Is Broadband over Power-lines dead?

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Abstract— **Recently there has been a significant amount of publicity about high levels of radiation from power lines using Broadband communications over Power Lines (BPL). Specific interference problems, or experimental measurements are typically cited. For smart grid, smart metering and advanced metering infrastructure applications, low data rate Power Line Communications (PLC) will be required. This paper describes a Matlab® program for calculating the radiation and resistive losses for power lines from BPL and PLC signals. Results are presented for Single Wire Earth Return (SWER) lines, for three phase overhead lines using typical conductors mounted on crossarms and for bundled aerial conductors. These results show that depending on the cable and signal frequency, BPL and PLC can be achieved without causing significant interference.**

Index Terms—PLC, BPL, Radiation, Power-line, smart grid, smart metering, AMI.

I. INTRODUCTION

When a power line is used for sending communication signals, there are two dominant loss factors to those signals. The first one is electromagnetic radiation. This both reduces the available signal power and causes interference to other users. The interference aspects are the most critical. The second loss factor is resistive loss, which due to the skin depth varying with frequency, causes an increasing attenuation with frequency.

There is a concern about the amount of radiation from communications signals on power lines, with amateur radio operators claiming BPL creates excessive levels of radiation [1, 2, 3]. The ACMA in conjunction with power companies have been doing experimental measurements to provide some factual data [4, 5]. The ACMA report on the Queanbeyan BPL trial [4] reported on measurements of spectra between 150 kHz and 30 MHz, but no conclusions are drawn to indicate if the radiation levels are acceptable or not. The ACMA report on the Hobart BPL trial [5], concludes the radiation is acceptable if FCC guide-lines are used. The situation is not clarified by the submissions to the ACMA [6] discussion paper on "The Management of Interference from Broadband over Power Line Applications", with most of the submissions reporting gut feelings rather than facts.

Finally commercial companies like MYVA[7] and MainNet [8] see BPL as having a potential to compete with ADSL and wireless broadband services, particular with governments wanting to provide broadband access to everyone [9].

It is unfortunate that these claims and reports do not distinguish between Low Voltage Overhead (LVOH) lines mounted on crossarms and Arial Bundled Conductors (ABC) or underground powerlines. This paper shows that there is a significant difference between the radiation levels from LVOH lines and from ABC or underground powerlines. To provide a rigorous basis for determining the radiation and resistive losses from powerlines, the Matlab® program described in this paper was developed. Electricity distribution companies and other communication providers can use the resulting data to determine the feasibility of power-line communications in their region.

In this paper we distinguish between PLC as a relatively low data rate application, with frequencies up to 200 kHz, primarily for use in smart grid, smart metering and advanced metering infrastructure (AMI) applications. In this paper, the term BPL is used for an application providing broadband communication access to the consumer, as an alternative to ADSL or broadband radio Internet access. BPL can require frequencies up to 100 MHz, depending on the desired system capacity.

II. RADIATION AND LOSS MODEL

A. Theoretical Background

The existing travelling wave model of a long wire antenna [10, 11] assumes that the antenna is less than 10 λ long and the current along the line is constant. This implies that no power is lost in radiation. Neither of these assumptions apply for power-lines, so that a radiation model based on fundamental equations has had to be developed.

The power radiated for an infinitesimal dipole is described in most antenna books [10, 11, 12]. The model presented in this paper cascades many of these infinitesimal dipole models to make up the whole transmission line. The power radiated by a small dipole in the far field, is dependent on the current in that dipole, I_o and is given by (1) [10] as:

$$P_{rad} = \eta_0 \, \frac{\pi}{3}\left(\frac{l\, I_0}{\lambda}\right)^2 \qquad (1)$$

where η_o = 120π. Because the line is long, I_o will not be constant. Three factors affect I_o:

1) I_o is reduced by dissipation due to series resistance. This

series resistance varies with frequency due to the skin depth varying with frequency.

2) I_o is altered in phase, along the line, due to wave propagation.
3) I_o is progressively reduced because power is radiated.

