Surge Protective Properties of Medium Voltage Underground Cable

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Abstract--**Lightning and switching surges are the most common causes of electrical failures of distribution transformers. Fast rising transients that reach the transformer can cause large turn-to-turn voltages at the line end of the windings and resonances, which result in large voltages to ground elsewhere in the windings, many of which may exceed the winding insulation strength. Field experience indicates that resistor-capacitor devices are effective in preventing switching induced insulation failures by introducing significant damping into the circuit. Since shielded underground cable has the ability to absorb high frequency energy, it may be able to provide similar protection to transformers. During this investigation, impulse and switching tests were performed on representative EPR and TR-XLPE insulated cables connected to distribution transformers. This analysis was directed toward quantifying the attenuation characteristics of different types of cables vis-à-vis fast fronted lightning impulse and switching induced breaker re-ignition transients. The conclusions of this report point to an economical way for protecting transformers from fast fronted voltage transients.**

Index Terms—**Cable insulation, circuit breakers, pulse generation, pulse measurements, power cable, power transformers, transient propagation, transformer windings.**

I. Introduction

Distribution transformers are ubiquitous, robust and are critical components to the delivery of electric power to homes and businesses throughout the world. Over 50 million distribution transformers operate on US electric utility systems, with more than 1 million new transformers added each year and approximately 500,000 removed for end of life or for system upgrades. The average life of distribution transformers is in excess of 30 years, with some lasting much longer, and a small percentage exhibiting a very short life. Failure rates are typically under 0.5%/yr of service (250,000/yr in the US). Lightning is responsible for most of the non-mechanical failures, as a result of high magnitude fast rising transients that can cause uneven voltages within the windings and produce part-winding resonance. Switching surges from vacuum and SF_6 circuit breakers are also capable of inducing extremely fast transients, associated with current chopping and destructive transient recovery voltages. Conservative sizing for the daily and seasonal cyclical loading, results in low average temperatures and modest insulation aging throughout the 30-year life. Very few distribution transformers are victims of overloading and insulation aging breakdowns.

Although distribution transformer failure rates are low, they could be reduced considerably if there was an economical way to dampen destructive high frequency transients. Measurements of switching-induced transients [1] have provided evidence for destructive voltages with frequencies well above the first winding resonance in the range of 50 kHz, and even exceeding 3 MHz. Circuits that are vulnerable to such destructive voltages are generally highly inductive, with very low power factor (almost no real load) and very little system damping to absorb the associated stored energy. Although most modern distribution transformers are protected by metal oxide (MOV) arresters, fast transients are not limited effectively due to inductances in leads [2] and/or rapid rise transients that are below the arrester operating voltage. In many cases, the line-to-ground voltages at arrester locations are a small fraction of the line-to-tap voltages within the transformer windings.

Hopkinson, et al [3] have instrumented and measured voltages on circuits that were associated with transformer winding insulation failures. Some of these insulation failures have occurred near the line ends of the transformers. A great many of the insulation failures have occurred near the mid-points of the windings, especially associated with taps. Fig. 1 is typical of transient voltage induced transformer winding failures.

In most of these circuits, replacing the failed transformer with another of similar or different construction has resulted in repeat failures, attributed to resonances and a lack of damping. Resistor-capacitor snubbers in parallel with the lightning arresters have provided circuit damping and have eliminated such damaging transients protecting the transformer. Although snubbers together with arresters do an

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excellent job, they are costly and may not be necessary for all installations.

