Influence of Cable Selection on Channel Frequency Response for Low Voltage Indoor Cables

A.S. de Beer, A. Sheri, H.C. Ferreira
Department of Electrical and Electronic Engineering Science
University of Johannesburg, P. O. Box 524,
Auckland Park, 2006, South Africa

Abstract — **The Channel Frequency Response (CFR) is an important parameter in the specification of Power Line Communications (PLC) equipment. In this paper, low voltage indoor power cables are investigated and their suitability for PLC operation are determined. This is done in terms of their Channel Frequency Response (CFR). Cable parameters such as inductance, capacitance, resistance, length and termination are investigated up to 100MHz. This work shows cable length and load impedance are the primary factors affecting CFR behavior. Long cables (in the 100's of meters) and low load impedances - lower that the cable characteristic impedance (few Ω) can dramatically limit the bandwidth of the CFR. Variances in geometry, dielectric and resistance are only secondary effects and do not affect CFR as drastically as length and load impedance.**

Keywords—PLC, Power Line Communications, Channel Frequency Response, CFR, Low Voltage Cable, Cable Selection, Cable Length, Load Impedance.

I. INTRODUCTION

It is envisaged that with the *Internet of Things* [1] and the *Smart Grid* [2], there will be an increase in the connectivity between electrical and electronic equipment. From a kettle to a power meter to a TV, each unit will be a node on a network. Power Line Communications (PLC) aim at utilizing electrical power cables to establish communication between these nodes. The power lines in such a system have the advantage of simultaneously supplying power as well as an electronic communications channel. If power and communications are supplied separately, it can lead to extra complexity and cost. This is especially true if the projections of billions of nodes are to be accepted for future networks [3].

Conventionally PLC has been used in two categories:

- Narrowband PLC with carrier frequencies from 3kHz to 500kHz. This is typically used for control signals of kbps range.
- Broadband PLC with carrier frequencies from about 2MHz to 70MHz. This is typically used for signals in the Mbps range such as internet connections and multimedia.

This paper is a study into the factors that govern the performance of a low voltage power cable as PLC channel. In particular the CFR is used to evaluate factors such as cable length, load impedance and cable propagation.

This paper has application where a cable must be selected, not only for power transfer, but also for a PLC channel. It gives the most important parameters to consider. Figure 1 shows a typical low voltage indoor power cable that can be selected for power transfer over which PLC is established.

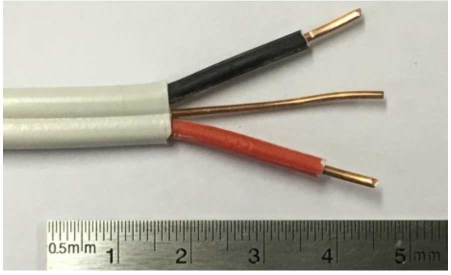

Fig. 1 – 1.5mm^2 Flat Twin and Earth low voltage indoor power cable. Typical of a cable investigated in this paper.

As a first step in investigating the high frequency performance of a cable the Channel Frequency Response (CFR) is determined. This is also called the Channel Transfer Function [4]. It is given by:

$$CFR = {V_{out}(f)}/{V_{in}(f)} \qquad (1)$$

and is the direct voltage transfer function between the input ($V_{in}(f)$) and output ($V_{out}(f)$) of the cable. The CFR is an important function in the description of a PLC channel's performance. The larger the bandwidth of the CFR, the higher the transfer rate of data.

In this paper, it is shown that:

- Due to transmission line effects the length of the cable is a primary factor to consider. The shorter the cable the higher the CFR cut-off.
- Second is the load impedance. The perfect load termination is the line characteristic impedance Z_0. This is not always possible as loads are governed by the power they deliver. The lower the load impedance the higher the attenuation and the CFR drops. For load impedances higher than Z_0, the CFR improves.
- The geometry of the cable (wire radius, separation and dielectric) does not affect the CFR as drastically as the cable length and load impedance.

II. THE CABLE AS TRANSMISSION LINE, PUL PARAMETERS, CHARACTERISTICS AND CFR

A cable used in PLC can be viewed as a transmission line since the length of the cable is usually several wavelengths longer than compared to the communications frequency signal. In this study the classic Per Unit Length (PUL) transmission line model is used. A PUL infinitesimal section is shown in Fig 2.

