SWITCHING OVERVOLTAGES IN POWER SYSTEMS

Juan A. Martinez-Velasco
Universitat Politècnica de Catalunya, Barcelona, Spain

Jacinto Martin-Arnedo
Estabanell Energía, Granollers, Spain

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Contents

Summary

Overvoltages can be produced by switching operations in power systems, and both routinely performed operations and unscheduled opening operations aimed at interrupting a short-circuit current can be the cause of overvoltages. This chapter is dedicated to the analysis of slow-front overvoltages caused by opening and closing operations. After a closing operation, transient currents will flow through the system, while after an opening operation a transient recovery voltage will appear across the terminals of the interrupting device. In both situations it is important to quantify the amplitude, frequency, and shape of the current and voltage oscillations. An important aspect to be considered during closing operation is the possibility of circuit breaker prestriking, which can also lead to dangerous overvoltages.

Switching overvoltages cannot be avoided, but their effects can be minimized. Generally, the occurrence and the magnitude of the overvoltage can be limited by the use of appropriate measures. In addition, overvoltages caused during closing operations are random by nature due to mechanical pole span and to the fact that closing may occur at any point of the source voltage wave. This chapter presents a description of the main scenarios that lead to overvoltages in both closing and opening operations, discusses the approaches to be used for calculating random switching overvoltages and summarizes the main techniques for mitigating these overvoltages.

An accurate calculation of switching overvoltages requires the use of advanced models and a digital computer program. This chapter presents guidelines for representing power components in switching overvoltage calculations and includes two illustrative case studies.

1. Introduction

1.1. Switching Overvoltages

The operation of switching devices can join or separate parts of a power system. After a closing operation, transient currents will flow through the system, while after an opening operation a transient recovery voltage will appear across the terminals of the interrupting device. The configuration of the network as seen from the terminals of the switching device determines amplitude, frequency, and shape of the current and voltage oscillations (Greenwood, 1991; Hileman, 1999; van der Sluis, 2001; Garzon, 2002; Das, 2010).

When capacitor banks for voltage regulation are placed in a substation, the switching devices interrupt a mainly capacitive load when operating under normal load conditions. The current and voltage are approximately 90° out of phase and the current is leading the voltage. When a large transformer is disconnected in a no-load situation, current and voltage are also approximately 90° out of phase but now the current is lagging. Closing a switch in a dominantly capacitive network will usually result in inrush currents, which can cause problems for the protection system.

Overvoltages can be produced by switching operations that are carried out in electrical networks; that is, switching overvoltages can be produced by closing an unloaded line, by clearing a fault or by interrupting currents in inductive or capacitive circuits where the possibility of restrikes exists. This implies that not only unscheduled opening operations that are intended for interrupting a short-circuit current are responsible for switching overvoltages, but also operations that are routinely performed in a power system.

Switching overvoltages in transmission and distribution systems cannot be totally avoided, but their effects can be minimized. Generally, the occurrence and the magnitude of the overvoltage can be limited by the use of appropriate measures such as series or parallel compensation, closing resistors, or metal oxide surge arresters, and in some cases by following procedures established for the proper design and operation of a system (Brown, Fisher, Neugebauer, & Panek, 1982; Greenwood, 1991; Hileman, 1999; van der Sluis, 2001; Garzon, 2002; Martinez-Velasco, 2009; Das, 2010).

A transient caused by a switching operation will propagate in either direction in the power system and will be transferred inductively or capacitively through transformers and couplings to other voltage levels. Part-winding resonances in transformer can also occur. The surges produced by all these operations vary in severity and magnitude and are not equally dangerous to the system insulation. In addition, switching surges are damped by resistances and conductances.

Overvoltages of the same peak value can be of different importance. Switching overvoltages do not cause flashovers to the same extent as caused by lightning. However, switching surges gain more importance as the system voltage rises; switching overvoltages may dictate the strike distances and insulator string length in EHV (e.g., above 345 kV) transmission lines (Hileman, 1999).

This chapter is dedicated to the analysis of slow-front overvoltages caused by switching operations in which the switch device is a circuit breaker. That is, only those situations in which the originated overvoltages may have times-to-crest from 20-5000 μs and time to half value of less than 20000 μs (IEC 60071-2, 1996).

1.2. Circuit Breakers

A circuit breaker is a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit. In normal operating conditions, a circuit breaker is in the closed position and some current is flowing through the closed contacts. The circuit breaker opens its contacts when a tripping signal is received. The performance of an ideal circuit breaker may be summarized as follows (van der Sluis, 2001):

1) When closed, it is a good conductor and withstands thermally and mechanically any current below or equal to the rated short-circuit current.
2) When opened, it is a good insulator and withstands the voltage between contacts, the voltage to ground or to the other phases.
3) When closed, it can quickly and safely interrupt any current below or equal to the rated short-circuit current.
4) When opened, it can quickly and safely close a shorted circuit.

The main consideration in the selection of a circuit breaker for a particular system voltage is the current it is capable of carrying continuously without overheating (the rated normal current) and the maximum current it can withstand, interrupt and make onto under fault conditions (the rated short-circuit current). Power system studies will quantify these values. Ratings can be chosen from tables of preferred ratings in the appropriate standard (IEEE Std C37.04, 1999; ANSI C37.06, 2000; IEEE Std C37.09, 1999; IEEE Std C37.011, 2005; IEC 62271-100, 2008; IEC 62271, 2011). The most recognized and influential circuit breaker standards are supported by the IEC and IEEE/ANSI (American National Standards Institute). Standards require that circuit breakers must be designed and manufactured to satisfy test specifications with respect to its insulating capacity, switching performance, protection against contact, current-carrying capacity and mechanical function.

For the analysis of simple switching transients and even for carrying out large system studies, it is often sufficient to model a circuit breaker as an ideal switch. However, when more accurate results are required, for instance, when the interaction between the electric arc and the system elements is of concern, a thorough knowledge about the physical processes between the circuit breaker contacts may be necessary. Although some previous work on circuit breaker modeling had been performed, it was in 1939 and 1943, when the models proposed by Cassie (1939) and Mayr (1943) were presented, when a significant progress in understanding arc-circuit interaction was made. Much effort has been done afterwards to refine those works and confirm their physical validity through practical measurements.

The chapter analyzes the most common situations in which a switching operation, either an opening or a closing operation, can lead to slow-front overvoltages. The cases included here are based on a simplified model of the system, which is assumed linear, although advanced modeling guidelines for digital simulation of complex systems are also presented. The chapter includes several practical examples and two more complex case studies.

2. Switching Overvoltages Caused by Opening Operations

2.1. Principles of Current Interruption. The Electric Arc

All methods of interrupting current in high voltage systems introduce a non-conducting gap into a conducting medium. This can be achieved by mechanically separating the metallic contacts so that the gap formed is either automatically filled by a liquid, a gas or even vacuum. However, insulating media may sustain electrical discharges which can prevent electrical isolation from being achieved.

In a real circuit breaker an electric arc is formed after contacts start separating. The arc changes from a conducting to a non-conducting state in a very short period of time, and is normally extinguished as the current reaches a natural zero in the alternating current cycle. This mechanism is assisted by drawing the arc out to maximum length, increasing its resistance and limiting its current. Various techniques are adopted to extend the arc; they differ according to size, rating and application. In high-voltage circuit breakers (> 1 kV), the current interruption is performed by cooling the arc.

The arc is a plasma channel formed after a gas discharge in the extinguishing medium. The plasma state is reached when the increase in temperature gives the molecules so much energy that they dissociate into atoms; if the energy level is increased even more, electrons of the atoms dissociate into free moving electrons, leaving positive ions.

