The USES Unit and Transients

A Method for Protecting Electrical Circuits From
the Effects of Transient Electrical Phenomena

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By

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ORIGINS AND NATURE OF TRANSIENT ELECTRICAL PHENOMENA

Electrical engineering deals with electric energy and its flow, that is, electric power. In electrical circuits two types of electrical phenomena occur simultaneously, permanent and transient phenomena (Reference 1). Permanent electrical conditions are best shown by an unchanging direct current circuit in which the generator and the loads are in balance with each other. This circuit has permanent characteristics of voltage, current and resistence. As part of this balance, each element of this circuit has stored energy, for instance, in the temperature of the lamp filament or the momentum of the motor and generator. If this system changes, when there is a transition between the balanced states of the permanent circuit conditions, then, a transition in the amounts of stored energy change in response. This migration of stored energy gives rise to transient (from transition) voltages and currents, which do not lend themselves to general mathematical representation because they are unique. Under certain conditions these transients can rise to destructive values. Understanding and control of transients is of great importance.

Only the phenomena of the balanced direct current circuit are truly permanent. All alternating current phenomena are transient as the voltage continually and periodically changes and with it the current, stored energy , etc. The development of a theory of alternating current phenomena as periodic transients was more difficult than that of direct current, until methods were derived to treat the periodic transients as permanent phenomena. By the introduction of the symbolic expressions of the imaginary number and of the equivalent sine wave, periodic transients could be treated as permanent quantities. The irregular, non-periodic transients which are not easily described theoretically are of great interest because of their unpredictable nature and sometimes damaging effects.

All electrical transient phenomena, both regular and transient, have been generally described as wave packets in the form of traveling wave pulses (Reference 2). From an alternative point of view they could be considered as time dependent changes of any point in the net work. However, because the mathematical solutions to the traveling wave equations are more rapidly converging and precise, the former view has been adapted and transient phenomena are considered to be traveling waves. For a concise mathematical treatment of transient phenomena, consult Reinhold Rudenberg's authoritative treatise (Reference 2).

In the early days of electrical engineering, power systems were designed according to the requirements of the steady-state operating conditions. Through materials research and operational experience, systems were developed that transmitted power and maintained voltages over considerable distances. During later experience in switching and in other intentional and accidental conditions, the transient phenomena appeared that could severely disturb regular operation of the system. In the modern power systems, the increased magnitude and density of energy cause transients to play an ever increasing role. Control of these irregular, non-periodic transients is as important as command of the steady state conditions of the system.

SOURCES OF TRANSIENTS

In long distance and high voltage systems, in addition to intentional switching processes, there frequently occur unintentional transients resulting from ground faults, short circuits, cable breaks, lightning strikes and even human error. Such accidents give rise to potentially damaging high excess voltages and currents, and to disturbances of different frequencies and wave shapes. These disturbances spread out in traveling waves at enormous velocity, approaching the speed of light, from the source of the transient through out the entire network. This causes electric and magnetic fields at any point to change with extreme rapidity, and severe damage to equipment may result.

Atmospheric lightning which is the voltage discharge spark between the ground and the thunder head clouds which reach 6 to 7 miles into the stratosphere. These clouds reach across an electric field gradient that has been generated by the vertical migration of conducting air masses through the earth's magnetic lines of flux. Both the magnetic field and the heat which causes the convection were contributed by the sun. Bolts of lightning have voltages between 500 and 1000 kV, durations between 0.5 and 20 micro seconds and amperages 1,000 and 50,000 amps. If lightning strikes a transmission line, disturbances can travel from 10 to 20 miles within an electrical distribution system. Lightning strikes result in high electric field concentrations which occur at the tops of transmission towers because of their geometry. This condition also occurs within the ground conductors which are frequently strung between towers above the transmission wires, and these conductors are the second most likely targets. When a transmission line is hit by lightning, a transient pulse travels in both directions until it is finally damped out and dissipated. Lightning represents the most dangerous transients in transmission and distribution networks.

The forked lightning in Figure 1 shows the highly variable and unpredictable path of natural electrical transients. Lines supported by wooden poles are sometimes more liable to ground faults owing to the added insulation provided by the towers. However, strong lightning strokes can splinter entire lines of towers of poles as shown in Figure 2. This pole was splintered when the high temperature created by strong transient currents vaporized the moisture in the wood and exploded the wood fibers. For lines supported by steel towers, the major damage is done by the electric arc that follows an insulator flash-over. For high voltages, the electric arc can be kept away from the insulator surface by ring electrodes or horn gaps as shown in Figure 3. This protects the insulators from thermal damage from ground faults or short circuit arcs.

