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Efficient Simulation of Thermal and Electrical Behaviour of Industrial Cables

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1. Introduction

Numerical modelling is applied in industrial applications in various ways. This chapter describes the application of modern simulation packages for distributed parameters combined with standard network type calculations and numerical procedures. In an application driven approach, simulation with distributed parameters is used as input for lumped parameter calculations. Thermal loading and electrical behaviour with regards to signal transmission in plant and process automation is dealt with. The main focus is on efficient modelling which yields sufficient accurate results for the application while covering the relevant range of operating conditions.

The well-known governing equations of electromagnetism and conservation equations for energy, momentum and mass may be solved via FEM and FVM methods to yield appropriate values for lumped parameters. Using these parameters an efficient network type calculation is carried out. Modelling and results for special cables used in power and data transmission are presented. Current carrying capacities for various operating conditions are studied.

2. Application

In industrial applications like materials handling, decentralized automation becomes widely applied. Loads like variable speed drives are not radially fed but connected to a power bus. Furthermore, power and data might be transmitted within one single cable. Here the need for thermal and electrical simulations arises.

A model is derived to calculate the ampacity for various operating conditions and Comsol (Comsol 2006) is applied to determine thermal resistances. For the data transmission cable, parameter and crosstalk are determined for multi core cables.

3. Thermal behaviour

When a non standard cable is used, the ampacity is to be determined for various laying and operating conditions. This maximum permissible current I_z for a cable with respect to thermal overload is usually determined for a well-defined operational condition and then related to various actual conditions via equation 1 (IEC 60287 , VDE 0299).

$$I_z = I_r \cdot \prod f_i \tag{1}$$

The "rated current" I_r and the correction factors f_i are to be determined to cover the relevant range of operational conditions. For optimal utilization actual operational conditions can be modelled in detail and appropriate corrections factors may be deduced.

3.1 Thermal Modelling

Joule heating is balanced by conduction, convection and radiation. All of the processes are temperature dependent and lead to a system of non-linear partial differential equations. A complete 3 D solution of the energy, momentum and continuity equation via a SIMPLEC (Patankar, 1980) type simulation (Bauder et. al. 1996, Schmidt 1996, Schmidt 2005) yields temperatures with reasonable accuracies.
Nevertheless this is no practical way to determine the required correction factors. More suitable is the lumped parameter approach. This modelling of heat flow with an electrical network requires appropriate simplifications. However, the resulting non-linear circuit is solved with standard numerical procedures and the maximum permissible current may be determined explicitly. As an example a typical multi-core flat cable is considered which is used for power and data transmission.

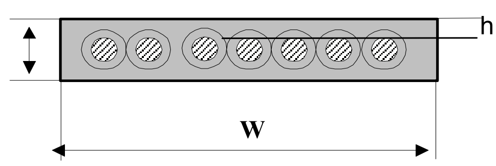

Figure 1. Schematic sketch of a typical flat multi core cable

3.2 Lumped Parameter Model

The usual modelling via an equivalent electrical circuit is applied (IEC 60287; Schmidt, 2005; Wutz;1991). Current sources account for temperature dependent Joule heating where cooling is modelled via resistances. The simple model with only one conductor is readily extended to the multi core case. The temperature depended heating is given via $P_v.= I^2 R_{el} (\vartheta)$. The thermal resistance of the insulation is modelled via *Rth_iso*, convection is modelled via *Rth_a* and *Rth_s* accounts for radiative heat transfer.

