REAL, REALISTIC RING WAVES FOR SURGE TESTING

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ABSTRACT – Five independent investigations on the coupling of surges into low-voltage circuits (data or power lines), and of their effects, show that a damped oscillatory transient is a real, realistic stress for equipment connected to these lines.

INTRODUCTION

Traditional surge testing performed on electromechanical equipment has been based on the unidirectional 1.2/50 μs impulse deemed to represent the threat of lightning in power transmission networks. The purpose of these tests was to demonstrate the ability of high-impedance insulation to withstand a voltage stress. As a complement to these traditional tests, a current waveform was defined to demonstrate the ability of low-impedance components, such as surge arresters, to carry the currents associated with simulated lightning discharges. Application of systematic tests based on these two waveforms, as part of the Basic Insulation Level concept, was a turning point in ensuring greater reliability of power systems.

These tests, however, were primarily aimed at demonstrating the ability of equipment to survive in the presence of the lightning phenomenon or transients in the low-voltage power cables. The reliability of systems in the presence of other electromagnetic disturbances requires considering other tests, dealing not only with equipment withstand capability, but also with its immunity.

With the development and increasing deployment of improved instrumentation, it became apparent that typical waveforms of surges in low-voltage circuits are not only the traditional unidirectional wave, but also a decaying oscillatory wave. The results of measurements performed over the years in widely different environments, however, [1], [2] have demonstrated the prevailing pattern of oscillatory transients.

SPECIFIC INVESTIGATIONS

This paper briefly cites the results of five investigations performed by the authors, which point out the need to consider damped oscillations as a necessary complement to the traditional unidirectional waveforms. Included are two unpublished investigations of coupling from a high-voltage line into low-voltage signal and control lines that were performed at facilities of the Italian Electricity Board, ENEL, in 1969 and 1975, as reported in this paper by G. Pellegrini. One investigation of surge coupling between a grounding conductor and other low-voltage conductors was performed in 1978 in support of IEEE Std C62.41 [3], [4]. Another investigation of the propagation surges was performed in 1987 by NIST at an industrial building in California [5]. Preliminary tests have been conducted in 1990 at the NIST facilities on semiconductor failure modes, illustrating the implications of oscillatory stress on semiconductor failure modes. These last three investigations are reported in this paper by F.D. Martzloff. From these five investigations, the conclusion is reached that oscillatory surges – Ring Waves – need to be included in a comprehensive test program for electromagnetic compatibility [6]

1. Surge voltages induced in low-voltage control and signal cables located near transmission lines impacted by lightning

To establish realistic surge immunity specification for equipment installed in high-voltage (HV) substations, it was imperative to identify the parameters of transient voltages induced in associated signal and control lines. To that end, investigations were carried out in 1969 at the ENEL "Verderio" HV Substation [7], [8].

Primary phenomena (lightning, switching, and faults) were simulated on the HV line. The resultant surges induced in control and signal cables running parallel to the line were identified and measured.

1.1 Simulation of primary phenomena – The phenomena considered in the investigation are lightning surges and switching surges (energizing and initial transient of ground faults). Rise time and duration were the two most significant parameters. The 1.2 μs rise time of the standard 1.2/50 μs impulse was selected as representative of the phenomena considered. The duration of the standard 1.2/50 μs impulse is representative of lightning, but too short for switching surges.

Therefore, simulation of the primary phenomena was obtained by a 1/500 μs Marx generator (600 kV, 18 kJ, 75 ohms internal impedance, output capacitance 3 nF), by applying this unidirectional pulse to a 31-km long line (line-to-ground, single phase). The resultant voltage pulse applied to the line, unloaded and not terminated on its characteristic impedance, was 106 kV peak and the line current 264 A peak.

The waveform of the generator open-circuit voltage is shown in Figure 1 and the resulting voltage applied to the line in Figure 2 (front of wave and complete waveform). The oscillograms show how the unidirectional impulse produces a wave characterized by a unidirectional component plus oscillations caused by the impedance mismatching at the end of the line and also along it, the latter associated with line towers having different heights.

