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TITLE Application of the LCL method to measure the unbalance of PLC-equipment connected to the Low-voltage Distribution Network			
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ABSTRACT

This study has been carried out on behalf of the Netherlands Radiocommunications Agency (Agentschap Telecom). The Netherlands Radiocommunications Agency is the government agency responsible for frequency planning and management in the Netherlands. Primary activities of the Radiocommunications Agency are frequency planning, issuing licences for frequency use, and enforcement of frequency use. As such the Radiocommunications Agency is responsible for both the EMC and the RF aspects of the use of Power Line Communication (PLC). Limits have to be determined with which PLC modems have to comply. Compliance with those limits has to be determined by suitable measurement methods. One of the methods proposed is the measurement of longitudinal conversion loss (LCL). The Radiocommunications Agency tasked NLR to carry out a study concerning the suitability of the LCL method for verification of Power Line Communication emissions.

Power Line Communication (PLC) is a system that uses the low-voltage distribution network as a transmission line to exchange data between computer users in-house or between a computer user in-house and users/servers on the internet. Dedicated transmission lines have a low and predictable level of radiated emission. However, the low-voltage distribution network is not designed as a transmission line for data signals up to 30 MHz, but is designed as a power line for 50 Hz. A number of differences between a transmission line and a power line exist which have their influence on the propagation and radiation of wanted (and unwanted) signals on the power line. The low-voltage distribution network consists of "transmission lines" which are not shielded or twisted. This implies that both common mode and differential mode currents on this transmission line may cause radiation. PLC modems generate differential mode signals. However, due to unbalance of the power line and unbalance in the equipment connected to it, part of the differential mode signal is converted to common mode signals.

The definitions provided in ITU Recommendations G.117 en O.9 provide a clear definition of the conversion of differential mode voltage to common mode voltage (and vice versa) for a not-perfectly balanced transmission line. The measurement method defined in these recommendations could be used to determine the mode conversion for the low-voltage distribution network, provided the characteristic impedance of this network would be constant and known. However, due to the fact that the "transmission lines" of the low-voltage network consist of individual wires

that are not bundled together to form a cable, the transverse impedance of this transmission line may vary significantly. In addition both the common mode impedance of the power line and the common mode impedance of the test bridge can show significant variations. Both the variations in transverse impedance and in common mode impedance have their influence on the measured LCL value. It is concluded that the LCL method is not suited to determine the amount of mode conversion on the low-voltage distribution network.

The probe defined by Macfarlane provides an adequate instrument to measure the mode conversion according to the ITU Recommendations. The advantage is that unbalanced measurement equipment can be used. The Macfarlane probe can be used for frequencies up to 30 MHz to measure the conversion from common mode to differential mode voltage (longitudinal voltage to transverse voltage or longitudinal conversion loss (LCL)) on a normal transmission line. In this case, some additional analysis has to be carried out to determine the common mode currents as a result of the common mode voltages. However, due to the uncertainties in the impedances of the low-voltage distribution network, the common mode current can not accurately be determined by determining the LCL with the suggested probe.

The objective of using the LCL method was to determine the level of common mode current due to mode conversion of the differential mode PLC signal on the low-voltage distribution network. Given the above-mentioned difficulties in determining the common mode current indirectly, it seems recommendable to determine the common mode current directly (by means of a current probe). Depending on frequency (wavelength) en line length, the common current distribution is either linear (triangular) or sinusoidal. Therefore the current should be measured on several locations along the line to determine the maximum current value. Due to the limited accessibility, measuring at several outlets maybe would be an option. Sufficient measurements should be made to determine the relationship between the transverse voltage V_T and the common mode current I_{cm} on a statistical basis. If measuring the I_{cm} directly is too complicated, I_{cm} has to be measured indirectly, e.g. by measuring the radiated H-field. In any case, determining the I_{cm} by measuring V_{cm} (LCL method) is not recommended.
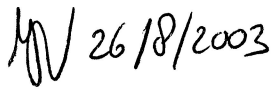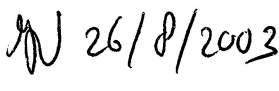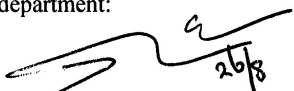
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Application of the LCL method to measure the unbalance of PLC-equipment connected to the Low-voltage Distribution Network

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Summary

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The definitions provided in ITU Recommendations G.117 en O.9 provide a clear definition of the conversion of differential mode voltage to common mode voltage (and vice versa) for a not-perfectly balanced transmission line. The measurement method defined in these recommendations could be used to determine the mode conversion for the low-voltage distribution network, provided the characteristic impedance of this network would be constant and known. However, due to the fact that the "transmission lines" of the low-voltage network consist of individual wires that are not bundled together to form a cable, the transverse impedance of this transmission line may vary significantly. In addition both the common mode impedance of the power line and the common mode impedance of the test bridge can show significant variations. Both the variations in transverse impedance and in common mode impedance have their influence on the measured LCL value. It is concluded that the LCL

method is not suited to determine the amount of mode conversion on the low-voltage distribution network.

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List of abbreviations

CISPR	International Special Committee on Radio Interference
CM	Common mode
DM	Differential mode
IEC	International Technical Commission
ITU	International Telecommunication Union
LCL	Longitudinal Conversion Loss
LVDN	Low Voltage Distribution Network
PLC	Power Line Communication
TCL	Transverse Conversion Loss
TEM	Transverse Electromagnetic

List of symbols

β	Phase constant
ε	Permittivity
γ	Propagation constant
λ	Wavelength
σ	Conductivity
μ	Permeability
ω	Radian frequency
C	Capacitance
G	Conductance
Hz	Herz
I_{cm}	common mode current
k	Transverse conversion factor
L	Inductance
MHz	Megaherz
R	Resistance
V_{cm}	common mode voltage
V_T	transverse voltage
Y_0	Characteristic admittance
Z_0	Characteristic impedance
Z_{cm}	Common mode impedance
Z_L	Load impedance
Z_{Lc}	Longitudinal impedance of cable
Z_{Le}	Longitudinal impedance of equipment
Z_{Tc}	Transverse impedance of cable
Z_{Te}	Transverse impedance of equipment

1 Introduction

Power Line Communication (PLC) is a system that uses the low-voltage distribution network (LVDN) as a transmission line to exchange data between IT-equipment in the same house or between IT-equipment in house and servers on the internet. Dedicated transmission lines have a low and predictable level of radiated emission. However, the LVDN is not designed as a transmission line for data signals up to 30 MHz, but is designed as a power distribution network for 50 Hz. A number of differences between a transmission line and a power line exist which have their influence on the propagation and radiation of signals on the power line. The LVDN consists of "transmission lines" which are *not shielded* or *twisted*. This implies that *both common mode* (longitudinal) and *differential mode* (transverse) currents on this transmission line may cause radiation. In order to limit the radiation due to Power Line Communication on the LVDN, limits for the PLC equipment have to be established. These limits should take into account the characteristics of the LVDN in terms of impedances, unbalance and "antenna performance". It is most likely that the PLC equipment itself can be reasonably balanced. The LVDN, however, will show significant unbalance due to geometry of the wires, conducting parts in its environment and the electrical/electronic equipment connected to it. Therefore two limits have to be derived for the PLC equipment: a limit to the differential mode output voltage (which will be converted to common mode currents due to the unbalance in the LVDN) and a limit to any additional unbalance introduced by the PLC equipment itself. To derive a limit for the differential mode output of the PLC equipment, the conversion of differential mode to common mode voltage by the LVDN should be determined. The question is whether the LCL method can be used to determine this conversion.

In the case of PLC, the LVDN is used to transport differential mode (transmission line) signals between PLC modems. Part of the differential mode currents will be converted to common mode (antenna) currents due to unbalance in the power line and the terminating equipment. These common mode currents are primarily responsible for the electromagnetic radiation (E-field, H-field). Therefore it is important to determine the amount of differential mode signal (transverse signal) that is converted into a common mode signal (longitudinal signal). The ITU has defined methods to determine the ratio of longitudinal signal level to transverse signal level (and vice versa) on transmission lines: these methods are called the Longitudinal Conversion Loss (LCL) method respectively the Transverse Conversion Loss (TLC) method (both described in Refs. 1 and 2). These methods can be applied to telecommunication systems: transmission lines, telecommunication equipment and a combination thereof. Although the TCL is the most important value with respect to the determination of the longitudinal (common mode) voltage caused by unbalance in the system, the LCL value is easier to measure in a noisy environment outside a shielded room. The LCL value is related to the TCL value because they both describe

the unbalance in a transmission line or system. The question is whether the LCL method also can be applied to determine the unbalance in *power lines*.

2   Existing LCL measurement methods

The International Telecommunication Union (ITU) has provided some guidance on how to measure the unbalance on transmission lines and terminating equipment. This guidance is given in ITU-T Recommendations G.117 and O.9 (Refs. 1 and 2). This chapter provides an overview of the information given in these Recommendations.

The Longitudinal Conversion Loss of a one- or two-port network is a measure (a ratio expressed in dB) of the degree of unwanted transverse signal produced at the terminals of the network due to the presence of a longitudinal signal on the connecting leads. It is calculated as

$$\text{Longitudinal Conversion Loss (LCL)} = 20 \log \left| \frac{V_{L1}}{V_{T1}} \right| \text{ dB} \tag{1}$$

and measured as shown in Figure 1. This technique is applicable to either the input or output terminals, e.g. transpose terminals a and b with d and e respectively.
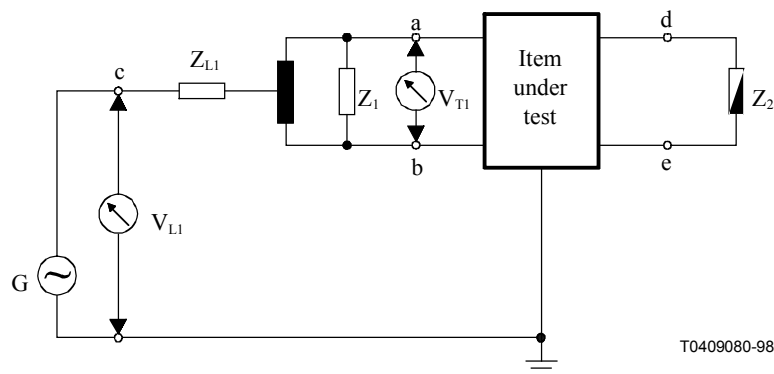

G   Signal generator. For details about Z_1, Z_2, Z_{L1}, see 5.2.

NOTE – This test bridge configuration, with transversal impedance Z_1 and longitudinal impedance Z_{L1}, does not in all cases represent conditions found in practice. Thus, some care is needed when translating measured unbalance parameters into unbalance information applicable to practical cases. This is discussed in more detail in Appendix I.

