GER-3204

Substation Transients and Solid State Controls

SUBSTATION TRANSIENTS AND SOLID STATE CONTROLS

by

W. C. Kotheimer
General Electric Company
Philadelphia, Pennsylvania

NORTHWEST ELECTRIC LIGHT AND
POWER ASSOCIATION
51 st Annual Conference

Chinook Hotel
Yakima, Washington

April 23, 1974

INTRODUCTION

Almost twenty years have elapsed since the first practical applications of solid state controls and protective systems in an electric power station. These cautious beginnings heralded a revolution in power system control and protection. Today it is commonplace to find in power stations numerous solid state equipments performing functions previously assigned to electromechanical devices. The change is continuing and now we look ahead to the application of a whole host of new solid state devices and equipments for power system control and protection.

From the beginning solid state equipment designers were concerned that certain environmental factors in a power station might strongly influence solid state devices, such as transistors in control equipments, whereas they had previously had little effect on electromechanical control devices. In particular they were most concerned about the transient electromagnetic fields associated with various normal station operations and the first solid state protective relays featured simple surge filters to minimize adverse effects. Figure 1 illustrates the reasons for this concern. The basic operating times and power levels for solid state devices (transistors and later, integrated circuits) are several orders of magnitude less than for electromechanical devices such as electromagnetic relays. Although not much data existed twenty years ago on the nature of transients in control circuits, it was anticipated that the new solid state devices might respond to them. Figure 1 also shows an area defining the approximate characteristics of control circuit transients which corresponds with the response of solid state devices. The implication is obvious.

Much has been learned in twenty years from numerous field installations and laboratory tests. The general nature and origin of control circuit transients are now fairly well understood. Also much progress has been made in identifying the features of station layout and solid state equipment design to eliminate this problem.

SOURCES OF TRANSIENTS IN STATIONS

For the purposes of this discussion consider the two general classes of conductor systems co-exist in an electric power station. The first of these, the high voltage power conductor class will consist of all the high voltage busses and power circuits, the primary circuits of current transformers and potential transformers, the line-to-ground paths of all capacitor like devices such as CVTs, carrier couplers, equipment bushing capacitances, and the station ground grid and all equipment grounds.

The second class of conductor systems is the low voltage class, which includes all auxiliary power circuits, instrument transformer secondary circuits, control, instrumentation and communication circuits, and station battery circuits. It is plain there are many circuits, some interconnected, others isolated, which are included in this class.

The two classes were said to co-exist. This is to be interpreted physically. Figure 2 illustrates this point. It shows a high voltage bus section with lumped capacitances connecting to the ground grid at various locations. As already mentioned, these capacitances are inherent in various high voltage equipments. A cage-like structure is formed. Threading through this cage is a portion of a low voltage control circuit. Any switching action or other phenomenon such as gap flashing, etc., which takes place on the high voltage system, causes rapid voltage and current disturbances in this system, which in turn give rise to transient electromagnetic fields in the immediate vicinity. The low voltage circuits being immersed in these transient fields are therefore subject to induction producing corresponding transient voltages and currents in the control system. The solid state control or protection equipments being connected in the low voltage conductor class in turn become exposed to these transients at their entry ports.

Transients may also originate in the low voltage system due to switching phenomena. The associated disturbances are transmitted to other locations where they may adversely affect solid state equipments.

TRANSIENT CHARACTERISTICS

The waveform of the transient voltage or current induced in a control circuit is largely determined by the nature of the originating transient in either the high voltage or low voltage circuits. Data which are available show that transients originating on low voltage circuits have characteristics distinctly different from those originating in high voltage circuits. These different characteristics and typical sources of these transients will now be described.

TRANSIENTS FROM HIGH VOLTAGE SOURCES

There have been numerous field tests showing data on waveforms of transients originating on high voltage circuits. From these we can summarize the following approximate values:

Voltage waveform	repeated damped oscillatory bursts
Crest voltage	500 to 3000 volts
Oscillating frequency	200 kilohertz to several megahertz
Burst repetition rate . . .	single to 100 per second
Individual burst duration	50 microseconds
Burst train duration	2 seconds maximum
Available current	up to 50 amperes crest
Mode	both Common and Transverse

The sketch in Figure 3 illustrates these characteristics. One of the most common mechanisms giving rise to this type of transient is the switching of a bus section by a high voltage disconnect switch. The transients originate in the re-striking or prestriking of the switch during either opening or closing operations. This is a very powerful transient source which may be coupled to a low voltage control circuit over a wide area, and thus appear on widely separated parts of that circuit. Usually it appears most strongly on secondary cables from high voltage instrument transformers and dc control wiring connected to high voltage equipment associated with the switched bus. Station auxiliary power circuits are also exposed to this type of transient causing equipment failures when operating from outdoor power outlets in the vicinity of the bus.

