_{AC,n(h)} \tag{16}$$

Where, ΔP_{cable} is the power loss in non-sinusoidal conditions in Watts (W), ΔP_a is the power losses in sinusoidal conditions for phase and neutral conductors in W, $\Delta P_{h_{ph}}$ is the harmonic power losses for phase conductors in W, $\Delta P_{h_{nt}}$ is the harmonic power losses for the neutral conductor in W, p is the phase (r, s, t), $I_{(1,p)}$ is the phase current for the fundamental frequency in Amps (A), $R_{AC(1,p)}$ is the phase AC resistance for the fundamental frequency in Ohms (Ω), $I_{(p,h)}$ is the phase 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.

From cables' power losses, the temperature rise can be calculated based on the maximum operating temperature and the ratio between the non-sinusoidal losses and the sinusoidal losses [9].

$$\Theta_H = \Theta_{H,R} * \frac{\Delta P_{cable}}{\Delta P_a} \tag{17}$$

Where, Θ_H is the temperature under non-sinusoidal conditions and $\Theta_{H,R}$ is the maximum operation temperature, both in Celsius.

Applying the result of (17) in (2) can calculate the aging and the expected loss of life.

III. Lifetime of Conductors Due to Other Stationary Disturbances

Aging studies in power equipment are especially centered in the overheating caused by the fundamental current and the present harmonic currents, as seen in the previous section. The issue is that this is not the only stationary perturbation in the power system. Unbalances and phase displacements are also stationary disturbances which can cause rise in the current magnitudes, increasing the power losses, operation temperature and aging factor.

Reference [10], made a complete the current decomposition for poly-phase systems. First it consider decomposition for single phase systems maintaining the same approach of [8], but using non-active current instead of reactive current. Then it separates the non-active current as shows in (20).

$$I^2 = I_a^2 + I_x^2 \tag{18}$$

$$I_x^2 = I_{au}^2 + I_{qd}^2 + I_{qu}^2 + I_h^2 \tag{19}$$

$$I^2 = I_a^2 + I_{au}^2 + I_{qd}^2 + I_{qu}^2 + I_h^2 \tag{20}$$

$$I^2 = [I_r^2, I_s^2, I_t^2, I_n^2] \tag{21}$$

Where I_a is the fundamental active current (same $I_{(1)}$), I_{au} is the active unbalance current, I_{qd} is the reactive displaced current, I_{qu} is the reactive unbalanced current and I is the general phase current vector.

With (20) and (13) can rewrite a new power losses equation adding displaced current and unbalanced current. Note that in balance systems, active power losses in the neutral conductor is equal to zero, but for unbalanced systems must consider possible active power losses in the neutral conductor.

$$\Delta P_{cable} = \sum_{p=1}^{4} I_{(1,p)}^2 * R_{AC(1,p)} + R_1 \left(\sum_{p=1}^{4} I_{au}^2 + \sum_{p=1}^{4} I_{qd}^2 + \sum_{p=1}^{4} I_{qu}^2 \right) + P_{h_{ph}} + P_{h_{nt}} \tag{22}$$

IV. Simulation and Results

To compare the effects of the stationary disturbances (harmonics, unbalance and phase displacements) against only harmonic currents, two cases are simulated. The first (case 1) only with harmonic currents and the second (case 2) include harmonic, unbalanced and phase displacement currents. To show aging model for stationary disturbances, (5) to (22) are implemented in a M-file in MATLAB. The diagram showed in Fig 1, represents the flowchart of the implementation.

The conductor used is a 4-core 2/0 cable with XLPE insulation. Fig 2 shows an example of the conductor configuration inside the cable and the physical and chemical parameters of the cable are shown in Table I. The harmonic spectrum for the simulation is presented in Table II and Fig. 3.

For each case, a total of 4001 simulations are performed. In each simulation, the magnitude of each harmonic is 0% (no harmonics), 10%, 50%, 100%, 200%, up to 400% (four times the magnitude of the harmonic). This percentage value is known as the Harmonic Load Factor (HLF) and represents the magnitude percentage for each simulation.

