TRANSIENT CONTROL LEVEL PHILOSOPHY AND IMPLEMENTATION
II. Techniques and Equipment for Making TCL Tests

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from *Proceedings, 2nd International Symposium on Electromagnetic Compatibility*, Montreux, 1977

Significance

Part 5 – Monitoring instruments, laboratory measurements and test methods

This is the second part of two companion papers introducing the concept of Transient Control Levels to the EMC community, a proposal to apply to the design of low-voltage equipment the same principles as the Basic Insulation Level (BIL) that were successfully applied to hig-voltage equipment.
The first paper (See "TCL philosophy") deals with questions of why tests should be made and what should be the specifications governing such tests. This paper amplifies somewhat on those themes, but is primarily concerned with questions as to how such tests might be made.

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II. Techniques and Equipment for Making TCL Tests

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Abstract

This is the second of a pair of papers describing how better transient protection might be achieved through the use of a Transient Control Level philosophy. The first paper deals with questions of why tests should be made and what should be the specifications governing such tests. This paper amplifies somewhat on those themes, but is primarily concerned with questions as to how such tests might be made.

Direct Injection of Transients

Equipment

Surge generators capable of producing the types of transients involved in the Transient Control Level (TCL) philosophy generally employ capacitors that are discharged into a wave-shaping circuit. That circuit would be resistive if unidirectional transients are to be produced, and inductive if oscillatory transients are to be produced.

It should be understood that the TCL philosophy is not written around any particular test circuit. Any circuit that produces open-circuit voltages and short-circuit current of the required characteristics will be satisfactory. Nevertheless, it does seem appropriate to give some specific guidance as to the types of generators that might be used.

Some representative examples of circuits are shown on Fig. 1. The switch may be either triggered or untriggered, depending upon the degree of sophistication desired. Components should be chosen and laid out in such a way as to minimize undesired residual inductance and radiated interference. Circuit voltages are frequently high enough to be hazardous; therefore, appropriate safety precautions must be taken. The two circuits shown on Figs. 1a and 1b are designed to produce the 100 kHz oscillatory TCL test wave and the unidirectional 1.2 x 50 microseconds ANSI test wave.

In Fig. 1a, the oscillatory frequency is determined primarily by C_1 and L_1 with the front time determined by R_2 and C_2. In Fig. 1b, the front and tail times are approximately:

$$t_{tail} = 0.7\ R_1C_1 \qquad \ldots(1)$$

$$t_{front} = 3.0\ R_2C_2 \qquad \ldots(2)$$

With different component values, this same type of circuit would then produce longer duration transients. Photographs of the waveforms produced by these generators are shown on Figs. 2 and 3. A significant point to note is that the shapes of the current and voltage are different. This is particularly true of the oscillatory generator, Fig. 1a. It is characteristic of inductive transient sources that the short-circuit current takes longer to reach its peak value than does the open-circuit voltage. Specifications should allow for this; it is generally unrealistic to require surge currents to rise to crest as fast as surge voltages, at least from inductive sources or into inductive loads.

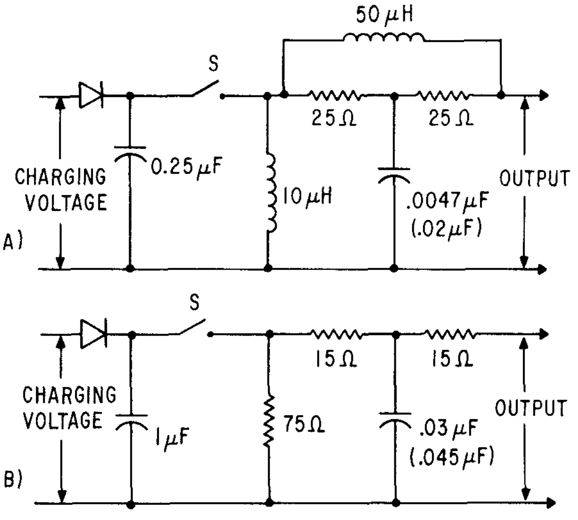

Fig. 1: Elementary Circuit Diagrams
A) Oscillatory Generator
B) Exponential Generator