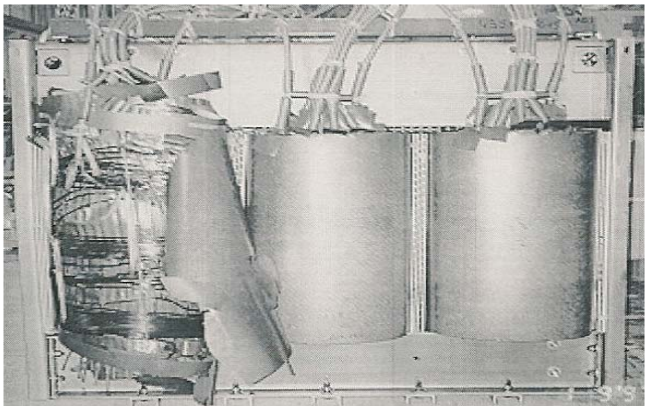

Fig. 1. Transformer layer-to-layer flashover with telescoped windings

In search for less expensive functional equivalents for snubbers, the issue of high frequency loss in the primary cable becomes relevant. Work done by Boggs et al. [4] indicates that shielded power cable contributes to the attenuation of transients. Furthermore, this work concluded that cable types differ substantially in their high frequency attenuation and resulting levels of circuit protection. If this is true, then it is fair to question what attributes are responsible for attenuation performance. Fig. 2 is a cut-a-way of a typical cable and shows several regions where high frequency dissipation can occur. In simplistic terms, a central conductor is covered with an electrical stress control layer, which is enclosed by an extruded dielectric. The dielectric is covered with a semconducting shield layer, which contains the electrical field within the cable insulation. This core is overlaid by a metallic shield which drains charging currents from the semi-conducting polymer. The cable is then typically covered with an overall jacket.

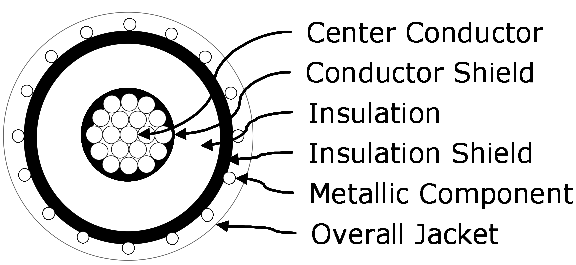

Fig. 2. Typical medium voltage underground distribution cable

There are several high frequency loss mechanisms within medium voltage shielded cable. The most significant are the losses in the shield layers and the insulation. Since user specification of the size and placement of the metallic component and the dimensions of the extruded polymer layers makes all cable manufactured to a user's specification identical in these areas, the differences in high frequency losses between cable manufacturers devolves to the differences in electrical properties of the extruded polymer layers.

The two generic types of medium voltage underground cable in use today are rubber-insulated (ethylene propylene rubber – EPR) and polyethylene insulated (tree-retardant, cross-linked polyethylene – TR-XLPE). Within the rubber insulated cables there is further differentiation due to formulation and cable design differences. EPR cable has somewhat higher dissipation factor and permittivity within the insulation than does TR-XLPE. The power consumed, or dissipated, within the cable insulation is proportional to the dissipation factor, permittivity, and frequency. At 60 Hz, the resulting power dissipation constitutes the insulation losses. With high frequency transients, the same properties appear and contribute to attenuating the surge and reducing its potential to do damage to both the cable and connected apparatus.

The high frequency attenuation properties of various solid dielectric distribution cables were investigated through surge tests of the cables connected to distribution transformers in order to determine the effect of the cable on the surges, which reach the transformer. The cables were selected to be identical in construction, except for the differences between the polymer materials used in the shield and insulation layers. The effect of length was also explored.

II. Test Program

The cable construction tested was typical of medium voltage underground residential cable, viz., #2AWG, 7 strand, aluminum 15kV, 100% insulated (175 mils), with a full neutral (10, #14AWG bare copper wires), and with an encapsulating overall polyethylene jacket. Three insulation types were tested, from high to low dielectric loss they were – EPR1, EPR2, and TR-XLPE. High frequency voltage surges were introduced by both an impulse generator and by a vacuum switch. The cables were tested in lengths of 50 to 800 meters.

A. Impulse Test Circuit

Impulse testing was performed to simulate utility service lightning performance conditions. Fig. 3 shows the test setup used to simulate a shielded cable fed distribution transformer. A Tektronix four channel digital oscilloscope and high voltage probes were used to record the data. An MOV arrester was included in the circuit to protect the equipment.