Using these parameters can obtain the following results. Fig. 4 shows the comparison of power losses in both cases and Table III show the power losses for 0%, 25%, 50%, 100%

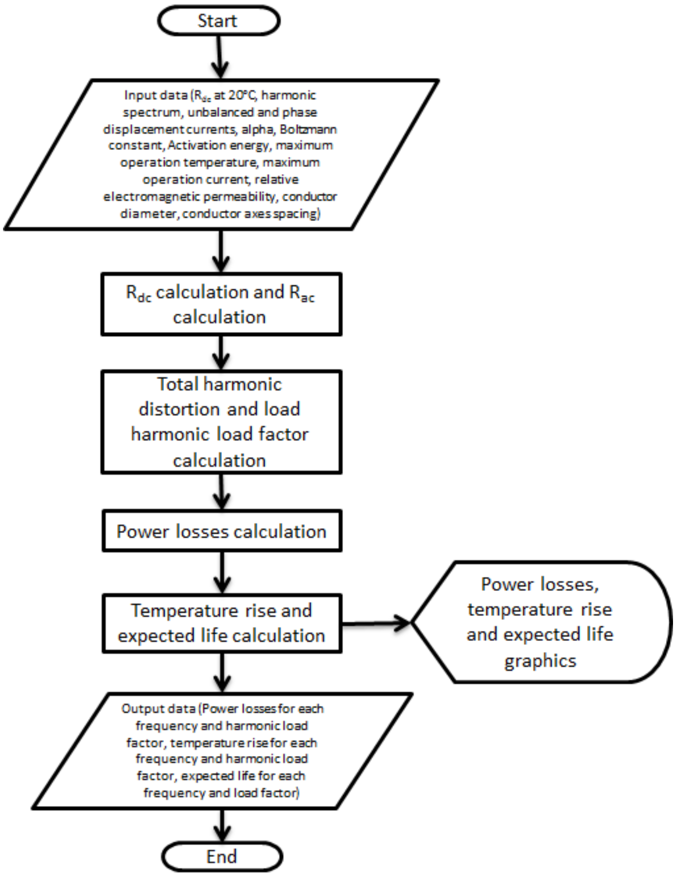

Fig. 1. Implementation flowchart

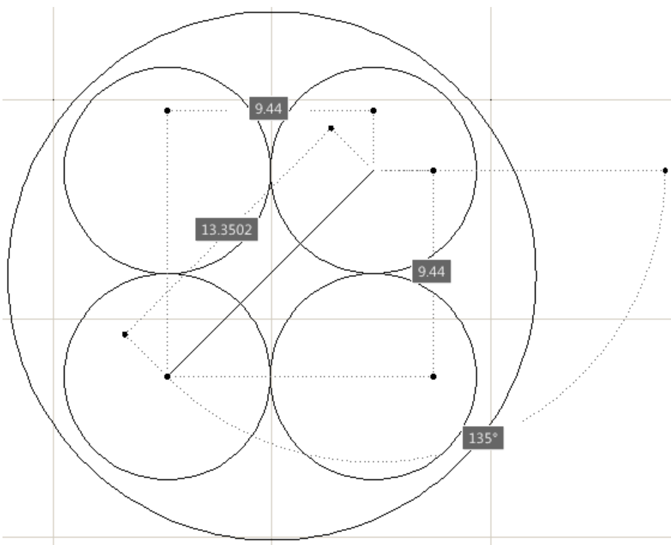

Fig. 2. Conductors distribution

200% and 400% of HLF for both cases and the respective difference.

Note that the difference between cases remains as HLF increase. The power loss difference for HLF=0% is approximately 16.58%, the same for HLF=100% and for HLF=400%. The maximum power loss for each simulation are 134.7% and 151.3%, which means that the contribution of power loss due

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
PHASE AND NEUTRAL HARMONIC CURRENT

Order	Phase R [A]	Phase S [A]	Phase T [A]	Neutral [A]
1	0.8130	0,7520	0,7265	50,3254
3	18.3740	17,3276	21,1859	27,0779
5	15.0173	18,7917	19,2327	11,1959
7	1.7594	1,5629	2,1625	0,3187
9	1.2810	1,3031	3,0700	10,5311
11	1.6384	0,1653	1,0050	1,8583
13	0.8949	0,7085	0,3555	2,2360
15	0.3587	0,7301	0,3705	2,2667
17	0.5723	0,0892	0,5294	1,4411
19	0.9388	0,7547	0,3076	0,3253
21	0.3455	0,3202	0,5284	2,2475
23	0.2578	0,6583	0,3844	1,0981
25	0.4453	0,1484	0,3680	0,8855