The IEEE-SWC test for solid state protective relays closely simulates the effect of this type of transient. Its waveform is shown in Figure 4.

Figure 5 illustrates a high voltage circuit in which this type of transient is generated, It consists of a loop in thevertical plane including a portion of the station ground mat, the vertical paths through two CVTs and a second horizontal path containing a circuit breaker and an air-break disconnect switch. On a 500 kV system such a loop might be about 40 feet high and about 120 feet wide. The self inductance of the loop would be about 100 microhenries. Figure 6 shows an equivalent circuit for this loop. C_A and C_C represent the CVT capacitance and L_N is the loop inductance. C_B represents the grading capacitors across the open contacts of a gas or high pressure air insulated circuit breaker. The switch restrikes whenever the voltage across it, due to the bus voltage on one CVT and a trapped charge on the other CVT, exceeds its dielectric strength. This takes place repeatedly as the disconnect switch blade moves. The maximum restrike occurs when the voltage across the switch is about twice peak line to ground potential. For a 500 kV system this is about 816 kV. When this occurs a transient current oscillates in the loop. The frequency of oscillation is determined by LN and CN. Also the peak magnitude of the current depends on the surge impedance of the loop $\sqrt{L_N/C_N}$, as well as on the initial voltage across the switch before the restrike. The frequency can be quite high and the currents can also be high. The frequency is higher when the circuit breaker is open, but the currents are smaller. The difference in the example shown is about 2 to 1.

These high frequency transient currents flow in the CVT ground leads and in the ground mat in close proximity to the secondary cable from the CVT. A high frequency transient magnetic and electric field is associated with this current. Figure 7 shows this transient magnetic flux linking the area of another loop comprised of the ground mat and the CVT secondary cable. Capacitor C4 completes this loop. It represents the total stray capacitance of the CVT secondary winding circuit to the CVT case. A value of about 500 pF is typical. At 1.5 megahertz this represents only about 200 ohms impedance. Because the intense flux linking the loop is changing very rapidly, it induces a rather large voltage, several kV, in even a modest size loop.

If the secondary cable runs for any significant distance parallel to the high voltage loop, another coupling mode comes into play. This is due to the effect of the transient electric field across the loop which produces high frequency displacement currents in this region flowing into all nearby conductors, the secondary cable included. In severe cases this can also produce transient potentials of several thousand volts at the sending end of the cable. These transients from both sources are transmitted by the cable and the station ground to various control and protective equipments.

Exposure to this type of transient can be reduced if the size of the secondary loop is minimized by routing of the secondary cable close to the CVT ground lead. Shielded secondary cables should be used with the shield grounded at both ends. Grounds on the secondary circuit of the CVT should be at the receiving end. Field experiments have shown that these techniques will reduce transients from this source on the order of 50 times.

TRANSIENTS FROM LOW VOLTAGE SOURCES

Typical of this class of transients are those which are produced on station battery circuits by the switching of inductive devices such as auxiliary relays, trip coils and alarm bells, etc. Similar transients are also produced on low voltage ac circuits.

The nature and severity of the transient impressed upon a low voltage circuit by switching of an inductive device is not dependent on the inductance alone. Actually, as will be explained, the inductance has a secondary role. The dielectric recovery rate of the switching contact and the circuit stray capacitances are the main factors.

