Calculating Radiation from Power Lines for Power Line Communications

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1. Introduction

The cost of electricity charged to consumers in Australia is predominantly set by state governments and does not vary depending on the actual cost that the electricity retailer has to pay the generators. This does not encourage users to reduce power at times of peak demand and the ratio between the peak demand and the average demand is growing. In the long term, user pays principle must apply and the cost of electricity charged will need to vary depending on the actual cost of production. This requires a communication system to be produced firstly to determine the date and time electricity is used, so that the usage and actual cost can be matched, and secondly to inform the consumer of the actual cost of electricity, so that appropriate actions can be taken, like turning off air conditioners when the cost per kW becomes high.

There are two ways that such a communication system can be developed. Firstly it can use the PLC for carrying the communication signals. Secondly the communication systems can be carried by third party suppliers. The WiMAX radio system currently being rolled out in Australia in Victoria and mobile phone based systems are examples of such systems. Using PLC has the advantage that the communication system is fully under the control of the electricity company and no fees need to be paid to third party operators.

In addition it is possible for the electricity supplier to use their power lines to provide BPL, giving internet access to customers, by putting communication signals up to 80 MHz onto the power lines. The frequency range used and bandwidth required for BPL is very different than that for PLC and the radiation losses are very different for BPL and PLC.

When a power line is used for transmitting communication signals, signal power is lost through electromagnetic radiation. This may cause interference to other users. There is a concern about the amount of radiation from power lines (ACMA 2005, 2007), with amateur radio operators claiming BPL creates excessive levels of radiation. Unfortunately much of the amateur radio literature does not distinguish between BPL and PLC. The second loss factor is resistive losses, which due to the skin depth causes an increasing attenuation with frequency.

The Matlab® program described in this paper and the results obtained from this program provide a rigorous basis for determining both the resistive losses and the radiation obtained from power lines. Electricity distribution companies and other communication providers can use this data to determine the feasibility of power line communications in their region.

SWER power lines are used in remote areas and are single phase lines where the ground is relied upon for the return path. As these power lines can be up to 300 km long, there is a

significant economic incentive to read the power meter for those customers remotely since a 600 km trip on dirt roads is likely to cost more than the customer's electricity bill. To achieve this JCU has been carrying out a research project for the Queensland electricity retailer ERGON for developing a PLC communication system for SWER lines.

2. Fundamental principles

2.1 Line radiation theory

The existing travelling wave model of a long wire antenna (Balanis, 1997, Walter, 1970 and Ulaby, 1994) assumes that the antenna is less than 10 λ long and the current along the line is constant, implying that no power is lost in radiation. Neither of these assumptions apply for power lines, so that a radiation model based on fundamental equations had to be developed.

The power radiated for an infinitesimal current element, also called an elementary doublet is described in most antenna books. The model presented in this paper cascades many of these infinitesimal current element models to make up the whole transmission line. The power radiated by a small length of conductor of length l in the far field, is dependent on the current in the conductor, I_0, and is shown in (Balanis 1997) to be:

$$P_{rad} = \eta \frac{\pi}{3} \left(\frac{l I_o}{\lambda} \right)^2 \tag{1}$$

where $\eta_0 = 120\,\pi$, is the λ wavelength. Antenna radiation patterns for long wire antenna Because the line is long, I_0 will not be constant. Three factors affect I_0:

1. I_0 is reduced by dissipation due to series resistance. This series resistance varies with frequency due to the skin depth varying with frequency.
2. I_0 is altered in phase, along the line, due to wave propagation.
3. I_0 is progressively reduced because power is radiated.

Using the conventional spherical coordinates r, θ and φ, the far-field electric field E_θ and the far-field magnetic field H_φ for this elementary doublet is given by (Balanis 1997) as:

$$E_\theta = \frac{j\eta_0 k I_0 l e^{-jkr} \sin(\theta)}{4\pi r} = \frac{j\eta_0 I_0 l e^{-jkr} \sin(\theta)}{2\lambda r} = \frac{j60\pi I_0 l e^{-jkr} \sin(\theta)}{\lambda r} \tag{2}$$

$$H_\varphi = \frac{j k I_0 l e^{-jkr} \sin(\theta)}{4\pi r} = \frac{j I_0 l e^{-jkr} \sin(\theta)}{2\lambda r} \tag{3}$$

where the wave number, $k = 2\pi/\lambda$. Note that since the current I_0 has a magnitude and phase, both E_θ and H_φ are complex quantities.

$$P_{rad} = \frac{1}{2} \text{Re} \left(\oiint_s E_\theta \times H_\varphi ds \right) \tag{4}$$

The far-field power radiated is obtained by integrating the Poynting vector over a closed surface, chosen to be a sphere of radius r, where r is much larger than the wavelength and the length of the power line dimensions as shown in equation (4). For an elementary doublet in free space, the inner integrand is independent of φ, resulting in a constant of 2π for that integration, so that:

$$P_{rad} = \frac{\pi}{2\eta_0} \int_0^{2\pi} |E(\theta)| r^2 \sin(\theta) d\theta = \frac{1}{240} \int_0^{2\pi} |E(\theta)| r^2 \sin(\theta) d\theta \tag{5}$$

For a very long wire antenna, such as a power line, the magnitude and phase of the current I_0 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 elementary doublet at that point. At a point along the line, the E_θ vector from the elementary doublet is added to the cumulative E_θ vector, to produce the new cumulative E_θ vector. For a line in free space, the cumulative fields are independent of φ, so that (5) can be used to evaluate the radiated power.

If the conductor is not in free space, but is a single power line, a distance h above an ideal groundplane, then equal and opposite image current will be induced below the groundplane. That changes the radiation pattern, so that the radiation is no longer independent of φ. A Medium Voltage (11 kV to 33 kV) single power line is typically 7 m above the ground. If this is used for power line communication signals up to 1 MHz, then the power line is far less than a quarter wavelength above the ground. The far-field electric field for an elementary doublet a distance h above a perfectly conducting ground plane will be:

$$E(\theta, \varphi) = E_\theta(2j Sin(\frac{\pi 2h}{\lambda} Cos(\varphi))) = -\frac{120\pi I_0 l e^{-jkr} \sin(\theta)}{\lambda r} Sin(\frac{\pi 2h}{\lambda} Cos(\varphi)) \tag{6}$$

The radiation pattern from the elementary doublet will then have a null along the conductor (θ=0), as it had for the free space conductor and in addition it will have a null along the groundplane (φ=90°) and a maximum perpendicular to the groundplane ($\theta = \varphi = $ 90°). The field in this direction depends on 2h, the separation between the line and the return path. For SWER lines, the ground plane is not a perfectly conducting plane and the distance of the ground return path below the ground level is given by Carson's equation (Carson, 1926, Wang & Liu, 2001, Deri & Tevan, 1981):

$$D = 2(h + \sqrt{\left(\frac{\rho_s}{2\pi F \mu_0}\right)}) \tag{7}$$

where h is the height of the SWER line above ground, ρ_s is the soil resistivity. To use this for a SWER line we replace the line separation 2h in equation (6) by D in equation (7).

At 50 Hz the return path is typically 1km below ground and at 100 kHz it is about 36 m below ground. In both cases the return path distance is still much less than a quarter wavelength, so no additional nulls appear in the field from the elementary doublet. Since the effective line spacing varies, the line capacitance and characteristic impedance also change with frequency.

Equation (6) can also be used to determine the radiation from overhead power lines where the PLC signals are applied in a differential form on two conductors with a line separation of *2h*.

From knowing the skin depth, the diameter of the conductor and its conductivity, the resistance of conductor for the elementary doublet length can be calculated. Knowing the current flowing through the elementary doublet, the resistive losses can then be calculated.

Knowing the current flowing into the present elementary doublet and keeping the characteristic impedance of the line fixed at the value for the operating frequency, the current I_0 flowing into the next elementary doublet can determined by subtracting the cumulated power lost in radiation and the cumulated resistive losses from the input power to the present elementary doublet as shown in (8).

$$I_0 = \sqrt{\frac{I_{in}{}^2 Z_0 - P_{rad} - P_{res}}{Z_0}} \qquad (8)$$

This process of adding an elementary doublet, calculating the resulting cumulative E_θ, cumulative radiated power, resistive losses and evaluating the current I_0 flowing into the next elementary doublet, is repeated to determine the E_θ and the power radiated and the resistive losses for the whole line. The accuracy of this model has been verified by the authors (Reid & Kikkert, 2008) by comparing its results for short line lengths with those from standard equations.

2.2 Transmission line parameters

To calculate the resistive losses and radiation losses, accurate transmission line parameters need to be used. The fundamental equations for transmission line parameters are shown in (Johnson, 1950). Those equations have been used by the author (Kikkert & Reid, 2009) to derive the line parameters for power lines.

