Part III

Voltage Surges, Over-voltages, Circuit Interrupters and Grounding Practices

17

Voltage surges – causes, effects and remedies

Contents

17.1 Introduction

Voltage surges are generally a phenomenon of high voltage (HV) power systems and can be considered as the most severe pollutant to the insulation of the power system and the terminal equipment. In this chapter we analyse the likely amplitude and steepness of surges that may arise under different system conditions and the most appropriate insulation co-ordination between the equipment connected on the same system. Insulation co-ordination provides a criterion in selecting the right equipment with a more economical insulation level for different applications and locations. Generally, locations away from the source of voltage surges, i.e. equipment installed in the downstream of a power system is subject to diminishing surge effects. For example, a rotating machine, which may be a motor or a generator, would rarely be subject to a direct lightning stroke as it would seldom be connected on a bus exposed to direct strikes. It is usually connected through a bus or a cable which is fed through a transformer. All these interconnecting devices would withstand most of the severity of a lightning stroke and it would be only somewhat attenuated and damped surge which the terminal equipment would be subject to.

This concept of diminishing value of voltage surges is a logical parameter to economize on the cost of insulation as far as permissible, without jeopardising the adequacy of protection to the system or the associated equipment. Different equipment installed at different locations on the same power system may thus have varying degree of basic insulation level (BIL), as discussed in Section 18.3. One may notice the variation in BIL from Tables 11.6, 13.2, or 14.1, and 32.1(a), for motors, switchgears and bus systems respectively when installed on the same power system. Similar variations would apply for other equipment also connected on the same system. The aim here is to cover the subject for a proper understanding without going into extensive details.

The type of a surge is identified by its shape, and its severity is measured by its amplitude (V_t) and time (t_1) to reach this amplitude. All over-voltages discussed in this chapter are termed surges, since their severity would last only for a few microseconds (μs). In our discussions here and elsewhere in this book, we classify the over-voltages into two categories for easy identification. One as the temporary or dynamic over-voltages discussed in Chapters 20 and 24 existing in the system for a slightly longer duration say, one half of a cycle to two to three cycles at the power frequency (50 or 60 Hz), and the other as voltage surges, appearing for a few μs, at transient frequencies of a few kHz.

17.2 Temporary over-voltages

These are of a relatively longer duration, and may have several successive peaks, lasting from one-half of a cycle to a few cycles at the power frequency, depending upon the time constant ($\propto R/X_L$) of the circuit that gives rise to such over-voltages. The likely causes of such over-voltages are discussed in Chapters 20 and 24. It is, however, felt necessary to give a brief review of the same for greater clarity of the present topic:

- Ground fault (Section 20.1)
- Sudden change of load (Section 24.6.2(ii))
- Resonance and ferro-resonance effects (Sections 20.2.1(2) and 24.4(1 and 2)).

17.2.1 Ground fault

High over-voltages occur on the healthy phases during a ground fault:

- When the system is grounded through an arc suppression coil and is under-compensated. Whereas the arcing grounds give rise to voltage surges.
- When the system has an isolated neutral.
- When the system is impedance grounded.

For more details on grounding systems and the extent of over-voltages refer to Chapter 20.

17.2.2 Sudden change of load

This is more pronounced on high-voltage and extra-high-voltage systems (66 kV and above) when:

- Carrying large powers and where there may be wide variations in the load demand
- Load rejection: The load side interrupter, feeding a large load at the far end, trips
- The load demand falls sharply as a result of substantial load rejection, when the generator feeding the system is suddenly under-loaded and tends to overspeed, raising its terminal voltage. While the field control system and the turbine governor will act immediately to regulate the system, the time to normalize the situation may be a few cycles, hence the necessity to protect the system against such over-voltages.

17.2.3 Resonance and ferro-resonance effects

Such a phenomenon may occur when a circuit comprising a capacitance C and inductance L is switched ON or OFF and when such circuit parameters undergo a change during normal operation, as a result of a sudden change of load. A power circuit will invariably possess such parameters. For example, leakage capacitances between phase to phase or phase to ground are present in a cable or a line conductor and these would rise when series capacitor banks are connected on the same system, say, to improve the system regulation. Similarly, leakage inductance is also present in a cable or a line conductor and that will also rise when a transformer or a shunt reactor, having nonlinear magnetizing characteristics (Figures 27.2(b_1) and (b_2)) is also connected on the same system. According to the field data collected on this phenomenon it has been observed that it is more pronounced on HV and EHV systems (36 kV and above) particularly under the following conditions:

1 When switching a lightly loaded circuit, having a

transformer, and the natural frequency of the linear part of the system corresponds to one of the harmonics of the magnetizing current.

2 When the systems that are series compensated are connected to a lightly loaded transformer or shunt reactor, under certain line conditions (Section 24.4).
3 When harmonic filter circuits are connected to a power system with saturated reactors (Figure 27.2(c)) resonance may occur between the reactor and the filter capacitors to give rise to over-voltages.
4 Resonance may also occur between the line inductance, series reactors and shunt capacitors.
5 Resonance may also occur between the line capacitance or the ground capacitance and the inductance of a series-connected limiting reactor, or the inductance of a transformer, connected on the system.

17.3 Voltage surge or a transient

The occurrence of a surge or a transient is not intentional, unlike an impulse, as noted later and may appear on an MV, HV and EHV system as a result of system disturbances, such as during:

- A lightning strike (Figure 17.1)
- A switching operation*
- Contact bouncing or
- A fast bus transfer*
- Because of a surge transference from higher voltage to the lower voltage side of a power transformer
- During faults such as during a ground fault in a resonant grounded system or an isolated neutral grounded system, and
- Arcing insulators and arcing grounds

These surges are of very short duration and may be defined by the following two parameters:

1 Prospective amplitude, V_t, to define the maximum amplitude a surge would reach. Only the first highest peak is of significance for this purpose, which will contain the maximum severity. The subsequent peaks are of moderate magnitudes and of little consequence for the system or the terminal equipment, see Figure 17.4 (similar to the making current I_M during a short circuit, Figure 13.19).
2 Time of rise, t_1. Depending upon the time of rise, a surge may be classified into three groups:

- Switching surges
- Lightning surges and
- Very steep or front of wave (FOW) surges.
  See Figure 17.3.

17.3.1 Switching surges

These are slow rising surges and have a front time of more than 10 μs. They are considered as long-duration surges due to their high total effective duration t_2 (Figure 17.2(b)). But they discharge very high energy, even during this short duration, and may deteriorate or damage the insulating properties of the system or the terminal equipment that is subject to such a surge and absorb its severity. For the purpose of energy discharge by a surge, the amplitude and duration of switching surges alone is considered (Section 18.6.3). The duration of these surges is much higher than that of the other two types of surges.

17.3.2 Lightning surges

These are fast rising and may have a front time of almost 1 μs or even less. They are therefore considered short-duration surges, see Figure 17.2(a).

17.3.3 Very steep or front of wave (FOW) surges

These are very fast rising and of very short duration and may have a front time as short as 0.1 μs or less (IEC 60071-1). As a result, while their energy discharge may be too small to be of any significance, their rate of rise is very rapid. This makes them capable of damaging a small part of the current-carrying conductor of the terminal equipment, rendering it highly vulnerable to an insulation failure. Sometimes a restrike of the interrupting contacts, or a quick re-closing of a power equipment, may also cause such surges. The situation may become worse:

- When interrupting small reactive currents, such as during the opening of an unloaded power line, an unloaded transformer or a motor running at no-load. In all such cases it may cause current chopping, leading to extremely steep switching surges (Section 19.6) or,
- When the system already had a trapped charge before a reclosure (Section 6.13.2).

All electrical equipment are designed for a specific BIL,

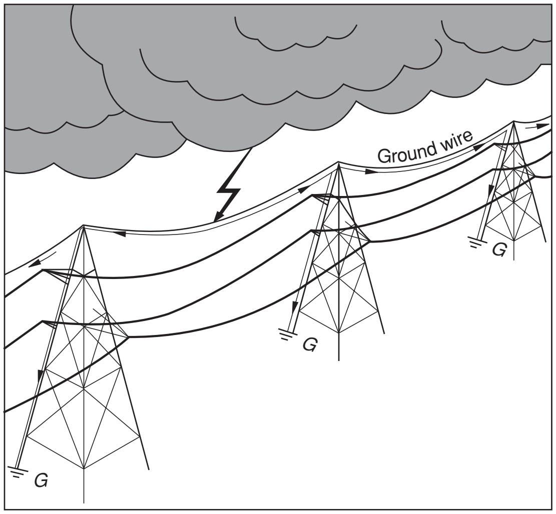

Figure 17.1 Discharge from clouds

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*A direct on-line switching is a single transient condition, whereas a quick bus transfer is OFF and ON, i.e. a double transient condition, hence more severe.

as indicated in Tables 11.6, 13.2, 14.1, and 32.1(a) for motors, switchgears and bus systems respectively, and Tables 13.2 and 13.3 for the main power system (for line clearances and insulators). If the actual severity of a prospective surge, is expected to be higher than these levels by way of higher amplitude and/or lower rise time the same must be damped to a safe level, with the use of surge arresters, surge capacitors or both as discussed later.

17.4 Fast bus transfer

Auto-reclosing is employed for a fast bus transfer. This subject relates to transient stability of overhead lines and is discussed under Section 24.9.1.

17.5 Causes of voltage surges

In actual operation, disturbances on a power system, causing sudden changes in the system parameters, are quite frequent and may generate temporary over-voltages and voltage surges, as summarized above. The system disturbances may be of two types, external or internal, as explained below.

17.5.1 External causes

These are mainly due to atmospheric disturbances as noted below. The effect of such surges is totally different from that of switching surges, and the amplitude is independent of the system voltage.

Lightning strike

There is no clear explanation of lightning. However, the most popular theory is the charging of clouds at high voltages, up to 20 million volts and a charging current 5–100 kA or so, due to the movement of hot air upwards and tiny droplets of water downwards. This process tends to make the tops of the clouds positive and the bottom negative, which creates a voltage gradient between the clouds and the earth. The voltage gradient may exceed the breakdown value of the air and cause a flashover. This flashover is similar to an electrostatic discharge of the atmosphere to the ground, as illustrated in Figure 17.1, and is termed a lightning strike. There may be up to 20 pulses in each lightning strike, each having a duration of about 50 μs. The phenomenon is comparable to the discharge of a highly charged condenser, the clouds forming one plate, ground the other and the air as the dielectric.

Electrostatically induced charges

- ***Due to the presence of thunder clouds in the vicinity:*** A charged cloud above and near a large object, an overhead line, for instance, induces a charge of opposite polarity than its own in the line. When this cloud bursts suddenly and discharges, its induced electrostatic charge travels in both directions on the line at a speed nearly equal to the velocity of light and equalizes the potential at all points. The potential at any point along the line rises suddenly from its normal value to the amplitude (V_t) of the travelling wave.
- Due to the friction of dust or free snow blowing past the conductors.

Electromagnetically induced currents

Due to lightning in the vicinity of the overhead lines. It is an indirect effect of a lightning strike. The lightning surges may impose very severe stresses on the line and cause damage to the line insulators and the terminal equipment without causing a trip by the protective device. These surges can be contained at the receiving end with the use of a surge arrester or a diverter (discussed later).

17.5.2 Internal causes

Making or breaking a power circuit causes a change in the circuit parameters and produces voltage surges. Those arising out of switching operations are attributed to internal causes. In this chapter we limit our discussions to the phenomenon of voltage surges, as related to internal causes and particularly as a result of switching. The requirement and the type of protection remains the same for external or internal causes of system disturbances.

17.6 Definitions

In the following text we will use a few new terms. For the sake of more clarity on the subject these are defined as follows.

17.6.1 An impulse

An impulse is an intentionally applied voltage or current in a laboratory. It is in the form of an aperiodic and unidirectional waveform (Figure 17.2). It rises rapidly without appreciable oscillations to a maximum value and then falls, usually less rapidly, to zero, with small, if any, loops of opposite polarity. The parameters which define a voltage or a current impulse are its polarity, peak value, rate of rise (front time) and time to half its value on the tail, as noted later.

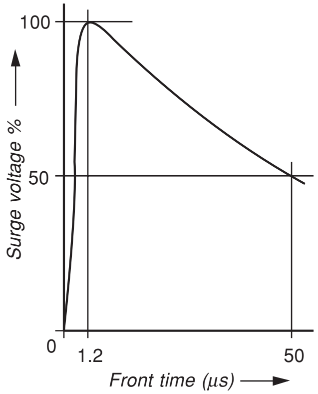
A transient of an external or internal nature, is then related to one such type of impulse, for laboratory testing a particular equipment or system, to establish its suitability.

Identifying a transient waveform with an impulse waveform

The distinction between a lightning transient and a switching transient may be made on the basis of the duration of the wave front (shape), rather than of its origin. Accordingly a voltage impulse with a wave front duration of less than 1 μs, up to some tens of μs, is generally considered a lightning impulse (Figure 17.2(a)) whereas an impulse with a front duration of some 10 μs to thousands of μs is considered a switching impulse

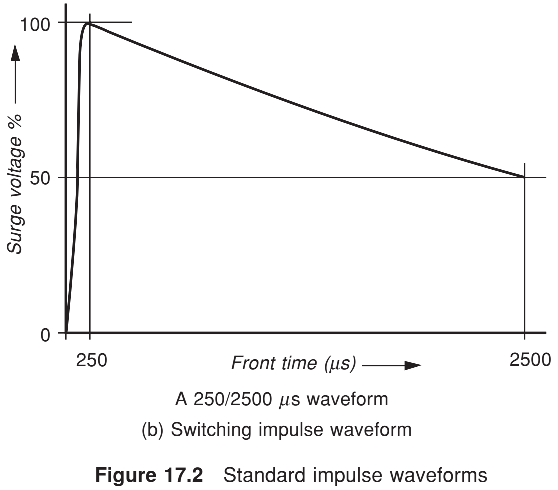
(Figure 17.2(b)) as per IEC 60060-1. The type of wave is generally designated as t_1/t_2 (Figure 17.3), where

1 t_1 = virtual front time of an impulse:
- For a voltage impulse having a front duration of less than 30 μs (normally lightning surges)
  t_1 = 1.67 × time taken by the impulse to rise from 30% of its peak value to 90%
- For a voltage impulse having a front duration of more than 30 μs (normally switching surges)
  t_1 = 1.05 × time taken by the impulse to rise from 0% to 95% of its peak value
  For the sake of laboratory testing and analytical studies, these surges have been represented by standard impulse waveforms. According to IEC 60060-1 a 1.2/50 μs impulse is called a standard lightning impulse, and a 250/2500 μs impulse a standard switching impulse.
- For equivalent current impulses, such as 8/20 μs for a 1.2/50 μs voltage surge and 30/60 or 30/90 μs for a 250/2500 μs voltage surge
  t_1 = 1.25 × time taken by the current to increase from 10% to 90% of its peak value.



