The "Lightning-Protected" Transformer

How to Improve Distribution Transformer Reliability, Safety, and Economics Through a Coordinated Approach to Overcurrent and Overvoltage Protection

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I. INTRODUCTION

Distribution transformers have received increased attention by utility purchasers over the past several years. The focus has been on improving efficiencies (lower losses) and reliability while maintaining an affordable purchase price.

New research into lightning characteristics, and recent research performed by EPRI Electrical Power Research Institute), and others on transformer surge characteristics, has provided new information to help utilities improve transformer reliability. Manufacturers are also developing new products based on this new data that will enable utility purchasers to improve transformer reliability by a significant order of magnitude.

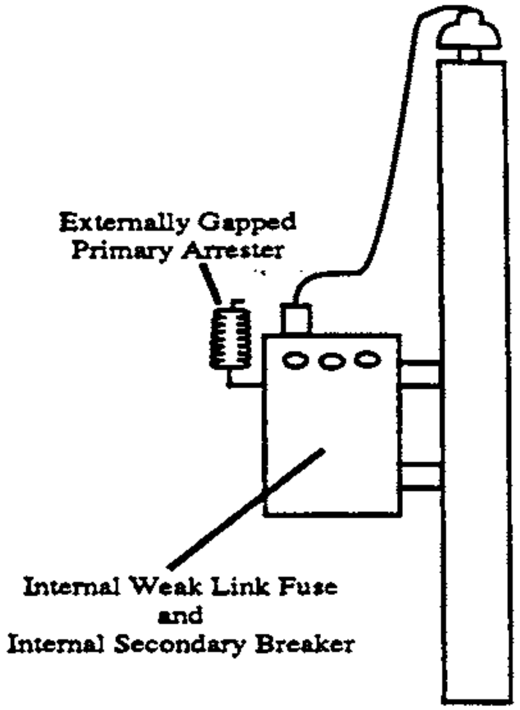
Transformer failure rates due to all causes have been stated to be 1% per year for the industry at large. This failure rate is considered to be normal for most systems throughout the United States using traditional transformer protection practices. Failure rate reductions to less than 0.1% per year are achievable.

Failure rate reduction provides economic incentive to the utility purchaser. Every 0.1% reduction in failure rate is worth approximately 1% of the purchase price of the transformer[1]. This would translate to a 9% savings on new transformer purchases assuming a 1% overall system failure rate is reduced to 0.1% annually on new purchases.

II. PRESENT CSP TRANSFORMER PROTECTION PRACTICES

The completely self-protected (CSP) transformer typically includes:

- *Externally gapped silicon carbide primary arrester*
- *Internal weak link fuse*
- *Internal secondary breaker*



This protection scheme has technical merit and should provide a more reliable installation than a typical conventional transformer installation. However, utilities have continued to be concerned with the CSP transformer for many reasons, including:

- ***No visible indication of failure***
- ***Continuity of service was more important than overload protection***
- ***Breaker operating problem-shafts, handles, linkages, emergency overload, signal lights, etc.***
- ***Breaker calibration concerns***
- ***Nuisance fuse blowings of internal weak link fuses***

The nuisance fuse blowings of internal weak link fuses probably has had the greatest impact on a CSP user's decision to switch to conventional designs. This problem was identified as a serious concern by the REA administration, as early as 1950. The REA conducted a survey of their members in the early 1950's, concerning their experience with CSP transformers. The survey results concluded that 13% of the failures of CSP transformers were caused by the internal weak link fuse blowing for no reason other than lightning. This resulted in an extended outage, since the transformer had to be replaced because the internal weak link fuse was not field replaceable.

There was considerable speculation in that day that secondary surges were a major cause of these nuisance fuse blowings. Core saturation due to secondary surges was speculated to be one major cause of nuisance fuse blowing especially where expulsion arresters were used on the primary side of the transformer. This concern in addition to the above noted concerns prompted the utilities to move away from the CSP transformer.

III PRESENT CONVENTIONAL TRANSFORMER PROTECTION PRACTICES

Utilities have continued to move away from CSP type transformers to conventional transformers with remote mounted arresters. The annual purchase of CSP type units is only about 20% of all distribution transformers purchased today. Figure 2 shows a typical transformer installation used by the majority of conventional transformer users. With this installation, the primary arrester is located on the source side of the fuse protecting the transformer. This arrangement requires the arrester to be mounted remotely from the transformer.