Figure 1 Measurement of Longitudinal Conversion Loss

The unbalance properties of an equipment port or a network port can be described in many ways by equivalent circuits. The one shown in Figure 2, employing an ideal choke with a tap, will be used here because it leads to simple expressions. (The factor *k* is a measure of the degree of unbalance.)
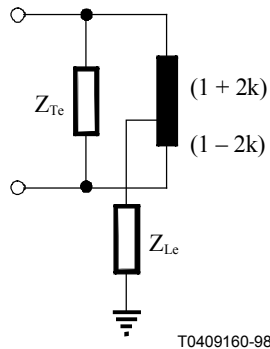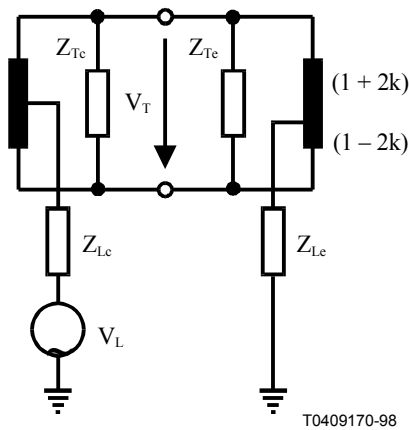
Z_{Te} Transverse impedance
Z_{Le} Longitudinal impedance
k   Transverse Conversion Factor

Figure 2 Equivalent circuit for the unbalance-to-earth at a port

This equivalent circuit type can be used both for the circuit (cable or the test bridge), that introduces the longitudinal voltage, and for the terminating equipment, as Figure 3 depicts (note that the cable and the test bridge are supposed to be perfectly balanced). In the case of PLC, Z_{Tc} and Z_{Lc} are the impedances of the test bridge and Z_{Te} and Z_{Le} are the impedances of the LVDN and the equipment connected to it (see Figure 4) or the impedances of the PLC equipment itself.

Z_{Te}, Z_{Le} Transverse or longitudinal impedance of the equipment
Z_{Tc}, Z_{Lc} Transverse or longitudinal impedance of the cable or
         the test bridge

Figure 3 Equivalent circuit for conversion of the longitudinal voltage V_L

Using the equivalent circuit, the following expression for the Longitudinal Conversion Loss LCL_c in the general case is derived:

$$LCL_c = 20 \cdot \log \left| \frac{1}{k} \left\{ (Z_{Lc} + Z_{Le}) \cdot \left(\frac{1}{Z_{Tc}} + \frac{1}{Z_{Te}} \right) + k^2 \right\} \right| \text{ dB} \qquad (2)$$

Note that this equation is valid for all values of *k*, i.e. even if the port would be totally unbalanced. However, in general, the terminating equipment is reasonably well-balanced, i.e. *k* is small, so that the above equation can be simplified to:

$$LCL_c = 20 \cdot \log \left| \frac{1}{k} \left(Z_{Lc} + Z_{Le} \right) \cdot \left(\frac{1}{Z_{Tc}} + \frac{1}{Z_{Te}} \right) \right| \text{ dB} \tag{3}$$

It can be concluded that

- the LCL increases when the unbalance *k* decreases
- the LCL increases if the common mode impedance Z_L increases
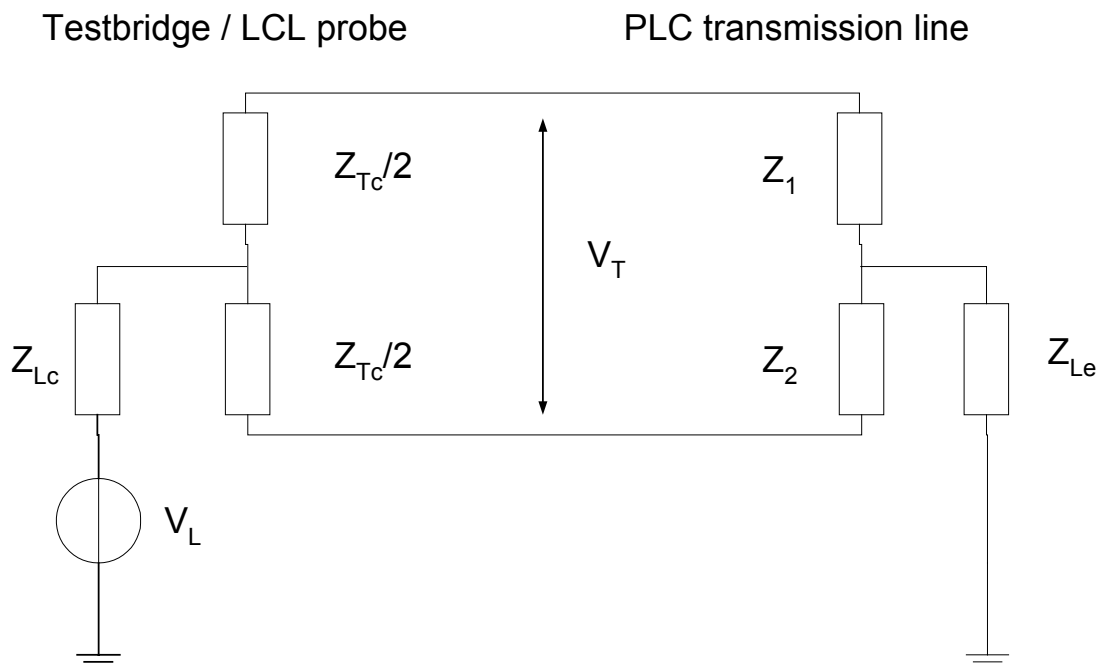- the LCL increases if the differential mode impedance Z_T decreases

Testbridge / LCL probe   PLC transmission line

Figure 4 Equivalent circuit for LCL measurement on PLC transmission line. Z_{Te} as in the ITU Recommendations is replaced by Z_1 and Z_2 to describe the unbalance in the transmission line

2.1 Discussion of ITU-T Rec. G.117 and Rec. O.9

For normal transmission lines (with a constant characteristic impedance along the line and matched sources and terminations), the LCL value provides not only insight in the longitudinal *voltage* but also into the longitudinal current (because they are related through the characteristic impedance). For analysis of the radiated emission of the transmission line, the Longitudinal *current* (common mode current, antenna current) is of importance. The LCL measurement method is designed for use on transmission lines with a <u>constant</u> and <u>known</u> characteristic impedance. Both the transverse impedance and the longitudinal impedance of the test bridge

should be adapted to the characteristic impedance of the transmission line or, if needed, to the input impedance of the transmission line terminated with a specific load.

The absolute input impedance of a line with, for example, a characteristic impedance of 200 Ω, terminated with a load impedance of 100 Ω, can vary between 100 Ω and 400 Ω (see Figure 10), depending on the line length. In this case the input impedance is complex!

When we define:

$$h = Z_{Le}/Z_{Lc} \quad and \quad g = Z_{Te}/Z_{Tc} \tag{4}$$

equation (3) can be rewritten as:

$$LCL_c = \left| \frac{1}{k}(Z_{Lc})(1+h) \cdot \left(\frac{1}{Z_{Tc}} \right)\left(1 + \frac{1}{g} \right) \right| \tag{5}$$

From the previous expression it can be concluded that the LCL is proportional to

$$LCL \propto \left| \frac{1}{k}(1+h)\left(1 + \frac{1}{g} \right) \right| \tag{6}$$

This implies that for the case $h >> 1$ the *LCL* value is *proportional* to h and for $h << 1$ the *LCL* value is independent of h. For $g << 1$ the *LCL* value is *proportional* to $1/g$ and for $g >> 1$ the *LCL* value is independent of g.

So, if the transverse impedance of the object under test Z_{Te} is (much) higher than the transverse impedance of the test bridge Z_{Tc}, the LCL value is not influenced by the value of the transverse impedance of the object under test (line + terminating equipment). The same applies to the Z_{Le}. If the common mode impedance of the equipment Z_{Le} is much smaller than the common mode impedance of the test bridge Z_{Lc}, then the Z_{Le} has no influence on the LCL.

In case of determining the LCL of transmission line, the length in terms of wavelength is of importance. For low frequencies (length of the cable much smaller than the wavelength), the circuit method can be used. In this case a test bridge with a low Z_{Tc} and a high Z_{Lc} would reduce the influence of the impedances of the transmission line under test.
For frequencies for which the length of the cable is more than a wavelength, the transmission line theory should be applied. In this case it will be difficult to measure the LCL accurately if there is a mismatch between transmission line and terminating equipment.

First we will address deviations in the *transverse impedance* of the test object. Assume that the test bridge was designed to carry out measurements on 400 Ω transmission lines. In the case that the input impedance of the line is 100 Ω instead of 400 Ω (1/g=4), the LCL value increases by 8 dB. On the other hand, if the test bridge was designed to measure on 100 Ω transmission lines and the input impedance of the line is 400 Ω (g=4), then the influence on the LCL value is marginal since g>>1. *It seems wise to select a value for the transverse impedance of the test bridge which is lower than the lowest input impedance of the line.*

Not only the transverse impedance (char. impedance) of the line is important. The actual value of the longitudinal impedance also has its influence on the LCL value. This issue is addressed by Grawon (Refs. **8** *and* **9***). The conclusions of Refs.* **8** *and* **9** *are that the longitudinal impedance has a large influence on the measured LCL value. When carrying out in-situ measurements the problem is often that there is no suitable reference potential. Therefore large metallic structures as heating or water supply systems of homes are used for this purpose. However, often the stray capacitance of the test bridge to ground dominates the common mode impedance. LCL values measured in this way can vary by as much as 50 dB. The author therefore proposes to analyse the LCL by taken a sufficient large number of measurements and analyse them statistically.*

It can be concluded that measuring with "standard" impedances provides a reproducable way of comparing the unbalance in transmission lines or telecommunication equipment. However, since in the case of Power Line Communication the actual impedances may be different from the standard ones, the level of mode conversion can not predicted accurately.

