Propagation Characteristics of Power Line Communication Signals Along a Power Cable

N. Okazima, Y. Baba, N. Nagaoka, A. Ametani, K. Temma, T. Shimomura

***Abstract*--The propagation characteristics of power line communication (PLC) signals along a single-core power cable having two 3-mm thick semiconducting layers are studied using the finite difference time domain (FDTD) method for solving Maxwell's equations. It turns out that a PLC signal of frequency 30 MHz suffers significant attenuation particularly when the conductivity of the semiconducting layers is around σ=0.001 and 1000 S/m, while it suffers little or less attenuation when σ is lower than about 10^{-5} S/m or σ is around 1 S/m. The mechanisms of the significant attenuation around σ =0.001 and 1000 S/m are discussed.**

***Keywords*: attenuation, finite difference time domain methods, power cable, power line communications, semiconducting layers.**

I. INTRODUCTION

Recently, considerable attention has been attracted to the power line communication (PLC). It uses power transmission/distribution lines and cables as a medium for data communications in a frequency range up to 30 MHz. Since the power lines and cables are not designed for effectively transmitting such high frequency signals, these signals might attenuate significantly along the lines and cables [1][2].

Steinbrich [3] has shown, experimentally and theoretically with his distributed-circuit representation for a single-core cable having semiconducting layers, that PLC signals of a frequency range up to 30 MHz attenuate significantly (about 4 dB/100 m at 30 MHz) along a 20-kV crosslinked polyethylene insulated (XLPE) cable. Note that this XLPE cable includes semiconducting carbon-polyethylene compound layers of conductivity 17 S/m and semiconducting carbon-filled paper layers of conductivity 0.05 S/m. Also note that semiconducting layers are usually incorporated between the core of a power cable and the insulating layer, and between the insulating layer and the sheath conductor, in order to prevent from discharging even if there are unexpected projections on the surfaces of the core and sheath, and also to accommodate the thermal expansion of the insulating layers.

On the other hand, Cataliotti et al. [4] have shown experimentally that the attenuation of PLC signals of a frequency range from 0.025 to 0.20 MHz along a power cable with semiconducting layers is not much significant (about 1 dB/km at 0.2 MHz), and the measured attenuation constant variation within this frequency range is reasonably well reproduced by their simplified equivalent circuit representation that neglects the presence of the semiconducting layers.

It appears from the above experimental results that power cables with semiconducting layers cause significant attenuation only for signals of frequencies above mega hertzs. In this paper, using the finite difference time domain (FDTD) method [5] for solving Maxwell's equations in the two-dimensional (2D) cylindrical coordinate system (e.g. [6]), the propagation characteristics of a PLC signal of frequency 30 MHz along a single-core power cable having two 3-mm thick semiconducting layers are studied. For the conductivity of the semiconducting layers, a wide range from 10^{-5} to 10^{5} S/m is considered, although the conductivity of actual semiconducting layers is known to range roughly from 10^{-5} to 10^{2} S/m.

II. REPRESENTATION OF A POWER CABLE

Fig. 1 shows the cross-section of a 130-m long single-core power cable, to be analyzed using the FDTD method. The radius of the core is set to 5 mm, and the inner radius of the sheath conductor is set to 25 mm. Both the core and the sheath conductor are perfectly conducting. Between the core and the 14-mm thick insulating layer of relative permittivity of 3, and