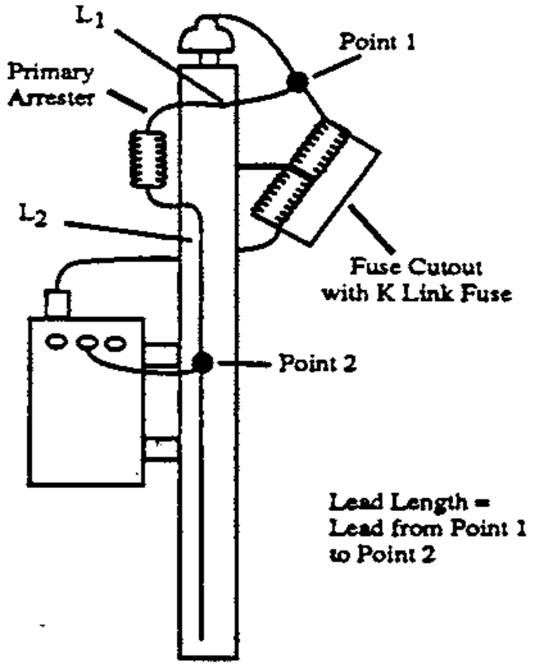


Figure 2 - Typical Conventional Transformer Installation witb Remote Mounted Arrester

If the anester could be mounted on the transformer tank, the lead length, $L_1 + L_2$, necessary to connect the arrester to the system would be substantially reduced. (It has been documented that the shorter the lead lengths between the arrester and the transformer, the better the overvoltage protection for the primary transformer windings). However, in this configuration shown in Figure 3, the fuse link now will be required to carry the surge energy, and this creates concerns about excessive nuisance fuse blowings due to lightning.

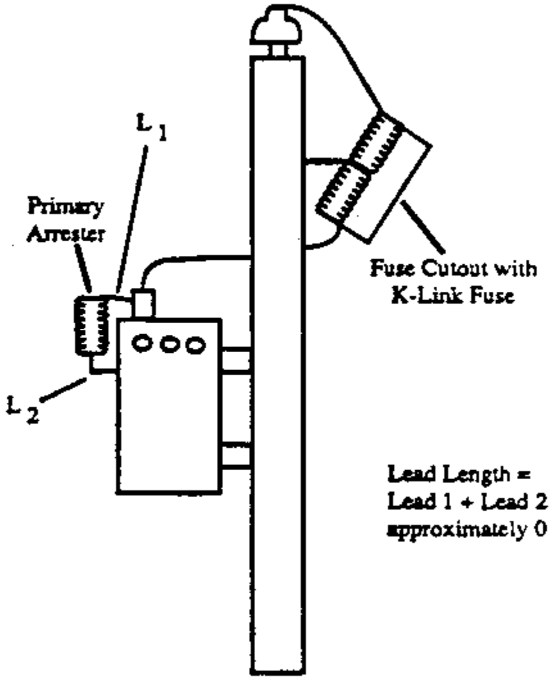


Figure 3 - Typical Transformer Installation with Tank Mounted Arrester

Many utilities have, however, elected to improve surge protection by tank mounting the surge arrester, or placing it under oil, and have compromised on the ability to protect the transformer from overloads by using a rather large fuse site to minimize nuisance fuse blowings due to lightning. Typically, the minimum fuse size used is a 12 amp K link or larger. The 12K link, in this case, simply serves to remove a failed transformer from service. Overload protection in reference to the ANSI transformer damage curve is not achievable with the 12K link as can be seen in Figure 4. (Figure 4 also illustrates the characteristics of a 5K link which would provide overload protection. The 5K link, however, would create concerns about excessive nuisance fuse blowings due to lightning based on its characteristics in the 0.1 to 0.01 second region).

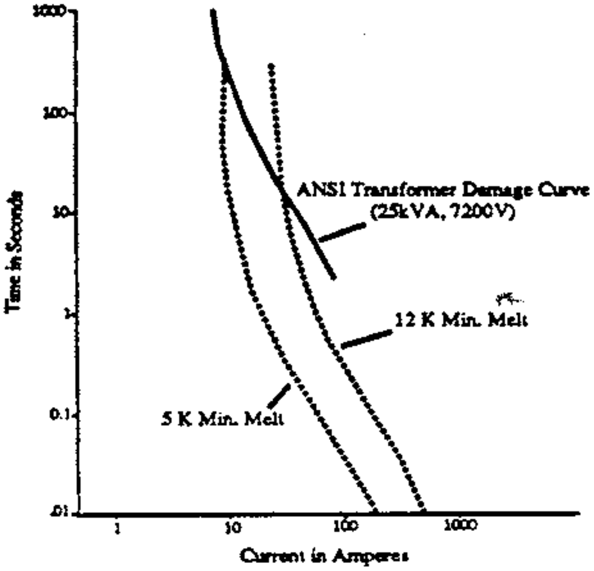


Figure 4 — Conventional Fuse Practice with Single Element Fuse Link

IV. CAUSES OF TRANSFORMER FAILURE

Distribution transformers fail for a variety of reasons:

- Lightning Surges
- Overloads
- Secondary Short Circuits
- Wildlife Flashovers
- Contaminated External Flashovers
- Leaks
- Manufacturing Defects
- Others

Lightning surges continue to be the major cause of premature transformer failures. It has been estimated to be a factor in 60-90% of all causes of failures.

There are three key factors that affect the surge performance of overhead pole type distribution transformers:

- *Fast Rise Time Surges that generate excessive voltage through the primary arrester and connecting leads.*
- *Lightning surges that enter the unprotected secondary winding.*
- *Overloads that weaken the transformer dielectric strength due to longer term thermal aging of the insulation and short term gas bubble evolution in the windings.*

Fast front surges and secondary surges both have the potential to fail new transformers where the dielectric strength is more than adequate from a traditional protection standpoint. However, when aged insulation, and transient overloads are taken into consideration, the problem becomes even more acute.

V. FACTORS AFFECTING TRANSFORMER SURGE PERFORMANCE

A. Real World Lightning: Recent research into the actual characteristics of lightning strikes has shown that the standard 8 x 20μs waveshapes used for insulation coordination studies is not representative of surges that are typical in the real world. Recent data has been documented, as shown in Figure 5, as being more representative of actual lightning surges in the field[2]. Figure 5 indicates, for example, that 57% of actual lightning surges have a rise time of 2.5μs or less which is substantially faster than the standard 8μs rise time.

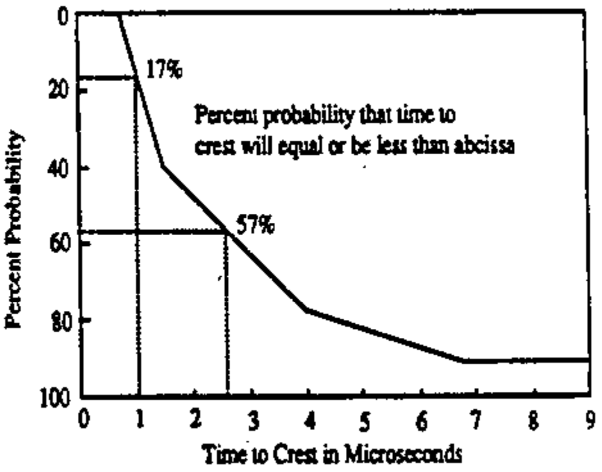


Figure 5 - Time to Crest vs. Probability

Fast rise time surge currents can generate substantial voltage drops in primary arrester connecting leads. In some cases, it can actually exceed the transformer arrester discharge voltage. This has a major effect on the margin of protection. For a conventional transformer installation, as shown in Figure 2, with a remotely mounted arrester, the voltage drop from the connecting leads must be added to the arrester dischage voltage when calculating protective margins.

Fast rise time surge currents can also result in an increased arrester discharge voltage. This increased voltage is more severe for silicon carbide arresters than for metal oxide varistor (MOV) arresters. Figure 6 shows the effects of fast rise time surges for both MOV and silicon carbide arresters as a multiplier to the arrester discharge voltage. For example, if the discharge voltage of a silicon carbide arrester for a 10kA 8x20µs surge was 35 kV, then using Figure 6, the discharge voltage for the same arrester for a 10kA 1x 10µs surge would be approximately 1.25 times 35kV or 44kV. The effects of fast rise time surge currents on the voltage drop due to the connecting leads and on the arrester discharge voltage substantially increase the voltage impressed on the transformer major insulation.