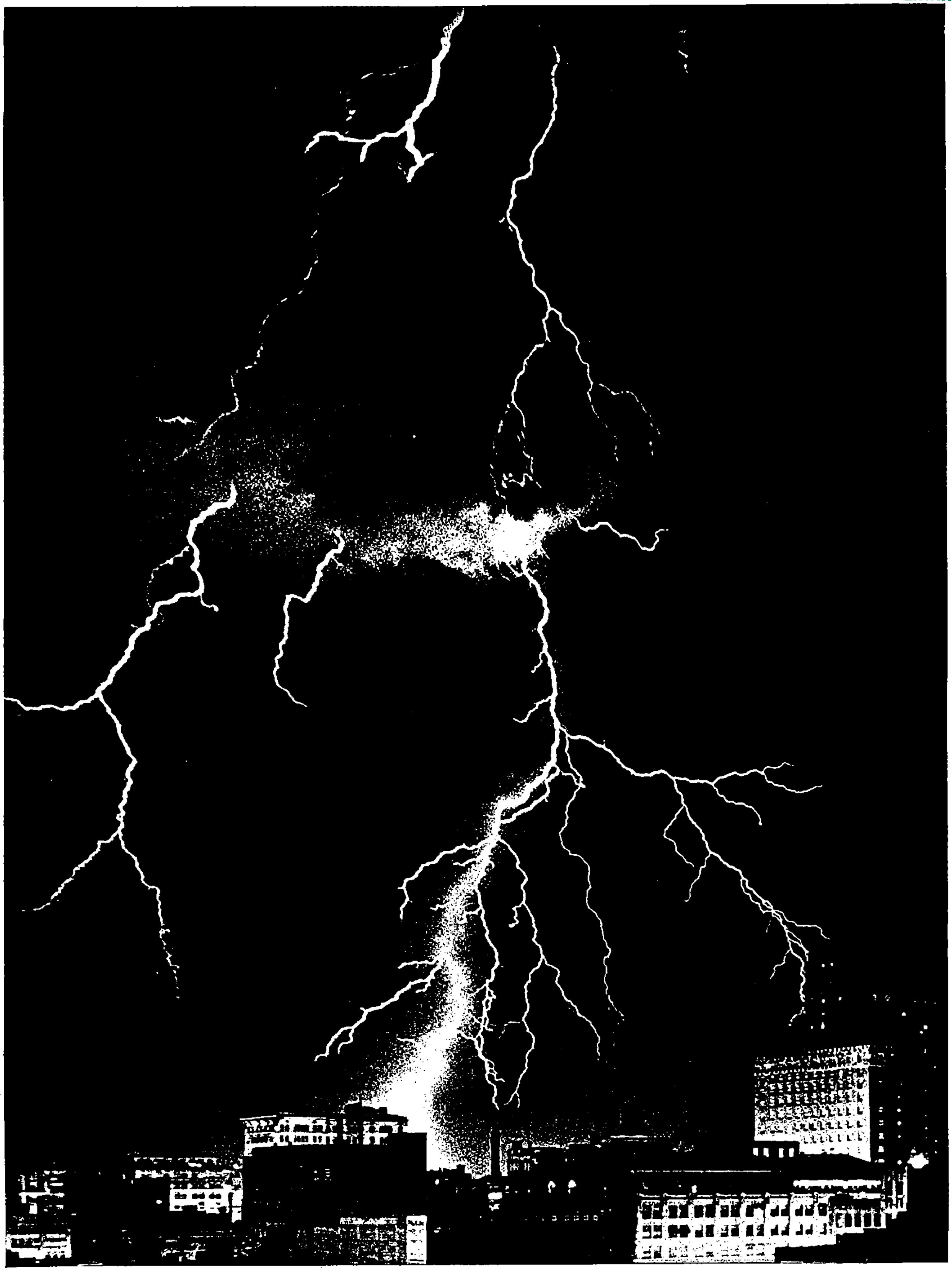
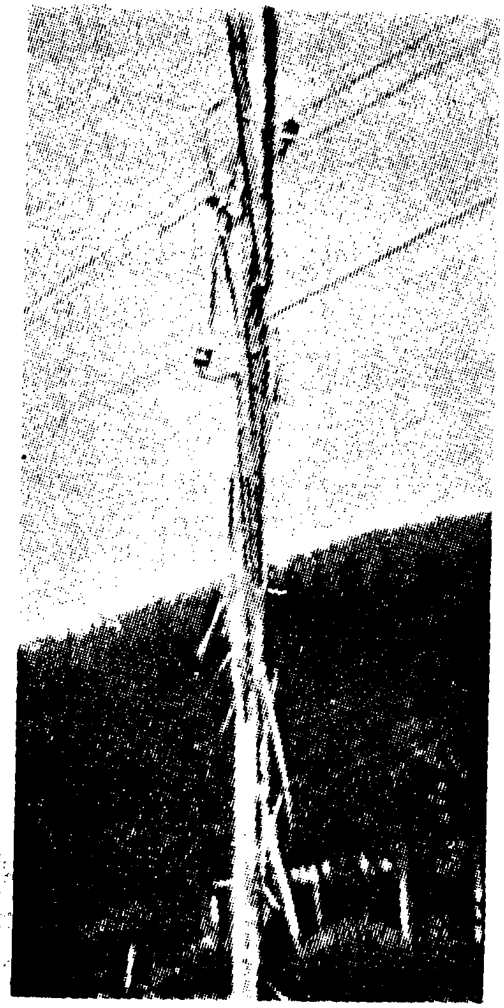


Figure 1. Forked lightning shows the highly variable and simultaneous paths taken by natural electrical transients

Figure 2. Wooden transmission pole splintered by the internal steam pressure created from the heat of a lightning transient passing from the line to ground in a dangerous ground fault.