In a conductor, most of the current flows in the outer layer of the conductor, with a thickness of the skin depth (δ). The equation for the resistance of the line is given by equation (9) (Johnson 1950):

$$R = \frac{\rho}{\sqrt{2}\pi a \delta} \frac{ber(q)\dfrac{d}{dq}bei(q) - bei(q)\dfrac{d}{dq}ber(q)}{\left\{\dfrac{d}{dq}bei(q)\right\}^2 + \left\{\dfrac{d}{dq}ber(q)\right\}^2} \quad \Omega / m \qquad (9)$$

where *ber* and *bei* are Kelvin-Bessel functions (Johnson 1950), a is the conductor radius, ρ is the resistivity of the conductor in ohm-meters, q is an intermediate constant and δ is the skin depth, F is the frequency in Hz and μ is the magnetic permeability ($4\pi \times 10^{-7}$ in free space), as given by equations (10) and (11).

$$q = \sqrt{2}\,\frac{a}{\delta} \qquad \delta = \sqrt{\frac{\rho}{\pi \mu F}} \qquad (10)$$

$$R_{dc} = \frac{\rho}{\pi a^2} \quad \Omega / m \qquad (11)$$

At high frequencies Fig 3.10 of (Johnson, 1950) shows equation (9) becomes approximately:

$$R = R_{dc}\frac{a}{2\delta} \qquad (12)$$

To avoid calculation Kelvin-Bessel functions and considering that the conductor is made up of several strands with a steel core and aluminium cladding, equation (9) can be approximated to:

$$R = \sqrt{\frac{R_{Cdc}^2 a_S^2}{4\delta} + R_{Wdc}^2}$$

(13)

where R_{cdc} is the DC resistance of the whole conductor, if it were made from aluminium only, R_{Wdc} is the actual DC resistance of the whole conductor and a_s is the radius of each strand. At high frequencies the resistance is determined by the skin depth in the aluminium cladding and the low frequency asymptote is the actual DC resistance of the whole steel core bundled conductor. If a conductor is made up of solid steel or solid aluminium, then $R_{Cdc} = R_{Wdc}$. The difference between (9) and (13) for Steel Cored Galvanized Zinc (SCGZ) conductors is less than 3.4% for frequencies above 3 kHz. For Aluminium conductors, the error is less than 3.4% for frequencies above 30 kHz. Equation (9) cannot be applied to SCAC conductors, so that equation (13) is an acceptable equation for all conductors at PLC frequencies.

The line inductance for a line, can similarly be approximated to:

$$L_i = \frac{\mu_r \mu_0}{\sqrt{\frac{a^2}{4\delta^2} + 1}}$$

(14)

$$L = \frac{4}{10K} Log_e\left(\frac{D}{a} + L_i\right) \quad mH / km$$

(15)

where L is the inductance of the line, L_i is the internal inductance, D is the distance between the conductor and the one carrying the return path. For SWER lines, this is given by equation (7). K is a constant, where $K = 2$ if the transmission line consists of a conductor above a ground plane and $K = 1$ if the transmission line consists of a balanced line.

$$C = \frac{2K\varepsilon_r}{36 Log_e(\frac{D}{a})} \quad \mu F / km$$

(16)

$$Z = \sqrt{\frac{L}{C}}$$

(17)

3. Matlab® implementation

3.1 Transmission line parameters

For SWER lines, three types of conductors are commonly used. The oldest lines use Steel Core Galvanised Zinc (SCGZ) cables. These are basically fencing wire and typically have 3 strands, each of 2.75 mm diameter (Olex, 2006). The DC resistance at 20 °C is 11 Ω. The zinc coating is very thin and it's thickness is not adequately specified and varies with age. As a result these lines are modelled as steel lines.

Most SWER lines have a high current backbone, which then feeds many lower current spurs. The newer spurs use Steel Core Aluminium Clad (SCAC) cables. Typically these cables have 3 strands, each of 2.75 mm diameter (Olex, 2006), with an aluminium area of 5.91 mm2 and a total area of 17.28 mm². The DC resistance at 20 °C is 4.8 Ω. The high power backbone typically uses Sultana (Olex, 2006) cables, which consist of 4 strands of Aluminium wires of 3 mm diameter around a galvanised steel core of 3 wires of 3 mm diameter. The DC resistance at 20 °C is 0.897 Ω. Since the conductivity of the steel is much less than the aluminium, these lines are modelled as pure aluminium conductors. Other power line conductor configurations are used in practice. They can be incorporated by simply specifying the correct wire diameter, the diameter of the whole conductor, the number of strands and for composite conductors, the area of Aluminium and the area of steel. In addition the conductivity and the permeability of the cable is also required. Those variables are listed at the start of the Matlab® program, the relevant ones for a SCAC conductor are as follows:

```
RhoC= 2.82e-8;      %resistivity of conductor 2.82e-8 for Al, 1.74e-7 for steel
RhoS= 30.0 ;     %resistivity of soil typical 30
DiaC= 2.75e-3;       %diameter of conductor strand in m for default 2.75mm
ALArea=5.91;        %Area of Aluminium in conductor SCAC
LineArea=17.82;      %Conductor Area SCAC
NSC=3;       %number of conductor strands default 3
DiaL=5.9e-3;   %Nominal Line Diameter m, 5.9 mm for SCGZ, SCAC
Er=4.5;       %Dielectric constant for the spacing between conductors. 4.5 for SWER from
measurements
RadC = DiaC/2.0;  %conductor radius for skin depth and resistance
RadL = DiaL/2.0; %Line radius for capacitance and inductance
Mu0=4.0*pi*1.0e-7;   %mu0 for free space
MuR=1.0;   % Mur=70 for steel (SCGZ), 1 for Aluminium (SCAC and Sultana)
MuC = Mu0*MuR;
Rdc = RhoC*1000.0/(NSC*pi*RadC*RadC);
RdcW = Rdc*LineArea/ALArea ;  %DC resistance of Aluminium part of the line.
```

For SCGZ conductors, the above values are changed to the SCGZ values. For SCGZ and pure aluminium conductors, the last line above is simply changed to:

```
RdcW = Rdc;  %DC resistance of Aluminium part of the line or Steel for a SCGZ line.
```

The Matlab® program uses these line parameters to calculates the skin depth using equation (10) and uses that together with equations (11) and (13) to determine the actual line resistance. The line inductance and characteristic impedance of the line is calculated using equations from (Johnson, 1950) and Carson's Depth equation (7) as needed. The transmission line impedance, is then used to determine the resistive losses of the transmission line and using equation (8) is used to determine the current flowing into the next elementary doublet. The relevant equations are:

```
SkinDepth = sqrt(2.0*RhoC/(twopi*Freq*MuC)); %Johnson 1950, pp 74
Rs = (sqrt(Rdc*Rdc*RadC*RadC/(4.0*SkinDepth*SkinDepth)+RdcW*RdcW));
   %Line resistance per km asymptote at actual DC resistance of line (RdcW).
Lr = 1.0/(sqrt(RadL*RadL/(4.0*SkinDepth*SkinDepth)+1)); % internal inductance
if FreeSpace == 'y'; %if 'y' Line in Free Space if 'n' line with groundplane or balanced
transmission line.
```

```
    RealZo = Mu0*c;    %Single line characteristic impedance in free space 376 ohm
  else
  if SWER == 'y';  %if 'y' SWER Line, use Carson for line separation, if 'n' have balanced line
      K1=2.0;  %for SWER K1=2 Line with Groundplane, like SWER line
      LineSep= 2.0*(h+sqrt(RhoS/(twopi*Freq*Mu0)));  %Carson's depth
      Cl = Er*K1/(36.0*log(LineSep/RadL));  %Line Capacitance nF/m SWER line
    else
      K1=1.0;  %for SWER K1=2 Balanced line.
      LineSep = 2.0*h;  %Line separation for differential line configuration
      Cl = Er/(36.0*log(LineSep/RadC));  %Line capacitance nF/m = uF/km Line in free
space
    end;
    Lkm = (4*log(LineSep/RadL)+MuR*Lr)/(K1*10);  %inductance (mH)/km
    Ckm = Cl*1000.0;  %line capacitance per km
    RealZo = sqrt(1.0e6*Lkm/Ckm);  % Real part of Z for resistive losses.
  end;
```

3.2 Radiated power

The evaluation of equation (6) is the core of the Matlab® program that is used to calculate the resulting E_θ fields for these cascaded line segments, using (2) to (3) and the intermediate equations shown in Reed & Kikkert, 2008. For a single line in space, the field is constant with respect to φ and equations (2) to (5) can be used to determine the radiation pattern and the radiated power. For a line above ground, equation (6) needs to be used and integration over both φ and θ need to be done. A 10 km line at 100 kHz is 3.33 wavelengths long and as shown in figure 1, has 14 main lobes.