The arc voltage after maintaining a constant value during the high current period increases to a peak value and then drops to zero with a very steep dv/dt. The current approaches its zero crossing with a more or less constant di/dt, but it can be slightly distorted under the influence of the arc voltage. The arc is resistive, so arc voltage and current reach the zero crossing simultaneously. After current interruption, the gas between the breaker contacts is stressed by the rate of rise of the recovery voltage, so the present charged particles start to drift and cause a *post-arc current*, which results in energy input in the gas channel. The problem of current interruption then transforms into one of quenching the discharge against the capability of the system voltage of sustaining a current flow through the discharge. This phase of the process is governed by a competition between the electric power input due to the recovery voltage and the thermal losses from the electric arc; it is known as the *thermal recovery phase* and has duration of a few microseconds. If the energy input is such that the gas molecules dissociate into free electrons and positive ions, the plasma state is created again and current interruption fails. This is called a *thermal breakdown*. If the current interruption is successful, the gas channel cools down and the post-arc current disappears. However, a later *dielectric failure* can still occur when the dielectric strength of the gap between the breaker contacts is not sufficient to withstand the recovery voltage (Jones, 2001; Martinez-Velasco & Popov, 2009).

Several theories have been proposed to describe the behavior of an electric arc during the interruption process. The most advanced models represent the breaker as a dynamically varying resistance or conductance whose value depends on the past history of arc voltage and current. Such approach can represent the effect of the arc on the system as well as the effect of the system on the arc.

Cassie's Theory: It assumes an arc channel with constant temperature, current density and electric field strength. Changes of the arc conductance result from changes of arc cross section, and energy removal is obtained by convection. The Cassie model is given by the following equation:

$$\frac{1}{g_{\mathrm{c}}}\frac{dg_{\mathrm{c}}}{dt}=\frac{1}{\tau_{\mathrm{c}}}\left(\left(\frac{v}{v_0}\right)^2-1\right)=\frac{1}{\tau_{\mathrm{c}}}\left(\left(\frac{i}{v_0 g_{\mathrm{c}}}\right)^2-1\right) \tag{1}$$

Mayr's Theory: This model assumes that changes of arc temperature are dominant, and size and profile of the arc column are constant. Thermal conduction is the main mechanism of energy removal. The Mayr model is given by the following equation:

$$\frac{1}{g_{\mathrm{m}}}\frac{dg_{\mathrm{m}}}{dt}=\frac{1}{\tau_{\mathrm{m}}}\left(\frac{vi}{P_0}-1\right)=\frac{1}{\tau_{\mathrm{m}}}\left(\frac{i^2}{P_0 g_{\mathrm{m}}}-1\right) \qquad (2)$$

In these equations, g is the arc conductance, subscripts c and m signify Cassie and Mayr respectively, v is the arc voltage, i is the arc current, τ is the arc time constant, P_0 is the steady-state power loss and v_0 is the constant part of the arc voltage. g_{c} is in the region of 1 µs (SF_6) and g_{m} is between 0.1 and 0.5 µs (SF_6). These parameters are not strictly constant for an actual arc, but observations indicate that during the brief time around current zero these parameters vary sufficiently slowly to assume them to be constant. The Cassie model shows a good performance for high-current region, but for current-zero region, agreement is good only for high rates of current decay. The Mayr model is more accurate during current zero periods.

Cassie-Mayr Theory: Assuming that before current zero, the current is defined by the driving circuit, and that after current zero the voltage across the gap is determined by the arc circuit, a complete description can be achieved by combining the two models (Browne, 1984).

2.2. Circuit Breaker Performance

A circuit breaker does not operate instantaneously on a tripping or closing signal, nor do the contacts part and close simultaneously. There is a finite time before the circuit breaker can interrupt a transient current. The interruption takes place during the passage of current through zero, although there can be some chopping of current because of instability of arc close to current zero. Before interruption occurs, the arc may persist for a number of cycles, depending on the circuit breaker design. An arc can keep burning and will not extinguish itself even at some low amperes. At some initial current zeros, the arc may reignite if the contact gap has not developed enough dielectric strength. The dielectric strength of the arc gap is primarily a function of the interrupting devices, while voltage appearing across parting contacts is a function of system parameters.

Circuit breakers may have to interrupt currents of the order of tens of kilo-amperes. At the first current zero, the electrical conductivity of the arc is fairly high, and since the current-zero period is very short, the reignition cannot be usually prevented. The most favourable condition for interruption is that in which the applied voltage reaches zero when current is zero; that is, interrupting a resistive current.

As the contact separation increases, the transient voltage of the arc does not succeed in igniting the arc because the electrical strength of the break gap increases. The gap has to withstand now the recovery voltage stress.

It takes some finite time for the protective relaying to signal a fault condition and for the breaker operating mechanism to set in motion. In standards for breakers, this tripping delay is considered equal to 1/2 cycle. As the contacts start parting, an arc is drawn, which is intensely cooled by the quenching medium (air, SF_6, or oil). The arc current varies during a very short interval and may have some oscillations. The arc is mostly resistive; that is, the voltage in the arc is in-phase with the current. The contacts part at high speed to prevent continuation of the arc. At a current zero, the dielectric strength of the arc space is sufficiently high. When the dielectric strength builds and a current zero occurs, the arc is interrupted. With modern high-voltage breakers, the arcing time is as low as 2 cycles or even lower, based on the system power frequency.

The interruption process is much dependent on the current being interrupted (i.e., resistive, inductive, or capacitive). Circuit breakers are tested at a low power factor because the system inductance predominates and the short-circuit currents, which impose the maximum switching duties on the circuit breakers, are mostly reactive. The rated interrupting time may be exceeded at low values of current and for close-open operations; also, the time for interruption of resistor current for interrupters equipped with resistors may exceed the rated interrupting time. The increase in interrupting time on close-open operation may be important from the standpoint of line damage and possible instability. As the short-circuit current consists of decaying ac and dc components, the faster the breaker, the greater the asymmetry and the interrupted current. Interrupting current at final arc extinction is asymmetrical in nature, consisting of an ac component and a dc component.

2.3. Transient Recovery Voltage

2.3.1 Definition

Transient conditions, especially those occurring during current interruption, must be properly evaluated before selecting an interrupting device. For a correct selection and application of a circuit breaker it is necessary to consider not only system parameters (i.e., operating voltage, available fault current, fault impedance ratio (X/R), load current level, dielectric withstand levels) but also the requirements imposed by the transient stresses that occur whenever a circuit is being energized or de-energized. The transient overvoltages occurring while clearing a circuit will be discussed here.

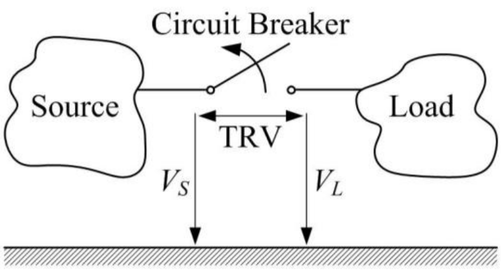

Figure 1. Graphical representation of a system for analysis of transient recovery voltage.

All types of circuit interrupting devices can be considered as a link that joins two electrical networks. As illustrated in Figure 1, on one side of the device is the electrical network that delivers power and can be identified as the source-side network (Garzon, 2002). On the other side there is an electrical network that consumes power and is identified as the load side network. When the contacts of a switch start to open, a transient voltage is developed across them. This voltage, known as *transient recovery voltage* (TRV), is present immediately after the current zero.

A comprehensive evaluation of the recovery voltage phenomena that take place in any electrical system must be based upon the conditions prevailing at the moment of the interruption of a current. The minimum requirements to be taken into consideration for this evaluation are the operating conditions (e.g., faulted current, load current), the parameters and topology of the network, and the switching arrangement. Depending on the different combinations of these conditions, it is obvious that the TRV can have many different characteristics. For example, it can exhibit a single frequency or a multi-frequency response. If all factors are taken into consideration, exact calculations of the TRV in complex systems is rather complicated and generally made with the aid of a digital computer program.

For those studies or applications where a less accurate result will suffice it is possible to simplify the calculations by reducing the original system to an equivalent circuit for which a simple mathematical solution can be obtained (Greenwood, 1991; van der Sluis, 2001; Garzon, 2002; Das, 2010; Martinez-Velasco & Popov, 2009). Nevertheless, the problem of how to properly select the equivalent circuits and the values of the constants to be used in the calculations still remains.