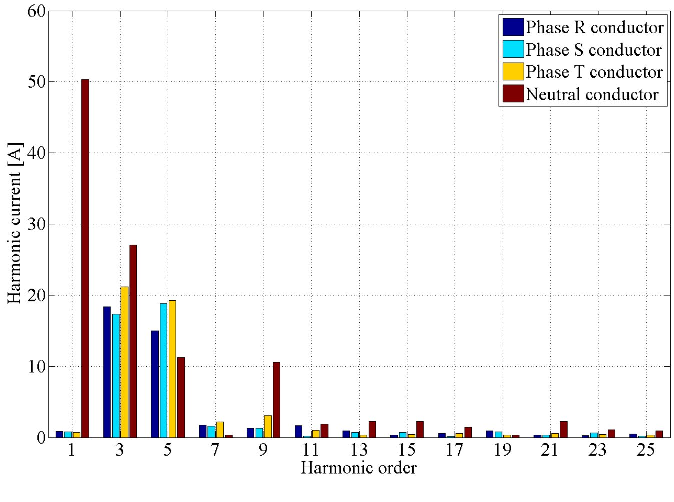

Fig. 3. Cable harmonic Spectrum

to unbalance and displacement currents cannot be neglected.

Fig. 5 and Table IV shows the temperature difference between both cases.

TABLE III
POWER LOSSES VALUES FOR BOTH CASES

HLF [%]	Power loss 1 [%]	Power loss 2 [%]	Difference [%]
0%	100.0000	116.5804	16.5804
25%	100.1357	116.7162	16.5804
50%	100.5429	117.1233	16.5804
100%	102.1715	118.7519	16.5804
200%	108.6859	125.2663	16.5804
400%	134.7436	151.3240	16.5804

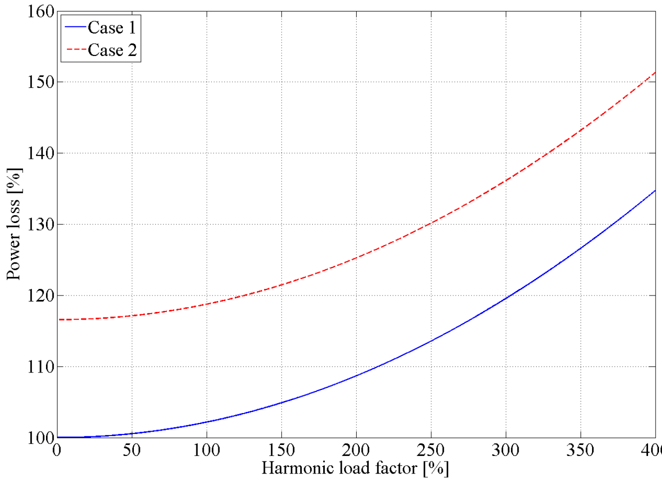

Fig. 4. Cable Power Losses

TABLE IV
TEMPERATURE RISE VALUES FOR BOTH CASES

HLF [%]	Temperature rise 1 [^oC]	Temperature rise 2 [^oC]	Difference [^oC]
0%	90.0000	104.9224	14.9224
25%	90.1221	105.0445	14.9224
50%	90.4886	105.4110	14.9224
100%	91.9543	106.8767	14.9224
200%	97.8173	112.7397	14.9224
400%	121.2692	136.1916	14.9224

These results shows that the temperature difference between both cases is approximately 14.92^{o}C when the Harmonic load factor is 0% and remains in the same value when the Harmonic load factor is 400% (same behavior of power losses). Both temperatures start in 90^{o}C and 104.92^{o}C, with an Harmonic load factor of 100% the temperature increase are 91.95^{o}C and 106.88^{o}C and with a HLF=400% the temperature are 121.27^{o}C and 136.19^{o}C. It can be concluded for this result that the contribution of temperature rise due to the stationary disturbance is the same at seen in power losses.

Figure 6 and Table V shows the cable expected life for each simulation.

Note that for a HLF=0%, the expected life due to other stationary disturbance simulation is drastically reduced to 19.91%. With the increase of the harmonic load factor, both curves approaching each other but never crossed (as seen in