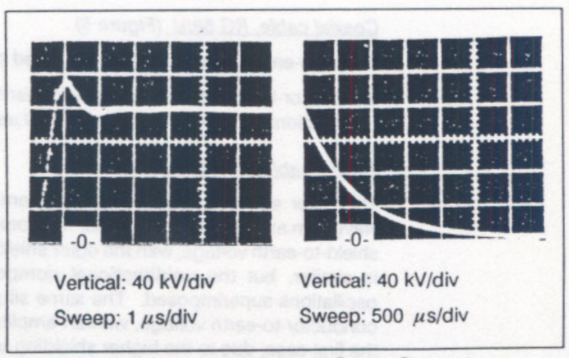


Figure 1. Open-circuit Voltage of Surge Generator Simulating Lightning on the Transmission Line

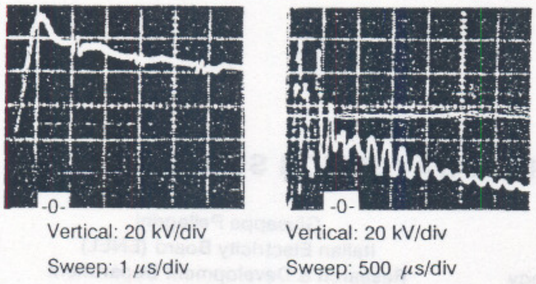
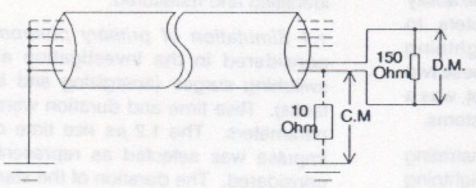


Figure 2. Surge Voltage Applied to the High-Voltage Line

1.2 Measurements on cables – Twelve types of cables were included in the test program. In the present summary, results are cited for typical unshielded and shielded cables, including coaxial and triaxial cables. For each cable, several measurements were made, including common and differential modes, with various combinations of earth connection for the shields and terminating impedances. Space limitation in the present paper prevent presentation of detailed test configurations and results; these can be supplied to interested parties by G. Pellegrini. Figure 3 illustrates one of the types of connections and combinations of grounding for one example of cable. The major point of this paper is to call attention to the occurrence of oscillatory waveforms in the cables, rather than detailed numerical values. For each cable, the characteristics of the voltages are summarized below, and selected oscillograms (Figures 4-7) illustrate the waveforms.



C.M. = Common Mode D.M. = Differential Mode

Figure 3. Typical Connections for Cable Measurements

<u>Control cable, unshielded</u> *(Figure 4)*

Common mode voltage: 200 kHz damped oscillation.

Differential mode voltage: 250 kHz damped oscillation.

<u>Telephone cable, 20 pairs, aluminum tape shield</u> *(Figure 5)*

Shield-to-earth voltage: 200 kHz damped oscillation.

Common mode voltage of the pairs (shield earthed at both ends): unidirectional component with a few microseconds duration and superimposed 400 kHz oscillation.

Differential mode voltage: not shown, but negligible value (less than 1 V).

<u>Coaxial cable, RG 58/U</u> *(Figure 6)*

Shield-to-earth voltage: 300 kHz damped oscillation.

Conductor-to-shield voltage (shield earthed at both ends): unidirectional component with about 40 μs duration

<u>Triaxial cable, RG 58A/U</u> *(Figure 7)*

The outer shield-to-earth voltage presents the same general waveform as the one observed for the coaxial cable. The inner shield-to-earth voltage, with the outer shield earthed at the ends is similar, but the unidirectional component has 400 kHz oscillations superimposed. The same situation occurs for the conductor-to-earth voltage, with an amplitude of about 15% of the first case, due to the higher shielding efficiency.

