RETROFITTING AC CABLES TO DC FOR PUBLIC LIGHTING, REFLECTIONS AND TRANSIENTS DURING SWITCHING

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ABSTRACT

The CombiCable is a power distribution cable that consists of four main conductors used for transportation of the three-phase AC power to the consumers. In the same cable, there are four auxiliary conductors situated around the main conductors and these are used for powering public lighting, traditionally with AC power. Recently, public lighting has shifted towards LED lighting, requiring DC power instead of AC. The question is if the four auxiliary conductors can be used for DC powering the public LED lighting, instead of adding a new underground cable for public LED lighting. Retrofitting the auxiliary conductors in the existing CombiCable means a considerable saving in material and labor costs, as there would be no need for replacement of the cable for applying DC-powered public LED lighting. Since the CombiCable has been widely applied in the Netherlands with over 40.000 kilometers of cabling, reusing these cables would save a lot of material and labor costs.

Some experimental research has been carried out to investigate whether it is possible to apply the combination of AC main power and DC power for the public lighting in the same CombiCable. Before implementation, the cross-coupling and electromagnetic interference between the AC and DC system have to be investigated to ensure the reliability of the system. In particular the impact of transient voltages and currents in the AC section of the cable as a result of switching actions in the DC section of the cable.

To investigate this problem, a simulation model of the CombiCable is a valuable tool. In this paper, a setup of a simulation model for the CombiCable will be described that makes it possible to investigate and observe the transient voltages in the cable during switching actions. The simulation results give insight into the behavior of the CombiCable when applying AC and DC simultaneously in the same cable.

KEYWORDS

Energy distribution, CombiCable, AC power, DC power

Introduction

Electrical power distribution in distribution grids is mainly being performed by the application of the CombiCable. Such a cable consists of four main conductors and four auxiliary conductors. The CombiCable construction is shown in Figure 1a and the conductor positions are shown in the cross-section of the cable in Figure 1b. It is shown that the cable is constructed by its conductors that are insulated by several insulation layers. It is further shown that the thickness of the four auxiliary conductors is relatively small and that these conductors are located on the outer side in between the main conductors.

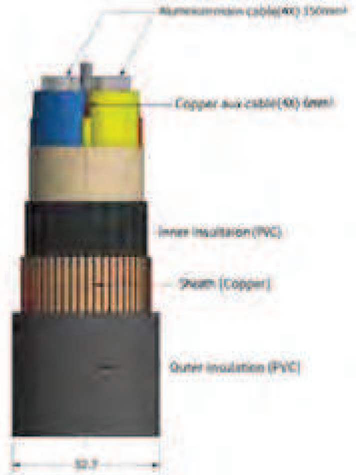

Figure 1a. CombiCable construction [1]

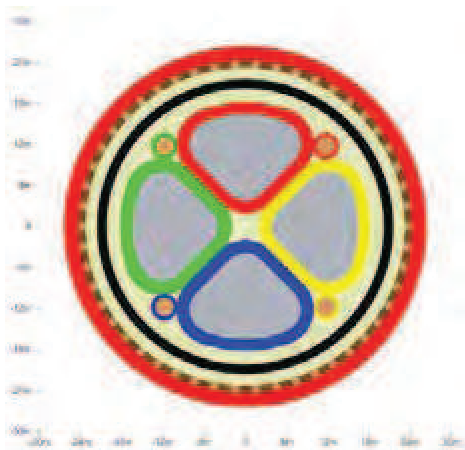

Figure 1b. Main and auxiliary conductor locations

In the normal steady-state operation of the distribution power grid, the main conductors of the cable carry the AC power current for distributing the AC power to the consumers. Simultaneously, the auxiliary conductors have been used for powering public lighting, for which also AC power is required. Nowadays, LED lighting is coming up more and more and these lights require DC power instead of AC. Investigating the feasibility to combine AC and DC power on the same cable is of large importance from several points of view. In the case of switching actions on the AC cable side during steady-state operation of the power grid, voltages are induced in the neighboring conductors since a change in magnetic field strength will result in an induced voltage. These induced voltages will propagate along the cable conductors. The severity of these induced voltages depends on the electrical and magnetic properties of the cable materials that influence the coupling between the adjacent conductors. As a result of the coupling between conductors, induced voltages can cause reflections occurring at cable junction points. Junction points are locations where there is a change in impedance resulting in a discontinuity of the voltage and current propagation. At a junction point, a part of the voltage will be reflected and the other part will be refracted. Reflected voltages could result in large voltage peaks in the cable. Some earlier research has been done on the applicability of the CombiCable [1], [2], [3]. Also, experimental modeling work has been done [4].

