Modelling and sensitivity analysis of the thermal behaviour of LV-cables for different current conditions

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***Abstract*—Asymmetry, unbalance and nonlinearity of loads affect the current distribution in both phase and neutral conductor cores in three phase power supply systems. Especially in cases of nonlinear single phase loads the neutral conductor can be loaded with an excessive current. Consequently, cable temperature, which is directly related to the power dissipation, is highly affected. Applying a maximum insulation temperature as boundary condition, the power conducting capacity of LV-cables will substantially be affected by asymmetry, unbalance and especially non linearity of loads. Physical cable parameters with respect to both thermal resistance and cable geometry were analyzed in order to determine the most relevant influencing parameters. The temperature distribution in the cable section is thermally calculated and is subsequently simulated, using 2D finite element modelling. Finally, measurements of the cable temperature are performed verifying the simulation results.**

***Index Terms*—Cable insulation, Insulation thermal factors, Losses, Power cable thermal factors, Power system harmonics, Power quality**

I. Introduction

Nonlinear loads (such as compact fluorescent lamps, IT equipment, variable speed drives,…), are widely used in both industry and office buildings. These loads, producing harmonic line currents, yield high neutral conductor currents, resulting in higher cable temperatures [1,2,3,6,7]. In the particular case where phase currents only consist of odd harmonics with $I_{2n+1} = q^n * I_1$ ($0 \le q \le 1$, n = 1,2,...), the maximum rms-ratio of the neutral conductor current and the phase current is obtained when q=1 and equals: $I_N/I_{phase} = \sqrt{3}$ [3]. Studies on bad power quality conditions [4] mention overheating of cables. A substantial heating of the cable can sometimes be detected, even when not excessively loaded.

This paper proposes a simple model for the calculation of the cable temperature. The model takes into account the load conditions and also the influencing parameters cable type, cable geometry and environmental conditions [10]. The model is validated by 2D Finite Element simulations and by measurements. Finally, a sensitivity analysis was performed in order to evaluate the influence of the different boundary conditions determining the cable temperature.

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II. Model

A. Scope

Besides the three phase conductors, the neutral conductor represents a fourth dissipating heat source in the cable. In common thermal cable dimensioning, this fourth heat source is only taken into account for 10% of unbalance current. Load unbalance, asymmetry and nonlinearity have a substantial influence on the current distribution over both phase and neutral conductor cores [3,9]. Consequently, an analysis must be worked out to the direct influence of these current characteristics on the heat, dissipated in phase cores respectively neutral conductor core.

B. Electrical Equations

1) Current

Phase currents can be expressed by using a Fourier Transform as given in (1):

$$\begin{cases} i_A(t) = \sum_{n=1}^{\infty} I_{A_n} \sin(n\omega t - \alpha_n) \\ i_B(t) = \sum_{n=1}^{\infty} I_{B_n} \sin(n\omega t - \beta_n) \\ i_C(t) = \sum_{n=1}^{\infty} I_{C_n} \sin(n\omega t - \gamma_n) \end{cases} \qquad \begin{cases} I_{A_{RMS}} = \sqrt{\sum_{n=1}^{\infty} \frac{I_{A_n}^2}{2}} \\ I_{B_{RMS}} = \sqrt{\sum_{n=1}^{\infty} \frac{I_{B_n}^2}{2}} \\ I_{C_{RMS}} = \sqrt{\sum_{n=1}^{\infty} \frac{I_{C_n}^2}{2}} \end{cases} \tag{1}$$

with n: harmonic order; I_{An}, I_{Bn}, and I_{Cn} the phase current amplitudes for harmonic n; $\alpha_n = 0$ + asymmetric deviation φ_{nA}; $\beta = n.2\pi/3$ + deviation φ_{nB}; $\gamma = n.4\pi/3$ + deviation φ_{nC}.

