Effect of High Frequency Cable Attenuation on Lightning-Induced Overvoltages at Transformers

Li-Ming Zhou, *Senior Member, IEEE* and Steven Boggs, *Fellow, IEEE*

Abstract: The high frequency attenuation of XLPE and EPR cables differ substantially. The absorption of high frequency energy between the cable termination at an overhead line and cable-connected transformers can reduce substantially lightning-induced turn-to-turn overvoltages at the top of the transformer primary winding. This is especially true when the lead lengths of the arrester across the cable termination are longer than desirable, resulting in greatly increased lightning induced voltages across the cable termination. The computed data presented in this paper indicate that the arrester lead length, lightning rising time, the type of cable, and the length of cable have substantial impact on the overvoltage to which a transformer is subjected and the voltage across the top few turns of the transformer winding. The greater high frequency losses of EPR cable can increase substantially the risetime of lightning induced overvoltages. This results in much lower overvoltages in the first few turns of distribution transformers connected to the underground cable.

Key Words: Distribution cable, power cable, surge overvoltages

I. INTRODUCTION

Fast transients in power systems can be generated by lightning impulses and switching of devices such as vacuum, air or SF_6 insulated interrupters [1]. In the case of lightning-induced overvoltages in distribution systems, the ultimate overvoltage in the absence of an arrester would be the same as in a transmission system, meaning very large relative to the BIL of the distribution system. Lightning current risetimes range from 0.1 µs to many µs. Gapless ZnO arresters limit the voltage early into the rise, which means at very short times. Thus a 40 kA lightning current waveform with a risetime of 0.2 µs can result in a voltage waveform across the arrester with a risetime of only 20 ns. In addition, the effect of arrester leads, typically with a total length (sum of high voltage and ground connection conductors) in the range of 1 to 3 m (3 to 10 ft) long, can increase the initial voltage across the cable termination by several times, from the range of 40 kV with no leads to 250 kV with 3 m (10 ft) total lead length (Figure 1). As a result of these phenomena, a distribution cable connected to an overhead distribution circuit may see transient waveforms in the range of 25 pu (relative to peak AC line-to-ground voltage) with risetimes in the range of 100 ns. In the absence of high frequency cable attenuation, these short risetime, large amplitude transients can cause a large voltage across the first few turns of a transformer winding, leading to turn-to-turn failure.

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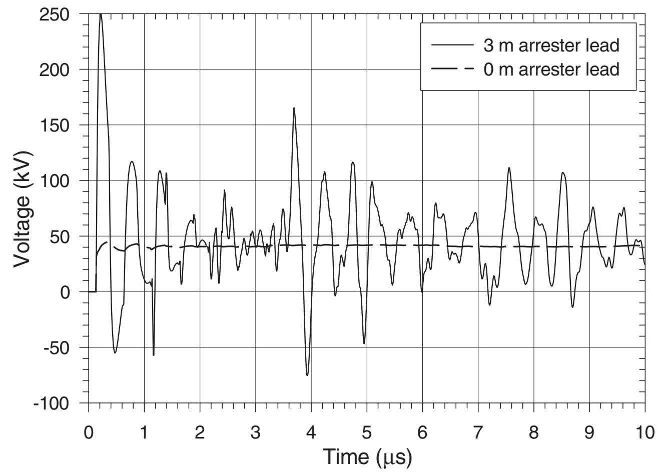

Figure 1. Waveform across the right-branch cable input for the configuration shown in Figure 2 for a 15 kV overhead line to cable connection at a riser pole. The lightning current was 40 kA with a risetime of 0.2 µs. The arresters are gapless. Data are shown for 0 and 3 m arrester lead lengths.

As seen in Figures 2-4, high frequency cable attenuation can reduce the amplitude, but more importantly, the rate of rise (dV/dt) of lightning and switching induced transients as a function of distance propagated down the cable, extending the transient risetime by absorbing high frequency energy, thereby reducing the turn-to-turn voltage at the top of the transformer windings connected along the cable. EPR cable, which has much greater high frequency attenuation than XLPE, is more effective in protecting cable-connected transformers from the effects of lighting surges. In the present work, we have modeled the distribution circuits shown in Figure 5 which were provided by a local utility, and we have computed the voltage across transformers and the transient voltage across the top 10% of the transformer windings. The effects of ZnO arrester lead length, lightning current rising time, the type of cable (TR-XLPE or EPR cable) and the length of cable were evaluated using the ATP-EMTP program. The distribution transformers were modeled as shown in Figure 6.