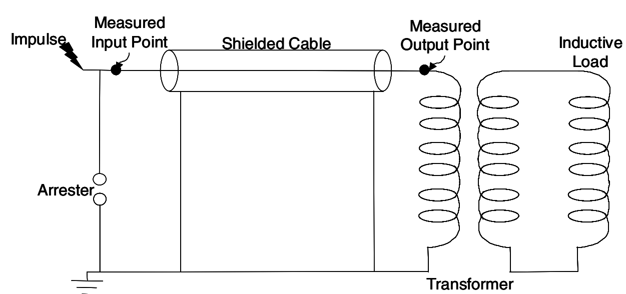

Fig. 3. Transformer impulse test setup

The transformer tested was a 150 kVA, three-phase unit rated 13,200 volts delta, with 208 Y/120 volts secondary. Although the transformer was a three-phase unit, all tests were on one phase. The inductive load on the secondary side of the transformer was the primary of a 50 kVA single phase transformer, rated 7620/13200Y to 120/240 volts secondary, with the secondary windings open-circuited. Inductance was used because reported field failures have generally been associated with light load conditions when power factor has been highly inductive. Experiments on the setups with and without inductance verified that voltage transients were more pronounced with the inductance present.

Factory impulse testing of transformers for BIL compliance is normally performed with a 1.2x50 µs full wave. Lightning can have much shorter rise-times, in the range of 0.5 µs or less. Transformer winding-failures are more likely as impulse rise-times become shorter. A direct strike near a riser pole can cause rise-times in the order of 0.1 µs for voltages that travel down the pole and reach the transformers.

To simulate the effects of such a lightning stroke, an impulse generator was charged to one million volts and discharged into the cable under test, which was shunted to ground by a set of adjustable sphere gaps. This test configuration produced rise times in the range of 50 to 100 nanoseconds.

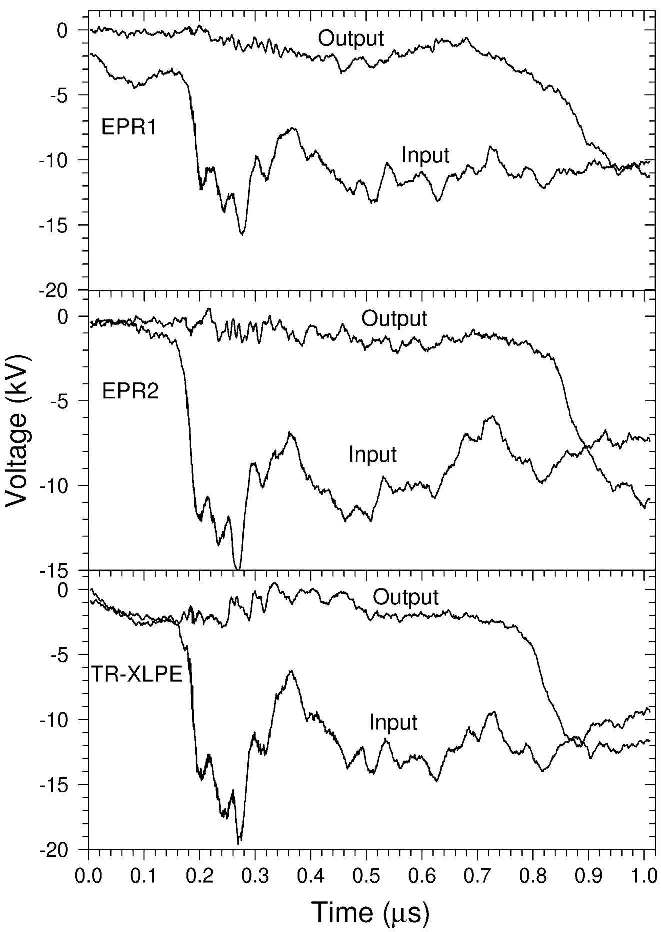

Fig. 4. Typical Impulse Test Recordings

With such fast rising waves at the input to the cables, differences in surge attenuation of the various cable insulations were expected. Fig. 4 shows typical input and output waveforms for the cables tested, with cable length and impulse generator sphere gap settings the same for each type of cable.