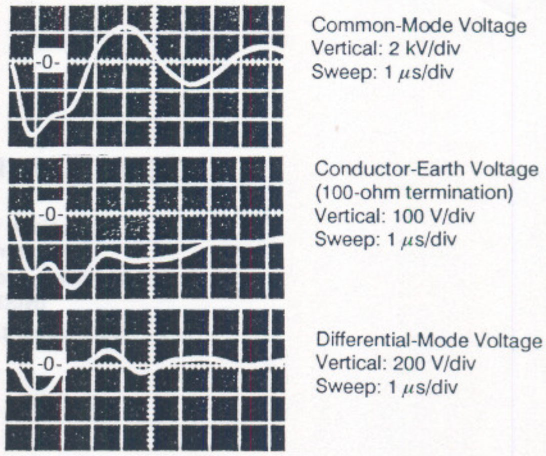


Figure 4. Transients Induced in Unshielded Control Cable

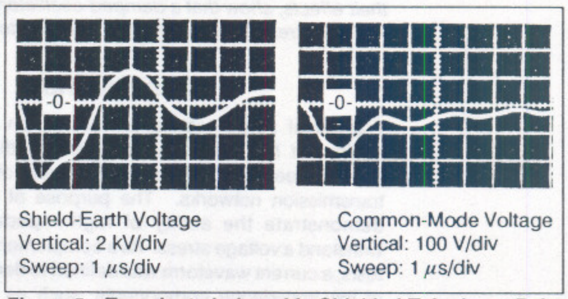


Figure 5. Transients Induced in Shielded Telephone Pair

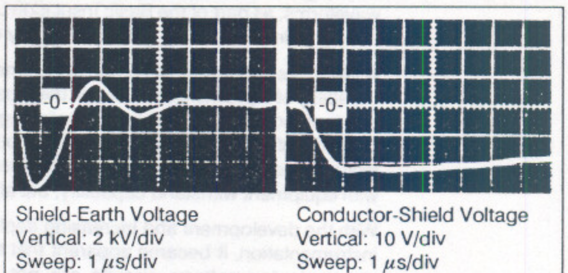


Figure 6. Transients Induced in Coaxial Cable

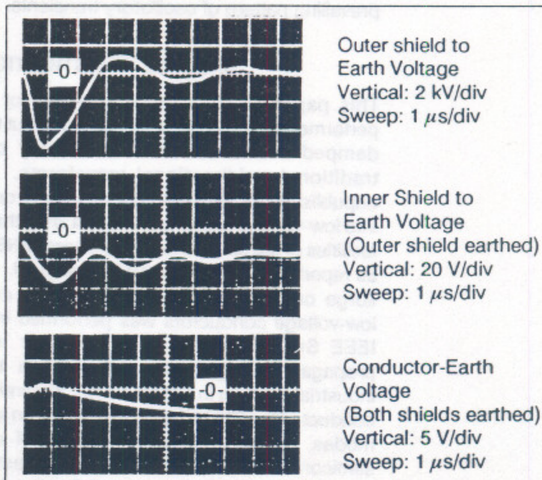


Figure 7. Transients Induced in Triaxial Cable

1.3 Discussion of results – The shape of a unidirectional pulse impressed onto a line though a generator is subjected to modifications due to the practical impossibility of terminating the line on its characteristic impedance. The actual phenomenon occurring on the line and impacting the secondary low-voltage cabling is quite different from the theoretical double exponential pulse. This interaction between the surge generator and its load occurs whenever a similar pulse is applied to other networks or structures.

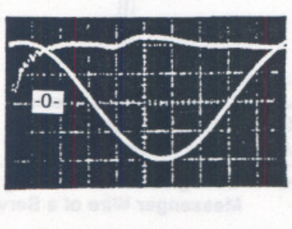
Whenever the predominant coupling is inductive, the surges in the victim cables have a damped oscillatory waveform at a frequency that may range from 100 to 300 kHz, with a damping dependent on the type of cable shield and the propagation of the induced voltage. When there is a common impedance coupling of the cables with the primary phenomenon, as in the case of the shield earthed at the ends, with consequent transient current flowing in it, the induced voltage shows a unidirectional component with superimposed damped oscillations.

2. Surges induced in control and signal cables near 6 kV and 380 V cables

This investigation, complementing the Verderio measurements, was carried out in 1975 at the ENEL "Turbigo" Power Plant. The purpose was to identify the surges induced in control and low-level (mA, mV) measurement cables installed along power cables in power plants, as well as in industrial plants [8], [9].

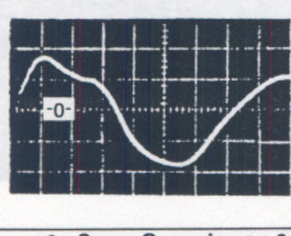
The causes of disturbances considered were the switching of power circuits at 6 kV and 380 V, occurring under worst case conditions of switching at the crest of the power-frequency voltage.

2.1 Primary Phenomena – The power circuits used for the investigation were a 6 kV cable feeding a 700 kW load in an operating power plant; the 380 V cables were connected to an artificial load of 2.5 Ω (120 A peak). The waveform of the 6 kV surges occurring at the closing of a circuit breaker is given in Figures 8 and 9. The waveform related to the 380 V cable is given in Figure 10. The waveform of the surge in the 6 kV cable (difficult to read in the reproduced oscillograms) has a rise time less than 1 μs, with a step after 4 μs due to the reflection in the proximity of the load (it has been verified that the waveform is independent on the presence of a load). Because the shield of the 6 kV cable was earthed only at the switchgear cell, the voltage between shield and earth at the other end of the shield was also measured (Figure 9), as this voltage may be the most likely to couple disturbances into adjacent control lines. The surge in the 380 V circuit has a rise time of about 50 ns.



