Effect of Shielded Distribution Cable on Very Fast Transients

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

***Abstract*—Fast transients in power systems can be generated by switching of vacuum and SF_6 insulated devices as well as by solid state devices such as those used in variable speed drives. Transients with ns risetimes can be generated which, in a cable-connected system, propagate down the cable to inductive devices such as motors and transformers. In general, the amplitude of such surges is not out of the ordinary; however, the very short risetime can cause unacceptable voltages across the first turn of an inductive device. A cable with high frequency loss does not generally decrease the amplitude of such surges appreciably but can lengthen the risetime substantially by absorbing high frequency energy from the surge. This reduces the voltage across the first turn of inductive devices and thereby protects them from damage and failure caused by such surges. In the present contribution, we quantify the high frequency losses and effect thereof on very fast transients for four types of shielded, 15 kV distribution cable, three made from various EPR compounds and one made from TR–XLPE.**

I. Introduction

THE AMPLITUDE of fast transients generated by switching of devices such as vacuum interrupters, SF_6 interrupters, and solid state switching devices used in variable speed drives is usually well below the system BIL, which means that surge protective devices such as ZnO arresters will have little effect on such surges. However, the risetime of such transients can be so short that the propagation time around the first turn of an inductive device is of the same order as the surge risetime, which results in a substantial portion of the surge voltage appearing across the first turn of a motor or transformer. This can cause progressive degradation and eventual failure of the insulation.

In the present contribution, we quantify the influence of various types of shielded distribution cables on the nonlinear voltage distribution in motors and transformers. Such cables have substantial high frequency loss caused by the semicons and dielectric. Such high frequency loss lengthens the risetime of a fast transient which propagates down the cable. Thus the severity of the surge presented to an inductive device such as a motor or transformer decreases as a function of the distance and type of cable through which the surge propagates.

The frequency range of interest corresponds to risetimes from about 10 ns to 1 μs, i.e., 30 MHz to about 300 kHz, respectively. While vacuum and SF_6 interrupters can generate transients well below 10 ns risetime, by the time such transients are coupled into the cable, the risetime has generally lengthened to no less than 10 ns.

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L.-M. Zhou is with the Electrical Insulation Research Center, Institute of Materials Science, University of Connecticut, Storrs, CT 06269-3136 USA.

S. Boggs is with the Electrical Insulation Research Center, Departments of Electrical Engineering and Physics, University of Connecticut. He is also with the Department of Electrical and Computer Engineering, University of Toronto.

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II. High Frequency Loss in Power Cable

The theory of high frequency loss in shielded power cables has been examined in detail [1]–[3], [8] and results from two primary sources. The first, which applies to all shielded power cables, is the loss in the semicons caused by conduction of the radial displacement current through the resistance of the inner and outer semicons. If we consider the dielectric to be lossless, which is a good approximation for "pure" XLPE, then the dielectric can be viewed as a high impedance (as a result of the relatively small capacitance per unit length across it relative to that of the semicons) which determines the current through the semicons. In the MHz range, the semiconducting layers generally have a large dielectric constant (in the range of 100–1000 or more) along with a substantial resistance. The loss in the semicons is maximized when the resistive impedance equals the capacitive impedance at the frequency of interest [4]. Thus to maximize the high frequency loss caused by the semicons, the dielectric constant of the semiconducting layers would be minimized while the conductivity of the semicons would be optimized so that conductivity is approximately equal to the product of the radial frequency (ω) times the absolute dielectric constant in the frequency range of interest. The loss in the semicon reduces away from this optimum in all directions, i.e., if the semicon dielectric constant increases or decreases, or if the semicon conductivity increases or decreases from the optimum.

The high frequency loss of cable dielectrics other than "pure" XLPE must be considered. However these losses, and the phase shift they cause in the current through the semicons, is so small that the loss in the semicons and the loss in the dielectric are simply additive under all conditions of technical interest [4]. Thus the loss of a cable can be predicted by measuring the dielectric properties of the dielectric and the dielectric properties of the semicons over the frequency range of interest and inserting these data into an electrical model for the cable. This has been done with good agreement to the measured loss of the cable.

We should note that the loss of properly functioning semicons is always negligible at power frequency, and optimization of loss at high frequency has no impact on the power frequency loss of the cable. As noted above, the semicon loss can only be optimized at one frequency (unless the semicon properties change with frequency in a way which allows optimization over a range of frequencies, as does sometimes occur). Thus if the semicon is optimized for high frequency loss, it will be far from optimized

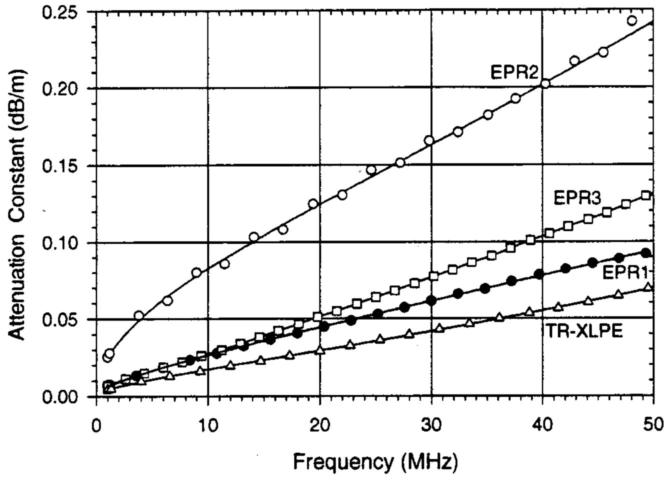

Fig. 1. High frequency attenuation of four types of shielded power cables, three cables made with different EPR dielectrics and one cable made with TR–XLPE. Note the substantial differences in attenuation of the various cables over the frequency range of interest.