Doubling the signal frequency, doubles the electrical length of the line and thus the number of lobes in the radiation pattern, and requires a halving of the angular interval for the determination of the radiated power for integrating equation (6) for E over θ and φ. In addition, the line has twice the number of elementary doublets, thus requiring 8 times number of calculations to be done. It is thus critical to get the optimum electrical line length for the elementary doublet and the optimum angular increment to obtain good accuracy, while minimising the number of calculations required. The initial work for this topic was done using a elementary doublet length of 0.01 λ or 0.1 km, whichever is the smallest, to ensure a high level of accuracy, so that for a 10 km line at 100 kHz, 299 line segments are used and at 100 MHz, 299980 line segments are used. For the results presented here the length for the elementary doublet is chosen to be 1/64 wavelength or 0.1 km, whichever is the smallest, since simulations showed that reducing the length below the 1/64 wavelength starts to affect the accuracy and 0.1 km is required since the printing of results are done at 0.1 km intervals. This then results in 200 elementary doublets for the line of figure 1.

The initial work for this topic was done at the 3600 angular intervals regardless of the signal frequency, to ensure that accurate fields were obtained for a 100 km long line at 100 kHz. It was found that one quarter of the number of elementary doublets used results in an accurate measure of radiated power, resulting in 50 angular intervals. The integration of the fields in the θ direction is done over the whole 0 to 360 degree region, and those in the φ direction only need to be done if from 0 to 90 degrees, due to symmetry. If the angular increment in the θ and φ directions are to be the same, then the number of angles is to be divisible by 4.
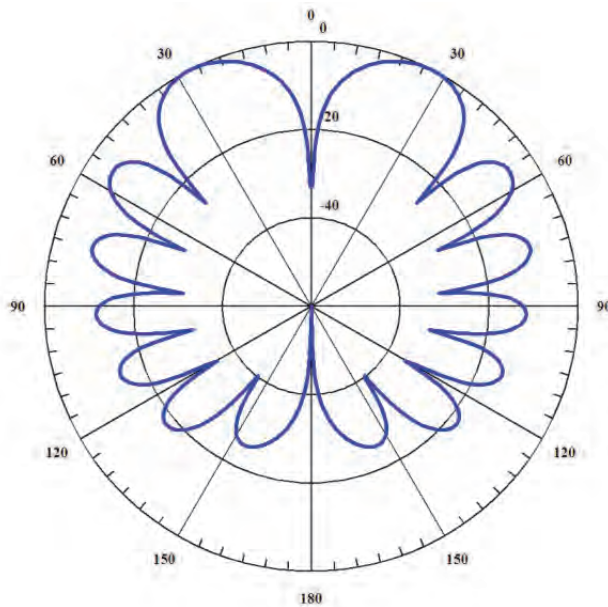
Fig. 1. Radiation pattern for 10 km long conductor in free space at 100 kHz.

As a result 52 angular intervals are required. This gives the same accuracy to 5 decimal places compared with 3600 angular intervals. To produce nice looking plots, as shown in figure 1, a minimum of 256 angles are used. The relevant code is shown below:

```
% N is the number of elementary douplets making up the
NumTh=4*round(N/16);   %number of angles per circle same as N by 4 as default.
if (NumTh > 3600) NumTh = 3600; end; %Limit to 0.1 degree.
if (NumTh < 256 ) NumTh = 256; end; %Limit to 256 for good looking plots
dtheta=twopi/NumTh;  %delta theta for a vector of angles and for integration 360 deg
```

For long power lines, the radiation pattern has many narrow lobes, as a result many angular intervals are required for the Matlab® evaluation of the radiation patterns. To avoid having to calculate sine and cosine for the same angles over and over again, these sine and cosine values are stored in an array, thus speeding up the calculations. This is done as follows:

```
% COMPUTE ANGLES, SINE OF ANGLES AND COSINE OF ANGLES
for angle=1:NumTh
    angles(angle)=dtheta*(angle-1) + 0.5*dtheta; %array of angles
    sinarr(angle)=sin(angles(angle));   %array of Sine used for both Theta and Phi
    cosarr(angle)=cos(angles(angle));   %array of Cos used for both Theta and Phi
end;
```

For a line in free space, this array is then used to calculate the cumulative E(θ) due to the elementary doublet length (dipL) having been added to E(θ) as shown below. This Esum(Theta) is the cumulative E(θ) and can then be used to calculate the cumulative radiated power as follows:

```matlab
for segment=1:1:N   %N is number of segments
   if I>0
      for Theta=1:1:NumTh    %Loop to consider all angles Theta 0-360
         Eed_M(Theta) = 60*pi*edL*I*sinarr(Theta)*sin(EedPhi);
      %Field of elementary doublet of length edL, eqn (6), complex variable.
      end;
      edL_Ph=twopi_edL*(segment-1);    %Phase of I in current edL segment.
      for Theta=1:1:NumTh    %Loop to consider all angles Theta
        E_RE(Theta)= cos(edL_Ph*(cosarr(Theta)-1))*Eed_M(Theta); % real E_ field
        E_IM(Theta)=-sin(edL_Ph*(cosarr(Theta)-1))*Eed_M(Theta); % imag E_ field
        Etp(Theta)=complex(E_RE(Theta),E_IM(Theta)); %Total E field
        Esum(Theta)=Esumd(Theta)+Etp(Theta); %Progressive sum
        Esumd(Theta)= Esum(Theta);   %store current value for next iteration
      end;
      % Calculate the radiated & dissipated power and attenuation
      PowerRadiated=0;
      for Theta=1:1:NumTh
        E_squared(Theta)= (real(Esum(Theta))*real(Esum(Theta)) +
          imag(Esum(Theta))*imag(Esum(Theta)))';
         PowerRadiated = (PowerRadiated +E_squared(Theta)*abs(sinarr(Theta))
            *dtheta)/240);   %Integration 360 deg, 240 = 4x60
      end;
      Pdiss = Pdiss + I*I*ResistperSegment;
      PdissN = Pdiss/Pin; %Resistive Loss, normalise wrt input.
        PRadN = PowerRadiated/Pin; %Radiated power, normalise wrt input.
      %calculate current at output of dipole.
      I2 = (Pin - PowerRadiated - Pdiss)/RealZo; %Current into next segment
      if I2>0
        I = sqrt(I2);
      else
        I = 0;  %No more current left all dissipated.
      end;
      AttenuationResulting = 20*log10(I/Io); %cumulative total attenuation of the line
      Pout = I*I*RealZo/Pin;
   end; %Exit if no current left.
  % more code writing to file, plotting etc.
end;
```

For a line above a ground plane, a 3 dimensional integration, with θ and φ must be made. Here the axis origin is at the groundplane and the maximum radiated field of the elementary doublet is perpendicular to the groundplane. The 3 dimensional field is calculated by adding another loop with a variable Phi, around the code for evaluation $E(\theta)$ as shown as follows:

```matlab
if I>0
  for Phi=1:1:NumPhi    %Loop to consider all angles Phi (0-90)
    for Theta=1:1:NumTh    %Loop to consider all angles Theta 0-360
    Eed_M(Theta,Phi) = 60*pi*edL*I*sinarr(Theta)*sin(EedPhi(Phi)); % eqn (6)
```

```
        end;
    end;
    edL_Ph=twopi_edL*(segment-1);    %Phase of I in current edL segment.
    for Phi=1:1:NumPhi    %Loop to consider all angles Phi (0-90)
    for Theta=1:1:NumTh    %Loop to consider all angles Theta
        E_RE(Theta,Phi)= cos(edL_Ph*(cosarr(Theta)-1))*Eed_M(Theta,Phi);  % real E
        E_IM(Theta,Phi)=-sin(edL_Ph*(cosarr(Theta)-1))*Eed_M(Theta,Phi); % imag E
      Etp(Theta)=complex(E_RE(Theta),E_IM(Theta));  %Total E field
        Esum(Theta,Phi)=Esumd(Theta,Phi)+Etp(Theta,Phi); %Progressive sum
        Esumd(Theta,Phi)= Esum(Theta,Phi);   %store current value for next iteration
      end;
    end;
    % Calculate the radiated & dissipated power and attenuation
    PowerRadiated=0;
    for Phi=1:1:NumPhi    %Loop to consider all angles Phi (0-90)
      for Theta=1:1:NumTh
        E_squared(Theta,Phi)= (real(Esum(Theta,Phi))*real(Esum(Theta,Phi)) +
          imag(Esum(Theta,Phi))*imag(Esum(Theta,Phi)))';
        PowerRadiated = (PowerRadiated + E_squared(Theta,Phi)*abs(sinarr(Theta))
          *dtheta)/240);        %Integration 360 deg 240 = 6x60
      end;
     if Phi == 1
          PowerRad2D=PowerRadiated; % same as for 2D plot.
      end;
    end;
     PowerRadiated=2*PowerRadiated*dtheta/pi; %note dtheta=dphi 3D radiated power
    RadN2D = PowerRad2D*(0.5+0.65*power(LineSepe,1.8))/Pin;
      % derived from 2D plot, same value
      % as 3D plot. allows 2D calculations to be used for lines with groundplane.
     Pdiss = Pdiss + I*I*ResistperSegment;
      PdissN = Pdiss/Pin; %Resistive Loss, normalise wrt input.
      PRadN = PowerRadiated/Pin; %Radiated power, normalise wrt input.
      %calculate current at output of dipole.
      I2 = (Pin - PowerRadiated - Pdiss)/RealZo; %Current into next segment
      if I2>0
          I = sqrt(I2);
      else
          I = 0;   %No more current left all dissipated.
      end;
      AttenuationResulting = 20*log10(I/Io); %cumulative total attenuation of the line
      Pout = I*I*RealZo/Pin;
  end; %Exit if no current left.
  % more code writing to file, plotting etc.
```