The purpose of the impulse testing was to measure the effect of the cables in attenuating high frequency surges and not to destroy transformers. For this reason the input impulses were restricted to a maximum of 40 kV. Changes in the surge rate of rise were of greatest interest, as very rapid rates of rise cause excessive voltage drop to occur across the line-end of the winding and tend to stimulate the effects of resonance within the windings, both of which can cause winding failure. In this test program, changes in the rate of rise between the input of the cable and the cable-transformer interface were measured as a function of cable insulation and cable length.

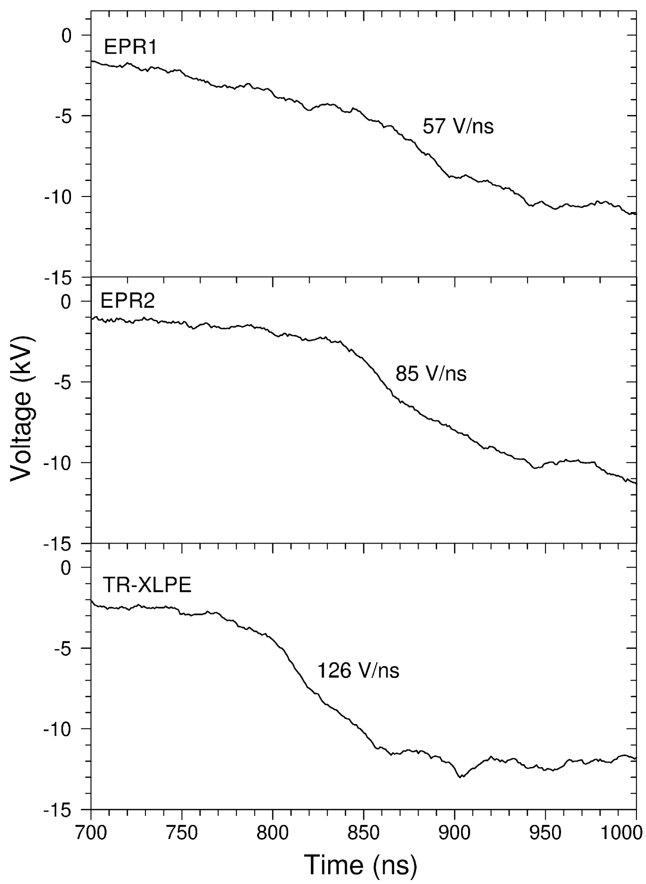

Fig. 5. Determining relative output rate-of-rise

The recorded rise-time of the impulse generator output varied somewhat during tests of shorter cable lengths, probably as a result of the small capacitive load. However the resulting trends in output rise-time as a function of cable dielectric were consistent in spite of such variations. Figure 4 shows typical input and output waveforms for 100 m cable lengths. To be systematic, the slope was defined as the maximum voltage change in a 70 ns window (Fig. 5). Data for 400 m cable lengths were more consistent with less high frequency noise (Fig. 6).

There is also evidence in Fig. 6 that the wave propagation velocity varies with insulation types, as would be expected. The propagation velocity of TR-XLP and EPR1 are estimated at 54% and 49% the speed of light respectively, which is much less than would be predicted from the permittivity of the dielectrics because the very high permittivity of the Test Results shields has a significant effect on propagation velocity.

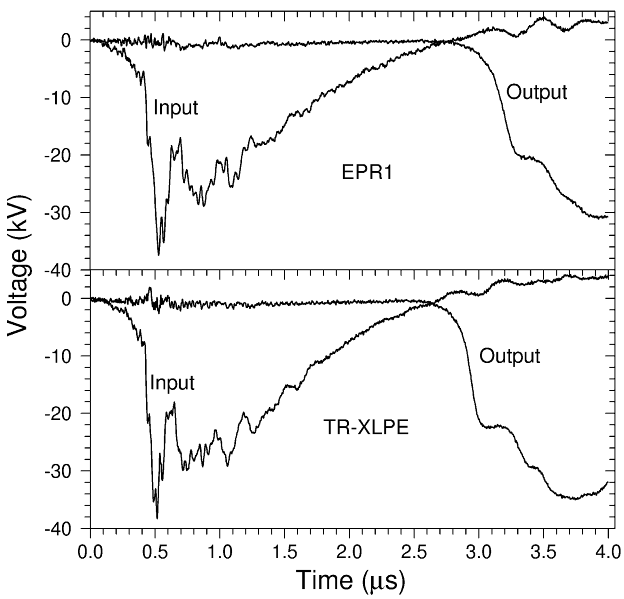

Fig. 6. Typical recording of longer cable length test showing well defined impulse waves.