Figure 8 shows a relay coil and a switch on a 125 volt dc circuit. The relay coil has a self-inductance of 50 henrys and a resistance of 2000 ohms. A capacitance is shown across the coil. It represents the stray capacitance across the coil due to external wiring and that which is internal to the coil. A value of 1000 pF is typical. If the switch was a perfect switch, it could interrupt the coil current instantly without restriking. When this happens, the coil current does not stop but continues to flow out of the coil into the stray capacitance. This becomes charged to a very high voltage and then begin to discharge back through the coil, reversing the current. This oscillation continues until the magnetic energy in the coil at the start is completely dissipated in the resistance of the coil. The maximum theoretical voltage across the coil is given by:

$$V_S \max \approx - \frac{V_{BB}}{R} \sqrt{\frac{L}{C_S}}$$

For the values shown in Figure 8, V_S can reach -14,000 volts. The frequency of the oscillation is low, several hundred hertz. Notice that the voltage appears only across the coil. Because the switch is perfect it completely isolates the rest of the dc circuit from the high voltage. Furthermore the transient frequency is very low, comparatively speaking.

Reality is not perfect however, and the imperfect performance of real switches supplies the mechanism for transferring the high potential stored in the stray capacitance to the dc system. This is illustrated in Figure 9.

It is reasonable to assume that the dielectric breakdown voltage of a pair of switch contacts is directly proportional to the contact separation. Furthermore for small motions, it can be assumed that the contact experiences a constant acceleration due to a constant spring force upon opening. The spacing of the contacts and the breakdown voltage then becomes a parabolic function of time. When the switch begins to open, a very small arcing plasma is generated between the contacts which effectively completes the circuit even though the contacts are moving apart. As the contacts move, this arc plasma lengthens, cools, and extinguishes. The dc current is suddenly chopped and the low frequency oscillatory voltage begins to build up across the coil. The voltage rises rapidly, exceeds the breakdown voltage of the contacts, re-establishing the plasma and discharging the stray capacitance into the dc system. The contacts are still moving, hence the plasma lengthens, cools and extinguishes again and the process repeats many times. As the contacts move apart, their breakdown potential increases parabolically until at some point in time the voltage built up across the coil cannot cause breakdown and low frequency oscillation is completed dissipating the remaining energy of the coil.

Every time the switch contacts break down, the stray capacitance, charged to a very high potential, is discharged into the dc system. This is the main phenomenon determining the nature of this transient. The coil merely serves as a means to charge the capacitance to a very high voltage.

Figure 10 shows an equivalent circuit which reveals the nature of this transient. The stray capacitance CS is shown charged to several kilovolts. The switch SW shown being closed represents the breakdown of the contacts connecting C_S to the dc system. The dc system wiring is represented by a distributed parameter transmission line extending in both directions. When SW closes, the instantaneous potential across the line jumps to several kilovolts instantaneously and then decays with a time constant

$$\tau D = \frac{Z_o}{2} CS$$

where Zo is the surge impedance of the dc system. This is usually less than 200 ohms. For CS = 1000 pF, this gives a time constant of only 0.1 microsecond. This very short duration pulse travels out on the dc system in both directions. It occurs each time the switch contacts break down, which can be several hundred times in one switch operation. Oscilloscope photos of this phenomenon are shown in Figure 11.

Fortunately this type of transient can be effectively suppressed before it ever gets onto the dc system by connecting various voltage limiting devices across the coil to prevent the large voltage build up thus greatly reducing the contact breakdowns, which are the basic origins of the transient. Recently metal oxide varistors have been found to be a very effective device for this function. They have the advantage that they do not seriously affect the drop out time of the inductive device. This is often a consideration for auxiliary relays.

CONCLUSIONS

The basic reason for the transient sensitivity of solid state equipment is now well known. It is a combination of fast response and low operating energy, the response time corresponding roughly with the time duration of typical transients found in power station control circuits. These transients are known to originate in switching phenomena on both the high voltage power circuits and in the low voltage control circuits. The modes of coupling are being identified and effective transient reduction means are being developed in the areas of station design and in solid state equipment design. Knowledge in these areas is growing rapidly so that as we look to the future, the reliable and accurate performance of complex solid state equipments in the electric power system environment is an assured fact.