The 3D calculation for a 10 km SWER line with a 100 kHz PLC signal takes a few minutes on a fast PC. The same calculations for a 300 kHz PLC signal take several hours and the calculations for a 1 MHz PLC signal are expected to take several weeks, since less than 1% of the calculations were done overnight. It is thus nearly impossible to evaluate the fields from

long lines at high frequency. Since the separation between the line and the return path is far less than a quarter wavelength for signals below 1 MHz, and as a result the dependence of the E fields has little dependence on φ. The radiated power derived from the field along the line and perpendicular to the ground plane can be used as an accurate measure of the radiated power of the power line. The accurate 3 D radiated power was calculated for many different frequencies, line lengths and line heights above ground. As a result, the radiated power for all these variations can accurately be determined as follows:

PowerRadiated = PowerRad2D*(0.5+0.65*power(LineSepe,1.8));

PowerRad2D is the power obtained from the 2D field, LineSepe is the line separation in wavelengths. When the line separation is less than half a wavelength, the error due to the above approximation is better than 0.01%. A 2D calculation for the radiated power can thus be used reducing the calculation time by several orders of magnitude without loss of accuracy. The 3D radiated power is thus:

$$P_{rad}(\theta,\varphi)_{rms} = P_{rad}(\theta)_{rms} \times (0.5 + 0.65 * \left(\frac{2h}{\lambda}\right)^{1.8})$$ (18)

As a result of (18) the above Matlab® code can also be used for long lines above ground, or to find the radiation of overhead power lines with the PLC signals driven on two conductors in a balanced fashion.

The main Matlab® program is over 500 lines long, but only the core parts of the code have been described in this section.

4. Wobble

Figure 2 shows the field pattern from a 100 km long straight line, with the left figure being in free space and the right figure obtained from a SWER line 7 m above ground. The maximum gain for the free space line is 52.9 dB, while the maximum gain for the SWER line
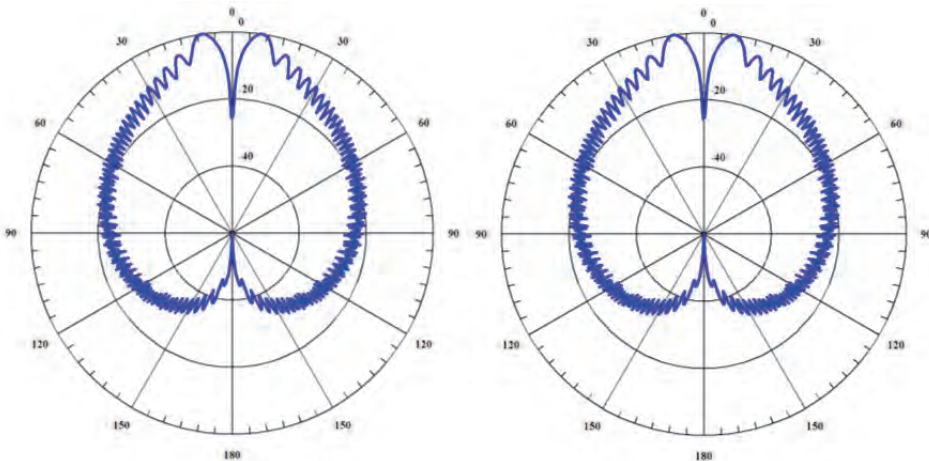
Fig. 2. Radiation Straight line, 100 kHz, 100 km long. Left free space, max gain 52.9 dB and Right SWER line max gain 21.6 dB.

is 21.6 dB. The radiation patterns look the same, so that the SWER line has 31.4 dB less peak radiated power than the free space line. The total radiated power from the SWER line is 32.4 dB less for the SWER line than the free space line.

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. Figure 3 shows the effect of the radiation loss as the change in line direction, called *wobble* in this paper, is varied every 0.1 km by a random angle with the standard deviation indicated. Figure 3 is for a 1 km long SWER line with a 1 MHz carrier frequency. If the wobble is comparable to the spacing between the side lobes, large changes in attenuation can result.

For the radiation results presented in the rest of this chapter, a 50 mrad wobble is used as that reasonably represents the power line geometry, has sufficient randomness and results in a sufficient increase in radiation, while avoiding the rapid changes in attenuation associated with a larger wobble. Including the wobble, results in a significantly increase in radiated power. The average results for figure 3 are obtained from 10 simulations at each value of wobble.
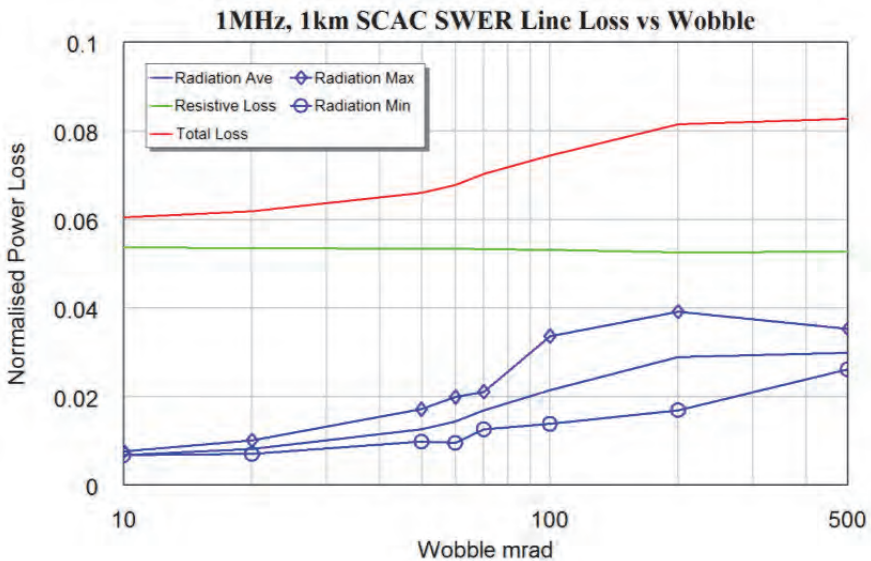
Fig. 3. Radiation loss of a SWER line with bends.

Figure 4 shows the radiated power for a line in free space and a SWER line when wobble is applied. The right graph of figure 2, shows the radiation patterns of a 100 km long straight SCAC SWER line with a 100 kHz carrier frequency, the right graph of figure 4 shows the corresponding radiation pattern of a SWER line with a 50 mrad wobble. The line with wobble has a 0.0415% radiation loss and the straight line has a 0.0118% radiation loss. The wobble will thus increase the radiated power by close to 4 times. The free space straight line has a radiation loss of 20.7%, while the line with wobble has lost all its input power after 90.5 km with a radiation loss of 60% and a resistive loss of 40%. Figure 5a shows these radiation losses versus distance for these four lines. It is interesting to note that for very long straight lines, the radiated power decreases as the line becomes longer. This is due to some

