# Radiation from a Single Wire Earth Return Power Line

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***Abstract*—It is desirable to use existing Single Wire Earth Return (SWER) lines for data communication as well as transmitting power in remote areas. The radiation losses of the SWER line to the communication signal is a critical system design parameter. The traveling wave model of a long wire antenna assumes firstly that the antenna is a small number of wavelengths long and secondly that the currents along the line are constant, so that no power lost in radiation. For practical Single Wire Earth Return (SWER) power lines which can be hundreds of kilometers long these assumptions are not valid. The model presented here overcomes these limitations.**

***Index Terms*—Power-line, Single Wire Earth Return, SWER, Travelling Wave Antenna, Power Line Communications.**

## I. INTRODUCTION

Single Wire Earth return (SWER) lines are used in many remote areas of Australia. These lines are typically several hundred kilometres long and service rural properties. A SWER line with its many branch lines covers hundreds of square kilometres. At the farm, cattle or sheep station, the 19.1 kV or 12.7 kV of the SWER line is transformed to 240 V for distribution around the farm. It would be highly desirable to be able to send control signals along these SWER lines for meter reading, load management, transmission system integrity verification, demand side management and many other control or monitoring functions require communications [1],[2].

In order to investigate the feasibility of using the SWER line for communications, the radiation losses of the SWER line to the communication signal needs to be determined. The travelling wave model of a long wire antenna [2], [3] assumes that the antenna is a small number of wavelengths long and assumes the currents along the line to be constant. This implies that no power is lost in radiation. Practical data carrier frequencies could be up to tens of MHz and with typical SWER lines being several hundred km long, the existing radiation model for long wire antennae is not valid. The radiation model presented here overcomes these limitations and allows the radiation from any long wire antenna to be determined.

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## II. TRANSMISSION LINE RADIATION MODEL

The power radiated for an infinitesimal dipole is described in most antenna books [3, 6, 7]. The model presented in this paper uses this infinitesimal dipole model and cascades many of these to make up the whole transmission line. The model calculates the radiation pattern from each dipole making up the transmission line and includes the attenuation of the current flowing in the line as a result of the radiation and series resistance. The sum of the fields generated by all these segments is then integrated over a spherical surface to find the total power radiated. The radiated power per km of line can then be determined for inclusion into a SWER line parameter model, as shown in Fig. 1, which incorporates the line resistance, inductance and capacitance and so develop a frequency response for a long transmission line.

The power radiated by a dipole in the far field k >> 1 is dependent on the current in that dipole, $I_o$

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

However, because the line is long, $I_o$ will not be constant. Three factors affect $I_o$:

$I_o$ is reduced by dissipation due to series resistance
$I_o$ is altered in phase, along the line
$I_o$ is reduced because power is radiated in previous sections

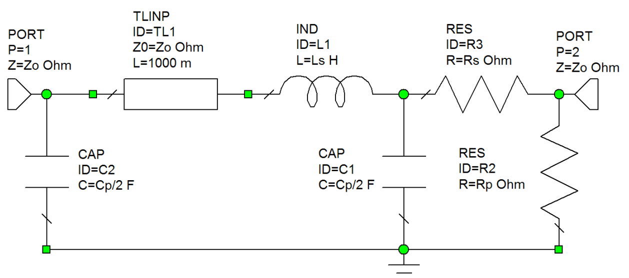


Fig.1. SWER line per km model. This is an early model and further work is required to refine it.

Fig. 1 shows the per km model of a SWER line, where the line inductance is $L_s$ and the line capacitance is $C_p$. To facilitate the cascading of these sections, and match the model with the actual line as much as possible, a constant value of characteristic impedance is used. This requires the total losses, consisting of the radiated power $P_{rad}$ and the power due to the resistance of the line $P_{res}$ to be modelled as an L section consisting of the series resistance $R_s$, together with a shunt resistance $R_p$. The resistive line losses and the radiation losses are both incorporated in both $R_s$ and $R_p$. If there are no radiation losses, then $R_s$ and $R_p$ are constant for each section. As can be seen from figs. 2 and 3, the radiated power per km varies depending on the total length of the line, as a result, $R_s$ and $R_p$ need to be varied, to accurately represent the losses of each line section, whilst maintaining correct characteristic impedance of the SWER line model. Due to the losses, the current flowing into the next section of the per km line model is:

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

The phase of the current in a segment changes along the line according to a general pattern for le (electrical length in the direction of wave travel, along the line) and he for separation between the lines:

$$I_{ph} = I_{in} \exp(jkx) \qquad (3)$$

where $k = 2\pi/\lambda$ and $x$ is either length or height in meters.