The electric field E_θ for this infinitesimal dipole can easily be shown [10, 11, 12, 13] to be:

$$E_\theta = \frac{j\eta_0 k\, I_0\, l\, e^{-jkl} \sin(\theta)}{4\pi r} \tag{2}$$

For a very long wire antenna, such as a power-line, the magnitude and phase of the current I_o and E_θ at a position along the line is iteratively determined by considering the radiation and resistive line losses up to that point. This is then be used to determine E_θ caused by the infinitesimal dipole at that point. At a point along the line, the E_θ vector from the infinitesimal dipole is added to the cumulative E_θ vector, to produce the new cumulative E_θ vector. The power radiated is then determined by integrating the Poynting vector over a closed surface, of a sphere of radius r to give [13]:

$$P_{rad} = \frac{\pi}{\eta_0} \int_0^{\pi} |E(\theta)|\, r^2 \sin(\theta)\, d\theta \tag{3}$$

This allows the radiation loss for the whole line up to that point to be determined by using (3), so that I_o flowing into the next infinitesimal dipole can be determined by subtracting the power lost in radiation and the resistive losses from the input power to the infinitesimal dipole. This process is then repeated to determine the E_θ and the power radiated by the whole line. The accuracy of this model has been verified by the authors by comparing its results to those obtained by standard equations for shorter antennae [13, 14].

B. Transmission Line Parameters

To calculate the resistive losses and radiation losses, accurate transmission line parameters need to be used. The effective line resistance R and internal inductance L_i can be shown [15] to be:

$$R = \frac{\rho}{\sqrt{2\pi a\delta}} \frac{ber\,(q)\frac{d}{dq}bei(q) - bei(q)\frac{d}{dq}ber\,(q)}{\left\{\frac{d}{dq}bei(q)\right\}^2 + \left\{\frac{d}{dq}ber(q)\right\}^2}\ \Omega/\mathrm{m} \tag{4}$$

$$\omega L_i = \frac{\rho}{\sqrt{2\pi a\delta}} \frac{bei\,(q)\frac{d}{dq}bei(q) - ber(q)\frac{d}{dq}ber\,(q)}{\left\{\frac{d}{dq}bei(q)\right\}^2 + \left\{\frac{d}{dq}ber(q)\right\}^2}\ \Omega/\mathrm{m} \tag{5}$$

$$q = \sqrt{2}\,\frac{a}{\delta} \tag{6}$$

$$\delta = \sqrt{\frac{\rho}{\pi\mu F}}\ \text{metres} \tag{7}$$

where *ber* and *bei* are Kelvin-Bessel functions [16], q is an intermediate constant given by (6), a is the conductor radius, ρ is the resistivity of the conductor in ohm-meters, δ is the skin depth and is given by (7), F is the frequency in Hz and μ is the magnetic permeability ($4\pi \times 10^{-7}$ in free space).

The line inductance for a parallel line of cylindrical geometry is then [15]:

$$L = \left[4log_e\frac{D}{a} + \left(\frac{\mu_c}{\mu_0}\right)\left(\frac{L_i}{L_{i0}}\right)\right] \times 10^{-7} \tag{8}$$

$$L_{i0} = \frac{\mu}{8\pi} \text{ and } R_0 = \frac{\rho}{\pi a^2} \tag{9}$$

where D is the distance between the centres of the conductors, μ_c is the magnetic permeability of the conductor and μ_0 is the magnetic permeability of free space. L_{i0} and R_0 are the internal inductance and resistance when $a << \delta$, i.e. at low frequency. At high frequency the right term in (8) is small and the inductance is constant. However for many communication frequencies over power-lines this is not the case and (8) must be used. The characteristic impedance of the power-line will thus vary with frequency.

The corresponding line capacitance is given on page 85 of [15] as:

$$C = \frac{\left(\frac{\epsilon}{\epsilon_0}\right)\times 10^{-9}}{36\, Cosh^{-1}\left(\frac{D}{2a}\right)}\ \text{farad/m} \tag{10}$$

Single Wire Earth Return power-lines are used in remote areas and are single phase lines where the ground is relied upon for the return path. For SWER lines, the distance of the ground return path below the ground level is given by Carson's equation [17, 18]:

$$D = 2(h + \sqrt{\left(\frac{\rho_s}{2\pi F\mu_0}\right)} \tag{11}$$

where h is the height of the SWER line above ground, ρ_s is the soil resistivity and F is the signal frequency in Hz.