In this work, the research on the cable is described to answer the question of whether it is possible to apply AC power and DC power simultaneously in the same cable when switching actions occurred. In previous experimental work [1], measurements have been performed on a CombiCable test setup to investigate the coupling between the main conductors and the auxiliary conductors. Based on these measurements, the coupling parameters are estimated and validated by a simulation model. In this paper, a simulation model for the CombiCable is presented to investigate the severity of switching effects on the cable. In [5] an overview is given of auxiliary loads on a public lighting network. The monitoring and control of public lighting is discussed in [6]. Many LED drivers that are suitable for connection to an AC grid can also be connected to a DC grid. The driver presented in [7] has no transformer at the input terminals and can therefore be directly connected to a DC grid. Droop control in case of a DC microgrid controlled public lighting is explained in [8].In [9] the use of the DC traction supply for use in public lighting via a three phase AC grid tied inverter is discussed. The use of DC microgrids is described in [10][11] and protection of DC grids in [12]. In [1] the application of the auxiliary conductors in a AC grid for a DDC micro grid are discussed.What is the reason to replace AC with DC for street lighting? The main advantage is that there is no voltage drop due to the inductance of the cable and therefore more street lights can be connected to a longer cable. In this way, costs are reduced as less power supply feeders are required per kilometer. Secondly, the earth leakage detection is possible over a longer cable because there is no leakage current due to the capacitance of the cable. Therefore any leakage current at the end of the cable can be detected at the power supply.

In section II we cover the basics of the CombiCable and how is applied for street lighting. Here we discuss the application of AC or DC and what the advantages of a DC grid for street lighting are. Also, the CombiCable is introduced and its parameters, and especially the cross-coupling, are discussed and presented. The mathematical model for a power cable is discussed in section III and the electrical wave propagation and reflection are outlined in section IV for a general power cable. In section V the simulation results for a cable subdivided into several segments are presented. The cross-coupling in the CombiCable when combined AC and DC distribution is done using the same CombiCable is discussed in section VI. The model showing the influences of cross-coupling are presented in section VII. Section VIII shows the final circuit model for the CombiCable that is used to show the cross-coupling between the AC and DC grid in the CombiCable. In section IX two simulations of a 4km and a 3km DC grid with 40 and with 60 street lights is presented.

Combicable

Traditionally the CombiCable is used to supply both households with AC via the main cores. Using a switch, the street lights connected to the auxiliary cores can be supplied from the same AC distribution system, as is shown in Figure 2.

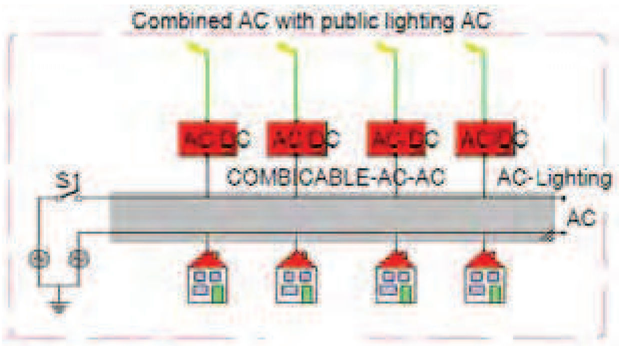

Figure 2. Distribution system using AC[13]

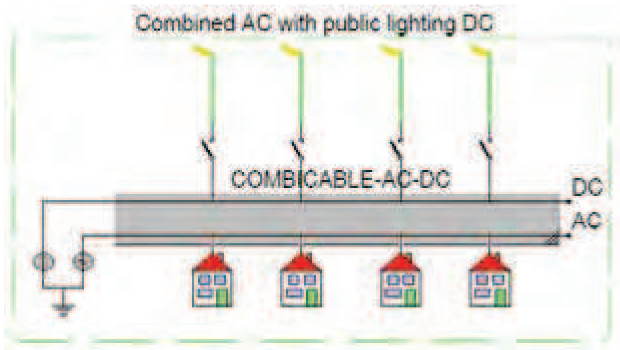

Figure 3. Distribution system using AC and DC[13]

Retrofitting the CombiCable means that the auxiliary cores are now used to distribute a DC grid for feeding the street lights, as is shown in Figure 3.Each street light has a remotely controlled switch, as the DC grid remains constantly supplied over the auxiliary cores. The reason for his is that the DC grid can also be used for feeding other applications such as telecom and surveillance.