II. CABLE ATTENUATION

The attenuation of shielded power cable is caused by three phenomena, (i) skin effect loss of the conductors, (ii) dielectric loss of the insulation, and (iii) dielectric loss in the semicons. As a result of the large conductors employed in power cables, skin effect losses are normally negligible. For cables insulated with XLPE, which has very low dielectric loss, low frequency losses are dominated by conductor resistance and dielectric loss while high frequency losses are dominated by

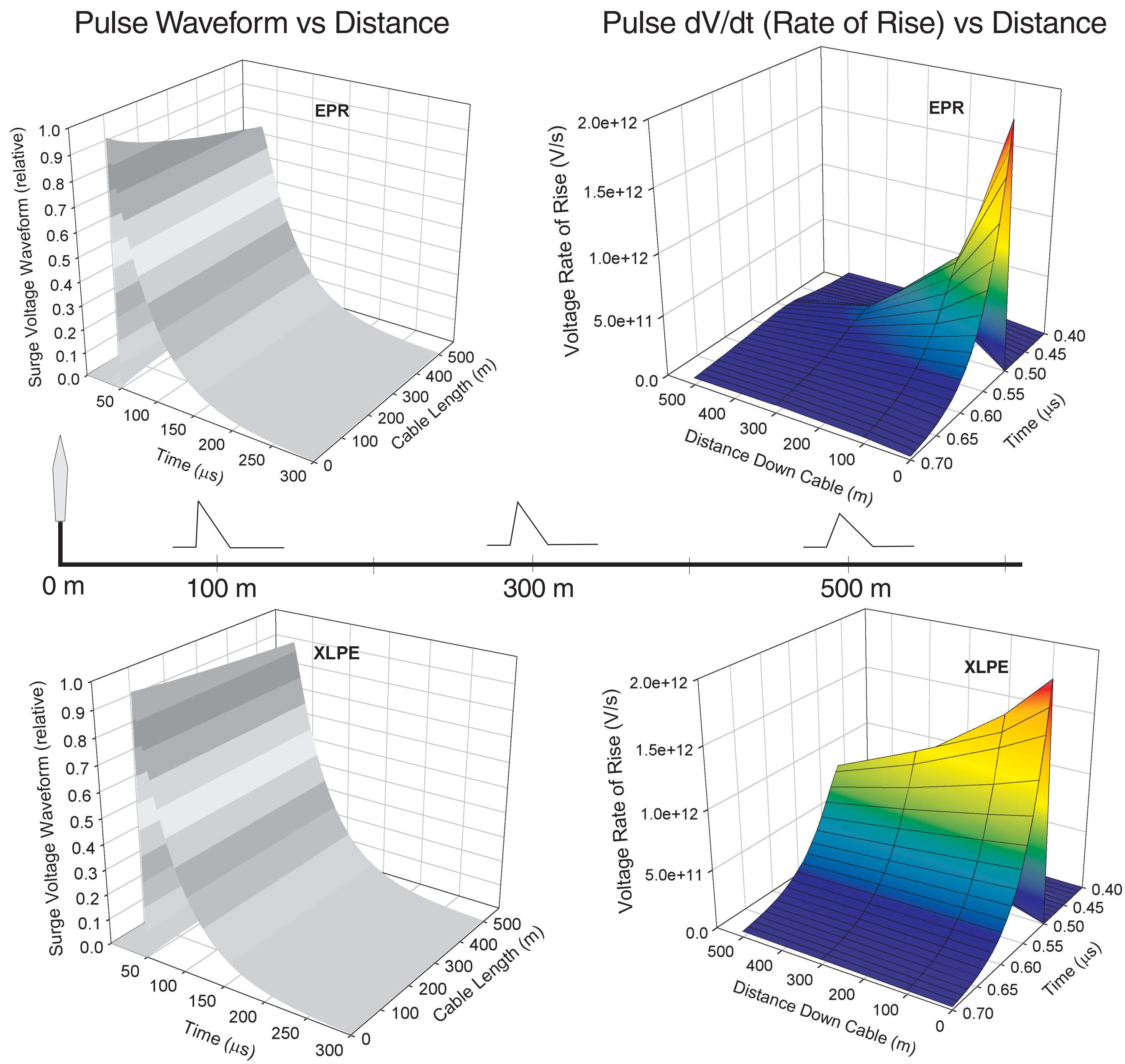

Figure 2. Cable pulse propagation characteristics for a fast risetime lightning surge-type waveform. The left 3-D plots show the voltage amplitude waveform as a function of distance propagated by the pulse down the cable. The amplitude decreases more rapidly in EPR cable than in XLPE cable, but the pulse amplitude attention is not very great. The right 3-D plots show how the rate of rise of the voltage changes with distance propagated in XLPE and EPR cable. The effect of EPR cable in decreasing the rate of rise of the voltage is dramatic. A decreased rate of rise reduces reflections and evens the voltage distribution along the winding of inductive devices such as transformers and motors, thereby avoiding exececssive voltage across the first few turns of the winding.

dielectric loss in the semicons which results from the propagation of radial displacement current through the resistance of the semicon [3,4]. This loss is maximum when the resistive impedance of the semicon is equal to its capacitive impedance. Since the resistive impedance is relatively constant with frequency while the capacitive impedance decreases with increasing frequency, the two tend to be equal only in a small range of frequency, usually in the MHz range. The magnitude of the attenuation is a strong function of the semicon dielectric constant, and the relative dielectric constant is usually in the range of 100 to 2000. Such high dielectric constants result in low attenuations and small contributions to the dielectric loss, as seen in Figure 7.

Figure 8 shows the measured attenuations vs. frequency for EPR cable and TR-XLPE cable. The TR-XLPE cable has a high frequency attenuation which is in the range caused by semicons. However, the EPR cable has an order of magnitude greater attenuation at high frequencies, in a range which is probably caused by dielectric loss in the insulation.