In many cases the results obtained with such simplified calculations can be used to determine if there is a need for more accurate calculations. Another possible application of the simplified calculation approach is that it can be used to evaluate possible corrective actions that may be taken to match the capability of the device with the characteristics of the circuit.

Transients caused by switching operations in linear systems can be analyzed by using the superposition principle. The switching process caused by an opening operation is obtained by adding the steady state solution, which exists prior to the opening operation, and the transient response of the system that results from short-circuiting voltage sources and open-circuiting current sources to a current injected through the switch contacts, see Figure 2. Since the current through the switch terminals after the operation will be zero, the injected current must equal to the current that was flowing between switch terminals prior to the opening operation. This approach is also known as the *current injection method*.

To obtain the TRV waveshape, the analysis of the transient response may suffice, since this voltage is zero during steady state; i.e., prior to the opening operation, see Figure 2. However, it is important to keep in mind that the recovery voltage will consist of two components: a transient component, which occur immediately after a current zero, and a steady-state component, which is the voltage that remains after the transient dies out. The actual waveshape of the voltage oscillation is determined by the parameters of the power system. Its rate of rise and amplitude are of vital importance for a successful operation of the interrupting device. If the rate of recovery of the contact gap at the instant of current zero is faster than the *rate of rise of the recovery voltage* (RRRV), the interruption is successful in the thermal region (i.e., first 4-8 μs of the recovery phase). It may be followed by a successful recovery voltage withstand in the dielectric region (above 50 μs) and then by a full dielectric withstand of the AC recovery voltage. If, however, the RRRV is faster than the recovery of the gap, then failure will occur either in the thermal region or in the dielectric region.

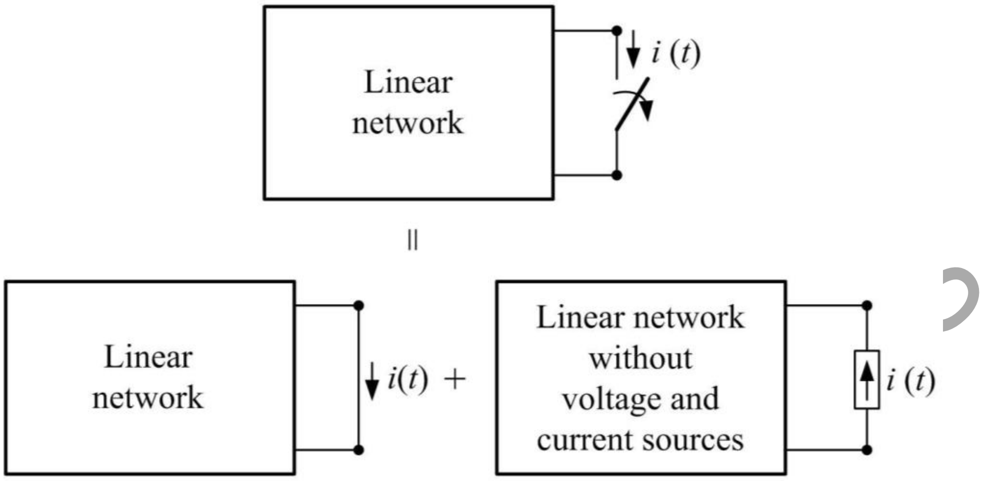

Figure 2. Application of the current injection method.

The essential problem of current interruption involves establishing an adequate electric strength across the breaker after current zero, so that reignitions and restrikes are eliminated. The factors that determine the rate of recovery of the dielectric medium are the nature of quenching gases, the mode of interaction of pressure and velocity of the arc, the arc control devices, the contact shape, the number of breaks, and the circuit in which the breaker is operating.

Figure 3 shows an example of recovery-voltage profile after current interruption. The two components of the recovery voltage are a high-frequency damped oscillation and the power-frequency recovery voltage.

TRV can be defined by specifying the crest and the time to reach the crest, and alternatively, by defining the segments of lines that envelope TRV waveshape. The calculation of the initial rate of rise is important and can be complicated due to the natural frequencies and traveling-wave phenomena in the two systems being disconnected by the breaker.

The TRV is affected by many factors, amongst which the power factor of the current being interrupted is important. At zero power factors, maximum voltage is impressed across the gap at the instant of current zero, which tends to reignite the arc in the hot arc medium. The steepest rates of the rise in a system are due to short circuits. Only three phase, symmetrical, ungrounded terminal faults need to be considered. This is because the most severe TRV appears across the first pole that clears an ungrounded three-phase fault occurring at the terminals of the circuit breaker.

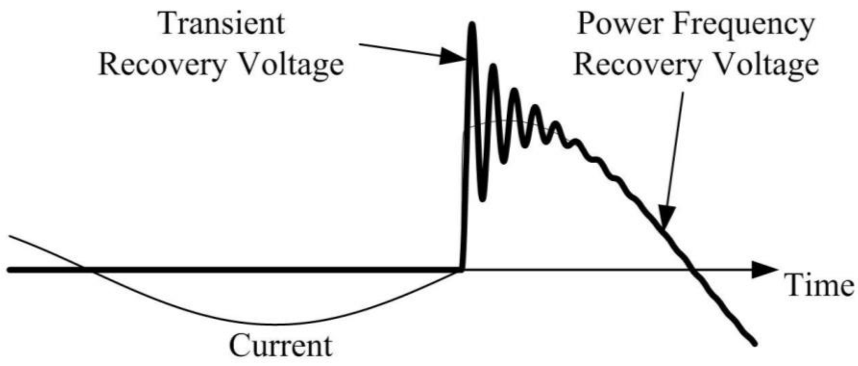

Figure 3. TRV and power-frequency recovery voltage after current interruption.

A good understanding of the transient phenomena associated to circuit breaker operations in power systems has led to improved testing practice and resulted in more reliable switchgear. Recommended characteristic values for simulation of the TRV are fixed in standards (IEEE Std C37.09, 1999; IEC 62271-100, 2008; IEC 62271, 2011).

To understand the different requirements applicable to circuit breakers, the most frequent and important cases of current interruption will be analyzed. Switching conditions for TRV analysis have been divided into two groups corresponding to the interruption of current under fault and normal operating conditions, respectively.

2.3.2. Current Interruption Under Normal Operating Conditions

2.3.2.1. Introduction

In a capacitive circuit when the current passes through zero, the system voltage is trapped on the capacitors. The recovery voltage, the difference between the source side and load side of the breaker, reaches a maximum of 2.0 per unit (pu) after 1/2 cycle of current interruption. The TRV oscillations are practically absent as large capacitance suppresses the oscillatory frequency and the rate of rise of the TRV is low. This may prompt circuit breaker contacts to interrupt, when there is not enough separation between them and precipitate restrikes. This is not the case when disconnecting an inductive load. The capacitance on the disconnected side is low and the frequency of the isolated circuit is high. Consequently, the TRV is oscillatory, and the rate of rise of TRV is fairly high.

Figure 4 shows the recovery voltage across the circuit breaker terminals when interrupting the current of very simple circuits (Martinez-Velasco & Popov, 2009). Observe the different waveshape that appear in each case. The representation of each circuit is that depicted in the figure, except for the interruption of the inductive current since in this case the current zero occurs when the voltage across the inductor terminals is maximum, and a capacitive element is needed to account for the trapped charge. The later oscillation is caused by the energy transfer between the inductor and the capacitor.