For SWER lines, at 50 Hz the return path is typically 1km below ground, while at 100 kHz it is about 40 m below ground. The line capacitance and the characteristic impedance of the line will thus change significantly.

C. Matlab® implementation.

Matlab® is used to calculate the resulting E_θ fields for these cascaded line segments, using (1) to (3) and the intermediate equations shown in [13, 14, 19]. The typical length of each line segment is 0.01 λ or 0.1 km, whichever is the smallest, to ensure a high level of accuracy and consistent plotting of the results. For a 10 km line at 100 kHz, 300 line segments are used and at 100 MHz, 299980 line segments are used. Since for the results presented here, the field integration is done at 0.1 degree intervals, massive calculations are required for determining the radiation and resistive losses from a power-line at high frequencies.

Since PLC and BPL systems typically operate on relatively short power-line sections, 1km and 10 km line lengths are used for most of the calculations presented in this paper. A 1 km power-line at 100 MHz is 300 λ long, which is far in excess of the < 10 λ limit imposed by conventional antenna models.

Practical power-lines are not absolutely straight. Any small bends, as the line direction changes to follow the terrain, has a major impact on the radiation pattern [14]. Figure 1 shows the effect of radiation loss as the change in line direction, called *wobble*, in this paper is changed by a random angle with the standard deviation indicated, every 0.1 km for a 1 km long SWER line with a 1 MHz carrier frequency. If the wobble is comparable to the spacing between the sidelobes, large changes in attenuation can result. For the radiation results presented in this paper, a 50 mrad wobble is used as that has sufficient randomness and results in a sufficient increase in radiation, while avoiding the rapid changes in attenuation associated with a larger wobble. Introducing the wobble results in a significantly increase in radiated power. Figure 2, shows the radiation pattern of a 30 km long overhead line with a 1 MHz carrier frequency and a 50 mrad wobble. The radiation pattern is very different than that from a classical long wire antenna.

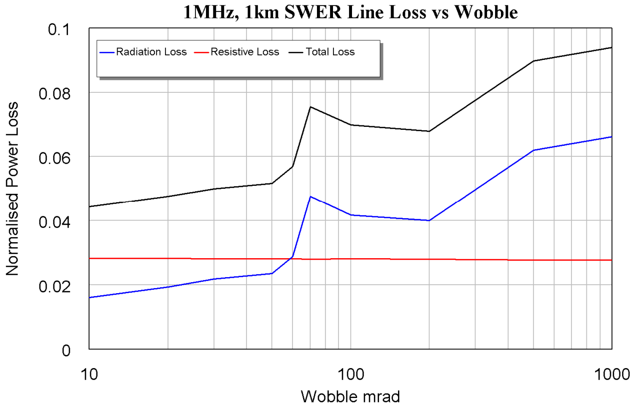

Figure 1. Radiation loss of a SWER line with bends.

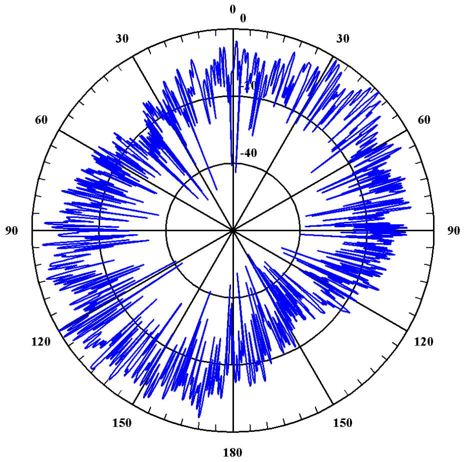

Figure 2. Radiation pattern LVOH line 30km long with 50 mrad wobble.