The power radiated by a single dipole segment ($l$) is found by integrating the Poynting vector over a closed surface, chosen to be a sphere of radius r.

$$W_t = \frac{1}{2}\mathrm{Re}\left( \oiint_s E_\theta \times H_\phi ds \right) \qquad (4)$$

where for the far field:

$$E_\theta = \frac{j\eta_0 k I_0 l e^{-jkl} \sin(\theta)}{4\pi r} \qquad (5)$$

$$H_\phi = \frac{jkI_0 l e^{-jkl} \sin(\theta)}{4\pi r} \qquad (6)$$

where $\eta_o = 120\pi$ and $k = 2\pi/\lambda$

For a dipole in free space, the inner integrand is independent of $\phi$, a constant of $2\pi$ can be brought out:

$$\mathrm{P}_{rad} = \frac{\pi}{\eta_0}\int_0^\pi \left|E(\theta)\right| r^2 \sin(\theta) d\theta \qquad (7)$$

The total power radiated by many segments is the result of a vector summation of the fields due to all the sections, for each value of the angles in both $\theta$ and $\phi$. For a line in free space, there is no variation of field in the $\phi$ direction, simplifying that integration. Each line segment making up the total line has a different current flowing in it, since some of the current is reduced due to radiation and resistive line losses.

We cannot use standard equations for the radiation from travelling wave antennas, as they assume that the current in the line is constant, rather than being attenuated due to radiation and resistive losses as is the case for long lines. Matlab is used to calculate the resulting $E$ field for a cascaded number of line segments, using equations 1 to 5 and the model of fig. 1. The typical length of each line segment is 0.02 λ, so that for the 300 km line and a 100 kHz carrier frequency of fig. 2, 5005 line segments are used in the calculation. For most of the results presented in this paper, the summation of the fields is carried out at 400 angles for the 180 degree variation of $\theta$. Since the current amplitude decreases and changes in phase, the Matlab model builds the radiation pattern cumulatively by increasing the length of the line by one segment at a time, calculating the current in that new segment and then calculating the resulting radiation pattern from the radiation pattern before this segment was added.

### *A. Verification of the Radiated Power of the Matlab model*

Balanis [2] indicates that the maximum segment size for an infinitesimal dipole in our model should be smaller than 0.02 λ as this is the maximum size for an infinitesimal dipole if the error between the ideal and actual is to be small. As a result, in our simulations, the length of the line segment is 0.02 λ is used for the long line simulations.

The number of angles used in the surface integration for calculating the radiated power can be varied. A coarse angular step size increases the speed of the computations but result in errors, particularly for long transmission lines as shown in fig. 2. It was found that 400 angles results in a sufficient accuracy for any SWER line less than 100 wavelengths long, corresponding to a 300 km line with a 100 kHz carrier frequency. Most of the results in this paper are calculated using 400 angles. Increasing the number of angles past 400, significantly increases the computational time and changes the results by less than 0.001 dB for line lengths up to 100 λ.

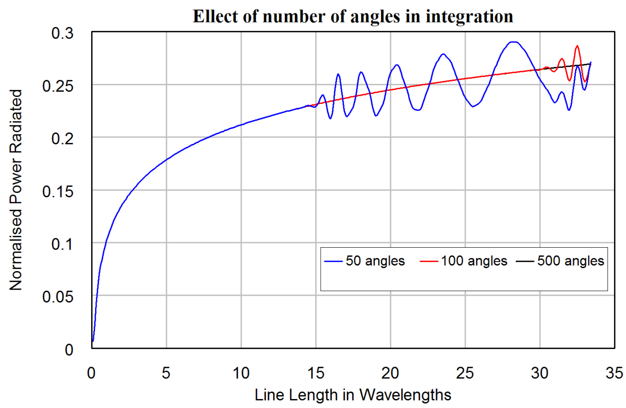


Fig. 2. Radiated power variations, due to angular spacing in spherical integration.