By Kirchoff's current law the rms neutral conductor current is calculated as:

$$I_{N_{RMS}}^2 = \sum_{n=1}^{\infty} \left[\begin{aligned} &\frac{I_{An}^2 + I_{Bn}^2 + I_{Cn}^2}{2} + I_{An} I_{Bn} \cos(\beta_n - \alpha_n) \\ &+ I_{Bn} I_{Cn} \cos(\gamma_n - \beta_n) + I_{Cn} I_{An} \cos(\alpha_n - \gamma_n) \end{aligned} \right] \tag{2}$$

2) Power dissipation and heat generation

Power dissipation in the cable leads to heat generation due to the cable series resistance. In the generalised approach, the cable series resistance can be written as given in (3), where both skin and proximity effects are included.

$$R = R_{dc}\left(1 + Y_s + Y_p\right) \tag{3}$$

where the skin effect is given in (4).

$$Y_s = \frac{11}{\left[\ 1{,}8\cdot 10^7\cdot\frac{R_{dc}}{f} + \frac{1}{4{,}5\cdot 10^6}\cdot\frac{f}{R_{dc}} - 2{,}56\cdot\left(\frac{1}{1{,}8\cdot 10^7}\cdot\frac{f}{R_{dc}}\right)^2\ \right]^2} \qquad (4)$$

and the proximity effect as

$$Y_p = Y_s\cdot\left(\frac{D}{S}\right)^2\cdot\left[\frac{1{,}18}{Y_s+0{,}27}+0{,}312\cdot\left(\frac{D}{S}\right)^2\right] \qquad (5)$$

D presents the conductor diameter and S the distance between the cable centers.

R is temperature dependent according to

$$R = R_{20}\left(1+\alpha\left(T-20\right)\right) \qquad (6)$$

where R_{20} [Ω/m] the reference resistanceat 20°C, and T [°C] and α the temperature respectively temperature coefficient of the conductor material (α_{Cu}=0.0041 and α_{Al}=0.0040). In this analysis, the considered conductor material is copper. The cross section of the neutral conductor is assumed to be equal to the phase conductor cross section, resulting in equal phase and neutral conductor resistances (R_{ph}=R_N).

For the test set up, a standard installation cable of 4x2.5mm² is used. The skin effect is not taken into account since, for a penetration depth of cable cross section (e.g. the radius = 0.875 mm for 2.5 mm² copper section), frequencies higher than 7 kHz were found. Normally, nonlinear loads harmonic spectra are considered up to 2 kHz (40th harmonic on 50 Hz supply) [5]. Consequently, in this case, resistive behaviour will be barely affected.

On the other hand, the proximity effect can increase the cable resistance due to the high ratio D/S. Fig. 1 shows the relative increase of cable resistance due to the proximity effect for different frequencies. Since the used cable cross section is 2.5mm² and harmonic spectrum is limited to 2kHz, the ratio $\sqrt{f/R_{dc}}$ is lower than 500. Consequently, also the proximity effect will be negligible.

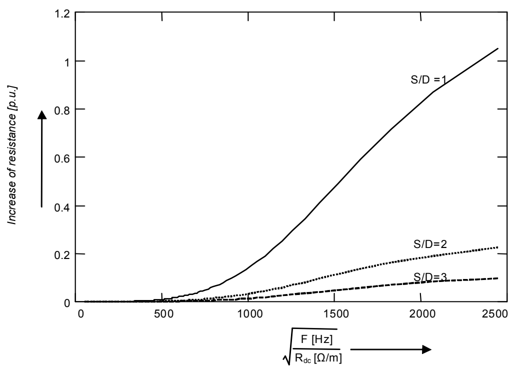

Fig.1 Proximity effect in relation to cable cross section and used frequency

The power dissipated in the cable, which represents the emitted heat, is calculated per core from its series resistance and the loaded rms-current, e.g. for phase A:

$$P_A = R_{ph} I_A^2 \quad \left[W/m\right] \qquad (7)$$

The total heat generated in the cable is calculated by

$$Q = \left(I_A^2 + I_B^2 + I_C^2\right) R_{ph} + I_N^2\, R_N \qquad (8)$$

with I_A, I_B, I_C and I_N the rms currents per cable conductor, and R_{ph} and R_N respectively the phase conductor and neutral conductor resistance [Ω/m].