A 1.2/50 μs waveform

(a) Lightning impulse waveform



A 250/2500 μs waveform

(b) Switching impulse waveform

Figure 17.2 Standard impulse waveforms

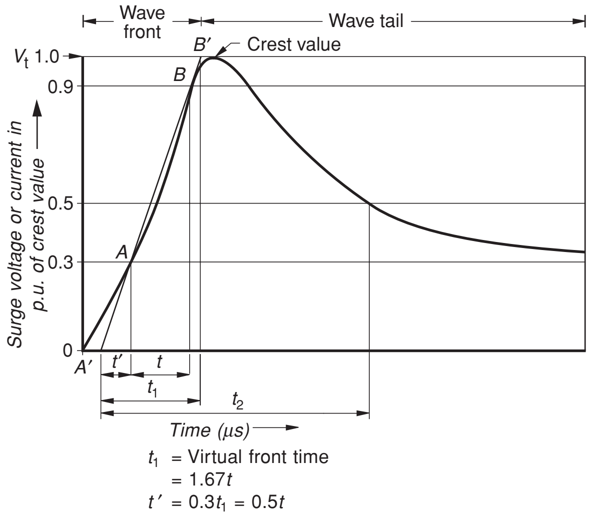


Figure 17.3 Defining a voltage or a current impulse waveform

2 t_2 = time interval between the origin and the instant at which the impulse has decreased to half of its peak value.

17.6.2 Transient recovery voltage (TRV) and its rate of rise (r.r.r.v.)* during the switching of an induction motor

TRV is the voltage (V_t) that may reappear across the parting cantacts of an interrupter immediately on a current interruption (current zero) (Figure 17.4) and cause a current across the parting contacts yet again, known as post-arc current. This current oscillates at a very high surge frequency f_s and is composed of a number of surge frequencies, as the leakage inductance L and the lumped capacitance C of the interrupting circuit undergo rapid changes with the propagation of the surge wave. The surge frequency is a function of circuit constants L and C (Equation (17.1)). Figure 17.4 drawn for one particular frequency, is only an illustration, and does not account for any subsequent restrikes. This is an important parameter. A very fast-rising transient can cause the surge voltage to be non-uniformly distributed over the entire length of the motor windings and affects the first or the entrance coil of the motor windings. This aspect is discussed in detail in Section 17.8.

The severity of the recovery voltage (TRV) of a surge is defined by its r.r.r.v., which is a function of its amplitude, V_t, and the front time t_1 (Figure 17.4), t_1 in turn being a function of the surge frequency f_s. The higher the surge frequency, the shorter will be the front time t_1. The shorter the time t_1, the higher will be the rate of rise and the steeper will be the recovery voltage and the more severe will be its effects on the terminal equipment.

Referring to Figure 17.4, if V_t is the peak value of the voltage surge of a particular transient voltage waveform in kV and t_1, the virtual front time or the time of rise of

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*r.r.r.v. – rate of rise of recovery voltage

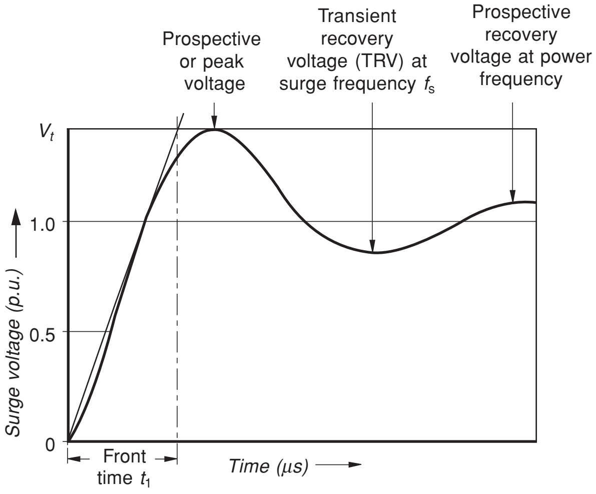


Figure 17.4 A transient recovery voltage ('TRV')

the transient voltage from its zero to peak value in μs, then the rate of rise of recovery or restriking voltage,

$$\text{r.r.r.v.} = \frac{V_t}{t_1}\ \text{kV}/\mu\text{s} \tag{17.0}$$

The significance of this term can be realized by the fact that the voltage stress of a surge, having a maximum amplitude of 4.5 p.u., with a front time t_1 of 0.5 μs, will roughly be the same or even less severe compared to a surge with an amplitude of only 2 p.u. and a front time of 0.2 μs because of more severe r.r.r.v. in the latter case $\frac{4.5}{0.5} < \frac{2}{0.2}$ p.u./μs (see Insulation Subcommittee, Rotating Machinery Committee, 1981).

When a fault occurs near the source of supply, the line lumped leakage capacitance C is small and the frequency of oscillations high, of the order of a few kHz (Equation (17.1)). But when the fault occurs at a distance from the source, C tends to become higher and the frequency of oscillations lower, of the order of a few hundred Hz. An introduction of some resistance in the interrupting circuit therefore will tend to damp (attenuate) the oscillations. When $R < 2\sqrt{L/C}$, (ϕ of $\cos\phi > 45°$), the system remains oscillatory and when $R > 2\sqrt{L/C}$, (ϕ of $\cos\phi < 45°$) the high-frequency oscillations can be totally damped. R may be introduced in the circuit through inter-connecting cables, interrupting devices and overhead lines etc., and thus mitigate the severity of transients during an arc interruption.

This practice is usually adopted in oil circuit breakers (BOCBs and MOCBs). In air blast circuit breakers (ABCBs), and SF_6 circuit breakers, a resistance is usually connected in shunt across the contact gap, such that R is introduced in the circuit during the making and interrupting processes only (see also Section 19.5.5).

17.6.3 Surge frequency

This is the frequency at which the surge travels. This frequency can be very high, of the order of 5–100 kHz or more, depending upon the circuit parameters. The natural frequency of oscillations of the transient recovery voltage of the circuit in terms of circuit parameters can be expressed as:

$$f_s = \frac{1}{2\pi\sqrt{LC}}\ \text{in Hz} \tag{17.1}$$

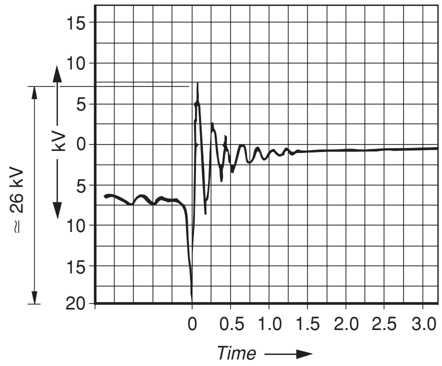
where

f_s = surge frequency in Hz

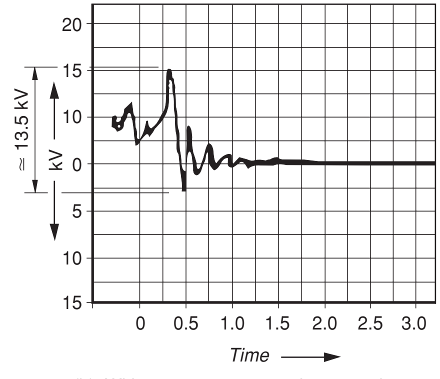
L = leakage inductance of the circuit in henry (H) and

C = lumped leakage capacitance of the circuit in farad (F) (L and C being the circuit parameters).

Refer to a typical oscillogram of a switching surge shown in Figure 17.5. Such a surge may exist on the system only until the interrupter is conducting, i.e. up to its contact making or contact opening, whatever the process of switching. It may be for only one half of a cycle to two cycles (10–40 ms for a 50 Hz system) in terms of normal frequency f of the system but many times more than this, in terms of surge high oscillating frequency f_s. The product of L and C will vary with a change in the circuit parameters. For instance, when a transient wave travels through a power system, having a number of equipment and devices connected to it such as a switching device to a cable, a cable to an overhead line or a transformer and an induction motor then the



(a) Without surge arrester maximum peak to peak voltage ≃ 26 kV



(b) With surge arrester maximum peak to peak voltage ≃ 13.5 kV

Figure 17.5 Oscillograms showing the effectiveness of a surge arrester on a 6.6 kV motor frequency of oscillations will continue to alter after every junction. At each junction the travelling wave will encounter a wave reflection and add more impedance in its circuit, as it will propagate ahead. After every reflection, the circuit parameters will change as will the frequency of oscillations. Thus, a number of oscillatory frequencies may exist in the system at a time, leading to a more complex phenomenon and making it difficult to accurately determine the effective surge frequency of the system and the r.r.r.v. By the use of oscillograms such as that shown in Figure 17.5, it is possible to determine such complex quantities.

The higher the frequency of the transient recovery voltage (TRV), the steeper will be the slope of the TRV (Figure 17.6), i.e. the higher will be the r.r.r.v. The r.r.r.v. is a measure of severity of the TRV that the terminal equipment and the devices may have to endure.

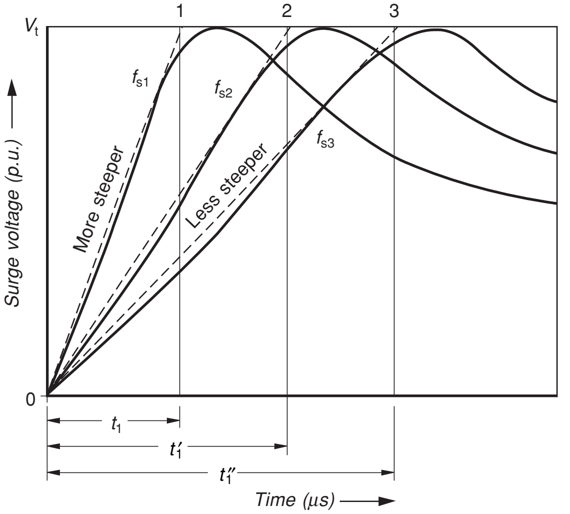
17.6.4 Surge impedance

The shape and characteristics of a surge wave are influenced by the circuit parameters, i.e. the leakage inductance L of the inter-connecting cables and the current carrying components of the equipment through which it travels and the leakage capacitance C of such cables and the motor dielectric lumped capacitance etc. (Section 19.6.1). The relation between L and C that determines the shape of the travelling wave is known as the surge or natural impedance Z_s of the system and is expressed as:

$$Z_S = \sqrt{\frac{L}{C}}\ \Omega \qquad (17.2)$$

where

L = circuit leakage inductance in henry (H), and
C = circuit lumped leakage capacitance in farad (F).



For same peak voltage 'V_t'
$t_1 < t_1' < t_1''$ and
$f_{s1} > f_{s2} > f_{s3}$
and r.r.r.v = $\frac{V_t}{t_1} > \frac{V_t}{t_1'} > \frac{V_t}{t_1''}$

Figure 17.6 The variation of r.r.r.v. with the front time $(t_1 \propto \frac{1}{f_s})$

Influence of surge impedance on terminal equipment

These values (L and C) help to determine the likely surge voltages that may develop during a switching operation while using different interrupting devices. For accurate analysis, it is advisable to obtain these values for an equipment from their manufacturers. Slamecka (1980) and others have also established such curves and have provided them in the form of nomograms for easy identification of this parameter, as reproduced in Figures 17.7(a) and (b). The surge impedance Z_s varies with variations in the design parameters, hence from manufacturer to manufacturer. These curves have therefore been provided in the form of bands. To account for likely variations in the design parameters by the different manufacturers one can, at best, obtain an average value of the surge impedance from these curves for a particular machine, as illustrated for a 500 h.p. ($\simeq$ 500 kVA, 6.6 kV) motor. But for an accurate value, it must be obtained from the machine manufacturer alone, as shown in Figure 17.7(c), for curves produced by Siemens for their motors.

The magnitude of the surge voltage, which is the product of $Z_s \times I_c (I_c$ being the current chopped), can be determined with the help of curves shown in Figure 17.8. These curves have been established with the help of the curves in Figures 17.7(a) and (b) and the values of I_c, assumed for various types of interrupters. The curves in Figures 17.7(a) and (b) reveal, that for larger ratings of machines, the surge impedance will tend to diminish, while for smaller ratings it will tend to rise. The curves in Figure 17.8 will thus reveal, that while a lower value of Z_s will tend to dampen the transients, the higher values will tend to enlarge, as corroborated in Section 18.5.1 (reflection of waves). Smaller machines are, therefore, subject to higher TRVs compared to larger ones.

Power cables connecting various equipment on a power system can be considered as lumped capacitances and can help in the natural damping of the amplitude (V_t) of the prospective surges, besides reducing their steepness (V_t/t_1) (Figure 17.6). Typical values of surge impedances for cables may be considered around 35–60 Ω, but the cable length has to be a safe one. Longer cable may raise the V_t beyond the BIL of the machine, as discussed in Section 18.6.2.

Example 17.0

Consider a 350 kW, 6.6 kV motor having a surge impedance, $Z_s \simeq 4000\Omega$ and a 500 kW, 6.6 kV motor having $Z_s \simeq 2400\Omega$ (from Figure 17.7(c)). Then with a VCB having a chopping current of 2A, the surge voltage at the instant of circuit interruption in case of 350 kW motor will be 2×4000 or 8 kV while for 500 kW motor it will be 2×2400 or 4.8 kV. Larger size motors having diminishing value of Z_s will thus be subject to lesser amplitude of surge voltages during a current chopping compared to smaller rating motors hence safer.

Corollary

As the size of the machine rises, likelihood of a re-strike of the arc plasma lessens during a circuit interruption.

