Thermal behavior of LV cables in presence of harmonic currents

Wilfried Frelin, Luc Berthet, Yves Brument, Marc Petit, Gonzalo Perujo, Jean-Claude Vannier

THERMAL BEHAVIOR OF LV CABLES IN PRESENCE OF HARMONIC CURRENTS

W. Frelin[1,2], L. Berthet[2], Y. Brument[3], M. Petit[1], G. Perujo[1], J.C. Vannier[1]

[1] Department of Energy – SUPELEC, 3 rue Joliot Curie 91192 Gif-sur-Yvette, France
[2] Electricité de France, 1 avenue du Général de Gaulle 92141 Clamart, France
[3] Electricité de France, route de sens 77250 Moret sur Loing, France

e-mail : wilfried.frelin@supelec.fr, marc.petit@supelec.fr, jean-claude.vannier@supelec.fr, luc.berthet@edf.fr, yves.brument@edf.fr, gonzalo.perujo@supelec.fr

***Abstract** – The proliferation of non-linear loads on public and industrial networks causes increases of harmonic current distortion. This paper deals with the thermal impact of harmonic distortion on LV cables, especially LV cables with neutral conductor. The thermal impact of harmonics is shown by measurements and FEM simulations on two different LV cable structures.*

Introduction

Nonlinear loads (computers, compact fluorescent lamps, variable speed drives...) produce harmonic currents and therefore increase the harmonic distortion of the currents flowing through power distribution systems. The RMS value of the currents in phase or neutral conductors increases, and thus the I^2R losses rise. This increase of losses creates additional heating in the cable [1]-[2], which may have a critical impact on the cable life expectancy [3]. In power distribution systems, LV cables supplying nonlinear loads are impacted by harmonics, in particular the neutral conductor [4]. When the harmonic content of phase currents includes triplen harmonics, the neutral current is non-zero. This current circulating in the neutral conductor can rise above phase current and bring to light a dimensioning problem of the neutral conductor. Previous works on a 50 sqmm LV-cable, computed by FEM methods, presented in [5] show the cable temperature increase in presence of harmonics.
This paper focuses on the thermal behavior of LV cables with neutral conductor, as shown in Fig. 1, when supplying non linear loads. These cables are composed of three 150 sqmm phase conductors and one neutral conductor with different sections. The two structures studied in this paper are made as follows: (i) a 90 sqmm solid neutral conductor (left scheme) and (ii) a 70 sqmm stranded neutral conductor with a lead sheath (right scheme). The first configuration is the one that is chosen for the new cable generation. After introducing the configuration of the experimental system, FEM modeling of LV cables is presented. Next, the thermal behavior of the two LV cables given by FEM simulation is presented and compared to measurement results.

Configuration of experimental system

The experimental system, shown in Fig. 2 and Fig. 3, has three parts: (1) a 230V 3 phase power supply is feeding a 40kVA transformer that supplies a five meter length LV cable and three 1-phase rectifiers with resistive loads or resistive and capacitive loads. Current harmonics are produced by the 1-phase rectifiers with RC loads, and in this configuration triplen harmonic currents circulate in the neutral conductor. (2) A thermal acquisition system with twelve thermocouples on each LV cable, which gives sheath and core temperatures. Fig. 1 gives position of sheath and core thermocouples, sheath thermocouples are pressed against conductors using special glue which aids heat transfer and core thermocouples are positioned on neutral and phase conductor cores without glue. (3) An acquisition system which measures phase and neutral currents. This acquisition system computes current amplitudes for each harmonic order (up to harmonic order 50) and records each current waveform. Before measurement, thermocouples and current acquisition system were gauged in laboratory, with accuracy materials.