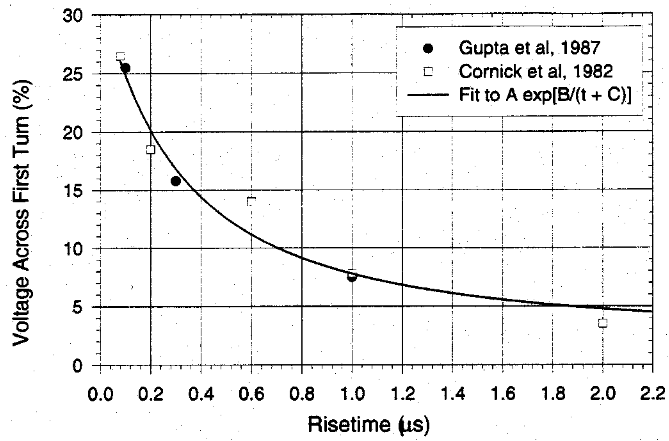

Fig. 2. Measured fraction of voltage across the first turn of a motor as a function of waveform risetime as measured by two researchers [5], [6], [9], along with a curve fit to the data which is used in later analysis. The data taken by different researchers on different motors are in good agreement. For risetime less than 500 ns, the voltage across the first increases rapidly.

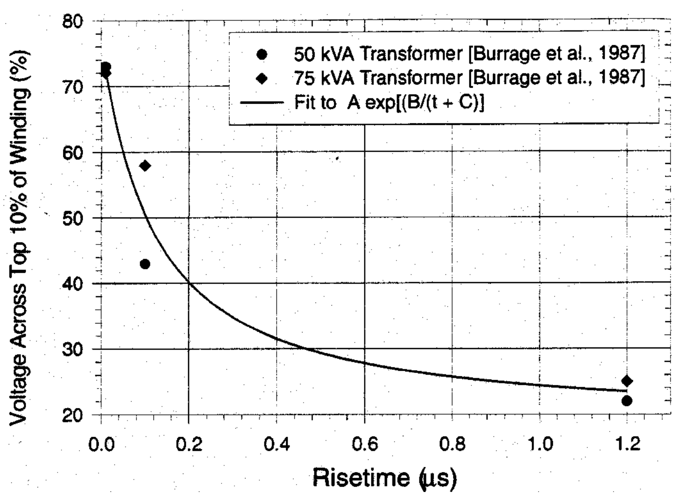

Fig. 3. Measured fraction of voltage across the top 10% of a transformer winding for two different transformers [7], along with a curve fit to the data which is used in later analysis.

for power frequency loss. The high frequency and power frequency loss of a cable or cable dielectric need not be correlated. Thus a cable might be developed which has very large high frequency loss without increased loss at power frequency.

The high frequency loss of four types of 15 kV class shielded power cables was measured using an HP 4191 A high frequency impedance analyzer in the range from 1 MHz to 50 MHz and a GR bridge at lower frequencies. Fig. 1 shows the measured high frequency loss of the four cable types. Note that the attenuation of the cable types differs by nearly a factor of four from the most lossy to the least lossy.

III. Voltage Distribution in Inductive Devices

When a fast transient impinges on an inductive device such as a motor or transformer, the transient propagates down the winding, which can be viewed, in one approximation, as a transmission line. If the risetime of the transient is less than the propagation time around the first turn of the inductive device, the full voltage of the transient can appear across the first turn. The voltage which actually appears across the first turn is a function of the transient risetime, decreasing with increasing risetime until, beyond some risetime, the voltage across the winding approaches its low frequency design distribution. Figs. 2 and 3 show data for measured voltage across the first turn of a motor and top 10% of a transformer winding as compiled from several sources, along with equations fit to the data which are used in the analysis below. These data indicate that the voltage across the top of the winding increases rapidly as the waveform risetime becomes shorter but approaches a "normal," low frequency distribution for risetimes longer than about 1 μs, which corresponds roughly to a lightning impulse.

Thus to protect an inductive device from switching transients we do not normally need to decrease the amplitude of the transient but only increase the risetime of the transient.

IV. Impact of Cable Loss on Waveform Risetime

As noted above, the high frequency loss in the cable causes the risetime of a wave propagating down the cable to lengthen as a function of distance propagated in the cable. A short risetime implies substantial energy at high frequencies, and if such energy is absorbed from the waveform, the risetime must become longer. Obviously, the greater the high frequency cable loss, the greater the effectiveness in lengthening the waveform risetime or the less length of cable required to achieve a given minimum risetime.