To verify the accuracy of the radiation model, the results produced by it was compared with known results. The conditions used in the model were set to be the same as those for the known equations, to ensure that a fair comparison is made. The results in tables I and II are normalised with respect to input power. Table I shows the power radiated by the line when the current in each line segment has the same amplitude and phase, as shown in the equations on page 137 of Balanis [2], and compares this with our Matlab model operating under the same conditions. These conditions are not physically possible, since the radiated power is many times greater than the input power, but the results verify the accuracy of our model.

TABLE 1 NORMALISED RADIATED POWER FIXED CURRENT, NO PHASE CHANGE

| λ (le) | JCU results Power Radiated dB | Balanis [2] results Power Radiated dB |
|---|---|---|
| 1 | 0.6286 | 0.6286 |
| 1 | 2.5145 | 2.5145 |
| 5 | 15.7159 | 15.7159 |
| 10 | 62.8637 | 62.8637 |
| 20 | 251.4549 | 251.4549 |
| 50 | 1571.5931 | 1571.5931 |
| 100 | 6286.37722 | 6286.37722 |

When the line current has a constant amplitude, but the phase is changed due to the signal travelling along the wire at the speed of light, the results presented in table II are obtained. These conditions correspond to standard long wire antenna equations. Again there is a very good agreement between the results from the JCU model and the results from Balanis. It can be seen that allowing the signal current to be a travelling wave, significantly reduces the radiated power. Since the current reduces in the full model, less radiation is expected from an actual SWER line. These results do incorporate resistive losses in the SWER line.

TABLE 2 RADIATED POWER FIXED CURRENT, PHASE CHANGE (INPUT =1)

| λ (le) | JCU Power Radiated | Balanis [2] Power Radiated |
|---|---|---|
| 1 | 10.1049% | 10.0660% |
| 2 | 13.3942% | 13.3772% |
| 5 | 17.7650% | 17.7544% |
| 10 | 21.0753% | 21.0656% |
| 20 | 24.3863% | 24.3768% |
| 50 | 28.7634% | 28.7640% |
| 100 | 32.0746% | 32.0652% |

Fig. 3 shows the resulting signal attenuation due to radiation on a SWER line in free space. These calculations do not include the effect of the ground. Since that produces an image current which opposes the line current, the radiation in an actual SWER line will be less than the free space mode. However since the return current varies with frequency and for a SWER line that is 8 m above ground at 50 Hz is typically 900 m below is ground, it is difficult to include the ground effect into the model at this stage.

For 100 wavelengths, table 2 gives a 1.68 dB radiation attenuation without current reduction. When the reduction of signal current and resistive losses are taken into account, the top blue line of fig. 3 shows 0.89 dB radiation attenuation at 100km. The red line is the attenuation due to the resistive dissipation alone. At 100 km, this is 3.03 dB and is more than the radiation. The black line is the total attenuation resulting from both radiation and resistive dissipation and is 5.05 dB at 100 km. Fig. 3 shows that for short lines radiation is the dominant loss factor, while for long lines the resistive losses dominate.

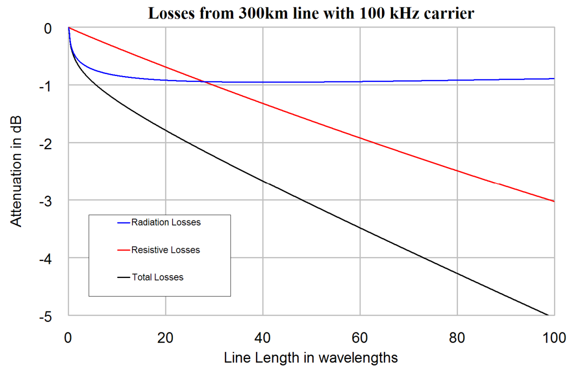


*Fig. 3. Attenuation due to radiation for a 100 kHz signal on a SWER line in free space. (100 wavelengths = 300 km).*

Fig. 3 shows that the radiated power does not increase much after 20 wavelengths. If there are no resistive losses, then the radiated power will increase monotonically, as shown in table II, however with resistive losses and a decreasing current amplitude caused by the resistive and radiated losses, the total radiated power will be nearly constant when the SWER line is longer than 42 λ. The peak power density in the main lobe of the radiation pattern will continue to increase as can be seen from the radiation patterns in Fig 4 to 6.