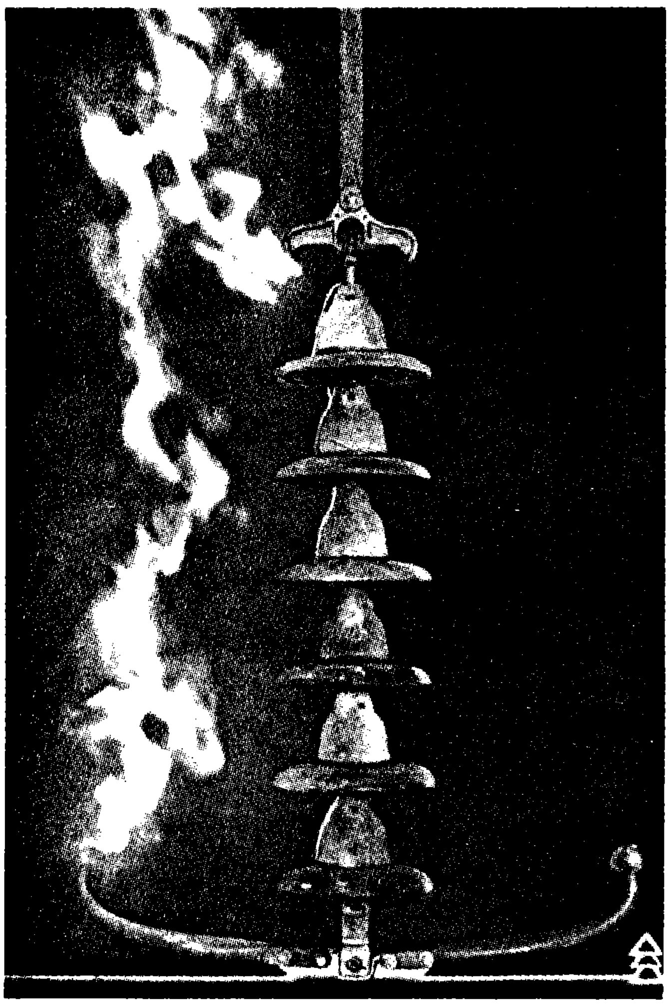


Figure 3. The insulator of a steel transmission tower is preserved by ring electrodes or horn gaps keeping the arc at a distance.

Usually the amplitude of the transient pulses is governed by the operating voltage of the system. The pulse caused by the closing switch is usually less than the operating voltage, whereas that of the opening switch, which usually involves spark ignition, can be up to 3 x the voltage. The pulse of the opening switch in an oscillatory circuit containing inductance and capacitance can be up to 5 X the voltage. Random pulses produced accidentally are usually more difficult to handle since they cannot be limited at their point of origin by suitable devices. The arcing ground fault of a high voltage cable is particularly severe because the magnitude of the ground fault arc is reignited every half period. Furthermore, during these half cycle periods between grounding at the fault, very high voltages can develop in the lines that exceed the voltage that caused the original flash- over. Thus a series of high voltage pulses are generated by the fault which travel in all directions throughout the network. These rapidly repeated pulses are like hammer blows to a complex mechanical system.

These voltage transients impact the distribution system in several ways. Every network has a number of natural oscillation nodes associated with oscillation frequencies owing to the large number of inductances and capacitances, particularly at the load voltage. When transient pulses excite natural frequencies within the network, their effects are multiplied. And when these natural frequencies are excited by step-pulse and discharge processes the effects become like sledge hammer blows to a complex mechanical system. These resonant effects are frequently the cause of high energy damage within the low voltage system that apparently got past the circuit breakers. These resonant effects can be protected against by attenuating pulses, by providing resonance damping or by removing the systems susceptible to resonance.

Traveling pulses can also cause serious damage to the windings of transformers and motors because these pulses are amplified by reflection at the high impedance entrance to the winding, and because the space between the windings restricts the amount of insulation that can be used. Flash-over and breakdown occurs between the coil and a grounded conductor and also between windings and layers within coils. The high voltage gradient caused by a transient often forms a spark which is a current flowing through ionized air or ionized insulation. The spark is the most destructive effect because in its plasma discharge of excess voltage, it ruptures air, oil and solid insulation material to cause permanent damage to the equipment.

If the normal operating voltage, across the two points between which a breakdown has occurred, is sufficient to maintain an arc across the breakdown gap, an arc will be maintained even after the traveling pulse has passed. This produces an internal short circuit turn which can very easily cause a coil to burn out. However, if the normal operating voltage cannot maintain an arc across the breakdown gap, the insulation is only punctured by the pulse, and the coil can still be used for a long time. This is usually the case for breakdown between successive turns as is shown in Figure 4. There is higher likelihood for permanent damage at higher voltage where the operating voltage can maintain the arc across the breakdown after the initiating pulse has passed. Figure 5 shows the entrance coil of a large transformer in which the traveling pulses initiated an arc which caused a very substantial burn out. Figure 6 shows the end winding of the first coil of a mid-sized generator that has undergone marked melting on all turns. In this case the arc was not maintained.