Figs. 4–7 show 3-D plots of the 10–90% pulse output risetime as a function of input risetime and cable length through which the pulse has propagated. The general shape of these 3-D plots requires some explanation for which we will refer to Fig. 5 which corresponds to EPR2, the cable with the greatest high frequency attenuation. We will first explain the shape of the output risetime as a function of cable length for short input risetime, the minimum for which is 10 ns on these plots. The output risetime results from the superposition of two effects, *viz.*, the input risetime and the lengthening of the input risetime caused by the attenuation of the cable. For simple 1-pole (6 dB/octave) filters, the input risetime, and the output risetime of the filter

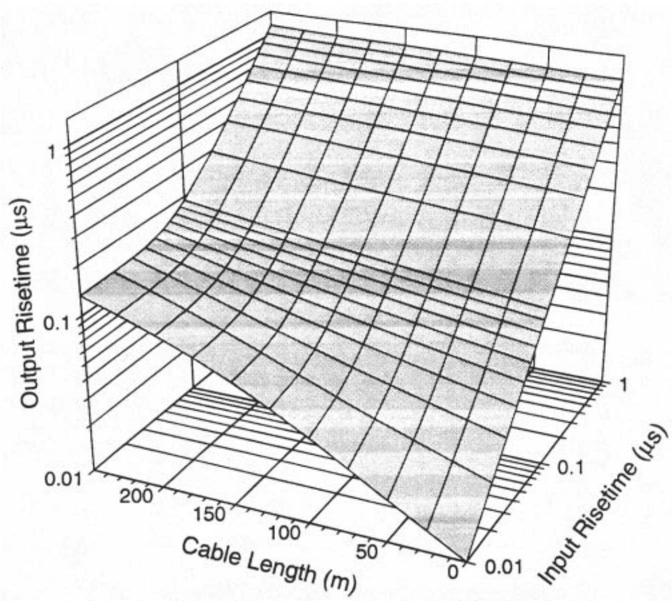

Fig. 4. 10–90% pulse output risetime as a function of pulse input risetime and the length of cable through which the pulse has propagated for EPR1.

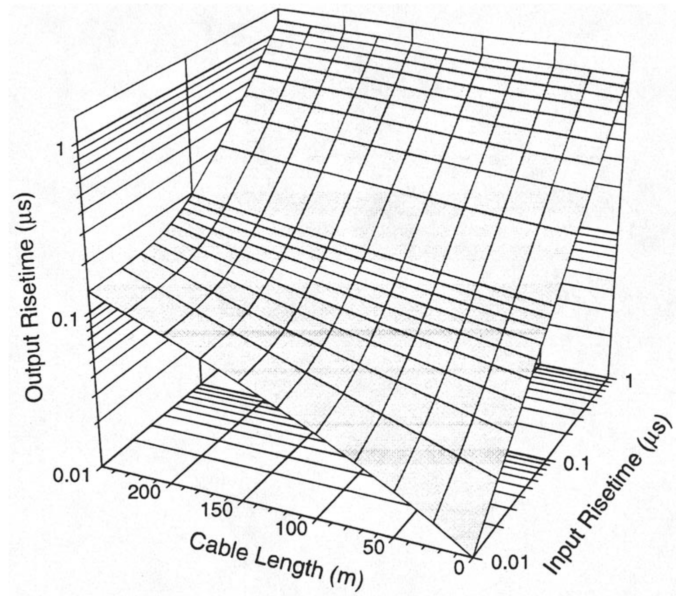

Fig. 6. 10–90% pulse output risetime as a function of pulse input risetime and the length of cable through which the pulse has propagated for EPR3.

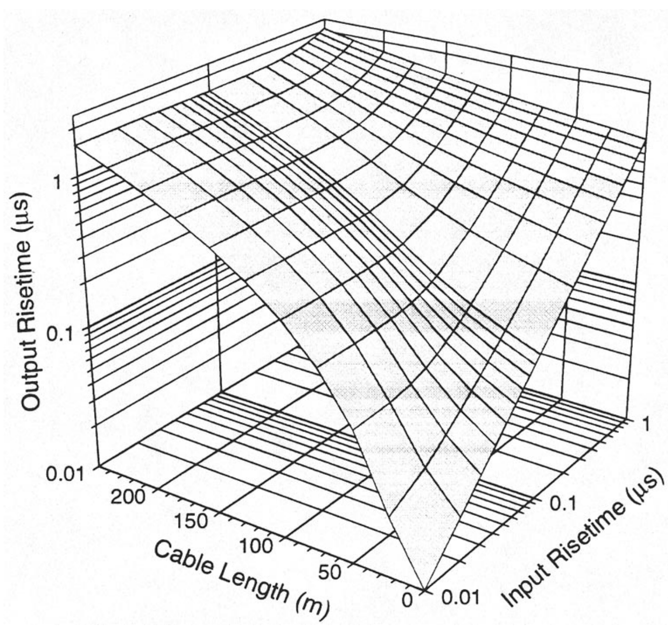

Fig. 5. 10–90% pulse output risetime as a function of pulse input risetime and the length of cable through which the pulse has propagated for EPR2.