2.2 LCL probe by Macfarlane

"A Probe for the Measurement of Electrical Unbalance of Networks and Devices", Ian P. Macfarlane, Senior Member IEEE, IEEE Trans. on EMC, Vol. 41, No.1, February 1999, pp. 3-13

The probe described in the article by Macfarlane (Ref. 3) is designed for the measurement of LCL (Figure 5). The advantage is that it uses 50 Ω instruments to measure the electrical unbalance of wire pair networks and two-terminal devices instead of wide-band balanced voltmeters which should have an extremely good balance. The probe as described in the article is optimised for use with balanced devices or conductor pairs having 100 Ω transverse characteristic impedance. The component values of the probe should be changed to accommodate conductor pairs or balanced devices having other values of characteristic impedance. According to the author, the probe has a useful measurement frequency range from less than 40 kHz to more than 30 MHz.
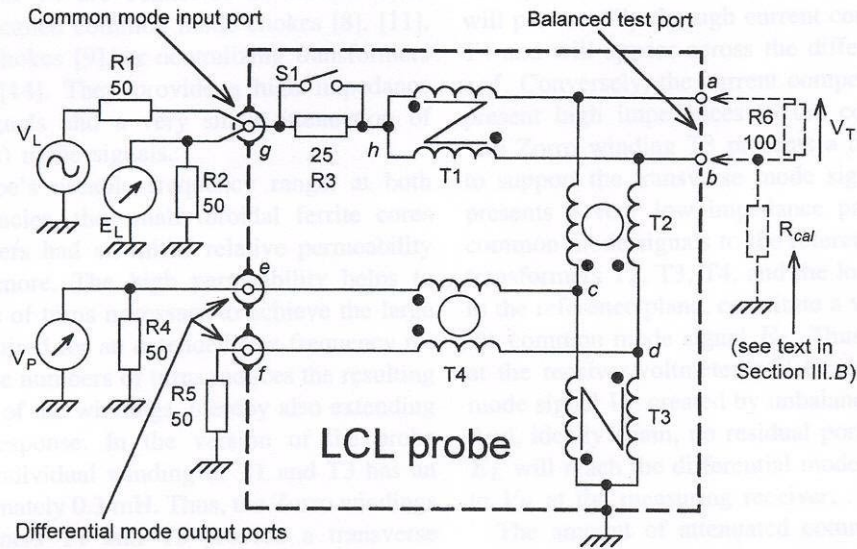
Figure 5 Macfarlane probe

In the appendix of the paper of Macfarlane, an expression is given for the LCL of the unbalance in a transmission line (twisted pair). It is assumed that the test bridge is perfectly balanced.

$$LCL = 20\log\left|\frac{2Z_0 + 4Z_{Le}}{\Delta Z} - \frac{\Delta Z}{2Z_0}\right| \ dB \qquad (7)$$

$\Delta Z = |Z_1 - Z_2|$ indicates the unbalance in the transmission line ($Z_1 + Z_2 = Z_0$). This expression is based on the work of Van Maurik (Ref. 5). Z_0 is the characteristic impedance (transverse impedance) of the transmission line and Z_{Le} is the longitudinal impedance of the transmission line to ground. ΔZ usually will be much smaller than Z_0.

The LCL value depends on the values of Z_0 and Z_{Le}. If the test bridge does not have a proper connection to ground, the common mode impedance Z_{Le} may be much larger than Z_0. In this case the LCL value will be proportional to the Z_{Le} value. Defining limits for the LCL value of the LVDN and associated PLC modems is only possible when the characteristic impedance and the common mode impedance are __constant__ and __known__.

The LCL is the value that is measured by using the probe described by Macfarlane. It provides a ratio for the longitudinal and transverse __voltages__. However, the radiated E-field and H-field are related to the longitudinal __current__ (common mode current)! Macfarlane shows that the common mode current is given by

$$I_{cm}(dB\mu A) \approx V_T(dB\mu V) - LCL(dB) - 20\log\left|2Z_0\frac{Z_{cm} + Z_{Tc}}{Z_0 + 4Z_{cm}}\right| \ dB \qquad (8)$$

with Z_{cm} the common mode impedance ($Z_{cm} = Z_{Le} + Z_0/4$) of the cable and Z_{Tc} the common mode impedance of the test bridge. *This equation shows that the common mode current can not simply be determined by dividing the transverse voltage by the LCL value. The common mode current is also a function of Z_{cm} (Z_{Le}) and Z_0.* The common mode current can be determined by measuring the V_T and the LCL and by taking the appropriate values of Z_{cm}, Z_{Tc} and Z_0 into account if they are known.

However, these equations are derived assuming that both the test bridge and the transmission line have a characteristic impedance of Z_0. *If Z_0 and Z_{Le} are not known (accurately), I_{cm} can not be determined (accurately) either!* If the transmission line does not have a constant characteristic impedance of Z_0, expression (23) can be used to determine the relationship between V_T and I_{cm}.

It can be concluded that the Macfarlane probe could be used to determine the LCL value of the LVDN, *if* the impedances of this network would be constant and well defined. However, as will be shown in chapter 3, this is not the case for the LVDN.

3   Characteristics of a low-voltage distribution network

3.1 The low-voltage distribution network as a transmission line
The in-house LVDN was modelled as a pair of two conductors (each 2.5 mm^2) running in a PVC tube. Each of the circular conductors normally has a uniform cross section over the whole length. Because of the space in the tube, the centre-to-centre distance varies between 3.4 mm and 10 mm.

The LVDN behaves like a transmission line if the dominant mode of propagation is the TEM-mode. This is the case for frequencies for which the centre-to-centre separation of the conductors is less than $\lambda/2\pi$. For higher frequencies other higher modes will also propagate. In this case the propagation can not be described by the transmission line model but should be analysed by full-wave analysis. If the separation between the conductors of the LVDN is not more than 10 mm, the network behaves like a transmission line for frequencies up to 5 GHz. PLC operates at a maximum frequency of 30 MHz.

Other conditions for the TEM-mode being the only propagating mode is that the surrounding medium is homogeneous and that the transmission line is lossless (R=0). If the surrounding medium is only slightly inhomogeneous and/or the transmission line only has small losses, as is

the case for the LVDN, a quasi-TEM mode will propagate. The quasi-TEM mode of propagation can also be described by the Transmission Line equations.

Based on the above, it can be concluded that the transmission line model can be applied to the low voltage network.

For low frequencies, were the length of the transmission line is small compared to the wavelength, the line can be analysed by using either lumped elements (circuit model) or by using distributed parameters (transmission line model). However, if the length of the transmission line is large compared to the wavelength (i.e. for high frequencies), the characteristics of the transmission line can no longer be described by lumped circuit elements. In this case only transmission line methods (with distributed parameters) should be applied to analyse the behaviour of the line.

The transmission line theory (TLT) can be applied to determine the differential mode voltages and currents along transmission lines. The TLT does not model the common mode currents, therefore the net current at each cross section is zero. In order to calculate the common mode current due to a differential mode excitation, a lumped element model can applied which also models the common mode impedances (Ref. 11). However, in this analysis we use the TLT to show that the LCL value can not be determined accurately if there is a large variation in differential mode impedances.

3.2 Characteristic impedance of the power line

The characteristic impedance of a balanced transmission line is given by:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{9}$$

The capacitance (C) per unit length (F/m) of two long, circular conductors of radius r, separated by distance d, equals:

$$\frac{C}{l} = \frac{\pi \varepsilon_r \varepsilon_0}{\ln\left[\dfrac{d}{2r} + \sqrt{\left(\dfrac{d}{2r}\right)^2 - 1}\right]} = \frac{\pi \varepsilon_r \varepsilon_0}{\cosh^{-1}(d/2r)} \tag{10}$$

The external self-inductance (L) value (H/m) for two long, parallel, circular conductors is given by:

$$\frac{L}{l} = \frac{\mu_r \mu_0}{\pi} \ln\left[\frac{d}{2r} + \sqrt{\left(\frac{d}{2r}\right)^2 - 1}\right] = \frac{\mu_r \mu_0}{\pi} \cosh^{-1}(d/2r) \tag{11}$$

The inductance and capacitance per-unit-length were determined for the LVDN (see Figure 6 and Figure 7) as a function of the (centre-to-centre) separation between the conductors. To calculate the capacitance, the relative permittivity of air was used since the isolation around each conductor only fills a small part of the total volume between the two conductors (except for the minimum separation).

The DC resistance (R) per unit length is given by:

$$\frac{R}{l} = \frac{\rho}{A} = \frac{1}{\sigma A} \tag{12}$$

The high frequency resistance per unit length is given by:

$$\frac{R}{l} = \frac{2R_s}{2\pi r} \frac{(d/2r)}{\sqrt{\left(\frac{d}{2r}\right)^2 - 1}} \tag{13}$$

with Rs=(1/σδ)=sqrt(πfμ/σ).

For frequencies above 10 kHz the resistance value will be smaller than the inductance value. Therefore the resistance will not be taken into account in this analysis.

The conductance (G) per unit length is assumed to be much smaller than the capacitance.

If both R and G are zero, then the characteristic impedance is given by

$$Z_0 = \frac{\eta}{\pi} \cosh^{-1} \frac{d}{2r} \approx \frac{\eta}{\pi} \ln \frac{d}{r} \tag{14}$$