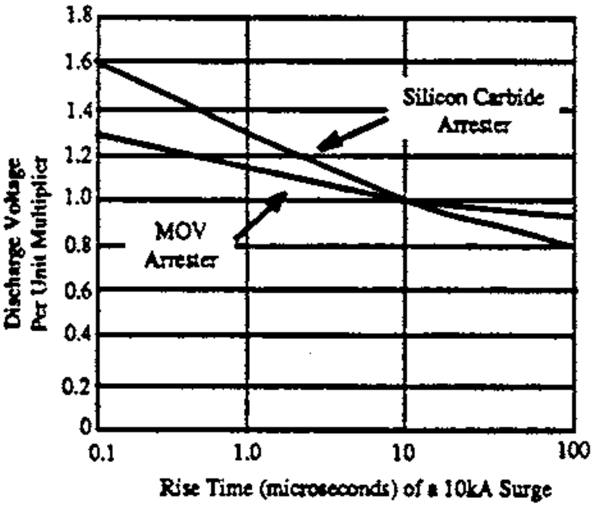


Figure 6
Effects of Fast rise Times on Discharge Voltage

B. Surges Entering Transformer Secondary Windings: The investigation of "secondary surges" and how they affect transformers has been studied extensively. References have been well documented over the past three years and new information from ongoing research is showing this to be a very significant cause of transformer failures.

Recent research shows that secondary surges can and do cause failures of overhead distribution transformers. For instance, one study by a southern utility concluded:

> *50 to possibly 70% of all impulse related pole type transformer failures are due to secondary surges.*

The subject is complex and involves the analysis of the entire secondary system including the customer loads, and the surge protection employed by the customer.

The conclusion that can be drawn from the laboratory investigations, transformer teardowns, and digital simulations of the problem are as follows:

- *Surges entering the unprotected secondary windings of a typical pole type transformer are a significant problem.*
- *The problem has gone undiagnosed until recently because secondary surge failures show up as primary winding failures.*
- *Although interlaced designs have a lower inherent failure rate than non-interlaced designs, both designs can and do fail from secondary surges.*
- *Primary arresters are ineffective in protecting against secondary surges.*
- *Low voltage arrester protection is the only effective means of eliminating the problem*^{3}.

C. Overloads: Overloads affect transformer dielectric performance in two ways:

- *Long term thermal aging of the insulation system reduces dielectric strength.*
- *Short term transient overloads can reduce dielectric strength* ***temporarily*** *as a result of gas bubble evolution in the windings*^{4}.

This well documented problem has been studied by ERDA (Energy Research and Development Administration) and EPRI. The conclusions from these studies clearly show that the dielectric strength of the transformer insulation system can be critically affected due to thermal aging and transient overloads.

Thermal aging permanently reduces transformer dielectric strength due to degradation of the paper insulation and the evolution of aging related contaminants in the oil (ie, water, acid, carbon dioxide), which occur as the transformer is operated over its life time.

Transient overloads temporarily reduce dielectric strength due to gas bubble generation in the oil because hot spot temperatures act on the paper insulation. This problem can be even more severe if sudden pressure changes occur. One such scenario is typical in the southern parts of the United States. Heavy air conditioning loads, on hot summer days, are usually accompanied by sudden lightning storms with large amounts of rain, and cause rapid cooling of the transformer. The transformer will experience a sudden drop of internal pressure, which

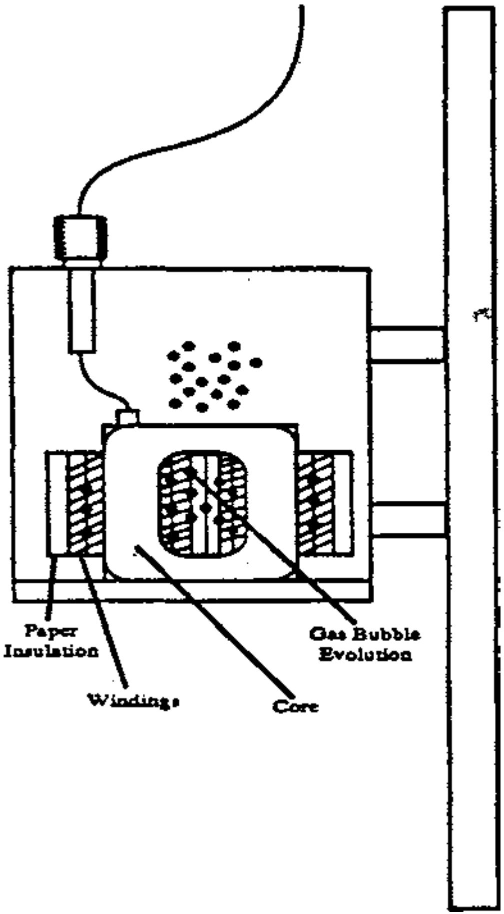


Figure 7 - Gas Bubble Evolution Due to Severe Overload

exacerbates the bubble formation in the transformer windings. (Figure 7 indicates the location of the gas bubble evolution in the windings of the transformer). A familiar analogy would be the soft drink fizz that occurs when the pressure is suddenly reduced above the liquid when the bottle is opened.