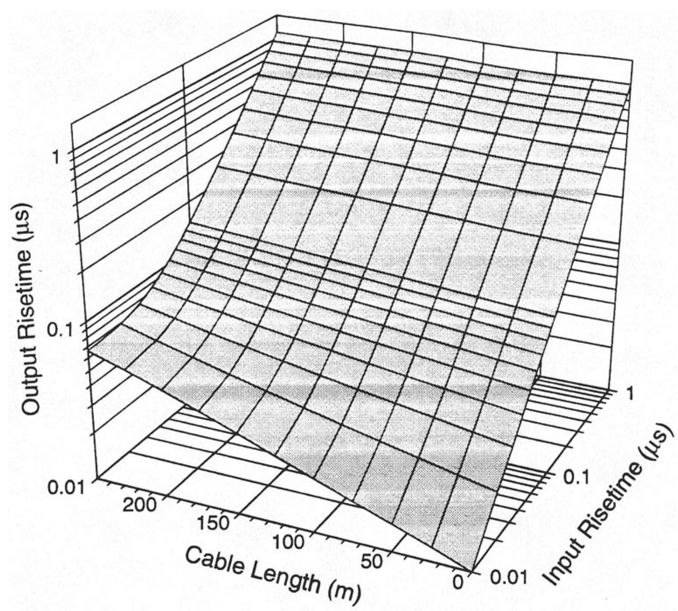

Fig. 7. 10–90% pulse output risetime as a function of pulse input risetime and the length of cable through which the pulse has propagated for TR–XLPE.

for a perfect stepwave input, add as the root mean square. In other words, if we take a 7 ns risetime waveform and observe it with an oscilloscope which has a 5 ns risetime, we will observe a risetime of 8.6 ns [sqrt($7^2 + 5^2$)] on the oscilloscope. The input waveform and cable attenuation represent an analogous situation except that the "filter" represented by the cable is not a simple 1-pole filter so that the above rule for computing the output risetime becomes an approximation. Still, it provides us with a conceptual basis for understanding what is going on. Thus for very short cable lengths, the risetime of the cable (i.e., the output risetime for a perfect step wave into the cable) is substantially less than the minimum input risetime of 10 ns, so that the resulting overall risetime does not differ appreciably from the input risetime until the cable length is about 50 m for EPR2. Beyond 50 m, the "cable risetime" increasingly dominates the overall risetime, as we can see from the "flat" region in the direction of increasing input risetime, which indicates that over this limited range (the flat region), the output risetime is essentially independent of the input risetime. We note the concave shape of the output risetime vs cable length which indicates that the output risetime lengthens less than linearly with distance propagated through the cable. This is the result of frequency dependent attenuation of the cable. As seen in Fig. 1, the cable attenuation is frequency-dependent, increasing roughly linearly with frequency. Thus as a transient propagates down the cable,

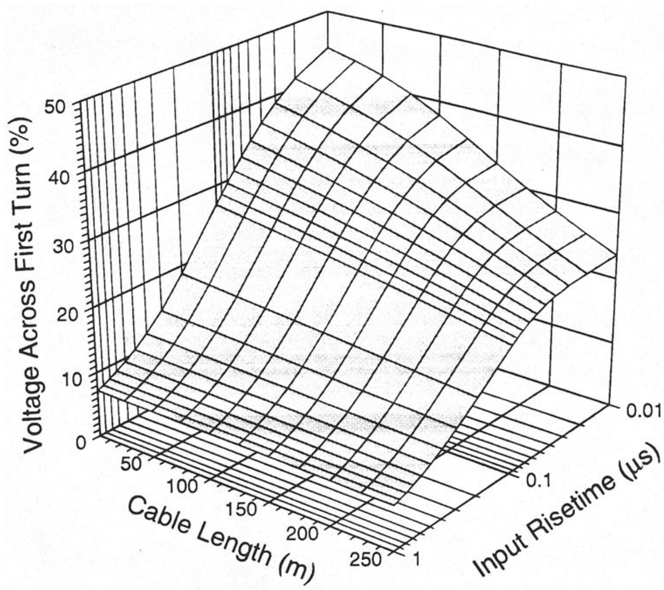

Fig. 8. Voltage across the first turn of a motor as a function of cable input transient risetime and cable length for cable EPR1.

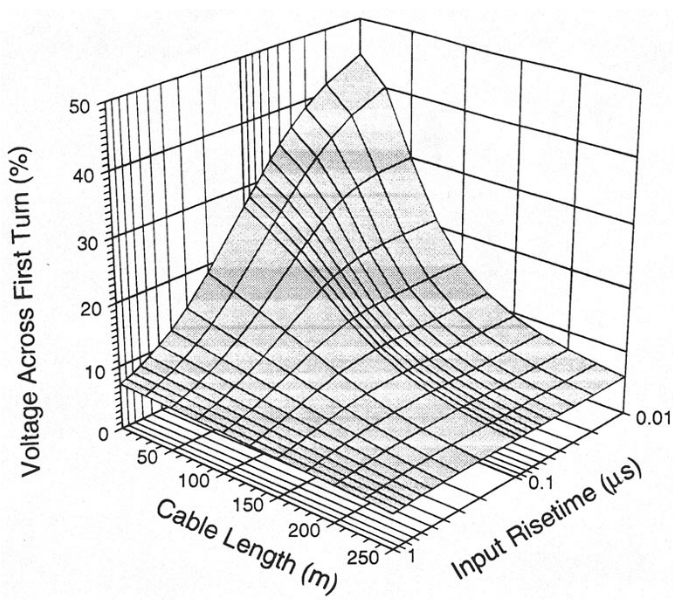

Fig. 9. Voltage across the first turn of a motor as a function of cable input transient risetime and cable length for cable EPR2.

the highest frequencies are attenuated more rapidly than lower frequencies and are effectively "lost" from the waveform. The remaining frequencies are attenuated less rapidly which results in less than linear lengthening of the risetime with distance propagated through the cable.