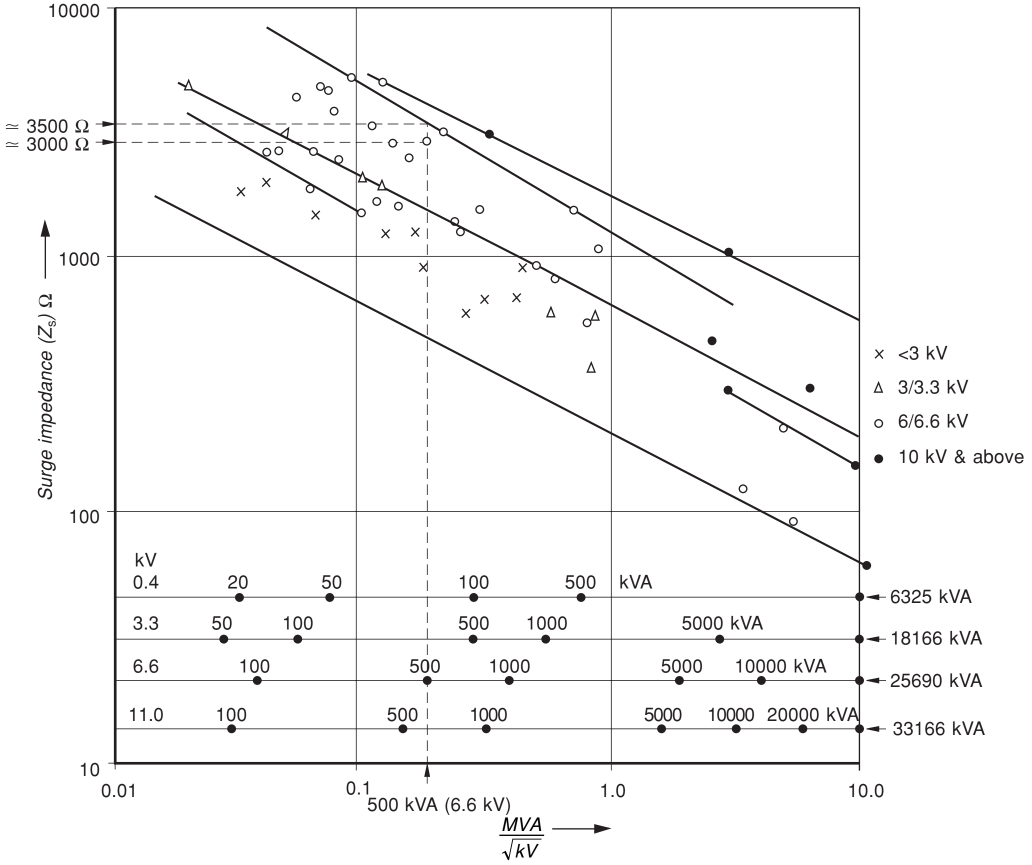


Figure 17.7(a) Surge impedance of rotating machines as a function of input $\text{MVA}/\sqrt{\text{Line kV}}$ (from Pretorious and Eriksson, 1982)

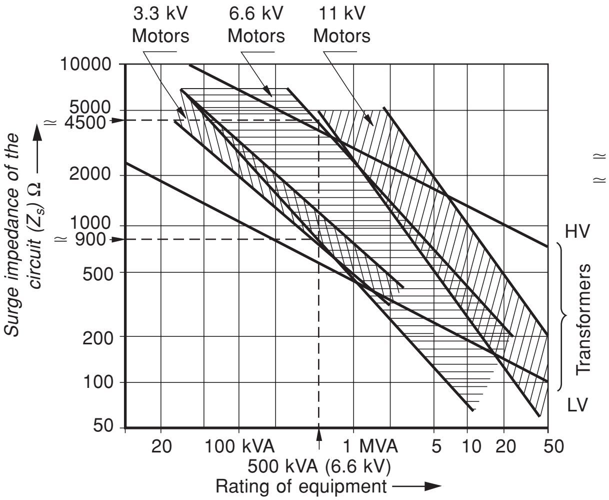


Figure 17.7(b) Typical values of surge impedances for MV motors and transformers

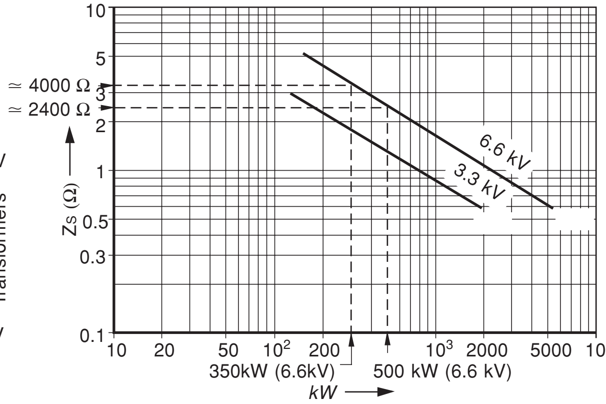


Figure 17.7(c) Surge impedance of MV motors as a function of output power (Source: Siemens)

17.6.5 Surge energy

When these surges strike a power system or equipment, they release very high energy, which the system and the terminal equipment should be able to absorb to be safe. This can be determined by a simple equation:

$$W = \frac{V_t^2}{Z_s} \times t \times 10^3 \text{ kW-s or kJ (1 W = 1 j/s)} \qquad (17.3)$$

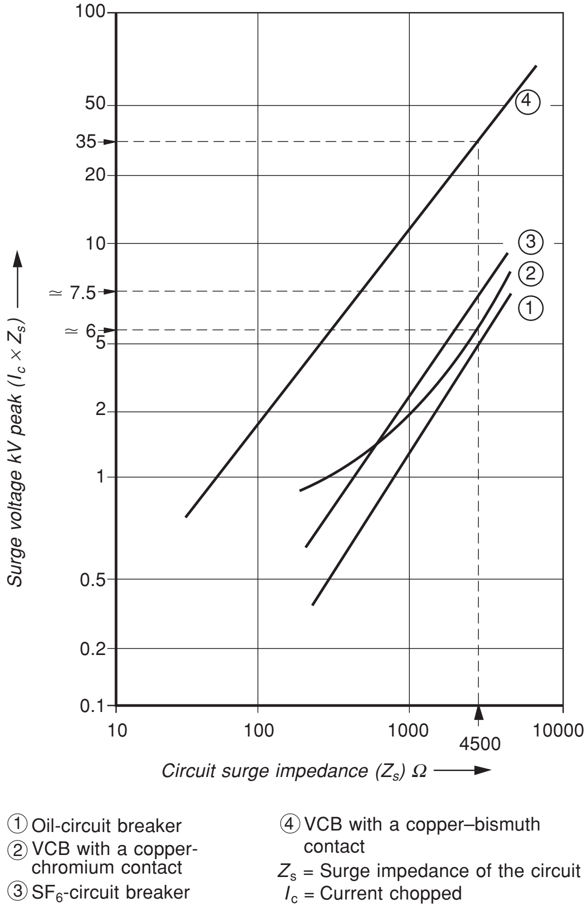


Figure 17.8 Likely surge voltages that may be developed by different types of circuit breakers during a switching operation as a function of circuit surge impedance

[Joule (J) is a measure of energy contained in a transient wave and that a surge arrester should be capable to absorb when installed on the system]

where
W = energy released in kW-s or kJ
V_t = prospective crest of the surge in kV
Z_s = surge impedance of the power system and the terminal equipment in Ω
t = duration for which the surge will exist (in seconds).

Since t_2 (switching) >> t_2 (lightning) > t_2 (FOW), therefore the energy released by a switching surge is usually many times greater than a lightning stroke or a front of wave (FOW) surge.

Subsequent examples will illustrate the amount of such energies and the means to dissipate them safely.

17.6.6 Velocity of propagation

The velocity of current or voltage waves in any medium is called the velocity of propagation of electricity in that medium. The velocity of electromagnetic waves (electricity) through a conductor is a measure of line or conductor parameters through which it propagates and is represented by

$$U = \frac{1}{\sqrt{L_0 C_0}} \text{ km/s} \qquad (17.4)$$

where
U = velocity of propagation in km/s and is free from the frequency of the travelling wave.
L_0 = line or conductor mutual inductance in H/km, through which it travels. This will depend upon the quantum of skin effect and the mutual induction between two or more adjacent current carrying conductors. In overhead lines, it is very low due to wide spacing between conductors. In cables also it is very low, although the conductors are placed in close proximity but they are transposed and nullify the effect of proximity.
C_0 = leakage capacitance in F/km.

The system parameters L and C are function of system voltage. With a rise in voltage, the leakage capacitance C will rise and mutual inductance L will fall due to larger clearances between the conductors, and hence, less induction in the adjacent conductors. The product of LC will remain almost the same for similar types of systems, and hence the velocity of propagation in one type of system. For instance, the velocity of propagation in an overhead line, even for different system voltages, will almost universally be in the same range. This is evident from the typical line parameters considered in Table 24.1(b), where the product of L and C is almost of the same order. It may, however, differ with the velocity in a cable. In a cable, the conductors are placed in close proximity to each other and are transposed (twisted) to nullify the effect of proximity. Also the cable may have a metallic sheathing and hence, provide an electrically symmetrical current-carrying system. Cables therefore possess a very low mutual inductance (L) and a very high leakage capacitance (C).

The product of L and C in cables is very high and so the velocity of propagation is very low. For a 33 kV, 3 × 300 mm² XLPE cable, for instance, taking parameters from Table A16.26 Appendix of Chapter 16

$$X_L = 0.115 \ \Omega/\text{km at 50 Hz}$$

or $$L = \frac{0.115}{2\pi f} = 0.336 \times 10^{-3} \text{ H/km}$$

and $$C = 0.23 \ \mu \text{ F/km}$$

$$\therefore \quad U = \frac{1}{\sqrt{0.366 \times 10^{-3} \times 0.23 \times 10^{-6}}} \text{ km/s}$$

$$= 1.09 \times 10^5 \text{ km/s or } 109 \text{ m}/\mu\text{s}$$

and for a 3.3 kV, 3C × 95 mm² PVC cable from Table A16.16

$$X_L = 0.088 \ \Omega/\text{km at 50 Hz}$$

$$\therefore \quad L = \frac{0.088}{2\pi f} = 0.28 \times 10^{-3} \text{ H/km}$$

and $$C = 0.715 \times 10^{-6} \ \mu\text{F/km}$$

$$\therefore \quad U = \frac{1}{\sqrt{0.28 \times 10^{-3} \times 0.715 \times 10^{-6}}}$$

$$= 0.706 \times 10^{5} \text{ km/s or } 70.6 \text{ m}/\mu\text{s}.$$

Similarly, consider an overhead line having the following parameters:

System voltage = 220 kV
Frequency = 50 Hz

$$X_L = 8.249 \times 10^{-4} \ \Omega/\text{km}$$

$$\text{and } B \text{ or } \frac{1}{X_c} = 1.42 \times 10^{-3} \ \Omega/\text{km}$$

$$\therefore \quad L = \frac{8.249 \times 10^{-4}}{2\pi f} = 2.63 \times 10^{-6} \text{ H/km}$$

$$\text{and} \quad C = \frac{1.42 \times 10^{-3}}{2\pi f} = 0.45 \times 10^{-5} \text{ F/km}$$

$$\therefore \quad U = \frac{1}{\sqrt{2.63 \times 10^{-6} \times 0.45 \times 10^{-5}}}$$

$$= 2.907 \times 10^{5} \text{ km/s}$$

(Also refer to Table 24.1(b)). The variation in line parameters considered here and produced in Table 24.1(b) may be due to change in line configuration and spacings.)

This is almost equal to the speed of light in free space and is true for straight conductors without any joints or discontinuities.

The velocity of propagation in a cable is much less than in an overhead line, as noted above. The frequency (f) of the electromagnetic waves at which they propagate has no bearing on the speed of propagation. The lightning surges, which propagate at very high frequency (consider a 1.2/50 μs wave, where 1.2 μs means the duration of one quarter of a cycle, the frequency of this wave in free space will be $= 1/4 \times 1/(1.2 \times 10^{-6}) = 208$ kHz), will also have a velocity of propagation equal to light, i.e. 3×10^{5} km/s (186 000 miles/s) or 300 m/μs. In motor windings it may be much less, due to discontinuities and a yet higher product of LC. For the purpose of deriving inferences of the influence of such waves on the performance of certain equipment, such as an electric motor, susceptible to such waves, the typical values for a 3.3 kV or 6.6 kV motor may be considered around 15–20 m/μs in slots and 150–200 m/μs in windings outside the slots.

17.6.7 Per unit voltage (p.u.)

The general practice to express an over-voltage is in p.u. This abbreviation will be used frequently in our discussions. One p.u. is the maximum voltage between the phase and the neutral, i.e.

$$1 \text{ p.u.} = \sqrt{2} \cdot \frac{V_1}{\sqrt{3}} \qquad (17.5)$$

17.6.8 Current zero

In an alternating current system the voltage and current components travel in the shape of a sinusoidal waveform (Figure 17.9) and oscillate through their natural zeros, 100 times a second for a 50 Hz system. The instant at which the power frequency current will pass through its natural zero, i.e. where $i = 0$, is termed its natural current zero (or current zero), where

$$i = I_{\max} \sin \omega t \qquad (17.6)$$

and

i = Instantaneous current component at any instant on the current wave
I = r.m.s. value of the current
$I_{\max}$ = peak value of the current
ω = angular velocity = $2\pi f$
t = time

Note
The term 'natural' is used to differentiate a power frequency current wave from an oscillating or transient high-frequency current wave.

17.6.9 Arc time constant

This is the time required by the quenching medium of an interrupting device to regain its original dielectric strength after the final current zero.

17.7 Causes of steep-rising surges

17.7.1 Arc re-ignition or re-strikes

This may occur between the parting contacts of an interrupting device while interrupting a low-power factor (p.f.) current. It is the re-ignition of the arc plasma between the parting contacts of the interrupting device. It may also reappear after a natural current zero, due to a high TRV, which the dielectric medium between the contact gap may not be able to withstand and break down. Figure 19.3 illustrates the theory of ionization and de-ionization of arc plasma. [The same is true during a closing sequence when the contact gap, just before closing, falls short of the dielectric strength of the medium in which it is making, and breaks down.] It is commonly termed as the restrike of the arc. This does not mean that the contacts that are parting will close again but the interrupting circuit will close momentarily, through re-ignition of the arc plasma,

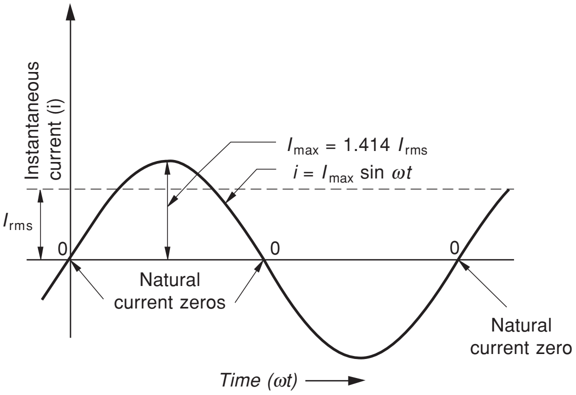


Figure 17.9 Representation of a sinusoidal current waveform

until the next natural current zero, or until contacts are made during a closing sequence.