It is well known that gas bubbles will significantly reduce the dielectric strength of oil. This condition makes the transformer more susceptible to primary surges, as well as secondary surges. Unfortunately, this condition often occurs during a thunderstorm, when the transformer is most likely to be struck by lightning. Studies performed on this phenomenon have estimated the dielectric strength can be reduced by as much as 50% of the rated withstand level due to a combination of aging, and transient overloads. This reduction in dielectric strength should be taken into account when evaluating margins of protection. An example of the effects of reduced BIL can be seen in Appendix B and C using 60% of rated BIL.

VI. THE "LIGHTNING-PROTECTED" TRANSFORMER

This new information from research on transformer performance gives us the chance to revisit the traditional methods of protecting transformers from failure. There is an opportunity to take the industry stated 1% per year failure rate and reduce it less than 0.1% per year with the "lightning-protected" transformer. The "lightning-protected" transformer shown in Figure 8, should consist of,

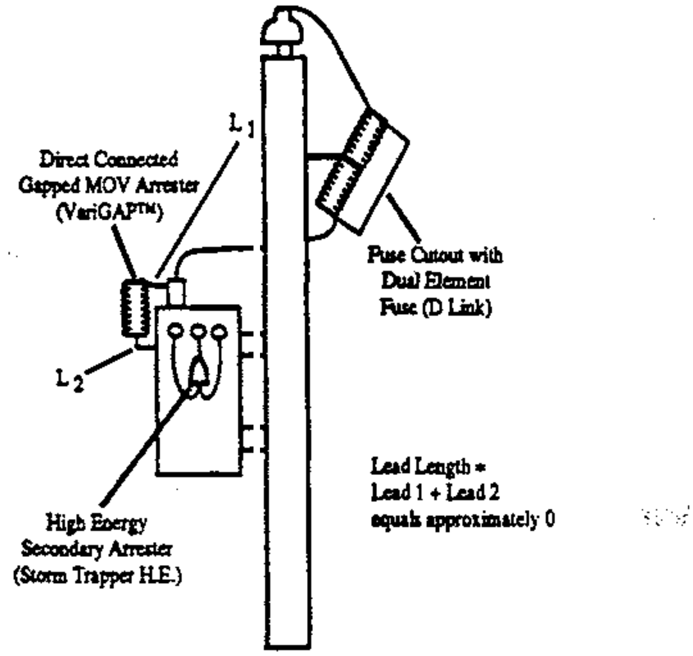


Figure 8 - A Lighting-Protected Transformer

- *Cutout mounted, dual element, high surge withstand fuse link*
- *High energy low voltage surge arrester on the secondary terminals*
- *Tank mounted direct connected* ***internally*** *gapped MOV arrester*

A. ***Dual Element, High Surge Withstand Fuse Link:*** The development of a new multiple element fuse link that is resistant to damage by surges, has helped make this new concept achievable. Figure 9 shows the characteristics of the dual element, high surge withstand fuse link.

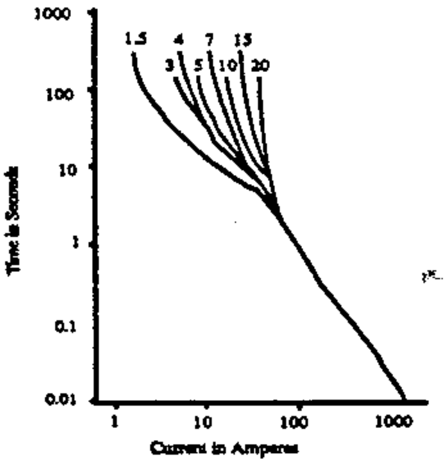


Figure 9 - D Link TCC

Previously discussed in Figure 4 was the application of a 12K link to minimize nuisance fuse blowings due to lightning with a compromise to overload protection in reference to the ANSI transformer damage curve. The new dual element fuse provides fhe high surge capability typical of larger amperage rated links while providing the overload protection of small amperage rated links (Refer to Figure 10). This fuse design makes it possible to place the primary arrester on the transformer tank, eliminating excessive lead connecting lengths, thus providing the best surge protection possible to the primary winding.