(Values in parentheses were used for transformer injection)

The generators of Fig. 1 may be operated to produce either single or repetitive pulses. A 60 (or 50) pulse per second rate is easily achieved by charging the storage capacitor from an ac

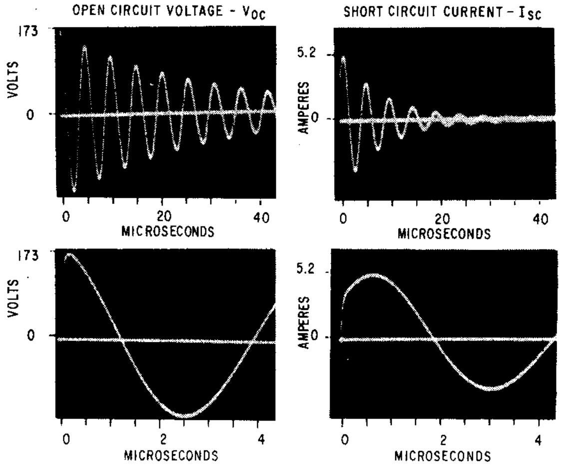

Fig. 2: Wave shapes produced by oscillatory generator (direct injection)

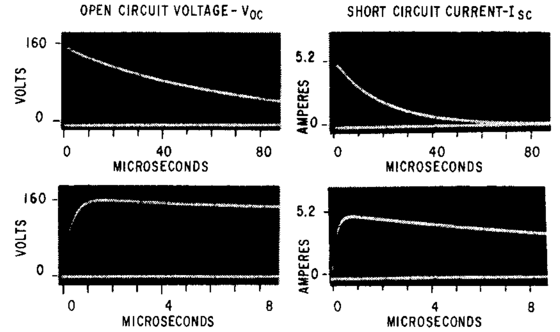

Fig. 3: Wave shapes produced by exponential generator (direct injection)

source and closing the output switch on the half-cycle following that which charged the capacitor.

The type of discharge switch depends on the voltage rating and the degree of sophistication required. Low-voltage thyratrons and thyristors are suitable up to about 500 volts, series strings of thyristors to about 2000 volts, and spark gaps at higher voltages. This type of circuit lends itself readily to superimposition of the transient to the power frequency voltage. Some investigations, such as circuits involving semiconductors, require that the timing of the transient with respect to the power frequency wave be controlled.

Types and conduct of tests

Experience has shown that great amounts of confusion can surround two seemingly simple questions: for what purpose does one wish to make a TCL test, and how does one define the severity of the test? With respect to the first of these questions, TCL tests fall into one of two categories: those aimed at determining what TCL is appropriate for a particular piece of equipment, and those to determine whether a particular piece of equipment meets the requirements of a certain TCL specification. While the subject may seem elementary, experience has shown that the distinction between the two is often lost. These distinctions are illustrated in Figs. 4 and 5.