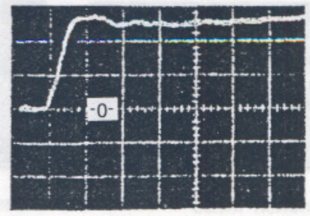
Vertical: 2.4 kV/div
Sweep 1: 1 μs/div
Sweep 2: 2 ms/div (Power-line voltage)

Figure 8. Surge Occurring on 6 kV Cable, between Conductor and Shield



Vertical: 1 kV/div
Sweep: 1 μs/div

Figure 9. Surge Occurring on 6 kV Cable, between Shield and Earth, at Floating End of Shield



Vertical: 100 V/div
Sweep: 0.1 μs/div

Figure 10. Surge Occurring on 380 V Cable

2.2 Measurements on cables – Two different sets of control and low-level cables, of the same type used in the operating plant, were included in the measurements of induced surges: one set laid down on the same tray as the 6 kV cables and near them, and another set in a PVC tube. For both the cable sets, two values of separation were used, a few centimeters and 0.3 m from the power cables. The length of the parallel runs of power cables and control cables varied between 100 and 300 m.

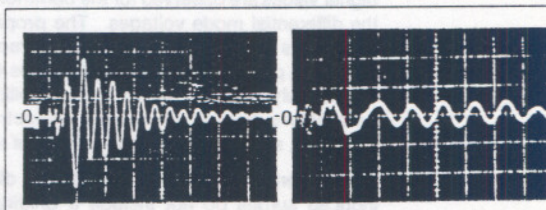
In this procedure the actual control and low-level cables were not used so that measurements could be carried out under reference condition independently of the service operating condition at the time of measurement. Using separate cables permitted changing the earthing condition of the shields at the process instrumentation in the field or at the supervisory system side.

The cables for which the measurement results are cited as representative examples (the complete test schedule included other types) were a 1-pair twisted thermocouple cable, and a 1-pair twisted, low-level signal cable.

The measurements were made with earthing of the signal source and of the cable shield at the field end (process instrumentation) or at the supervisory system end (according to some manufacturers specifications). At the signal source (process instrumentation side) the cable circuits were short-circuited. At the measurement side, the pairs were left in open-circuit condition, in order to simulate the real operating condition (normally corresponding to the multiplexer input).

For each cable, the characteristics of the voltages are summarized below, and selected oscillograms (Figures 11-14) illustrate the waveforms. For the sake of brevity, the oscillograms are given only for the common mode (CM) and differential mode (DM) measurements with the earthing of the signal circuit and of the cable shields at the process instrumentation in the case of the 0.3 m cable separation.

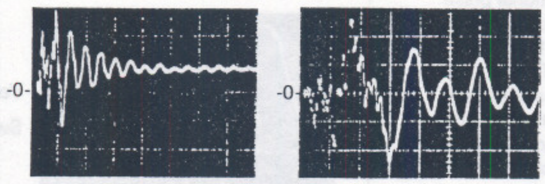
The results depend on the condition of earthing of the signal circuit and cable shield at the side of the computer and for a few cm separation from power cables present values (differential mode only) that are generally higher, up to one order of magnitude. The waveforms, however, present the same characteristics (frequency of oscillation, damping). Once again, the major object of citing these results in the context of this paper is to show waveforms, not detailed data.



Common Mode
Vertical: 12.5 V/div
Sweep: 10 μs/div

Differential Mode
Vertical: 200 mV/div
Sweep: 5 μs/div

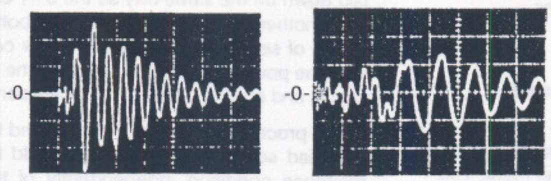
Figure 11. Transients Induced in Thermocouple Pair by Surge Occurring in 6 kV Cable