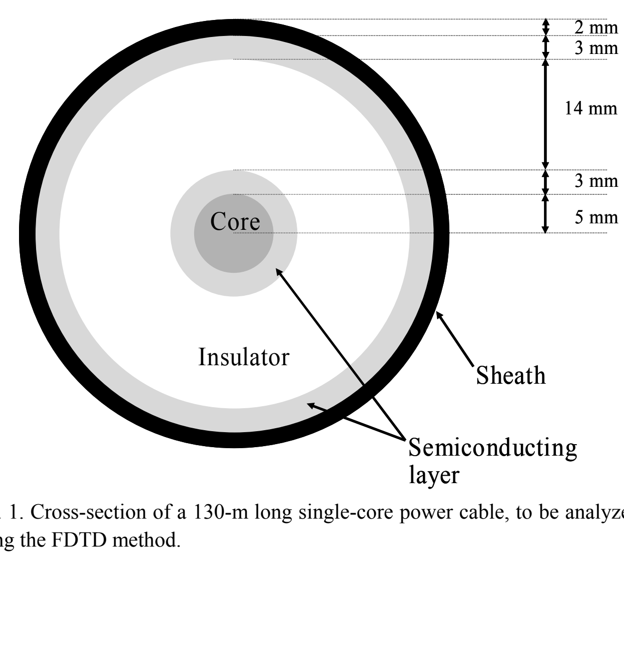

Fig. 1. Cross-section of a 130-m long single-core power cable, to be analyzed using the FDTD method.

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between the insulating layer and the sheath conductor, 3-mm thick semiconducting layers are installed, respectively. The relative permittivity of the semiconducting layers is set to ε_r=3. The semiconducting-layer conductivity is set to a value in a range from σ=10^{-5} to 10^5 S/m in the present study.

At one of the ends of the cable, a 10-V single wave, which is the positive half cycle of a sine wave of frequency f =30 MHz, is applied between the core and the sheath conductor. The other end of the cable is connected to the Liao's second-order absorbing boundary [7]. The working space of 130 m × 27 mm for the FDTD computation is divided into 1 mm × 1 mm square cells. The time increment is set to 4 ps.

III. Analysis and Results

Figs. 2 (a), (b), (c), (d) and (e) show waveforms of the voltage between the core and the sheath conductor at different distances of 20, 40, 60, 80 and 100 m from the excitation point when the frequency is f =30 MHz and the semiconducting-layer conductivity is σ=10^{-5}, 10^{-3}, 1, 10^3, and 10^5 S/m, respectively. Fig. 3 shows the dependence of the propagation speed of a 30-MHz signal on σ. Fig. 4 shows the dependences of the magnitude of the voltage between the core and the sheath conductor at different points on σ.

It appears from Figs. 2 and 3 that the magnitude of a voltage pulse decreases with increasing propagation distance in all cases considered. However, the dependence of attenuation on σ is not monotonous: attenuation is significant around σ =10^{-3} and 10^3 S/m, while it is not when σ is lower than about 10^{-5} S/m or σ is around 1 S/m. When σ=10^{-3} S/m and 10^3 S/m, dispersion is also marked.

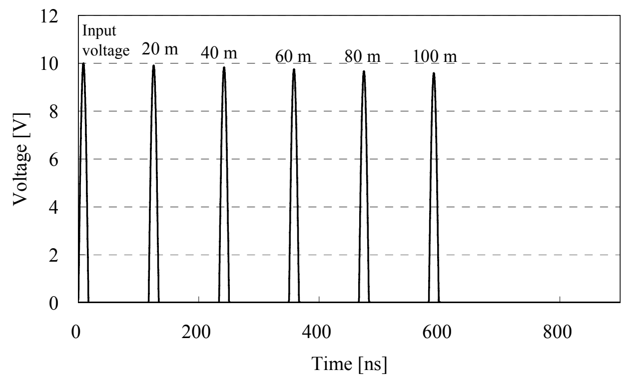
IV. Discussion

A. Dispersion

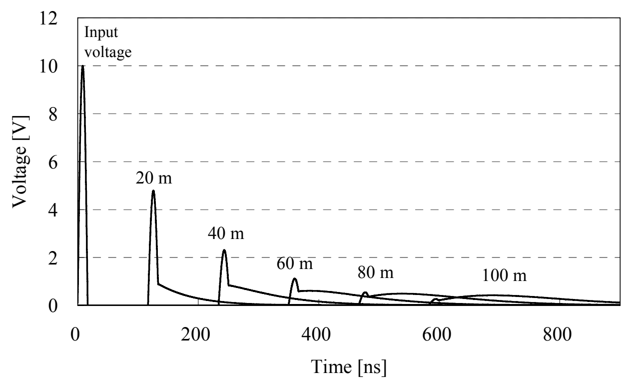
It appears from Fig. 2 (b) that a voltage pulse suffers marked dispersion for σ=10^{-3} S/m. The reason for this marked dispersion or prolonged wavetail is probably due to discharging of the semiconducting layers. The time constant of the layer is given by