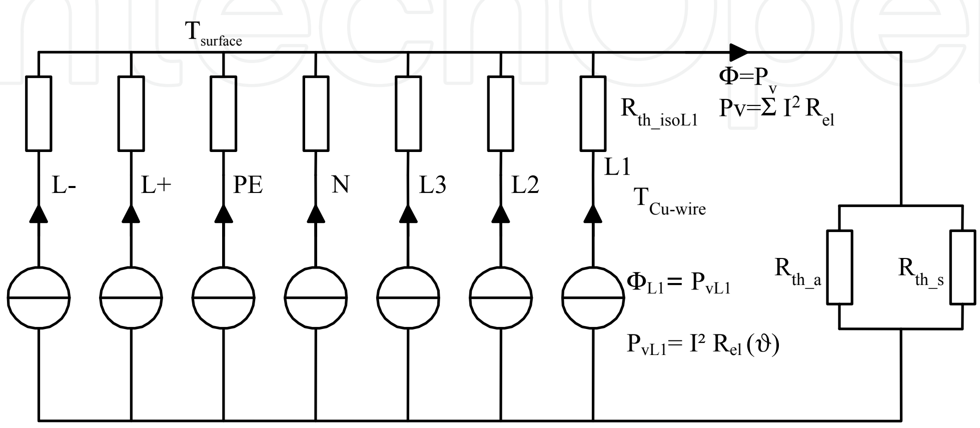

Figure 2. Equivalent circuit with seven conductors and a single surface temperature

With this simple model the surface temperature of the cable is calculated from equation 2, using the effective thermal resistance which covers the heat transfer from the surface of the cable to the ambience.

$$\Delta \vartheta_{Sur} = \Phi \cdot \frac{R_{th\_a} R_{th\_s}}{R_{th\_a} + R_{th\_s}} \tag{2}$$

The total heat flux is given by the summation over the conductors which may be at different temperatures as indicated in equation 3.

$$\Phi_{ges} = \left(\sum_{i=1}^{N\max} I_i^2 \cdot R_{el\_i}(\vartheta_{C\_i}) \right) \tag{3}$$

This may be expanded to account for various operational conditions or for a more geometrically detailed model of the surface. Therefore the temperature of the surface may be calculated from a single non-linear equation (xx) if core temperatures ϑ_{C_i} are known.

$$\Delta \vartheta_{Sur} = \left(\sum_{i=1}^{N\max} I_i^2 \cdot R_{el\_i}(\vartheta_{C\_i}) \right) \cdot \left(\frac{R_{th\_a}(\vartheta_{Sur}, \vartheta_{amb}) \cdot R_{th\_s}(\vartheta_{Sur}, \vartheta_{amb})}{R_{th\_a}(\vartheta_{Sur}, \vartheta_{amb}) + R_{th\_s}(\vartheta_{Sur}, \vartheta_{amb})} \right) \tag{4}$$

The core and the surface temperature are related by the heat flux and may be substituted as required. Therefore effective thermal resistances may be presented in terms of surface or core temperatures. On the other hand, core temperatures have to be calculated from a set of non-linear equations.

$$\Delta \vartheta_{C\_j} = I_j^2 \cdot R_{el\_i}(\vartheta_{C\_i}) \cdot R_{th\_iso} + \left(\sum_{i=1,}^{N\max} I_i^2 \cdot R_{el\_i}(\vartheta_{C\_i}) \right) \cdot \left(\frac{R_{th\_a}(\vartheta_{Sur}, \vartheta_{amb}) \cdot R_{th\_s}(\vartheta_{Sur}, \vartheta_{amb})}{R_{th\_a}(\vartheta_{Sur}, \vartheta_{amb}) + R_{th\_s}(\vartheta_{Sur}, \vartheta_{amb})} \right) \tag{5}$$

Since the maximum permissible temperatures of the cores are known equation 5 may be simplified substantially. The electrical resistance of the core is calculated at the maximum permissible temperature. Then the related maximum permissible currents may be calculated. If the cores are loaded with the identical currents then this model leads to a single non linear equation and the maximum current can be given for different number of loaded cores.

$$\begin{aligned} I &= I_1 = I_2 = \ldots.. = I_N \\ I &= \sqrt{\frac{\Delta \vartheta_{C\_j}}{R_{el}} \cdot \frac{1}{R_{th\_iso} + N \cdot R_{thAmb}(\Delta \vartheta_{C\_j}, T_{amb})}} \end{aligned} \tag{6}$$

Maximum permissible currents for various operating conditions can be calculated efficiently. The relevant quantities for the application i.e. I_r and f_i (eq. 1) are readily taken from theses results.