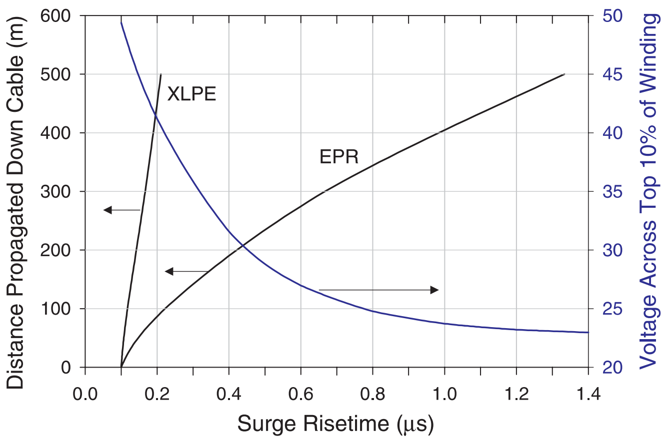

Figure 3 shows how the waveform risetime changes as a function of distance propagated down the EPR and XLPE cable, along with the effect this has on the voltage across the top 10% of a typical distribution transformer. Take, for example, a propagation distance of 300 m (about 1000 ft). We can see that the risetime at that distance for an XLPE cable would be about 0.15 µs. Following that risetime up to the curve for voltage across the top 10% of the winding, we can see that this risetime would result in about 43% of the peak surge voltage dropping across the top 10% of the winding. However, for EPR cable, the risetime would be about 0.65 µs, and the voltage across the top 10% of the winding would be only 26% of the peak surge voltage, which reduces greatly the surge-induced stress on the winding.

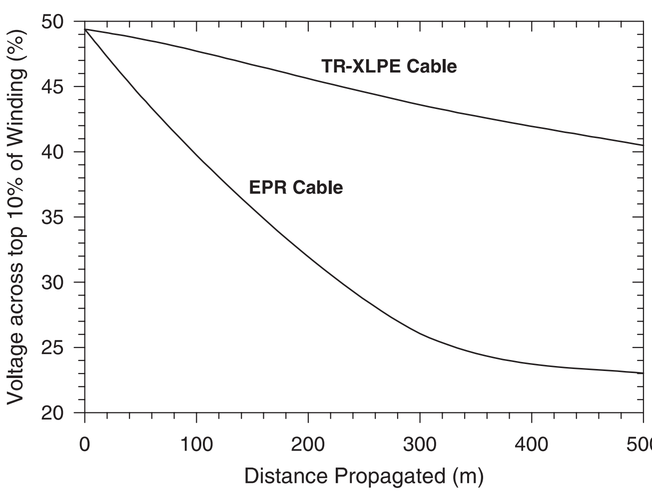

Figure 4 shows the relationship between the percent of the overvoltage across the top 10% of the transformer winding as a function of the distance propagated by a 0.1 µs risetime lightning impulse down EPR and TR-XLPE cables. The greater high frequency attenuation of the EPR cable causes the percent of the voltage across the top 10% of the winding to drop much more rapidly than for TR-XLPE cable, thereby protecting the transformer from failure at the top of the winding.

III. DISTRIBUTION NETWORK MODEL

A section of distribution network provided by a utility is shown in Figure 5, which consists of single-phase 13.2 kV distribution lines, two riser poles, two ZnO arresters at the riser poles, shielded power cables and seven distribution transformers. The cables are connected at riser poles, which are fitted with ground leads connected to driven ground rods. Our previous work indicated that the ground rod to earth resistance in the New England area ranges from a few ohms to a few kΩ. In the present model, we have employed the somewhat optimistic value of 50 Ω. The distribution overhead lines are modeled with 150 Ω characteristic impedance, and the riser pole ground leads are modeled as having a 75 Ω characteristic impedance as implemented in the ATP-EMTP using the constant-parameter line model. ZnO arresters were modeled as exponential current-dependent resistor with typical current-voltage characteristics of a distribution-class metal oxide arrester. A high frequency model of a single-phase distribution transformer provided in the literature [2] was used in the present model without consideration of transformer core loss (Figure 6).