C. Thermal calculations

From the total generated heat (8), thermal calculations were made to estimate the maximum temperature occurring in the cable. Subsequently, from the respective heat sources P_A, P_B, P_C and P_N , temperature distribution is calculated using a 2D finite element model as discussed in § III.A.

The considered cable is an XVB-F2 (Belgium standard for installation cable) cable 4x2.5mm² with geometry as shown in Fig. 2. The conductor cores represent the heat sources, dissipating a power P_A, P_B, P_C and P_N. For the test set up as described in § III.B, the cable was thermally isolated by an extruded polyethylene (PE) shield around the cable insulation (thermal conductivity: 0.038 W/mK). Thus the thermal inertia of the system is increased in order to reduce fast ambient changes.

As the measurements have proved, the side effects at the beginning and the end of the cable can be neglected when considering the thermal resistances in longitudinal (through 4x2.5 mm² copper: R_{cu}) and in radial direction [9] (through PVC and extruded PE insulation: R_{PVC} and R_{PE}). The radial thermal resistance can be calculated by

$$R_{rad} = \frac{\ln\frac{D}{d}}{\lambda\cdot L\cdot 2\pi} \qquad (9)$$

with D [m] the outer diameter of the cylindrical shell, d [m] the inner diameter, λ [W/mK] the thermal conductivity of the material (PVC, XPE or PE) and L [m] the length of the considered cable.

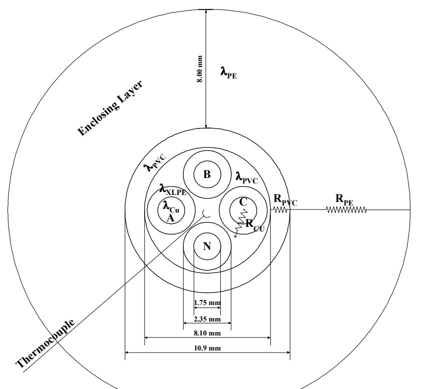

Fig. 2 Cable Section Geometry

The longitudinal thermal resistance is calculated using

$$R_{long} = \int_0^{\frac{L}{2}} \frac{x}{\lambda \cdot A} dx = \frac{L^2}{8\lambda A} \qquad (10)$$

With L [m] the length of the cable, λ [W/mK] the thermal conductivity of copper and A [m²] the copper cross section. The large difference in results obtained from equations (9) and (10) justifies the assumption that the entire dissipated heat is carried out in radial direction

Consequently, heat transfer from the cable core to the outer surface of the PE-insulation is due to conduction through the PVC electrical cable insulation and the PE thermal insulation. On the PE surface the heat is transferred to the environment by convection. Heat radiation is considered to be small and consequently will be neglected.

1) Convection

With (8) the temperature rise ΔT_{conv} of the outer surface due to convection is calculated by

$$\Delta T_{conv} = \frac{Q}{h.A} \qquad (11)$$

with A the cooling surface per meter ($A=\pi D$) and h the convection coefficient, which is temperature dependent (through the number of Grashof). Q depends on the copper temperature due to the cable resistance. The copper temperature, in its turn, depends on the conduction through the cable insulation and on the temperature of the outer surface. Consequently, iteration between convection and conduction calculations will be necessary [9].

2) Conduction

The maximum occurring temperature in the cable is derived from the temperature of the outer surface and the temperature drop through the cable insulation due to conduction of the dissipated heat and can be calculated using

$$\Delta T_{cond} = \frac{Q.\ln\frac{D}{d}}{\lambda \cdot 2\pi} \qquad (12)$$

Applying the PE thermal insulation has the additional advantage that the heat transfer through the cable insulation can be assumed homogeneous in a better approximation. To such an extent, the heat generating area can be considered as a circle in the centre of the cable section (Fig.3). The radius of this equivalent heat generating cylinder can not be smaller than r_{ci} and can not be higher than r_{co}. The radius was chosen as r_{cc}, from the centre of the cable to the core centre. Sensitivity analysis has proved that using r_{ci} or r_{co} (=respectively 60% of r_{cc} and 140% of r_{cc}) for the radius of the heat generating spot, causes a deviation of respectively +15% and -10% in ΔT.