If we now consider the output risetime as a function of input risetime, at zero cable length the two are, of course, the same. For very large input risetimes, the cable has only a modest effect on the waveform risetime as a function of distance propagated, as the attenuation at the (low) frequencies corresponding to such a long risetime is not very great. For a very long cable length, the minimum risetime becomes large and constant as a function of input risetime until the input risetime becomes comparable to the cable risetime. At 250 m, the cable risetime is about 1 μs

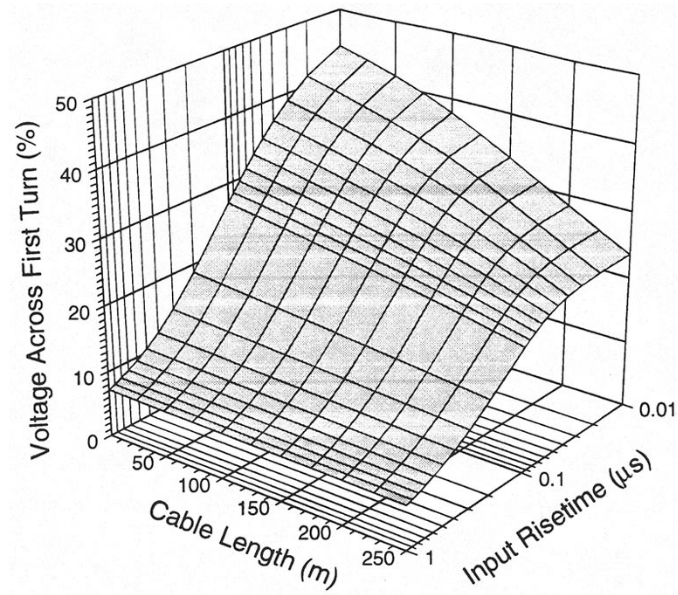

Fig. 10. Voltage across the first turn of a motor as a function of cable input transient risetime and cable length for cable EPR3.

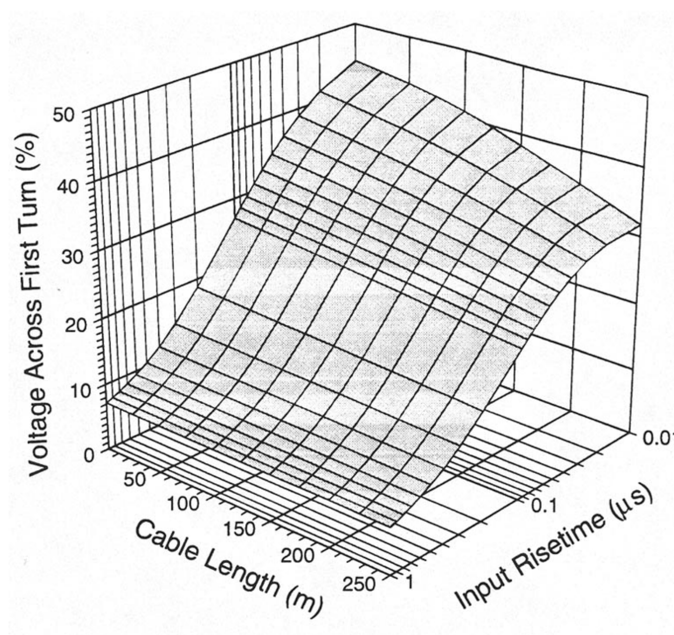

Fig. 11. Voltage across the first turn of a motor as a function of cable input transient risetime and cable length for cable TR–XLPE.

(for short input risetimes), and the output risetime increases to about 1.5 μs for an input risetime of 1 μs, which is close to the 1.414 μs which would be expected from the root mean square.

V. First Turn Motor Voltage vs Cable Length

Figs. 8–11 show the voltage across the first turn of a motor as a function of input transient risetime and cable length for the four types of cables based on the data of Fig. 2. As would be expected from the attenuation data of Figs. 4–7, EPR2 reduces the surge magnitude across the first turn most quickly as a result of having substantially greater high frequency attenuation than the other cables. Seventy-five (75) meters of EPR2 reduce the

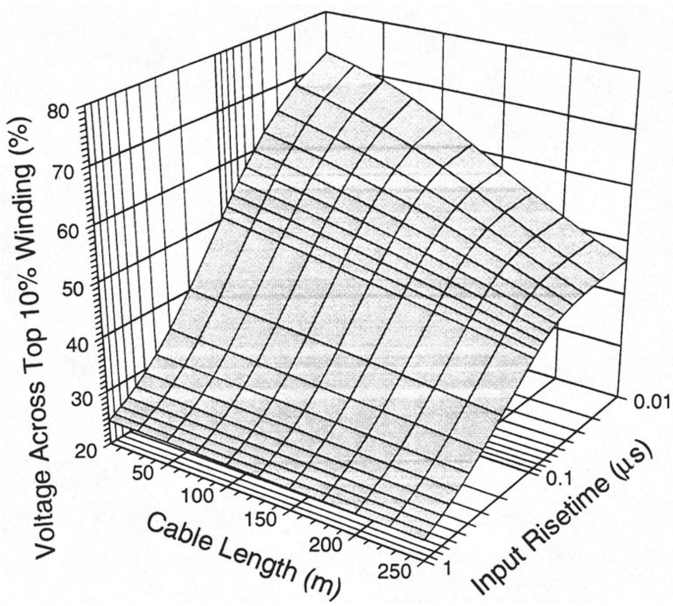

Fig. 12. Voltage across the top 10% of a transformer winding as a function of cable input transient risetime and cable length for EPR1.