3.3 Determination of Lumped Parameter Values

Assuming a constant temperature at the surface, one can approximate the thermal resistance from conduction. The values are readily found by solving the well-known energy conservation equation for heat conduction. Both FEM/FVM calculations yield high accuracy for arbitrary geometry and non-linear materials.

$$\nabla \circ \lambda \cdot \nabla \vartheta = -s \tag{7}$$

s denotes the source term i.e. ohmic heating, λ denotes the thermal conductivity
From the solution, i.e. the temperature field, the thermal resistances can be calculated by the ratio of temperatures to applied power. The thermal resistance calculated from this basic relation is in good agreement with an analytical approximation. More complex are convective and radiative heat transfer. The thermal resistance for natural convection may be represented by

$$R_{th\_a} = \frac{1}{aA} \tag{8}$$

The heat transfer coefficient a may be determined via the boundary layer approach (VDI Wärmeatlas 2006)

$$a = \frac{Nu \cdot \lambda}{L} \tag{9}$$

Nusselt number:

$$Nu = \left[0{,}825 + 0{,}325 Ra^{1/6}\right]^2 \tag{10}$$

Rayleigh number:

$$Ra = Gr \cdot \Pr \tag{11}$$

Prandtl number:

$$\Pr = \frac{\eta c_p}{\lambda} \tag{12}$$

Grasshof number:

$$Gr = \frac{g\beta \Delta T L L'^2}{\nu^2} \tag{13}$$

η viscosity, cp thermal capacity, λ thermal conductivity, β compressibility, ν viscosity, L length of surface, L′ effective length
Clearly, the heat transfer coefficient might be taken from detailed SIMPLEC type calculations, but this is not really efficient. So this is only used to check the boundary layer results for uncertainties. These are effective length and the like.
Likewise the thermal resistance for radiation is temperature dependent. The simplest model (Wutz, 1991; Schmidt, 2005) leads to

$$R_{th\_s} = \frac{1}{A\varepsilon\sigma(T + T_u)\cdot\left(T^2 + T_u^2\right)} \tag{14}$$

Considering different ambient conditions e.g. cable layings these effective resistances have to be re-determined.

3.4 Results of thermal modelling

As an example, the results are given for two different laying conditions. The maximum permissible current for the relevant range of ambient temperatures is shown below.

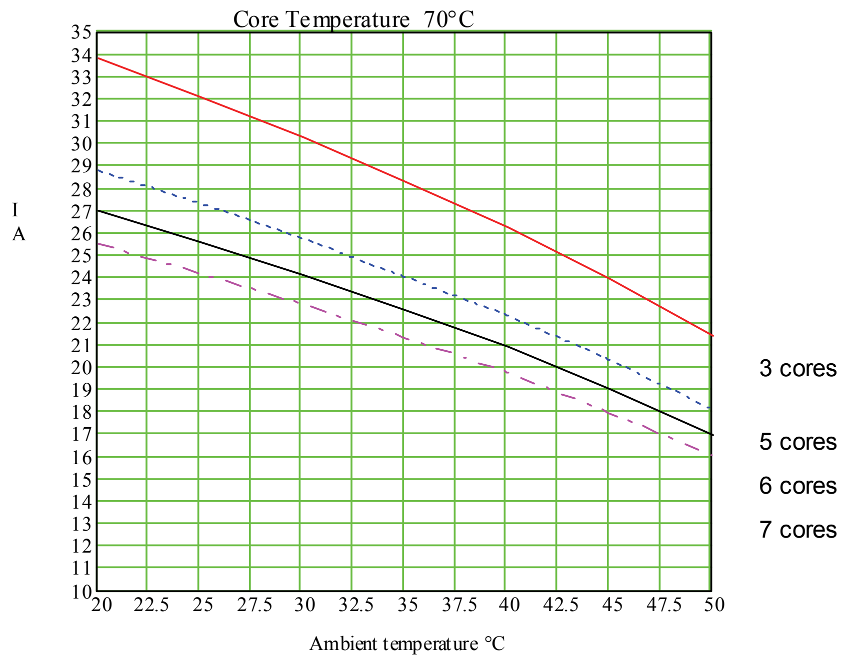

Figure 3. Maximum currents for laying on a concrete wall (70°C conductor temperature)