$$\tau = CR = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(r_2/r_1)}\frac{\ln(r_2/r_1)}{2\pi\sigma} = \frac{\varepsilon_0\varepsilon_r}{\sigma}, \qquad (1)$$

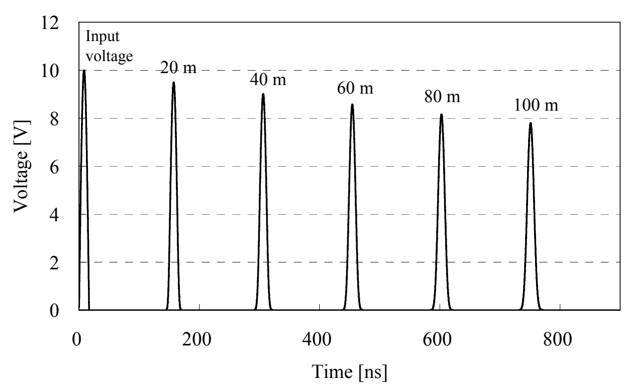
where C is the per-unit-length capacitance of a semiconducting layer, R is its radial-direction per-unit-length resistance, r_2 is the outer radius of the semiconducting layer, r_1 is its inner radius, ε_0 is the permittivity of vacuum, ε_r is the relative permittivity of the semiconducting layer, and σ is its conductivity. For ε_r = 3 and σ=10^{-3} S/m, the time constant is τ =27 ns, which is close to the half cycle (17 ns) of a 30 MHz signal. On the other hand, when σ =10^{-5} and 1 S/m, the time constants of the semiconducting layer are τ =2700 ns and 0.027 ns, which are much different from the half cycle of the 30 MHz signal. Therefore, discharging process of the semiconducting layer is not observable for these cases.



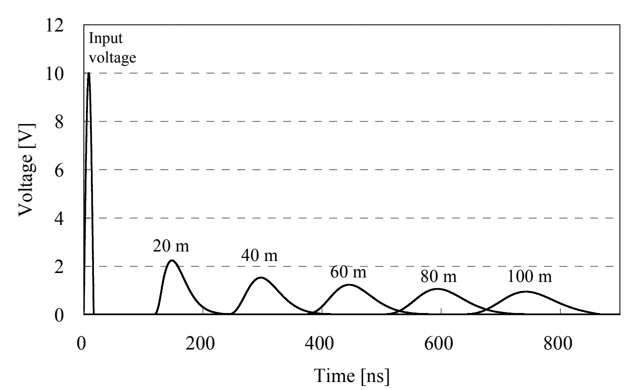
(a) σ=10^{-5} S/m



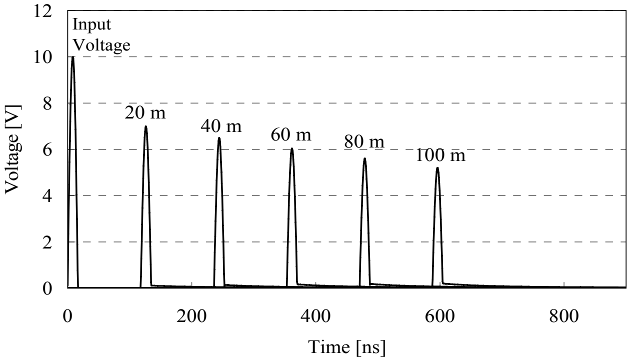
(b) σ=10^{-3} S/m



(c) σ=1 S/m



(d) σ=10^3 S/m



(e) $\sigma = 10^5$ S/m

Fig. 2. Waveforms of the voltage between the core and the sheath conductor at different distances from the excitation point when the signal frequency is f =30 MHz and the semiconducting-layer conductivity is σ =10^{-5}, 10^{-3}, 1, 10^3, and 10^5 S/m.