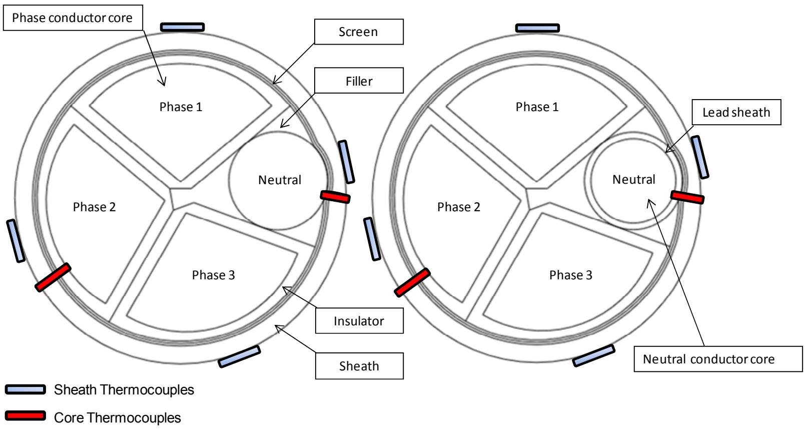

Fig. 1 . Cable geometry and thermocouple position

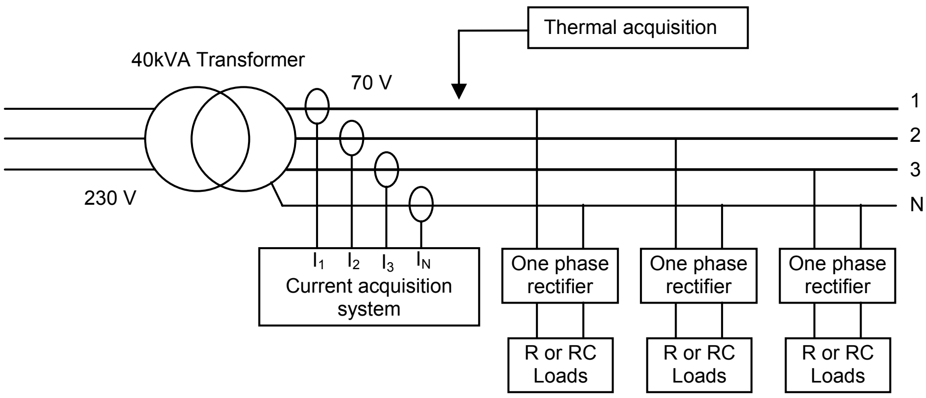

Fig. 2. The configuration of experimental system

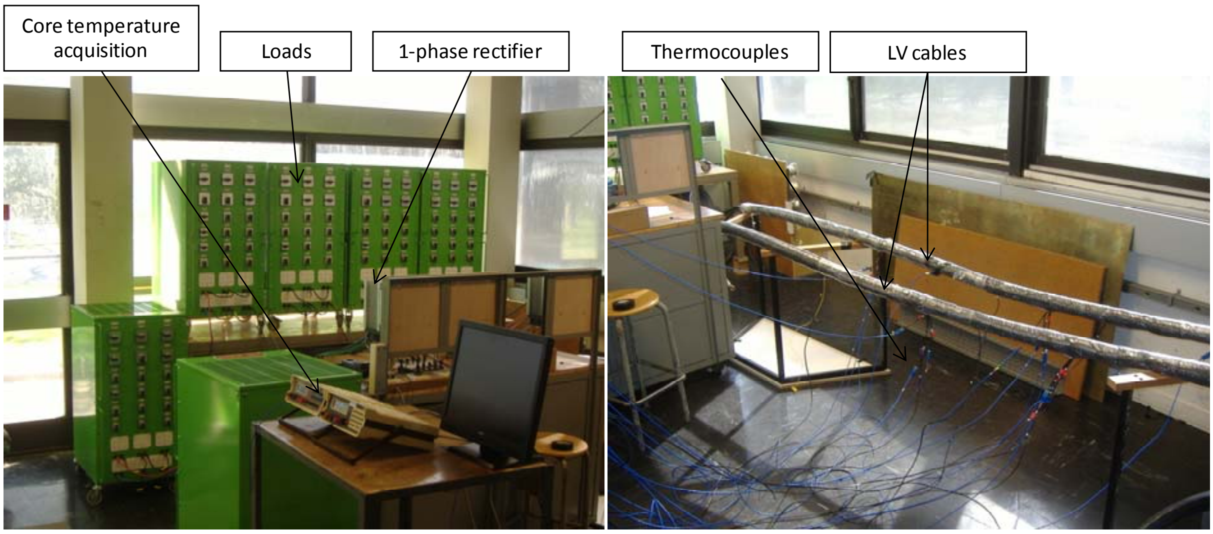

Fig. 3. Experimental system

FEM Modeling

Finite Element Method (FEM) is used to solve the heat transfer equation coupled to an electrical model of the conductors. Stranded conductors (the phases of the two LV cables considered and the neutral of one of them) are considered for simulation as solid conductor with the same section. The electrical current for each conductor in linear and non-linear conditions is described in table I. Let us note that in a symmetric and balanced network, the neutral current without harmonics is equal to zero.

Table I
Electrical equations

Linear conditions (1)	Non linear conditions (2)
$\begin{cases} I_A = I_1\sqrt{2}\cos(\omega t) \\ I_B = I_1\sqrt{2}\cos\left(\omega t - \frac{2\pi}{3}\right) \\ I_C = I_1\sqrt{2}\cos\left(\omega t + \frac{2\pi}{3}\right) \\ I_N = 0 \end{cases}$	$\begin{cases} I_A = \sum_{h=1}^{\infty} I_h\sqrt{2}\cos(h\omega t + \varphi_h) \\ I_B = \sum_{h=1}^{\infty} I_h\sqrt{2}\cos\left(h\left(\omega t - \frac{2\pi}{3}\right) + \varphi_h\right) \\ I_C = \sum_{h=1}^{\infty} I_h\sqrt{2}\cos\left(h\left(\omega t + \frac{2\pi}{3}\right) + \varphi_h\right) \\ I_N = 3\cdot\sum_{h=1}^{\infty} I_{3h}\sqrt{2}\cos(3h\omega t + \varphi_{3h}) \end{cases}$