If the wire radius is approximately 0.89 mm and the centre-to-centre distance between the two wires varies between 3.4 mm and 10 mm, the ratio of the distance to the wire diameter (d/r) varies between 1.9 and 5.6. In this case the characteristic impedance varies roughly between 150 Ω and 290 Ω (Figure 8). This is a variation in impedance by a factor of two.
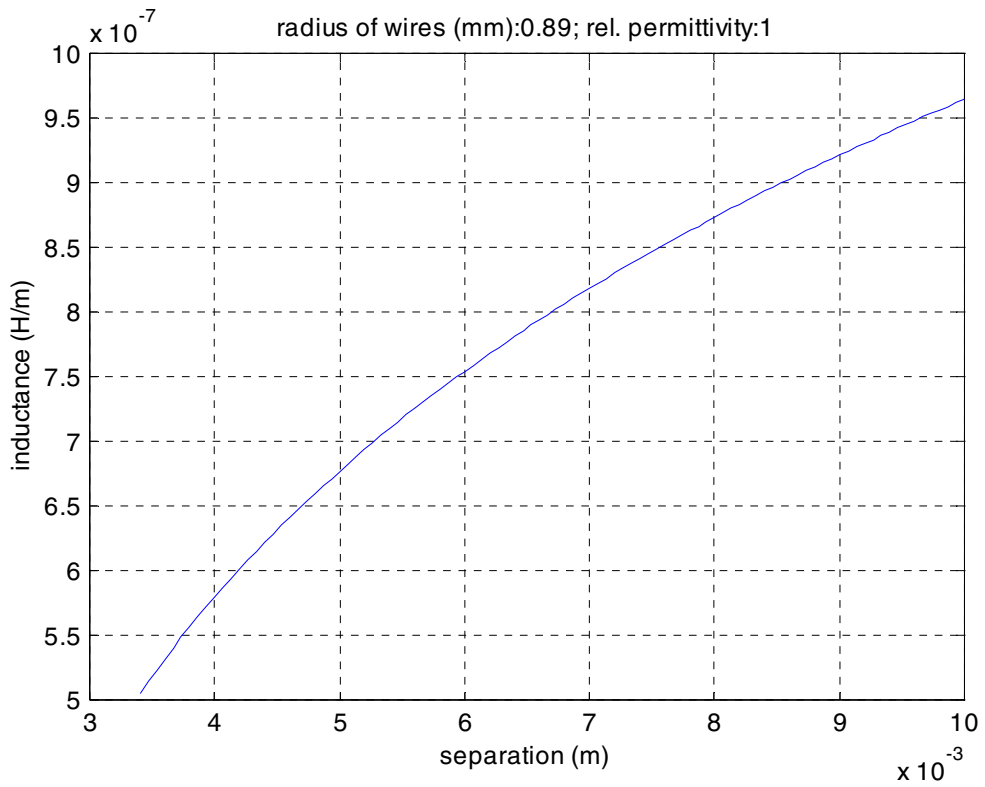
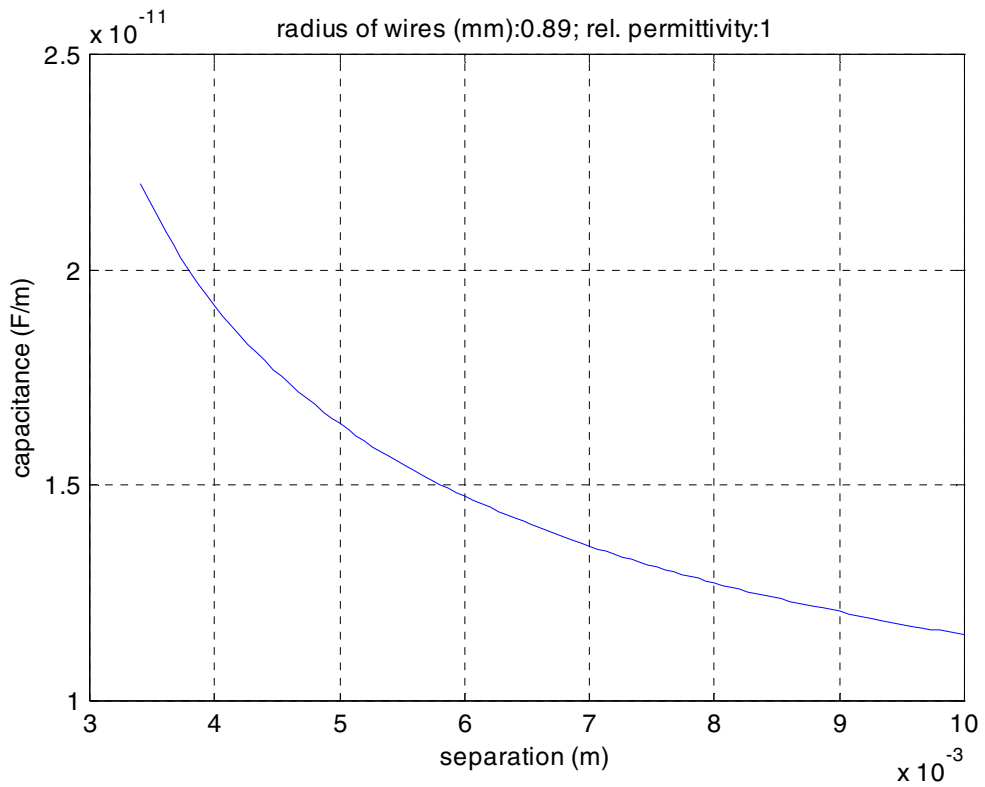Figure 6 Inductance as a function of separation

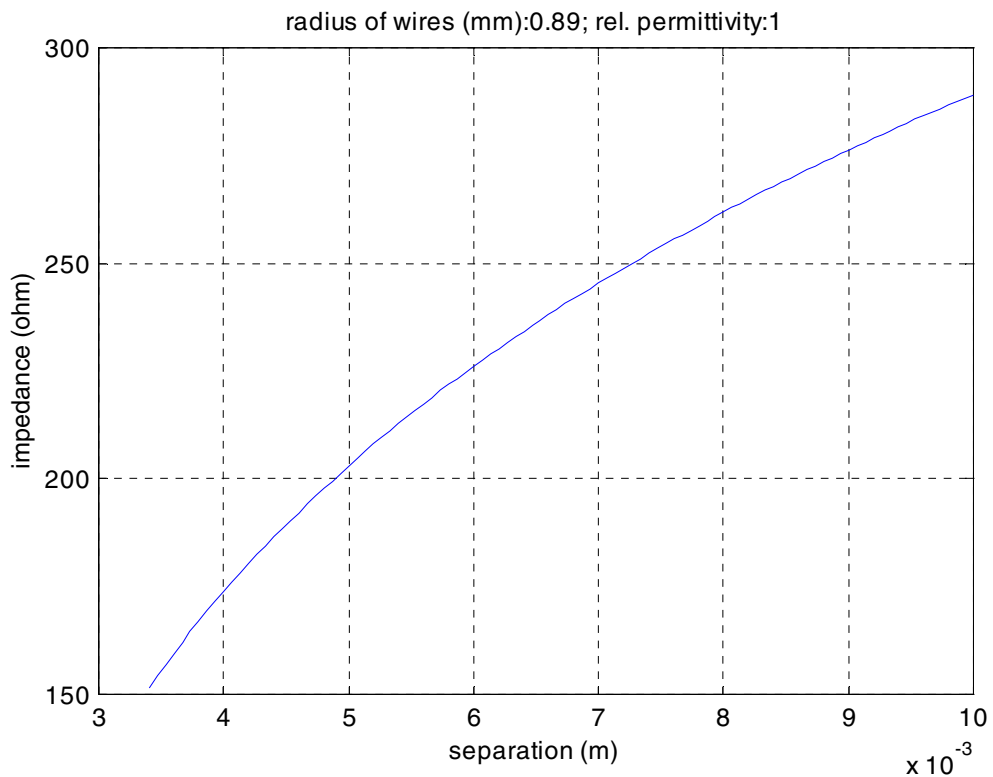Figure 7 Capacitance as a function of separation

Figure 8 Characteristic impedance as a function of wire separation (wire radius 0.89 mm)

The propagation constant is defined by

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{15}$$

In the case of a lossless line (R=0 and G=0 and therefore α=0), the propagation constant is given by

$$\gamma = j\beta = j\omega\sqrt{LC} \tag{16}$$

The propagation constant is needed to determine the input impedance of a line with characteristic impedance Z_0 terminated with a load Z_L.

3.3 Mismatch between line impedance and load impedance

To analyse the mismatch between the line impedance and the load impedance we first assume that the separation between the conductors is constant over the line length, resulting in a constant characteristic impedance, but that the line impedance does not match the load impedance.

The input impedance of a transmission line depends on the characteristic impedance of the line (Z_0), the line length (l) and the load impedance (Z_L):

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)} \qquad (17)$$

Suppose the characteristic impedance along the transmission line would be *constant*. In this case the input impedance of the line would *vary depending on the line length*, if the load impedance (Z_L) does not match the characteristic impedance (Z_0), see Figure 9. CASE 1 (*mismatch*) is presented in Figure 10 for a transmission line with characteristic impedance of 200 Ω (Z_0) terminated with a load impedance of 100 Ω (Z_L). This input impedance is the Z_{in} in Figure 9and the Z_{Te} in Figure3.
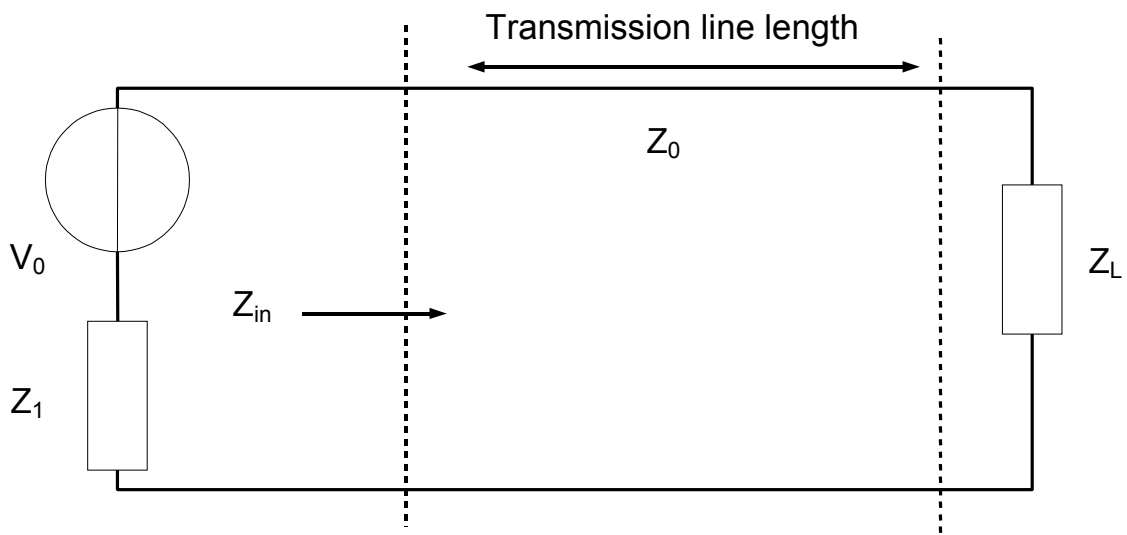

Figure 9 Transmission line circuit diagram for CASE 1,2,3

The input impedance value of this circuit, presented in Figure 10, is the absolute value of the complex impedance. The real part and the imaginary part of the input impedance are given in Figure 11 and Figure 12. Only for line lengths which are a multiple of λ/4, the imaginary part of the input impedance is zero and the input impedance is real! If the line is excited by a source with open circuit voltage V_0=1 V and an output impedance Z_1=100 Ω, the input voltage changes with the line length in wavelengths (Figure 13), following the input impedance. Since the line length in terms of wavelengths is of importance, the impedance for a specific absolute line length (in meters) is a function of frequency.

In case the load impedance is only 10 Ω (CASE 2), the mismatch is even more significant and the input impedance varies between 10 and 4000 Ω (Figure 14).One the other hand, if the

characteristic impedance would *match* the load impedance (CASE 3), *no variation* in input impedance would be present (Figure 15). In this case (no mismatch), the input voltage does not depend on the line length.