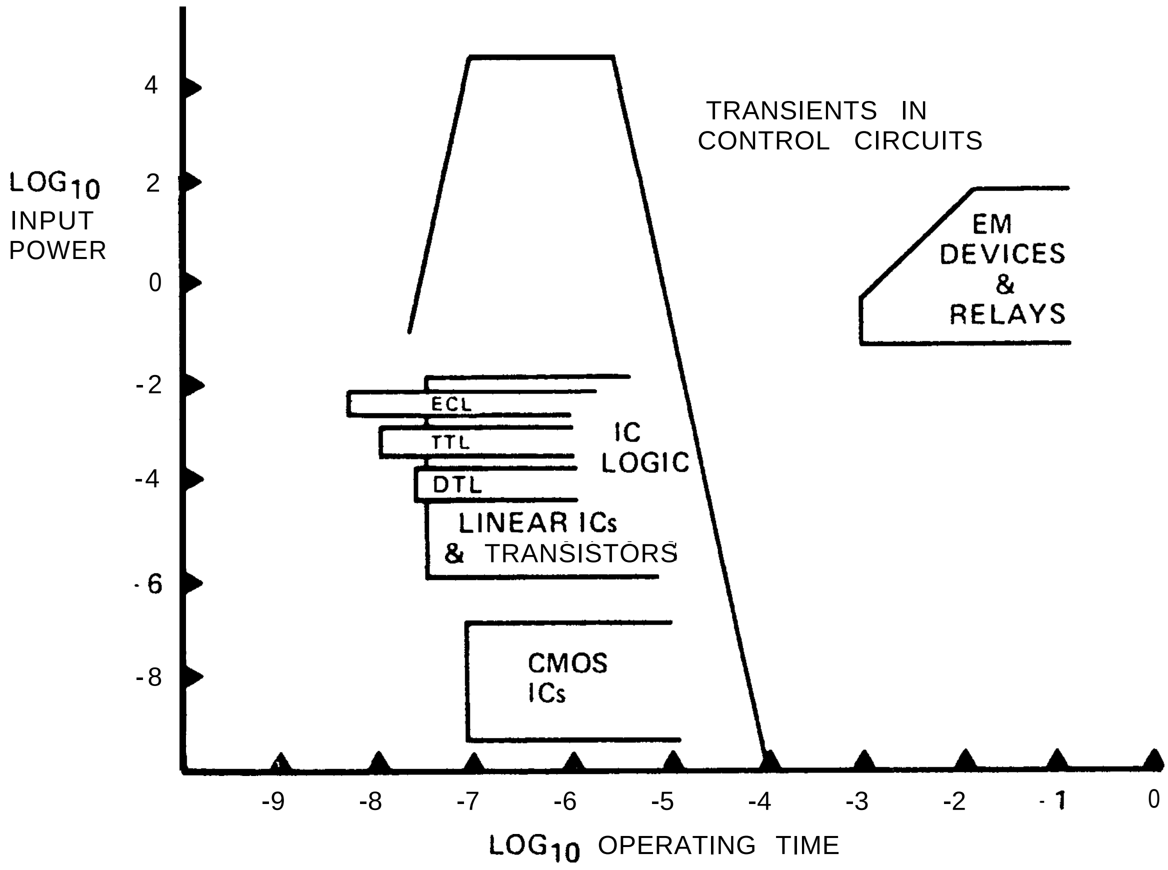


Figure 1. Comparative Response — Electromechanical and Static Devices

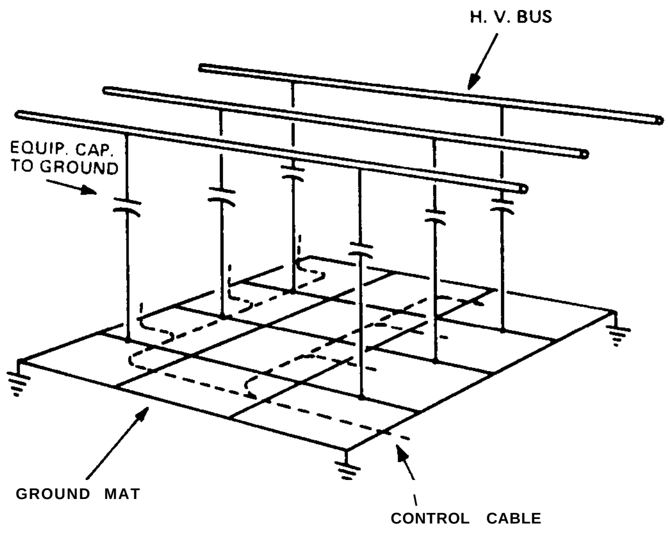


Figure 2. The H.V. Structure