B. Impulse

Waveform rise-times (maximum dV/dt) were obtained from the recorded data over a range of cable lengths (50 to 800 meters), and over a range of sphere gap settings of 1 to 3 cm, which corresponds to impulse front-of-wave shape range of 15kV/50ns to 33kV/90ns.

Fig. 7 is a summary of the impulse test results extracted from the recorded impulse data. The results are presented as the output of the high frequency impulse in v/ns rate-of-rise, measured at the transformer line terminals. These results, when presented as change in rate-of-rise from input to output, yield the same relative attenuation performance of the different cable types.

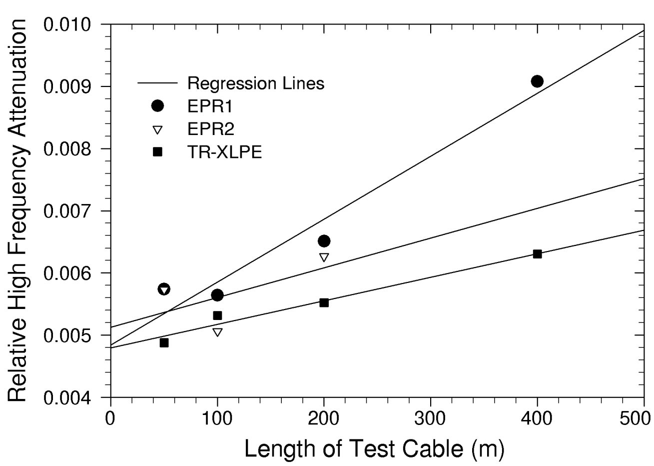

Fig. 7. Summery of high frequency attenuation results

The results of testing at each impulse level each yield the same relative results with EPR1 attenuating the high frequency impulse to a greater degree than does either TR-XLPE or EPR2. The degree of attenuation provided by EPR1, relative to TR-XLPE and extracted from the data, is presented in Fig. 7 and Table I.

The significance in the results is not in the absolute numbers, but in the consistency with which EPR1 outperforms TR-XLPE in attenuating high frequency voltage surges. The variance of results caused by test and analysis methods raises questions about the precision of the absolute results.

TABLE I
COMPARISON OF THE DEGREE OF HIGH FREQUENCY SURGE ATTENUATION EPR1 COMPARED TO TR-XLPE

Cable Length - Meters	Gap	1 cm	1.5 cm	2 cm	2.5 cm	3 cm
	50	-	160%	-	-	-
	100	221%	137%	135%	175%	163%
	200	146%	133%	163%	156%	142%
	400	244%	198%	149%	130%	154%

Developing the methodology to determine expected performance by circuit analysis appears to be a better way of quantifying the effect in a usable way. A companion paper [5] by Boggs (et al) explores the development of equivalent results by circuit analysis.

C. Switching Transient Testing Set-up

The second part of the test program involved testing the cable in a circuit with a vacuum interrupter. Switching is the other source of potentially damaging voltage surges. The circuit used in the test program is shown in Fig. 8.

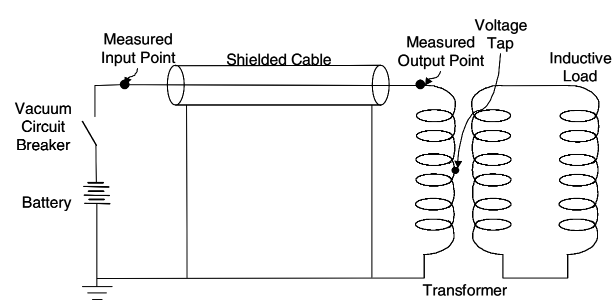

Fig. 8. Switching surge test setup

In the case of these switching tests, the transformer tested was a 50 kVA, single-phase unit rated 7970/13800Y to 120/240 volts secondary. The inductive load on the secondary side of the transformer was the primary of a 50 kVA single phase transformer, rated 7620/13200Y to 120/240 volts secondary, with the secondary windings open-circuited.