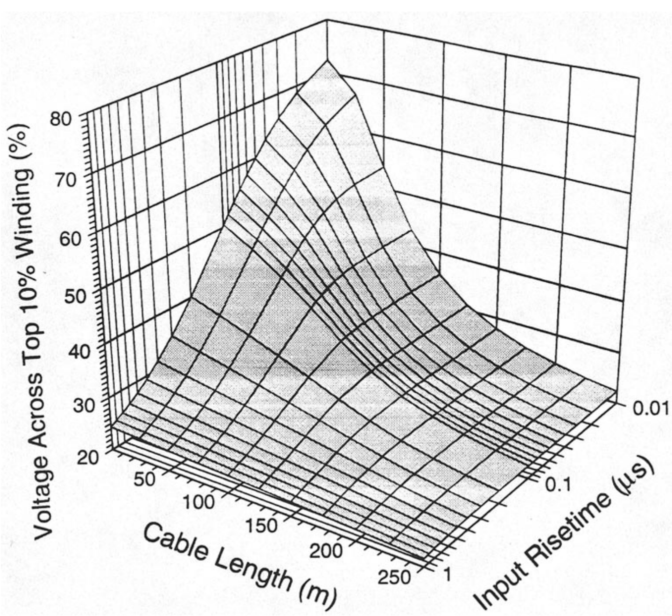

Fig. 13. Voltage across the top 10% of a transformer winding as a function of cable input transient risetime and cable length for EPR2.

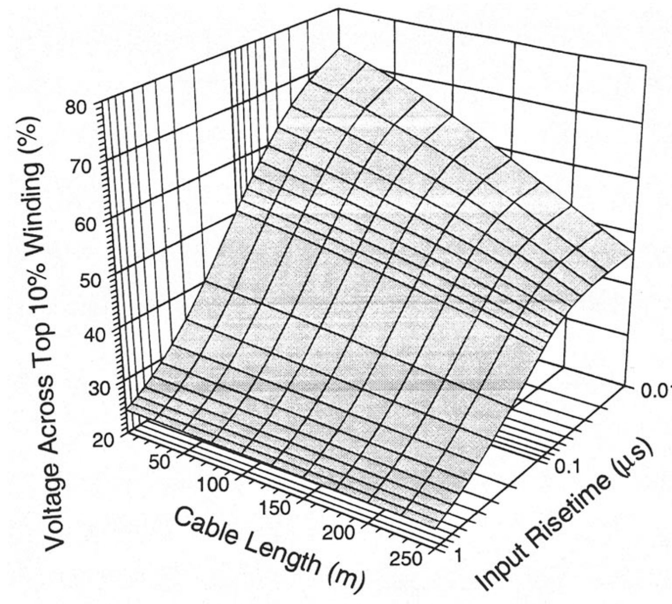

Fig. 14. Voltage across the top 10% of a transformer winding as a function of cable input transient risetime and cable length for EPR3.

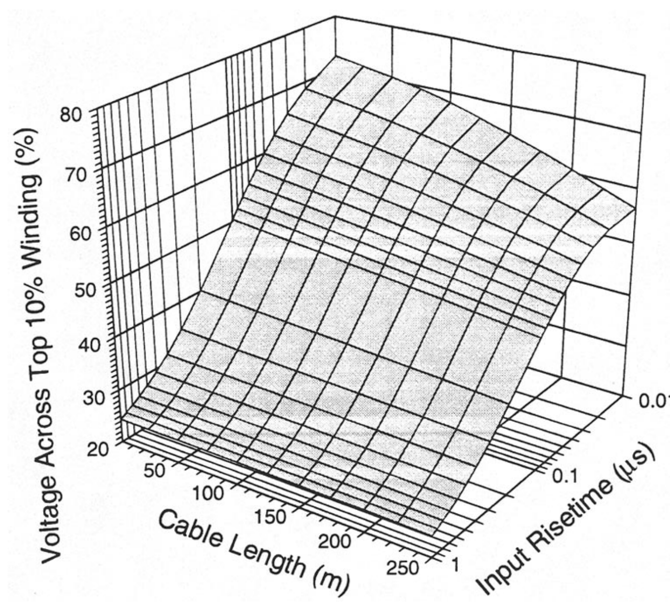

Fig. 15. Voltage across the top 10% of a transformer winding as a function of cable input transient risetime and cable length for TR–XLPE.

voltage across the first turn to near normal levels for any cable input risetime. 250 m of EPR1 or EPR3 would be required to effect a similar reduction or in the range of 400 m TR–XLPE. Thus modest lengths of cable can be very effective in limiting the voltage drop across the first turn of a motor caused by very fast transients as generated by vacuum or SF_6 switchgear or by solid state switching devices in variable speed drives.