This may better be understood with the help of Figure 17.10, when the making contacts begin to separate. The arc plasma becomes de-ionized by the immediate next current zero. At this current zero a recovery voltage across the parting contacts will appear the magnitude of which will depend upon the p.f. of the circuit and the instant at which the interruption occurs on the voltage wave. It is illustrated in Figure 17.11, through curves (a) to (d). The higher the p.f. of the interrupting circuit (i.e. under healthy conditions), the closer the system voltage and current

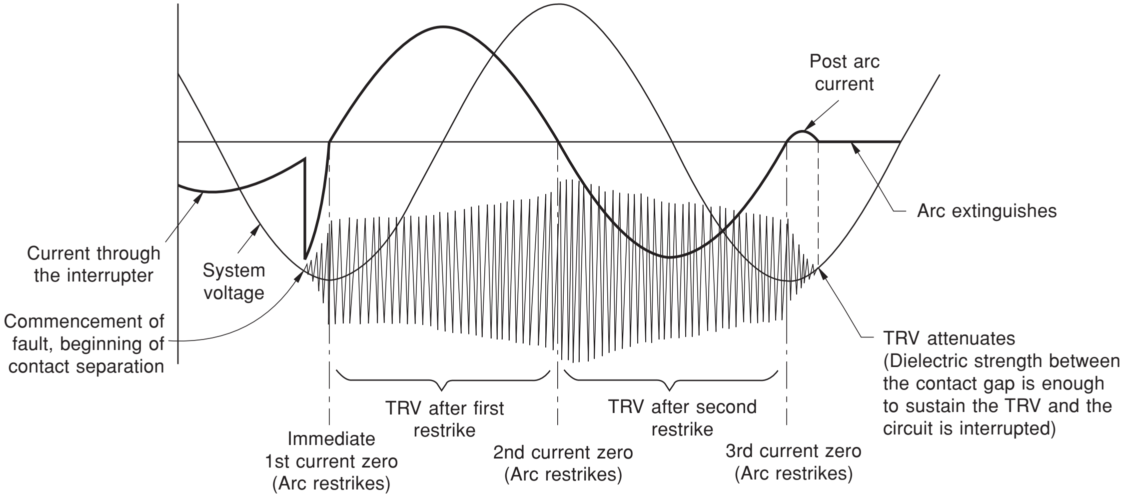


Figure 17.10 Approximate representation of arc re-ignition during a fault-interrupting process

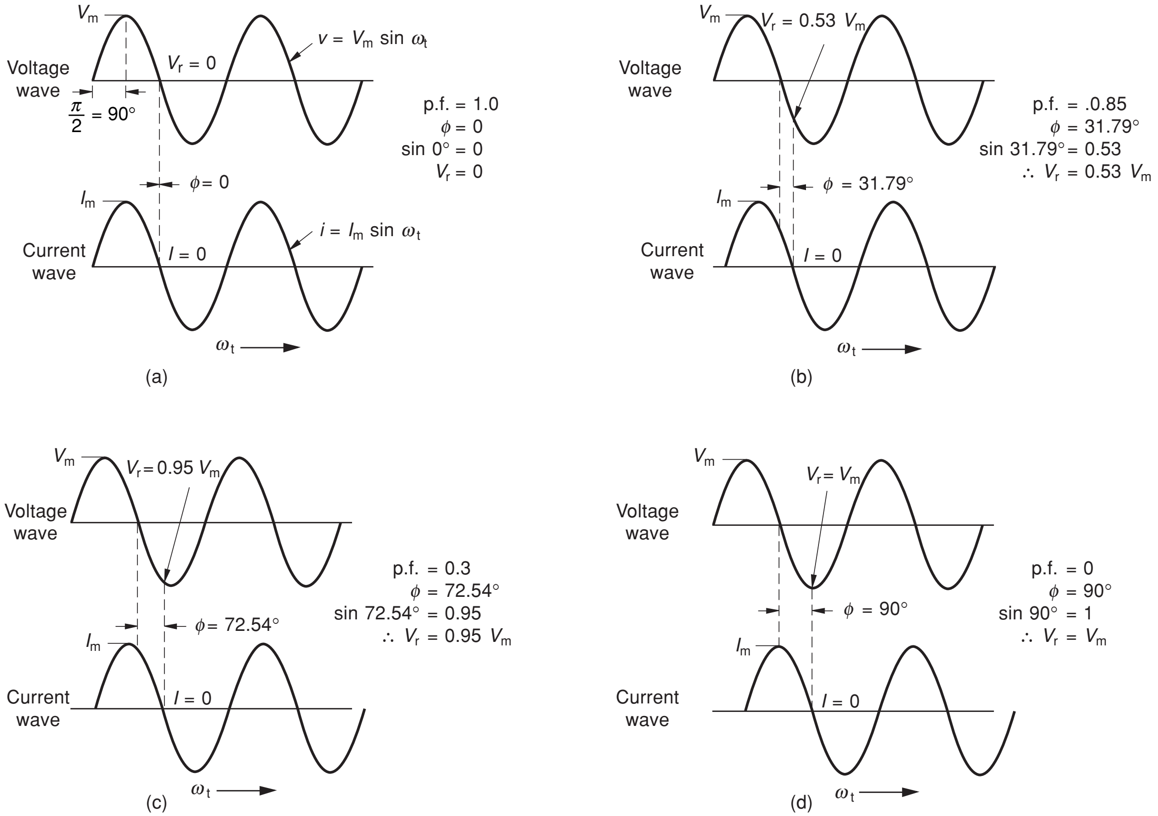


Figure 17.11 Amplitude of recovery voltage at a current zero during a switching operation of an inductive circuit at different p.fs.

phasors will be. This will cause the recovery voltage to be of a moderate magnitude (zero voltage at unity p.f. curve (a)) causing no re-ignition of the arc plasma and the circuit will interrupt successfully. At lower p.fs., however, such as during starting conditions of a motor or a transformer, or on fault, the recovery voltage at a current zero will be very high (curves (c) and (d)) and it may be enough to break down the dielectric medium between the parting contacts if they are still close to each other. This will cause a re-ignition of the arc plasma that had de-ionized immediately before current zero. The arc will thus remain ionized and will temporarily make the electrical contacts until the next natural current zero. The TRV at the next natural current zero, now higher than before due to reflections, will try to break down the dielectric medium between the parting contacts once again if this fell short of the required dielectric level to withstand the impressed TRV. This will establish an arc yet again, while the contacts have travelled farther apart. The process of such arc re-strikes is termed multiple re-ignitions or more commonly multiple re-strikes. They continue until the arc plasma is finally extinguished and the breaker has fully interrupted. It may be noted that the moving contact of an interrupting device is spring loaded and on a trip command tries to part with some force from the fixed contact. It will continue to move away until it reaches its far end and interrupt the contacts fully. Irrespective of the dielectric strength of the arc chamber and amplitude of the TRV, the situation will attenuate at a stage when the contact gap has become large enough that the TRV is unable to break down the dielectric medium across the gap to cause a further re-strike.

Since TRV and the dielectric strength between the parting contacts both rise gradually and rapidly (TRV after every restrike due to reflections and dielectric strength due to longer contact travel) there is almost a race between the two. Depending upon which rises faster than the other, will there be a restrike of the arc or an attenuation of the TRV. The theory of arc re-ignition can, therefore, also be termed the dielectric race theory. Figure 17.10 roughly illustrates this phenomenon. The actual waveforms will be much more complex being of a transient nature and can be obtained through oscillograms.

17.7.2 Switching surges

(i) Switching surges in an inductive circuit

When a coil of inductance L, consisting of Z number of turns, is energized through a voltage e, the flux, ϕ, linking the inductive circuit will undergo a rapid change from one peak (+ve) to the other (–ve), within one-half of a cycle of the voltage wave (Figure 1.5(c)), i.e.

$$e = -Z\,(\mathrm{d}\phi/\mathrm{d}t) = -L\,(\mathrm{d}i/\mathrm{d}t) \qquad (1.4)$$

The negative sign indicates the direction of the e.m.f. that opposes the change in the flux and thus the current.

Referring to a normal magnetizing curve of an inductive core, it will be observed that the normal peak flux occurs near the saturation point (Figure 17.12). At the instant of switching, the flux may go up to $2\Phi_m$ and cause an excessive saturation of the magnetic core, making the induced e.m.f. rise disproportionately. Hence the phenomenon of switching surges. If the core already has some residual flux in its magnetic circuit, at the instant of switching, the surge voltage will attain yet higher values and further intensify the switching surges.

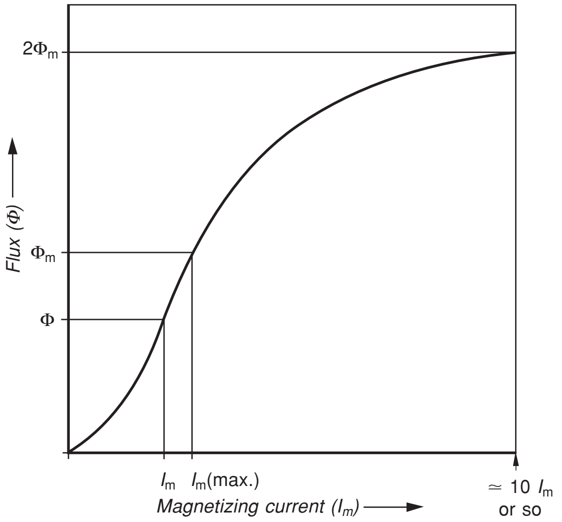


Figure 17.12 A normal magnetizing characteristic of an inductor coil

Excessive saturation of the magnetic core reduces the value of L, and raises the magnetizing current disproportionately, say up to ten times the normal value or even more, as discussed in Section 1.2.1.

To analyse switching surges we may consider the following two possibilities:

- Surges generated during a switching ON or contact-making operation, and
- Surges generated during a switching OFF or contact-interrupting operation.

(ii) Surges generated during a switching 'ON' operation

Field data collected from various sources have revealed failure of a motor's windings, even during an energizing process. It has been shown that a motor may be subject to an over-voltage of 3–5 p.u. with a front time 't_1' as low as 1 μs or even less (signifying the steepness of the TRV) during switching ON. The phenomenon of a switching surge is thus a matter of a few microseconds only, resulting from the restrike of the transient recovery voltage (TRV) during its first few cycles only, at a very high transient frequency, in the range of 5–100 kHz.

To explain this, consider a switch being closed on a motor. The moving contacts will approach the fixed contacts of the switching device and before they close, a stage would arise when the dielectric strength of the gradually diminishing gap between the closing contacts will no longer be able to withstand the system voltage and breakdown, causing an arc between the closing contacts. Under this condition, the voltage across the gap and thus also across the motor terminals, may rise in the following way:

- By the first pre-strike of the arc gap, the TRV may reach 1 p.u., when the motor is assumed to be at a standstill without any self-induced e.m.f. before closing of the contacts.
- When this TRV of 1 p.u. reaches the motor terminals, it will experience a surge reflection and almost double, subjecting the motor windings to a stress of almost 2 p.u. (more appropriately 1.5–1.8 p.u.) as measured during actual tests (see Pretorius and Eriksson, 1982). It is less than 2, due to the circuit impedance, and other effects, such as more than one junction of the inter-connecting cables from the switching device up to the motor terminals. All such effects damp the quantum of the reflected wave. See also Section 18.5.1.
- To make all the three poles simultaneously of a switching device during a switching ON sequence is rather impractical, whatever precision of the closing mechanism of the switching device be achieved. This is due to possible variations, even negligible ones, in the three contact travels or actual contact making. It is generally one pole of the device that will make first and then the other two poles will make. There could be a gap of a few milliseconds between the first contact making and the second. This aspect is vital when analysing the surge conditions during a switching ON.

The closing of one pole causes an oscillation in the corresponding phase of the motor winding which leads to oscillations in the other two phases that are still open. It has been seen that if the first pole pre-strikes at the maximum voltage, i.e. at 1 p.u. across the making contacts, the peak voltage across the other two poles may approach a value of

0.5 p.u. + (1.5–1.8 p.u.)

or up to 2.0 to 2.3 p.u. (See Cormick and Thompson, 1982)

At this voltage when these two poles pre-strike they cause a surge voltage at the motor terminals of

1.5–1.8 times the 2.0–2.3 p.u.

i.e. 1.5 × 2 p.u. or 3 p.u. to 1.8 × 2.3 p.u. or 4.14 p.u.

The above would be true if the motor is assumed to be at a standstill. If the motor had been running at almost full speed, this voltage would assume yet higher proportions, say, up to 5 p.u. due to the motor's own self-induced e.m.f., which may fall phase apart with the system voltage. Such a situation may arise during a fast bus transfer, when a running motor is switched over from one source to another or during a re-acceleration period after a momentary power failure. But since the amplitude and rate of rise of the recovery voltage (r.r.r.v.) at switching ON are influenced by the surge impedance of the closing circuit, which is formed by the surge impedance of the motor and the inter-connecting cables, the time of rise, t_1 (Figure 17.6) and the amplitude of the surge voltage, V_t, would rise with the length of the cable between the switching device and the motor terminals (Section 18.6.2). Such transient voltages will exist on the system just up to the contact making and are thus of extremely short duration (in μs).

Such pre-strikes before contact making are a natural phenomenon and may occur in all types of switching devices, such as an OCB, MOCB, ABCB, SF_6 or vacuum interrupters. But the severity of the pre-strikes and the magnitude of the transient voltages will depend upon the medium of quenching, which will determine the contact gap, before a pre-strike occurs (Figure 19.1) and its speed of closing.

Consider a vacuum interrupter having a dielectric strength of 50 kV at approximately 1.2 mm contact gap (Figure 19.1). Assuming the dielectric properties to be almost linear in this region, the contact gap, while switching a 6.0 kV motor for instance, will break down when the contacts are:

$$6 \times \frac{1.2}{50} \quad \text{or} \quad 0.144 \text{ mm apart}$$

Considering the speed of the moving contact as 0.6 m/s (typical), then the duration of pre-strikes before this contact will touch the fixed contact will be

$$= \frac{0.144}{10^3} \times \frac{1}{0.6} \times 10^6 \ \mu\text{s}$$

$$= 240 \ \mu\text{s}$$

For the parameters of the motor circuit, if the frequency of the TRV is considered as 17 kHz, arising out of pre-strikes, then the number of pre-strikes at transient frequency before the contacts make will be

$$2^* \times 17 \times 10^3 \times 240 \times 10^{-6}$$

or 8 (*each one cycle will cause two strikes).

The pre-strikes will give rise to voltage surges from 3 to 5 p.u. as discussed above and for which all the terminal and the inter-connecting cables must be suitable. The following are field data collected from actual operations to illustrate this phenomenon:

- On switching ON a 6.0 kV motor, a front time as low as 0.5 μs and the peak voltage transient, V_t, up to 15 kV, i.e. 3 p.u. has been measured:

$$\left(1 \text{ p.u.} = \frac{\sqrt{2}}{\sqrt{3}} \times 6 \text{ kV}\right)$$

- Voltage transients up to 3.5 p.u. with front times as short as 0.2 μs are mentioned in Working Group 13.02 of Study Committee 13 (1981) and Slamecka (1983).