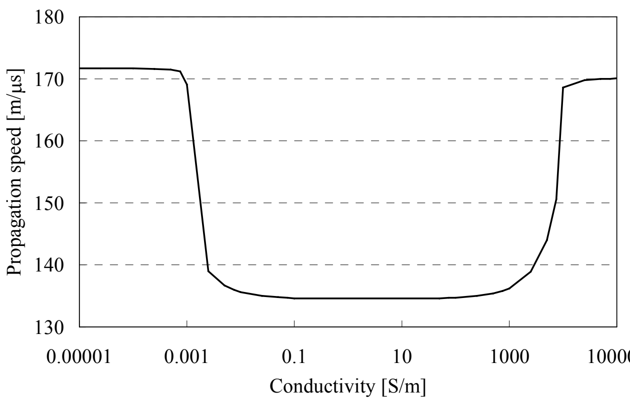


Fig. 3. Dependence of the propagation speed of a 30-MHz signal on the semiconducting-layer conductivity σ.

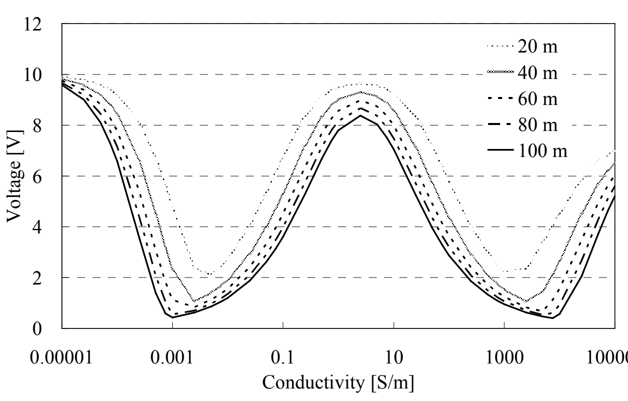


Fig. 4. Dependences of the magnitude of the voltage between the core and the sheath conductor at different points on the semiconducting-layer conductivity σ.

It is clear from Fig. 2 (d) that a voltage pulse suffers dispersion for σ=10^3 S/m. The reason for this dispersion is that the axial current propagates in the lossy semiconducting layers since the penetration depth (2 mm) for f = 30 MHz and σ=10^3 S/m is close to the thickness of the semiconducting layer (3 mm). This will be discussed further in III. C.

B. Propagation Speed

From Fig. 3, the propagation speed of a 30-MHz signal is about 170 m/μs when σ is lower than about 10^{-4} S/m. This is almost equal to the theoretical speed (300/√3 =173 m/μs) of a wave propagating in a lossless medium of relative permittivity 3.

When σ ranges from 10^{-2} to 10^2 S/m, the propagation speed is about 135 m/μs, which is lower than the propagation speeds for $\sigma < 10^{-4}$ S/m and $\sigma > 10^4$ S/m. The reason for this lower speed (135 m/μs) is discussed below. The index of the skin effect is given by penetration depth (e.g. [8]), d, which is

$$d = \frac{1}{\sqrt{2\pi f \sigma \mu_0}}, \tag{2}$$

where μ_0 is the permeability of the semiconducting layer. Equation (2) yields d=65 mm for f = 30 MHz, σ=1 S/m (middle of a range from 10^{-2} to 10^2 S/m), $\mu_0=4\pi\times10^{-7}$ H/m. Since this penetration depth is larger than the thickness of each semiconducting layer (3 mm), the axial current propagates mainly along the surface of the core and the inner surface of the sheath conductor, and the magnetic field energy is stored between the surface of the core and the inner surface of the sheath conductor. The corresponding inductance is, therefore, given by $L'=\mu_0 \ln(25/5)/(2\pi)$. Since the time constant of the 1-S/m semiconducting layer is τ =0.027 ns from (1), charge would move radially from the surface of the core to the outer surface of the inner semiconducting layer, and from the inner surface of the sheath conductor to the inner surface of the outer semiconducting layer immediately. Therefore, electric field energy is stored in the insulating layer, and the corresponding capacitance is given by $C'=2\pi\varepsilon_0\varepsilon_r/\ln[(25-3)/(5+3)]$. From L' and C', the corresponding propagation speed is given by