of the fields cancelling as new elementary doublets are added. Figure 5 shows that the wobble increases the radiated power significantly and on average, the radiated power keeps increasing as the distance increases. For short lines, less than 3 km, the lobes of radiation are broad and the wobble is small compared to the beamwidth, so that the straight line and the line with wobble result in virtually the same radiation. For long lines the wobble is comparable to or larger than the beamwidth of the radiation pattern lobes and the difference between the radiation from the straight line and the line with wobble becomes larger.
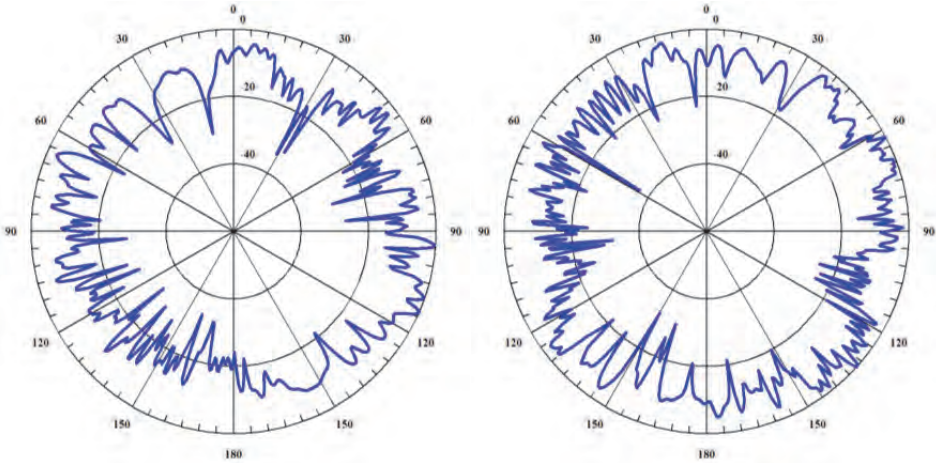
Fig. 4. Radiation line with 50 mrad wobble, 100 kHz, 100 km long. Left free space, max gain 49.8 dB and right SWER line max gain 18.4 dB.
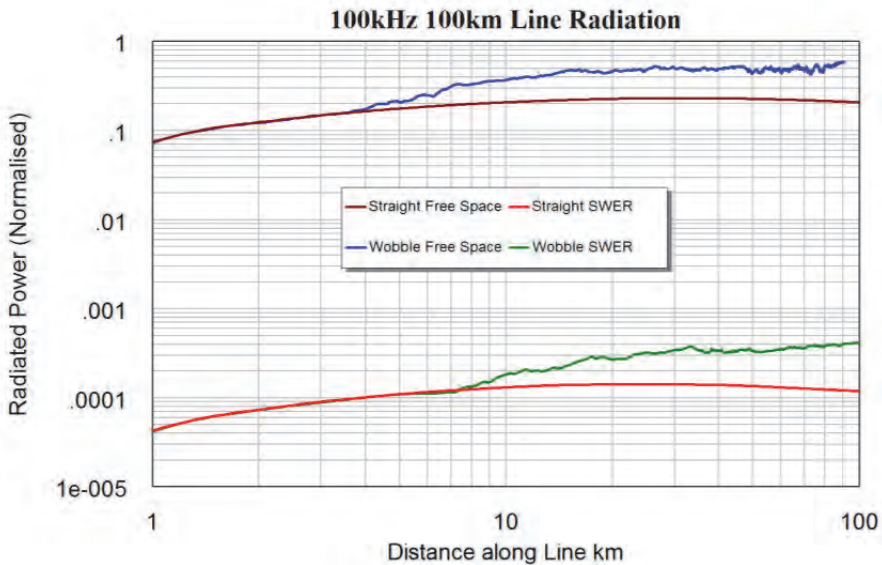
Fig. 5. a. Radiation loss for a 100 kHz signal on a 100 km long line.

Figure 5b shows the resistive loss corresponding to the radiation loss of figure 5a. Having a high radiation loss, results in a smaller current flowing along the line and thus less resistive (I^2R) losses. The radiation losses from SWER line are so small that the resistive loss with and without wobble is nearly the same.
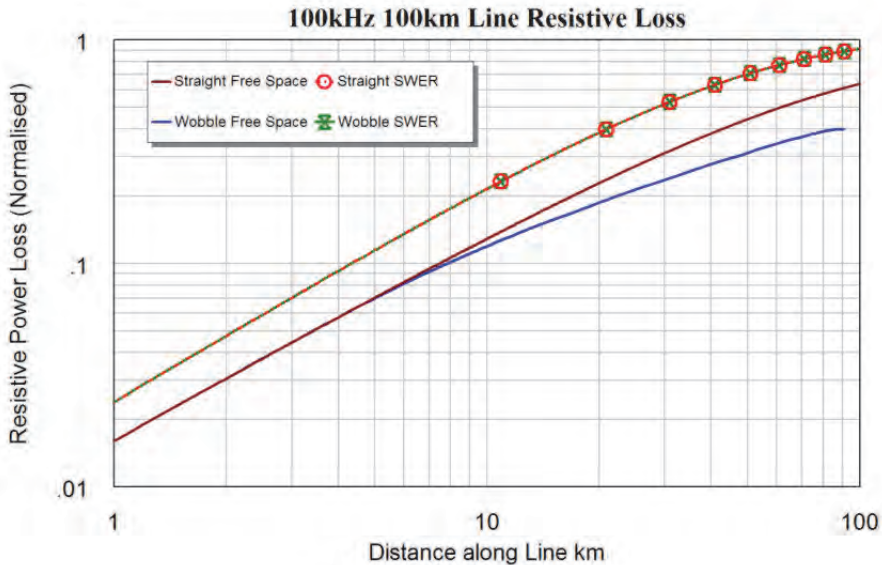
Fig. 5. b. Resistive loss for a 100 kHz signal on a 100km long line.

5. Results

5.1 SWER Lines

The first line type for which results are presented is a 3/2.75 SWER line consisting of either an aluminium clad steel (SCAC) or a galvanised steel (SCGZ) cable with three 2.75 mm diameter strands. The SWER line is typically 7 m above ground with the earth return distance varying according to equation (7). The author has made measurements on an 18 km long SCGZ SWER line SWER line (Kikkert & Reid 2009) at Mt Stewart station, 100 km west of Charters Towers in North Queensland, Australia. A comparison between the SWER line measurements and the results from the model presented here, using equations (7) to (17) and including the ground pad and earth return path resistance is shown in figure 6. It can be seen that there is a remarkable agreement, thus verifying the schematic model of the line using equations (7) to (17) and the corresponding Matlab® code in section 3.1.

The parameters for a 3/2.75 SCGZ SWER line obtained from the Matlab® program are shown in figure 7. The line resistance increases significantly with frequency. The earth return path depth (7) varies from close to 2 km at 10 Hz to 16 m at 10 MHz. Due to the current being carried in the steel conductor for SCGZ lines, the inductance varies with frequency. For aluminium or copper conductors, the internal inductance of equation (14) is negligible, so that the inductance is mainly governed by the external inductance. For steel conductors, with μ_r typically being 70, the internal inductance is larger, so that the

inductance changes significantly with frequency. As a result of both of these effects, the characteristic impedance of the SWER line varies from 565 Ω at 50 Hz to 270 Ω at 100 kHz.
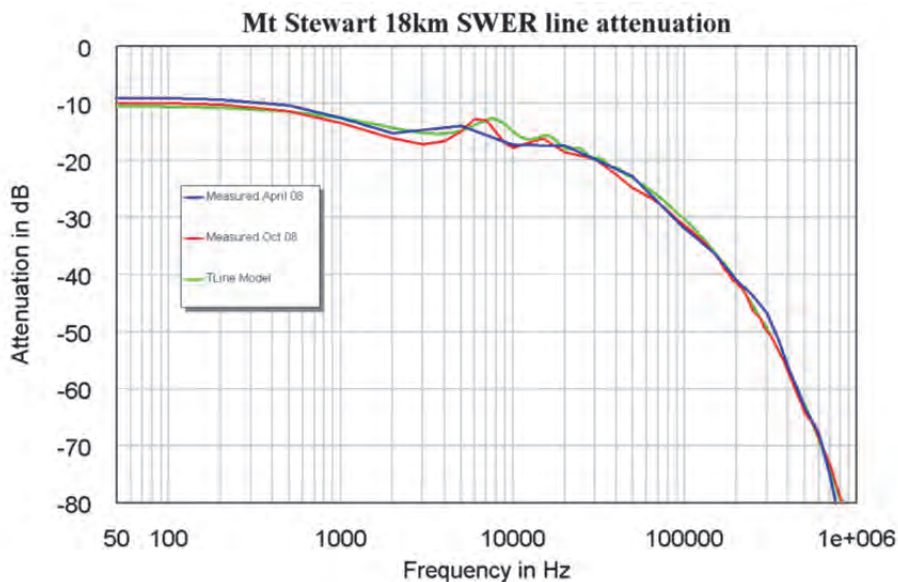

Fig. 6. Measurements and model comparison.

Figure 7 also shows the radiated power, expressed as a resistance. Below 300 kHz, the radiation is negligible, but at 5 MHz the same power is lost in radiation as in resistive losses. The radiation losses increase proportionally to the frequency[2.77]. Figure 8 shows the same plots for a SCAC conductor. Comparing figures 7 and 8 shows that the corner frequency where the line resistance starts to increase is much lower for the SCGZ conductors.

The parameters for a 3/2.75 SCAC SWER line obtained from the Matlab® program are shown in figure 8. The line resistance increases significantly with frequency. Despite the earth return path depth (7) varying from close to 2 km at 10 Hz to 16 m at 10 MHz, the characteristic impedance of the SWER line only varies from 344 Ω at 50 Hz to 258 Ω at 100 kHz. Figure 8 also shows the difference between the resistance of the line of it were a pure Aluminium line and the resistance of the SCAC line. Above 1 MHz all the current is carried in the Aluminium cladding. Figure 8 also shows the radiated power, expressed as a resistance. Below 300 kHz, the radiation is negligible, but at 1.5 MHz the same power is lost in radiation as in resistive losses. Equation (18) shows that the radiation losses increase proportionally to the frequency raised to the power 2.77. Comparing figures 7 and 8 show that the resistive losses of the SCGZ line are much higher than the SCAC line.