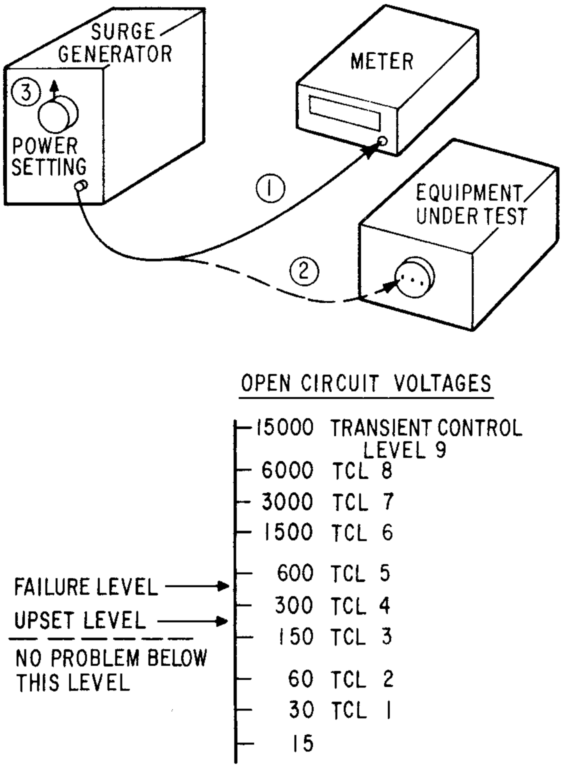

Fig. 4: Determining upset or failure levels of a piece of equipment

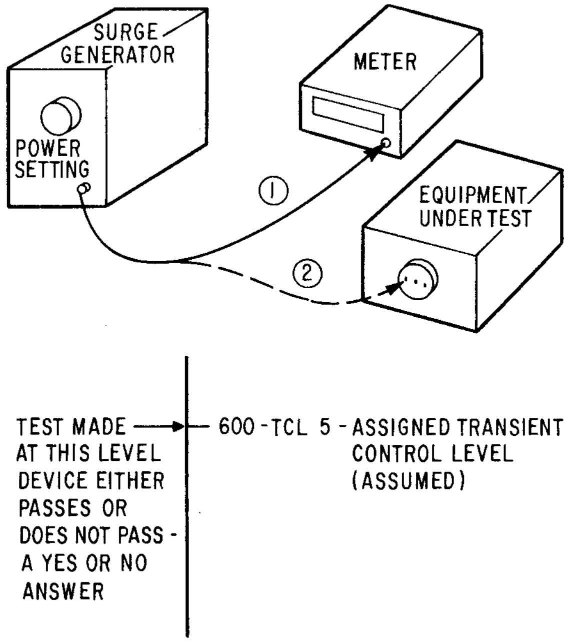

Fig. 5: Acceptance tests on a piece of equipment

In Fig. 4 the problem is to determine what the intrinsic withstand or upset level of the piece of equipment might be. In this type of test the surge generator is set to some level, the transient is applied to the terminals of the equipment under test, and the results are observed. The output level of the surge generator is then measured, probably in terms of the open-circuit voltage produced by that power setting. The power setting of the surge generator is then increased in steps until the device under test either upsets or fails catastrophically. The actual voltage or current amplitudes and wave shapes at the terminals of the equipment depend upon the input impedance of the equipment; and these might be unduly complicated to specify. The failure, however, will occur at some definite setting of the transient generator. If the setting of the generator (position of the knobs) was left unchanged, the energy level of the transient that produced failure or upset could then be described in terms of the voltage or current that the generator produced when connected to an open circuit or to a short circuit. This level will seldom be a nice round number, either so many volts or so many amperes. If one were to quote a level of transient that a device could withstand, that level would be the next lowest of the agreed-upon sequence of levels. If the levels from which the choice were to be made were as shown on Fig. 4, the appropriate level to quote would be level 3.

The alternative problem is that of Fig. 5, in which the aim is to determine whether or not the piece of equipment under test is able to withstand the transients associated with the specified transient control level. In this type of test, the transient generator is set to deliver a specified current into a short circuit and to deliver a specified voltage to an open circuit. If the source impedance levels have been properly chosen and implemented, these two conditions will be met simultaneously at one power setting of the transient generator. With the setting of the transient generator left unchanged, the output terminals of the generator are then connected to the input terminals of the device under test. An appropriate number of transients are applied to the equipment, and the equipment is monitored for correct operation during the test or monitored after the test to determine whether it works or not.

The preceding material has touched upon the question of how one defines the level of transient. Superficially, this might seem a trivial question to which an easy answer can be given -- the level of the transient is measured in terms of the voltage applied to the terminals of the device under test. However, this simple answer is deficient in that it neglects the input impedance of the device under test. If the device under test has a low input impedance or is fitted with surge protective devices, it might not be possible to develop a specified voltage without injecting excessively high currents into the device, currents higher than the naturally occurring transient source would be able to supply. For low impedance circuits, it is more appropriate to define the transient in terms of current. However, a specification considering only surge current is not sufficient in that the impedance of the circuit might be so high that a specified current might be developed only by applying excessive voltage. For these reasons it seems best not to define a test in terms of the voltage or current developed at the terminals of the device under test. Rather, in the TCL philosophy, the tests are defined in terms of the capability of the surge generator to deliver specific voltages or currents into specific loads. If one is dealing with surge generators suitable for direct connection to the terminals of the device under test, the most convenient loads are open or short circuits. In cases where the transient is to be superimposed to the power frequency voltage, it will be necessary to disconnect the power supply for the short-circuit test.