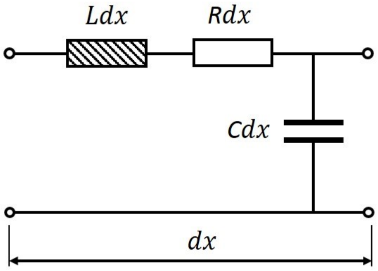

Fig. 2 – Per Unit Lentgh (PUL) model of a RLC Transmission Line.

A. Transmission Line Model

A lossless transmission line consists of only the inductance per meter (L) and capacitance per meter (C) PUL parameters. In this study R (in Ω/m) is added to simulate losses – especially due to the skin effect. Dielectric losses – usually represented by G (in S/m) are omitted (Fig. 2)

From transmission line theory, the characteristic impedance of the line is given as function of the RLC PUL parameters as:

$$Z_0 = \sqrt{\frac{R+j\omega L}{j\omega C}} \tag{2}$$

Also from transmission line theory, it is recognized that a signal will propagate on the line with a propagation constant γ. The propagation constant is complex in general or [5]:

$$\gamma = \alpha + j\beta \tag{3}$$

$$\text{with } \alpha = \sqrt{\frac{1}{2}\left[\sqrt{(R^2+\omega^2L^2)\omega^2C^2} - \omega^2LC\right]} \tag{4}$$

$$\text{and } \beta = \sqrt{\frac{1}{2}\left[\sqrt{(R^2+\omega^2L^2)\omega^2C^2} + \omega^2LC\right]} \tag{5}$$

B. Channel Frequency Response (CFR)

For a derivation of the CFR as summarized in this section refer to [5].

The reflection coefficient at the load is given by:

$$\varGamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{6}$$

where Z_0 is the characteristic impedance of the line and Z_L the load impedance. The reflection coefficient at the source is given by:

$$\varGamma_S = \frac{Z_S - Z_0}{Z_S + Z_0} \tag{7}$$

where Z_S is the source impedance.

The voltage on the sending side (input) of the transmission line is:

$$V(0) = \frac{V_S Z_0 + V_S Z_0 \varGamma_L e^{-2\gamma\mathcal{L}}}{(\varGamma_L \varGamma_S e^{-2\gamma\mathcal{L}} - 1)(Z_0 + Z_S)} \tag{8}$$

The voltage at a length $\mathcal{L}$ (output) is:

$$V(\boldsymbol{\mathcal{L}}) = \frac{V_S Z_0 e^{-\gamma\mathcal{L}}(1+\varGamma_L)}{(\varGamma_L \varGamma_S e^{-2\gamma\mathcal{L}} - 1)(Z_0 + Z_S)} \tag{9}$$

The CFR is defined as the frequency response of the line output divided by the input or from (8) and (9):

$$CFR = \frac{V(\boldsymbol{\mathcal{L}})}{V(0)} = \frac{e^{-\gamma\mathcal{L}}(1+\varGamma_L)}{\varGamma_L e^{-2\gamma\mathcal{L}} + 1} \tag{10}$$

Note that in the CFR (10), the source impedance Z_s, source voltage V_s and source reflection coefficient $\varGamma_S$ are canceled. The CFR is therefore a function of only the propagation constant γ, the line length $\mathcal{L}$ and load reflection coefficient $\varGamma_L$.

A summary of the parameters and relationships influencing the CFR is shown in Fig. 3. It shows that the line length $\mathcal{L}$ and load impedance have a direct influence on the CFR. It will be shown that these two parameters are the most important when assessing PLC line channel performance. L, C and R are secondary in sensitivity and their influence on CFR is not as direct as length $\mathcal{L}$ and load impedance Z_L.