Cable transmission line model

Switching actions in cables might result in high-frequency voltages and current waves propagating along the cable and causing reflections to occur. To investigate the behavior of propagating voltage and current transients and the influence of reflections, an accurate model of the CombiCable is needed. Several cable models are available with each their limitations concerning accuracy. For investigating switching effects, a transmission line model is needed as shown in Figure 4 [14]. This figure shows a cable segment having a certain physical length indicated by dx, consisting of infinite small segments within each segment the cable's electrical and magnetic properties are taken into account. A total physical cable section with a certain length can be modeled by an infinite amount of these cable segments. The transmission line model is shown for a two-conductor cable segment. The transmission line cable model is a sufficient base model for modeling the CombiCable that provides sufficient accuracy for investigating switching effects and studying the voltage and current reflections along the cable.

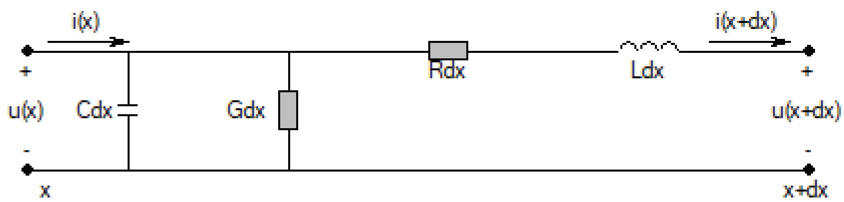

Figure 4. General transmission line model [14]

When considering the model shown in Figure 4, we can find the expressions for the series impedance and the shunt admittance. The series impedance is formed by the resistance *r* and the self-inductance *l* is can be written as[14]:

$$z = r + j\omega l \tag{1}$$

The shunt admittance is formed by the conductance *g* and the capacitance *c* and can be written by:

$$y = g + j\omega c \tag{2}$$

In Figure 4 and equations (1) and (2):

r is the resistance per unit length [Ω/m]

l is the self-inductance per unit length [H/m]

g is the conductance between two conductors per unit length [S/m] **c**
is the capacitance between two conductors per unit length [F/m] **z** is the series impedance [Ω/m]

y is the shunt admittance [S/m]

When taking Figure 4 as a starting point, we need to perform some mathematical analysis to arrive at a set of applicable equations. Applying Kirchhoff voltage and current law to the circuit in Figure 4, we can describe the voltage difference over the series impedance and the current difference between the locations *x* and *x*+*dx* by taking (2) into account, we arrive at the Telegrapher's equations [14]:

$$dV = Izdx \tag{3}$$

$$dI = (V + dV)ydx \tag{4}$$

These expressions can also be written in the form of two linear first-order differential equations:

$$\frac{dV}{dx} = zI \tag{5}$$

$$\frac{dI}{dx} = yV \tag{6}$$

Taking the derivative within respect to *x* of (5) and (6), the following second-order differential equations are obtained:

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} \tag{7}$$

$$\frac{d^2I}{dx^2} = y\frac{dV}{dx} \tag{8}$$

When these equations are combined, meaning that when (6) will be substituted into (7) and (5) will be substituted into (8), we arrive at a set of second-order linear differential equations:

$$\frac{d^2V}{dx^2} = zyV = \gamma^2 V \tag{9}$$

$$\frac{d^2I}{dx^2} = yzI = \gamma^2 I \tag{10}$$

In (9) and (10), γ is the so-called propagation constant of the transmission line and it determines the voltage and current wave propagation properties when the wave is traveling along the cable. In general, the propagation constant γ takes into account the attenuation of the wave and its phase shift. According to (11). The so-called characteristic impedance of the line *Z0* depend on *z* and *y* according to (12):

$$\gamma = \sqrt{zy} \tag{11}$$

$$Z_0 = \sqrt{\frac{z}{y}} \tag{12}$$

Based on these two differential equations and applying the boundary condition for both the voltage and current values at the receiving end of the transmission line section, V_r and I_r, two general solutions can be found for describing the voltage and current values at any location *x* along the transmission line. Finally, the voltages and currents at any location *x* can be described by two hyperbolic equations, according to (13) and (14) [14]:

$$V(x) = V_r \cosh(\gamma x) + Z_0 I_r \sinh(\gamma x) \tag{13}$$

$$I(x) = I_r \cosh(\gamma x) + \frac{V_r}{Z_0} \sinh(\gamma x) \tag{14}$$

Electrical wave propagation and reflection

The transient voltages and currents will propagate as electromagnetic waves along the cable according to (13) and (14). The propagation properties depend on the cable's electrical and magnetic parameters and are described by the propagation constant γ. The traveling wave propagation velocity *v* can be described in terms of the permittivity and the magnetic permeability of the cable material, described by the equation:

$$v = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}} \tag{15}$$

In (15):

- ε_0 is the permittivity of vacuum [F/m]
- ε_r is the relative permittivity of the cable insulation material
- μ_0 is the permeability of vacuum [H/m]
- μ_r is the relative permeability of the cable material

Having the expressions for the general voltage and current for a propagating wave along a transmission line, we can observe the reflections that occur at a junction point along the line when switching actions occur. When a traveling voltage wave arrives at a junction point, that's a point where the wave experience a change in impedance, reflection occur and this means that an incident wave and a reflected wave must be distinguished. The resulting voltage at the junction point is equal to the sum of the incident wave and the reflected wave and thus the resulting voltage depends directly on the amount of reflection and thus on the difference in impedances.