Equation (3), which results from a simplification of Maxwell's equations, allows the calculation of the current density repartition in each conductor. By using this equation, skin and proximity effects are taken into account. The parameter V is adjusted for each phase conductor to have the same current. For neutral conductor, V is adjusted to fix neutral current to its value.

$$\begin{cases} i\omega\sigma\mu_0\mu_r A_z + \nabla\wedge(\nabla\wedge A_z) = -\dfrac{\mu_0\mu_r\sigma V}{L} \\ j = -\sigma\dfrac{dV}{dz} - i\omega\sigma A_z \end{cases} \tag{3}$$

With μ_0 the permeability of free space, μ_r the relative permeability, ω the pulsation, σ the electrical conductivity, A_z the vector potential, V the electric potential difference along the cable, L the cable length, j the current density and i the complex number.

The aim of electromagnetic calculation is to estimate Joule losses in cable, which are in fact the heat quantity Q in thermal calculation. Equation (4) explains Joule losses in cable in linear and non linear conditions respectively.

$$\begin{cases} P_j = R_1 I_1^2 + R_2 I_2^2 + R_3 I_3^2 \\ P_j = \sum_{h=1}^{\infty} R_{1h} I_{1h}^2 + R_{2h} I_{2h}^2 + R_{3h} I_{3h}^2 + R_{Nh} I_{Nh}^2 \end{cases} \tag{4}$$

Where

R_1, R_2, R_3 are the resistance (phase 1, phase 2, phase 3 respectively) at fundamental frequency.

I_1, I_2, I_3 are the fundamental current (phase 1, phase 2, phase 3 respectively).

R_{1h}, R_{2h}, $R_{3h,}$ R_{Nh} are the resistance for harmonic h (phase 1, phase 2, phase 3 and neutral respectively).

I_{1h}, I_{2h}, I_{3h}, I_{Nh} are the current for harmonic h (phase 1, phase 2, phase 3 and neutral respectively).