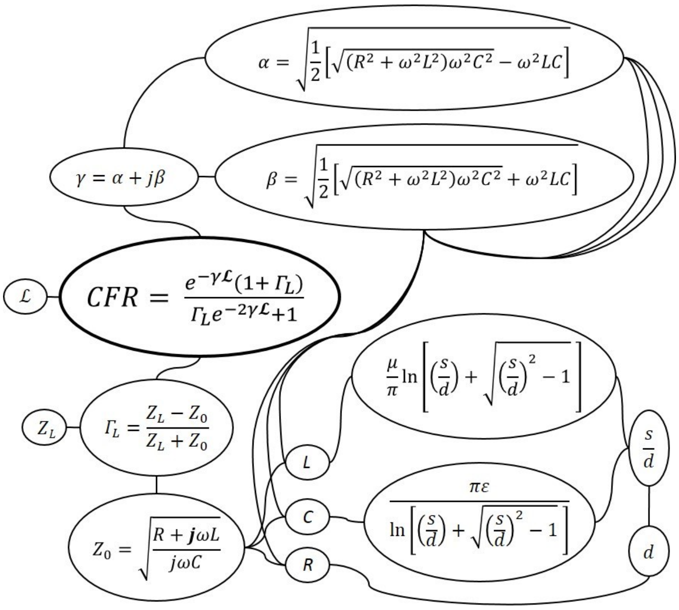

Fig. 3 – Parameters and relationships influencing the CFR.

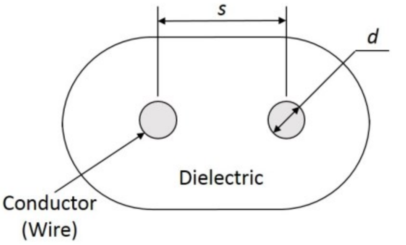

Fig. 4 – Geometry of a Flat Twin and Earth low voltage indoor power cable (See also Fig. 1). Note the earth wire is omitted.

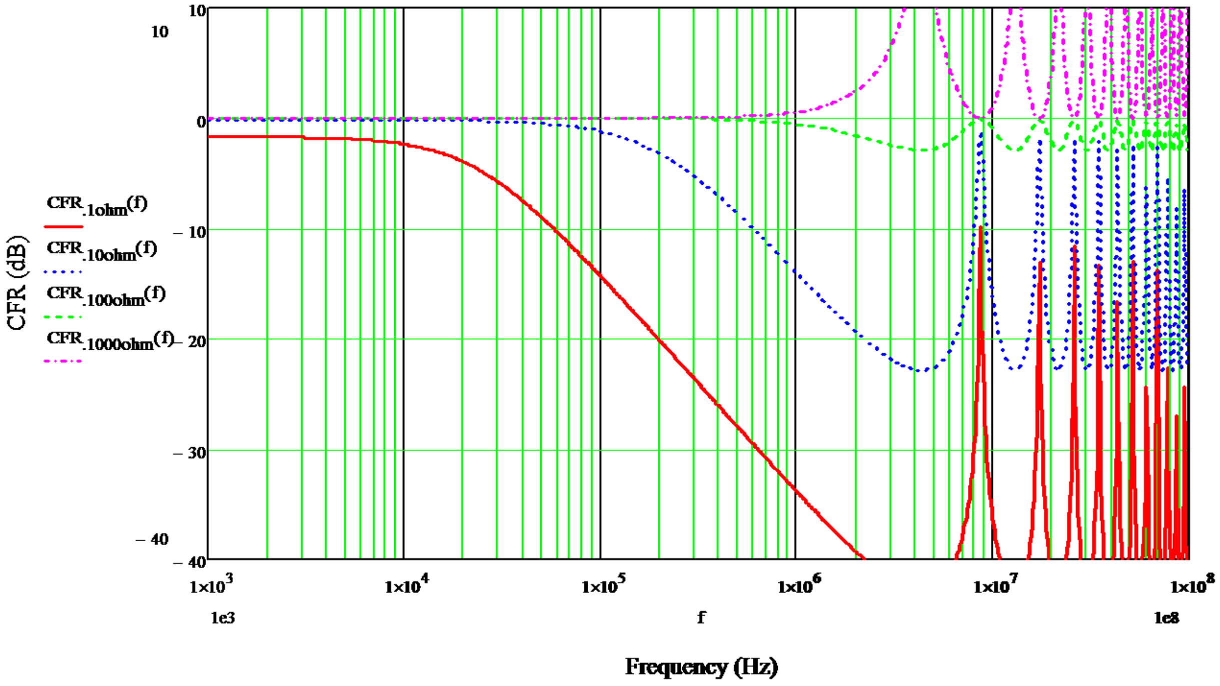

Fig. 5 – CFR of a 1.5mm^2 Flat Twin and Earth low voltage indoor power cable of 10m length and different values of load impedance