The reflection coefficient for a wave propagating through the cable towards the load can be expressed in terms of the impedances, according to (16):

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{16}$$

In (16):

Z_L is the impedance of the load [Ω]

Z_0 is the cable characteristic impedance [Ω]

The meaning of the load and the cable impedance can be made clear by considering a simple practical simulation circuit. This test circuit that consists of a voltage source, a switch, a transmission line, and a load impedance is built up to show the effect of voltage reflections that occur along the transmission line. In Figure 5, this test circuit is shown.

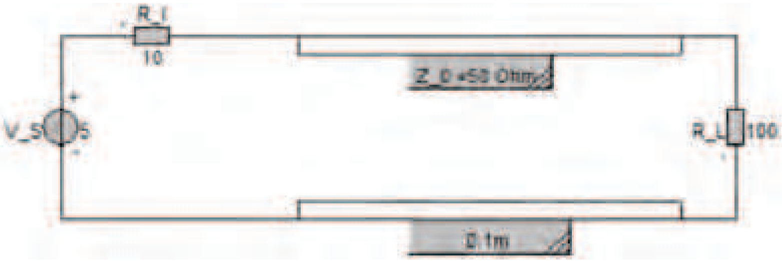

Figure 5. Simulation test circuit for reflection measurement

In Figure 5, the voltage source impedance is 10 Ω and the voltage is equal to 5 V, the cable impedance is equal to 50 Ω and the load impedance is 100 Ω. The voltage source at the sending end of the cable has an impedance of 10 Ω. The voltage source in Figure 5 was switched on at time instant t = 0s. The propagation time between the sending and the receiving end of the test circuit is about 1 ns, meaning that this is a short cable section. Directly after switching on the voltage source, voltage division takes place because the 10 Ω resistance of the source is in series with the 50 Ω cable impedance. This results in a voltage level of about 4,17 V (17) to travel along the cable section towards the load impedance.

$$V = 5\,V \cdot \frac{50\,\Omega}{50\,\Omega + 10\,\Omega} = 4.17\text{ V} \tag{17}$$

At time instant *t = 1 ns*, the voltage arrives at the load impedance at the receiving cable end, equation (16) is applied and the reflection coefficient at the load impedance is equal to 1/3. This results in a reflected voltage level of:

$$V = 4.17\,V \cdot \frac{1}{3} = 1{,}39\,V \tag{18}$$

The resulting voltage level at the load impedance at time instant t = 1ns is equal to the sum of the incident wave and the reflected wave and in this case, this is equal to 5,56 V. After this first reflection instant, the reflected voltage wave travels back to the sending end, meaning that at the voltage source the reflection coefficient is equal to -2/3 as at this location there is a junction point as well. At time instant t = 2 ns, the reflected voltage arrives at the sending end and the reflected voltage is about -0,93 V. At time instant t = 3 ns, the voltage at the load side is equal to 4,32 V. The procedure will repeat until the final steady-state voltage value is reached.

From (16), it can be seen that if the load impedance is large compared to the cable impedance, the reflection coefficient is approximately equal to "1", meaning that the reflected voltage has the same value as the incident voltage. The result is a doubling of the voltage peak at the load impedance. In the situation that there is a short cable section terminated with a high load impedance, many voltage reflections occur in a short period as the propagation time of a short cable is relatively small and thus the attenuation is also small. High voltage peaks can be built up in this way and this may stress the cable insulation material.

CombiCable model and switchings

The transmission line model explained in the previous section is the most accurate model for investigating voltage and current reflections resulting from switching actions. However, some simplification to this model can be made without losing much accuracy. A simplified cable model can be made by dividing the cable length into lumped sections, so-called PI sections. Each section represents a piece of the total cable length and has lumped circuit parameters. This is done for the CombiCable model.