Figure 9 shows the line losses for a 3/2.75 SCGZ SWER line. For frequencies below 1 MHz, the radiation losses are very small in comparison to the resistive losses. For a to 10 km line and 100 kHz, the radiated power is 0.008% and for lower frequencies it is smaller. As a result radiation is negligible for all CENELEC-A (9 kHz to 95 kHz) frequencies. The resistive losses for SCGZ lines are such that for a 70 km SWER line a 33 dB attenuation results. This is still well below the typical dynamic range of PLC modems.
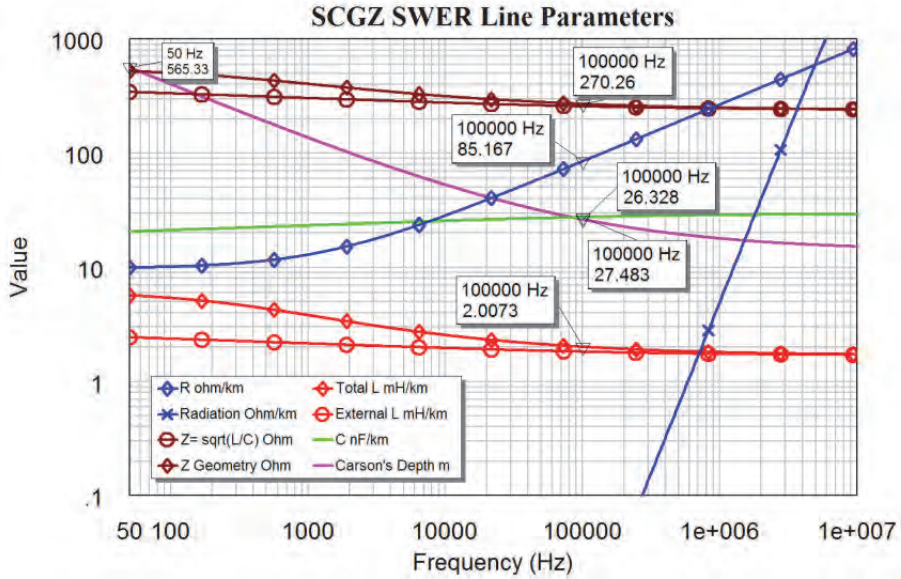
Fig. 7. Steel Core Galvanized Zinc (SCGZ) conductor per km transmission line parameters.
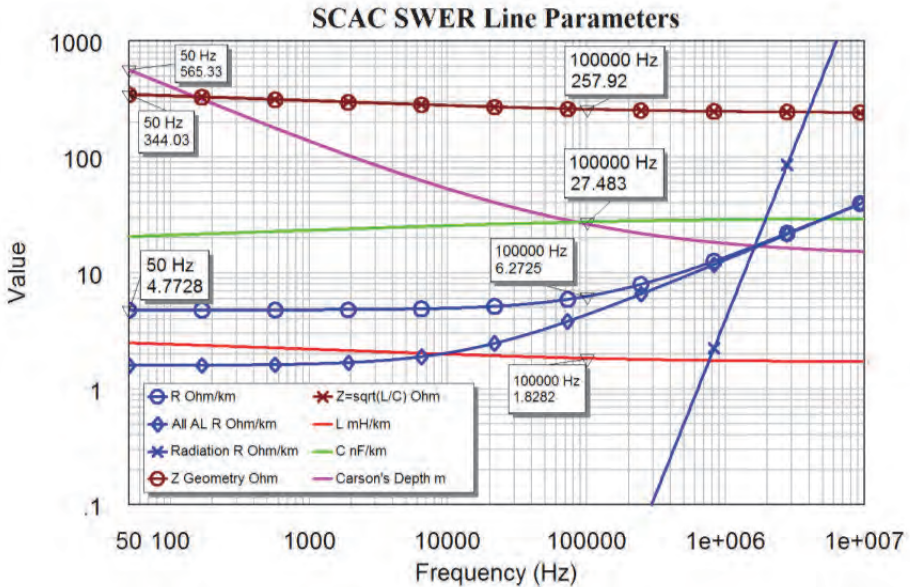

Fig. 8. Steel Core Aluminium Clad (SCAC) conductor per km transmission line parameters.

Figure 10 shows the corresponding line losses for a 3/2.75 SCAC SWER line. Comparing figures 9 and 10, show that for a 3/2.75 SCAC line the resistive losses are much lower. The

radiation losses are the same, but the resistive losses are significantly smaller. A 300 km SCAC SWER line at 100 kHz has a 37 dB attenuation, similar to that of a 70 km SCGZ line.
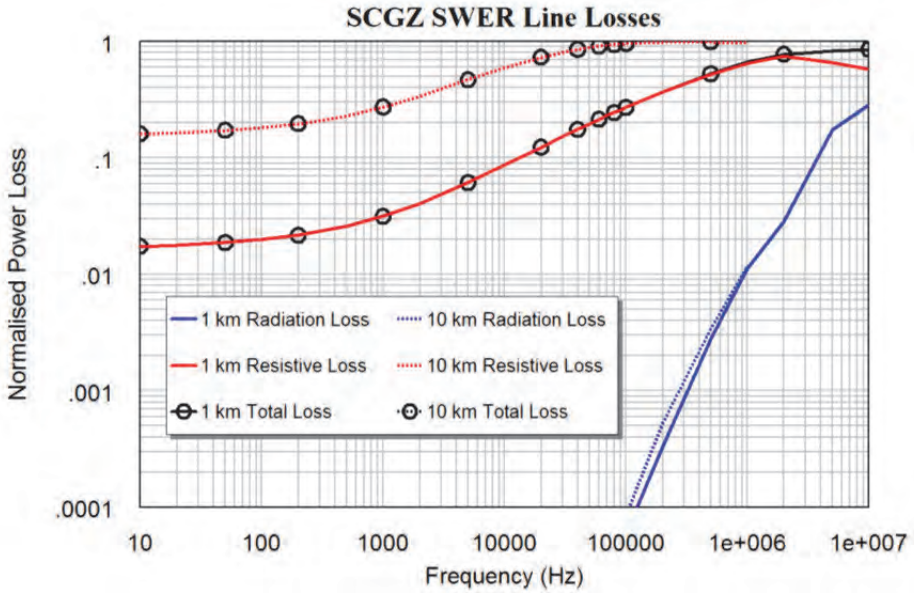
Fig. 9. SCGZ SWER line losses versus frequency.
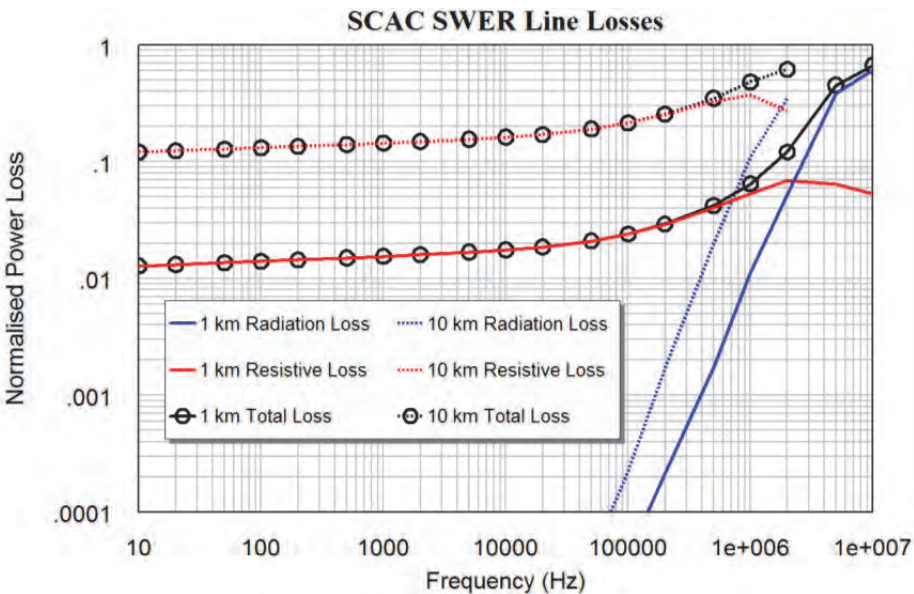
Fig. 10. SCAC SWER line losses versus frequency.