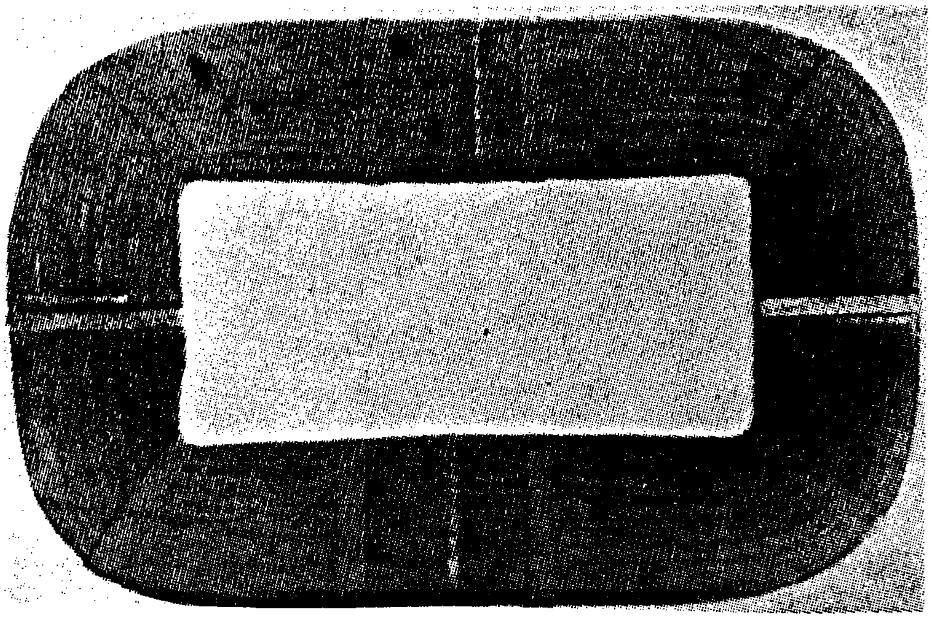


Figure 4. The dark spots indicate breakdown between successive turns in A low voltage transformer secondary coil.

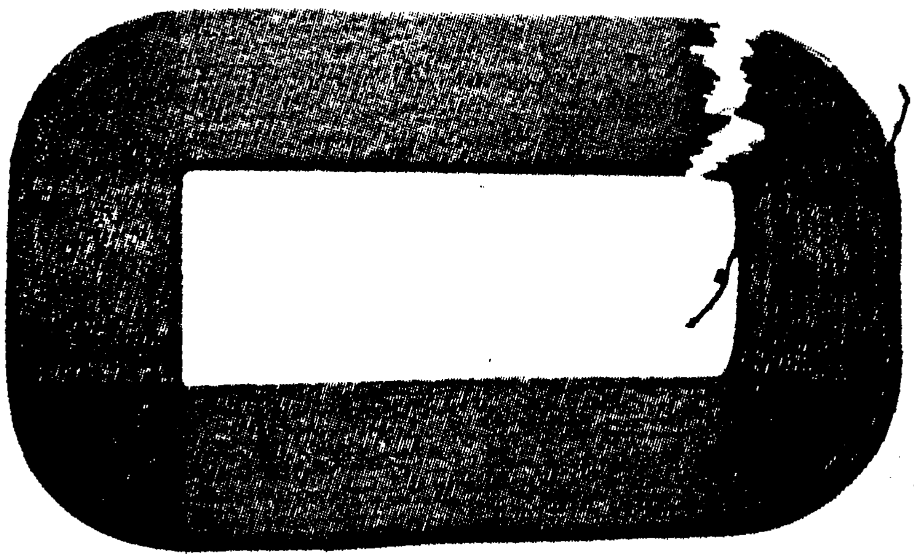


Figure 5. Substantial burn-out of the primary coil in a high voltage transformer in which the operating voltage sustained an arc after the initiating transient pulse had passed.

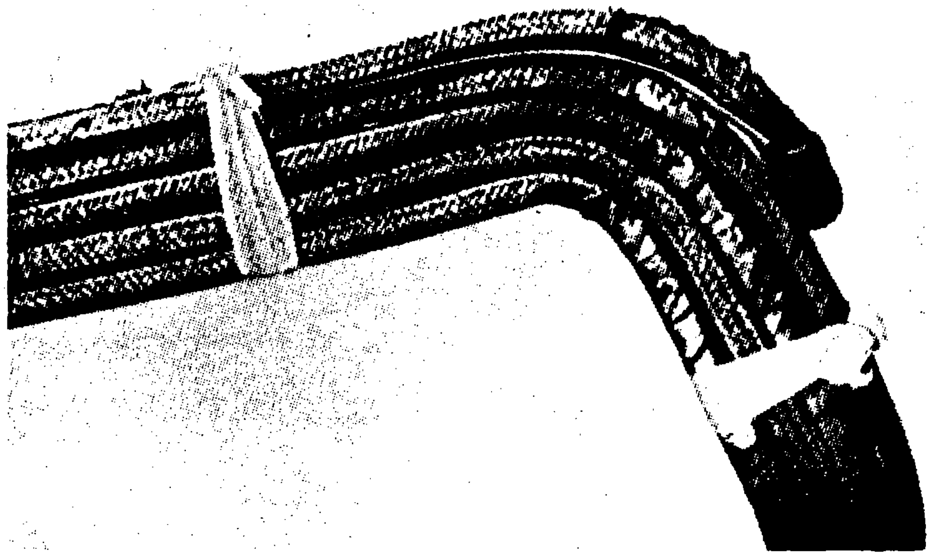


Figure 6. The end winding of the first coil of a mid-sized generator that has under gone marked melting on all turns.