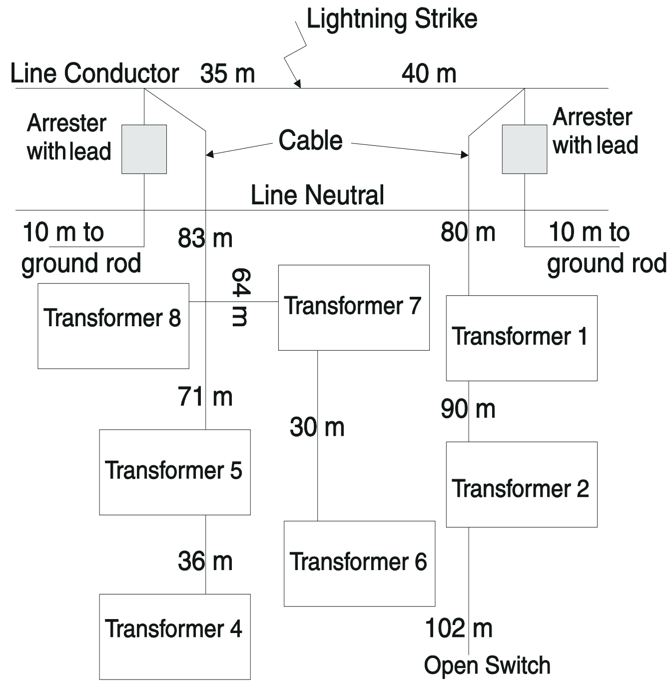

Figure 5. Section of utility 13.2 kV distribution system which has been modeled. The transformers are modeled as shown in Figure 3. The cable lengths are labeled in metres.

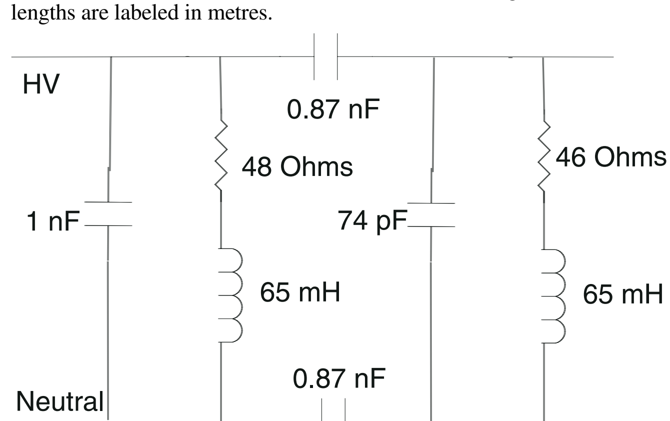

Figure 6. High frequency electrical model for single-phase distribution transformer [2].

A Marti frequency-dependent single-core cable model was constructed in the ATP-EMTP which resulted in the same electromagnetic propagation characteristics as the actual cable. The Marti model is based on skin effect losses, which go as the square root of frequency. In the frequency range of

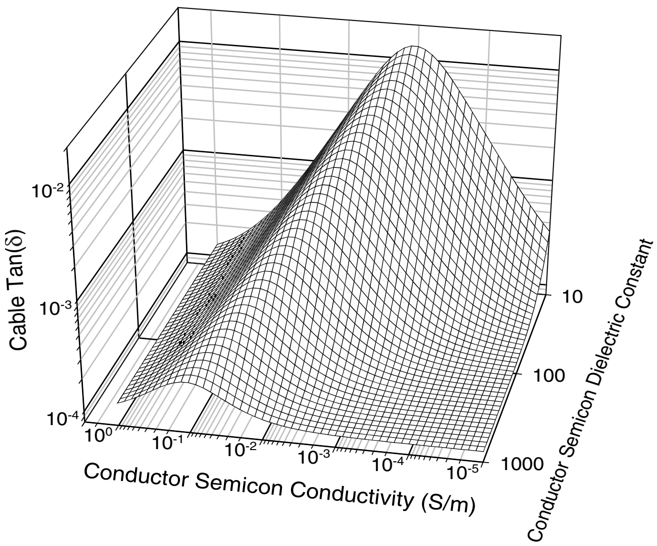

Figure 7. Cable dielectric loss at 2 MHz as a function of conductor semicon conductivity and dielectric constant for a typical 15 kV class cable geometry. The characteristics of the ground shield semicon are such that they contribute little to the overall cable loss. The tan(δ) of the cable insulation is set to 0.001, which defines the lower bound of the cable loss.

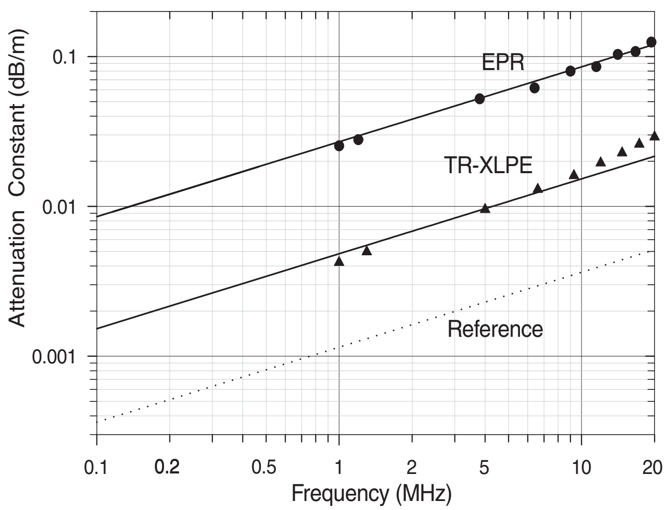

Figure 8. High frequency attenuation of an EPR cable and a TR-XLPE cable. Symbols provide the data as measured with a high frequency impedance analyzer (HP4191A) while lines provide the calculated loss as implemented in the ATP-EMTP program. The attenuation of EPR cable is about an order of magnitude greater than that of TR-XLPE cable.

interest, the measured losses could be fit well with a square root of frequency dependence. The conductor conductivity was adjusted in the model so that the computed loss was close to the measured loss, resulting in the parameters shown in Table 1. As shown in Figure 8, good agreement was obtained between the measured and modeled high frequency cable attenuations in the relevant frequency range to about 20 MHz, which corresponds to a wavefront risetime of about 15 ns. For comparison, a reference cable model with about one order of magnitude less attenuation than TR-XLPE (or two orders of magnitude less attenuation than EPR cable) was also employed as "lossless" cable. The measured cable characteristics and model parameters which matched measured losses are given in Table 1.