The parameters are [2]:

R = 2973 mΩ/km

L = 1417 µH/km

Cac (capacitance aux-core) = 66 nF/km

Cas (capacitance aux-sheath) =78 nF/km

The accuracy of the PI-section models depends on the number of sections that are used for a certain cable length. The accuracy of the model is investigated by simulation of a switching action on the cable. In this simulation, the cable has a length of 100 meters and at the sending end, a DC power voltage of 350 V is applied. The voltage responses are shown for two pieces of sections for 100 m. CombiCable. In Figure 6, the voltage responses at the cable receiving end are shown. The red line shows the response when 1 section is used. The green line shows the transient response voltage when 50 sections are used. The auxiliary cable is switched on the DC power voltage of 350 V at time instant t = 0 while the cable receiving end is terminated with a 150 W load. In Figure 6, the voltage responses at the cable receiving end are shown. From these plots, it can be seen that the voltage peak is about 825 V and after about 40 ms the voltage oscillation is damped out.

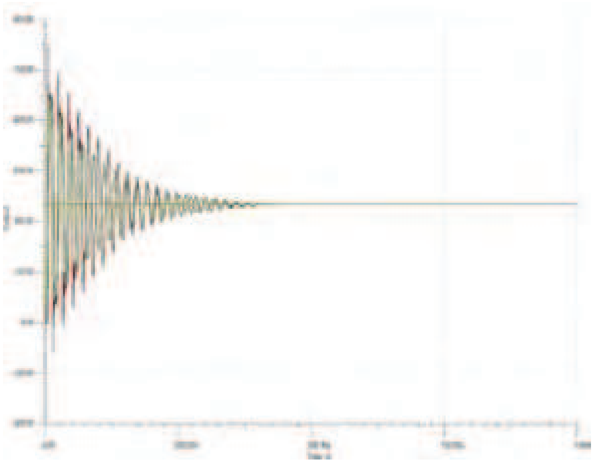

Figure 6. Switching transient voltage

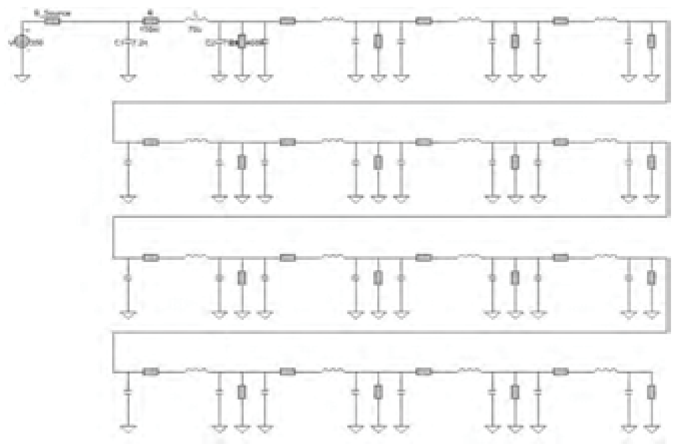

Figure 7. CombiCable model represented by 16 PI sections

In Figure 7, the final model is shown representing the CombiCable with a length of 100 meters. This model is used to perform further switching tests to measure the voltage response and it consists of 16 PI-sections.

Cross coupling

In the previous sections, the reflection and transmission in a general single conductor cable model were elaborated. The CombiCable consists of 4 main conductors and 4 auxiliary conductors within the same shield. The PI-section cable model from Figure 7 considers the inductance of a single conductor. In reality, most AC cables contain more conductors and there is inductive and capacitive coupling between the conductors. The parameters used for the PI-section cable model from Figure 7 are such that they can be considered as equivalent for a multiconductor cable and they include the effect of the inductive and capacitive coupling between the conductors and the shield. These are the parameters that are measured by the manufacturer and given in the datasheet. In the CombiCable also the coupling between the conductors is present, but secondly, there is also coupling between the main and auxiliary conductors. It are these couplings that are of interest when investigating whether the CombiCable can be used for combined AC and DC power transfer. In the following sections, we will elaborate on the coupling between the conductors and how this is incorporated in the model. Secondly, simulations will visualize the effect of this coupling between the main conductors in use for AC and the auxiliary conductors in use for DC power transport.

Cross coupling model

The CombiCable is modeled by an equivalent circuit model, that includes all couplings between all conductors and the shield. The influence of cross-coupling can be studied independently from reflections, given the fact that the eigenfrequencies of the reflections are a multiple of the low-frequency effects due to the cross- coupling.