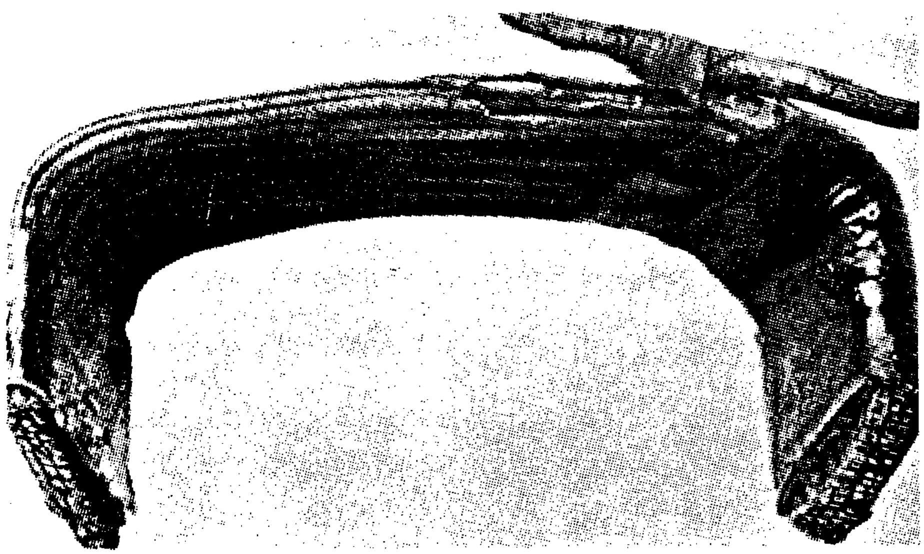


Figure 7. The entrance coil to an induction motor that has burned out in the first few windings by a pulse initiated breakdown.

In contrast, Figure 7 shows the entrance coil to an induction motor that was burned out in the first few turns by a pulse-initiated break down. Figure 8 shows a relay coil that has had several turns burned out by a traveling pulse.

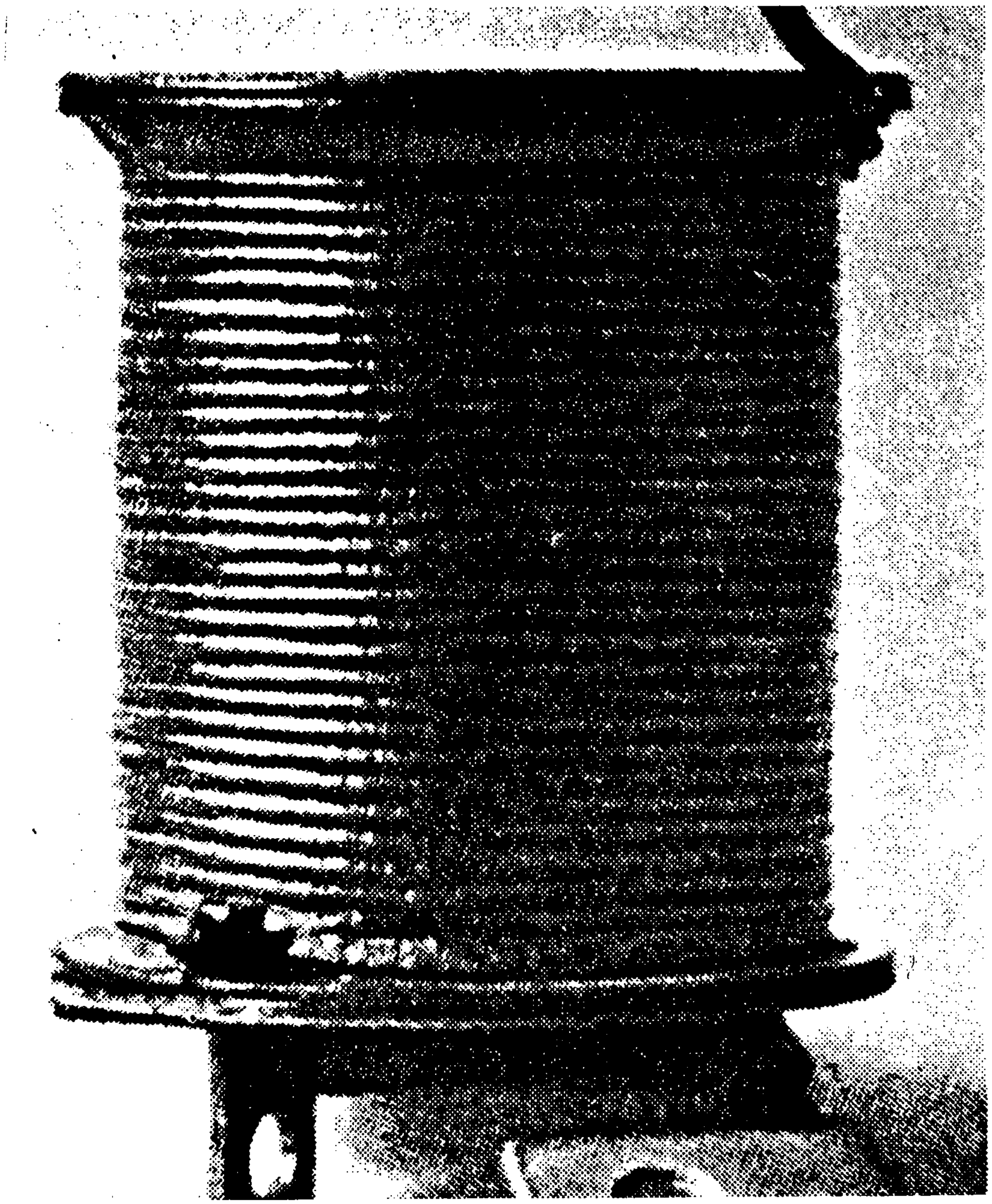


Figure 8. A relay coil that has had several turns burned out by a traveling pulse, as shown by the damaged windings at the lower left.