As examples of why these quantities are of importance, open-circuit voltage is of importance if one is studying the ability of insulation to withstand voltage, or if one is studying the ability of an isolated circuit to withstand interference. Short-circuit current is the quantity of most relevance if one is studying the ability of circuit protective devices to withstand surge currents, or if one is studying the interference produced on signal circuits by current flowing upon the shields of cables.

Transformer Injection of Surges

Direct injection tests are most appropriate to determine whether or not a piece of equipment by itself would be damaged by a specific level of transient. A problem of greater complexity is determining whether a group of interconnected pieces of equipment will operate correctly in the presence of transients. Generally, the equipment cannot be tested for proper operation unless it is part of a completely interconnected system. This usually implies there must be a source, a load, and appropriate interconnected wiring. It would also seem to go without saying that the method of injecting the transient into the wiring should realistically duplicate the way in which the natural electromagnetic field induces transients into the wiring. One such test technique is shown on Fig. 6. In nature, an electromagnetic field might be set up between the conductors and ground, the field being distributed over the entire length of the interconnecting wiring. In Fig. 6, a similar magnetic field is produced, but confined within the core of a pulse injection transformer. If this transformer is placed around the wires under consideration, the current and voltage induced into those wires are nearly the same as that produced by the distributed magnetic field of nature. The magnetic field is set up in the core of the transformer by discharging a surge generator through an exciting winding on the core.

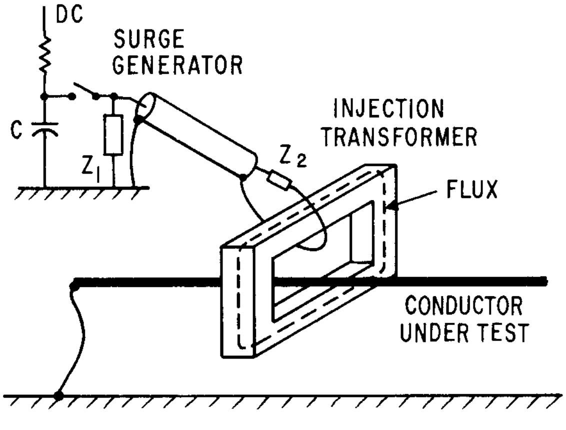

Fig. 6: A magnetic field confined in the core of an injection transformer

Some considerations regarding the capabilities of such transient injection follow. First, it should be remembered that the circuit under test is primarily exposed to the changing electromagnetic field contained in the core of the pulse injection transformer. If the source under test is a high impedance circuit, the natural effect of that changing magnetic field is to induce an open-circuit voltage, the magnitude and duration of which will depend upon the amplitude and rate of change of the magnetic field in the core, but which will not be significantly affected by the length of the circuit under test. However, if the circuit is of low impedance, the magnetic field will induce a circulating current in the circuit. The shape of this current will be of a duration longer than that of the open-circuit voltage, and will be nearly the same as the duration of the current produced by the pulse generator in the primary of the transformer.

The magnitude of this current will depend upon the impedance of the circuit under test. That impedance is governed both by the internal impedance of the terminal equipment and the characteristics of the wiring used to interconnect those pieces of equipment. Just as with direct injection of transients, there can be ambiguities in specifications if the characteristics of these impedances are not taken into account. If, for example, the wiring under test is fitted with a shield grounded at each end, the natural measure of the transient is the current induced on the shield. If the wiring is unshielded and connected to high impedance loads the natural measure of the transient is the induced voltage. Again, a complete specification of the test circuit must deal both with the maximum voltage and the maximum circuit current that may be produced.