III. Influence of Load Impedance and Cable Length

In this section the influence of cable (line) length $\mathcal{L}$ and load impedance Z_L is investigated. This is done by plotting the CFR (10) for different values of $\mathcal{L}$ and Z_L and by keeping R, L and C constant. R, L and C are functions of the geometry and the separation distance s, wire diameter d, as well as permittivity ε and permeability μ_0. Separation distance and wire diameter with insulation (dielectric) for a Flat Twin and Earth low voltage indoor power cable are shown in Fig. 4.

A. *Effect of Load Impedance*

The effect of different load impedances for a 10m, 1.5mm^2 Flat Twin and Earth low voltage indoor power cable is shown in Fig. 5. The ratio between s and d (Fig 4) for this Flat Twin and Earth is 3.785, $\varepsilon_r=3.0$ and the wire diameter is 1mm. The characteristic impedance of the cable was experimentally determined to be around 115Ω [5]. For a load impedance above Z_0, output voltage is increased (due to resonance of the transmission line). Below Z_0, the CFR shows low pass cut-off behavior. This is especially problematic if the load impedance is around 10Ω and lower.

B. *Practical Load Impedance*

In a practical low voltage 220V$_{rms}$, 50Hz indoor system, current is determined by the installation. Maximum current from a power outlet is typically 15A so that the 50Hz load impedance can be 15Ω. At the low voltage distribution board, 100A can be drawn so that the load impedance at 50Hz can be as low as 2.2Ω.

This is clearly a problem as can be deducted from Fig. 5. The load impedance can be expected to be sub 10Ω for frequencies higher than 50Hz in some cases, "killing" the PLC signal in the narrow band range of 3-500kHz.

Although the load impedance rises as frequency increases; it may not be enough for good communication. The prevalence of non-resistive switching loads (switch mode power supplies) necessitates the use of Electromagnetic Interference (EMI) filters. These filters shunt high frequency interference made by modern supplies and keep the noise from reaching the mains supply. Unfortunately, it also shunts PLC signals. A typical EMI filter is shown in Fig. 6. The mains supply side is to the left between "L" and "N". The termination of the transmission line cable is now dominated by the input capacitance of 0.27µF. In general, this so-called X-capacitor presents a low impedance to the line. This can be seen form the familiar:

$$X_C = \frac{1}{2\pi f C_X} \tag{9}$$

where X_C is the imaginary part of the impedance of the X-capacitor C_X in ohm. At $f=100kHz$, X_C is around 6Ω and at $f=100MHz$, X_C is around 6mΩ. It therefore presents a load close to a short circuit to the transmission line above 1MHz.

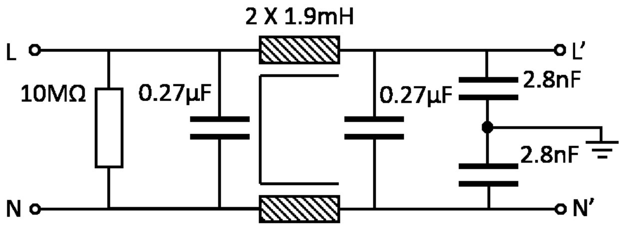

Fig. 6 – EMI Filter as possible load. Note the 0.27µF capacitor across Live (L) and Neutral (N) which is terminating the cable.