Common Mode
Vertical: 2.5 V/div
Sweep: 10 μs/div

Differential Mode
Vertical: 50 mV/div
Sweep: 5 μs/div

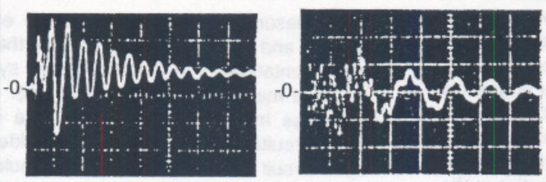
Figure 12. Transients Induced in Thermocouple Pair by Surge Occurring in 380 V Cable



Common Mode
Vertical: 12.5 V/div
Sweep: 10 μs/div

Differential Mode
Vertical: 200 mV/div
Sweep: 5 μs/div

Figure 13. Transients Induced in Signal Pair by Surge Occurring in 6 kV Cable



Common Mode
Vertical: 2.5 V/div
Sweep: 10 μs/div

Differential Mode
Vertical: 50 mV/div
Sweep: 5 μs/div

Figure 14. Transients Induced in Signal Pair by Surge Occurring in 380 V Cable

2.3 *Discussion of the results* – The surges induced in the measurement cables have common-mode levels of less than 100 V peak and differential-mode levels of less than 1 V peak mode on the signal lines (pairs).

The waveforms are substantially damped oscillatory waves (single shot), affected by a damping dependent on the propagation characteristics of the 6 kV and 380 V cables. The frequency of the oscillations ranges from about 100 to 200 kHz; higher values are observed for the common mode and lower for the differential mode voltages. The propagations affect each other; it is important to note that, in practical cases, the final waveform parameters of induced surges cannot be predicted or precisely defined due to the variability of the installation parameters (length of cables, dielectric constant of the insulation, separation from the ground of reference, etc.).

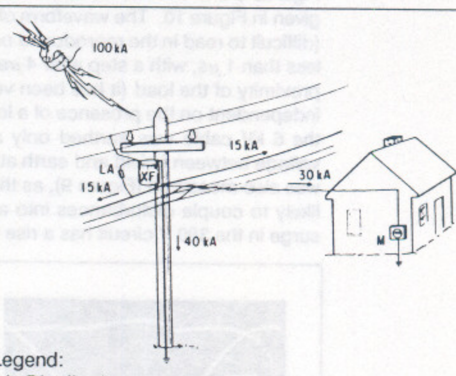
It is evident that, in particular for the differential mode, the induced surges do not include a unidirectional component. Such a component appears only in limited amount for the common-mode on the pairs within a cable, whenever the surges are induced by the transients on the 380 V power cable. In this case, because these 380 V cables are unshielded, the capacitive coupling occurs in the low frequency range.

3. Conversion of unidirectional lightning current in ground conductors into oscillatory surges

Tests were performed in the General Electric High Voltage Laboratory [3], aimed at simulating the passage of current in the grounding (protective earth) conductor of the service drop to a building. The motivation for the test was part of a general investigation on propagation of surges in low-voltage wiring without a preconceived notion on the waveform of the surges. As it turned out, the injection of a unidirectional current produced an oscillatory voltage.

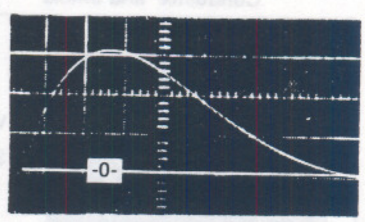
The building wiring system was simulated by erecting a service entrance panel and several branch circuits, in a geometry representative of the normal wiring practice applied in the U.S. The service drop was simulated by using a pole-type distribution transformer including its connection to the earth reference (the ground plane of the laboratory in this test), a three-conductor service drop, and the prescribed grounding of the neutral at the service entrance (Figure 15). The service drop conductor configuration was the conventional, three-conductor "messenger wire" strung between the pole and the building. This messenger wire serves as a mechanical support as well as the multiple-grounded neutral conductor, with the two other conductors wrapped in a long pitch around the messenger.

Unidirectional 8/20 μs current impulses were injected between the *neutral* terminal of the distribution transformer and the *ground plane*. For the initial scenario of 30 kA in the messenger wire, resulting from an assumed 100 kA stroke (Figure 15), several flashovers were observed in the branch circuit wiring. The current had to be reduced to 1.5 kA for flashovers to stop. The resulting voltages were then measured between the *phase and neutral* conductors at various points of the branch circuits. In all cases, a large oscillatory component at 500 kHz was present in the measured voltage, in addition to a unidirectional component. Figure 16 shows the injected unidirectional current and Figure 17 shows the induced voltage appearing at one of the receptacles at the end of a branch circuit.