Heat transfer in the inner of LV cable is dominated by conduction, thus the temperature repartition in each domain may be calculated from the Poisson equation (5).

$$-\nabla \cdot \left(\lambda \nabla T\right) = Q \tag{5}$$

With λ the thermal conductivity, T the temperature and Q the heat quantity.
On the sheath surface the heat is transferred to the environment by natural convection and heat radiation. The heat flux φ through the sheath surface S is given by the Newton law:

$$\varphi = \left(h_c + h_r\right) S \Delta T \tag{6}$$

With h_c the convection coefficient for natural convection and h_r an equivalent convection coefficient for heat radiation. For natural convection, the convection coefficient h_c can be expressed from

$$h_c = \frac{Nu\,\lambda}{D} \tag{7}$$

With λ the air conduction coefficient, D the LV cable diameter and Nu the Nusselt number which is calculated for natural convection by [6]

$$Nu = 0.53\,Ra^{0.25} \quad and \quad Ra = \frac{g\beta\left(\Delta T\right)D^3}{va} \tag{8}$$

With Ra the Rayleigh number, g the gravitational acceleration, β the expansion coefficient of air, v the kinematic viscosity of air and a the thermal diffusivity.
The heat flux φ_r dissipated by heat radiation between two surfaces S_1 and S_2, respectively at the temperature T_1 and T_2, can be calculated by [7]. Considering that S_2>>S_1, the heat flux expression given by [7] can be simplified and expressed by equation (9), with S_1 the sheath surface (S_1=S).

$$\varphi_r = \sigma_b\,\varepsilon\,S\left(T_1^4 - T_2^4\right) \tag{9}$$

With σ_b the Boltzmann constant, ε the thermal emissivity, T_1 the sheath temperature and T_2 the ambient temperature (T_1 and T_2 in Kelvin).
Introducing the equivalent convection coefficient h_r, equation (9) can be rewritten as follows

$$\varphi_r = h_r\,S\,\Delta T \quad with \quad h_r = \sigma_b\,\varepsilon\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right) \tag{10}$$

The global convection coefficient is the sum of the convection coefficient given by natural convection (7) and the equivalent convection coefficient given by heat radiation (10). For an ambient temperature of 23°C and a thermal emissivity of 0.9, the global convection coefficient value is spread from 12.7 to 14. Electrical conductivity is temperature dependent according to:

$$\sigma_{(T)} = \frac{\sigma_{20}}{1 + \alpha\left(T - 20\right)} \tag{11}$$

With σ_{20} the electric conductivity at 20°C, α the temperature coefficient of the conductor material, T the conductor temperature, $\sigma_{(T)}$ the electrical conductivity at the temperature T.

Fig. 4 shows the simulation process to obtain the LV cable temperature. The electromagnetic calculation gives the Joule losses in the cable which represent the heat quantity in thermal module. In a first time, the electromagnetic calculation is done with an initial temperature in the conductor core of 20°C and a corresponding electrical conductivity. Then thermal calculation is launched and a new temperature profile is known. As electrical conductivity depends on temperature, a new electromagnetic calculation is required with an update of the electrical conductivity at the temperature calculated previously. Simulations are computed until a constant temperature is obtained.

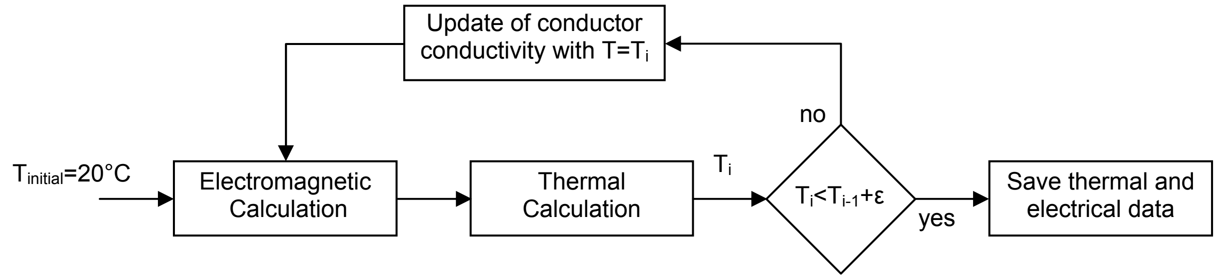

Fig. 4 Simulation process

Table II gives the electrical and thermal properties of the LV cable materials.