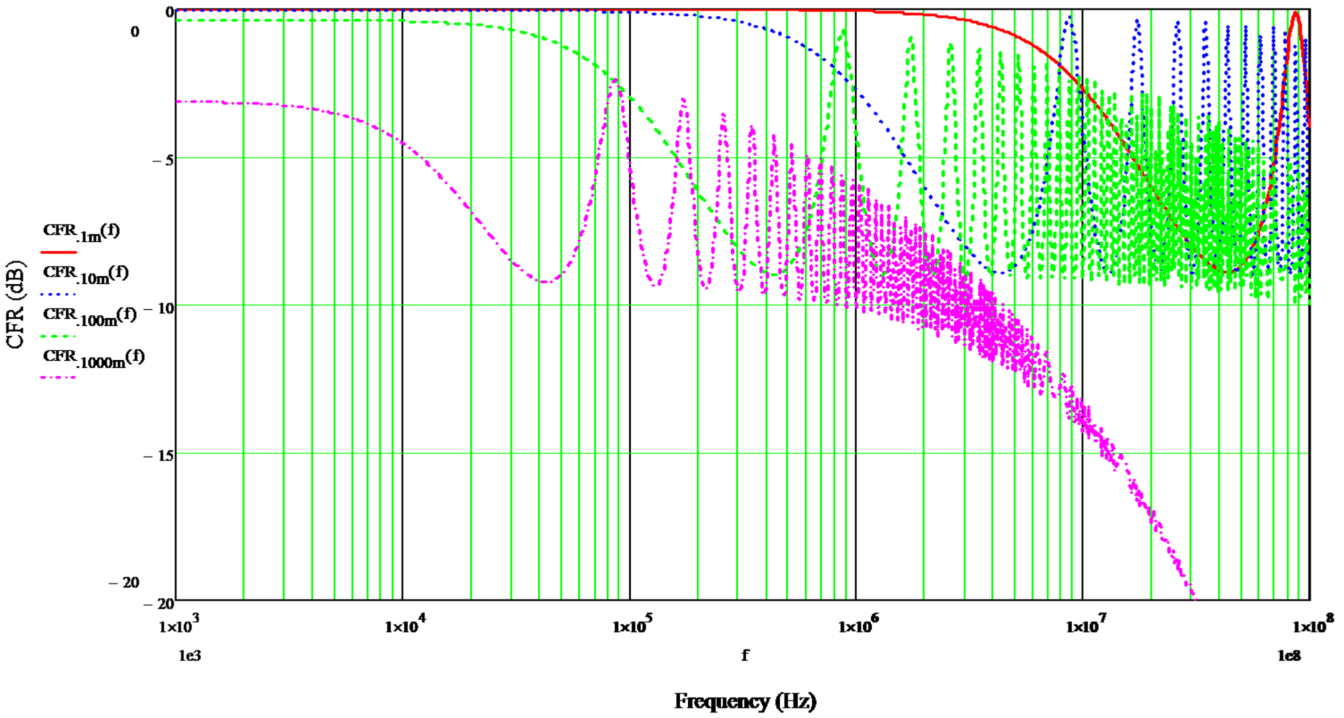

Fig. 7 – CFR of a 1.5mm^2 Flat Twin and Earth low voltage indoor power cable of different lengths and 50Ω load impedance