In (12), Q is temperature dependent again. Consequently, at each iteration, the copper temperature is calculated from the ambient temperature and the temperature rise due to both convection (11) and conduction (12):

$$T_{cu} = T_{amb} + \Delta T_{conv} + \Delta T_{cond} \qquad (13)$$

From T_{cu}, by (6) and (8), Q is calculated for a new iteration step, thus proceeding until iteration converges.

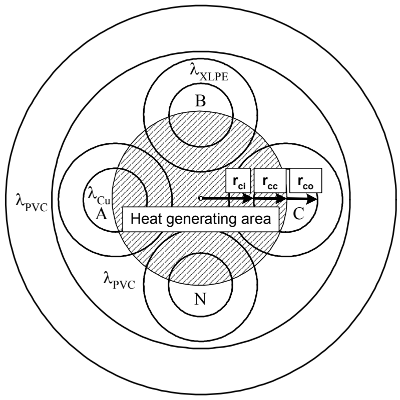

Fig.3 Equivalent heat generating area

III. Validation of the Model

A. Simulations

The temperature distribution over the cable section (Fig.2) is calculated using 2D finite element modelling with respective heat sources P_A, P_B, P_C and P_N in each copper conductor.

The outer border of the PE thermal insulation was assumed to be isotherm on a temperature calculated from the ambient temperature T_{amb} and (11) Here again at each iteration step, (11) was recalculated from the derived copper temperature.

Simulation of the temperature distribution over the cable section for a balanced, symmetric and nonlinear load (PCs, 20A/phase), provides the image of Fig. 4. Notice that no local heat spots are found.

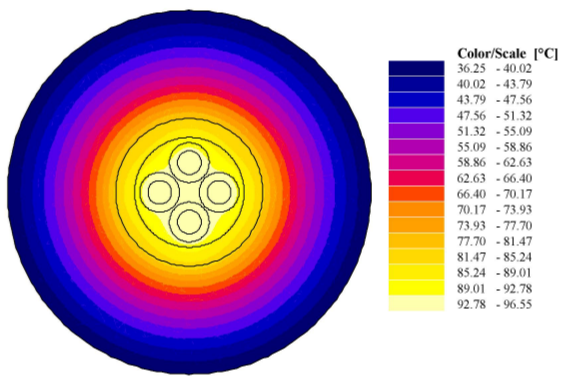

Fig.4 Simulated temperature distribution for balanced symmetric nonlinear load (PCs), 20A/phase

B. Measurements

Measurements were performed to verify the theoretical results from the temperature analysis. An XVB-F2 4x2.5mm² cable, thermally isolated as described in [9], was loaded by both linear and nonlinear load. The different load conditions were generated by means of a free programmable power source. Fig. 5 shows a distorted voltage, generated by the power source and applied to a linear load, and the corresponding current.

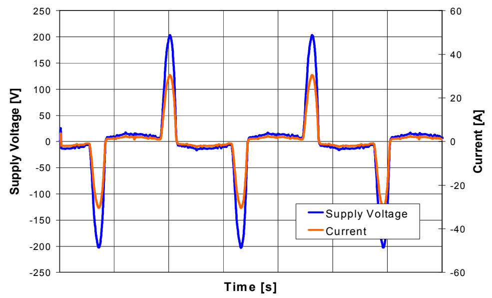

Fig.5 Supply voltage and current waveform simulating a high number of PC loads

In order to measure the temperature in the cable, at each meter, a thermocouple probe is penetrated into the centre of the cable (Fig. 2). The temperature is assumed to be homogeneous over the core section and the temperature drop over the core insulation is considered to be small. At start up every minute the temperature is logged in order to determine the point of steady state.

C. Evaluation

Table 1 gives, for different load conditions, the comparison between the copper temperatures obtained from measurements, calculations using the model and 2D FE simulations. A good correspondence between the three methods can be observed.