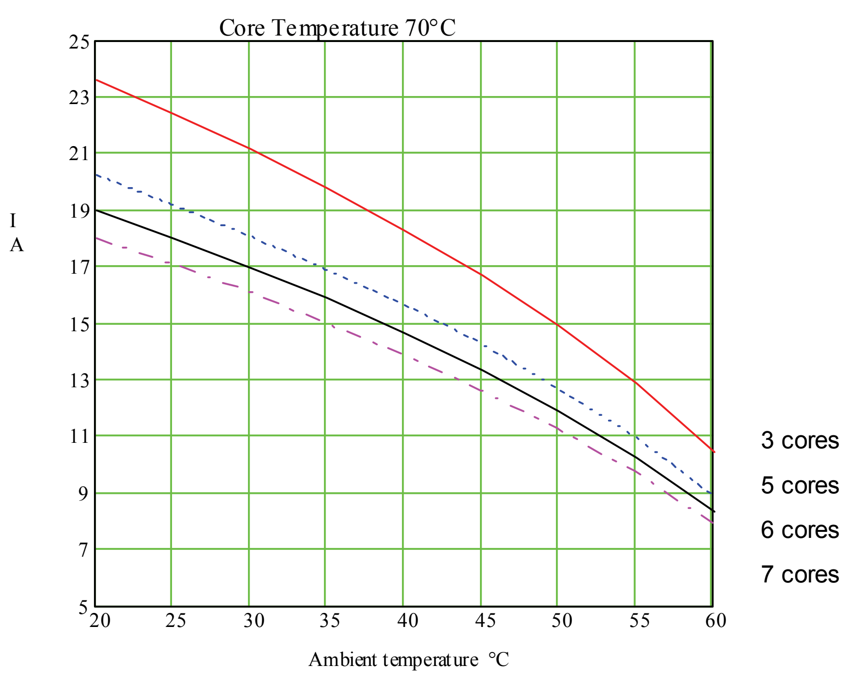

Figure 4. Maximum currents for laying on an insulating wall (70°C conductor temperature)

In figure 3, maximum permissible currents for a standard PVC installation (70°C max) are given for a laying on a concrete wall. In comparison, figure 4 gives these permissible currents when the cable is laid on an insulating wall.

The current carrying capacity (e.g. three cores loaded) is higher than that found in the standards. The standards deal mostly with round cables. Usually this type of cable has air pockets and is not compact. The flat cable considered here has no air pockets whatsoever and conduction to the surface is more effective. Furthermore, the surface area is larger than that considered in standards.

All of the results are in good agreement with measurements by Graf (Graf 2003). The reduction with temperature is also in very good agreement with derating factors given in standards (IEC 60287 and VDE 0299).

4. Modelling of the Electrical behaviour

In automation, so-called hybrid cables with elaborate screening are commonly used to transmit data and auxiliary power within a single cable. A different approach is investigated here with AS-I (Actor Sensor interface) communication. Usually this communication employs a two-wire flat cable without shielding and piercing contacts. Data are encoded with sin square pulses at 167 kHz.

The feasibility of using standard multi core cables for data and power transmission is investigated. Various cables are investigated and compared to standard cables as given by the specifications.

Firstly, the cable parameters are determined and checked against the standard requirements. Secondly, the coupling between pairs of conductors is detailed to access cross talk from the power transmission to the signal carrying conductors. Again results are checked against measurements.

4.1 Modelling

Depending on cable laying various stray capacitances or inductances may come into play. E.g. cables may be mounted directly on a metal support (aluminium or sheet steel). This may affect stray and total capacitance with regard to the signal. Inductance and losses might increase considerably with steel supports.

Relevant frequencies are smaller than 500 kHz and installations are limited to extensions of approximately 100 m. Thus a quasi static approach may be used.

Lumped parameters are determined by calculations using Comsol (Comsol 2006). These parameters are used in network calculations where coupling and distortions are determined.

4.2 Capacitances

The geometry of the cables are specified and the capacitances are readily calculated when the dielectric properties of the insulation are known. Materials in use vary e.g. from EPDM to PUR partly with PVC core insulation.

The potential distribution is calculated from a standard Laplace equation, since there are no space charges.

$$\nabla \circ \varepsilon \cdot \nabla \Phi = 0 \tag{15}$$

Φ potential, ε dielectric constant

Boundary condition are used to mimic the As-I conditions. Within the AS-i system there is strictly no grounding. Coupling to the actual ground/earth is via stray capacitances.