5.1.1 SWER line radiation resistance

The Matlab® program described in this chapter, prints the calculated normalised cumulative radiation and resistive losses every 100 m along the SWER line. Taking the difference between these cumulative results and averaging these for a line length of 30 km or when the total losses are less than half the input power, whichever is the shorter distance, allows a per km radiation resistance to be determined as a function of frequency. To ensure that the SWER line configuration is identical as the frequency is varied using different Matlab® program runs, the seed for the random wobble is initialised to the same value at the start of each run. Figure 11 shows the resulting radiation resistance for SCGZ and SCAC conductors for a SWER line 7 m above ground and a 50 mrad wobble every 100 m. Despite the resistive losses being very different, the per km radiation losses are nearly the same. Figure 11 also shows a least square error fit as follows:

$$R_{rad} = 1.35 \times 10^{-16} \times Frequency^{2.77} \quad \Omega / km \tag{19}$$
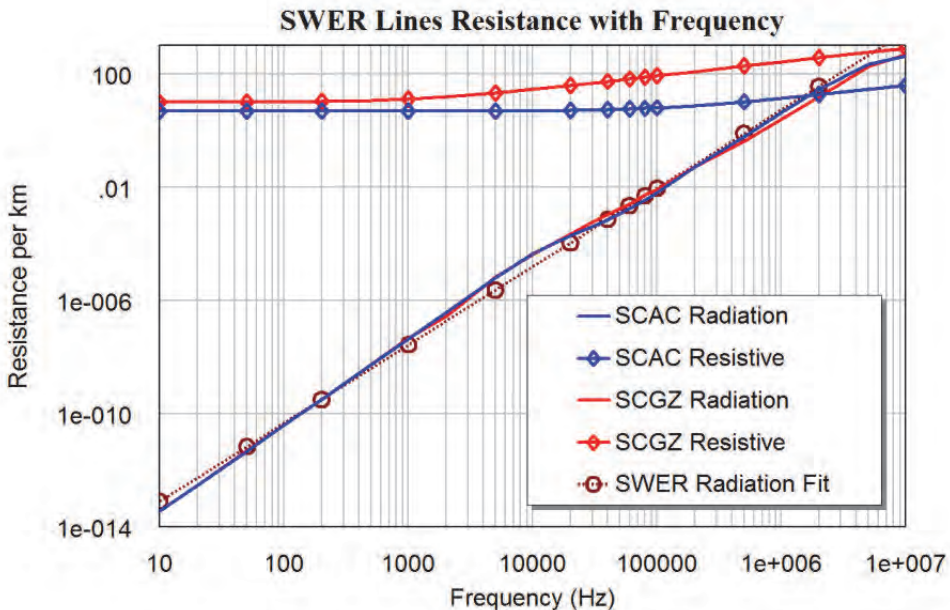

Fig. 11. SCAC SWER line resistances versus frequency.

Figure 11 shows that despite the coefficients of equation 21 being non-integer values, equation (19) gives a good approximation of the results obtained by the Matlab® program. At high frequencies, the radiation losses become quite high and within a short distance, all the input power is lost in resistive and radiation losses.

Figures 10 and 11 shows that for SCAC SWER line at 2 MHz, the radiation losses are equal to the resistive losses. For larger frequencies the radiation losses increase rapidly, causing a very high line attenuation. Since PLC transmissions by Electricity Utilities use frequencies below 150 kHz, figures 7 to 11, show that such PLC transmissions will not cause any

interference as the radiated power is very small. However figures 7 to 11 show that SCAC SWER lines, SCGZ SWER lines and MV or LV three phase overhead power lines, where one phase is used for PLC and the earth path is used for the return path, are unsuitable for communication signals above 500 kHz, as the radiation losses will be significant, so that interference to other services in the MF band such as AM broadcast transmissions, may occur.

5.2 Overhead lines mounted on a crossarm

The second type of transmission line considered in this paper is the typical traditional open wire low voltage overhead (LVOH) line consisting of four All-Aluminium Conductor (AAC) cables each with 7 strands of 4.75 mm diameter mounted on a crossarm. 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. The results presented here are for a set of wires with a 550 mm spacing, which is typical in Australia for the outer sets of 240 V LVOH conductors on a crossarm.
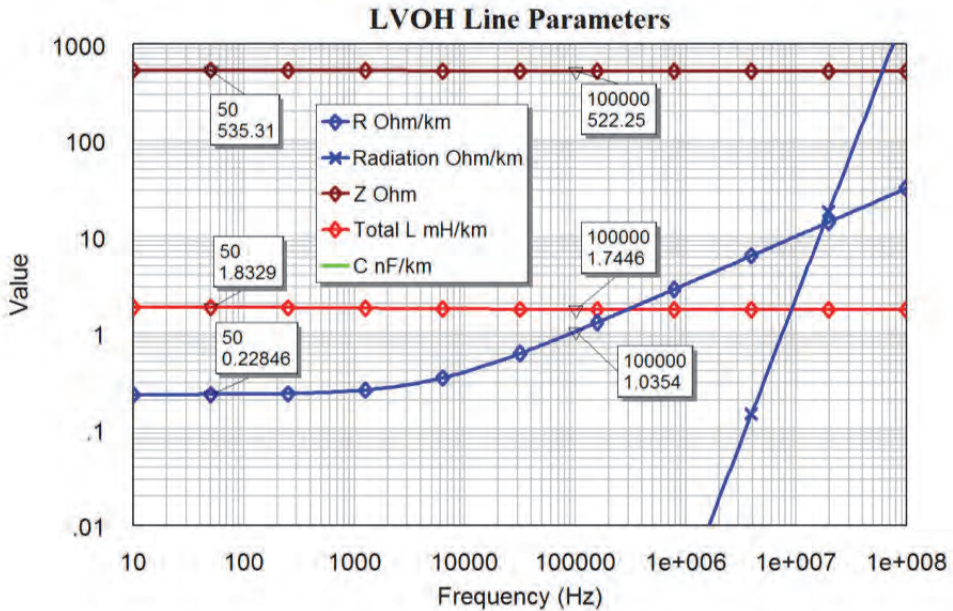

Fig. 12. LV overhead line on crossarm parameters versus frequency.

The parameters for the overhead line are shown in figure 12. The characteristic impedance of the line is 522 Ω and is virtually independent of frequency. There are only small variations of line inductance and capacitance with frequency. The plot for radiation in figure 12 corresponds to equation (20) and the OHL radiation curve fit in figure 14. For PLC applications, the signal is coupled onto these lines in a differential manner, and no ground return is used. Figure 13 shows that, the radiation losses of this line are much less than that of the SWER line.

Figure 14 shows the radiation and line resistance versus frequency for OHL and ABC lines as obtained from the Matlab® program described in this chapter. The least square error fit for frequencies above 1 kHz for OHL on crossarm conductors is:
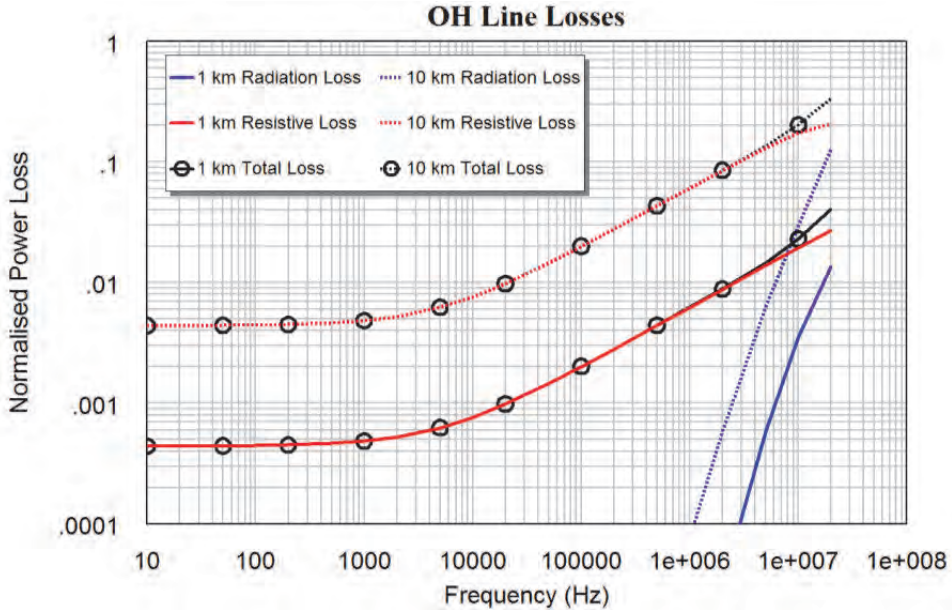

Fig. 13. LV overhead line line on crossarm losses versus frequency.

$$R_{rad} = 2.38^{-21} \times Frequency^3 \quad \Omega \, / \, km \tag{20}$$

The radiation resistance and the line resistance are the same at just above 20 MHz, so that these lines can be used at more than 10 times the frequency of SWER lines. If the PLC signal is coupled onto the all three phase lines in a common mode, i.e. the PLC signals is coupled onto all the lines in-phase, the neutral line is not connected to the PLC signal and the ground is used for a return path, then similar radiation losses to SWER lines are obtained. For a 10 km line, at 2 MHz, less than 0.05% of the input power is radiated and the line can thus be used for transmitting communication signals at those frequencies.

Broadband over Power Lines (BPL) uses signals in the frequency Range 525 kHz to 80 MHz. Field trials (ACMA 2007, ACMA 2009) have been carried out in Australia. The tests at Queanbean (ACMA2009) used frequencies in the range of 2.5 MHz to 22.8 MHz. Figure 13 shows that at 20 MHz and a 1 km line length, 15% of the power is lost in radiation while 25% is lost in resistive losses. BPL is thus not a suitable system to be used on LVOH lines. PLC signals using the CENELEC A band of 35 to 95 kHz for smart metering can be applied on these lines without any significant interference to existing radio services.