Since the characteristic impedance of the LVDN is not fixed (it depends on the separation of the conductors), there will always be a mismatch between the line impedance and the load impedance. In addition, the equipment connected to the LVDN is not designed to match the impedance of the LVDN. Due to this mismatch, the input impedance and the input voltage change as a function of line length and frequency. This means that when the transverse voltage at the input of the line is measured according to the LCL method, the level will vary depending on the length of the line.
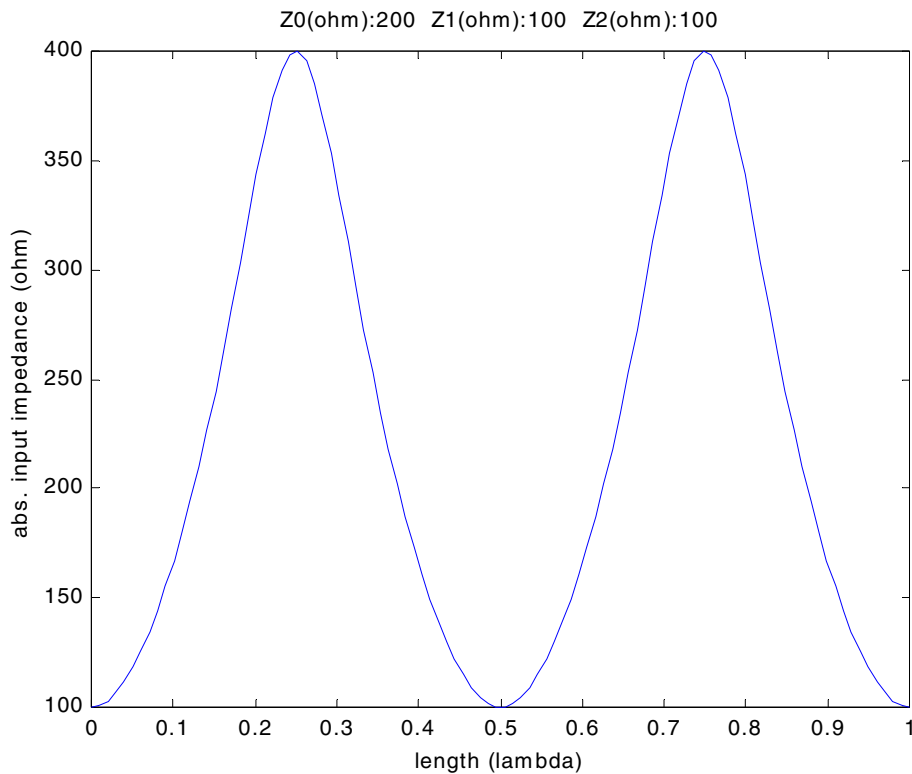

Z0(ohm):200 Z1(ohm):100 Z2(ohm):100

Figure 10   Input impedance as a function of line length (lambda) in case of a mismatch between line impedance and load impedance (CASE 1, Z_2=100 Ω)
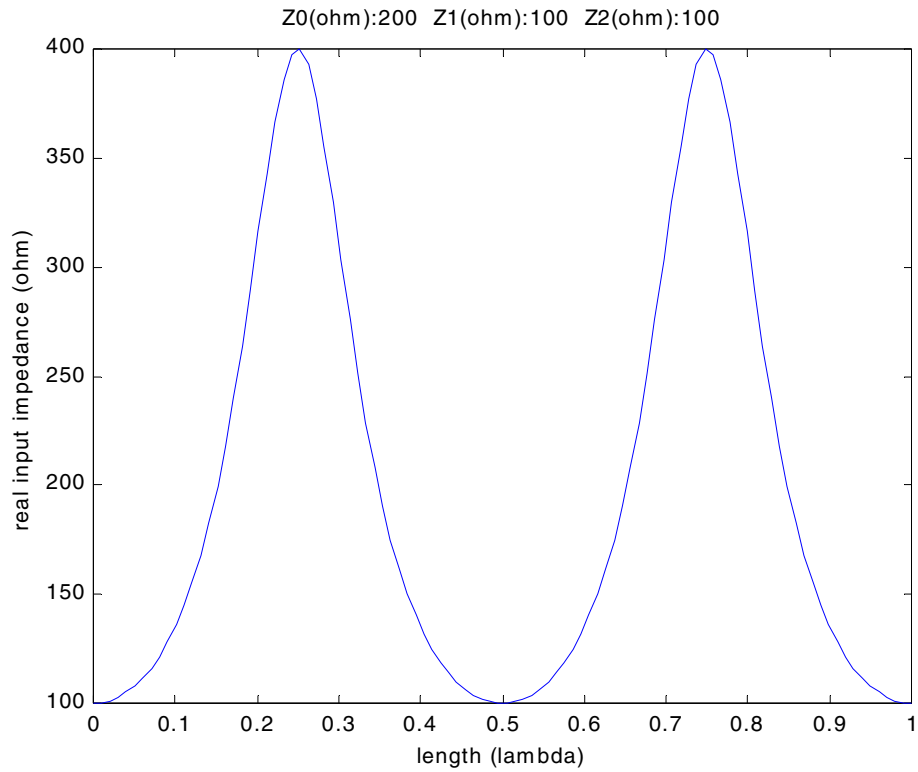
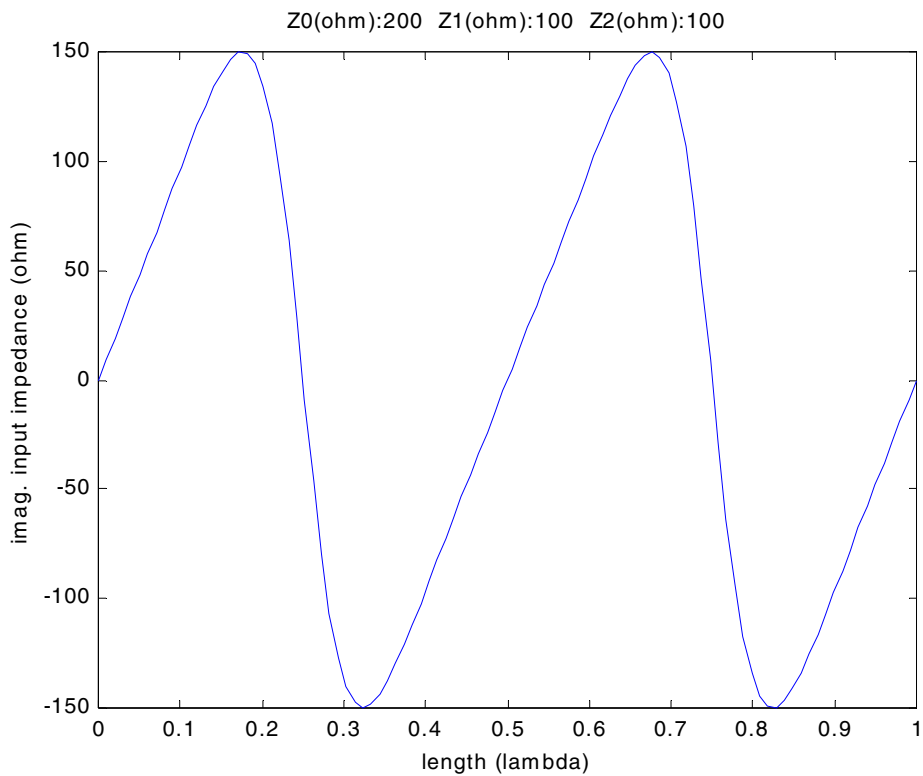*Figure 11 Real part of the input impedance in case of a mismatch*

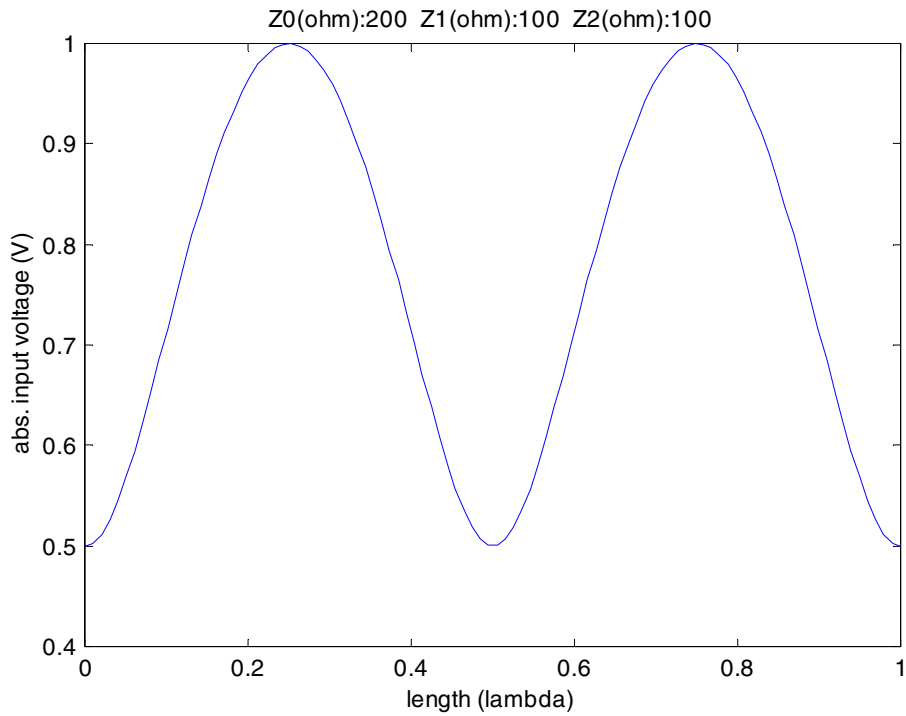*Figure 12 Imaginary part of the input impedance in case of a mismatch (CASE 1)*

Figure 13 Input voltage as a function of line length (lambda)) in case of a mismatch between line impedance and load impedance (CASE 1)
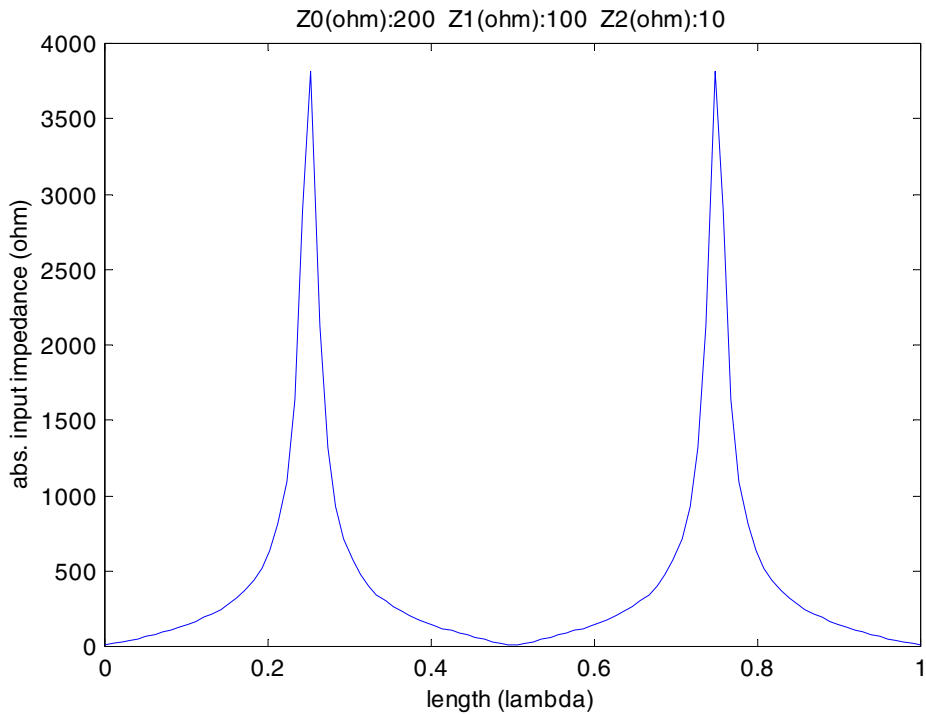