Therefore "floating potentials" are used as boundary condition for the conductors. A potential is set at the boundaries of the conductors which are not carrying the signals such that no current flow occurs.

$$\int_{surface} \vec{n} \circ \vec{J} = 0 \tag{16}$$

Energies are calculated from the according fields.

$$W_{el} = \frac{1}{2} \iiint_{Volume} \vec{E} \circ \vec{D} \, dv \tag{17}$$

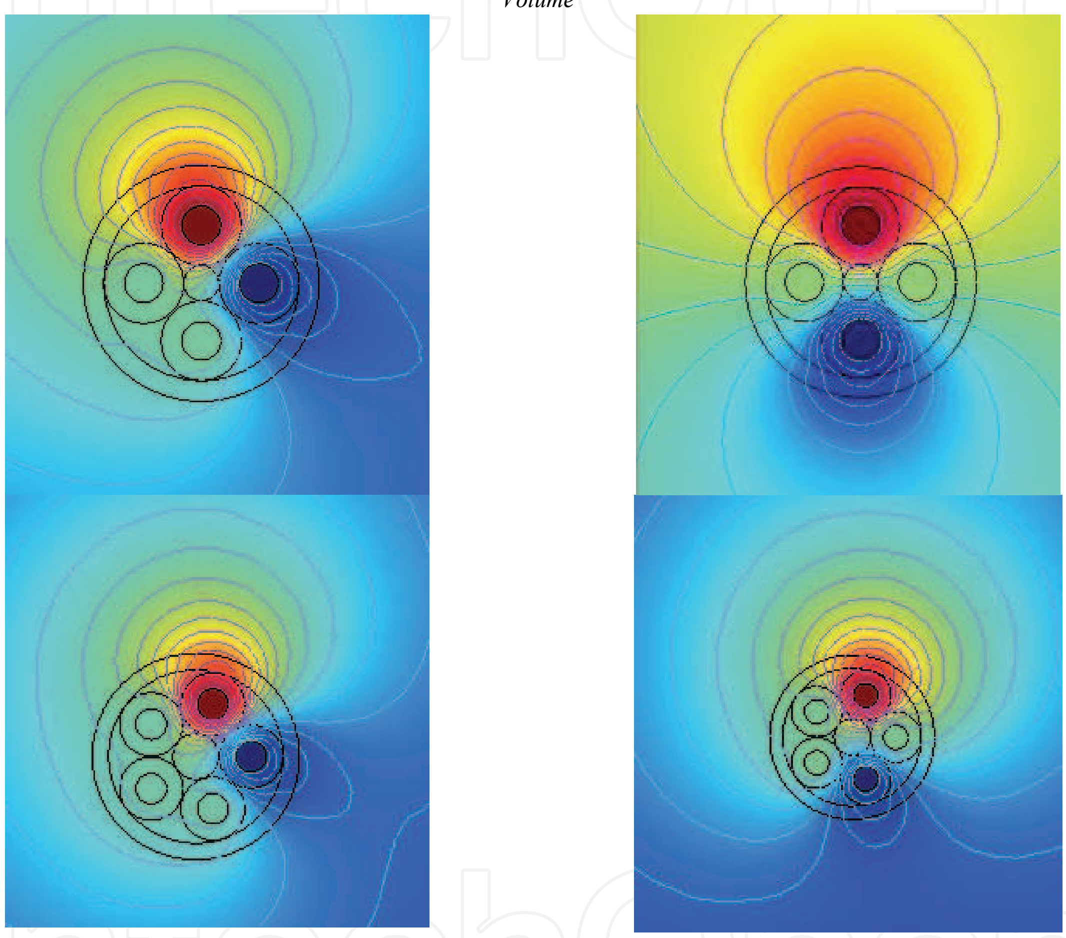

Figure 5. Potential distributions for calculating capacitances using the folating potential approach.