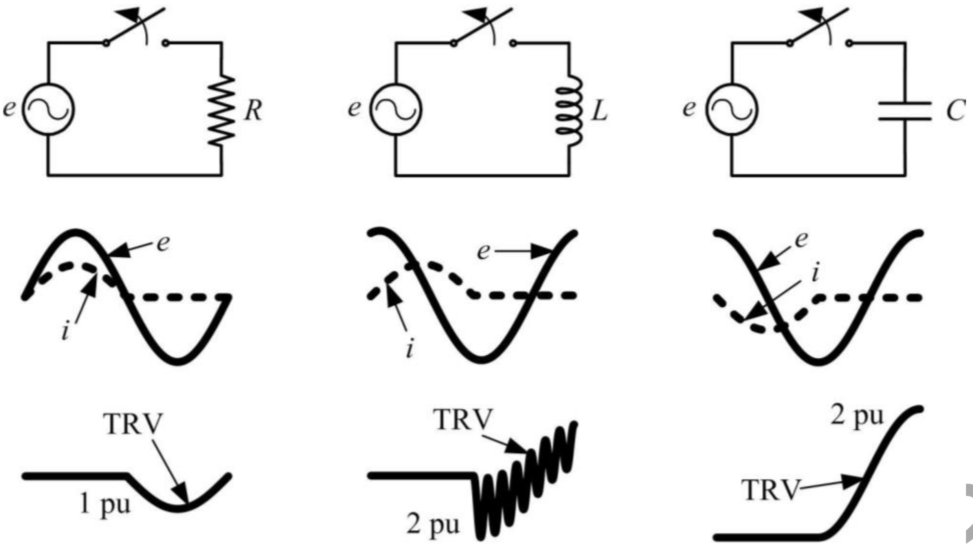

Figure 4. Transient recovery voltage of simple circuits under normal operating conditions.

Although real systems are much more complex than the circuits analyzed above, these cases show that switching under normal operating conditions can be categorized as resistive, inductive and capacitive. Resistive switching is the easiest to clear, while inductive and capacitive are more difficult since the recovery voltage is on the order of twice that for a resistive case, and even higher in three-phase systems (see below). In addition, inductive switching may produce a high-frequency TRV, which is associated to a premature current zero, known as *current chopping*, and may cause a severe TRV. A short description of the processes originated with the interruption of capacitive and inductive currents, as well as some of the problems that they can cause, is presented in the following paragraphs.

2.3.2.2. Interruption of Capacitive Currents

This scenario usually corresponds to the disconnection of capacitor banks and unloaded lines or cables. Power systems contain lumped capacitors such as capacitor banks for voltage regulation or power factor improvement and capacitors that are part of filter banks to filter out higher harmonics. On the other hand, lines and mainly cables may be seen as a capacitive load by the switching devices. Capacitive switching requires special attention because, after current interruption, the total voltage across the contacts can reach a value higher than 2.0 pu, and this can cause a dielectric breakdown of the switching device.

The rate of rise of the recovery voltage when interrupting power frequency capacitive currents is low, and a circuit breaker will try to interrupt the current even at the first-current zero, when the contact gap is small and still ionized and has not recovered the dielectric strength. However, since lower currents will contribute less energy to the arc, it is natural to expect that interrupting lower currents should be a relatively simpler task;

but this is not always the case because relatively low currents in comparison to a short-circuit current may cause arc instability or restrikes across the contacts during interruption.

If the circuit breaker restrikes, there will be an inrush current flow which will force the voltage in the capacitor to oscillate with respect to the instantaneous system voltage to a peak value that is approximately equal to the initial value at which it started but with a reversed polarity. The shunt capacitor being disconnected then discharges through the circuit breaker and the amplitude of this current depends on the instantaneous value of the capacitor charge. The high frequency of the current is caused by the inductance between the capacitor bank and breaker. This high-frequency current is superimposed upon the power-frequency current and creates additional current zeros. If the restrike happens at the peak of the system voltage, then the capacitor voltage will reach a value of 3.0 pu. Under these conditions, if the high-frequency inrush current is interrupted at the zero crossing, then the capacitor will be left with a charge corresponding to a voltage of 3.0 pu and half cycle later there will be a voltage of 4.0 pu applied across the circuit breaker contacts, as shown in Figure 5. If the sequence is repeated, the capacitor voltage will reach a 5.0 pu value (Garzon, 2002). If damping is ignored, there could be a theoretical unlimited voltage escalation across the capacitor.

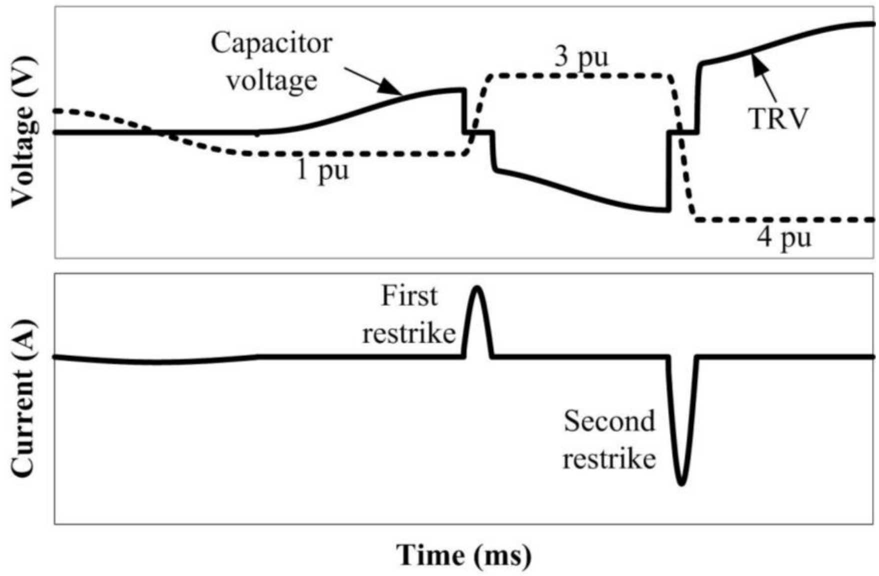

Figure 5. Restrikes and voltage escalation during the interruption of a capacitive current.

Three-Phase Capacitor Bank: Disconnecting a three-phase capacitor circuit is more complex. The instant of current interruption, the trapped charge level and the recovery voltage for each breaker pole depend on the capacitor bank connections (van der Sluis, 2001; Das, 2010).

a) A three-phase grounded capacitor bank can be represented as three single-phase circuits. In a solidly grounded circuit, interruption theoretically takes place at current zero and therefore, for all practical purposes, the system voltage is at its peak; that is, the phase-to-ground voltage stored in the capacitor is equal to 1.0 pu at the time of the current zero. The source side, on the other hand, will follow the oscillation of the power frequency voltage, so half cycle later the source voltage reaches its peak with opposite polarity, and the total voltage across the contacts reaches a value of 2.0 pu.

b) In an ungrounded bank the first phase to open remains connected to the other phases through the neutral and the neutral acquires trapped charge from the other two phases, see Figure 6. Assume phase A current is the first interrupted in an ungrounded three-phase wye-connected bank. This will occur when the voltage of phase A is at its peak. Figure 6a shows that after phase A is interrupted, the circuit configuration changes, and connects the capacitors in phases B and C in series. These capacitors are charged with equal and opposite polarities. The charge trapped in phase A is 1 pu and that trapped in phases B and C is 0.5 pu. The current in phases B and C will interrupt simultaneously as soon as phase-to-phase current becomes zero. This will occur at 90° after the current interruption in phase A at the crest of the phase-to-phase voltage so that an additional charge of √3/2 is stored in the capacitors, as shown in Figure 6b. These charges will add to those already trapped on the capacitors in Figure 6a, and thus voltages across the capacitor terminals are: phase A = 1.0 pu, phase B = - 0.37 pu, phase C = 1.37 pu (Das, 2010). Further escalation of voltages occurs if the phases B and C are not interrupted after 90° of current interruption in phase A. So if the circuit has an isolated neutral connection, then the voltage trapped in the capacitor for the first phase to clear has a phase-to-ground value of 1.5 pu and the total voltage across the contacts half cycle later will be equal to 2.5 pu. In fact, the recovery voltage in an ungrounded capacitor bank may reach higher values if the load side is not purely capacitive.

When analyzing switching of three-phase unloaded transmission lines, the capacitive coupling between the phases and the capacitance to ground has to be taken into account, see Figure 7. When the first phase (e.g., phase A) has cleared, voltage of the neighboring phases is coupled into the voltage V_A. When the second phase clears, then the third phase is still at system voltage and this voltage couples into the line-side DC voltages of the other phases. The value of the coupling factor depends on the tower structure and circuit design but usually has a value between 0.2 and 0.4. For a double circuit, when two circuits are hanging in the same tower, the coupling factor can be higher when the neighboring circuit is in operation. When unloaded high-voltage transmission lines are switched off, a combination of the voltage jump at the supply side, the transient voltage oscillation at the supply side, the voltage oscillation at the line side, and the capacitive coupling with the neighboring phases can result in a recovery voltage for the first phase to clear above 2.5 pu (van der Sluis, 2001).