Figure 14 Input impedance as a function of line length (lambda) in case of a significant mismatch between line impedance and load impedance (CASE 2, Z_2=10 ohm)
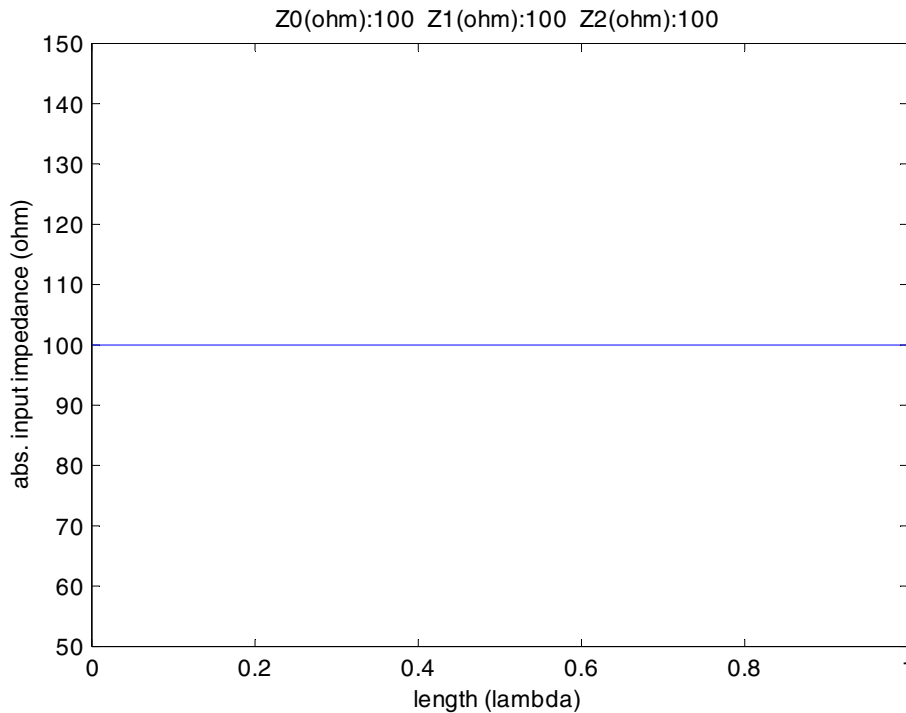
Z0(ohm):100 Z1(ohm):100 Z2(ohm):100

Figure 15   *Input impedance as a function of line length (lambda) in case of a matching load (CASE 3)*

3.4 Non-uniform transmission line

In Figure 8 the characteristic impedance was given for a specific constant separation of the conductors. If a random variation occurs in the separation of the wires (due to the space in the tube in which the cable was installed), the characteristic impedance varies accordingly. In Figure 16 a simulated random variation of separation between two conductors of the LVDN is presented. The total line length (25 m in this example) is divided in 100 segments. For each segment a different separation between the wires is assumed, slightly different from the neighbour segments. The characteristic impedance is assumed to be constant over the length of a segment (for a frequency of 10 MHz, each segment measures $\lambda/120$ in this example).

The local characteristic impedance (which depends on the distance between the conductors) is shown in Figure 17. Note: this is not the input impedance of the line but the characteristic impedance of each segment! The correlation between the conductor separation and the characteristic impedance per segment is clearly visible.
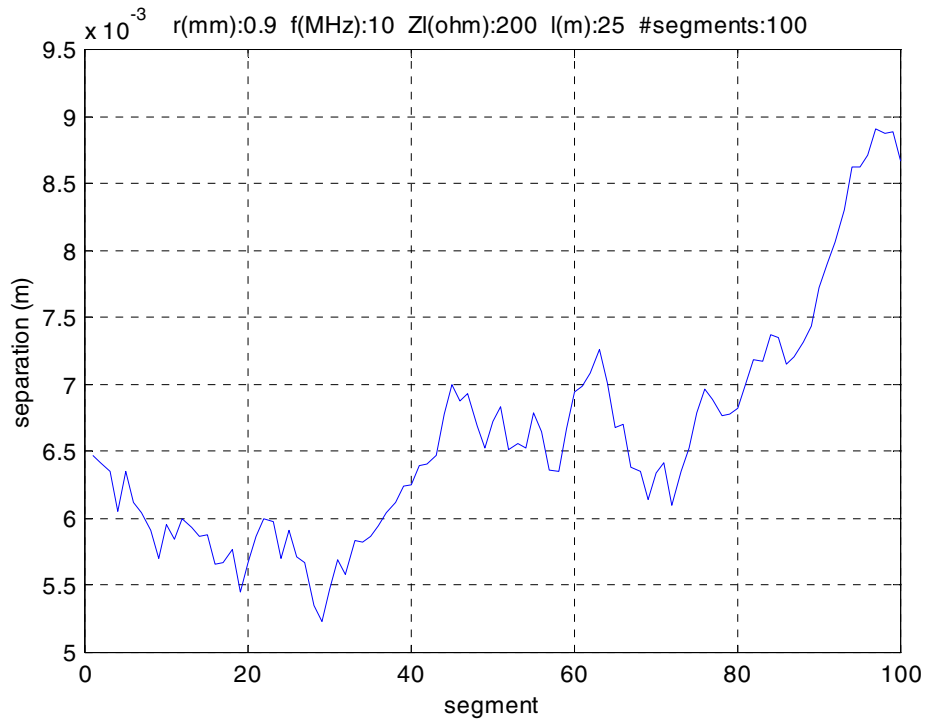
x 10^{-3} r(mm):0.9 f(MHz):10 Zl(ohm):200 l(m):25 #segments:100

Figure 16 Random variation in separation between the two conductors

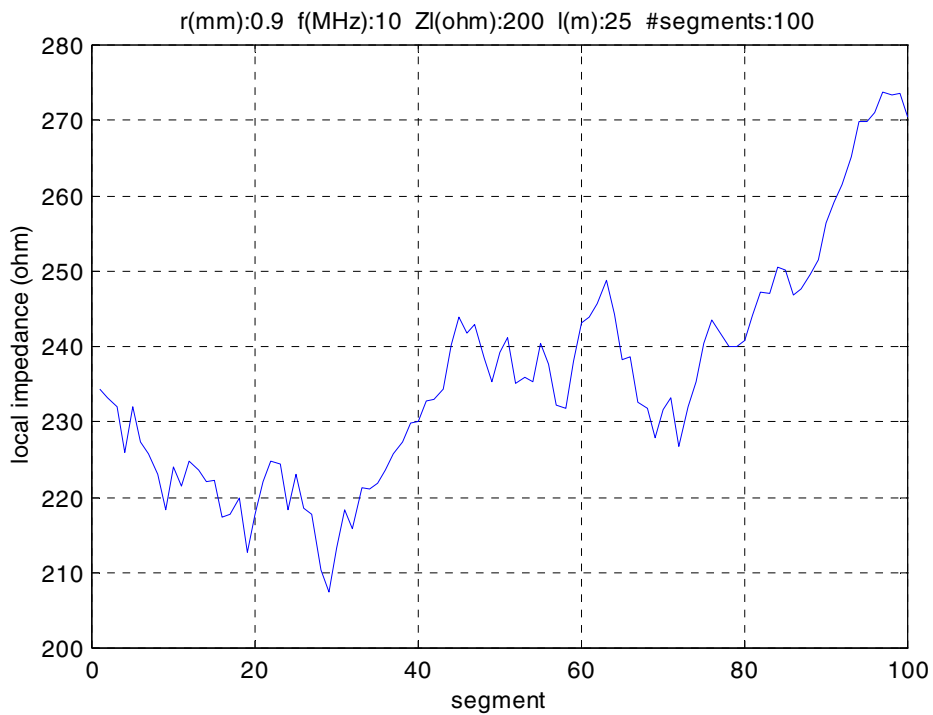r(mm):0.9 f(MHz):10 Zl(ohm):200 l(m):25 #segments:100

Figure 17 Local characteristic impedance of the low-voltage distribution network (CASE 4)

The differential mode voltage along the line depends on the local characteristic impedance. To determine the local voltage, each segment was modelled as a two-port. The relation between the

voltage and current at port 1 and the voltage and current at port 2 of the segment can be described by a Transmission (ABCD) matrix (Ref. 4).

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix} \tag{18}$$

For each segment (characterised by its local characteristic impedance $Z_0 = 1/Y_0$ and local propagation constant $\gamma = j\beta l$), the elements of the Transmission matrix can be determined:

$$
\begin{array}{ll}
A = \cos\beta l & B = j\,Z_0\sin\beta l \\
C = j\,Y_0\sin\beta l & D = \cos\beta l
\end{array}
\tag{19}
$$

The above matrix elements apply to a transmission line which is lossless. The advantage of the Transmission matrix (in contrast to the Scattering matrix or the Impedance matrix) is that the input and output of each element can be cascaded. This way the voltage and current along the line can be calculated. The "transmission line" shown in Figure 17 was used to calculate the voltage along the line. For convenience, a voltage of 1 V was assumed over the load impedance of 200 Ω located at segment 1 (CASE 4), see Figure18. The result for a line consisting of 100 segments is shown in Figure 19. What you see is a combination of the sinusoidal behaviour of the voltage along the transmission line (as in the case of constant characteristic impedance and a mismatch at the end of the transmission line) and the increasing voltage due to the increasing local characteristic impedance. A similar calculation was made for the differential mode current distribution along the line (Figure 20). However, the load impedance may differ much more from the average line impedance. Therefore a similar simulation of the behaviour of voltage (Figure 22) and input impedance (Figure 23) was carried out for the case of a load impedance of 10 Ω (instead of 200 Ω) and a different separation of wires (CASE 5, Figure 21). The variations in voltage and impedance are even more significant for this case. The differential mode current generates a small amount of radiated E-field and H-field (Ref.7). However, the common mode current normally generates a higher E-field and H-field than the differential mode current.