It seems appropriate to measure these voltages and currents on a dummy circuit of fixed dimensions. The dimensions must be fixed since length, diameter, and height all affect the inductance, the most important component of the impedance. The inductance of a conductor is almost directly proportional to its length, but proportional only to the logarithms of the diameter and of the height above the ground plane. In the absence of any other specifications, it is suggested that the surge generator and injection transformer be such that the specified short-circuit current be induced on a conductor 3 meters long, having a diameter of 0.41 centimeter, and spaced 5 centimeters above the ground plane. Such a conductor may be provided by the shield of RG-58 coaxial cable.

An example of a test structure having these dimensions is shown on Fig. 7. Representative examples of the transients that may be produced are shown on Figs. 8 and 9.

It is harder to inject a transient indirectly into a cable than it is to produce a transient for direct injection tests, because of the limitations of the injection transformer. If Fig. 8 is compared with Fig. 2, it will be noted that both the current and the voltage are less, and that the ratio of voltage to current is less when the transient is injected via a transformer than when it is injected directly. This results from the characteristics of the injection transformer. If the transformer has high magnetizing

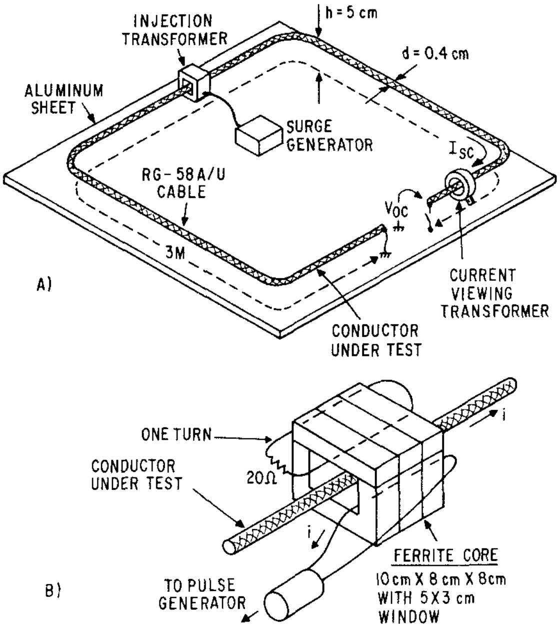

Fig. 7: Transformer injection of transients:
A) Conductor geometry
B) Injection transformer

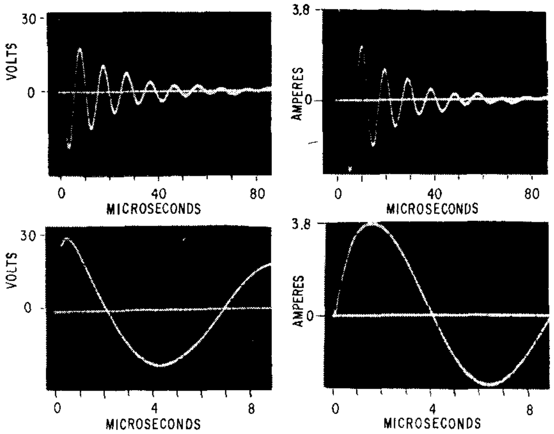

Fig. 8: Waveforms produced by oscillatory generator (transformer injection)

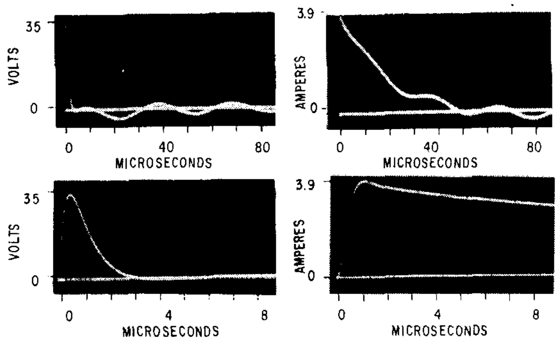

Fig. 9: Waveforms produced by unidirectional generator (transformer injection)

inductance and low leakage inductance, the exciting current -- and hence, magnetic flux -- will be proportional to the integral of the exciting voltage. In such a case, the open-circuit voltage induced on the cable will be of the same shape and amplitude as the driving voltage from the surge generator.