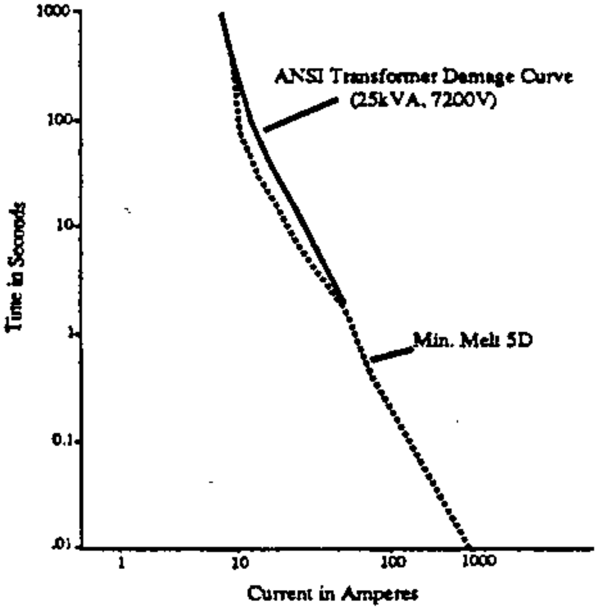


Figure 10 -Dual Element Fuse Protection

In addition, a high surge withstand fuse mounted in series and on the source side of an arrester can provide protection in the event of arrester failure by limiting the amount of time the arrester will see fault current. This provides a safety assurance that there is protection from the hazards on an unprotected failed arrester.

B. ***High Energy Low Voltage Surge Arrester:*** The application of a **high energy** low voltage arrester to the secondary terminals of the distribution transformer will **eliminate** failures caused by secondary induced surges. Field experience with transformers that have employed secondary surge protection has clearly shown a **substantial** reduction in failure rate performance compared to units not protected with arresters on the secondary.

Over 40,000 transformers with secondary protection have been installed, with the first units being placed in service in 1986. The overall cumulative failure rate of this population of transformers due to all causes is less than 0.05%. These transformers are installed in mostly east coast locations from Florida to Pennsylvania, representing some of the most severe lightning exposure environments.

C. ***Tank Mounted Direct Connected Internally Gapped MOV Arrester:*** The availability on a new internally gapped MOV distribution arrrester (VariGAP™), offers a means to further protect the primary winding from lightning surges. This new technology provides up to a 30% improvement in surge protection, and provides up to a 50% improvement in temporary overvoltage capability over traditional gapless MOV distribution arresters. This can be seen in Figures 11A, B, and C which show a comparison of protective margins for various protection schemes and various conditions of transformer dielectric strength.

This new technology is available in both porcelain and polymer housed designs, and will extend transformer dielectric life, even under the most severe conditions of lightning duty and transformer overload conditions.

Percent Margin of Protection with Arresters for Conventional Overhead Transformers