Table 1: Copper temperature: measured, calculated (model) and simulated (Equal linear or nonlinear loads on the three phases)

I_{phase} [A]	Meas [°C]		Calc [°C]		Sim [°C]	
setpoint	lin.	n lin.	lin.	n lin.	lin.	n lin.
5	24.1	24.2	24.5	25.0	24.1	25.0
10	30.5	36.9	29.7	36.5	29.7	36.2
15	47.5	60.6	45.9	58.0	45.9	57.5
20	69.2	98.9	66.6	99.4	66.2	96.6

IV. Sensitivity Analysis

A. Load conditions

Since the heat dissipation of all cable conductors is simplified to one heat generating area (Fig.3), the total heat generated in the cable is to be calculated according to (8). Currents I_A, I_B and I_C are directly related to the supply voltage and the load on one phase. The neutral current I_N however is determined by the interaction of the loads on the different phases. This interaction can be categorised according to load asymmetry, load unbalance and non linearity of the load which is expressed in the neutral current equation (2).

In the study of the influence of unbalance, the magnitude of the phase currents I_A, I_B and I_C are changed, while the phase angles of the currents are: $\alpha = 0°$; $\beta = 2\pi/3$; $\gamma = 4\pi/3$. Any asymmetry or non linearity is left out of consideration.

Fig.6 gives the cable temperature results for $I_B=I_C=20A_{rms}$ and for a decrease of I_A expressed as a percentage of $I_B=I_C$. As the phase current I_A decreases, the total power delivered to the load decreases with a percentage of 1/3 of the decrease of I_A. The occurring cable temperature for a perfectly balanced situation, delivering a same decreasing total power to the load, is given as well. It can be concluded that for a constant power delivery to the load, unbalance has a strong increasing effect on the cable temperature.

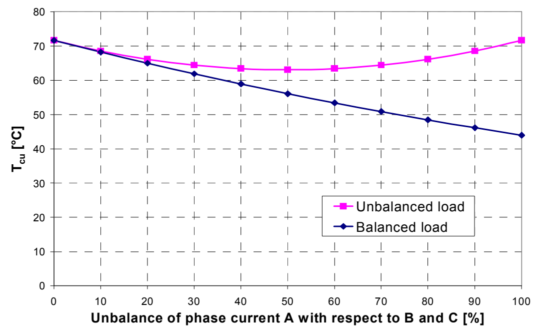

Fig.6 Influence of load unbalance (I_A=%I_B and $I_B=I_C$) on copper temperature

In the study of the influence of asymmetry, the phase angles ϕ_A, ϕ_B and ϕ_C (as defined in IIB .1) are changed, while the phase current magnitudes are all equal. Non linearity is left out of consideration. Calculated results for cos ϕ_A=1, and a variation of cos ϕ_B=cos ϕ_C capacitive or inductive, are given in Fig.7. Generally it can be concluded that pure asymmetry has a substantial increasing effect on cable heating.

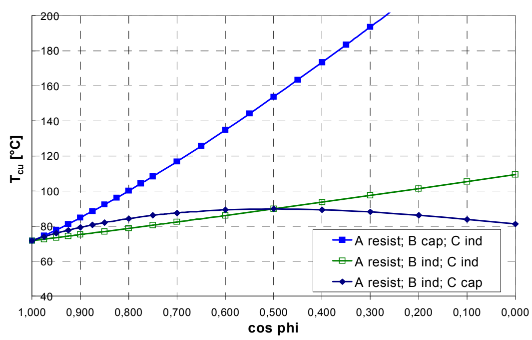

Fig.7 Influence of asymmetry (cos ϕ_A=1 and variation of cos ϕ_B=cos ϕ_C on copper temperature)

Non linearity is expressed by higher harmonic frequency components with their respective phases in equation (1) and (2). For a symmetrical balanced nonlinear load, triple N harmonics add up in the neutral conductor [3], thus increasing neutral conductor current and cable temperature.

For a combination of non linearity, asymmetry and unbalance no general unambiguous conclusion can be drawn about the influence on the cable temperature, since each non linear load has its specific spectrum. However, through equation (1) and (2), the proposed model is able to predict the occurring cable temperature for all possible load conditions.