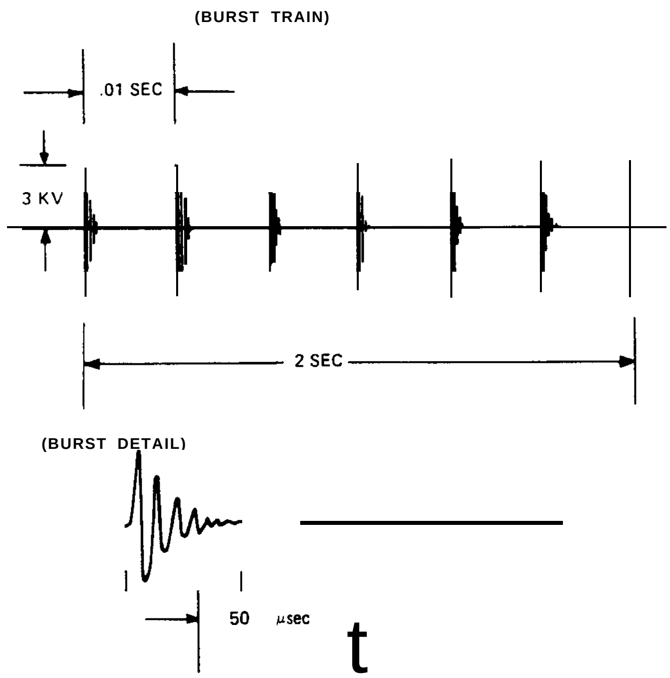


Figure 3. H.V. Transient Waveform

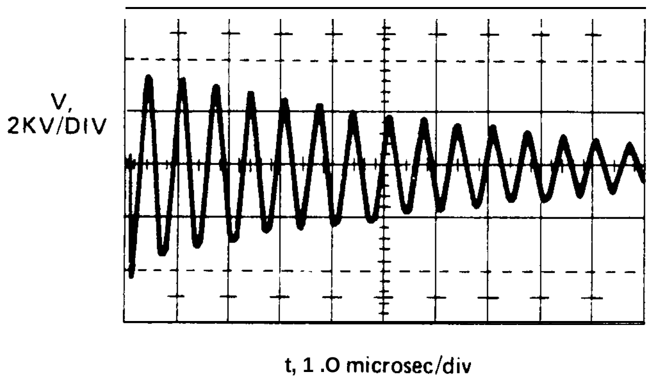
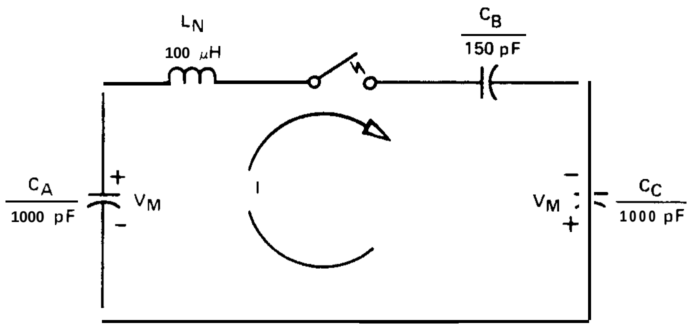