As a practical consideration, it is often desirable that the cable joining the two pieces of equipment under test be threaded through the core only once, either because of the physical characteristics of the cable or because of the effect on the transient response of the transformer of multiple turns. This limits the magnetizing inductance to relatively low values. The current in the exciting winding -- and hence the flux in the core -- is then proportional more nearly to the generator voltage than to the integral of that voltage, particularly for surge generators of internal impedance high compared to the impedance of the transformer. As a consequence, open-circuit voltage induced onto the cable may be of shorter duration than desired, approaching the derivative of the driving voltage. The amplitude of the voltage might also be limited by saturation of the core. These effects are more troublesome for longer duration transients, as may be noted by comparing Fig. 9 to Fig. 3.

Two measures were taken to improve the wave shape of the open-circuit voltage. The first of these was that some resistive loading, via an auxiliary winding, was used on the injection transformer to provide partial integration of the flux. The second was that the front time of the open-circuit voltage from the exciting pulse generator was made longer through the use of higher values of wave shaping capacitance. While these compensating techniques were partially successful, there is still ample room for improvement in the art of making equipment for transformer injection tests.

Injection transformers are not constrained to be operated with only one turn, or even equal turns, on the primary and secondary. Either voltage or current may be emphasized by operating the transformer with unequal turns, although such operation should be recognized as affecting the impedance of the test circuit. In general terms, the effects of unequal turns are:

a) More turns on secondary gives (for a fixed number of turns on the primary):
  - Less short-circuit current
  - More open-circuit voltage
  - A decrease in the frequency of the natural oscillatory mode of the cable under test.

b) More turns on primary gives (for a fixed number of turns on the secondary):
  - More short-circuit current
  - Less open-circuit voltage
  - A decrease in the frequency of the natural oscillatory mode of the pulse generator
  - A longer rise time of the current pulse.

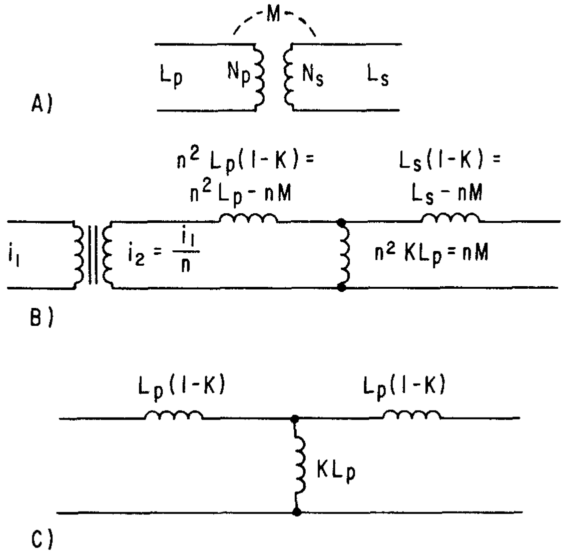

Fig. 10: Equivalent circuits of injection transformers
A) Basic transformer
B) Equivalent circuit referred to secondary
C) Equivalent circuit if $N_P = L_S$ and $L_P = L_S$

If one wishes to determine by analysis the characteristics of the test circuit, one may derive equivalent circuits for the injection transformer and the conductor under test. For the injection transformer, the Tee equivalent shown on Fig. 10 is generally satisfactory.

In Fig. 10

$$M = 1/4\ (L_A - L_B) \qquad \ldots(3)$$

$$K = M(L_P L_S)^{-\frac{1}{2}} \qquad \ldots(4)$$

$$r = N_S/N_P \qquad \ldots(5)$$

L_A and L_B are the inductances measured with the primary and secondary windings connected first in series aiding and then in series bucking.

The cable under test could probably be treated equally satisfactorily as a Tee equivalent of inductance and capacitance. A complete equivalent circuit, less the resistive loading shown on Fig. 7, would then be as on Fig. 11. Numerical analysis of this circuit with the aid of a computer program such as ECAP is entirely feasible. While the task has not been done, such analysis might point the way to test circuits better adapted to producing the desired TCL test waves.