The test cable was connected to one of the two bushings on the transformer. The other bushing was connected to ground. Each of the transformer secondary bushings (X1 and X2) were connected to one of the high voltage bushings on the inductive load. All equipment was grounded appropriately. The switch was a 15 kV, three-phase vacuum breaker. An adjustable battery was used as the power source to energize the circuit. Data were collected at three battery settings – 10, 14, and 18 volts DC. The vacuum switch was closed to allow the battery to charge the circuit, and then opened to record the effect. The authors' objective was to have the breaker interrupting 5 to 10 amps.

A single-phase transformer was selected for the switching testing in order to have ready access to a mid-winding tap. The objective was to obtain a measure of partial winding resonance, which is characteristic of surges caused by switch contact re-ignitions and not an effect associated with lightning induced surges. The circuit was specifically designed with a highly inductive secondary load in order to cause switch contact re-ignitions. Data were recorded at the cable connection to the vacuum breaker, the cable connection to the transformer, and the mid-winding tap of the transformer (Fig. 8). Fig. 9 presents typical data.

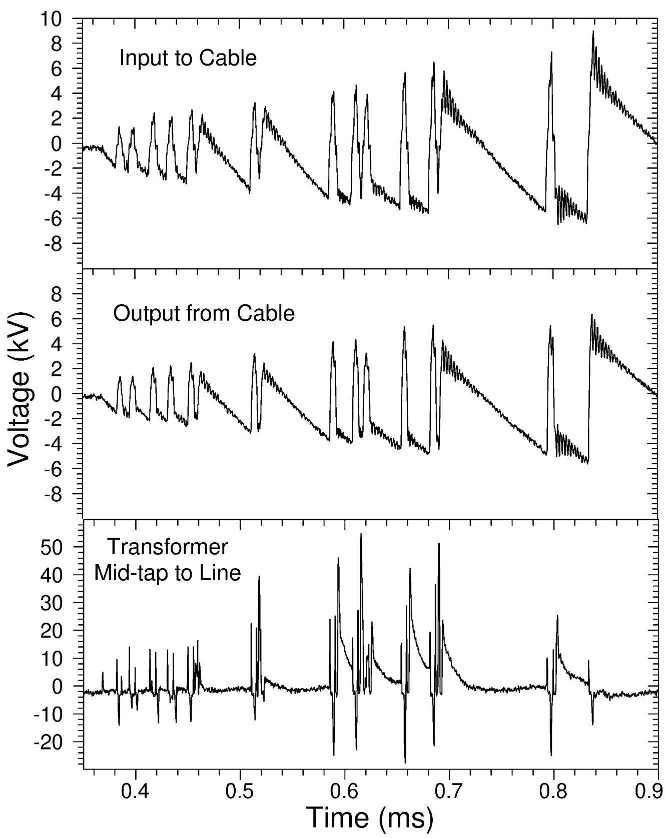

Fig. 9. Typical results of the switching testing showing the re-ignition of the switch contacts and the transformer high mid-tap voltage caused by winding resonance. This recording is from a 200-meter sample of TR-XLPE.

Although the surges generated by this testing were less aggressive than those produced by the impulse generator (300 to 700 kHz bandwidth versus impulses in the 2 to 3 MHz range), they still qualified as steep-front waves. The relative ability of the connected cable to attenuate the potentially damaging surges reaching the transformer was also evident in the test results.

The cable length, regardless of cable type and DC charging voltage, has an effect in determining the maximum mid-tap voltages attained, presumably as a result of resonance between the cable and transformer.

The resulting data can be analyzed in several ways to determine surge attenuation. The maximum amplitude of surges at the vacuum switch appeared to be dictated more by cable length than by cable type as would be expected of pulses with a fundamental frequency in the range of 300 to 700 kHz range. However, the type of cable has a significant impact on the rate of rise of the surges including the surges between the transformer line terminals and the mid-taps, the number of switch contact re-ignitions, and the number of voltage spikes recorded on the mid-tap. Fig. 10 illustrates how different cable types impact the amount of surge activity recorded at the transformer mid-tap.