The Matlab® program calculates the skin depth (7) and uses that and (4) to determine the actual line resistance. The line inductance is calculated using (5) and (8) and that is then used to evaluate the characteristic impedance of the line using (10) and (11). The power-line is terminated in that characteristic impedance at both the source and load, to prevent reflections.

Since a typical power-line network has many bends, T junctions and spurs, representing it by a single line as is done here is not ideal. However, the frequency dependence of the radiation losses obtained from this Matlab® model gives a very valuable guideline on the frequency limits for the power-line configurations presented here. The model presented here assumes a perfect balance in the signal currents flowing in the pair of lines making up the BPL/PLC signal path. If the line couplers are designed to ensure that no unbalanced signals are created, then this is a valid assumption.

III. RESULTS

A. SWER Lines

In this study three types of power-lines are considered. The first is a SWER line consisting of a single aluminium clad steel (SCAC) cable with three 2.75 mm diameter strands. At typical PLC frequencies, all the currents flow in the Aluminium cladding, so for PLC frequencies, there is no difference between SCAC and Aluminium cables. The SWER line is typically 7 m above ground with the earth return distance varying according to (11). This is the worst case for radiation, since the distance between the line and it's return path is large and SWER lines are up to 300 km long.

The parameters for the SWER line obtained from the Matlab® program are shown in figure 3. The line resistance increases significantly with frequency. Despite the earth return path depth (11) varying from close to 2000 m at 10 Hz to 20 m at 100 MHz, the characteristic impedance of the SWER line only varies from 690 Ω at 10 Hz to 445 Ω at 10 MHz.

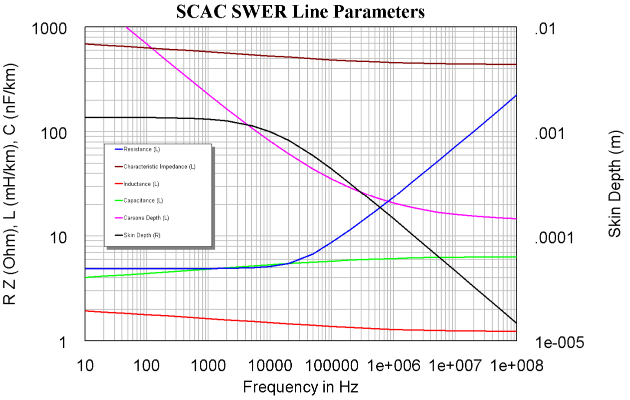

Figure 3. SWER line parameters versus frequency.

Figure 4 shows the normalised power loss from radiation and resistive losses of a 1 km and 10 km long SWER line. For the 1 km long line and frequencies below 1 MHz, the radiation losses are less than the resistive losses. For frequencies below 200 kHz, the radiation is small, but above this frequency there is a very rapid rise in radiation. Figure 5 shows the radiation losses versus SWER line length with the signal frequency as a parameter. SWER lines can thus be used for PLC signals up to 200 kHz but unsuitable for BPL as the radiation losses and the resulting interference to other services will be too great.

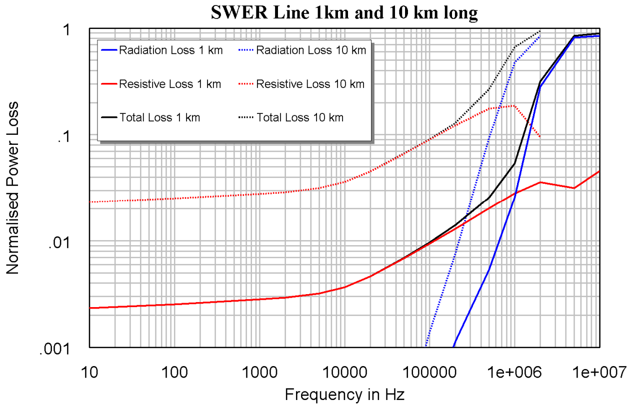

Figure 4. SWER line losses versus frequency.