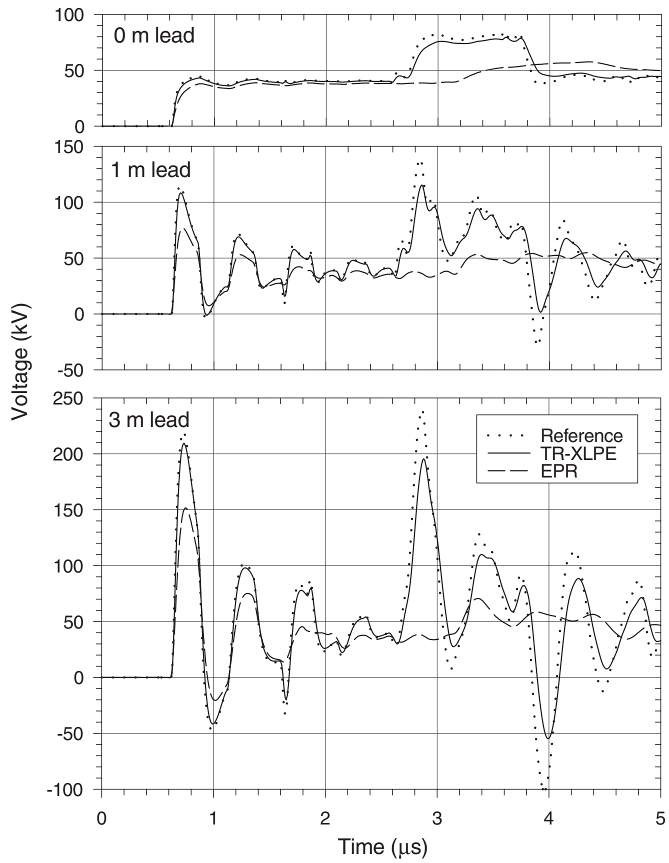

Figure 9. Lightning-induced voltage at Transformer 1 (Figure 2) for a 0.2 µs risetime, 40 kA lightning surge with arrester lead lengths of 0, 1, and 3 m. Reference refers to an "lossless" cable. Note that longer arrester lead lengths result in a large increase in the initial overvoltage. The attenuation of EPR cable reduces the initial transient magnitude and increases the risetime (decreases dV/dt) of the surge. Both of these effects will reduce the voltage across the first turns of the transformer winding. In addition, the attenuation of the EPR cable damps out reflections in the system so that the second large transient at around 3 µs becomes negligible when the system is connected with EPR cable.

IV. LIGHTNING INDUCED OVERVOLTAGES

A. Effect of Arrester Lead

Lightning strikes are normally modeled as current surges. The peak in the probability density distribution for lightning current is in the range of 40 kA. The current risetime can vary from about 0.1 to several µs. This current is injected into the

Table 1. Cable Parameters

	Velocity (m/s)	Dielectric Constant	Z_o (Ω)	Conductor Resistivity (Ω-m)
EPR Cable: Conductor Radius, 6.6 mm; Insulation radius 18.86 mm				
Measured	1.6e8	3.6	33	2.65e-8
Modeled	1.6e8	3.6	33	1.018e-5
XLPE: Conductor Radius, 6.2 mm; Insulation Radius, 16 mm				
Measured	1.85e8	2.6	35.5	2.65e-8
Modeled	1.85e8	2.6	35.14	3.05e-7
Lossless Cable, Conductor Radius, 6.2mm; Insulation Radius, 16mm				

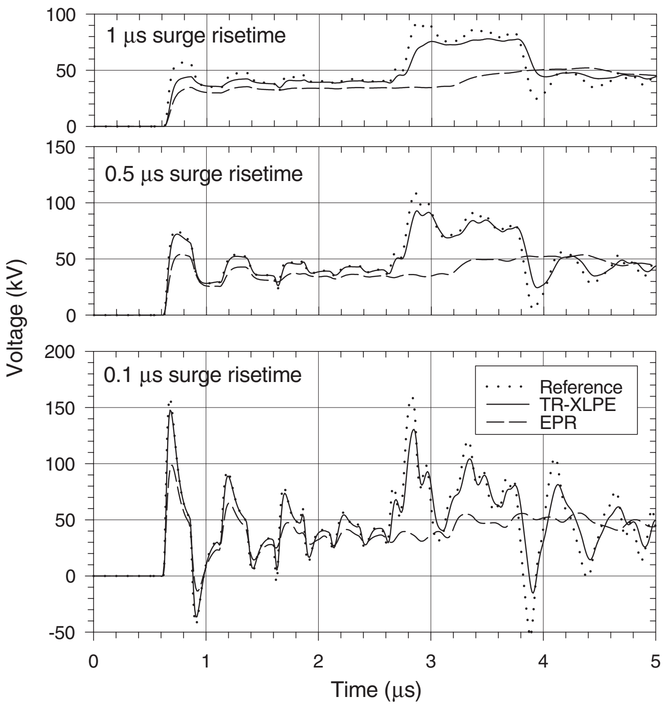

Figure 10. Lightning-induced voltage at Transformer 1 for 40 kA lightning surge for various risetimes with an arrester lead length of 1 m. With decreasing current risetime, the transient overvoltage magnitude increases as does the dV/dt of the waveform. Again EPR cable reduces the initial peak voltage and damps the waveform rapidly.