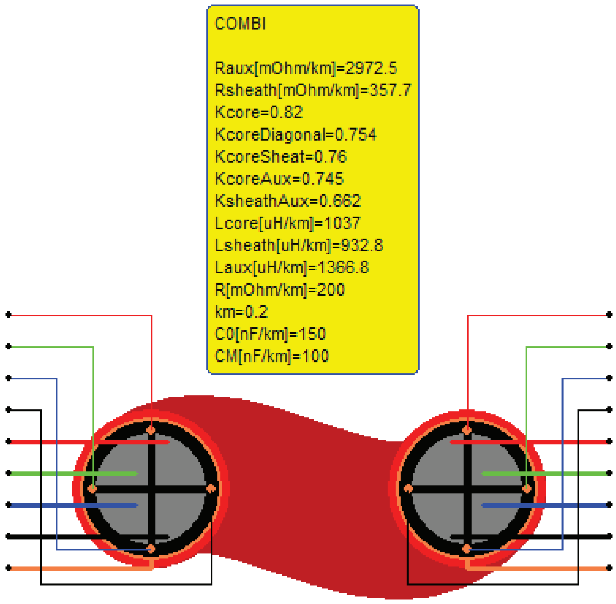

Figure 8. Final circuit model

Figure 9. Online CASPOC cable calculator [13]

For example, Figure 6 shows an eigenfrequency for reflection of roughly 50kHz. The effects of cross-coupling are mainly related to switching actions on the DC lines and the magnetic field from the AC 50Hz current. Fast transient response is expected when turning on a load on the AC as well as on the DC side. Any reflections because of this switching can be calculated using a single PI section, however, multiple PI sections will increase the accuracy. To keep the final circuit model limited in size, only a single PI section is included in the CombiCable model. If multiple PI sections are required, multiple models can be placed in series, where the length for each model equals the total cable length divided by the number of sections. More important inside the CombiCable circuit model are the inductive and capacitive couplings between each conductor and the shield. Therefore the model includes both four main conductors, four auxiliary conductors, and the shield. Each conductor is modeled by an inductance and all conductors are coupled to each other by their mutual inductance. Secondly, the capacitance between all conductors and between the conductors and the shield is modeled. The parameters for the inductive coupling are based on the geometry of the cross-section of the cable. It is assumed that the length of the cable is of a multitude larger than the diameter of the cable. In that case, from the two-dimensional geometry, the mutual inductance and capacitive coupling can be calculated. The resulting parameters are the inductance per conductor as well as the mutual inductance between all conductors. In that way, the inductive cross-coupling between conductors finally defines the total inductance of the CombiCable. The capacitance is defined between all conductors that face each other, as well as the capacitance between the conductors and the shield. The final circuit model is shown in Figure 8. The electrical connections are both on the left and right sides of the cable for each conductor. The parameters for the model are shown in the yellow box in this figure. The Caspoc design tool[12], in Figure 9, is used to calculate the parameters for this typical cross-section of the CombiCable.

Circuit model

The CombiCable model is used in simulations to investigate the cross-coupling between the AC and DC distribution grid. The cross-coupling is studied by using the complete circuit model, where each core is modeled by its equivalent inductive and capacitive model. The mutual inductive coupling and the capacitance between each core are included in this model and thus the simulations can reveal how much disturbance the AC grid is induced on the DC grid and vice versa.

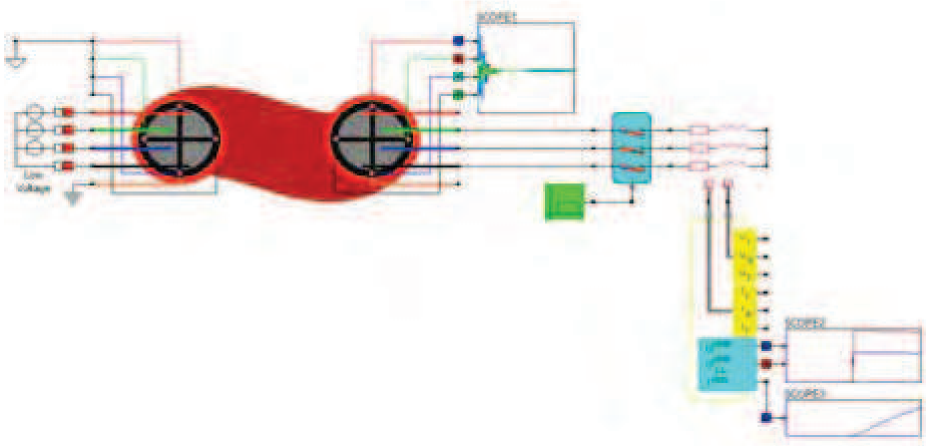

Figure 10. Simulation of disturbance in a DC grid due to switching in the AC grid.

In Figure 10, the simulation shows the disturbance in the DC grid due to a switching action on the AC grid. The load in the AC grid increases suddenly and this is causing a transient on the DC grid. The DC grid is not supplied in this simulation, so at the end of the cable, we can measure the induced voltage.