Thus a switching 'ON' phenomenon may give rise to steep fronted waves, with a front time as low as 0.2 μs and high to very high TRVs (V_t) with an amplitude up to 3–5 p.u. Both are the causes of damage to the windings' insulation of a motor.

Note

Above we have analysed the case of an induction motor during a switching sequence for systems of 2.4 kV and above. The phenomenon of voltage surges in transformers, capacitors, inter-connecting cables or overhead lines etc. is no different, as the circuit conditions and sequence of switching will remain the same for all.

It is another matter that all such equipment would have a better insulation level (BIL) compared to an induction motor and may not be as endangered by such surges as the motor. In the subsequent text we have placed more emphasis on motors, being typical of all.

(iii) Surges generated during an interrupting sequence

This can be analysed in the following steps:

- When the interrupting circuit has a high p.f. (cos ϕ), i.e. a healthy tripping and also circuits that are non-capacitive.
- When the interrupting circuit is under-loaded and has a low p.f., i.e. when it is highly inductive and also circuits that are capacitive.
- Interrupting large inductive or capacitive currents.

17.7.3 Healthy tripping

In the first case, it is easy to interrupt the circuit, which poses no problem of current chopping (premature tripping) leading to re-ignition of arc plasma before a current zero or a prolonged arc after a current zero for the following reasons:

1 **No current chopping:** An induction motor or a transformer should be operating at near full load, to possess a high p.f. and carrying a near full load current during such an interruption. Even the most modern, very fast operating interrupting devices, such as a VCB (Section 19.5.6) will not be able to cause a premature interruption (current chopping). The interruption will thus be devoid of any surge voltage.

2 **No restrike at current zero:** When the voltage and the current phasors are close to each other (Figure 17.11(b)) or approaching a unity p.f. (Figure 17.11(a)), they will reach a current zero almost simultaneously. A p.f. such as 0.85 and above will have a residual voltage of not more than 53% of the system voltage at the current zero. Generally, an induction motor running almost at full load will have a p.f. of more than 0.85 (Table 1.9) and a recovery voltage of not more than 53% across the parting contacts at a current zero. This voltage will be insufficient to break the dielectric medium across the gap between the separating contacts and will not be able to establish an arc. Hence, the interruption of a circuit at a high p.f. will be devoid of multiple restrikes that are responsible for the surge voltages. The circuit will interrupt at the first current zero. The situation will be similar in a fully loaded transformer.

17.7.4 Interrupting small inductive or capacitive currents

In the second case, when the circuit has a low p.f. or carries a capacitive charging current, a condition which may occur in the following cases (for ease of analysis we have classified them into two categories):

- When interrupting an under-loaded induction motor, or a transformer, such as when they are operating at or near no-load.
- Interrupting a cable or an overhead line when extremely under-loaded, such as when operating at a near no-load.

Normally the interruption should take place at the first natural current zero. Modern high-speed interrupting devices, however, may interrupt too small a current than rated, such as noted above, prematurely, i.e. before a natural current zero. This may lead to steep fronted high TRVs, similar to those discussed earlier, capable of restriking an arc between the parting contacts, until at least the next current zero. In actual operation, this TRV is seen to rise to 2.5–3 p.u. The phenomenon is termed current chopping and is dealt with separately in Section 19.6. It is detrimental to a successful interruption of the switching device and may cause damage to the terminal equipment, such as the inter-connecting cables, induction motors and transformers etc.

17.7.5 Interrupting large inductive or capacitive currents

- Interrupting when the motor is in a locked rotor condition (Section 1.2) or is still accelerating and carrying a highly inductive current of the order of six to seven times the rated current at a p.f. of about 0.2–0.3.
- Interrupting an induction motor under a stalled condition which is almost a locked rotor condition.
- Tripping an inductive or capacitive circuit immediately after a switch ON as a result of a momentary fault or for any other reason and even during a fast bus transfer (temporary tripping and reswitching).
- Interrupting the equipment such as an induction motor, a transformer, a cable or an overhead line on a fault, such as on a short-circuit or a ground fault.
- Interrupting a charged capacitor.

In all the above cases, whether the load is inductive or capacitive, the voltage and the current phasors are more than 70° apart. At a current zero, the system voltage will reappear almost in full (around 95% or so) across the parting contacts of the interrupting device (Figure 17.11(c)). This voltage is detrimental to the successful interruption of the circuit at the current zero, unlike in the previous case.

Circuit interruption is a transient condition, as it constitutes abrupt changes in the circuit parameters L and C, which also alter the characteristics of the transient wave and its behaviour. The characteristics of a transient wave depends upon the circuit's surge impedance, Z_s, which, in turn, depends upon the circuit parameters L and C:

$$\left(Z_s = \sqrt{\frac{L}{C}} \right)$$

Therefore, if the arc does not extinguish at the first current zero, it will give rise to voltage surges (TRVs) at very high surge frequencies

$\left(f_s = \frac{1}{2\pi\sqrt{LC}}\right)$

of the order of 5–100 kHz or more.

The generation of voltage surges is almost the same as discussed when the circuit was being closed (Section 17.7.2(ii)). The sequence of generation of the voltage surges can be analysed for more clarity as follows.

The magnitude of surge voltages will depend upon the instant at which interruption of the switching device will take place, on the voltage and the current waves. Refer to Figure 17.11, illustrating the relative displacement of the voltage and the current waveforms at low p.fs. of, say, 0 and 0.3, which may occur during such interrupting conditions as noted above. This is when the load was inductive. Had the load been capacitive, the voltage and current phasors would have again been almost 90° apart, the current leading the voltage by nearly 90°, and same interrupting conditions would arise as in the case of an inductive load.

Under such switching conditions the voltage and current waves would be out of phase by almost 70° or more, and at every current zero the recovery voltage would be almost at its peak (95% or so), which would reappear across the interrupting contacts, re-ignite the arc plasma and cause a reflected wave of similar magnitude. The situation is further aggravated by the motor's or the transformer's self-induced e.m.f. or the capacitor's own charge, which may also fall phase apart with the recovery voltage and add up to the same. The cumulative effect of all such voltages may cause a significant rise in the TRV, which may become steep fronted and assume almost a similar magnitude as we analysed in the case of a 'switching on' sequence, i.e. up to 3–5 p.u., at surge frequencies, with a front time of even less than 1 μs (Section 17.7.2(ii)). The phenomenon is quite complex. Theoretically only an approximate analysis can be carried out, as we have done in the case of a switching ON. Use of oscillograms, as illustrated in Figure 17.5, may be an accurate means of measuring the exact magnitude and shape, i.e. steepness and front time of the TRVs, to determine the r.r.r.v of such high-frequency TRVs. The consequences of such steep fronted TRVs on circuit interruption may pose the following problems in successful interruption:

1 The magnitude of surge voltage will depend on the instant at which interruption of the switching device shall take place, as illustrated in Figure 17.11. A TRV of 3–5 p.u., for a normal interrupting device, may be large enough to prevent the arc from being extinguished at the next current zero. It may be capable of breaking the dielectric strength of the interrupting contacts and re-establishing an arc after a current zero, until the next natural current zero at least. In the subsequent half cycle, after the first current zero and until the next current zero, the arc will repeatedly restrike at a very high transient frequency of the order of 5–100 kHz or more, depending upon the circuit constants L and C. For a 12 kHz surge frequency, for instance, the arc will restrike for at least 120 cycles of f_s or 240 times, as determined below, before the next current zero:

   Time for half cycle of a 50 Hz normal system

   $$= \frac{1}{2} \times \frac{1}{50} \text{ or } \frac{1}{100} \text{ seconds}$$

   In this time the surge frequency will undergo

   $$12 \times 10^3 \times \frac{1}{100} \text{ or } 120 \text{ cycles}$$

   The repeated restrikes of the arc for about 240 times will result in steep fronted, extremely severe TRVs, sometimes even more severe than a lightning surge. They are capable of inflicting serious damage to the inter-connecting cables and the end turns of the connected equipment, be it a motor or a transformer, besides damage to the interrupting device itself and its interrupting contacts. The generation of surge voltages beyond 5 p.u. is, however, seldom noticed due to self-attenuation. The circuit parameters themselves provide the required damping effect.

2 In the above one-half of a cycle of the natural frequency, the moving contact would separate by 1/100 s. In fast-operating interrupting devices, this time is normally adequate to achieve a sufficient contact gap and to restore adequate dielectric strength to interrupt the circuit by the next current zero and allow no further restrikes of the arc. Otherwise the arc may be reestablished and the process may continue until the TRV itself attenuates or the contact moves farther away, to extinguish the arc naturally as a result of a larger contact gap. The fast-operating interrupting devices such as an SF_6 or a VCB may interrupt the circuit at the first current zero and the worst, by the next current zero whereas other interrupting devices may take a half to one and a half cycles of normal frequency to interrupt the circuit and extinguish the arc. This is long enough to cause severe damage to all the connected equipment and components unless adequate measures are taken to protect them by providing surge suppressors or surge capacitors or both.

3 The same theory will apply in capacitor switching except that the interrupting current will now be leading the voltage by almost 90° instead of lagging. See also Section 23.5 to determine the amount of surge voltages and inrush currents.

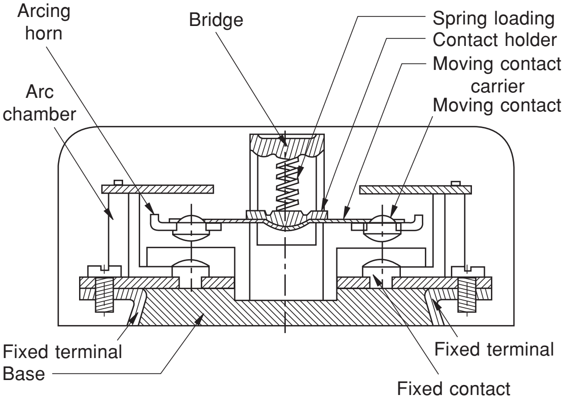
17.7.6 Switching surges on an LV system

These do not occur on an LV system due to inadequate switching voltage. An LV system is therefore not affected during a switching operation like an HV system. In a capacitor bank or an induction motor, at most there can be an over-voltage, up to twice the rated voltage across the terminal equipment, when a switch is closed on a circuit that is already charged, and the impressed voltage falls phase apart with the induced e.m.f. The following is a brief analysis to corroborate this statement:

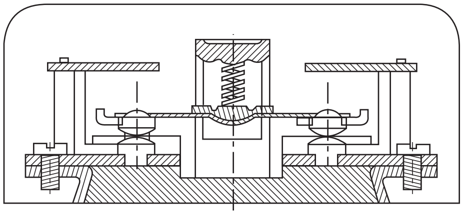
- The BIL of the LV system and the equipment connected on it are suitable for withstanding such over-voltages (Tables 11.4 and 14.2 or 14.3).

- As a result of a better insulation and insulating medium of an LV interrupting device, compared to its voltage rating, there are no restrikes of the contact gap after a current zero. The TRV is insufficient to establish an arc.
- However, abnormal transient voltages are sometimes noticed on the LV side of a transformer as a result of transference from the HV side or due to contact bouncing, which are not necessarily switching surges. Although the line side impedance would greatly dampen such transferred surges and in all probability may not be a cause for concern, it is advisable to protect large LV motors which are installed next to such a source, like a transformer which may experience a transferred surge and which may be enough to cause a damage. For more details on transferred surges refer to Section 18.5.2.

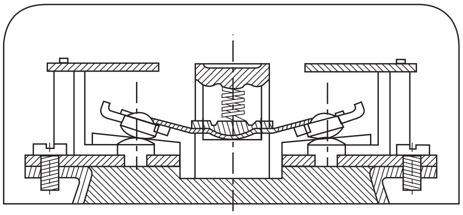
It is also possible that the trapped charge of the transformer during a fault in the down stream is released to the terminal equipment being switched at that instant and damage the equipment as discussed in Section 6.13.2 and illustrated in Figure 6.35.



1. Contacts in open position



2. Contacts just making



3. Contacts fully made and under spring pressure (before bouncing back)

Figure 17.13(a) The phenomenon of contact bouncing

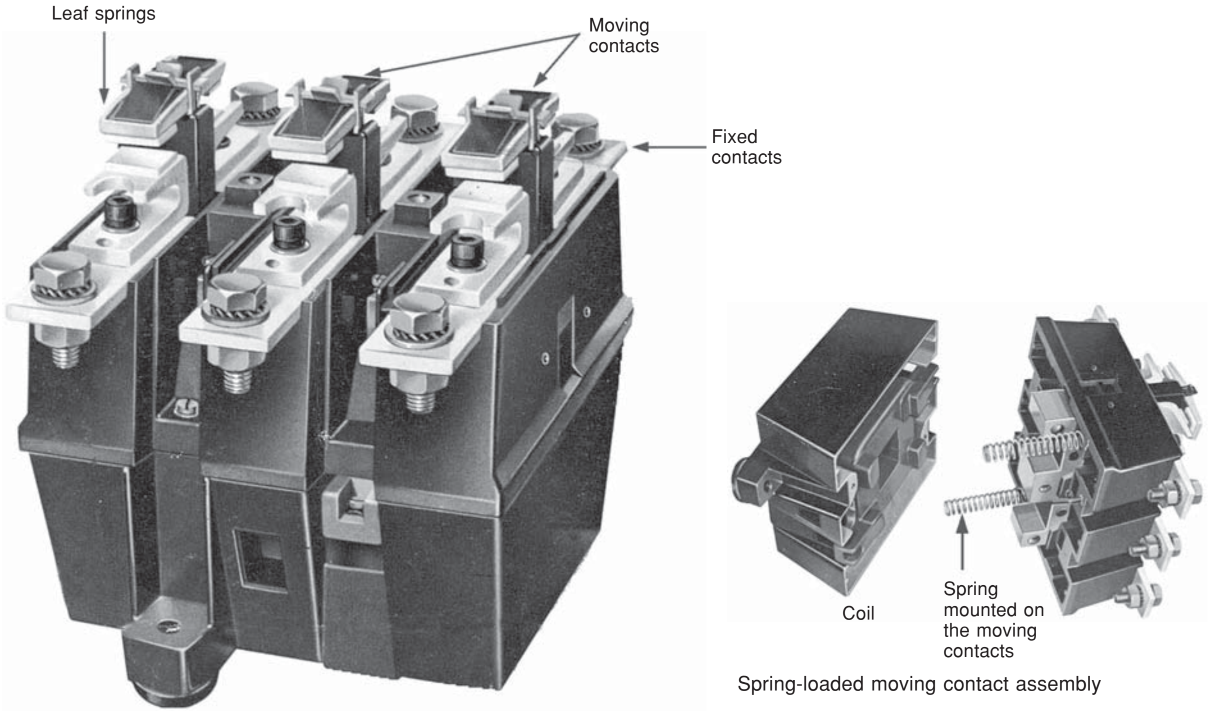
17.7.7 Voltage surges caused by contact bouncing

This occurs in a contactor during its closing operation, and may result in pitting and burning of contacts. It may also give rise to high-voltage transients (not necessarily switching transients), similar to the phenomenon of a current chopping (Section 19.6). The moving contacts, while moving, acquire a certain amount of velocity and momentum, and release this, in the form of kinetic energy, to the fixed contacts as soon as they make contact with them. The contact mechanism, being flexible and spring loaded (Figures 17.13(a) and (b)), has a tendency to bounce back. After being bounced, the contacts attempt to close again. The situation is a near replica of an open transient condition discussed in Section 4.2.2(a) and so are its consequences. During bouncing, however, the circuit is never broken, as arcing persists between the contacts. The contacts may bounce again, and the process may repeat, depending upon the design of the closing mechanism, until the process attenuates and the contacts finally close. Figure 17.13(a) illustrates such a phenomenon. This is not a desirable feature, yet it is not totally avoidable, due to design limitations. But extremely low-bounce closing mechanisms have been developed by the leading manufacturers to ensure an almost bounce-free closing of the contacts. These mechanisms have a closing time as low as 0.5 ms or one fortieth of a cycle of a 50 Hz system by adopting a near-balanced closing action through a low-inertia magnetic coil, leaf spring cushioning effect of moving contacts and contact spring, etc. Closing time is the time between initiation of the closing operation and the instant when the contacts touch.