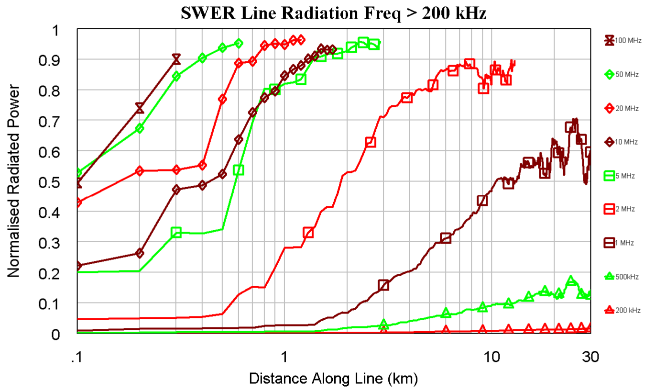

Figure 5. SWER line radiation losses versus frequency 200 kHz - 100 MHz.

B. *Overhead Lines Mounted on a Crossarm*

The second type of transmission line considered in this paper is the typical traditional open wire low voltage mains consisting of four All-Aluminium Conductor (AAC) cables each with 7 strands of 4.75 mm diameter mounted on a cross-arm. The line consists of two sets of wires with a 550 mm spacing and a larger spacing between these sets of wires to accommodate the power-pole. Two of the wires with a 550 mm spacing are used for a balanced signal pair.

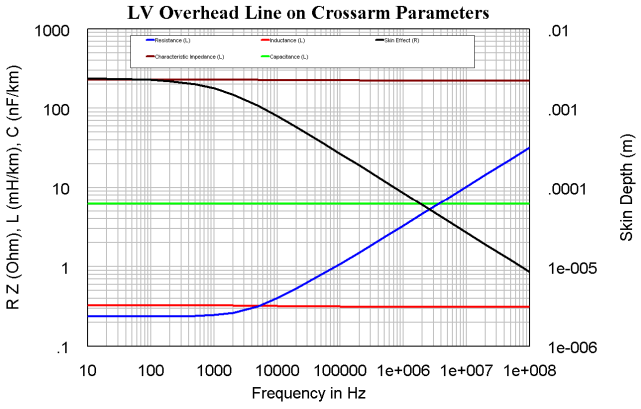

Figure 6. LV overhead line parameters versus frequency.

The parameters for the overhead line are shown in figure 6. The characteristic impedance of the line is 225 Ω and is virtually independent of frequency. There are only small variations of line inductance and capacitance with frequency.

The Low Voltage Overhead (LVOH) power-line mounted on crossarms, is the typical power-line configuration used in the USA and Australia. This type of power-line has been targeted by the American Radio Relay League (ARRL)[1] as a producer of interference due to BPL. This configuration is now a non-preferred line configuration by ERGON (The Queensland Regional Electricity Supplier).

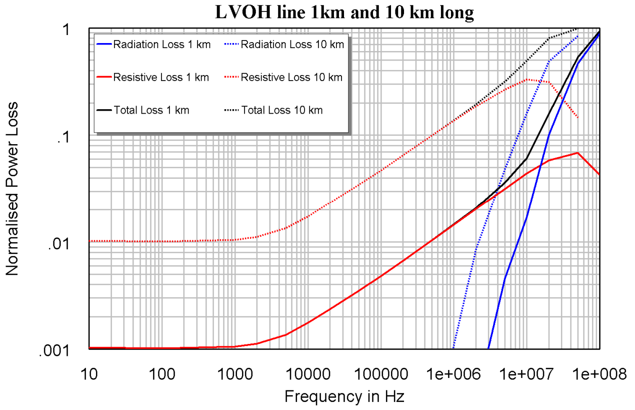

Figure 7. LV overhead line losses versus frequency.

Figure 7 shows the normalised power loss from radiation and resistive losses of a 1 km and 10 km long LVOH line. For the 1 km long line and frequencies below 15 MHz, the radiation losses are less than the resistive losses. For frequencies below 5 MHz, the radiation is small, but above this frequency there the radiation rises rapidly.

Figure 8 shows the radiation losses versus LVOH line length with the signal frequency as a parameter. These figures show that a LVOH lines can be used for PLC and PBL signals up to 5 MHz. LVOH lines will cause significant radiation for communication signals above 10 MHz, and can only be used for BPL signals above 10 MHz if no other radio services use those frequencies, or if used HF signals are notched out of the transmitted BPL spectra.