The actual construction of a cable is of importance to study the transient recovery voltage that occurs when switching unloaded high-voltage cables. For three-phase cables with the three conductors in a lead sheet with a grounded screen, the same coupling effects as with transmission lines occur. When each conductor has its own grounded screen, only the capacitance to ground plays a role and the resulting TRV has the same shape as the TRVs in the case of switching capacitor banks with a grounded neutral in a grounded system.

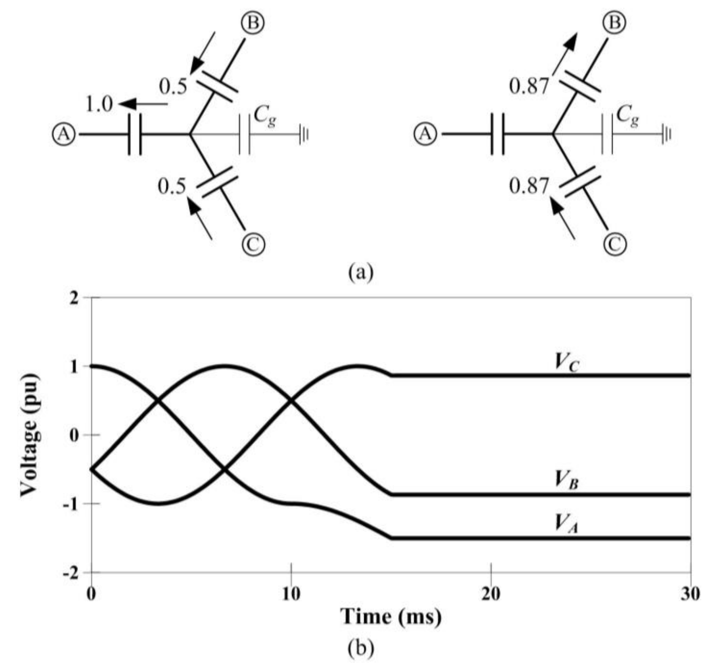

Figure 6. Disconnection of an ungrounded capacitor bank. (a) Trapped charges: (i) Phase A clears first, (ii) Phases B and C clear in series. (b) Load-side voltages after switching off an ungrounded capacitor bank.

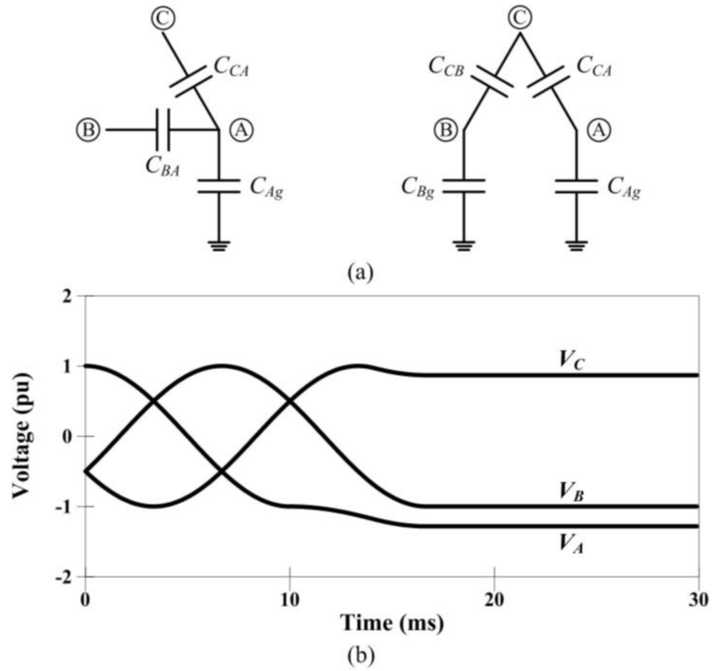

Figure 7. Disconnection of an unloaded high-voltage transmission line. (a) The coupling effect of the line capacitances: (i) Phase A clears first, phases B and C are still at voltage (ii) Phases A and B have been cleared and phase C is still at voltage. (b) Line-side voltages.

2.3.2.3. Interruption of Small Inductive Currents

Small inductive currents occur when unloaded transformers are taken in and out of service, motors are disconnected, or electric furnaces are switched off. A one-phase representation of a circuit for small inductive currents is given in Figure 8. The inductance L of the load is dominant, which means that the load makes the current to lag the voltage. The capacitance C of the load is usually very small; a few nanoFarads (nF) for a distribution transformer and a few picoFarads (pf) for an air-core reactor, depending on the design.

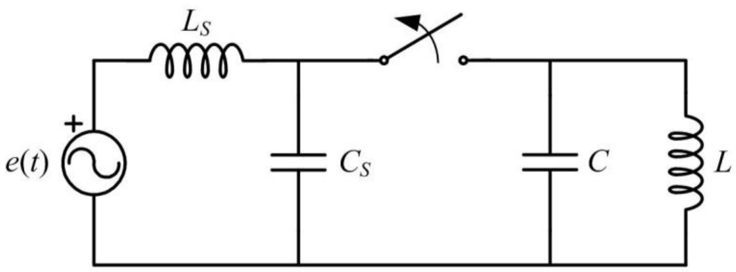

Figure 8. One-phase lumped element representation of a circuit for small inductive currents.

When an interrupting device interrupts a small inductive current, the current can be interrupted at a short arcing time. Interrupting devices such as high-voltage circuit breakers are designed to clear a large short-circuit current in milliseconds so that the cooling of the arc maintained by a small current is easy. The gap between the arcing contacts, after current interruption, is rather small and the capability to withstand dielectric breakdown is relatively low. When interrupting full fault level currents, minimum arcing times of 8 or more milliseconds are typical for SF_6 circuit breakers and 4 milliseconds is rather common for vacuum interrupters, but when dealing with low inductive currents these minimum arcing times are reduced, in most cases, to less than half. Due to the short arcing time at the instant of interruption, the gap between the contacts is relatively short, and since the voltage is at its peak, then in many cases this small gap may not be sufficient to withstand the full magnitude of the recovery voltage, which begins to appear across the contacts immediately following the interruption of the current.

When the small inductive current is interrupted, the load capacitance C is charged at a voltage close to the supply voltage, because $L >> L_S$. After current interruption, C discharges itself through L by means of an oscillating current with frequency:

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \left(f_0 = \frac{\omega_0}{2\pi} \right) \tag{3}$$

After current interruption, the energy trapped in the load side will redistribute itself between the inductance and the capacitance. The frequency of this oscillation can be up to a few kHz and thus creates a very steep dv/dt at the load side of the switching device. Such steep increase of the TRV at the load can cause a dielectric breakdown of the extinguishing medium between the narrow contact gap, and a re-ignition occurs. If there is a reignition, the energy trapped in the load side inductance and capacitance of the circuit will oscillate between the inductance and the parallel capacitance thus generating an overvoltage. In addition, the inductive load is connected with the supply again and a high-frequency current flows through the arc channel. When the switching device interrupts this high-frequency current, capacitance C is charged to a higher value because the di/dt of the re-ignition current is considerably higher than the power frequency current, which was interrupted first. In the mean time, the arcing contacts have moved further apart and have increased the capability to withstand dielectric breakdown of the contact gap. However, the voltage stress caused by the oscillation at the load side has increased as well and another re-ignition might occur. This process may repeat itself as successive reignitions occur across a larger gap and at increased magnetic energy levels, and therefore at higher mean voltage levels, resulting in a high frequency series of voltage spikes such as those shown in Figure 9.

The reignition voltages can be reduced by increasing the load side capacitance. A reduction of the source side capacitance C_S will also reduce the prospective overvoltage. In addition, the load side inductance can directly influence the amplitude and frequency of the reignition current by changing the rate of change of current (di/dt) at the critical current zero instant.