PROTECTIVE MEASURES

Dangerous pulses are produced in high voltage networks, sometimes by normal switching operations, but more frequently by short circuit faults and above all by arcing ground faults and associated capacitive effects. Particularly dangerous are the effects of lightning strikes which occur frequently in transmission lines of all voltages. For all parts of the network, the voltage amplitude of the pulse is a serious stress on insulation, although the short duration of most traveling pulses is shorter than the delay time for the breakdown for most insulation and serious damage is avoided.

To protect transformers and rotating machinery against damaging voltage transients, various systems have been devised to reduce the transient through pulse shaping. Ohmic resistances, induction chokes , capacitor bypasses and spark gaps all tend to flatten the steep rises of pulses, reduce sharp voltage discontinuities and reduce the intensity of pulse trains. These reductions in the transient voltage gradient protect the windings in machinery. See (Reference 2) for exact mathematical treatments.

Choke coils and bypass capacitors have long been used to give protection against over-voltage. High frequency components of the voltage and the current will not penetrate the coil and thus will be choked off. These components will readily enter a capacitor and can be made to bypass a circuit in which they would cause disturbances. Coils and capacitors also act as shock absorbers by temporarily storing the energy contained in the more sustained pulse trains. Because relay coils and series connected loads carry the entire transient, it is difficult to protect them against transients, particularly in the vicinity of capacitors which magnify the transients.

Fuses and circuit breakers are not effective protection against transients because of the high velocity of these pulses. Fuses depend upon the existence of enough current and resistive heat to melt the metal strip. Thermomagnetic devices require sufficient current and heat to overcome the inertia of the switching element. General Electric has developed an electronic circuit breaker, Spectra RMS, that is sensitive to RMS currents and is not biased by current harmonics. However, These devises also let transients pass because sufficient current must still be present for these devices to respond and the transient has come and gone before this happens. Circuit breakers should only be relied upon to protect the circuit from excess steady-state voltage or current and not from transient pulses.

In this short review of protective measures, it is seen that the only protection against transient pulses is to moderate the pulse shape in order to reduce the voltage gradient. Beyond this pulse shaping measures, which are often ineffective in dealing with large or repeated transients, the only protection is to provide more massive components and thicker, more inert insulation. Certain transient effects can be reduced or diverted. However, the electrical system is wide open to these pulses, and particularly vulnerable to the pulses that excite resonances. This exposure becomes more critical as the need to protect more sensitive electrical machinery and equipment increases.

THE USES UNIT PROTECTS AGAINST TRANSIENTS.

Recently the USES System (References 3-11) has been successfully used as protection against voltage and current transients. USES is particularly effective because the means of transient attenuation is the self-healing, wrap-around magnetic choke (see Reference 7) which is not sacrificial in nature, but continues to attenuate the great majority of the pulses indefinitely. The term, self-healing, means that most transients are reduced by phase balancing rather than by component dissipation as with the MOV. The USES Unit is also equipped with metal oxide varisters and gas tube reactors which provide sacrificial protection against the higher energy pulses. These sacrificial elements are connected to indication lamps and can easily be replaced if required. The USES System offers several lines of protection:

(1) The USES Circuit, as shown in Figures 9 and 10, contains several inductors and by-pass capacitors that have traditionally been used to reduce the voltage gradients of current and voltage transients. This traditional, pulse shaping protection thus lessen the impact of transients on the windings of motors and transformers.

(2) Through the phase balancing in the magnetic choke system, USES attenuates unbalanced voltage and amperage transients which only appear on one phase at a time. The wrap-around magnetic choke is an inductive system which responds very rapidly, in less than 5 nano-seconds, to eliminate the transient spikes as they appear. In addition to protecting the loads against the transient spikes, the balancing of the amperage and voltage between phases improves the operation conditions for poly phase motors and reduces the motor-generated harmonics. USES provides a damping protection that reduces the possibility of resonance and eliminates by cancellation most transient pulses. Only the higher energy pulses are dissipated by the sacrificial varisters and gas tube reactors.

(3) USES also is a superior power factor correction device (Reference 6) that is not impacted by high current harmonics. When USES is used for power factor correction, then the large power factor correction capacitors can be removed from the system, thus eliminating tank circuits and the potential for resonance which may be excited by harmonics or transients.

(4) USES is a magnetic linkage between the electrical phases which provides a ready mechanism for damping out resonances that exist between the phases. With no USES linkages, the mechanism for damping these resonances is the capacitive and inductive coupling between the phase conductors which is much slower. USES brings a three phase system into phase balance by damping these oscillations and therefore increases the circuit efficiency and stability.

USES has been certified by the Underwriters Laboratory and by the Canadian Standards Association as a superior, industrial grade surge suppressor, (References 3 and 4)