For a normal transmission line, the level of common mode current can be determined by measuring the LCL and the differential mode voltage V_T, and correcting for the circuit impedances (see equation (8)). Measuring the differential mode voltage however is difficult because it depends on the line length (Figure 13 and Figure 22) and on the local impedance (Figure 19 and Figure 23).

The simulations show that because the characteristic impedance is not constant along the line, local variations exist in voltage and current. It can be concluded that due to variations in the line impedance and due to mismatch between line impedance and load impedance, large variations can occur depending on line length and frequency. Using these values to determine the LCL value and eventually the common mode current I_{cm} would lead to very inaccurate values.
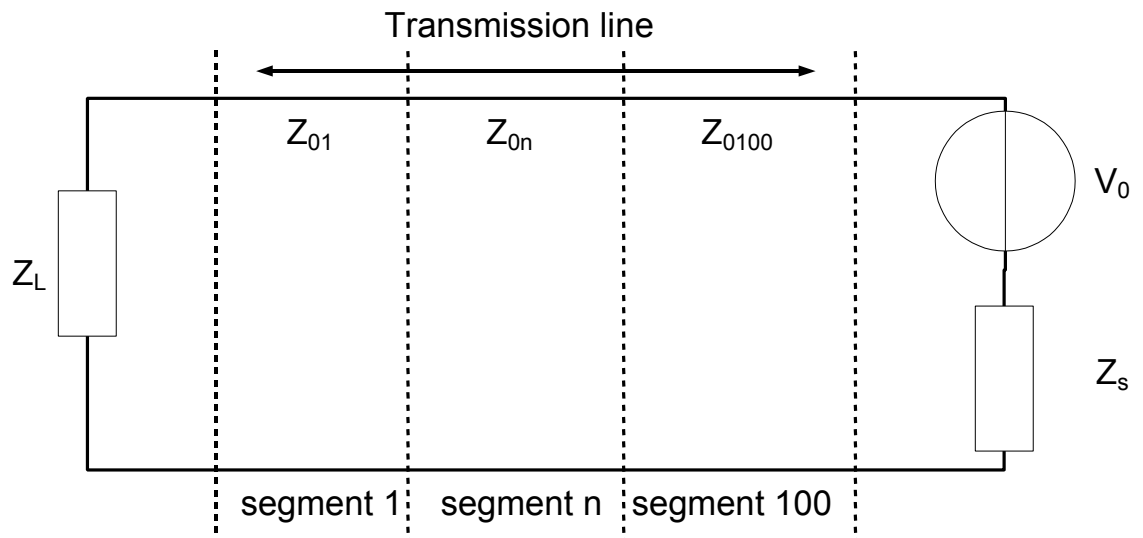

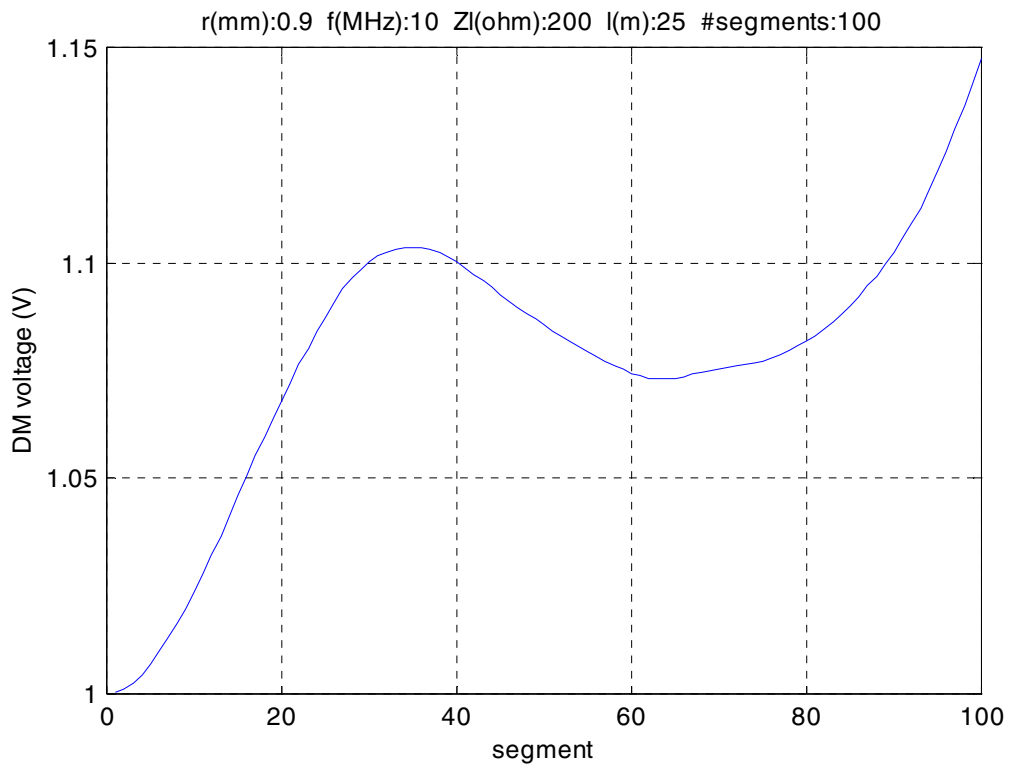*Figure 18 Transmission line circuit diagram (CASE 4,5)*

r(mm):0.9 f(MHz):10 Zl(ohm):200 l(m):25 #segments:100

Figure 19 Differential mode voltage along the line. The variations are due to the local impedance variations (CASE 4).

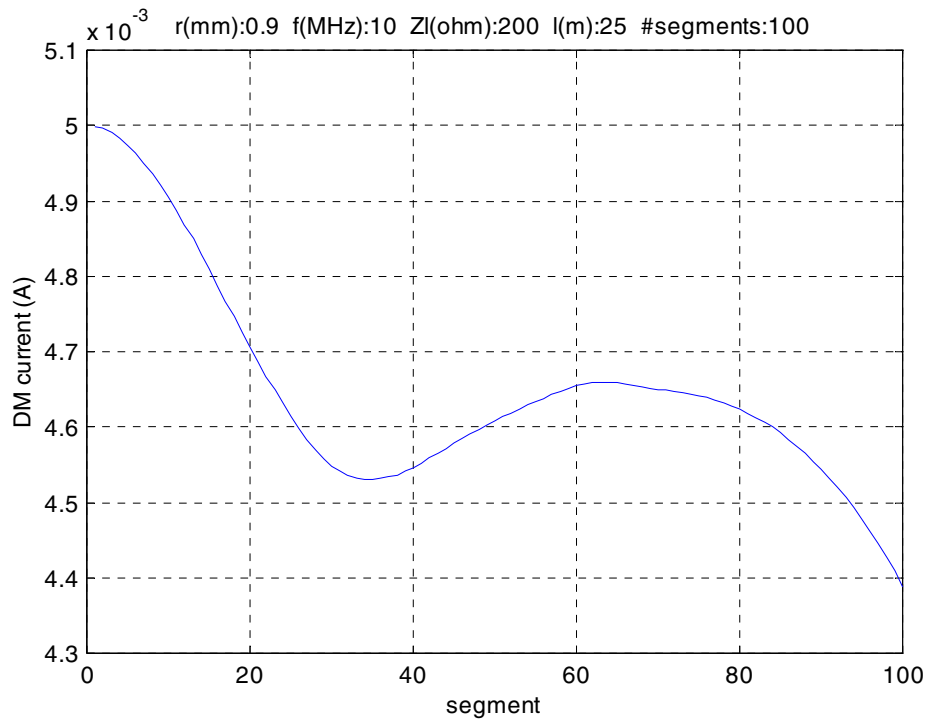r(mm):0.9 f(MHz):10 Zl(ohm):200 l(m):25 #segments:100