impedance of the distribution network at the point of the strike. We assume that the lightning strikes near mid-span, as shown in Figure 5. The initial impedance seen by the lightning-induced current will be a 75 Ω, as the transient propagates down the overhead line in both directions away from the strike position. The transmitted surges propagate along the overhead line until they reach the ZnO arresters, where a change in surge impedance causes reflections and refractions. When a typical 40 kA, 0.2 µs lightning surge is injected, the lightning overvoltage waveform at the right cable termination of Figure 5 is as shown in Figure 1. The magnitude of the transient voltage which propagates down the cable to the transformers is mainly determined by arrester discharge voltage, the lead lengths on the arresters, and the rate-of-rise of surge current. This voltage is approximately the sum of arrester voltage and the arrester lead-induced voltage, which is a function of the lead length and rate-of-rise of current surge (dI/dt). In the ideal case of no leads, the voltage propagating down to the cable is around 40 kV.

However, a total arrester lead length up to 3 m is often encountered in practice. These leads produce an overvoltage due to the rate-of-rise of current propagating down the leads. Figure 9 shows the voltage waveform across Transformer 1 (Figure 5) for arrester lead lengths of 0, 1, and 3 m. In each case, three waveforms are shown, one for a "lossless" cable, one for a TR-XLPE cable and one for an EPR cable. With increasing arrester lead length, the overvoltages across the transformer increases significantly. For instance, the voltage peaks of about 200 kV are produced across Transformer 1 for an arrester lead length of 3 m, which is about twice of the typical BIL (95 kV) of 15 kV class switchgear. However high-frequency attenuation in the cable can reduce this overvoltage substantially. As is clear from Figure 9, the greater high frequency attenuations of the EPR cable both reduces the amplitude of the initial overvoltage (the first peak in Figure 9) and also increases the surge risetime. The EPR cable also damps the waveform very rapidly, so that by the time of the second large voltage peak for the lossless and TR-XLPE cables (around 3 µs in Figure 9), the voltage amplitude for the EPR cable is negligible. Thus the EPR cable both decreases the impact of the first voltage peak and nearly eliminates subsequent voltage peaks.

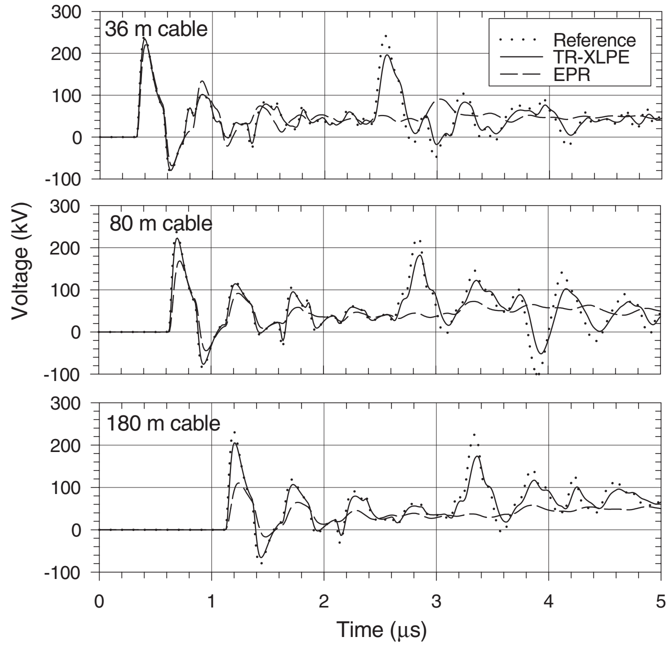

Figure 11. Lightning-induced voltage at Transformer 1 for a 0.1 µs, 40 kA lightning surge with 2 m arrester lead length and various cable lengths. Greater cable length decreases dV/dt of the initial transient. Again EPR cable damps the waveform rapidly to reduce the effect of reflections.

B. Effect of Surge Rate-of-Rise

The rate-of-rise of lightning current has significant influence on the level of overvoltages produced at the cable termination. We investigated this influence with a 40 kA lightning current waveform with risetimes varying from 0.1 to 1 µs. The voltage across the transformers was calculated in the case of 1-m arrester lead lengths. Figure 10 shows the voltages across Transformer 1 (Figure 5) for 0.1, 0.5 and 1 µs lightning current risetime and indicates that shorter current risetimes cause greater peak voltages and larger dV/dt across the transformer. Again, EPR cable reduces the initial peak magnitude, decreases the maximum dV/dt to which the transformer is exposed, and damps the surge waveform to minimize the effect of subsequent voltage peaks caused by reflections.