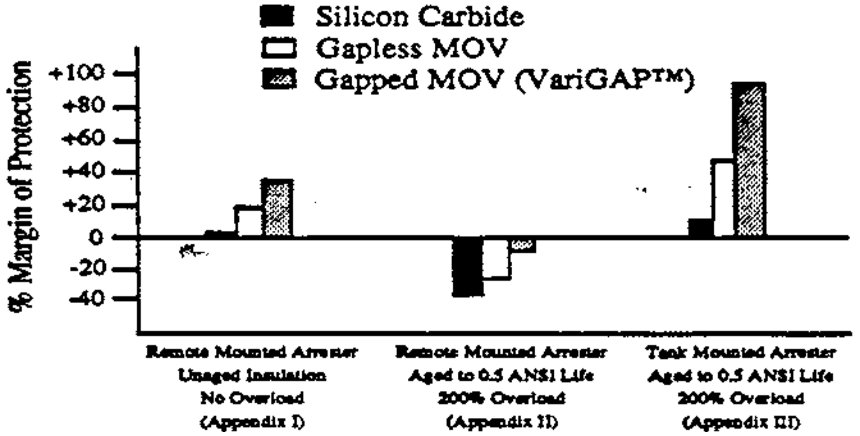


Figure 11A
12470V System with 20kA 1 x 10 s Surge

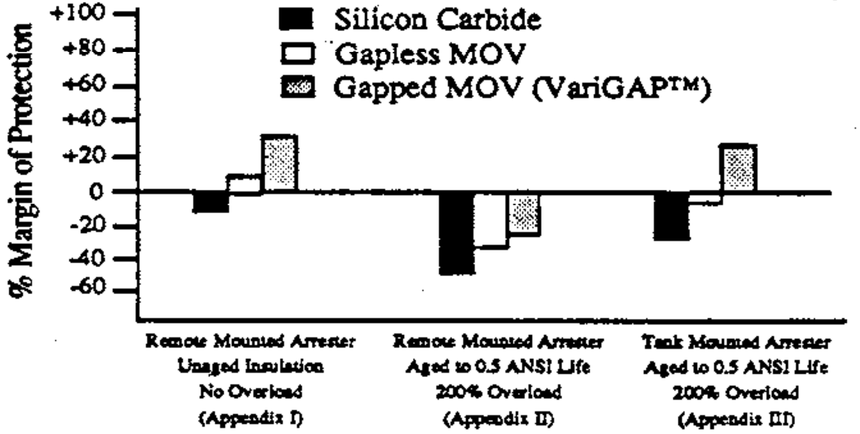


Figure 11B
24940V System with 20kA 1 x 10 s Surge

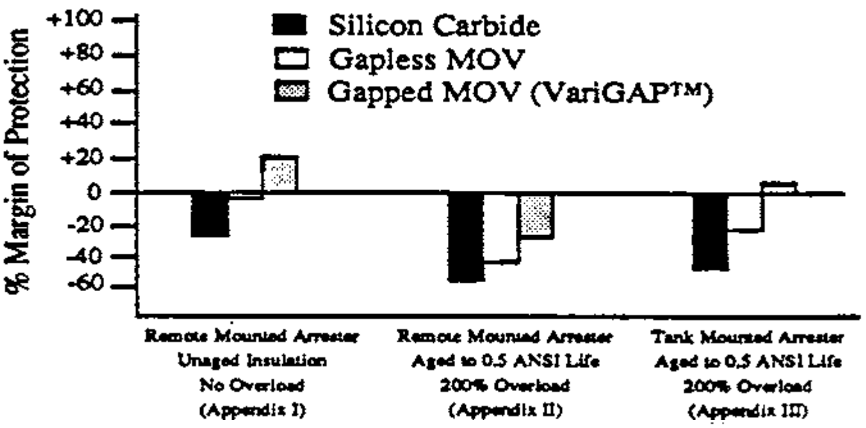


Figure 11C
34500V System with 20kA 1 x 10 s Surge

VII. CONCLUSIONS

The "lightning-protected" transformer includes a cutout mounted dual element link, a high energy low voltage surge arrester and a tank mounted internally gapped MOV arrester. Each protective device helps to increase the protection of the transformer and, thus, substantially reduce the failure rate.

- The cutout mounted, dual element link provides the high surge capability typical of larger amperage rated links while providing the overload protection of small amperage rated links. These characteristics make it possible to place the primary arrester on the transformer tank, eliminating excess lead lengths, thus, providing the best surge protection possible to the primary winding.
- The high energy low voltage surge arrester will eliminate failures caused by secondary induced surges.
- The tank mounted direct connected internally gapped MOV arrester provides up to 30% improvement in surge protection and provides up to 50% improvement in temporary overvoltage capability over traditional gapless MOV distribution arresters.

A substantial reduction in transformer failure rate from the industry stated 1% per year to a level of less than 0.1% is now achievable with the "lightning-protected" transformer. This level of failure rate protection offers an economic incentive of a 9% savings on new transformer purchases.

REFERENCES

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2 J. J. Burke, "The Application of Surge Arresters on Distribution Systems," presented at the 1989 Power Distribution Conference, Austin, Texas, October 25, 1989.

3 P. J. Hopkinson, S.D. Smith and C. W. Williams, "Alternative Methods of Protecting Distribution Transformers From Low-Side Current Surges", based on presentation at Southeastern Electric Exchange 1988 Engineering and Operating Division and Real Estate Section Conference, June, 1988.

4 "Surge Characteristics and Protection of Distribution Transformers", EPRI EL-3385, Project 1532-1, Final Report, January, 1984.

APPENDIX A

Protective Margins for Conventional Overhead Transformers – Remotely Mounted Arresters Unaged Insulation, No Overload								
System Voltage (V)	Rated BIL	Arrester Rating (kV)	Arrester Discharge Voltage (kV)			Protective Margin with 5 feet of Lead Length [a]		
			10 kV 8 x 20µs	10 kA 1 x 10µs [b]	20 kV 1 x 10µs [c]	10 kA 8 x 20µs	10 kA 1 x 10µs	20 kA 1 x 10µs
Heavy Duty Silicon Carbide Distribution Arrester								
12470	95	9	35	44	54	+153%	+48%	+1%
24940	125	18	70	88	109	+72%	+16%	-16%
34500	150	27	104	130	161	+41%	0%	-25%
Heavy Duty Gapless MOV Distribution Arrester								
12470	95	9	30	33	39	+171%	+79%	+20%
24940	125	18	60	66	78	+102%	+45%	+6%
34500	150	27	89	98	115	+64%	+27%	-3%
Heavy Duty Gapped MOV (VariGAP™)								
12470	95	9	21.7	24	29	+292%	+116%	+38%
24940	125	18	43.4	48	59	+172%	+84%	+26%
34500	150	27	65.1	72	88	+122%	+63%	+17%