Figure 4. Waveform of IEEE-SWC Test



$$\frac{1}{C_N} = \frac{1}{C_A} + \frac{1}{C_B} + \frac{1}{C_C}$$

$$C_N = 115 \text{ pF}$$

$$f = \frac{1}{2\pi\sqrt{L_N C_N}} \qquad 1.5 \text{ MHz}$$

$$I_{max} = \frac{2V_M}{\sqrt{\frac{L_N}{C_N}}} = 875 \text{ amperes}$$

Figure 6. Equivalent Circuit of H.V. Transient Source

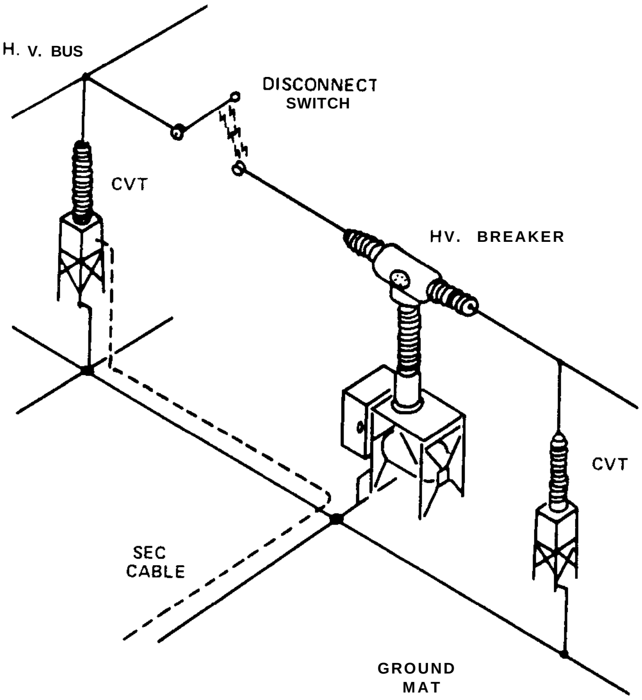


Figure 5. H.V. Transient Source

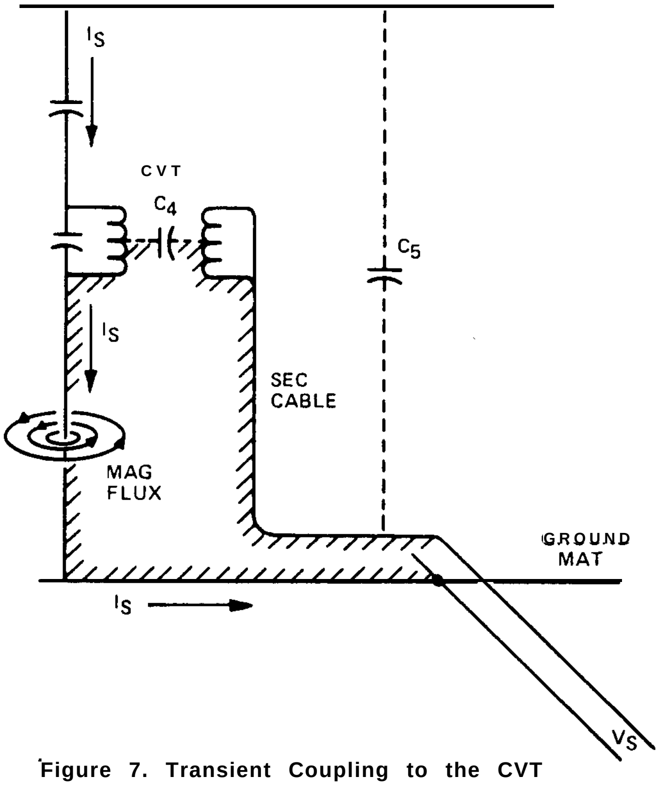


Figure 7. Transient Coupling to the CVT Secondary Circuit

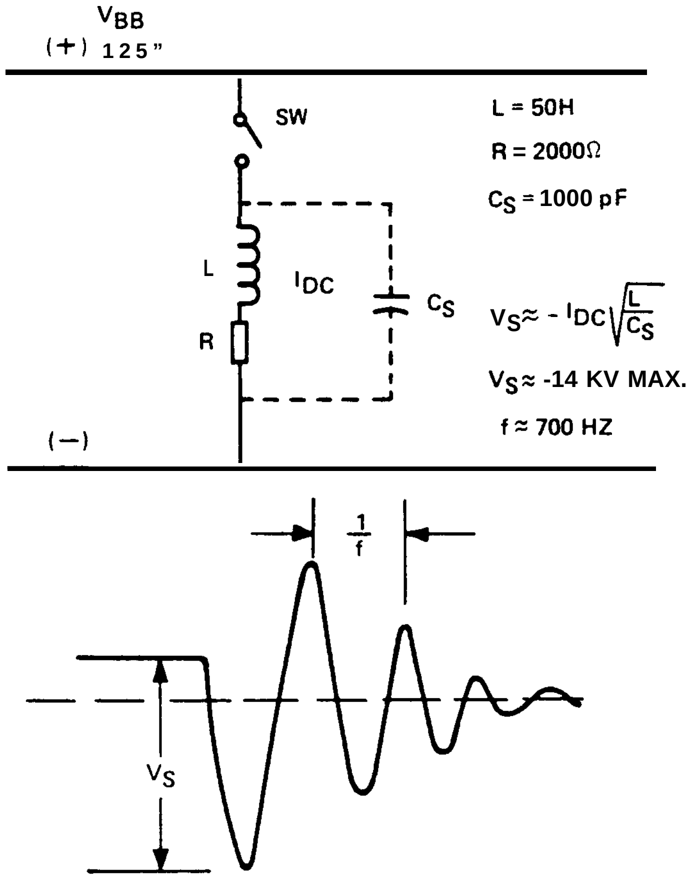


Figure 8. Switching an Inductance with a Perfect Switch