C. Effect of Cable Length

The voltage across Transformer 1 was calculated as a function of cable length between the riser pole and Transformer 1. Other cable lengths were kept the same as shown in Figure 5.

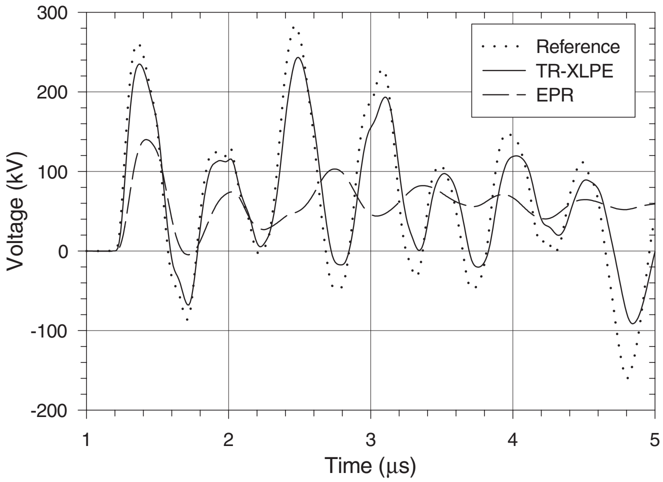

Figure 12. Voltage across Transformer 4 (Figure 2) for a 0.2 µs risetime, 40 kA lightning surge with 3 m arrester lead length. The reflection from the open circuit causes a series of voltage peaks which are reduced in magnitude and damped out as a function of time by EPR cable in comparison with TR-XLPE cable.

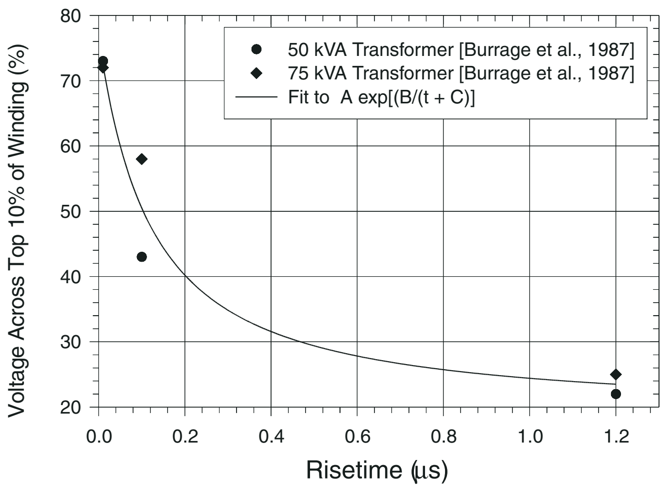

Figure 13. Measured fraction of the voltage across the top 10% of a transformer winding for two different transformers [5], along with a curve fit to the data which is used in the present analysis.

Figure 11 shows results for cable lengths of 36, 80 and 180 m (120, 265, and 600 ft) . Longer cable length reduces substantially the magnitude of the first voltage peak and decreases its dV/dt (increases the risetime). The subsequent largest voltage peak results from the reflection of initial peak from an open switch. The waveform travels along 192-m cable to reach the open switch, where the voltage transient is reflected back to Transformer 1. The magnitude of the resulting peak is reduced from about 200 kV for TR-XLPE to about 40 kV when EPR cable is employed.

D. Effect of Traveling Waves

The reflection and refraction of the short risetime, lightning induced voltage at impedance mismatches in the system causes the voltage and dV/dt across the various transformers in a network to vary. As indicated above, in the right underground branch of Figure 5, the surge voltage is doubled at the open switch. In the left cable, Transformers 4 and 6 are lo-

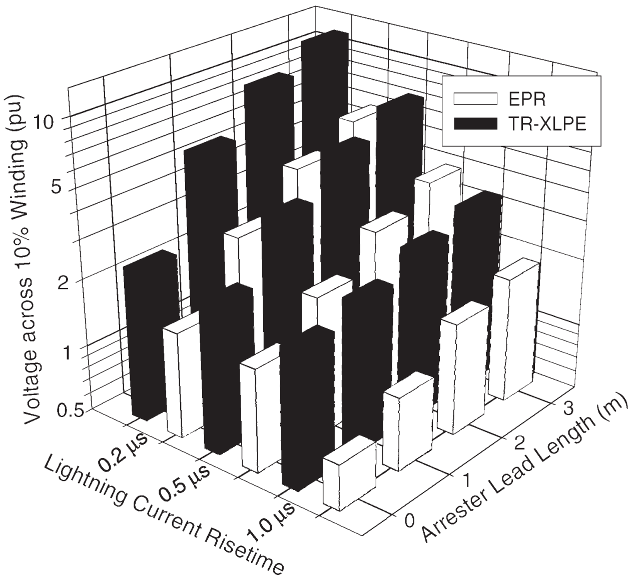

Figure 14. Voltage in pu relative to peak line-to-ground voltage (10.78 kV) across the top 10% of the winding of Transformer 4 for a 40 kA lightning surge as a function of the lightning surge risetime, arrester lead length, and type of cable employed.