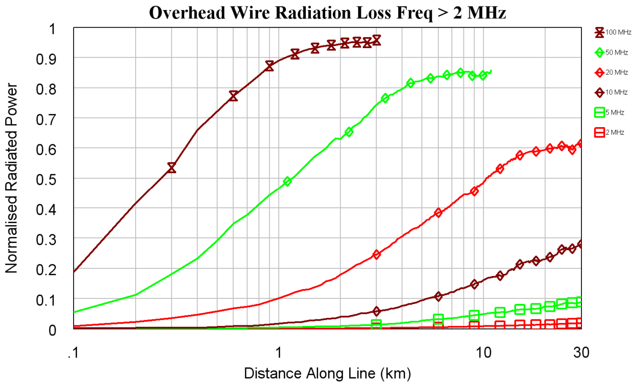

Figure 8. LV overhead line radiation losses versus frequency, 2-100 MHz.

C. *Aerial Bundled Conductors*

The final type of transmission line considered is a Aerial Bundled Conductor (ABC), consisting of four insulated, compacted aluminium cables grouped together with common insulation. Each conductor is made up of 19 strands, 2.52mm in diameter. Each compacted conductor is 11.4 mm in diameter and the spacing between the centres of the conductors is 14.9 mm. The cable type is XDAB22AA004 from Olex [20]. This conductor is now the preferred conductor type for overhead power lines. Applying those parameters to equations (4) to (10), results in the line parameters shown in figure 9. The characteristic impedance is 30.8 Ω and is virtually constant with frequency.

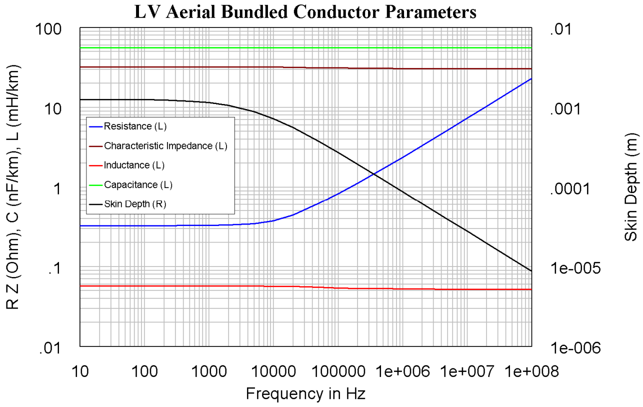

Figure 9. Bundled aerial conductor parameters versus frequency.

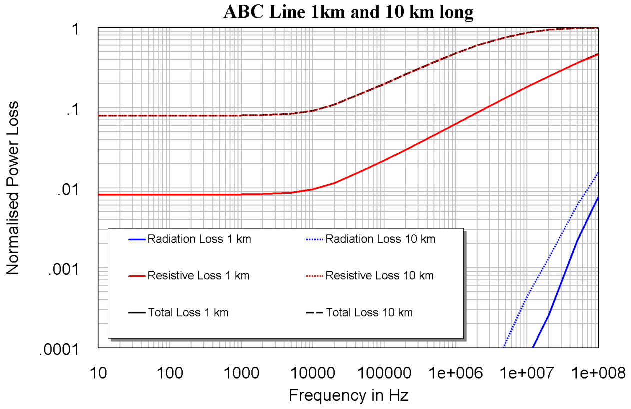

Figure 10. ABC line radiation losses versus frequency.

Figure 10 shows the normalised power loss from radiation and resistive losses of a 1 km and 10 km long ABC line, it show that for frequencies below 100 MHz, the radiation losses are insignificant compared with the resistive losses. Figure 10 shows that for frequencies below 10 MHz, the radiation is less than 0.2% and will thus be virtually undetectable.

Figure 11 shows the radiation losses versus line length with the signal frequency as a parameter for an ABC line and shows that 100 MHz signals will only travel 13km before all power is lost. The range of the BPL signals depends on the carrier frequency used, since the skin depth determines the resistive losses.