B. Cable parameters

In this analysis some cable parameters are changed with respect to those from Fig.2. Changing the thermal conductivity or the thickness of the cable insulation has a relatively small influence on the copper temperature, as can be seen from Fig.8 and Fig.9 respectively. Fig10 shows the copper temperature as a function of the copper section for different load conditions.

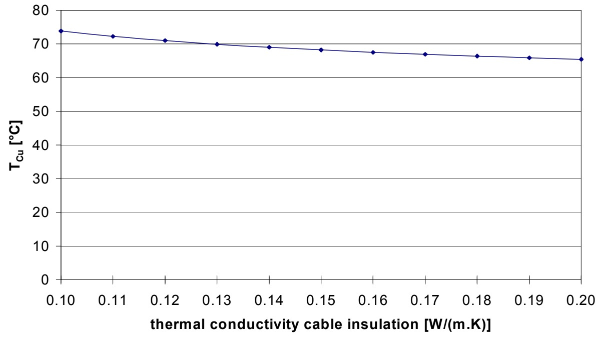

Fig.8 Copper temperature as a function of the thermal conductivity of the cable insulation (reference value: 0.13 W/(m.K))

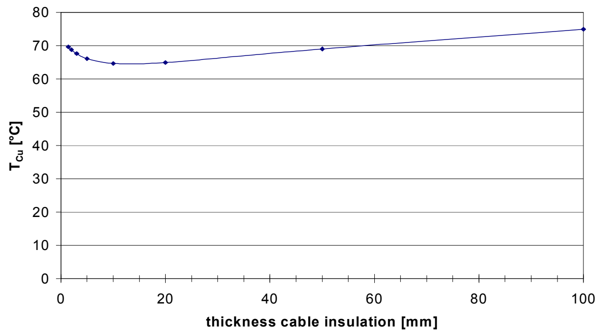

Fig.9. Copper temperature as a function of the thickness of the cable insulation (reference value: 1.4 mm)

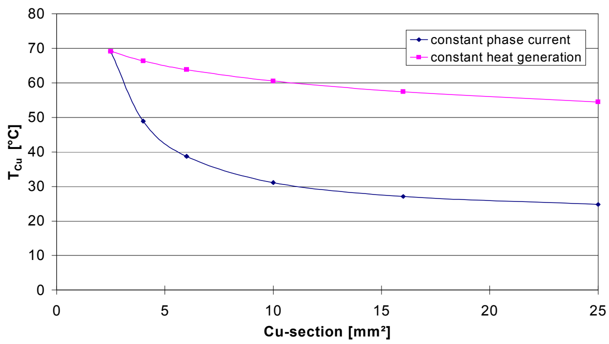

Fig.10 Copper temperature as a function of the copper section for different load conditions (reference: section of 2.5 mm², sinusoidal phase current of 20A). The thickness of the cable insulation is kept constant.

For a constant heat generation, the copper temperature decreases slightly with higher section. For a certain phase current, it is worthwhile to increase the section to lower the temperature and consequently lower cable power losses. However, the section should not be taken too high because the additional temperature decrease is less for higher sections.

C. Environmental conditions

Fig.11 shows the effect of convection on the copper temperature (constant ambient temperature). The contribution of the convection term in formula (13) is circa 10°C and decreases with increasing thickness of the enclosing layer.

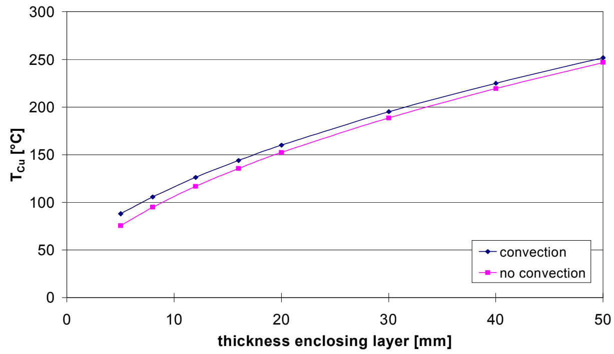

Fig.11 Effect of convection at the surface of the enclosing layer on the copper temperature. A value of 0.0263 W/(m.K) (air) is taken for the thermal conductivity of the enclosing layer.