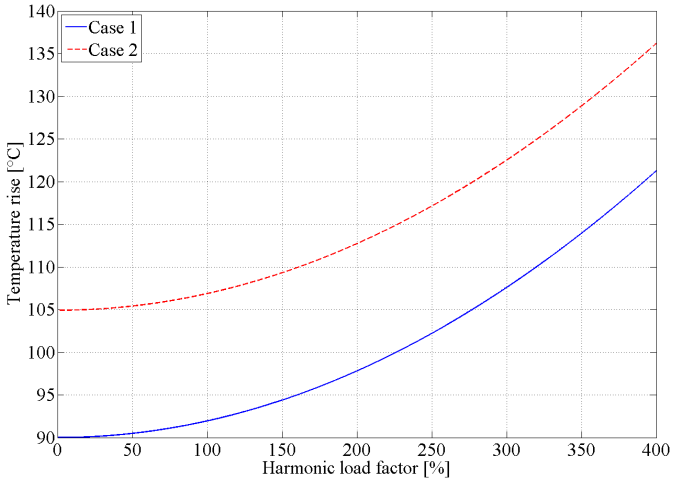

Fig. 5. Cable Temperature Rise

TABLE V
EXPECTED LIFE VALUES FOR BOTH CASES

HLF [%]	Expected Life 1 [%]	Expected Life 2 [%]	Difference [%]
0%	100.0000	19.9124	80.0876
25%	98.6346	19.6614	78.9732
50%	94.6545	18.9282	75.7263
100%	80.3431	16.2708	64.0723
200%	42.2478	8.9866	33.2612
400%	3.9103	0.9913	2.9190

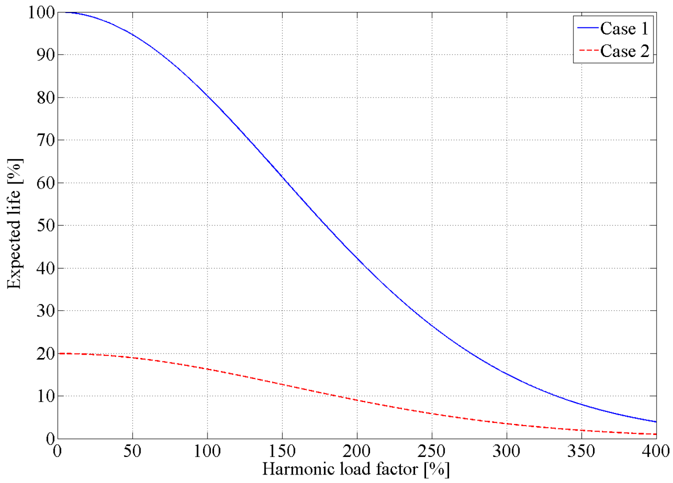

Fig. 6. Cable Expected Life

Fig. 6 in HLF=400%). This indicates that when the harmonic load factor is low, unbalance and phase displacement currents contribute to reduce the cable expected life. Only after the HLF=200% the harmonic currents cause a significant reduction of life and case 1 tries to reach case 2.

V. DISCUSSION

The results show that stationary disturbance like waveform distortions cause rapid deterioration of dielectric materials. The main research focuses on the effects generated by harmonics and phase displacement in the current, but not in the voltage. Voltage disturbance also may cause a reduction of lifetime, but the involved physical effects are others and the approach to determine such reduction is different as well.

Due to the presence of current disturbances in the system, cable temperature rise calculations are focused on the effects of power losses due to the Joule's Effect, and how they degrade the dielectric material, like the XLPE for the simulation case. When the focus is on the effects of voltages disturbances, especially harmonics voltages, researchers work on the electrical stress in solid type insulators. This study is performed applying higher voltages for long intervals of time to different species of solid type insulator, measuring temperature, electric field and other values. Then using statistical treatment on the samples [12] can propose the best fitting probabilistic model which represent the aging in the dielectric material. The drawback of this approach is the need of multiple samples exposed to many stresses, in order to establish the most appropriate probabilistic model and thus achieving the estimated expected life.

It is clear that the wave distortions are not the only stationary disturbances that decrease useful life. Any disturbance can causes increases in the voltage or current levels for long intervals of time. But very few studies employed other types of disturbances, as seen in the review of models and techniques for the estimation of overheating in LV conductors due to other stationary disturbances like phase displacement.

VI. CONCLUSIONS

This article presents a methodology for the estimation of overheating in LV cables due to stationary disturbances, applying existing methods which consider only waveform distortions, specifically current harmonics.

Also this paper simulates two cases for the overheating method. One with only current harmonics, another considering also phase displacements and unbalances currents.

For the simulation the other stationary disturbances (not harmonics) have a contribution in power losses and temperature rise. The main contribution is due to the harmonic current, considering that only work up to the 25th harmonic. The differences between both cases maintain a value all the time for power losses and temperature.

A completely different result is observed in the analysis of expected life curve. This is because while the HLF is increasing, the reactive current (phase displacements and unbalances) made the main contribution in reduction of expected life. Once the HLF reaches 200%, the contribution of the harmonic current is large enough, but even for HLF = 400%, both curves never cross.

It is important to note that displacement and unbalance current are not being affected by changes in the harmonic spectrum resistance (there only take the fundamental AC resistance).

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