Notes:

a. All calculations are based on direct connected arresters.

b. Discharge voltages 10 kA, 1 x 10µs current surge are calculated at:
   1. 1.25 x 10 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
   2. 1.10 x 10 kA, 8 x 20µs discharge voltage for MOV arresters.

c. Discharge voltages for 20 kA, 1 x 10µs current surge are calculated at:
   1. 1.35 x 20 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
   2. 1.15 x 20 kA, 8 x 20µs discharge voltage for MOV arresters.

APPENDIX B

Protective Margins for Conventional Overhead Transformers – Remotely Mounted Arresters
Insulation Aged to 0.5 ANSI Life, Severe Overload (approx. 200%), 60% of Rated BIL

System Voltage (V)	Reduced BIL 60%	Arrester Rating (kV)	Arrester Discharge Voltage (kV)			Protective Margin with 5 feet of Lead Length (a)		
			10 kV 8 x 20µs	10 kA 1 x 10µs (b)	20 kV 1 x 10µs (c)	10 kA 8 x 20µs	10 kA 1 x 10µs	20 kA 1 x 10µs
Heavy Duty Silicon Carbide Distribution Arrester								
12470	57	9	35	44	54	+52%	-11%	-39%
24940	75	18	70	88	109	+4%	-31%	-50%
34500	90	27	104	130	161	-15%	-40%	-55%
Heavy Duty Ungapped MOV Distribution Arrester								
12470	57	9	30	33	39	+75%	+7.5%	-28%
24940	75	18	60	66	78	+20%	-13%	-36%
34500	90	27	89	98	115	-1%	-24%	-42%
Heavy Duty Gapped MOV (VariGAP™)								
12470	57	9	21.7	24	29	+136%	+29%	-17%
24940	75	18	43.4	48	59	+63%	+10%	-24%
34500	90	27	65.1	72	88	+33%	-2%	-30%

Notes:

a. All calculations are based on direct connected arresters.
b. Discharge voltages 10 kA, 1 x 10µs current surge are calculated at:
    1. 1.25 x 10 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
    2. 1.10 x 10 kA, 8 x 20µs discharge voltage for MOV arresters.
c. Discharge voltages for 20 kA, 1 x 10µs current surge are calculated at:
    1. 1.35 x 20 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
    2. 1.15 x 20 kA, 8 x 20µs discharge voltage for MOV arresters.

APPENDIX C

Protective Margins for Conventional Transformers – Tank Mounted Arresters
Insulation Aged to 0.5 ANSI Life, Severe Overload (approx. 200%), 60% of Rated BIL

System Voltage (V)	Reduced BIL 60%	Arrester Rating (kV)	Arrester Discharge Voltage (kV)			Protective Margin with 0 feet of Lead Length (a)		
			10 kV 8 x 20µs	10 kA 1 x 10µs (b)	20 kV 1 x 10µs (c)	10 kA 8 x 20µs	10 kA 1 x 10µs	20 kA 1 x 10µs
Heavy Duty Silicon Carbide Distribution Arrester								
12470	57	9	35	44	54	+63%	+30%	+6%
24940	75	18	70	88	109	+7%	-15%	-31%
34500	90	27	104	130	161	-13%	-30%	-44%
Heavy Duty Ungapped MOV Distribution Arrester								
12470	57	9	30	33	39	+90%	+73%	+46%
24940	75	18	60	66	78	+25%	+14%	-4%
34500	90	27	90	98	115	0%	-8%	-22%
Heavy Duty Gapped MOV (VariGAP™)								
12470	57	9	21.7	24	29	+163%	+138%	+97%
24940	75	18	43.4	48	59	+73%	+56%	+27%
34500	90	27	65.1	72	88	+38%	+25%	+2%

Notes:

a. All calculations are based on direct connected arresters.
b. Discharge voltages 10 kA, 1 x 10µs current surge are calculated at:
    1. 1.25 x 10 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
    2. 1.10 x 10 kA, 8 x 20µs discharge voltage for MOV arresters.
c. Discharge voltages for 20 kA, 1 x 10µs current surge are calculated at:
    1. 1.35 x 20 kA, 8 x 20µs discharge voltage for silicon carbide arresters.
    2. 1.15 x 20 kA, 8 x 20µs discharge voltage for MOV arresters.