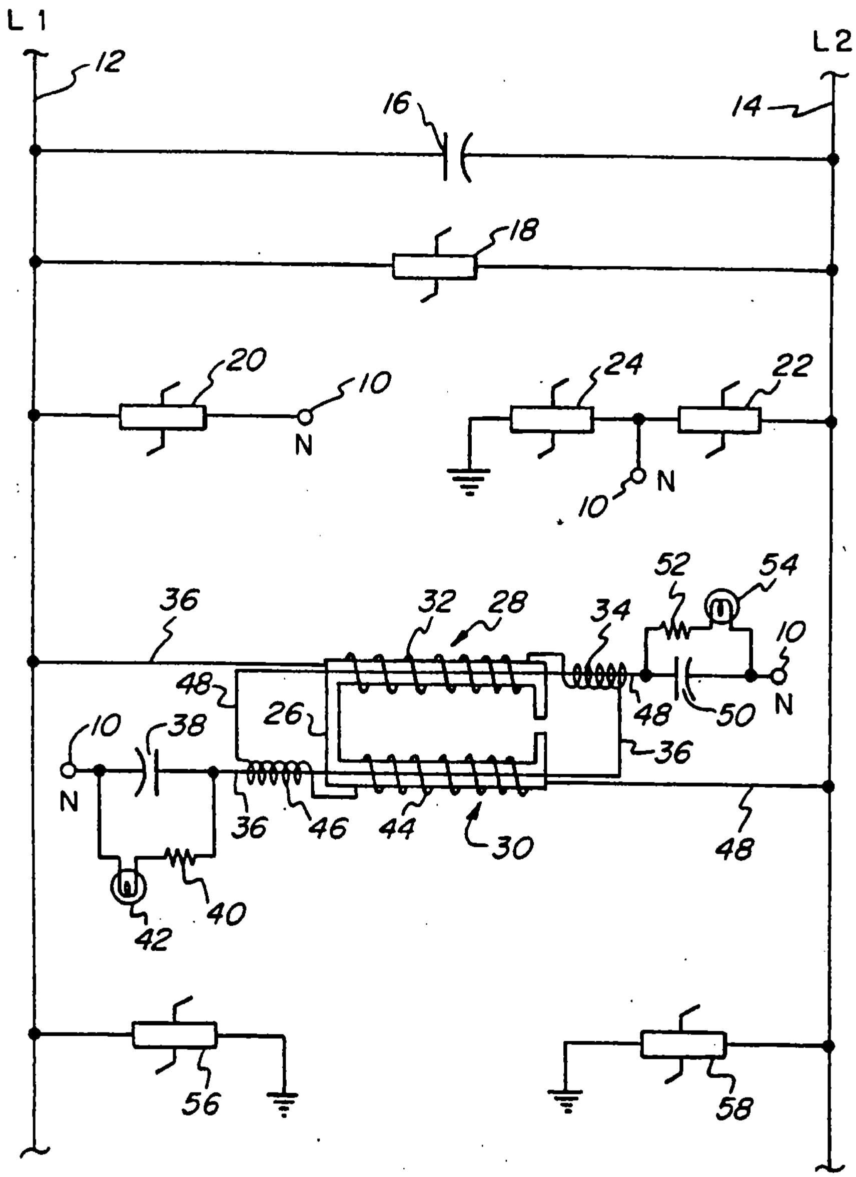


Figure 9. USES Circuit in Single Phase between L1 and L2: Capacitor 16, Inductive Choke 28, Metal Oxide Varistors 18, 20, 22, 24, 56, 58, Indicator Lamp 54, 42. From (Reference 5).