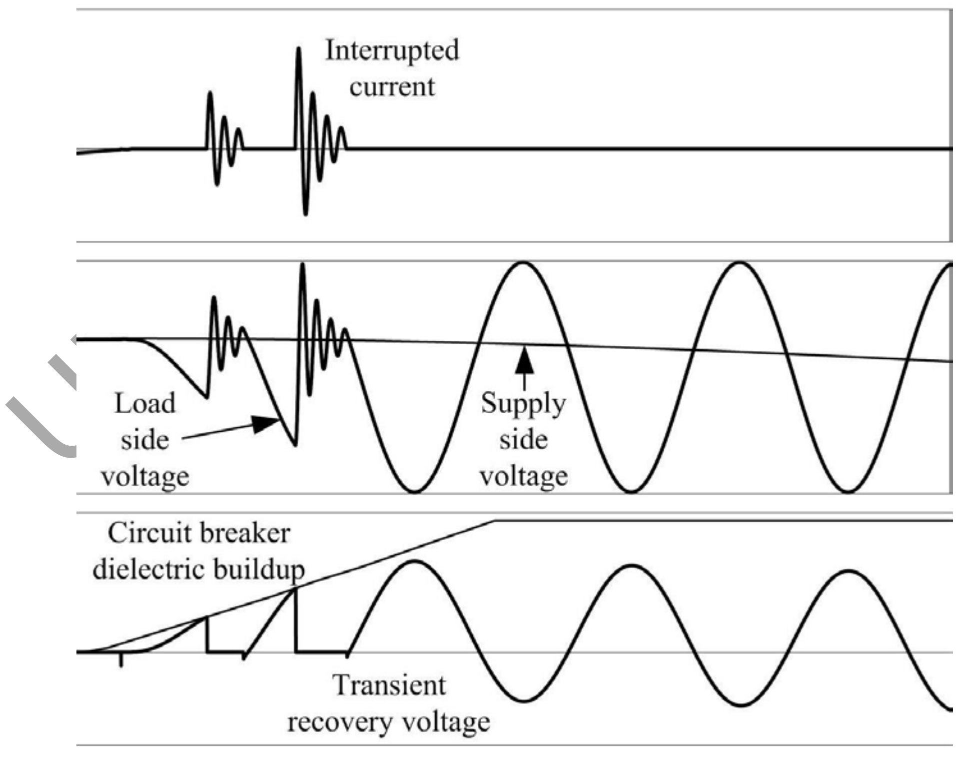

Figure 9. Voltage surges caused by successive reignitions after successful interruption of a small inductive current.

A further complication that may take place is that due to their low magnitude the currents may be forced to zero prematurely caused by arc instabilities, thus creating the condition known as *current chopping*. This phenomenon can occur irrespective of the breaker interrupting medium, though some mediums (e.g., vacuum) may be more prone to current chopping.

If the current is interrupted at current zero, the TRV is usually within the specified values. However, if premature interruption occurs, due to current chopping, the interruption will be abnormal and it can cause reignitions and high-frequency overvoltages. When the breaker chops the peak current, the voltage increases almost instantaneously, if this overvoltage exceeds the specified dielectric strength of the circuit breaker, reignition takes place. When this process is repeated several times, due to high-frequency reignitions, the voltage increase continues with rapid escalation of voltages. The high-frequency oscillations are governed by the electrical parameters of the concerned circuit, circuit configuration and interrupter design, and result in a zero crossing before the actual power frequency current zero.

The overvoltage is dependent on the chopped current. The importance of current chopping can be easily understood by neglecting the influence of losses at the load side. After current interruption at current zero, the energy stored in the load side is the energy stored at the capacitance, whose voltage is at the maximum. This energy is transferred to the inductance and vice-versa, and the following expression holds:

$$\frac{1}{2}CV_{\max}^{2} = \frac{1}{2}LI_{\max}^{2} \tag{4}$$

where $V_{\max}$ and $I_{\max}$ are the maximum values of the voltage across the capacitance and of the current through the inductance, respectively. At the time the current is interrupted, $V_{\max}$ is equal to the voltage at the source side.

The frequency of the oscillation for both voltage and current is given by expression (3).

When premature current interruption occurs, the energy stored at the load side is stored in both the inductance and the capacitance, and it is equal to:

$$\frac{1}{2}LI_{0}^{2} + \frac{1}{2}CV_{0}^{2} \tag{5}$$

where V_0 and I_0 are the values of the voltage across the capacitance and of the current through the inductance at the moment the current is interrupted.

In this case, the frequency of the oscillations will be the same that for the previous case, but the maximum voltage at the capacitance is obtained from the following equation:

$$\frac{1}{2}CV_{\max}^{2} = \frac{1}{2}LI_{0}^{2} + \frac{1}{2}CV_{0}^{2} \tag{6}$$

from where:

$$V_{\max} = \sqrt{\frac{L}{C} I_0^2 + V_0^2} \tag{7}$$

This equation can be normalized with respect to the voltage at the source side. Since the current chop occurs with a voltage across the capacitance very close to that of the source side, the following expression results:

$$V_{\max(\text{pu})} \approx \sqrt{1 + \frac{L}{C}\left(\frac{I_0}{V_0}\right)^2} \tag{8}$$

The interruption at current zero is just a particular case in which $I_0 = 0$ and $V_{\max} = V_0$ (or $V_{\max(\text{pu})} = 1$). In many real cases, the value of L is large and the value of C is small; therefore, regardless of the value of I_0, the maximum voltage that can be caused at the load side, and consequently the TRV across the circuit breaker when current chops, can be much larger than when the current is interrupted at current zero.

Figure 10 compares the load side voltage and the transient recovery voltages that are generated when arc interruption takes place at current zero and before current zero (current chopping), respectively (Martinez-Velasco & Popov, 2009). It is obvious from this example that the second case is more severe. If the circuit-breaker voltage intersects the dielectric recovery characteristics of the breaker, reignition occurs and the process is repeated again. With every reignition, the energy stored is reduced until the dielectric strength is large enough and further reignitions are prevented. Overvoltages of the order of two to four times may be produced on the disconnection of inductive loads.

The phenomena of chopping and reignition, with associated high-frequency oscillatory overvoltages, are attributed to the design of the circuit breaker. Circuit breakers are designed to cope with high fault currents. If a design is concentrated only on an efficient performance for high currents, it will be also efficient for small current and will try to interrupt before the natural current zero. This may produce current chopping and reignitions with adverse consequences. The breaker design should incorporate features to cope equally well with small and high currents. In practice, all types of circuit breakers can chop; however, the instantaneous current magnitude at which the chopping occurs varies among the different types of interrupting mediums and it is higher for vacuum interrupters (Martinez-Velasco & Popov, 2009). In theory, when current chopping happens the current is reduced instantaneously from a small finite value to zero, but in reality this event does not happen so suddenly simply because of the inductance that is present in the circuit and, as it is well known, current cannot change instantaneously in an inductor. It is therefore to be expected that some small finite element of time must elapse for the transfer of the magnetic energy that is trapped in the system inductance.