For the two signal carrying conductors there operational capacity is readily taken from that energy and the applied boundary conditions.

$$C = 2 \frac{W_{el}}{(\Phi_2 - \Phi_1)^2} \tag{18}$$

For assessing the coupling the mutual capacitances are to be determined from the capacitance matrix. The capacitance matrix is again computed from electric energy. The coefficients are given by the energies with only conductors i and j set to a voltage/ potential of 1 V and all other set to 0V. The capacitance of a conductor to ground is then given via the sum over the according row (Simonyi 1996).

$$C_{ii} = \iiint_{Volume} \vec{E} \circ \vec{D}\, dv \qquad \Phi_i = \begin{cases} 1V & i = j \\ 0V & i \neq j \end{cases} \tag{19}$$

$$C_{ij} = \frac{1}{2}\left(\iiint_{Volume} \vec{E} \circ \vec{D}\, dv - \left(C_{ii} - C_{jj}\right) \right) \qquad \Phi_l = \begin{cases} 0\,V & l \neq i = j \\ 1\,V & l = i, j \end{cases}$$

A comparison of the capacitance calculated via the floating potentials and via matrix yields good agreement.
Potential distributions are shown in figure 5 for four and five core cables. The capacitance is deducted from the floating potential approach. Adjacent and distant conductor pairs are compared.

4.3 Inductances and resistances

Inductances are calculated from DC flux coupling analogous to the capacitive matrix (Simonyi 1996). The governing equation reads

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = J \cdot \vec{e}_z \tag{20}$$

An iron support structure was assessed for some typical values of the permeability (100-2000). With calculation at 167 kHz skin effect, proximity and eddy currents were studied.
The governing equation becomes

$$\left(j\omega\sigma - \omega^2 \varepsilon\right)\vec{A} + \nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = J \cdot \vec{e}_z \tag{21}$$

Losses and therefore resistance are quite affected by skin and proximity effects. With iron support structures additional losses may contribute remarkably.

4.4 Lumped parameter modelling

An equivalent circuit is used where a voltage is applied to a conductor pair and the voltage of the As-I pair is determined using standard network calculation. Tools like PSPICE are applied here. As an example the equivalent circuit for multi core round cables are shown in figure 6.

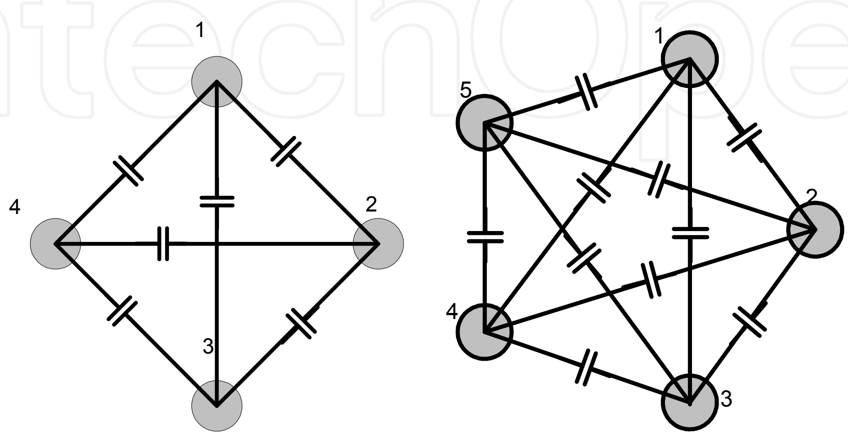

Figure 6. Equivalent circuit of a multi core cable used for capacitive coupling, where capacitance to ground is not shown for clarity

Attenuation and distortion is calculated from equivalent circuits were the cable is modelled by a multitude of the circuits shown in figure 7.

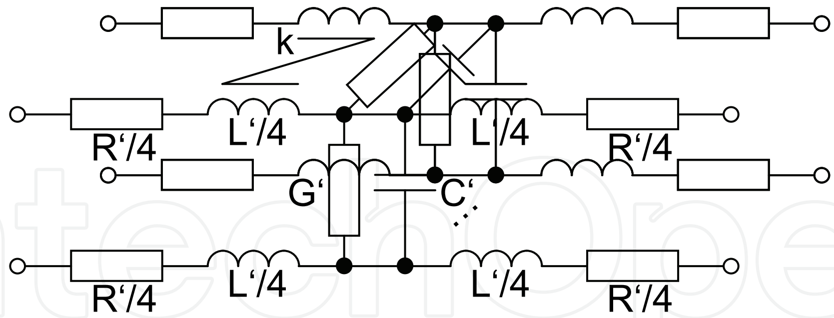

Figure 7. Equivalent circuit for a short piece of a four conductor cable

Other equipment is also modelled with standard equivalent circuits. These include the so called As-I master, the power supply and the slaves. With this modelling different topologies are investigated.