When switching an induction motor, there may therefore also be a transient current for a few milliseconds in addition to the starting current. The magnitude of surges will depend upon the instant at which the contacts will make on the voltage wave. It may be up to fifteen to twenty times the rated current, or two or three times the starting current (see Figure 4.5). Thus, a contactor, on bouncing, will enhance its voltage amplitude as discussed in Section 17.7.2(ii) and will continue to do so until the process attenuates. The contacts may even weld together in such circumstances. The situation becomes even more difficult when the load is inductive or capacitive, which it is in most cases. The contact interruption, although it poses similar problems to those discussed in Section 17.7.2(iii), is less severe in this case than contact making, as there is now no contact bouncing.

To tackle the problem of arc quenching, large LV contactors, say, 100 A and above, and all HV contactors are provided with an arc chamber with splitter plates, (see Figures 19.11 and 19.12).

It is for this reason that a contactor is classified by the duty it has to perform, according to IEC 60947-4-1, as noted in Table 12.5.



Spring-loaded moving contact assembly

Figure 17.13(b) A typical view of a contactor showing arrangement of fixed and moving contacts (Courtesy: L&T)

17.7.8 Voltage surges caused by static devices

Yet another source of LV voltage surges is the switching of static devices as discussed in Section 6.13.

17.8 Effect of steep fronted TRVs on the terminal equipment (motor as the basis)

A healthy contact making or interruption, not associated with any restrike voltage transients, can be assumed as carrying only the nominal switching surges, as defined by a 250/2500 μs impulse, with a front time of 10 μs and above (Section 17.3.1, Figure 17.2(b)). This will usually cause no harm to the terminal equipment. But a switching sequence, involving a restrike of the arc, between the moving and the fixed contacts of the interrupting device, gives rise to steep fronted transient voltages of up to 3–5 p.u., as discussed earlier. The switching surges may exist on the system for not more than a half to one and a half cycles of the power frequency, and can have a front time t_1 as brief as 1 μs or less. In extreme cases, it can even reach a low of 0.2 μs (see Working Group 13.02 of Study Committee 13 (1981) and Slamecka (1983)) and become capable of causing severe damage to the terminal equipment. All such waves are termed front of waves (FOWs).

When such a surge penetrates electrical equipment such as an induction motor's winding, most of its stress may appear only across a small part of the windings (the line end coil or the first coil). The front of the surge will become less steep as it penetrates the windings, due to lumped capacitances C of the winding insulation and also because of partial reflections and damped refractions (Section 18.5.1) from the discontinuities of the windings as well as eddy currents (Section 1.6.2.A-iv) which will add to 'L'. The interturn voltage stress will thus be higher for the line end coil of the windings than the subsequent coils as shown by the following example.

Example 17.1

A simple switching surge of, say, 250/2500 μs (Sections 17.3.1 and 17.6.6 for velocity) would mean that in free space, considering the speed of propagation as 200 m/μs, it will propagate by

$$\frac{250}{10^6} \times \frac{200}{1000} \times 10^6 = 50 \text{ km}$$

by the time it reaches its first peak. Considering an average velocity of propagation in windings inside the slots and overhangs as 100 m/μs (typical), the surge in windings will travel 25 km, by the time it reaches its first peak. This distance is too large for the normal length of a motor or a transformer windings or the inter-connecting cables and/or the overhead lines etc. For all theoretical considerations, therefore, we can assume this switching surge to be uniformly distributed over the entire length of the current-carrying conductors and thus is only moderately stringent. It is possible that the surge may not even reach its first peak by the time it has travelled the entire length of the windings. The maximum transient stress per unit length of the conductor, V_t/l and also between the turns of the coils will be low (V_t being the amplitude of the prospective surge and ℓ the length of the winding per phase).

The circuit constants L and C through which the first peak of the switching surge will travel will determine the shape and severity (steepness) of the surge. As the wave travels forwards it will change these constants at every junction and the discontinuities of the windings. Consequently will change the shape of the wave front, which will be diminishing gradually in steepness until it loses all its severity.

If the switching is also associated with repeated restrikes of the contact gap of the switching device causing steep fronted voltage transients with a magnitude of 3.5 p.u. or so and a front time, t_1, as low as 0.2 μs (assumed), the above concept of transient voltage distribution over the length of windings will change abnormally. It would now travel only $0.2/10^6 \times 100 \times 10^6$, i.e. 20 m, by the time it reaches its first peak. This distance is too short and may involve just one coil or a few end turns of it, be it motor or a transformer windings, and very short lengths of the inter-connecting cables or the overhead lines etc. Such switching surges will be non-uniformly distributed, as the voltage stress of 3.5 p.u. will be distributed just over a length of 20 m. For a system voltage of 6.6 kV, the transient stress per unit length would be

$$= 3.5 \times \frac{\sqrt{2}}{\sqrt{3}} \times \frac{6.6 \times 1000}{20}$$

$$\simeq 943 \text{ V/m}$$

If we consider some length of the inter-connecting cables and deduct this from the total length of 20 m, the interturn stresses may assume much more dangerous proportions. The interturn insulation of the windings must be suitable to withstand even a higher impulse level than calculated above. As standard practice, the whole coil, if it is preformed, is tested for the prescribed impulse withstand level as in Table 11.6. It should be ensured that the actual steepness and amplitude of the FOW is well within the prescribed BIL.

The first few turns of the line end coil of a motor or transformer and short lengths of inter-connecting cables and overhead lines and their associated terminal equipment, will thus be subject to severe stresses and will be rendered vulnerable to damage by such steep fronted transient voltages.

Various experiments conducted by different agencies have revealed that the voltage stress across the first coil alone may be as high as 70–90% of the total transient voltage across a motor windings, having a front time, t_1 as low as 0.2 μs. (see Working Group 13.02 of Study Committee 13 (1981) and Slamecka (1983)).

Slamecka (1983) has produced curves, to illustrate the TRVs appearing across the entrance coil for different front times t_1, for different lengths of conductor of the first coil (Figure 17.14). From these curves, one can draw an inference that the greater the length of the entrance coil of the machine, the higher will be the interturn stresses to which it will be subject and vice versa. As illustrated in Example 17.1, a transient voltage wave having a front time of 0.2 μs will propagate about 20 m in the windings and will affect only this length of the entrance coil. This is illustrated in Figure 17.14. As the TRV propagates ahead and penetrates deeper into the slots, it will have its amplitude damped and will subject the coils ahead to much less TRV. The curves in Figure 17.14 also suggest that if the length of the entrance coil is reduced, it will be subject to fewer stresses, as the remaining TRV will become distributed to the following coils. A slightly less steep surge, which is more probable, may travel through the length of the inter-connecting cables and yet envelop the whole windings. It has been observed that TRVs with a front time of 0.5 μs and more are fairly evenly distributed over the entire length of windings.

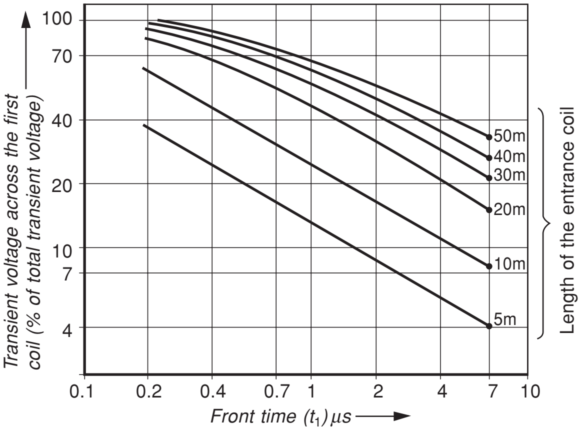


Figure 17.14 A transient voltage stress across the first (entrance) coil of an induction motor as a function of front time (t_1) and length of entrance coil 'ℓ' (from Slamecka, 1983)

Different installations with different lengths of inter-connecting cables, type of switching device, size and design parameters of a machine (particularly a rotating machine), will influence the steepness of surges and their distribution over the length of windings. Different studies at different locations have revealed the following information:

- If the surge is very steep, say, with a front time of 0.2 μs or less, and the cable length is short, say, 10 m (presumed), it may inflict all its severity to only the entrance coil of the machine and sometimes even only a few entrance turns of this coil. However, with the technological improvement of switching devices, the arc pre-strikes are now less predominant or non-existent and hence, the switching surge may not be as steep as described here.
- In all probability the steepness may be between 0.2 and 0.4 μs, in which case, depending upon the length of the inter-connecting cables and that of each motor coil, the maximum surge may appear across the last few turns of the entrance coil or the first few turns of the second coil, as a result of multiple reflections at the discontinuities and the joints. Multiple reflections may raise the amplitude of the incidence wave up to twice its initial value, as discussed later. Alternatively, if it be fairly evenly distributed throughout the whole winding, the last coil where it makes its star point or

a few last turns of this last coil may be subject to severe voltage surges due to multiple reflections at the star point.

Generally, it is the steepness of the surge that has a greater severity on inter-connecting cables and machine windings. The travelling waves and their partial reflections at the discontinuities of the windings influence the surge's amplitude and distribution over the length of the windings. The windings' length, shape, inductance L and leakage capacitance C and speed and size of the machine may be termed vital parameters that play a significant role in determining the prospective amplitude (V_t) of a voltage surge and its distribution over the length of the windings. Below, we briefly discuss such parameters to better understand the phenomenon of voltage surges and their influence on the terminal equipment and inter-connecting cables.

17.8.1 Surge impedance

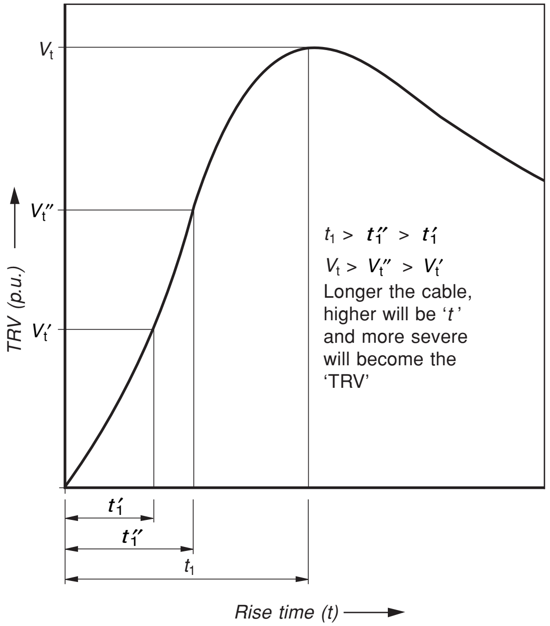
The value of L and C of a machine determine its surge impedance $Z_s = \sqrt{L/C}$ and surge frequency $f_s = 1/(2\pi\sqrt{LC})$. A low surge impedance will help to damp the prospective amplitude, V_t (= surge current × Z_s), of the surge voltage and hence the stress on the windings. A low surge frequency will help to limit the number of restrikes of the arc plasma and in turn the amplitude of the surge, V_t. A lower f_s will also reduce the steepness, V_t/t_1, of the surge. Hence, a low Z_s as well as a low f_s are always desirable. It is possible to modify the Z_s of a machine at the design stage to contain the prospective voltage, V_t, within safe limits if the type of interrupter, length of inter-connecting cables and the characteristics of the likely prospective surges are known.

Note

The length of the inter-connecting cables plays a vital role in containing or enhancing the severity of the incidence wave. After the interrupter, the surge enters the cable and propagates ahead. As it propagates, it rises in amplitude, at a rate of V_t/t_1 (Figure 17.15) until it reaches the far end of the cable. The longer the cable, the higher will become the amplitude of the incidence wave which will be more severe for the terminal equipment (refer to protective distances, Section 18.6.2). The length of the inter-connecting cable is therefore recommended to be as short as possible. The manufacturers of the interrupting device usually suggest a maximum safe length for different sizes of cables, depending upon the voltage of the system and the equipment it is feeding*.

The approximate values of the surge impedances of motors and transformers of various ratings and voltages may be obtained from their manufacturers and drawn in the form of a graph, as in Figure 17.7. With the help of these values, one can determine the likely surge voltage for different interrupting devices from the graphs of Figure 17.8.

To this value may be added about 1.5 p.u. of the system voltage (to approximately account for the equipment induced e.m.f. and the applied voltage (Section 19.6)) to determine the total peak voltage likely to arise on a no-load or during a fault interruption. This total peak voltage should be less than the impulse voltage withstand level of the equipment. For motors, it should be well within the impulse test values given in Table 11.6 (for resin rich formed coils). The effect of cable length is ignored, presuming that the cable length is short and does not contribute in enhancing the severity of the incidence wave.