Similar results will apply for underground cables, where all the active conductors are also bundled together in one cable. ABC overhead lines and underground lines are thus very suitable for providing both PLC and BPL.

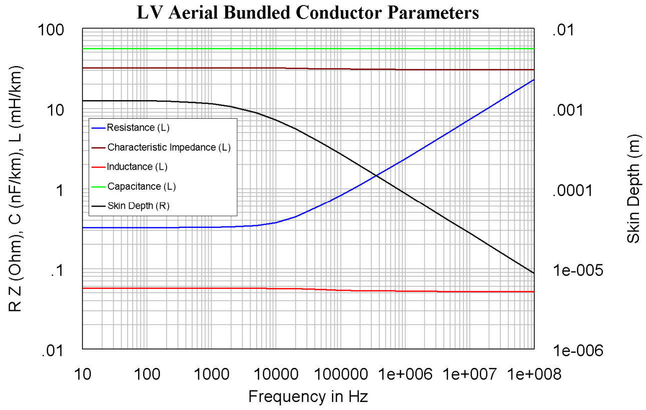

Figure 11. ABC line radiation losses at high frequency.

IV. IS BPL OR PLC DEAD?

The results presented here show that SWER lines produce little radiation for frequencies below 200 kHz. As a result, they can be used for PLC applications, such as smart metering. However it is unlikely that any spare communication capability is available for customer internet access. Since the radiation losses dominate all other losses for frequencies above 1 MHz, BPL is not possible.

LVOH lines have little radiation for frequencies up to 5 MHz and they can thus be used for both PLC and for a limited bandwidth BPL. Since radiation is the dominant loss above 15 MHz for a 10 km line, the BPL frequencies should be restricted below this. In any case great care needs to be taken to ensure that any frequencies used by existing LF, MF or HF services are avoided. Whether BPL is used for LVOH lines is primarily an economic decision. If ADSL or wireless broadband are available, then the potential interference problems and the resulting reduction in available channel bandwidth may make it difficult to justify BPL.

As shown in figure 10, ABC and underground lines are very suitable for both PLC and BPL and cause negligible radiation. An ADSL telephone line, a ABC power-line and an underground power-line all have a similar geometry and consist of 4 conductors separated by small insulation layer, with 2 conductors being used to carry the communication signals. The main difference between these system is that for BPL all users share the same cable and thus the same channel bandwidth, while in ADSL the customer has the line for themselves. BPL is successfully used on underground power-lines in Europe [7]. In Dresden, DREWAG has a captive market in some of its BPL coverage area, since the telephone network is incapable of providing ADSL. Figure 11 shows high resistive losses at high frequencies. However since the skin depth determines the line resistance above 20 kHz and the ABC conductor is made up of 19 strands compared to one strand for a typical ADSL line, the resistive losses for ABC lines are much less than for ADSL lines. Internode [20] shows that a typical ADSL line has 60 dB attenuation at 4.5 km and 300 kHz. The same length of ABC line has 12.6 dB attenuation at 100 MHz. For this line less than 1.5% of input power is radiated at 100 MHz. The ABC line will thus have more than 300 times the data capacity of a typical ADSL line.

PLC is very much alive for smart grid, smart metering and AMI applications, regardless of the power-line configuration used. BPL is dead for use on SWER lines. BPL is very sick for LVOH power-lines. BPL is healthy and competitive for ABC and underground power-lines.

V. CONCLUSION

This paper considered the radiation and resistive losses from SWER, LVOH and ABC power-lines. All these lines can be used for PLC communication at low data rate, such as is required for smart grid, smart metering and AMI applications.

SWER lines are unsuitable for Internet applications as their radiation is too large for frequencies above 200 kHz. LVOH lines mounted on crossarms will cause significant radiation for signal frequencies above 5 MHz. Higher frequency channels can be used provided no other radio communication systems are using those channels, thus tilting the economics against BPL. ABC overhead lines and underground cables, can be used for BPL applications, with little radiation, and covering larger distances than ADSL.

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