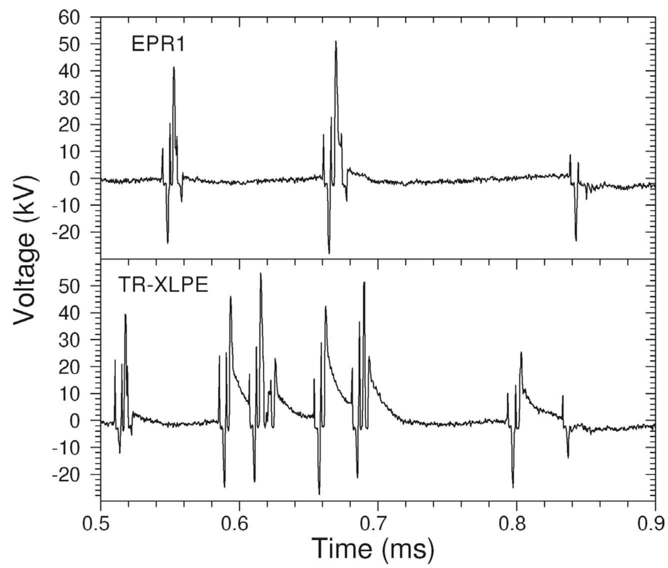

Fig. 10. Example of the different level of winding resonance occurring at the transformer mid-tap with the different cable types.

D. Switching Surge Test Results

Tables II through IV provide a summary of attenuation differences among the tested cables, using the three techniques described. In each table the relative attenuation was compared to the results obtained for TR-XLPE cable by dividing the TR-XLP results by those for the EPR cables.

TABLE II
COMPARISON OF THE DEGREE OF HIGH FREQUENCY SURGE ATTENUATION COMPARING MAXIMUM TAP VOLTAGE SURGE RATES-OF-RISE VS TR-XLPE

		TEST CABLE LENGTH - METERS			
		400	200	100	50
10V-DC	EPR1	279%	114%	202%	125%
	EPR2	-	88%	90%	131%
14V-DC	EPR1	108%	140%	112%	192%
	EPR2	-	134%	154%	331%
18V-DC	EPR1	104%	107%	123%	383%
	EPR2	-	87%	127%	196%

TABLE III
COMPARING THE NUMBER OF SWITCH CONTACT RE-IGNITIONS VS TR-XLPE

		TEST CABLE LENGTH - METERS			
		400	200	100	50
10V-DC	EPR1	100%	144%	100%	179%
	EPR2	-	108%	75%	136%
14V-DC	EPR1	140%	91%	121%	100%
	EPR2	-	56%	100%	110%
18V-DC	EPR1	450%	150%	143%	343%
	EPR2	-	94%	333%	171%

TABLE IV
COMPARING THE NUMBER OF MID-TAP VOLTAGE SPIKES VS TR-XLPE

		TEST CABLE LENGTH - METERS			
		400	200	100	50
10V-DC	EPR1	100%	200%	74%	150%
	EPR2	-	129%	74%	131%
14V-DC	EPR1	145%	125%	138%	67%
	EPR2	-	88%	145%	62%
18V-DC	EPR1	420%	110%	317%	200%
	EPR2	-	48%	283%	200%

The average degree of high frequency surge attenuation versus TR-XLPE for each of the three battery-voltage comparisons show for EPR1: 166%, 172% and 170% respectively. For EPR 2 it is 149%, 132% and 124%

III. CONCLUSIONS

The following are the authors' conclusions resulting from this test program:

1. Medium voltage, shielded power cables do indeed have a similarity to conventional resistive-capacitive resonance damping devices by introducing resistive damping at high frequencies through dielectric loss.
2. EPR insulated cable has dielectric properties which provide more dampening of high frequency surges than TR-XLPE insulated cable
3. Attenuation of high frequency voltage transients in EPR insulated cable appears to be in the range of 40% to 100% better than with TR-XLPE, which results in less stress on transformer windings.
4. The choice of cable cannot preclude the need for either conventional surge arresters or resistive-capacitive resonance dampening devices for all cases; however, the choice of cable can yield a level of protection, which will reduce the need for such devices in many situations. Since the need for damping devices is usually discovered through transformer failure, the use of cable with good damping characteristics will reduce the incidence of such failures.