VI. Transformer Voltage vs Cable Length

Figs. 12–15 show the voltage across the top 10% of a transformer winding as a function of cable input risetime and cable length. Again and as expected, cable EPR2 reduces the voltage across the top 10% of the winding most quickly as a function of cable length with only 75 m required to reduce substantially the overvoltage, as compared to 250 m for EPR1 or EPR3, and over 400 m of TR- XLPE. Thus, again, the effect of fast transients can be eliminated through modest lengths of cable which has relatively large high frequency attenuation.

Figs. 16 and 17 summarize the data for motors and transformers based on reasonable worst cases for the two situations from the literature. Of course, the transient which can be generated by switching phenomena should not depend on whether a motor or transformer is connected to the system, so that both surges should be plausible worst cases for either a transformer or motor. In both cases, we see that the length for diminishing returns of EPR2 is in the range of 100 m while that for EPR1

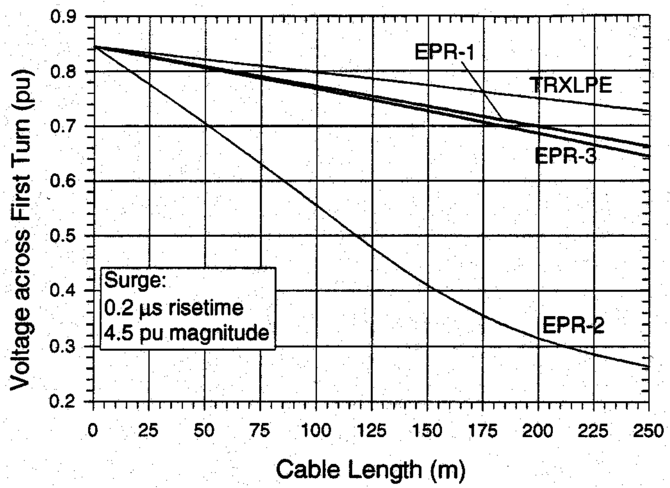

Fig. 16. Voltage across the first turn of a motor as a function of cable length for a 0.2 μs transient with an amplitude of 4.5 pu which is a reasonable worst case based on field measurements [5], [9].

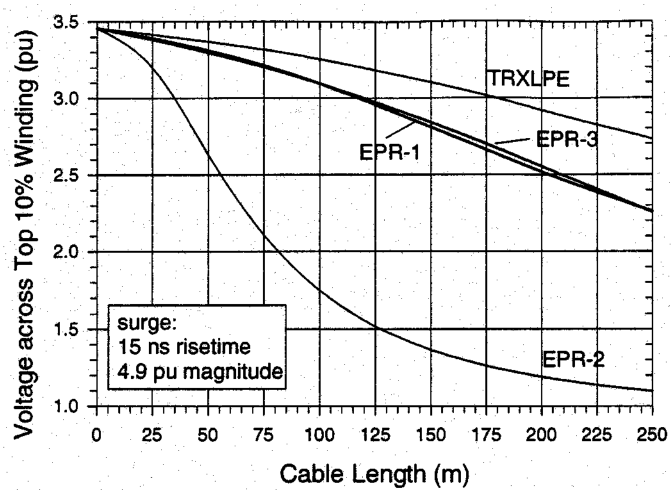

Fig. 17. Voltage across the top 10% of a transformer winding as a function of cable length for a 15 ns, 4.9 pu surge into the cable which is a reasonable worst case based on field measurements [6].

and EPR3 is in the range of 350 m, at least for the transformer case. TR-XLPE has relatively little attenuation.

Figs. 18 and 19 show the effect of various lengths of EPR2 and TR–XLPE cable on the probability density distribution (i.e., the area under the curve is normalized to unity) of fast transient induced voltages across the first turn of a motor based on measured distribution of largest transient magnitudes (and corresponding risetimes) measured at various motor installations [5], [9]. 100 m of EPR2 cable reduces the maximum voltage across the first turn from about 0.9 pu to about 0.55 pu (Fig. 18), while a similar length of TR–XLPE cable reduces the maximum voltage from 0.9 pu to 0.8 pu (Fig. 19). Thus the high frequency attenuation of the cable has a substantial effect on the surge voltages to which the motor winding is subjected during normal service.

VII. Conclusions

Attenuation or loss in power cables is generally seen as a “bad” attribute, and clearly low loss at power frequency

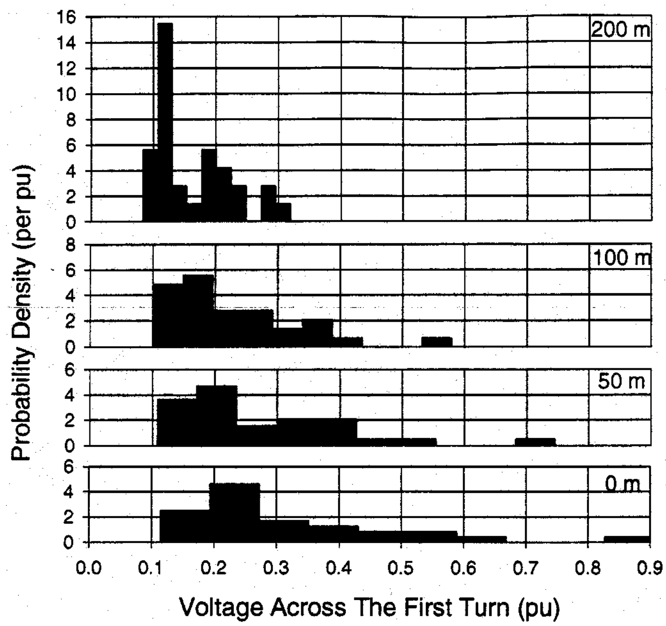

Fig. 18. Probability density distribution vs cable length of EPR2 for measured worst case transient magnitude and risetime distribution for typical motor installations [5], [9].