Equipment for Generation of Electric and Magnetic Fields

The test equipment described so far has been aimed at the injection of current or voltage pulses into the terminals of electronic equipment. There is also sometimes a need to subject equipment to an engulfing electric or magnetic field, principally to check for magnetic field leakage of the cabinet. Sometimes these effects

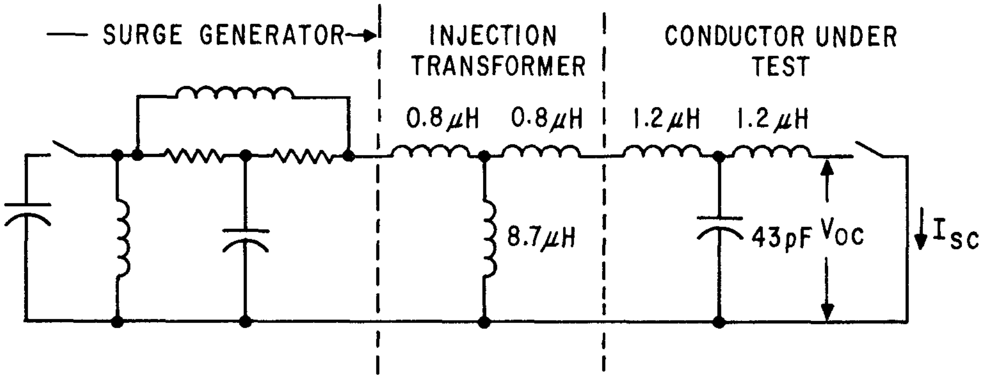

Fig. 11: Equivalent circuit of a surge generator connected to cable through an injection transformer:

o the compensating loop of Fig. 7 is not included

o component values shown are those appropriate for the test ferrites of Fig. 7.

are checked with a wire-wrapped technique in which a coil of wire is wrapped around the item to be tested and the coil then excited from a pulse generator. The type of magnetic field so produced is perhaps not the best that may be derived for direct effects testing. In the study of nuclear electromagnetic pulse (NEMP) effects, use is often made of stripline simulators in which a pulse generator is matched to a large open transmission line. In such simulators attention is given to insuring that there is a suitable transition from the small geometry of the pulse generator to the large geometry of the test chamber. The pulse generators and working chambers are also carefully matched to each other to allow the production of the required short-duration, rapidly changing fields. For the production of more slowly varying electromagnetic fields, such as those resulting from lightning, the physical design of such chambers can frequently be simplified. The rise times involved are not as fast as those in the NEMP studies and the requirement of plane wave propagation in the test chamber is not as important. A test chamber suitable for many types of equipment might be like that of Fig. 12. It would basically consist of a one-turn loop antenna of rectangular cross section enclosing a volume of about 1 m^3. Such a coil, when excited by the pulse generator sketched, would produce in its working volume a magnetic field of approximately 1000 amperes per meter or an electric field of about 20 kV per meter.

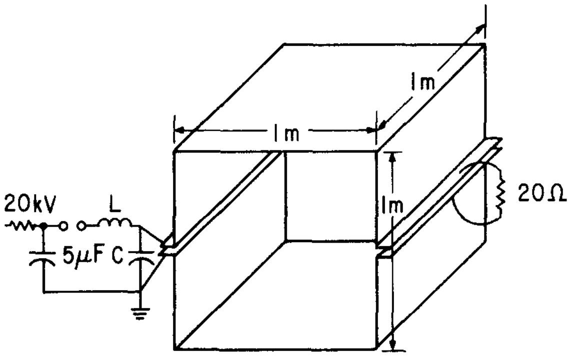

Fig. 12: Possible test chamber for evaluating electric and magnetic field effects

Conclusions

The equipment capable of performing the types of tests implied in the TCL concept is basically simple in nature. If only the lower levels need be generated, and if the equipment need not be very refined, it can be built in virtually any laboratory.

Ultimately, of course, one might expect suitable test equipment to become available commercially, and indeed some equipment is already available. This is particularly true of equipment suitable for direct injection of transients. Techniques for indirect injection have not yet been as well worked out. There is a need for further development in that area, supported by commercial test equipment.

The true need for subjecting electronic hardware to electric and magnetic fields has not yet been determined, and accordingly very little has been done toward producing equipment for such tests.