Longer the cable, higher will be 't' and more severe will become the 'TRV'

Figure 17.15 Influence of cable length on the TRV

Example 17.2

Consider a 500 hp (≃ 350 kW) 6.6 kV motor. The surge impedance from Figure 17.7(b) $Z_s \simeq 4500\ \Omega$. This surge impedance may generate the following TRVs during an interruption by different interrupting devices, according to Figure 17.8:

OCB (MOCB or LOCB):

5 kV + 8.1 kV = 13.1 kV

$$\left(1\text{ p.u.} = \frac{\sqrt{2}}{\sqrt{3}} \times 6.6 = 5.4\text{ kV and } 1.5\text{ p.u.} = 8.1\text{ kV}\right)$$

SF_6 breaker: 7.5 kV + 8.1 kV = 15.6 kV

Vacuum breaker with copper–chromium contacts:

6 kV + 8.1 kV = 14.1 kV

Vacuum breaker with copper–bismuth contacts:

35 kV + 8.1 kV = 43.1 kV.

From the above it can be noted that the surge voltages that may develop during a switching operation, with all types of breakers except Cu–Bi VCBs, are within the prescribed impulse withstand voltage of 16.2 kV as in Table 11.6, column 2. In Cu–Bi VCB switching it may be as high as 43.1 kV, which is far beyond the prescribed impulse withstand level of 16.2 kV. Such breakers, as standard manufacturing practice, are fitted with metal oxide surge arresters. Otherwise a suitable surge arrester must be provided near the motor.

Note

The above example is just for illustration to have an idea of TRVs generated by circuit interruption in different mediums. With continuous improvisation in the arc quenching techniques, the new generation SF_6 interrupters are almost restrike free (Section 19.5.5).

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*In case of static drives also generating similar switching surges, their manufacturers provide the maximum safe cable lengths as a standard practice, Section 6.13.2.

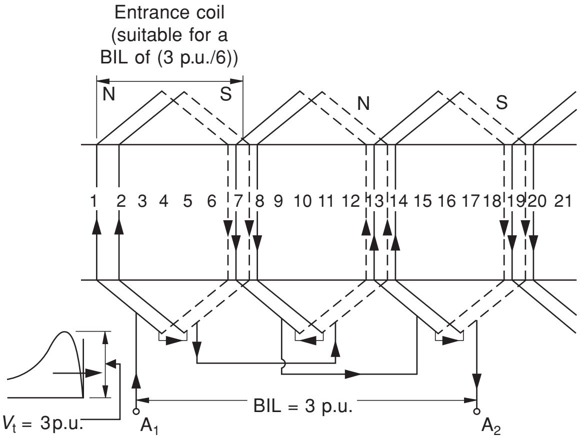
Similarly, with the use of better material for the making contacts in case of vacuum interrupters their high chopping tendency is also almost overcome by achieving a low chopping current (Section 19.5.6). The new generation vacuum interrupters therefore have low tendency of current chopping even at very low currents. In face of SF_6 and vacuum technologies, therefore, BOCBs, MOCBs and ABCBs are gradually waning out except for old installations. This too until they are also retrofitted with the new generation interrupters. Also 1–5 p.u. considered may arise under the worst conditions.

17.8.2 Number of turns per coil

This is another vital parameter of a machine, influencing the distribution of voltage surges over the windings. As noted earlier, protection of interturn insulation is very important, particularly when the machine has a multi-turn coil arrangement and where the turn insulation is likely to be overstressed by the incident waves. Single turn coils, having the same turn and coil insulation and coils deeper in the slots, are less influenced. A fast-rising voltage wave at the motor terminals will lift the potential of the terminal (entrance) turns, while turns deeper in the windings or the slots will be subjected to lesser severity due to discontinuities and partial reflections. They are, therefore, sluggish in responding to the arriving surges and are subject to attenuated severity of the surge and are less stressed than the entrance turns. To protect the line end coil or its first few turns, it is essential to keep the length of the coil as short as possible, as illustrated in Figure 17.14, to subject the whole coil to an equal interturn stress. Otherwise the severity of the surge may affect only the entrance coil or its few entrance turns.

Example 17.3

Consider a winding having six numbers of coils/phase as shown in Figure 17.16, and suitable for a surge voltage (BIL) of 3 p.u. (Table 11.6). If the surge travels only to the first coil, which is suitable for 3/6 or 0.5 p.u., then all the effect of the surge (3 p.u) will impinge across this coil alone and greatly overstress its interturn insulation. Thus, a 3 p.u. surge would stress the inter-turns by 3 p.u./0.5 p.u. or six times the voltage for which the insulation of the coil is designed or its inter-turns are made suitable for six times more than a uniformly distributed transient wave. Hence, the relevance of the length of the entrance coil in a steeply rising voltage wave.



Winding showing 6 slots or 6 coils per phase and one turn per coil
If, there be *n* number of turns per coil,
then voltage across each turn = $\frac{V_t}{6n}$.

Figure 17.16 One-phase winding, illustrating Influence of the arriving surge on the entrance coil

Consequently an FOW, whose amplitude, V_t, is well below the insulation level (BIL) of the machine, may adversely affect the interturn insulation of the first coil. Even if the winding is capable of withstanding such transients, their repeated occurrence may gradually degrade its insulating strength to a point of a possible failure over a period of time. A steep-fronted wave may damage the insulation in the form of microscopic holes called ‘pinhole’ failures. While a single pinhole may be of little relevance, a number of them may cause hot spots, leading to eventual failure of the insulation (see also Section 9.6).

17.8.3 Rating of a rotating machine

It has been seen that smaller rating MV machines are more susceptible to steeply rising voltage surges, compared to larger ratings, due to their relatively weaker interturn insulation and require more careful attention to their adequate protection. We attempt to explain this phenomenon as follows:

1 In smaller ratings although the ratio of copper to insulation of the windings in the slot is low (the content of insulation high), the turn insulation is low, roughly in the same proportion. This is because of the higher number of turns per coil which diminish the dielectric quantity, hence the endurance of the turn insulation, as witnessed during tests. The higher number of turns also pose a problem in forming the coils, particularly at bends, as it is difficult to maintain the same quality of insulation. Table 17.1 (see Pretorius and Eriksson, 1982) suggests typical ratios for different voltage systems in three smaller frame sizes used for an MV motor.
2 Lower ratings have low *L* and *C* and therefore have a higher Z_s (Figures 17.7 (a), (b) and (c)) and do not help in damping or taming the surges.
3 Similarly, high-speed machines too have more coils per slot, subjecting the interturn insulation to higher stresses.
4 The length of the entrance coil is another important parameter, which may be subject to most of the voltage stress up to 70–90%, as noted earlier, for very fast rising ($t_1 \leq 0.2\ \mu$s) TRVs. So are the last few turns of the entrance coil, or the first few turns of the second

Table 17.1 Typical ratios of copper to turns insulation per coil in smaller frame sizes

Frame size (Table 1.2)	*Ratio of copper to insulation*		*Turns per coil*		*Turn insulation to voltage surges*
	6.6 kV	11 kV	6.6 kV	11 kV	
400	1.5	0.8	12	20	Highly vulnerable
500	2.0	1.2	9	15	Moderately
630	2.2	1.3	6	10	vulnerable

Note
For our discussion, the frame size 400 alone is more critical. Frame sizes 500 and 630 are only indicative to illustrate the comparison.

coil, for fast-rising surges ($t_1 \simeq 0.2 - 0.4\ \mu$s). Or the last few turns of the last coil making the star point of the windings, when the TRV is almost uniformly distributed (t_1 approaching 0.4 μs). The steepnesses are only indicative to illustrate the severities of surges and their influence on the turn insulation. For a particular size and design of motor, the steepness and its influence may vary somewhat.

Other than the above, the inter-connecting cable length between the switching device and the machine also plays an important role in the distribution of the fast-rising voltage surges as discussed earlier. It is the cable that will bear the initial severity of the rising surge, before the surge reaches the motor terminals. Hence, upon the rise time, t_1, will depend the safe maximum length of the inter-connecting cables to provide the maximum damping effect. For very fast-rising waves, in the range of 0.2–0.4 μs or so, cable lengths in the range of 30–300 m are seen to provide the maximum damping effect. Actual simulation tests or studies of similar installations are, however, advisable, for a more accurate assessment.

For a less steep surge, the situation will be different. Now, the longer the cable, the higher will be the amplitude that the surge will attain by the time it reaches the motor terminals. For example, for a surge with a rise time, t_1 of 1 μs, the cable must be at least 100 m or more in length (considering the speed of propagation as 100 m/μs), and sometimes it may not be practical to provide this. The steepness of surge is thus a very vital parameter in deciding an ideal cable length to achieve the desired damping effect through cables. A slightly shorter length than this may subject the terminal equipment to a near peak amplitude of the arriving surge. It is therefore advisable to keep the length of the inter-connecting cables as short as possible, to subject the terminal equipment to only a moderate amplitude of the arriving surge, much below its prospective peak. (For more information on the subject refer to Section 18.6.2 on protective distances of surge arresters.)

17.8.4 The need to protect a rotating machine from switching surges, contact bouncing and surge transferences

Switching surges have been seen to be the severest of all. But it has been a greatly debated subject whether a protection is overemphasized against switching surges, particularly when the occurrences of such high TRVs may be rare yet are significant to cause concern. Opinions may differ. Technological improvements and application of the latest techniques in the extinction of arc plasma, making use of high-speed interrupting devices, using SF_6 or vacuum as the insulating and the quenching medium, meticulous design of the arc chamber, design and material of the making contacts have achieved an interruption almost devoid of restrikes. In addition to adapting to the latest insulating practices for motor insulation (Section 9.3) such as vacuum impregnation and additional bondage and bracing of the windings' end turns. All these have diminished to a great extent if not totally eliminated the effect of these surges on machines. Nevertheless, to take account of the possibility of these surges causing damage to the terminal equipment, generally 3.3 kV and above, it is advisable that protection be provided as a preventive measure to protect the costly machines and, more importantly, the risk of a shutdown of a plant in the event of a possible failure of the machine. More so when a rotating machine has a low level of insulation (low BIL) compared to an oil-filled transformer.

Dry type equipment, such as rotating machines, have lower impulse withstand levels compared to a liquid type machine, such as a transformer or a switchgear assembly. A comparison of impulse voltage withstand levels for the same system voltage for motors (Table 11.6) and for switchgear assemblies (Tables 13.2 or 14.1) will reinforce this point. A motor is always vulnerable to both internal and external voltage surges. Circuit switching is the most onerous of all and can overstress the windings of a machine if it is not protected adequately, leading to an eventual breakdown, if not an immediate failure.

During an interruption, an SF_6 interrupting device is found to be normally devoid of a switching surge, as there is no chopping of current. During a closing sequence, however, in both a VCB and an SF_6 breaker, the switching surges are almost within the same range, say, 1.5 to 2.5 p.u., as recorded during a simulation test on a 400 kW, 6.6 kV motor (see Central Board of Irrigation and Power, 1995).

Misconception

1 It is a misconception that only large high-voltage motors need be provided with surge protection, in preference to small machines, because they are more likely to encounter dangerous surges. Analysis of various motor circuits, as noted earlier, indicates that smaller and higher-speed motors are more vulnerable to the effects of voltage surges rather than the larger or lower-speed motors due to one or more of the following reasons:

- The lower ratings of rotating machines, having full load current of around 60 A and less, i.e. 600 kW or less for a 6.6 kV system and 300 kW or less for a 3.3 kV system, are generally prone to cause dangerous steep fronted TRVs when being interrupted on no-load by a VCB or a vacuum contactor, as a result of possible current chopping. For a full load current of 60 A, the no-load current would be approximately 50%, i.e. 30 A or even less (Section 1.7). It is therefore possible that current chopping may take place just before a natural current zero at around 10% of it, i.e. 3 A or so. Refer to Figure 17.17. The latest vacuum interrupters with Cu–Cr alloy contacts (Section 19.5.6) may not allow the current to reach its natural zero for a normal interruption and may chop it somewhere near 3–5 A and cause TRVs. Moreover, the lowest rating of the interrupting device itself may be large enough for this current to be interrupted at current zero and cause current chopping.

Note
For development in AgW and CuW contact materials to reduce the chopping current in VCBs see Section 19.5.6.

2 Transient voltage damage usually appears in some

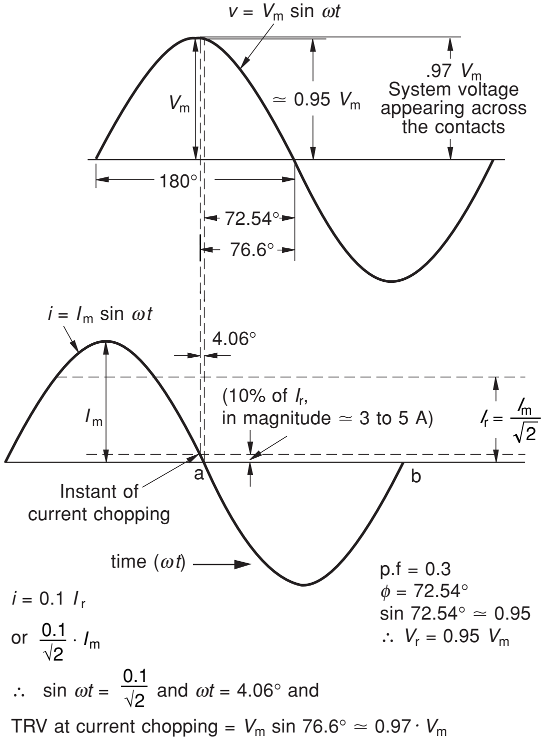


Figure 17.17 Current chopping, say, at 10% of an inductive current of 0.3 p.f. giving rise to almost a full system voltage

other form of dielectric failure such as caused by thermal over-loading, under-voltage and stalling etc., totally masking the original cause, which could be due to switching. Field research and statistical study of failures have revealed that almost 35% of total dielectric failures in power stations have been caused by surges, rather than any other reason (Central Board of Irrigation and Power, 1995). Surge protection for a smaller motor, say, up to 300 kW in a 3.3 kV and 600 kW in a 6.6 kV system is thus advisable. Manufacturers of the rotating machines, being the best judges, to suggest the most appropriate protection required for their machines, depending upon the surge impedance of the machine and the likely voltage surges that may develop using different types of switching devices.

Dielectric envelope

This is a curve that defines the limits of surge voltages and the corresponding front times that a machine will be able to sustain without a failure during a switching operation or a lightning strike. Such a curve must be available for all machines and is provided by their manufacturers. Figure 17.18 shows a dielectric envelope for a 6.6 kV motor as recommended by IEEE, also considering motor ageing. The figure also shows a curve provided by Electra (1981; see also Gibbs et al., 1989). This curve is based on the data obtained on new machines from a few motor manufacturers.