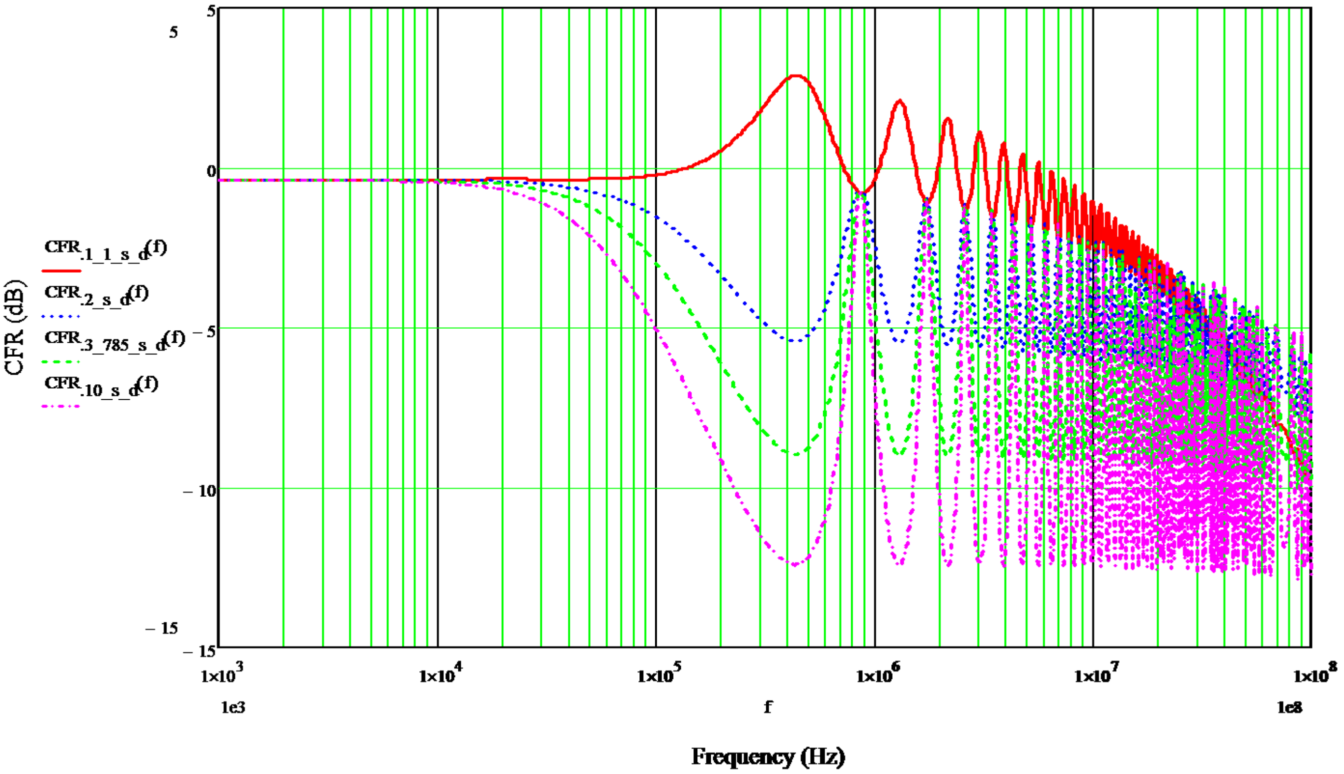

Fig. 8 – CFR of a 100m, 1.5mm^2 Flat Twin and Earth low voltage indoor power cable of different geometries and 50Ω load impedance. Ratios of separation (s) to wire diameter (d) of 1.1, 2, 3.785 and 10.

Low load impedance is possibly the largest threat to the efficient use of PLC and designers should take note of this. One possible countermeasure is to increase signal levels.

C. Effect of Cable Length

Figure 7 shows the results of the CFR of a 1.5mm^2 Flat Twin and Earth terminated in a 50Ω load. The ratio between s and d

(Fig 4) for this Flat Twin and Earth is 3.785, ε_r=3.0 and the wire diameter is 1mm. For cable lengths up to 100m, the attenuation in the CFR is not more than -10dB. For 1km, the CFR starts showing low pass cut-off behavior from 1MHz.

Although results are not shown, the CFR rolls of dramatically if the 50Ω load impedance used in Fig. 7 is replaced with 10Ω. With 10Ω load impedance the attenuation is -15dB at 100kHz. This reiterate the importance of load impedance as parameter for PLC performance.

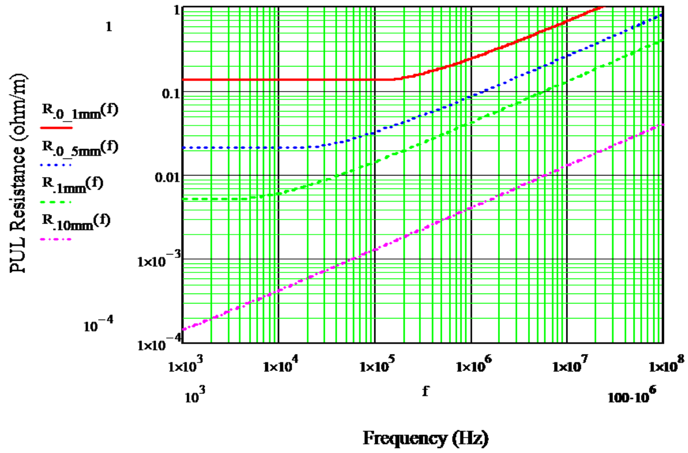

Fig. 9 – PUL Resistance of a 1.5mm^2 Flat Twin and Earth low voltage indoor power cable for different values of wire radius

IV. INFLUENCE OF CABLE GEOMETRY

Cable geometry refers to the physical lay-out of the cable as shown in Fig. 4. In Fig. 3 it is shown that the ratio of the separtion between the connductors s and the wire diameter d (i.e. s/d) as well as the d on its own influence R, L and C. In this section the effect of the ratio s/d as well as the wire radius ($d/2$) on the CFR is investigated.