Table II
Electrical and thermal properties of LV cable

	Core	Insulator	Filler	Screen	Sheath
λ (W/K.m)	160	0.25	0.16	26	0.2
σ (S.m^{-1})	3.10^7	10^{-7}	10^{-15}	$1.8.10^6$	10^{-15}

Results

In order to investigate thermal behaviour of the cable under linear and non linear supply conditions, different simulations and measurements were carried out with a constant RMS current, fixed to 210A for each case. Table III summarizes the harmonic spectrum for the three different cases, the first case corresponding to linear conditions and the other two cases to non-linear conditions with different harmonic contents.

Table III
Different cases with their current profiles for constant RMS current

		I_1/I_1	I_3/I_1	I_5/I_1	I_7/I_1	I_9/I_1	THD
linear	Case 1	100%	/	/	/	/	0%
non-linear	Case 2	100%	8.3%	7.4%	6.8%	3.4%	13.5%
	Case 3	100%	26.2%	14.2%	6%	2%	30.5%

Table IV gives the RMS neutral current value for the three different cases. These current profiles were applied to the two different structures of LV cables.

Table IV
RMS neutral current value for different cases

	Case 1	Case 2	Case 3
RMS neutral current (A)	/	56	164

Fig. 5 and Fig. 6 summarize results given by simulations and measurements for cases described in table III and the two different LV cable structures. Fig. 5 gives core temperatures on phase 2 and neutral conductors obtained by simulations and measurements for the different cases. Fig. 6 gives sheath temperatures on phase 2 and neutral conductors obtained by simulations and measurements for the different cases. Each measurement result is composed of two or three values (due to the thermocouple number) and presents a small gap due to the difficulty to lay properly thermocouples. These figures show a good agreement between FEM simulations and measurements.

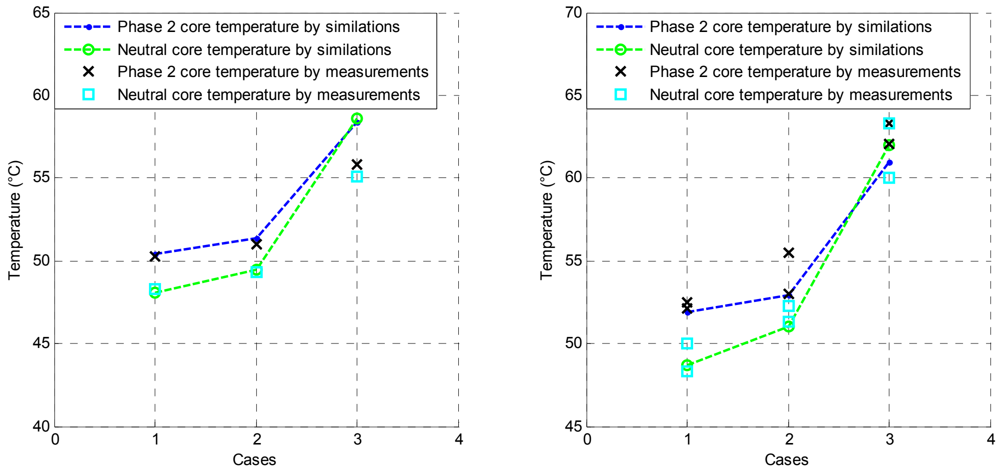

Fig. 5. Phase 2 and neutral core temperature for the two different LV cable structures given by simulations and measurements (LV cable with solid neutral conductor on the left and LV cable with stranded neutral conductor on the right)