5.3 Aerial bundled conductors

The final type of transmission line considered is an Aerial Bundled Conductor (ABC), consisting of four insulated, compacted aluminium cables grouped together with common insulation. Each conductor is made up of 19 strands, 2.52 mm in diameter. Each compacted
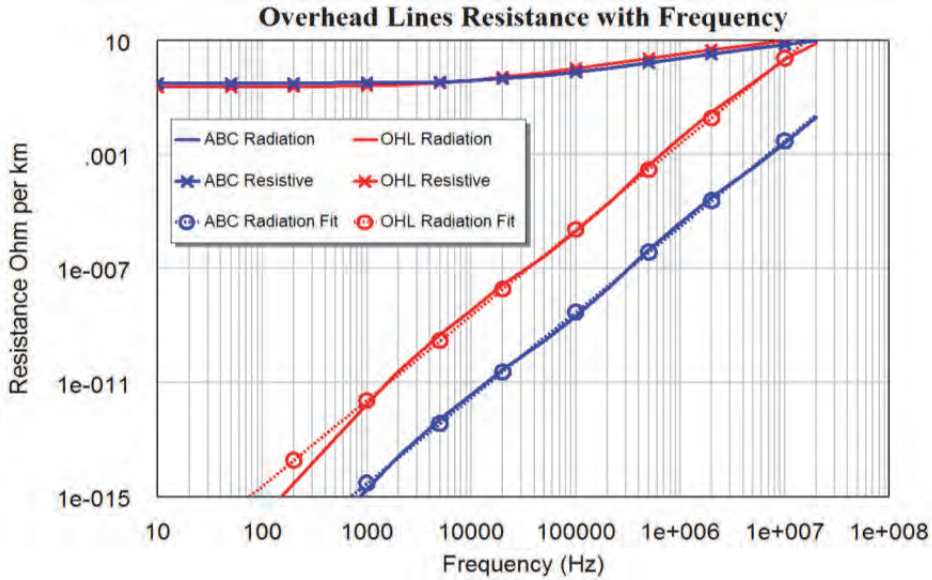
Overhead Lines Resistance with Frequency

Fig. 14. LV overhead line resistances versus frequency.

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, 2008). The parameters of this line is shown in figure 15. The radiation resistance shown in figure 15 corresponds to equation (21) and the least curve fit for ABC in figure 14. For ABC lines, this corresponds to:

$$R_{rad} = 3.0^{-24} \times Frequency^3 \quad \Omega / km \qquad (21)$$

Comparing equations (19), (20) and (21), shows that for OHL on crossarm and ABC liones, the radiation resistance increases with the third power of frequency, while for SWER lines the radiation resistance increases with the frequency raised to the power 2.77. The difference is due to the earth return path and thus the effective line separation for SWER lines changing with frequency as shown by Carson's equation (7). Because the effective line separation is much larger for SWER lines, the radiation from SWER lines is much larger than those for the OHL and ABC lines.

Figure 16 shows the losses for ABC conductors for 1 km and 10 km ABC lines. The corresponding figures for the SWER and OHL on crossarm conductors are figures 9, 10 and 13. Comparing these figures show that ABC conductors have very little radiation.

Comparing the resistive, conductor, losses for OHL on crossarm and ABC conductors in figure 14, shows that at low frequency ABC conductors have a higher resistance than OHL on crossarm conductors but at high frequencies ABC conductors have a lower resistance. This is because the ABC conductors have 19 strands in the conductor, while the Moon conductor (Olex, 2008) used for the OHL on crossarm conductor has 7 strands. As a result the skin effect is less severe for ABC conductors. The calculations presented here have not considered that the 19 strands of the ABC conductors are compressed and that this will reduce the conductor surface available at high frequencies and thus increase the line resistance above the value calculated. Unfortunately the extent of this increase is not presented in any cable manufacturer's catalogue, since the main application for these lines is at 50 or 60 Hz.
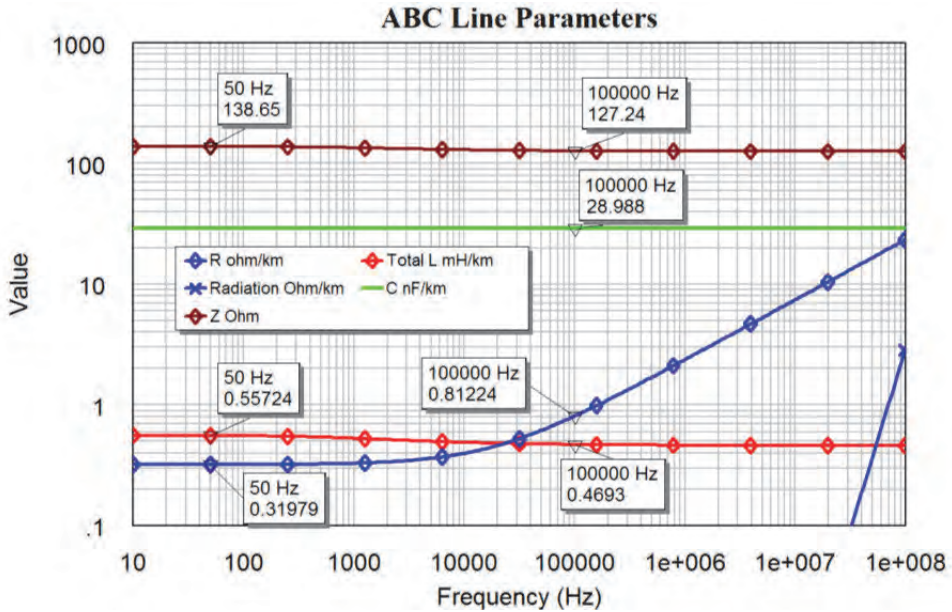
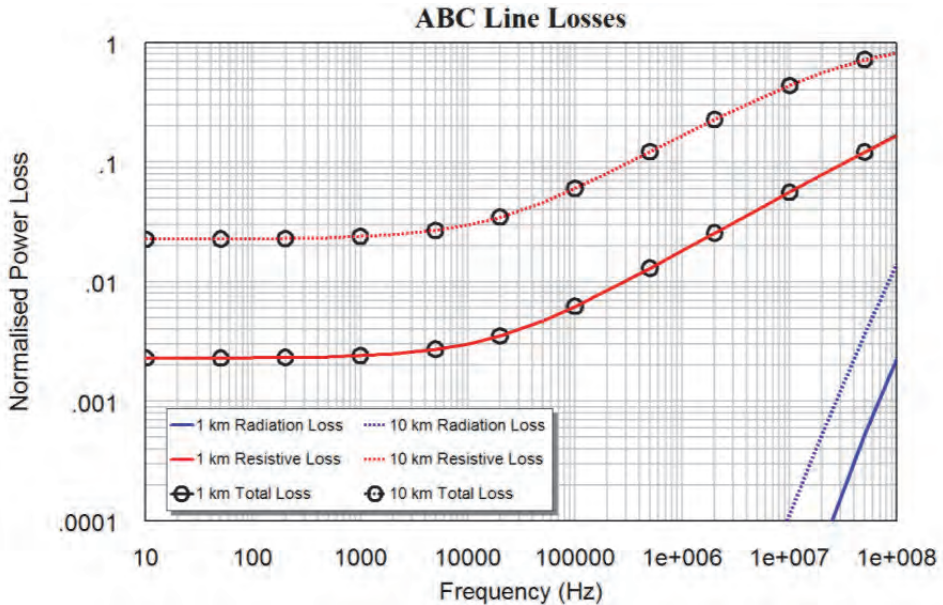Fig. 15. Aerial Bundled Conductor line parameters versus frequency.

Fig. 16. Aerial Bundled Conductor line losses versus frequency.

Figure 16 shows that for frequencies below 100 MHz, the radiation losses are less than 2% of the input power. However the resistive losses are such that for frequencies above 20 MHz,

all the input power is lost before the end of a 30 km line. The low level of radiation losses will ensure that no significant interference to other services will occur. ABC lines can thus be used for transmitting BPL signals at frequencies up to 100 MHz, however the resistive losses prevent great distances being reached.

Similar results will apply for underground cables, where all the active conductors are bundled together in one cable. BPL can thus safely be used on ABC lines and underground cables. The success of BPL on those lines will primarily depend on economic rather that technical matters.

PLC signals using the CENELEC A band for smart metering can be applied on these lines without any significant interference to existing services.

6. Conclusion

The radiation from power lines cannot be determined from expressions from long wire antennae, since those expressions assume that the signal current in the power line is constant, the power line is straight and its length is less than 5 wavelengths. None of these assumptions are true for powerlines and as a result the radiation patterns and the radiated power must be determined from first principles using a Matlab® program. This program can be used to determine the radiated power from both SWER lines and overhead power lines where the PLC signals are coupled to 2 lines in a differential mode.

The results presented here show that SWER line result in little radiation for frequencies below 100 kHz, typical overhead lines mounted on a crossarm have little radiation for frequencies up to 2 MHz and bundled conductors have little radiation at frequencies up to 100 MHz.

All lines can thus be used for the 9-95 kHz CENELEC A frequency band to permit PLC communication for smart-metering and network control. Conventional overhead lines mounted on crossarms will cause significant interference levels for signal frequencies above 2 MHz and should not be used for BPL. Bundled conductors, ABC and underground, can be used for BPL applications, with little radiation, but with significant resistive losses at high frequencies.

7. Acknowledgment

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