$$v' = \frac{1}{\sqrt{L'C'}} = \sqrt{\frac{2\pi}{\mu_0 \ln(25/5)} \frac{\ln(22/8)}{2\pi\varepsilon_0\varepsilon_r}} = 132 \text{ m/}\mu\text{s}, \tag{3}$$

which agrees well with the FDTD-calculated propagation speed (135 m/μs).

When σ is higher than 10^4 S/m, the propagation speed is about 170 m/μs. In this case, the semiconducting layers act as good conductors. Therefore, both magnetic and electric energies are stored in the insulating layer, and the propagation speed is equal or close to 173 m/μs (=300/√3).

C. Attenuation

It is clear from Figs. 2 and 4 that the dependence of attenuation on the seminconducting-layer conductivity σ is not monotonous: the attenuation is significant for σ=10^{-3} and 10^3 S/m, while it is not when σ is lower than about 10^{-5} S/m or σ is around 1 S/m. In the following, the reasons why significant attenuation occurs around σ=10^{-3} and 10^3 S/m are discussed.

When the conductance of the semiconducting layer $G=1/R=2\pi\sigma/\ln(r_2/r_1)$ is equal to its suceptance $S=2\pi fC=2\pi f\, 2\pi\varepsilon_0\varepsilon_r/\ln(r_2/r_1)$, the magnitude of the conduction current propagating in the radial direction across the layer is equal to that of the displacement current. The relation can be written more simply by

$$\sigma = 2\pi f \varepsilon_0 \varepsilon_r . \tag{4}$$

Equation (4) yields $\sigma=5\times10^{-3}$ S/m for $\varepsilon_r=3$ and $f=30$ MHz, which is close to 10^{-3} S/m. Therefore, the reason for the significant attenuation of a 30-MHz signal around $\sigma=10^{-3}$ S/m is due to the propagation of the conduction current across the lossy semiconducting layers.

A high-frequency conduction current tends to propagate near the surface of a conductor, which is called skin effect. Equation (2) yields a penetration depth, d=2 mm, for $f=30$ MHz, $\sigma=10^3$ S/m, $\mu_0=4\pi\times10^{-7}$ H/m. This is close to the thickness of the semiconducting layer, 3 mm. Therefore, the axial conduction current flows in the lossy semiconducting layers because of the skin effect. This is the reason for the significant attenuation of a 30-MHz signal around $\sigma=10^3$ S/m.

V. CONCLUSIONS

The propagation characteristics of a PLC signal of frequency $f=30$ MHz along a single-core coaxial cable having two 3-mm thick semiconducting layers have been studied using the FDTD method for solving Maxwell's equations in the 2D cylindrical coordinate system. It has become clear that a PLC signal suffers significant attenuation particularly when the semiconducting-layer conductivity σ is around 10^{-3} and 10^3 S/m. Therefore, it is quite difficult to conduct power line communications in a system having a power cable with semiconducting-layer conductivity of about $\sigma=10^{-3}$ or 10^3 S/m. The reason for the significant attenuation of a 30-MHz signal around $\sigma=10^{-3}$ S/m is that the conduction current propagates across the lossy semiconducting layers since the conductance of the semiconducting layer is almost equal to its suceptance for this conductivity of the semiconducting layers. The reason for the attenuation around $\sigma=10^3$ S/m is that axial conduction current flows in the lossy semiconducting layers because a penetration depth (2 mm) for $f=30$ MHz and $\sigma=10^3$ S/m is close to the thickness of the semiconducting layer (3 mm).

VI. REFERENCES

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