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V. BIOGRAPHIES

Philip Cox was born in Memphis, Tennessee, USA on 3 July 1958. In 1980, he received a BSEE, with concentration in Clinical (biomedical) and Power Engineering, from Christian Brothers College (University) in Memphis. Other education includes courses in computer programming, law and pre-med. He is a licensed/registered Professional Engineer in Vermont and Tennessee (USA). He has over 24 years of experience in the electrical power industry and has held various positions at Memphis Light, Gas And Water. Experience includes lighting design, power applications engineering consultation and his current position as Underground Electric Transmission & Distribution Systems Engineer (MLGW). He has served on various Insulated Conductor Committee (ICC) working groups as standards/guide contributing writer, chairman and vice-chairman. He has authored several papers and presentations for the IEEE-Power Engineering Society.

Harry L. Hayes, III is a Senior Member of IEEE and has been a member of IEEE for twenty-five years. He received his BSEE Degree from Washington University (St. Louis, MO) in 1978. He received his MA Business Administration and MA Finance Degrees from Webster University (St. Louis, MO) in 1983. He joined Ameren Corporation (formerly Union Electric Co.) in 1979 and has held various engineering positions. He is currently a Consulting Engineer in the Distribution Standards Group. His work has included specialized projects in connectors, transformers, and cables. Mr. Hayes is an active member of numerous ANSI and IEEE Working Groups and Task Groups. Currently, he serves as Vice-Chairman of Discussion Group A16D (Characteristics of EPR Cables) of the IEEE-Insulated Conductors Committee and Vice-Chairman of IEEE 386 Standard for Separable Insulated Connector Systems for Power Distribution Systems above 600 V. Mr. Hayes also serves as Chairman of the Association of Edison Illuminating Companies Cable Engineering Committee.

Phil Hopkinson is an IEEE Fellow and long service Transformer Engineer. He received his BS in EE from Worcester Polytechnic Institute in 1966. He also graduated from GE's Advanced Engineering Course in 1970 and simultaneously received his MS in System Science from Brooklyn Polytechnic Institute. From 1966 to 2002, Phil held numerous design and engineering management assignments in the transformer businesses of GE, Cooper Power Systems and Square D Co in liquid filled, dry, and cast resin transformers of all power ratings and voltage classes. In 2001, Phil formed a power transformer consulting company, called HVOLT Inc. and since 2002 has managed HVOLT full time. He currently holds 15 US patents, is a Registered Professional Engineer in North Carolina, and is Technical Advisor (TA) to the US National Committee for IEC TC14 for Power Transformers. He has authored IEEE Transactions papers on the effects of DBPC in Transformer Oil, on Low Voltage surge phenomena in Distribution Transformer windings, and has Chaired NEMA's activities and was primary author of NEMA TP-1 Guide for Energy Efficiency for Distribution Transformers. He has chaired numerous IEEE and NEMA Working Groups and from 2001-2003 was Chairman of IEEE's Policy Development Coordinating Committee.

Rick Piteo (M'04) graduated from the University of Massachusetts in 1971with a B.S in Electrical Engineering. He also attended Western Connecticut State University and Pace University where he focused on Business and Computer Science courses. He is a Professional Engineer in the State of New York and has worked as a Project Engineer/Project Manager on many power and industrial related projects. His employment experience has included the design of power station grounding systems and the design of corrosion protection systems for both nuclear and fossil power stations. He has also participated in Nuclear Safety System Analysis projects and Safety Systems Interaction Projects. Most of Mr. Piteo's experience has been with Architect Engineering Companies in the New York Metropolitan Area. He is now working at Orange and Rockland Utilities as a Sr. Underground Transmission and Distribution Engineer, where he designs and manages the construction of underground transmission and distribution engineering projects.

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.