Legend:
LA: Distribution system arrester
XF: Distribution transformer
M : Watthour meter

Figure 15. Configuration Simulating Lightning Current in Messenger Wire of a Service Drop to a House



Vertical: 500 A/div
Sweep: 2 μs/div

Figure 16. Injected Current in Messenger of Service Drop

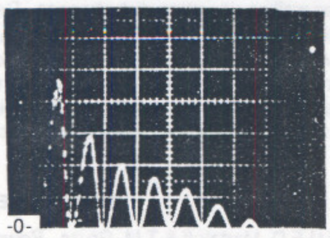


Figure 17. Transient Induced as 2.2 kV Differential Mode by a 1.5 kV 8/20 us Impulse in Messenger Wire

4. Response of a building wiring system to a unidirectional surge applied at the service entrance of the building

During a series of measurements aimed at defining the surge propagation characteristics of an actual building wiring [5], it was found that applying a unidirectional surge at the service entrance of the building, on the primary side of the transformer installed within the building, results in oscillatory transients. In contrast with the previous test where *current surges* were injected in the *grounding conductors*, in this test series *voltage surges* were injected *phase-to-phase* on the transformer primary. Figure 18 shows the voltage waveform at the transformer primary resulting from a standard 1.2/50 surge voltage. Note the occurrence of a small oscillation (12%) at the crest, but the predominant waveform of the surge is unidirectional, a situation somewhat different from the interaction between the Marx generator and the mismatched high-voltage line seen in Figure 2.

The resulting transient inside the building is a superposition of a unidirectional component and an oscillation (Figure 19), that is, the same situation of common impedance discussed in paragraph 1.3. This transient then propagates throughout the wiring inside the building.

In Figure 19, a line has been drawn on the oscillogram to show the unidirectional component in the resulting oscillatory transient. Note that the first cycle of the oscillation has an amplitude of three times the unidirectional component, compared to the 12% ring of the applied unidirectional surge. Details of the propagation characteristics are presented in Ref [5]. A significant finding was that for the dimensions of the building (length of the conductors), the faster front (0.5 μs) of the 100 kHz Ring Wave produced reflections which would not occur with a slower 1.2/50 μs impulse. On the other hand, much faster waves, such as the 5/50 ns burst [10] were found to be quickly attenuated. Thus, this ring wave produces a unique stress on equipment connected to the end of a branch circuit, such as an electronic control circuit in standby mode, the subject of the next investigation.

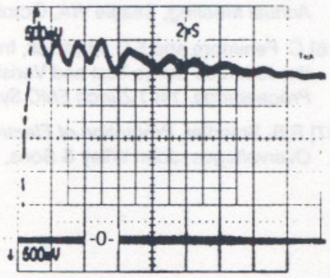


Figure 18. Applied Unidirectional 1.2/50 us Voltage at Primary of Service Transformer of Building

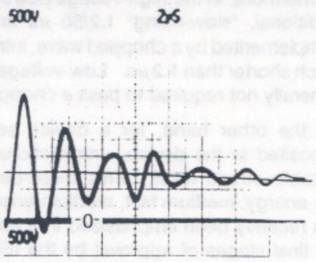


Figure 19. Oscillatory Transient Appearing in Building as Result of Application of the Figure 18 Surge

5. Effects of oscillatory surges on semiconductors

Various published and unpublished test results [11], [12] have reported that the reversal of bias on a semiconductor junction produced by applying an oscillatory surge can have a strong effect on the surge withstand capability of the device. The failure is also more likely when polarity reversals are applied during conduction, forcing the junction from a forward bias to a reverse bias.

This uncontested but not widely acknowledged finding was recently illustrated again by a series of measurements performed at NIST in preparation of qualification tests for an equipment using triacs for power control. The test schedule called for both the unidirectional wave, described as "Combination Wave" [13], and the 100 kHz Ring Wave defined in several U.S. standards and under consideration in IEC standards in progress [14].

Figure 20 shows one example of failure of the semiconductor occurring, not at the crest of the first part of the oscillation – which would be the expectation under a unidirectional stress – but upon reversal of the polarity during a Ring Wave test. This observation has rekindled interest in the issue and further tests are planned to better characterize the behavior of power semiconductors under ring wave stress.