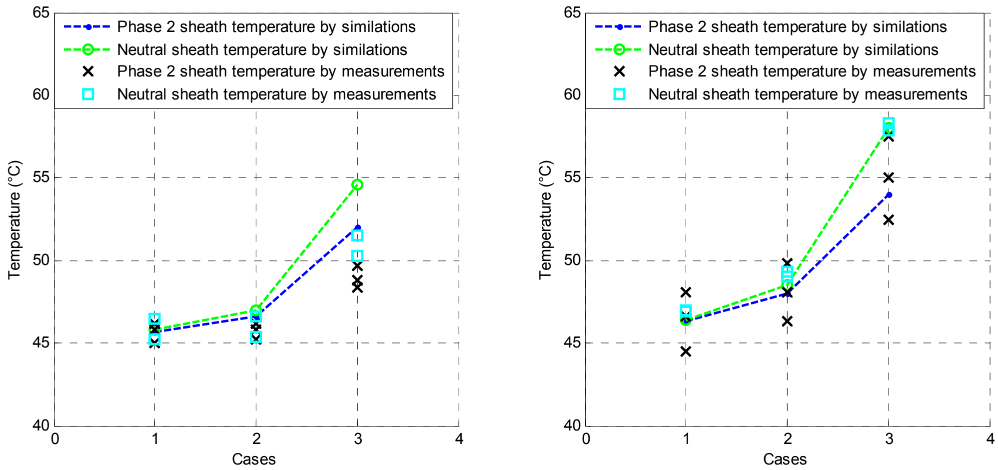

Fig. 6. Phase 2 and neutral sheath temperature for the two different LV cable structures given by simulations and measurements (LV cable with solid neutral conductor on the left and LV cable with stranded neutral conductor on the right)

It can be noticed that without harmonics, the thermal behaviour of the two LV cables is the same because there is no current in neutral conductor and phase conductors are the same. Then these figures show that neutral and phase conductor temperatures are higher with harmonic currents because the neutral conductor acts as a fourth thermal source.

The simulated temperature distribution given by case 3, for the two cable structures, is presented in Fig. 7, cable with solid neutral conductor on the left and cable with stranded neutral conductor on the right. This figure shows that LV cable with solid neutral conductor is less sensitive to harmonics than LV cable with stranded neutral conductor. As the solid neutral conductor cross section is higher, compared to the stranded neutral conductor cross section, Joule losses and temperatures are lower with the same harmonic content.

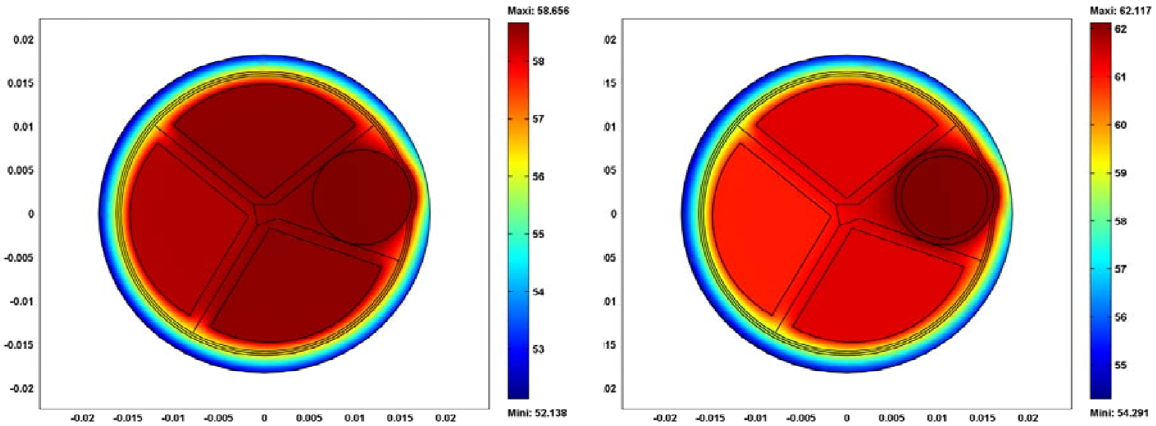

Fig. 7 Cable temperature of LV cable with solid neutral conductor (left) and LV cable with stranded neutral conductor (right) for case 3.