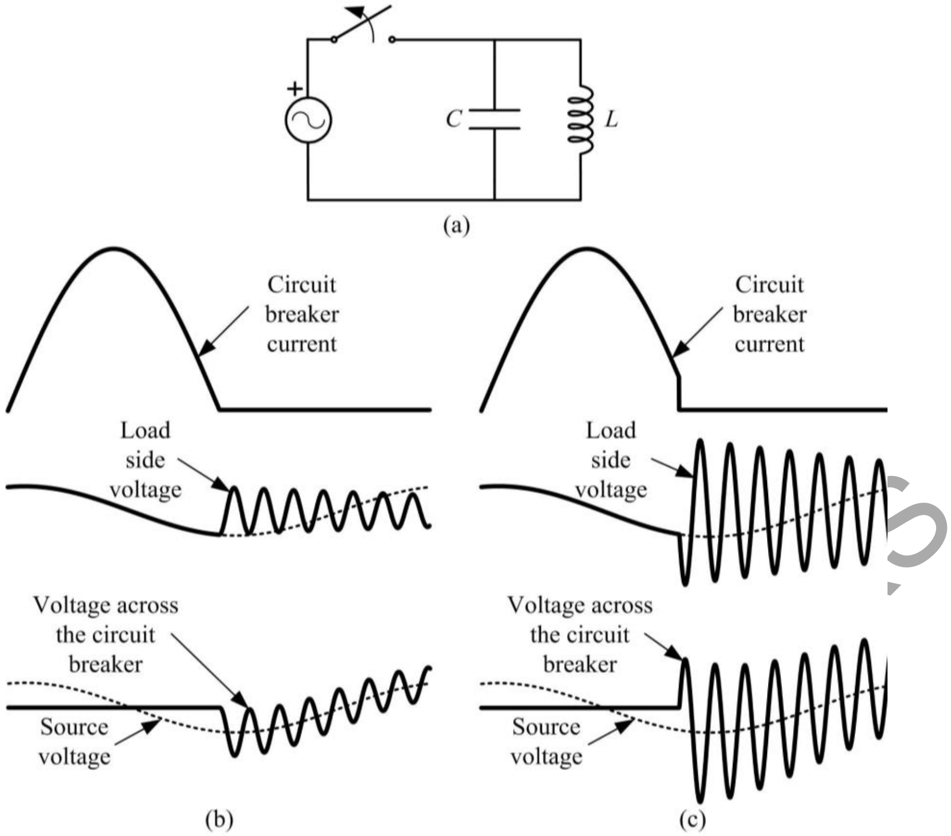

Figure 10. Transient recovery voltage during interruption of a small inductive current. (a) Equivalent circuit. (b) Arc interruption at current zero. (c) Arc interruption before current zero.

Virtual Current Chopping: In the case of *current chopping*, the instability of the arc around current zero causes a high-frequency transient current to flow in the neighboring network elements. This high-frequency current superimposes on the power frequency current whose amplitude is small and which is actually *chopped* to zero. In the case of *virtual chopping*, the arc is made unstable through a superimposed high-frequency current caused by oscillations with the neighboring phases in which current chopping took place. Virtual current chopping is not a true chopping phenomenon but rather it is the normal interruption of a fast transient current (van der Sluis, 2001).

Refer to Figure 11 and assume that a reignition occurs after the interruption of the power frequency current in phase A. A reignition current i_A will then flow to ground through the capacitance in the load side of the circuit breaker in phase A, while components i_B and i_C will flow in phases B and C due to the coupling of their respective capacitances. The high-frequency transient current produced by the reignition superimposes on the power frequency, can be larger in magnitude than the power frequency current, as in the figure, and force current zeroes at times other than those expected to occur normally with a power frequency current. When the neutral is ungrounded, as in Figure 11, one half of the reignition current would return through each of the other two phases.

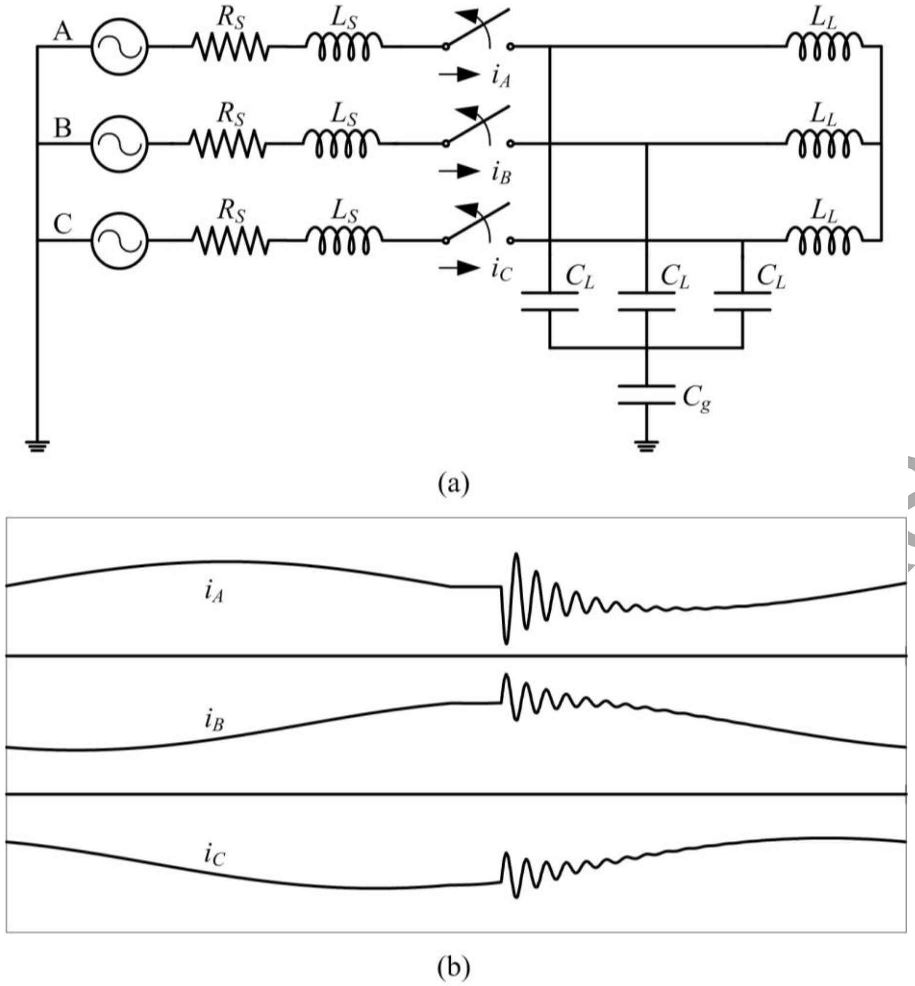

Figure 11. Virtual current chopping. (a) Circuit diagram. (b) Phase currents.

Some types of circuit breakers are capable to interrupt these high frequency currents, so it is possible to assume that in some cases the circuit breaker may clear the circuit at a current zero crossing that has been forced by the high frequency current and that the zero crossing occurs at a time prior to that of the natural zero of the power frequency current. When this happens, it looks the same as if the power frequency current has been chopped since a sudden current zero has been forced. Since the high frequency current zeroes will occur at approximately the same time in all three phases, see Figure 11b, the circuit breaker may interrupt the currents in all three phases simultaneously thus giving rise to a complicated sequence of voltage transients that may even include reignitions in all three phases (Garzon, 2002).

The characteristics of the transient processes originated when interrupting a circuit under normal operating conditions can be summarized as follows (Schmunk & O'Leary, 1987):

- The interrupted currents are much lower than the currents that exist when interrupting under fault conditions. In some cases, the current can be very small.

- The interruption of a normal load is made with a high and inductive power factor, and causes a low to moderate TRV, since it is not strongly driven during the transient period.
- The interruption of a shunt reactor is made with an almost zero power factor and it may cause high transient overvoltages, since the following transient occur when recovery voltage conditions are at a maximum.
- The interruption of an unloaded transformer will be likely premature, because of low magnitude current; that is, the current may chop. But the energy available is mostly retained within the core due to residual magnetism and will not contribute to driving the TRV.
- The interruption of capacitor banks, unloaded lines and cables is made with an almost zero power factor. As with the interruption of shunt reactors, the recovery voltage conditions are at a maximum, but in this case post-interruption transient is moderate due to the voltage retention of the capacitive circuit. The magnitude of the recovery voltage will depend of the capacitive bank connection and the system grounding.

2.3.3. Current Interruption Under Fault Conditions

2.3.3.1. Introduction

The short circuits or faults that can occur in high-voltage networks can be classified as either terminal/bolted or short-line faults. A terminal fault is defined as one where the short circuit takes place at, or very near, the terminals of the circuit breaker, while a short-line fault is one where the short circuit occurs at a relatively short distance downstream from the circuit breaker on its load side. Depending on the characteristics of the network and the type of the fault, the typical TRV can be represented by either single-frequency or double-frequency waveshapes for the terminal faults, and by a multi-frequency that includes a saw-toothed waveshape component for the short-line fault.