A. Influence of Separation to Diameter Ratio

Figure 8 shows the CFR of a 100m, 1.5mm^2 Flat Twin and Earth low voltage indoor power cable of different geometries and 50Ω load impedance. The wire radius was kept at 0.5mm (d=1mm). The top trace in Fig. 8 is for s/d=1.1. This is the case when the conductors are close to one another such as in a twisted cable. The second trace is for s/d=2; third trace for the 1.5mm^2 Flat Twin and Earth of Fig.1 (s/d=3.785) and bottom trace for s/d=10.

Differences in geometry does not alter the CFR as dramatically as changes in load impedance or cable lentgh. Maximum attenuation in the CFR is around -13dB.

B. Influence of Conductor Radius and the Skin Effect

The PUL R in Fig 2 is highly nonlinear due to the skin effect. Fig. 4 shows that this has an influence on the propagation constant γ and characteristic impedance Z_0, both influencing the CFR. In this section the effect of the nonlinear PUL resistance on the CFR is determined.

In this study, R is represented as a piecewise approximation. The skin depth is first calculated as:

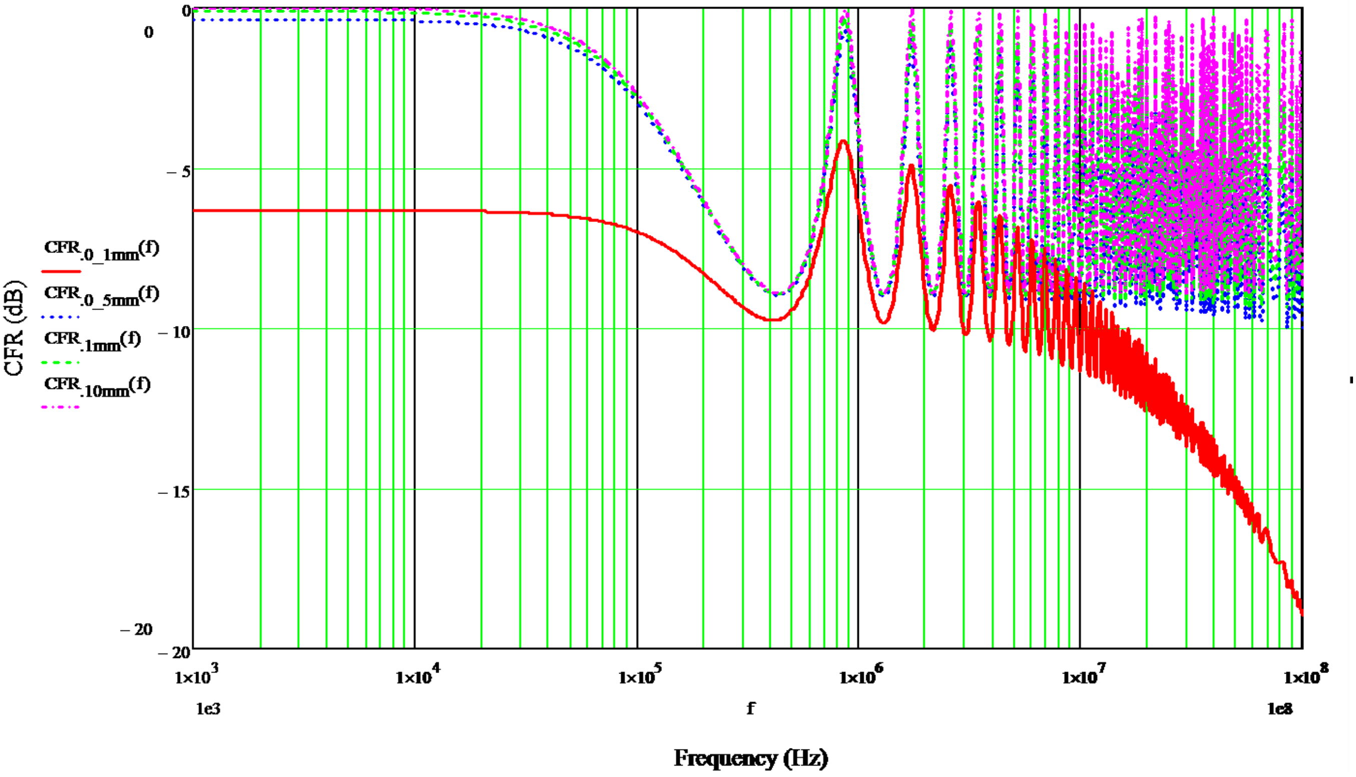

Fig. 10 – CFR of a 100m, 1.5mm^2 Flat Twin and Earth low voltage indoor power cable for different values of wire radius (50Ω load)

$$\delta = \frac{1}{\sqrt{\pi . f . \mu_0 . \mu_{r\_Cu} . \sigma_{Cu}}} \tag{10}$$

where $\mu_0 . \mu_{r\_Cu}$ is the permeability of the copper conductor, σ_{Cu} the conductivity of copper and f the frequency. δ is the average distance the propagating wave penetrates the skin of the conductor. At higher frequencies the effective area of conduction becomes smaller and the resistance increases. By calculating the effective area of conduction, R is determined.

Results for these calculations are shown in Fig. 9. R in Ω/m is given for different wire radii. This figure shows that when the skin depth δ is larger than the wire radius, the resistance is constant at its DC value. As the frequency increase the skin depth decreases and becomes smaller than the wire radius. From this point onwards, R increases with frequency. Fig 9 shows resistances for wire radii of 0.1mm, 0.5mm, 1mm and 10mm.