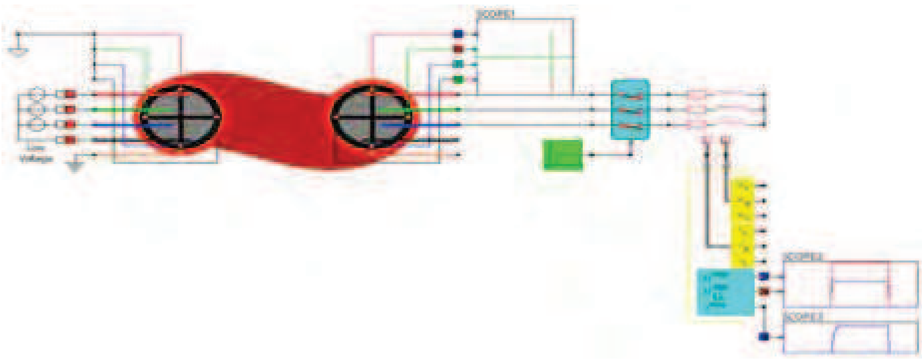

Figure 11. A load on the AC grid is connected. Scope 1 shows a voltage spike occurring in the DC grid while disconnecting the AC load on Scope 2 and 3.

In Figure 11, a load on the AC grid is connected during an interval of 70ms. Especially the turn-off of this AC load is visible in the DC grid, where it generates a large induced voltage spike. The disturbance of switching a DC load in the DC grid on the AC grid is shown in Figure 12, where during several periods of the A grid a load is connected to the DC grid. Because of the cross-coupling, the DC currents induce an unbalance in the electromagnetic field inside the CombiCable, giving rise to a current in the neutral core for the AC grid. A small 50Hz ripple can be observed in the overall AC grid on the neutral core and this influences the line and phase voltages in the AC grid.

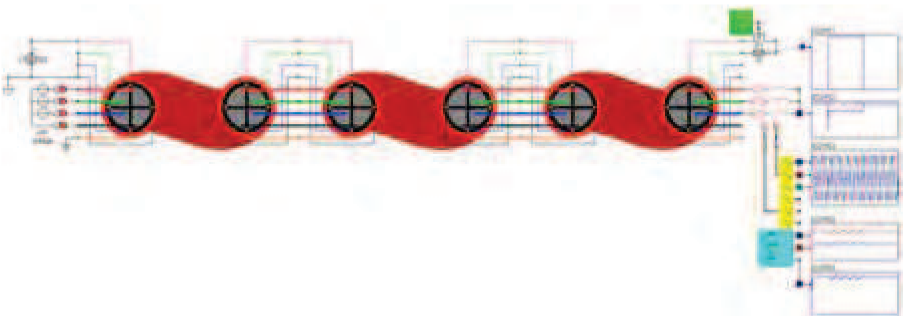

Figure 12. A small 50Hz ripple can be observed,on scope 2, on the neutral core of the AC grid.

DC Grid model

In Figure 13, a DC bipolar grid of 3km feeding 60 street lights at a distance of 50 meters. Use is made of a bipolar grid of plus 350 V, 0 V, and minus 350 V. This means that three cores are required, where the current is distributed by the plus and minus core, while the neutral core carries no current. The initial current during powering the grid is shown in the upper scope where the initial current is compared to an initial current of a single component model. Visible is the transient from the DC grid model with pi sections, compared to the first-order response from the single component model. The voltage after 3km of the grid is reduced to 312 volts, yet enough to feed the street lights at the end of the cable.