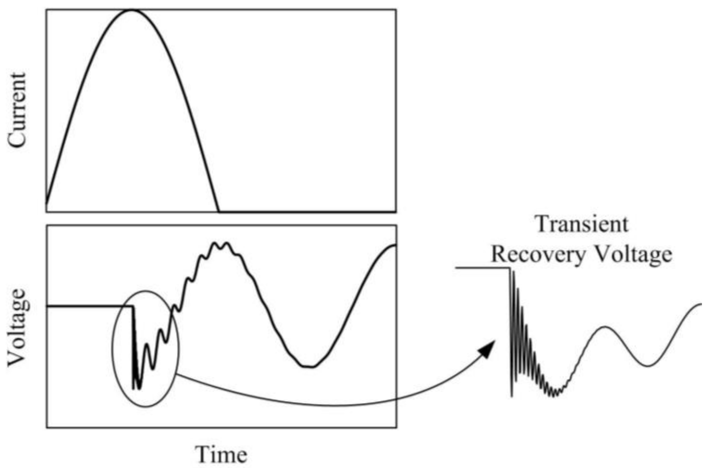

Figure 12. Voltage and current waveshapes during symmetrical fault current interruption.

Figure 12 shows the interruption of a symmetrical rated-frequency short-circuit current; that is, when the current reduces naturally to zero once every half cycle. This represents the minimum natural rate of current decay (di/dt) so that for conventional power systems, which are inherently inductive, the induced voltage following current interruption is minimized. However, other current interruption situations may exist in which the sinusoidal waveshape is superimposed on a damped unidirectional current to form an asymmetric wave (see Figure 13), which will cause different circuit breaker stress. A related condition, which occurs in generator faults, corresponds to the power frequency wave superimposed on an exponentially decaying component so that zero current crossing may be delayed for several half cycles. Standards distinguish between fault current close to a generator and fault current far from a generator (IEC 60909, 2001).

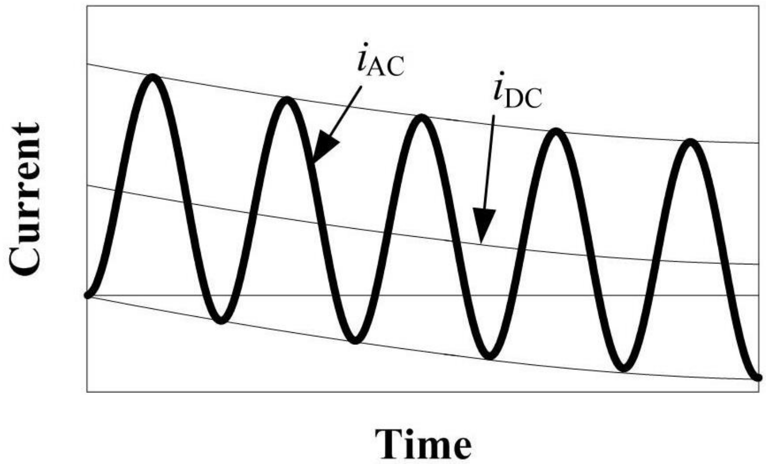

Figure 13. Short-circuit current waveshape with a DC component.

The type of fault is important to the performance recovery of the circuit breaker. Following a short-line fault, the circuit breaker is more likely to fail in what is called the thermal recovery region. This is a region of approximately the first ten microseconds following the interruption of the current, when thermal equilibrium has not yet been re-established. For a terminal fault it is more likely that if any failures to interrupt do occur, they will be in the dielectric recovery region, which is the region located between approximately 20 microseconds up to about 1 millisecond, depending on the rating of the circuit breaker.

Although the cases to be analyzed are many, they present some common characteristics: the current is high, much above normal load currents; the power factor of the circuit is low and inductive; after the current zero, the voltage across the circuit breaker is near the maximum value, so the TRV is strongly driven. TRV waveshapes caused by fault current interruption are usually classified into three types: exponential (also known as ex-cos), oscillatory (also known as 1-cos) and saw-toothed. Figure 14 shows the three waveshapes and the typical fault conditions that can cause each of them (IEEE Std C37.011, 2005; Wagner, 1987; Martinez-Velasco & Popov, 2009).

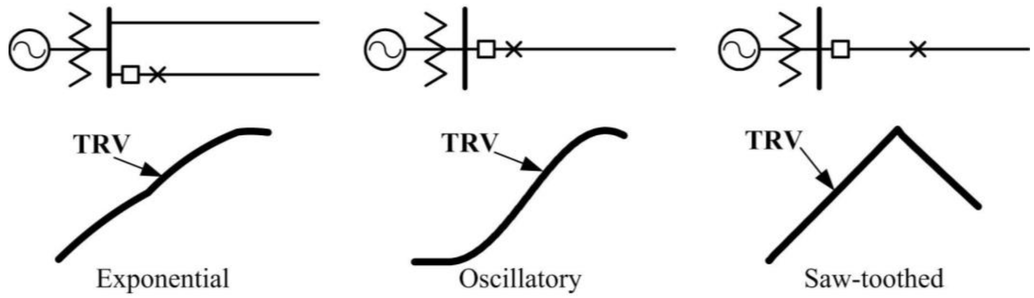

Figure 14. Characteristic transient recovery voltages under fault conditions.

A short description of some processes originated with the interruption under fault conditions is presented in the following paragraphs.

To obtain the TRV that can be caused by a three-phase fault the circuits shown in Figure 15 are used. They show how the current injection method can be applied to obtain the TRV caused by both grounded and ungrounded three-phase faults. One can observe that the ungrounded fault is more severe and increases the TRV a 50% times with respect to what would be caused by a grounded fault.

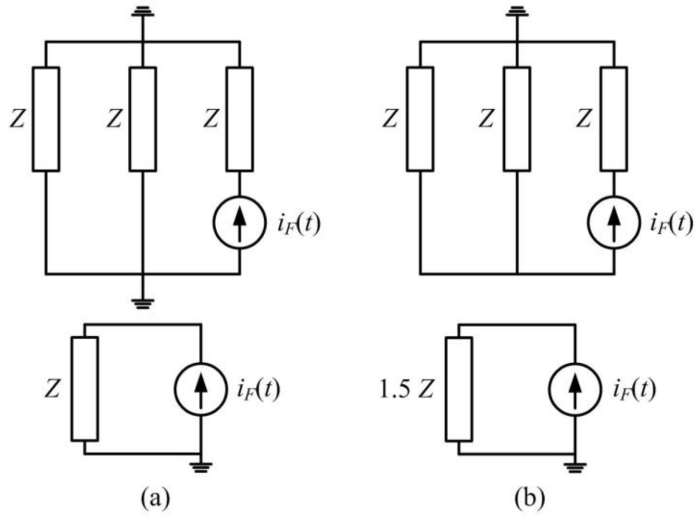

Figure 15. Equivalent circuits to calculate the TRV during three-phase faults. (a) Grounded fault. (b) Ungrounded fault.

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Biographical Sketches

Juan A. Martinez-Velasco was born in Barcelona (Spain). He received the Ingeniero Industrial and Doctor Ingeniero Industrial degrees from the Universitat Politècnica de Catalunya (UPC), Spain. He is currently with the Departament d'Enginyeria Elèctrica of the UPC. His teaching and research areas cover Power Systems Analysis, Transmission and Distribution, Power Quality and Electromagnetic Transients. He is an active member of several IEEE and CIGRE Working Groups. Presently, he is the chair of the IEEE WG on Modeling and Analysis of System Transients Using Digital Programs.

Jacinto Martin-Arnedo was born in Barcelona (Spain). He received the M.Sc. and Ph.D. degrees from Universitat Politècnica de Catalunya (UPC), Barcelona, Spain. From 1999 to 2010 he was working with ITC-2 as an Electrical Engineer in tasks related with the design of Distribution Power Network. He is currently working with Estabanell Energia as engineering manager. His research interests include Power Quality studies and Transient Analysis of Power Systems using EMTP-type tools.