Fig. 10 shows the CFR of a 100m, 1.5mm^2 Flat Twin and Earth low voltage indoor power cable for different values of wire radius (50Ω load). The CFR attenuation is above -10dB for 0.5mm, 1mm and10mm. The 0.1mm radius wire is unlikely to be used as it cannot carry enough load current in a practical 50Hz system.

From these results it can be concluded the conductor resistance is a secondary effect when influencing the CFR and that cable length and load impedance dominates CFR behavior.

V. CONCLUSION.

From the work in this study a few conclusions can be drawn for the CFR of a low voltage power cable:

- Due to transmission line effects the length of the cable is a primary factor to consider. The shorter the cable the higher the CFR cut-off. This work shows that for a 1.5mm^2 Flat Twin and Earth low voltage indoor power cable, lengths larger than 100m might not be practical for broadband PLC especially if the load impedance is much smaller than the characteristic line impedance Z_0.
- Second to the effect of the length is the effect of the load impedance. The perfect termination is the line characteristic impedance Z_0. This is not always possible. The lower the load impedance the higher the attenuation and the CFR drops. For load impedances higher than Z_0, the CFR improves.
- This paper shows that the cable length and load impedance are the two primary factors affecting CFR.
- The geometry of the cable (wire radius, separation and dielectric) does not affect the CFR as drastically as the cable length and load impedance and are secondary.

REFERENCES

[1] L. Atzori, A. Iera, G. Morabito, “The Internet of Things: A survey”, *Comput Netw*. 54, pp. 2787–2805, 2010

[2] Farhangi, Hassan. "The path of the smart grid." *Power and Energy Magazine, IEEE* 8.1: pp. 18-28. 2010

[3] A. Nordrum, (2016). Available from: https://spectrum.ieee.org/tech-talk/telecom/internet/popular-internet-of-things-forecast-of-50-billion-devices-by-2020-is-outdated. (Accessed Oct 18, 2017).

[4] L. Lampe, A. M. Tonello, and T. G. Swart, Eds., Power Line Communications: Principles, Standards and Applications From Multimedia to Smart Grid. New York, NY, USA: Wiley, 2016.

[5] A. Sheri, A. De Beer, S. Padmanaban, A. Emleh and H. C. Ferreira, "Characterization of a power line cable for channel frequency response — Analysis and investigation," *Conference Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Milan, 2017, pp. 1-4.