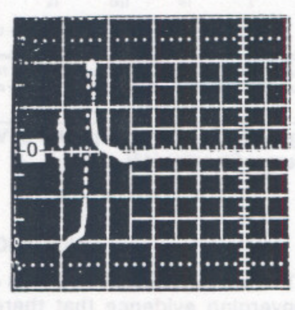


Figure 20. Failure of Triac During 100 kHz Ring Wave Test

SURGE IMMUNITY SPECIFICATIONS AND TESTS

The four independent experiments cited in this paper include induced transients and injected transients, carried out at different times, countries, and installations. The results show that the surge environment of low-voltage circuits, for ac power systems as well as for control systems, is dominated by damped oscillations with a frequency range of 100-500 kHz.

This observation, especially for surges of large amplitude, should not be misconstrued as denying the significance of other surge test stresses, such as the Electrical Fast Transient [10] where the interference aspects of the test are its major objective. Furthermore, in the high-voltage power apparatus domain, the traditional, "slow-rising" 1.2/50 μs impulse has often been complemented by a chopped wave, introducing transition times much shorter than 1.2 μs. Low-voltage equipment, however, is generally not required to pass a chopped-wave test.

On the other hand, for a device sensitive to total energy deposited in the device, unidirectional waveforms provide a suitable stress level. This three-part stress range – fast, low-energy; medium fast, medium-energy; slow, high-energy – has recently been emphasized in a revision of Ref [4], now in the final stages of approval by the IEEE, where the range of recommended surge tests includes the EFT, the 100 kHz Ring wave, the 1.2/50-8/20 μs Combination Wave, a new 5 kHz Ring Wave, and a new unidirectional, high-energy 10/1000 μs wave. The latter is similar to the 100/1300 μs test under consideration by IEC TC77 [6], although the latter may involve extremely high energy levels encountered only under special circumstances [15], [16].

Discussions in IEC standard-writing groups produced the argument that the amplitude density spectrum of the 1.2/50 μs impulse is so wide that it would cover the spectrum of the damped oscillatory ring wave. In fact, the ring wave shows a peak that extends almost one order of magnitude higher in frequency, as shown in Figure 21 [17]. Furthermore, the reversal of polarity effects discussed above are not produced by the 1.2/50 μs impulse. In the IEC, both waveforms are considered in the general overview of immunity tests [6] and in dedicated basic standards [13], [14].

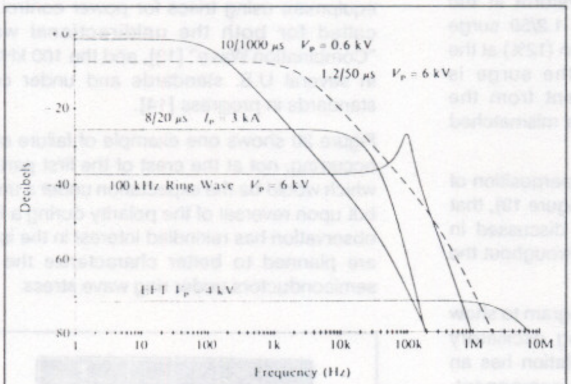


Fig. 5-12. Plot of Fourier transform of various nominal waveforms. The peak voltage or current is labeled with the name of each waveform. The zero dB reference is 1 V or 1 A. The spectrum of the 1.2/50 μs waveform is shown with a dashed line for clarity.

Figure 21. Frequency Spectra of Various Test Surges
Source: Standler [17]

CONCLUSIONS

1. The five independent examples cited in the paper provide converging evidence that there is a difference in the environment and its effect between power transmission systems, where the unidirectional test impulse reigns, and the low-voltage utilization circuits, where ring waves are a more realistic representation of the stresses encountered by modern electronic equipment.

2. To evaluate withstand capability of bulk solid insulation, it may be stressed adequately by unidirectional impulses. However, more complex devices such as windings or semiconductors may exhibit failure modes that will be more prevalent under ring wave test conditions.

3. The two basic surge waveforms, the Combination as well as the Ring Wave, should be taken into consideration for damaging as well as upsetting disturbances. Depending on the nature of the equipment, its characteristics, and installation type, one waveform may be preferred to the other. The choice is the responsibility of relevant product committees, best qualified for assessing the exposure of their equipment, on the basis of a comprehensive menu of real, realistic waveforms.

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