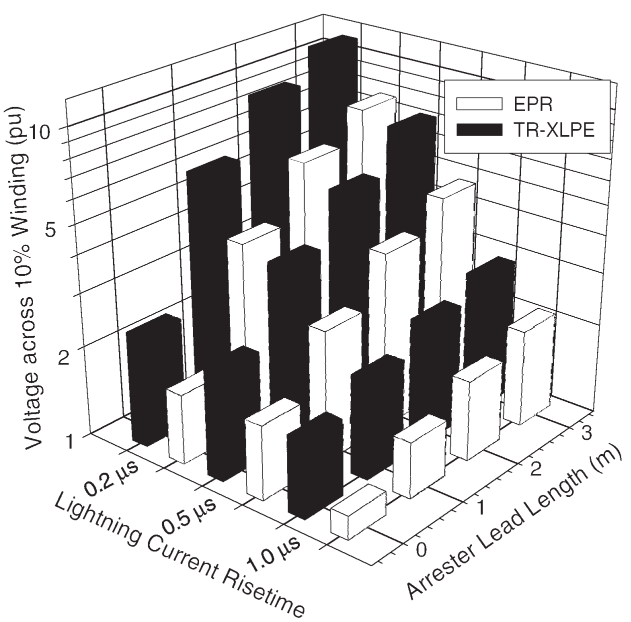

Figure 15. Similar data to Figure 12 except for Transformer 1.

cated at the far ends of cables where reflection of the transient waveform from the open circuit results in higher voltages across these transformers. As shown in Figure 12, the maximum overvoltage across Transformer 4 for a 0.2 µs risetime, 40 kA current surge and 3 m arrester lead length is about 250 kV for TR-XLPE cable. EPR cable reduces the first peak to about 120 kV and the subsequent peaks to less than the BIL of 95 kV. At the same time, the EPR cable causes the risetime to increase from about 80 ns to about 200 ns. The combination of reduced peak voltage and increased risetime (decreased dV/dt), reduces considerably the turn-to-turn voltage at the top of the transformer winding.

E. Voltage across First Turns of Transformer Windings

As noted above, the high frequency attenuation of EPR cable reduces the peak magnitude and increases the risetime of voltages across the transformers connected to the cables relative to transformers connected with TR-XLPE cable. These effects combine to reduce the voltage across the first turns of the transformer. The voltage across the first turns of a transformer is a function of the surge waveform risetimes as a result of transmission line effects within the transformer winding, i.e., the time required for propagation of the electromagnetic transient down the winding. Figure 13 shows data for the peak voltage across the top 10% of a transformer winding as a function of the waveform risetime. Based on computed magnitude and risetime of the first peak across transformer winding, the voltage across the top 10% of the transformer winding in pu relative to peak line-to-ground voltage was computed for a 40-kA lightning impulse with risetime of 0.2, 0.5 or 1 µs and for ZnO arrester lead lengths ranging from 0 m to 3 m. Typical results from these computations are shown in Figures 14 and 15 for transformers 4 and 1, respectively. These data indicate that the arrester lead length, lightning current risetime, and the type of cable connecting the transformer to the overhead circuit have a large effect on the lightning induced surge voltage across the top 10% of the transformer winding. In the case of TR-XLPE cable, the top of the transformer winding is exposed to several such peak voltages per lightning impulse as a result of reflections in the system, while for the EPR cable, the transformer is exposed to only one such overvoltage as subsequent peaks are nearly completely damped by the high frequency loss of the cable.

V. CONCLUSION

The computed data indicate that the type of cable employed (EPR or TR-XLPE), arrester lead length, and the rate-of-rise of lightning current have a large effect on the voltage across a transformer and the turn-to-turn voltage at the top of the transformer winding. Arrester lead lengths vary widely and are often much greater than desirable. Further, little care is taken to assure that the arrester is connected as close as possible and directly across what it is intended to protect. In the case of a connection between a cable and overhead line, the arrester is intended to protect the cable, i.e., limit the voltage between the cable conductor and cable neutral wires or tape. As such, the arrester should be connected directly between the cable conductor and cable neutral with an additional connection to the system neutral which is as short as possible.

The shorter the risetime, the larger rate-of-rise of lightning current induced overvoltages in the network. The worst case is a combination of long arrester lead and short risetime lightning currents. The industry standard 1.2 µs lightning surge risetime was set before lightning current risetimes could be measured accurately. As a result, the standard lightning surge risetime is much longer than the worst case lightning current risetime which is in the range of 0.1 µs.

The type of cable employed has a substantial impact on the overvoltages to which the transformer is subjected. A cable such as EPR with large high frequency attenuation lengthens the risetime of transients as they propagate down the cable (i.e., decreases dV/dt) so that the voltage amplitude to which the transformer is subjected is reduced substantially. Thus high frequency cable attenuation undoubtedly has an appreciable impact on overall system reliability, especially in areas with high incidence of lightning.

VI. REFERENCES

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