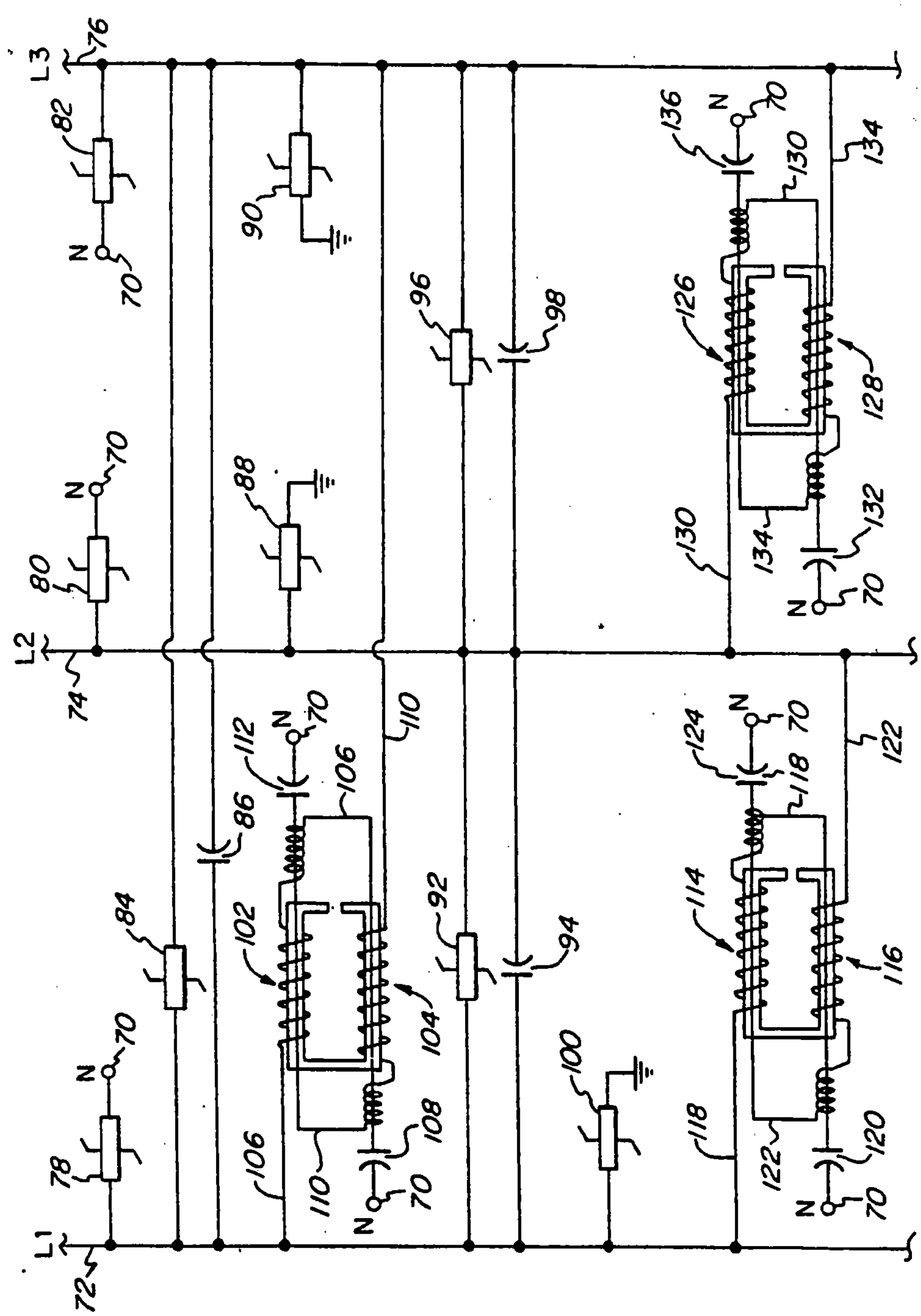


Figure 10. USES Circuit in three Phases in WYE Configuration between L1, L2, L3 and Neutral: Capacitors 86, 94, 98, Series Capacitors 120, 138, 132, 108, 112, Inductive Chokes, 114, 116, 126, 128, 192, 104, Metal Oxide Varistors, 78, 80, 82, 88, 90, 92, 96, 100, Neutral Terminal, 70. From (Reference 5).

FIELD EVIDENCE USES PROTECTIVE EFFECT

When USES Units are installed at the service entrance, the plant is isolated from externally generated transients. When USES Units are installed throughout the plant on motor control panels close to significant inductive loads, each panel, with a USES Unit, is also isolated against internally generated transients. Pure Power Systems, Inc. has many testimonial letters from factories with machinery sensitive to voltage transients which state that the USES System has kept their machinery running smoothly. Testimonial letters with strip recorder charts demonstrate that there was a great reduction of voltage faults after USES was installed. A letter from the Town of Dublin, Connecticut states that after installation of USES into the Town Hall, the police communication tower received a direct lightning strike without damage to other equipment in USES-protected circuits in the building.

A Power Quality Engineering Firm in Boston writes that several clients experienced premature failures of chiller units on apartment roof tops. These units had long power feeds at low voltage and were susceptible to under voltage and to lightning damage. After installing USES Units, there have been no failures. The USES raised the voltage evenly by 1% to 2% on all three phases, and protected the chillers against minor and major voltage transients. This application is useful to all air cooled multi-compressor cooling equipment. Installation is simple because there is usually space within the chiller control cabinet enclosures to place the USES Units.

Between October 1993 and July of 1994, the Coldwater Seafood Corporation of Cambridge, MD, bought 11 USES Units and had them installed in the north end of their refrigeration plant. On Saturday, November 26, 1994, the plant had a low voltage event. Although the voltage sag lasted less than a second, it caused the plant considerable electrical damage, knocking out 2 of the three transformers that supplied the plant's south end freezers. The phase protection on that set of transformers, designed to protect against single phasing, never tripped, its magnetic coil melted. Single phasing did occur, after which, several south end refrigeration motors and other three phase equipment burned out.

No damage was sustained by the north end of the plant, even though all the transformers owned by Coldwater Seafood are wired in parallel, and the north end usually draws between 10-20 times the current of the south end during the normal weekend. A conservative estimate of the damage that would have occurred in the north end was between 6 and 8 million dollars or roughly 200 times the cost of the USES Units.

According to the Coldwater news release, all the north end loads were protected by USES Units, which evidently did stabilize voltage, as claimed. The USES Units protected the north end by over-riding the voltage sag with energy stored within the magnetic choke system and by isolation the motors from the voltage transients associated with the sag. These units not only saved the motors from damage, preventing the loss of temperature in the freezers which contained 5 to 6 million pounds of fish, but they protected the transformers, which were up line. The investment in USES has certainly been repaid, particularly since they also reduce the kW demand in the north end by 30 to 40 kW.

Recently, at the IUSA Copper Tube Plant in Pasteje, Mexico, six USES Units were installed on inductive motor circuits containing single and multiple motor loads. Shortly after installation, a high energy transient passed through the plant, damaging other circuits. At the time of the surge, the light plastic lid of one of the USES Units blew off exposing the scorched USES Circuit. This was the only damage done to the circuits where the USES Units had been installed. The USES Unit is repairable under the 3 or 6 year warranty. The copper re-refining furnace was protected by the USES Unit and did not have to be closed for repair, as did the rest of the plant.

The Copper Tube Plant event is an example of high energy damage occurring within a plant which is protected by circuit breakers. The USES Unit released a high energy and potentially dangerous resonance condition through operation of the unique magnetic choke inter-phasic linkage. Without this sacrificial link provided by the USES Unit, the resonant energy could well have been released by arcing in a motor, capacitor or transformer, permanently damaging the equipment.

In all these examples, USES has protected equipment against damage and kept the plants running smoothly. The USES System also improves the power factor, reduces the motor generated harmonics and improved the operating conditions of the machinery, thus reducing maintenance and increasing equipment useful life time. For other information about USES, refer to References 3 through 11. The pamphlet entitles, "THE USES UNIT" (Reference 7) discusses the mechanisms by which USES improves the power factor and balances the phase amperages and voltages, thus protecting against transients.

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