## *B. Radiation Patterns of the Matlab Model*

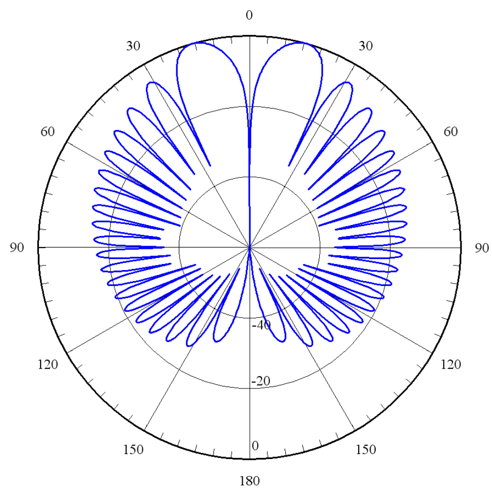


Fig. 4. Radiation pattern from 10 λ (30 km at 100 kHz) line with 500 segments. This plot shows 40 lobes as for a traveling wave.

In order to verify the Matlab model further, the radiation patterns obtained from the transmission line are determined. To allow these to be compared with typical radiation patterns for travelling wave antennae, a free space radiation model, with no ground effects, is used. These radiation patterns use the full radiation model and include typical resistive losses of SWER line conductors and include the reduction in current due to radiation and resistive losses. The velocity of propagation of the current along the line is assumed to be that of the speed of light.

The radiation pattern for 10 λ in fig. 4 shows the correct number of lobes, that is, 20 on either side as predicted by Balanis. The line length is increased in figs. 5 to 7. These figures show that as the line length increases, the number of lobes increases, although they cannot always be counted as they begin to merge into one envelope. These results agree with the radiation patterns obtained from long wire antennae in that the radiation patterns show a main lobe at a slight angle to the direction of travel of the input signal and there is a significant front to back ratio.

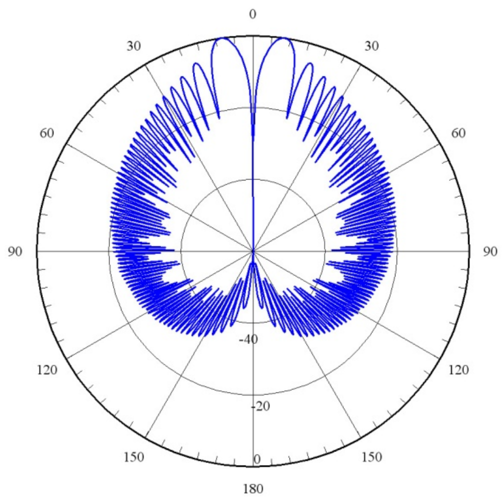


Fig. 5. Radiation pattern from 33.4 λ (100km at 100kHz) line with 1670 segments.

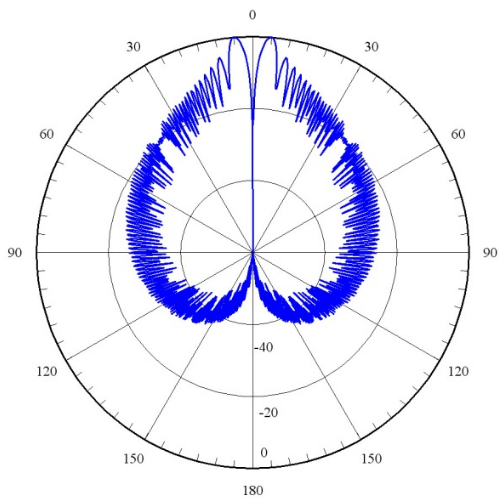


Fig. 6 Radiation pattern from 100.1 λ (300km at 100kHz) line with 5005 segments.

## III. Conclusions

A Matlab® model has been developed (with SWER lines as the expected application). The results presented here for a line in free space shows a relatively small amount of radiation due to long transmission lines. Less radiation will occur when the effect of the ground plane is taken into account, so that the radiation from a SWER line is fairly small. The model allows frequency, distance above a ground plane and segment size to be selected according to processing resources available.

The radiation model has shown that the power radiated is proportional to the log of the distance.

At this stage mutual coupling [2] between the segments is not yet included, however it is expected that this has a small contribution.

These results do show that it should be possible to develop a communication system that can use SWER lines for the transmission medium.

## IV. Acknowledgements

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