4.5 Results und Discussion

The capacitance matrices are calculated for various cables. Since manufacturers do not necessarily provide actual values of dielectric constants or their tolerances, these values have to be varied. Once adjusted to meet measurements of capacitances, tolerance might be investigated.

The standard requirements for AS-i cables are $C' < 80$ pF/m, 0.4 µH/m $< L' <$ 1.3 µH/m, $R' <$ 90 mΩ/m; $G' \leq$ 5 µs/m; 70 Ω $\leq Z \leq$ 140 Ω. Theses requirements for resistance and capacitances, are usually met by cables with reasonably large cross-sections (> 1,5 mm²) .

As expected, the parameters of all investigated As-I standard cables fulfil the requirements. Resulting capacitance of 40pF/m to 60pF/m may increase by 38% if the cable is laid on a metal support. With an iron support (µr up to 2000) the inductances increase by approx. 15%.

Almost all round cables which have been investigated fulfil the requirements. These include either four or five cores, cross sections of 1.5 mm² up to 4 mm² with various insulations. Inductances were well within the limits, capacitances reached up to 70 pF/m. Values of the characteristic impedance Z were not met for some five core cables. But adjacent pairs of conductors must not be used for As-i data transmission when a round cable is used. Despite this, a seven core flat cable was found to meet the requirements when two adjacent conductors carry the data signal.

Only differences in capacitive coupling affect data transmission, since data are encoded with differential signals. If a four wire cable would be completely symmetric, there were to be no coupling at all when not using any adjacent conductor pairs. If adjacent cores are used, the amplitude of the capacitive coupled signal reaches 28% of the coupling amplitude. With a five-core cable, this capacitive coupling reaches app. 15% for non adjacent pairs and 23% for adjacent pairs. Coupling inductance reaches approx. 0.2 µH/m. Metal support structures have only a weak influence since cores are helically wound along the cable run.

With the flat cable, the outer conductor pair is used for data transmission. The capacitive coupling reaches app. 15% when a metallic support is used and approx. 5% without a metal support. The coupling inductance reaches up to 0.15 µH/m. The protective earth, which is next to the "As-i cores", carries the harmonics from frequency inverters. Due to the relatively high frequency, this may well affect data transmissions. To improve signal integrity the protective earth core may be grounded at several points along the cable run. Also, short circuit current at power frequencies may lead to voltages that exceed safe operating conditions. Surge protection becomes mandatory.

Experimental results

The line parameters were measured with a precision impedance meter. Coupling was measured with a 10 kVA arbitrary wave form generator. 5 kHz square pulses with amplitudes up to 850 V were applied to check the capacitive coupling. Current pulses at 5 kHz with up to 13 A were used to measure inductive coupling. Results from calculations were in reasonably good agreement with measurement.

The amount of erroneous As-i telegrams was assessed. There was virtually no telegram repetition with the 4 core cable (no adjacent cores). Considerable inductive coupling led to telegram repetition with the flat cable and even more with the 5 core round cables. This is in accordance with the inductances. With increasing amplitudes malfunction of the AS-I data transmission was found. Reasonable agreement was also found for calculated and measured attenuation and signal wave forms.

Further investigations are will carried to simulate the complete data transmission including the translation of the physical signal wave form to actual data.

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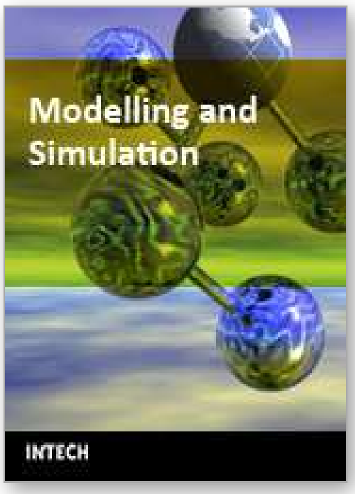

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