Fig12 shows the influence of the thermal conductivity and the thickness of the enclosing layer on the copper temperature. For thick enclosing layers with low thermal conductivity (e.g. dry sand) the copper temperature may increase highly. For thermal conductivities with values of 0.5 W/(m.K) and higher [11,12] the copper temperature is nearly constant (independent of thermal conductivity and thickness of enclosing layer).

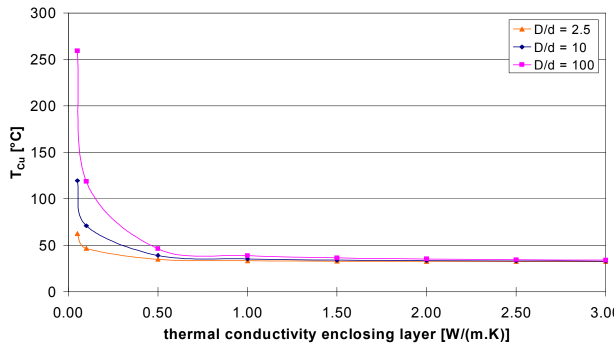

Fig.12 Influence of the thermal conductivity of the enclosing layer on the copper temperature for different diameter ratios of enclosing layer (D) and cable (d). Only conduction is considered.

V. CONCLUSION

From the analysis, a number of conclusions can be drawn concerning the influence of asymmetry, unbalance, nonlinearity and cable parameters on cable temperature, in cases where the neutral conductor cross section is the same as the phase conductors. Assuming constant power delivery to the load is held as criterion, both unbalance and asymmetry have an increasing effect on the cable temperature as well as non linearity from the moment that triple N harmonics are present in the current spectrum. These phenomena will be more pronounced for four wire cables with reduced cross section of neutral conductor. Consequently, for a precise description of the power conducting capacity of a cable, phase rms current can no longer be held as the only restricting parameter. A more adequate calculation of the conducting capacity must be considered. It is proven by analysis and measurement that the operating temperature of the cable (e.g. 98,8 °C in this specific test set up for an ambient temperature of 21.2 °C) can rise above its prescribed value (90°C), while current load is still in respect with the common standards [13].

Moreover, next to a negative effect on the life span of the cable insulation, these high temperatures result in a substantial increase of the cable losses, up to 4 % per 10 K raise in temperature. A higher cable section (i.e. one section increase) will reduce cable losses with approx. 10%. Both, thickness and cable thermalconductivity of insulation hardly affect cable temperature. However, enclosing material around cable and dry soils (low thermal conductivity) highly affect cable temperature.

VI. References

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VII. Biographies

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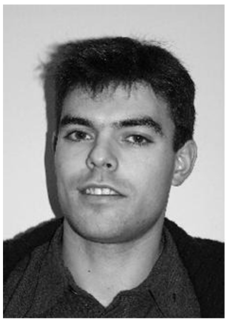

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Ronnie J. M. Belmans (S'77-M'84-SM'89) received the M.S. degree in electrical engineering and the Ph.D. degree from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1979 and 1984, respectively, and the special Doctorate and the Habilitierung from RWTH Aachen, Germany, in 1989 and 1993, respectively.

He is currently a Full Professor at the Katholieke Universiteit Leuven, teaching in the areas of electrical machines, power electronics, and variable-speed drives. His research interests include power quality, electrical energy systems, electrical machine design, and vibrations and audible noises in electrical machines. He was with the Laboratory for Electrical Machines of RWTH Aachen as a Von Humboldt Fellow from October 1988 to September 1989. From October 1989 to September 1990, he was a Visiting Professor at McMaster University, Hamilton, ON, Canada. He obtained the Chair of the Anglo-Belgian Society at London University for 1995-1996. He is currently a Visiting Professor at Imperial College, London, U.K. Dr. Belmans is a Fellow of the Institution of Electrical Engineers, U.K., the International Compumag Society, and the Koninklijke Vlaamse Ingenieursvereniging.