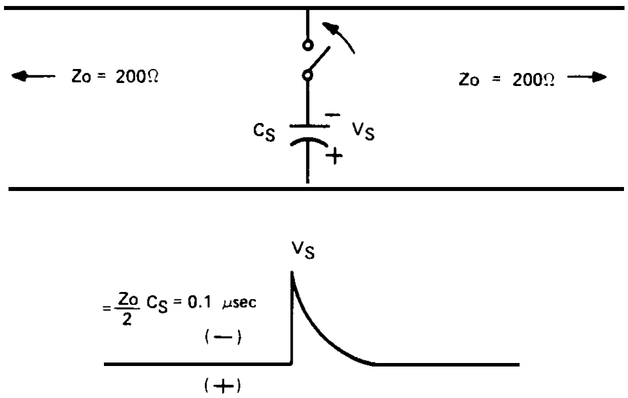


Figure 10. Equivalent Circuit of L.V. Transient

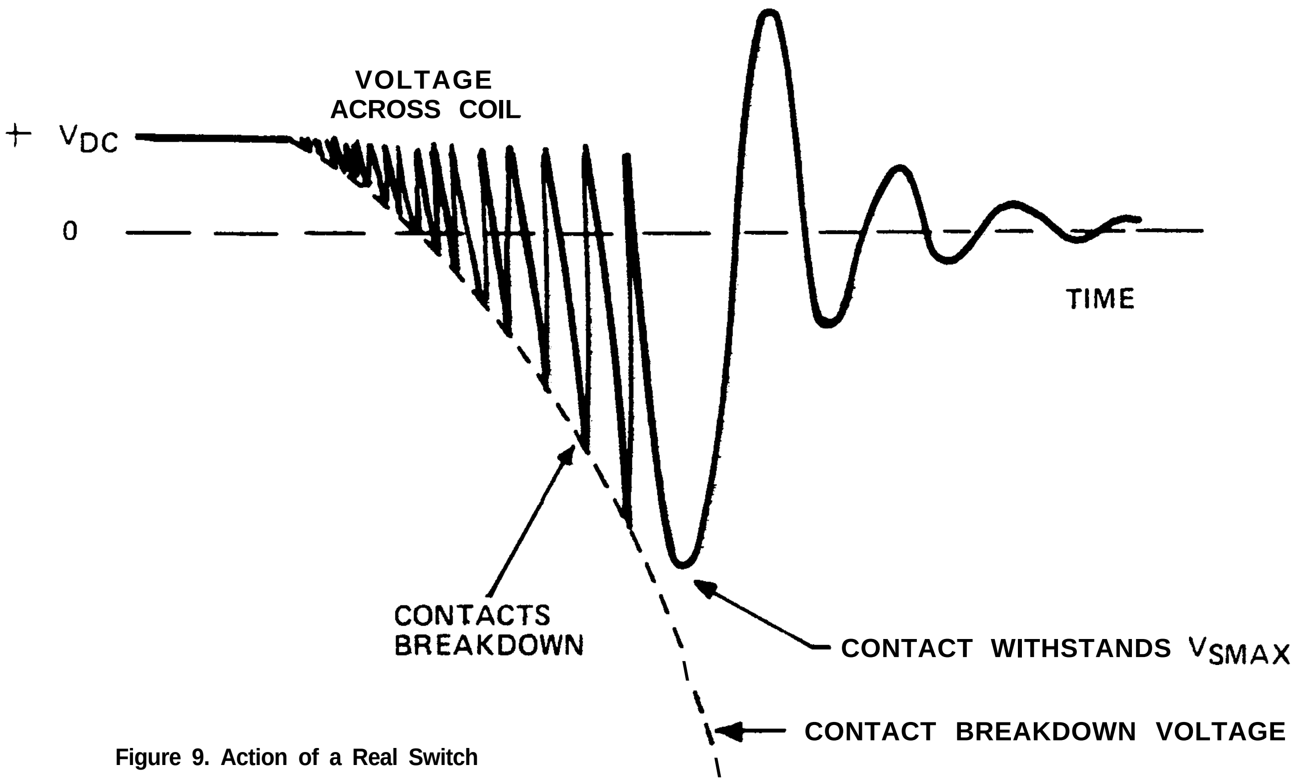


Figure 9. Action of a Real Switch

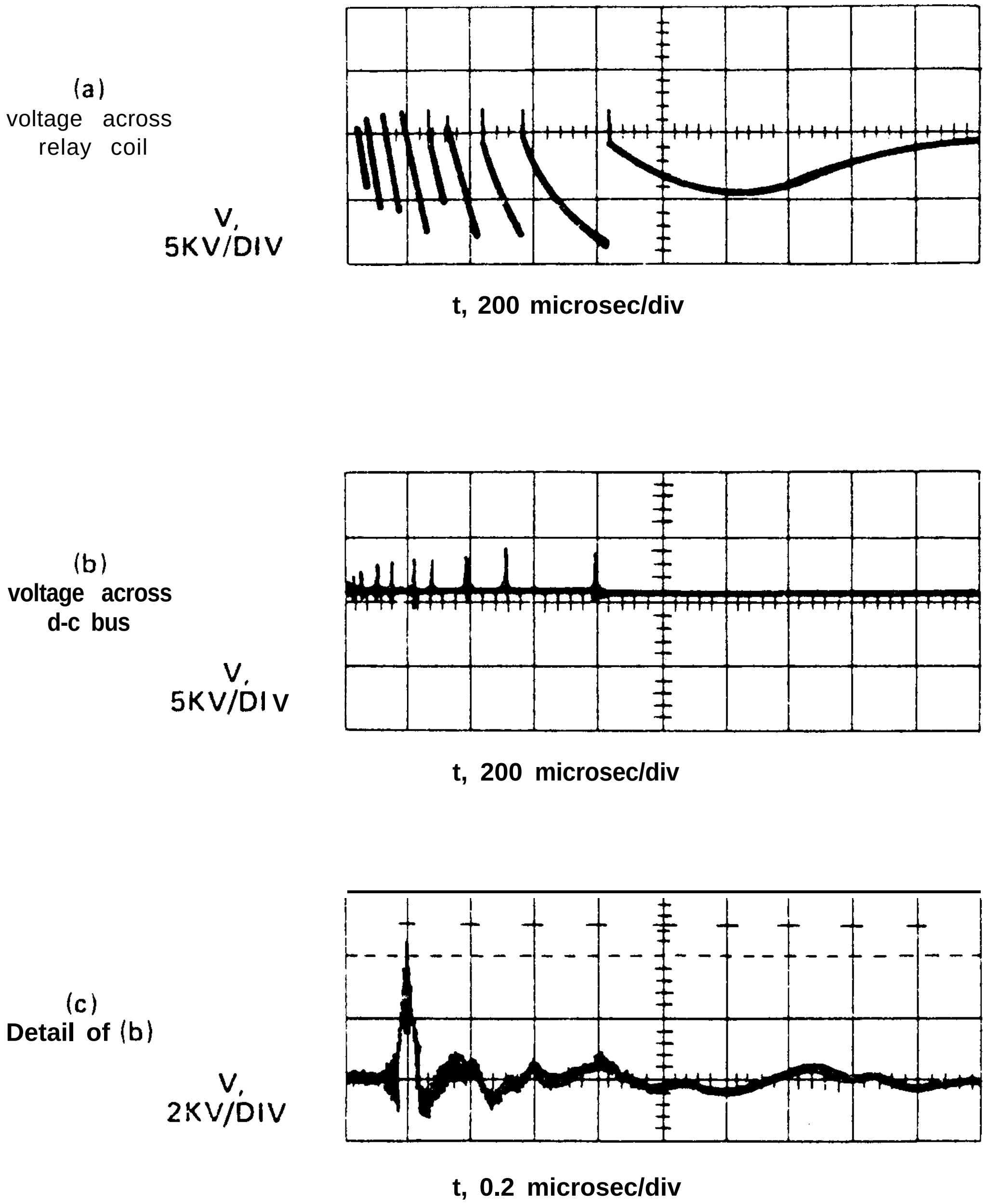


Figure 11. Waveforms of L.V. Source Transient