The first conclusion of the different simulations and measurements presented previously is that harmonics increase temperature in LV cable. Another point of view is to consider that harmonics reduce the transport capacity, i.e. the maximum current supported by the cable.
In order to show the reduced level of current that can circulate in LV cables in the presence of harmonics, the current which gives a 90°C temperature in one of the four conductors is calculated. Both cable structures are considered and computed in underground conditions because this is the main use of these LV cables. Fig. 8 gives the maximum fundamental current value which can circulate in both LV cables for each case described in table III and shows the difference of transport capacity with the two neutral conductor structures. It can be seen that harmonics reduce this fundamental current, in other words if harmonic content increases, the amount of loads connected to the LV cable has to be reduced.

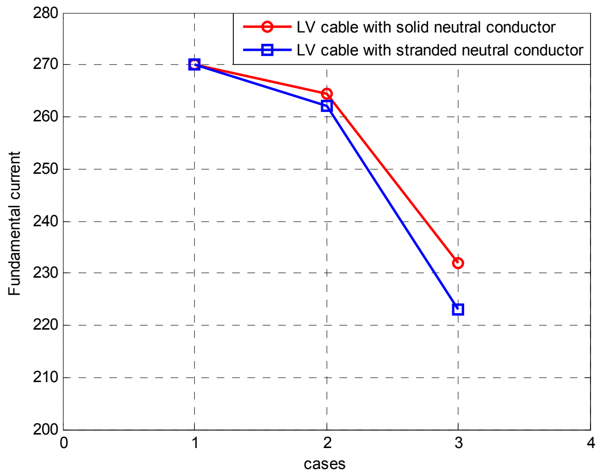

Fig. 8 Influence of harmonics on the transport capacity

Conclusion

Simulations and measurements presented in this paper show temperature increases on a 150 sqmm LV cable in presence of harmonics. The circulation of triplen harmonic currents in the neutral conductor, which in this case acts as a fourth heating source, contributes to the thermal heating of the LV cable. It can be seen that the LV cable with solid neutral conductor is less sensitive to harmonics due to a smaller neutral conductor resistance. This paper shows a good agreement between FEM simulations and measurements. At last, it is shown in simulations that the transport capacity is reduced when harmonic distortion is higher.

Acknowledgment

The authors wish to thank Department LME of EDF R&D, especially Y.Brument and R. Fonder, for their valuable material and scientific support during the test. The authors also wish to acknowledge Y. Jannot for his valuable discussions and suggestions.

References

[1] J. Desmet, D. Putman, F. D'hulster and R. Belmans, Thermal analysis of the influence of nonlinear, unbalanced and asymmetric loads on current conducting capacity of LV-cables, IEEE PowerTech Conference, June 23-26, Bologna, Italy, 2003.
[2] J. Desmet, D. Putman, G.M. Vanalme and R. Belmans, Modelling and sensitivity analysis of the Thermal behaviour of LV-cables for different current conditions, 11th International Conferences on Harmonics and Quality of Power, 2004.
[3] Claudio R. Pachecho, Jose C. de Olivera and Anderson L.A. Vilaca, Power Quality Impact on Thermal Behaviour and Life Expectancy of Insulated Cables, 9th International Conference on Harmonics and Quality of Power, vol.3, pp. 893-898, 2000.
[4] Thomas M. Gruzs,A Survey of Neutral Currents in Three-Phase Computer Power Systems, IEEE Transactions on Industry Applications, vol. 26, no. 4, July/august 1990.
[5] W. Frelin, L. Berthet, M. Petit, P. Dessante and J.C. Vannier, Evaluation of thermal heating in LV-cables in presence of harmonics, using FEM methods, 18th International conference on Electrical machines, September 6-9, Vilmoura, Portugal, 2008.
[6] A. M. Bianchi, Y. Fautrelle and J. Etay, Transfert Thermique, Presses polytechniques et universitaires romandes, 2004
[7] Y. Jannot, Transfert thermique, handout of Ecole des Mines de Nancy, 2008.