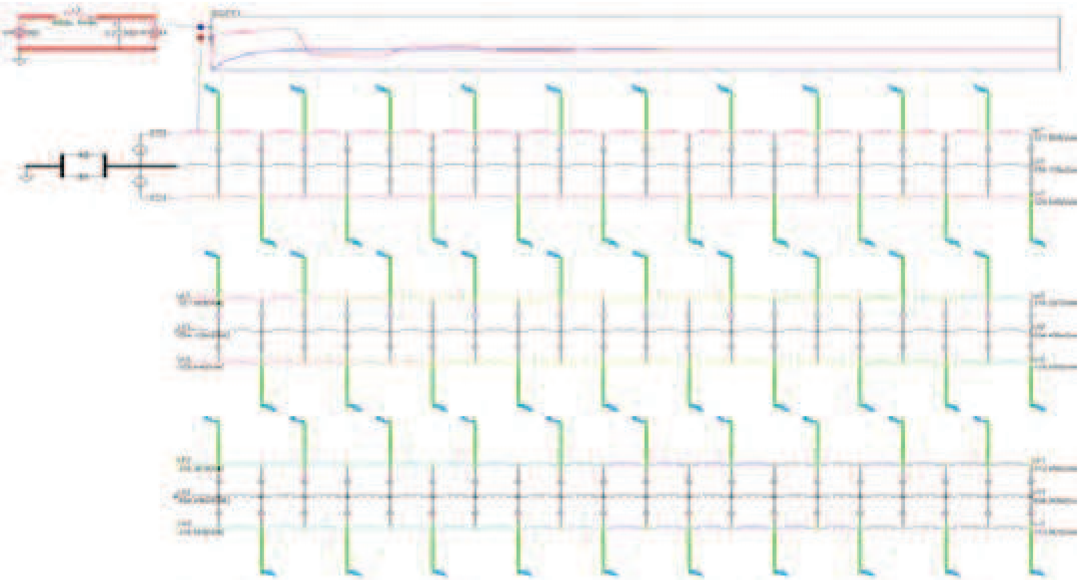

Figure 13. DC bipolar grid of 3km feeding 60 street lights at a distance of 50 meters.

In Figure 14, a DC grid is modeled with 40 street lights each at 100 meters distance over a total length of 4km. A cable with dual cores (*plus, minus*) of 4mm2 is used to power the street lights. On both sides of the DC grid, a power supply is connected feeding the street lights from both sides. The power supply at one side of the grid is having a nominal voltage of 350 volt. The other supply has a nominal voltage of 380 volt. In this way, the power supply with a higher nominal voltage will supply more power (around 2.2kW) to the grid than the one with lower nominal voltage, which supplies only 1.5kW. The importance of the simulation is that it illustrates how the feeding of the DC grid can be done from two sides independently and the amount of power to be delivered can be controlled by controlling the DC voltage. This so-called droop control is utilized in DC grids to avoid power congestion and to have natural power management[15][16].

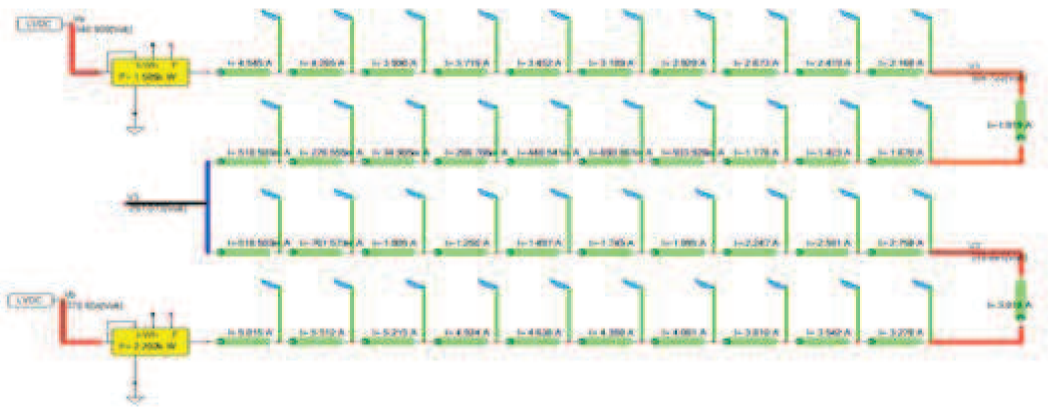

Figure 14. DC grid with 40 street lights each at 100 meters distance with a total length of 4km.

Conclusion

To investigate the application of DC grids in public street lighting, the influence of the cable in the DC grid for street lighting is discussed. In this paper, the retrofitting of the CombiCable for both AC and DC distribution is investigated and it is shown that the CombiCable can be used for combined AC and DC distribution. The main cores are used for the distribution of AC, while three auxiliary wires are used for DC distribution. The overall conclusion when retrofitting the CombiCable for combined AC and DC distribution is that the CombiCable can be used for combined AC DC power distribution. Reflections exist in the cable but are damped naturally and are not influencing the power distribution. Cross-coupling exist and can influence both distributions. It is shown that a pi section model is required to model the wave propagation and reflections in the cable. Retrofitting the existing AC cable where the auxiliary wires are used for the DC grid is possible, but the cross-coupling between the AC and DC grid in a single cable should not influence both grids. The simulations show that there is coupling between the AC and DC grid on the same cable. Disturbances due to the cross-coupling are performed in simulation and from this data the disturbance can be calculated. Final simulations show the application of a DC grid for feeding several kilometers of street lighting. Using droop control the power management in the DC distribution can be controlled naturally.

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