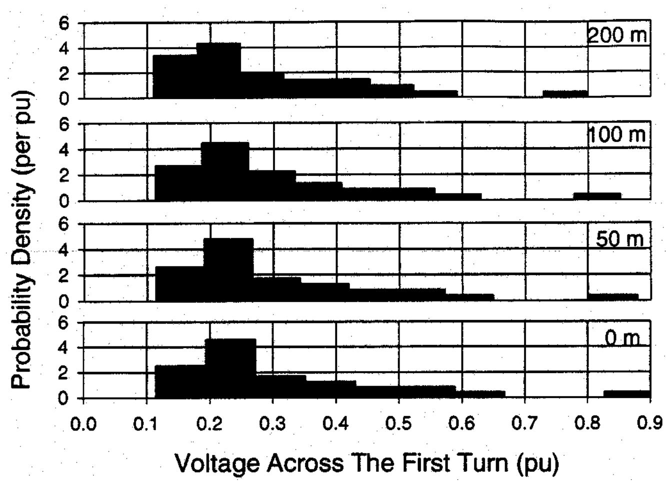

Fig. 19. Probability density distribution vs cable length of TR–XLPE for measured worst case transient magnitude and risetime distribution for typical motor installations [5], [9].

is preferable to high loss, all other characteristics being the same. However, loss at high frequencies can be a very positive attribute in that such loss can protect industrial plant and utility power system components from the detrimental effects of very fast transients generated by switching devices and power electronics. In present cables, high and low frequency loss tend to be correlated to some degree; however, this correlation is not fundamental, and design of a shielded power cable which has large high frequency loss without increased power frequency loss is within the realm of possibility.

In the present contribution, we have quantified the effect of presently available cables on high frequency transients and found that the loss of such cables varies widely. While the high frequency loss of power cables is not a specified characteristic, we feel confident that the loss characteristics of the higher loss cables is dominated by the dielectric rather than the semicons and should therefore be a characteristic of any cable made with that dielectric. The high frequency loss of lower loss cables may not be so well defined, as such loss may be dominated by the semicons, which are not well specified for conductivity and dielectric constant, both of which could vary with cable manufacturing conditions, moisture, temperature, etc. Of course, full characterization of the higher loss cables should also include measurement of the loss vs temperature, and while the loss of most dielectrics does change with temperature, that change is not nearly as great as the change in conductivity of a semicon with temperature.

The alternative to using a cable to protect an inductive device from the effect of fast transients is often the use of a capacitor across the device terminals, which is most common for motors. However, capacitors are substantially less reliable than either cable or motors, and the inclusion of such a capacitor may protect an expensive motor from failure at the cost of reduced overall system reliability. Cable is extremely reliable, and use of a cable as the protective device may be more economical than use of a capacitor, especially when the implications of capacitor failure on overall system reliability are considered.

In summary, high frequency loss of power cables protects power system components from the detrimental effects of fast surges. Where a motor or transformer is connected directly to switchgear or power electronics, a cable installation might be designed specifically to protect the motor or transformer. In other situations, use of a cable with large high frequency loss throughout a power system will reduce the magnitude of transients propagating therein and thereby reduce the failure rate of transformers, motors, capacitors, and other components connected to the power system.

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Li-Ming Zhou was graduated with a Ph.D. degree in electrical engineering from Xi'an Jiaotong University (Xi'an, P. R. China) in 1995. From 1995 to 1998, he visited Eindhoven University of Technology (The Netherlands), Technical University of Ilmenau (Germany), ABB Corporate Research Ltd. (Switzerland), and University of Oklahoma as a Research Scientist. His past research interests have included SO_2/NO_x removal from flue gas by pulsed corona discharge, dielectric barrier discharge for conversion greenhouse gases to methanol and synthesis gas ($H_2 + CO$), and dielectric and arc interruption capability of SF_6 and its mixtures. He has authored and co-authored more than 40 technical articles. He is presently a Post Doctoral Fellow at the Electrical Insulation Research Center, University of Connecticut.

Steven Boggs received his Ph.D. and MBA degrees from the University of Toronto in 1972 and 1987, respectively. He spent 12 years with the Research Division of Ontario Hydro and 6 years as Director of Engineering and Research for Underground Systems, Inc. Steve is presently Director of the Electrical Insulation Research Center of the University of Connecticut and Research Professor of Materials Science, Physics, and Electrical Engineering. He is also an Adjunct Professor of Electrical Engineering at the University of Toronto. He has published widely in the areas of partial discharge measurement, high frequency phenomena in power apparatus, high field degradation of solid dielectrics, and SF_6 insulated systems. He was elected a Fellow of the IEEE for his contributions to the field of SF_6 insulated systems.