Figure 20 Differential mode current along the line (CASE 4).
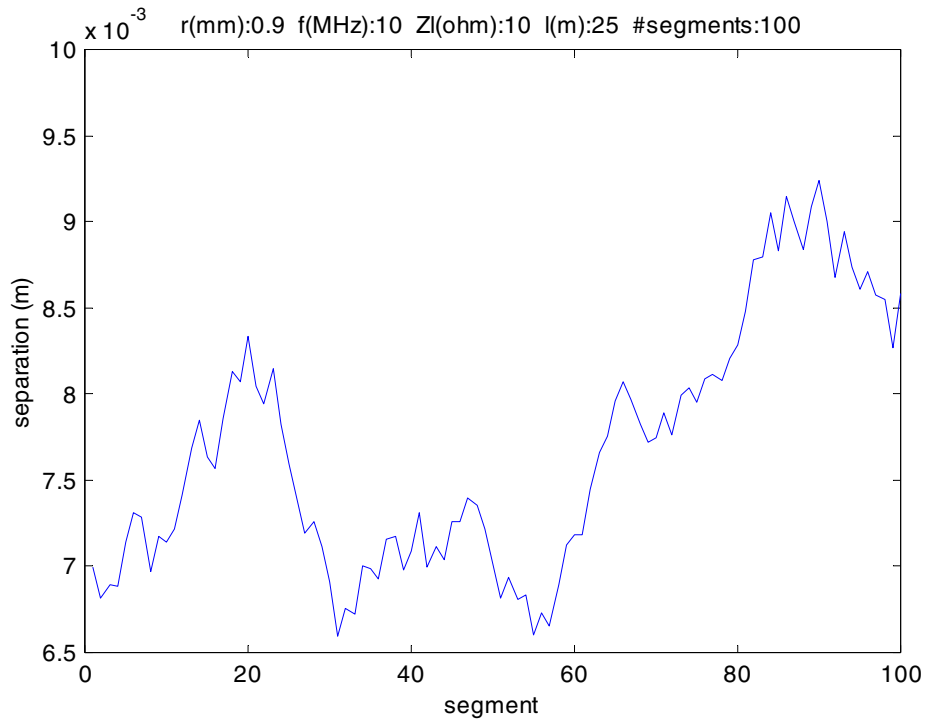
Figure 21 Separation between wires (CASE 5)
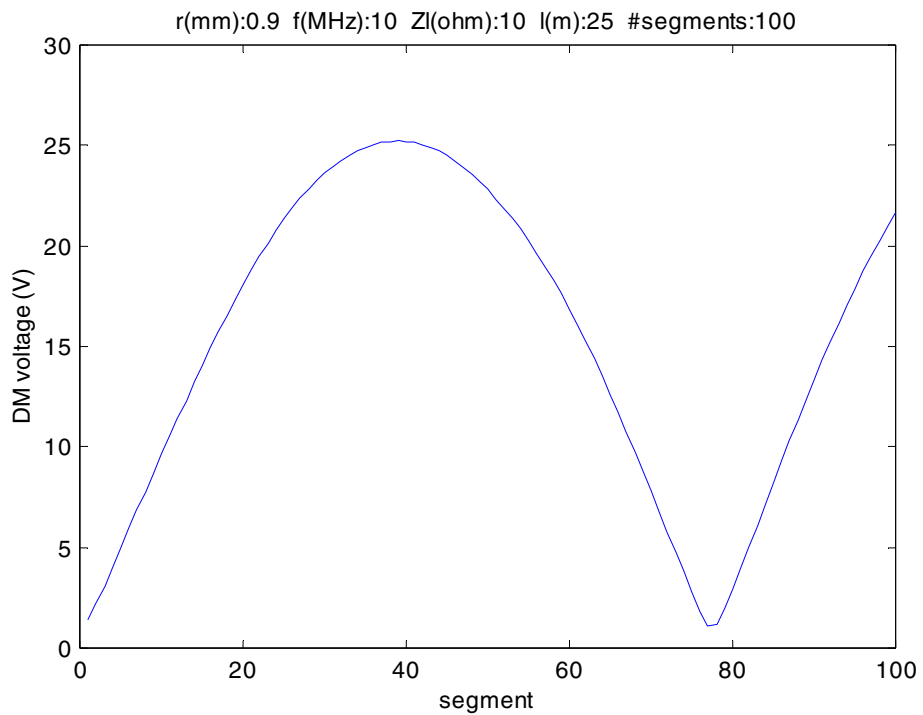
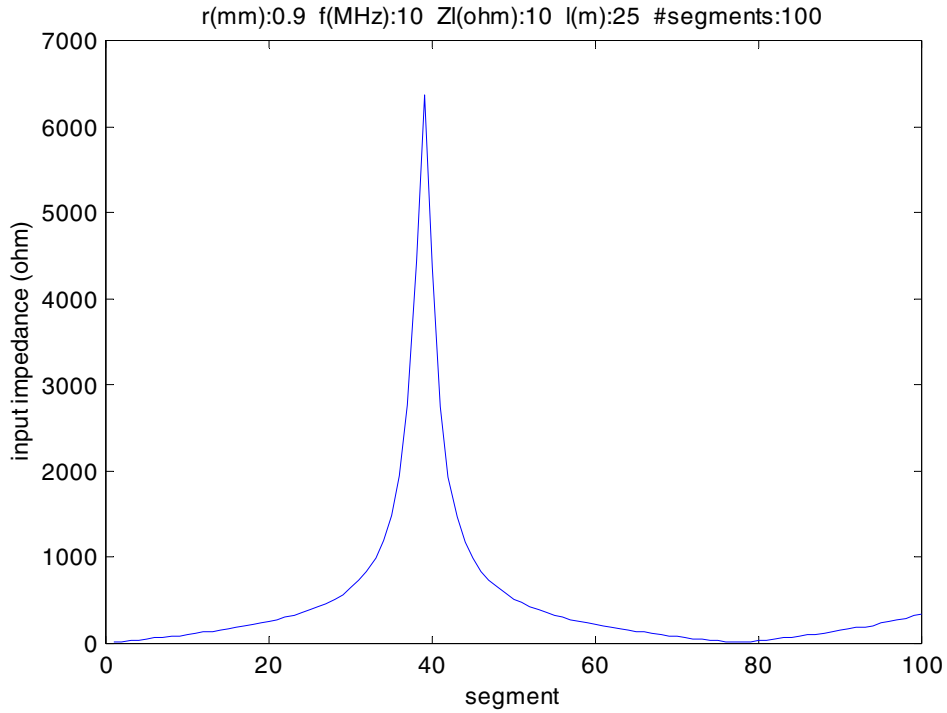*Figure 22 Differential mode voltage along the line (CASE 5)*

r(mm):0.9 f(MHz):10 Zl(ohm):10 l(m):25 #segments:100

Figure 23 Input impedance non-uniform transmission line (CASE 5, load impedance 10 Ω)

3.5 Emission characteristics of low-voltage distribution network

As mentioned earlier, the common current is of interest if we want to determine the radiation by the LVDN. The nearby electric field due to the CM current is given by (Ref. 6):

$$E_{cm} = \frac{I_{cm}}{4\pi\varepsilon_0 r^2 \varpi} \tag{20}$$

with *r* the distance to the line. The far electric field due to a sinusoidal shaped current distribution is (Ref. 10)

$$E_{cm} = \frac{\eta I_{cm}}{2\pi r} \tag{21}$$

The H-field can be estimated by

$$H = \frac{I_{cm}}{2\pi r} \tag{22}$$

In all cases, the E-field and the H-field are directly proportional to the common mode current (I_{cm}).

For a transmission line with a constant and known characteristic impedance, the common mode current can be calculated according to equation (8). Goedbloed (Ref.6) and Van Maurik (Ref.5) both defined an alternative relation between the common mode current (I_{cm}) and the transverse voltage (V_T):

$$Y_{cnv} = \frac{I_{cm}}{V_T} = \frac{Z_1 - Z_2}{2(Z_1 Z_2 + Z_{LT}(Z_2 + Z_1))} \tag{23}$$

Z_{LT} is the total common mode impedance, $|Z_1-Z_2|=\Delta Z$ describes the cable unbalance and $Z_1+Z_2=Z_0$ equals the differential mode impedance of the transmission line (see Figure 4). Expression (23) can be approximated by

$$Y_{cnv} = \frac{I_{cm}}{V_T} \approx \frac{2\Delta Z}{Z_0^{\ 2} + 2Z_{LT}Z_0} \tag{24}$$

From equation (23) it is obvious that if the cable is totally balanced ($\Delta Z=0$), the common mode current is zero.

As has been shown in section3.2, the characteristic impedance Z_0 is not constant and varies over de line length. Therefore $|Z_1-Z_2|=\Delta Z$ is probably not constant either. In addition the equipment connect to the LVDN determines the load impedance. Gawron showed that the common mode impedance also shows significant variations (Refs. 8 and 9). Therefore the common mode current I_{cm} will show significant variations which are not related to the level of V_T.

The distribution of the common mode current I_{cm} is not determined by the (local) characteristic impedance Z_0. This current distribution is determined by common mode impedances and the "antenna physics" of the power line (length in terms of wavelength, boundary conditions, interaction with the environment, etc.).

For line lengths shorter than $\lambda/4$ the current distribution will be linear with a maximum at the near end and falling of to zero at the far end (in the case of high common mode impedance at the end). In this case the maximum common mode current can be measured directly by means of a current probe at the near end.

For line lengths longer than $\lambda/4$, the current distribution will be sinusoidal and the current level at the near end will depend on the actual line length. It is therefore difficult for these line lengths to measure the current directly with a current probe, because the current level will vary depending along the power line. Several measurements will have to be made along the line to determine the maximum value (for a specific frequency).

Due to the uncertainties in the impedances of both the equipment/cable under test and the test set-up, it is concluded that the method of determining the common mode current I_{cm} by means of the LCL method as defined in ITU Recommendations G.117 and O.9 and the LCL probe suggested by Macfarlane is not suitable for application on the LVDN.

4 Conclusions

To determine the radiated interference generated by the use of Power Line Communication on the LVDN, the common mode *currents* have to be determined. The generated electric and magnetic field are proportional to the common mode currents on the transmission line. The LVDN is excited by a differential mode voltage source (PLC modem). Therefore *two limits* have to be derived for the PLC equipment:

• a urrents due to the unbalance in the LVDN) and
• a limit to any additional unbalance introduced by the PLC equipment itself.

To derive a limit for the differential mode output of the PLC equipment, the conversion of differential mode to common mode voltage by the LVDN should be determined. *The question was whether the Longitudinal Conversion Loss (LCL) method could be used to determine this conversion.*

The definitions provided in ITU Recommendations G.117 and O.9 provide a clear definition of the conversion of differential mode voltage to common mode voltage TCL, and vice versa LCL, for a not-perfectly balanced *transmission line terminated with a matched load*. However, due to the fact that the "transmission lines" of the low-voltage network consist of individual wires which are not bundled together to form a cable, the transverse impedance of this transmission line may vary significantly along the line. The equipment connected to the LVDN will *not be matched to the average characteristic impedance of the LVDN*. In addition both the common mode impedance of the power line and the common mode impedance of the test bridge can show significant variations. Both the variation in transverse impedance and in common mode impedance have a significant influence on the measured LCL value. *Therefore, it is concluded that the LCL method is not suited to determine the amount of mode conversion on the LVDN.*

The *probe defined by Macfarlane* provides an adequate instrument to measure the mode conversion according to the ITU Recommendations. The advantage is that unbalanced measurement equipment can be used. The Macfarlane probe can be used for frequencies up to 30 MHz to measure the conversion from common mode to differential mode voltage (longitudinal voltage to transverse voltage or longitudinal conversion loss (LCL)) on a normal transmission line. In this case, some additional analysis has to be carried out to determine the

common mode currents as a result of the common mode voltages. However, *due to the uncertainties in the impedances of the LVDN, the common mode current can not be determined accurately by determining the LCL with the suggested probe.*

The objective of using the LCL method was to determine the level of common mode current due to mode conversion of the differential mode PLC signal on the LVDN.

• It can be concluded that the LCL method *can be used* to determine the unbalance of a single piece of telecommunication equipment like a *PLC modem*. The LCL method could even be used to determine the unbalance in a short (w.r.t. the wavelength) power line if the probe impedances are selected with care.

• However, the *LCL method can not be used* to determine the unbalance of long (w.r.t. the wavelength) power lines due to the large variations in impedance.

What is the alternative for the LCL method? Given the above mentioned difficulties in determining the common mode current *indirectly by means of LCL*, it seems recommendable to determine the common mode current *directly by means of a current probe*. Depending on frequency (wavelength) and line length, the common mode current distribution is either linear (triangular) or sinusoidal. Therefore the current should be measured on several locations along the line to determine the maximum current value. Sufficient measurements should be made to determine the relationship between the transverse voltage V_T and the common mode current I_{cm} on a statistical basis.

Due to the limited accessibility of the LVDN wiring, measurement of the common mode current may be difficult. If measuring the I_{cm} directly is too complicated, the *radiated H-field and E-field* have to be measured *directly*. The relationship between the transverse voltage V_T and the radiated field has to be determined on a statistical basis.

In any case, determining the I_{cm} by determining V_{cm} (LCL method) is not recommended.

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