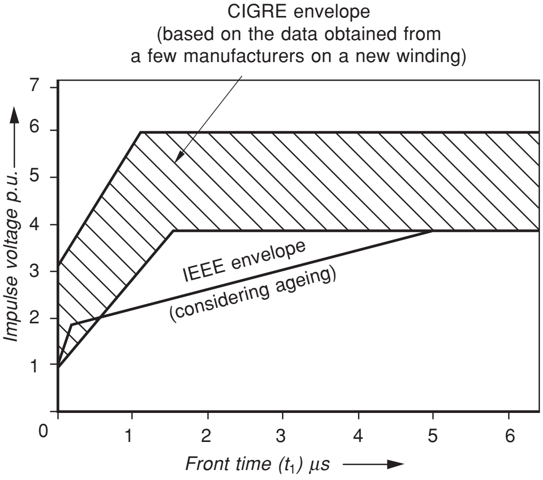


Figure 17.18 Dielectric envelopes for a 6.6 kV motor

Surge protection

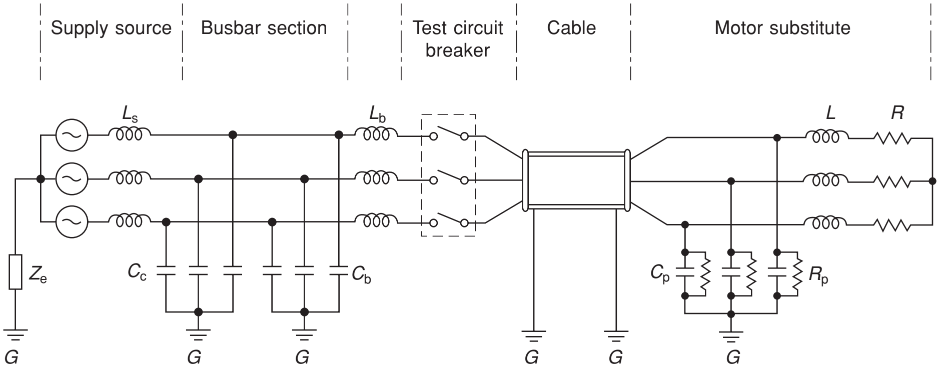
Protection for the machine should be such that the voltage surges and their rise times, whenever they occur in the system, shall fall within this envelope of the machine. (Refer to Section 17.10 for a total surge protection.)

17.9 Determining the severity of a transient

17.9.1 Simulated test circuit

From the above it is essential to predetermine the nature, magnitude and steepness of such transients to decide the most appropriate protection or preventive measures for an MV motor, particularly, for critical installations, such as a power station or a process plant, to avoid the least risk. In our discussion so far, the circuit conditions, as assumed and the analysis of the voltage surges as generated, were purely statistical and varied from machine to machine and from one installation to another. The purpose so far has been to provide a general analysis of surge voltage phenomenon, its consequences on the machine and possible remedies and/or protection. For absolute motor protection, accurate transient conditions must be known. To determine the transient conditions accurately, a working committee of the IEEE-Cigre has suggested a simulated test circuit (Electra, 1981; Gibbs *et al*., 1989) for all manufacturers of interrupting devices (1) to determine the behaviour of their devices, with predetermined circuit parameters, almost representing a normal supply side of the machine; (2) to assess the behaviour of the machine during a switching operation and subsequent restrikes, if any, as a guideline for the user; and (3) to decide on the more appropriate switching device for the machine and its surge protection, based on the dielectric capability of the machine (Figure 17.18). The test circuit is illustrated in Figure 17.19 simulating:

- On the supply side of the interrupter, an equivalent



Typical parameters as recommended by CIGRE

Z_e = Grounding impedance = 5 Ω
L_s = Source inductance = 4 mH
C_c = Compensation capacitance = 0.0 or 7.0 μF
C_b = Busbar capacitance = 40 nF
L_b = Busbar inductance = 25 μH
L = Load inductance
R = Load resistance
C_p = Load parallel capacitance
R_p = Load parallel resistance
Unipolar breaker Z_0 = 40 Ω
Cable = 100 m screened, 3 × 95 mm^2 Al armoured and grounded at both ends.

Figure 17.19 A simulated test circuit

busbar, inductance and lumped capacitance with a provision to connect p.f. correction capacitors, if required, to represent a replica of the actual installation.

- On the load side, the interrupter is connected through a cable to the equivalent circuit, with the required quantities of lumped resistance and reactance, to represent the motor to be tested, under a locked rotor condition. The circuit would also represent an interruption immediately after a start, to check for the most onerous operating condition for the interrupter to generate the highest surges as discussed earlier.

Test results

The test circuit may be connected to the test voltage and then switched to obtain the required oscillograms during switching operations and assess the following:

- Any restrikes and their number
- Amplitude of voltage surge (V_t) generated and
- Its rise time (t_1).

With these data, one can determine the dielectric curve the machine must have when switched with such an interrupting device. This can be compared with the actual dielectric curve of the machine (Figure 17.18) obtained from its manufacturer to decide the compatibility of the interrupting device for the machine or vice versa and the extent of surge protection, if necessary. For more details and results of similar simulation tests, see Central Board of Irrigation and Power (1995).

17.10 Protection of rotating machines from switching surges

For adequate protection of the machine it is essential to know the amplitude, V_t, and the rise time, t_1 of the severest voltage surge (FOW) that may occur on the system. It is recommended that the actual field tests be conducted for large installations according to the recommended simulation test circuits, noted above, to ascertain these surges.

The tests may be conducted on a few ratings with different sizes and lengths of cables to simulate the near actual condition of the installation. One should be more conservative than liberal on cable lengths to obtain safe results. The most appropriate impulse level must be chosen, such as 3.5 p.u. for a rise time of 0.2 μs, for the machines to suit the system conditions, according to Table 11.6 for rotating machines, or Tables 13.2 and 14.1 for switchgear assemblies, Tables 32.1(a) and 32.2 for bus systems and Tables 13.2 and 13.3 for all other equipment and power systems. It should be noted that steeply rising surges that fall within the range of machine windings and inter-connecting cables alone are of relevance and not those that are faster or slower. The steepness of the surge will determine its propagation through the windings and its effects on the coils or the inter-turns, such as whether the first coil, second coil or the last coil or the first few or the last few turns require protection as discussed earlier. Since the actual installation may differ from that considered in analytical studies, it is possible that the results obtained may differ slightly from those analysed. It is therefore advisable to be more conservative in selecting the amplitude and rise time of the prospective surges. While the machine may be selected with a standard impulse level, and if the probable amplitude and/or the rise time are expected to be more stringent, separate protection must be provided, as discussed later. The general practice has been to insulate all the coils equally, according to the standard impulse level of the machine. The following are preventive measures that can mitigate the effects of such surges:

1 By improving the p.f. of the interrupting circuit: This is to achieve quicker extinction of the arc, i.e.

interrupting the circuit at the first natural current zero, as far as possible, and averting any restrikes. It may be noted that at every current zero the arc due to contact separation extinguishes and there is no conducting path between the contacts until a restrike takes place. The p.f. of the interrupting circuit can be improved in the following ways:

- Modern interrupting devices have an amount of resistive interruption as a result of appropriate design and choosing the right material for making contacts (see Section 19.2), which helps to moderate the highly inductive interrupting current. Some manufacturers even provide a resistance shunt across the parting contacts in large rating interrupters, which forms part of the circuit during interruption only, similar to the theory of a surge arrester (Section 18.1).
- By installing p.f. improvement capacitors to compensate the no-load magnetizing current of the circuit being switched (Section 23.13). The capacitors may be installed in the same switching circuit to be switched with the inductive load.

2 In capacitor switching, introduction of an inductor coil (Section 23.11) can contain not only the inrush current but also tame the current phasor to shift closer to the voltage and thus limit the TRV on an interruption.

3 By selecting the rating of the interrupting device as close to the full-load current of the system or machine as possible. An excessive rating than necessary may have tendency towards current chopping.

4 More care needs to be taken when there are a number of such motors connected on the same bus and switched in tandem, tending to multiply the switching effects (Figure 17.20).

Since the standard insulation level (BIL) of a machine or a system is already defined, according to Tables 11.6, 14.1, 32.1(a), 13.2 and 13.3, the machines are accordingly designed for this basic insulation (BIL) only. When the prospective surges are expected to be more severe than this, separate protection becomes imperative. This is particularly important for a rotating machine which, besides being a dry equipment, also has only a limited space within the stator slots and hence has the smallest BIL of all, as is evident from Table 11.6, compared to Tables 14.1, 32.1(a) and 13.2. The following aspects therefore must be kept in mind while attempting to protect a rotating machine

- The surge protective device (SPD) must be suitable for absorbing energy of the long duration (250/2500 μs) switching surge at the commencement of arc interruption.
- The SPD must offer a low residual voltage (V_{res}) to protect the machine adequately from over-voltages.
- The SPD must have capability to sustain FOWs should they arise during switching operations. That means they should also be able to see the high frequency surges rather than high amplitude surges only.

For its comprehensive protection the above can be considered in two parts.

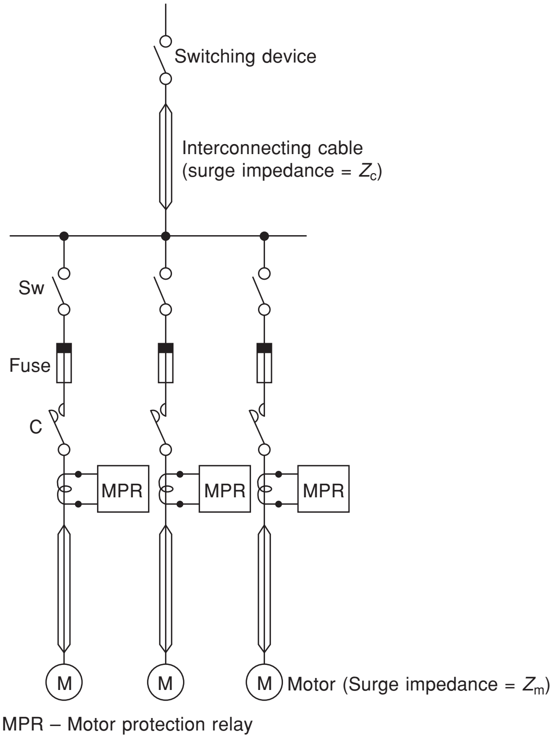


Figure 17.20 A number of motors connected in tandem on a common bus

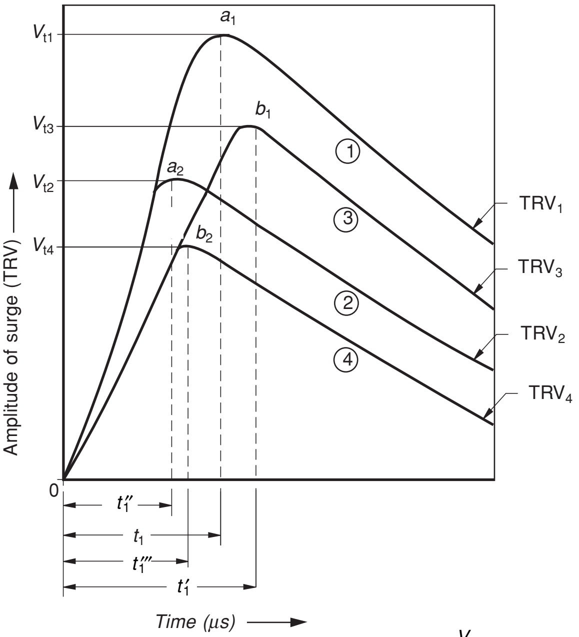
17.10.1 Major insulation area

This is the winding insulation to the body, which is more vulnerable to prospective voltage peaks, V_t, as a result of TRVs. When the TRV exceeds the BIL of the machine, it can be damped to a safe limit with the use of a surge arrester, say, from peak a_1 to a_2, as illustrated in Figure 17.21. Details of a surge arrester and the procedure for its selection are discussed below. See also Example 17.6. The selection of the arrester will also depend upon the method of star (neutral) formation of the stator's star-connected windings. If it is solidly grounded, the reflections will be less severe, as the incident surge will be discharged through the ground and cause less reflections. But when the star point is left isolated, it may cause severe voltage stresses to the end turns of the coil due to repeated reflections. The procedure to select a surge arrester takes account of this.

17.10.2 Minor insulation area

This means the insulation turn to turn ($e_{t1} = V_t/n$, n being no. of turns, Figure 17.22), which is more vulnerable to the steepness of a surge (V_t/t_1). If e_{t2} is the design insulation level of the winding turn to turn then, for a safe condition, $e_{t2} > e_{t1}$. If the design voltage falls short of the arriving surge, surge protection must be provided.

A surge arrester is not able to reduce the steepness (r.r.r.v.) of the arriving surge. While motors with single-turn coils may be safe as turn to turn insulation becomes



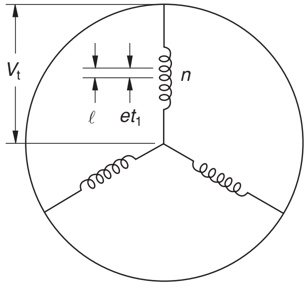
Curve–0a$_1$ – Original steep fronted TRV$_1$, r.r.r.v. = $\frac{V_{t1}}{t_1}$

Curve–0a$_2$ – Damped TRV$_2$ with the use of a surge arrester alone, r.r.r.v. may still be higher than recommended for a particular winding, r.r.r.v. = $\frac{V_{t2}}{t_1''}$

Curve–0b$_1$ – Tamed and damped TRV$_3$ with the use of a surge capacitor alone r.r.r.v. $\simeq \frac{V_{t3}}{t_1'}$

Curve–0b$_2$ – Tamed and damped TRV$_4$ with the use of a surge capacitor and a surge arrester in parallel, r.r.r.v. = $\frac{V_{t4}}{t_1'''}$. It should be less than the impulse withstand level of the equipment.

Figure 17.21 Taming and damping of a steep-fronted TRV with the use of a surge capacitor in association with a surge arrester



Required condition : $et_1 < et_2$

where, et_1 = Actual turn to turn voltage that may develop across the machine winding

et_2 = Design voltage of the winding turn to turn.

= V_t/n, where V_t is the permissible or design impulse voltage

n = Number of turns

ℓ = Length of winding per turn

Figure 17.22 Turn-to-turn insulation

the same as the major insulation with respect to the body, motors with more turns per coil may not remain safe. In such cases the steepness of the arriving surge must be reduced to a safe level. Very fast-rising waves can be tamed (r.r.r.v. controlled) with the use of surge capacitors or surge suppressors. Surge capacitors possess a good energy absorption capacity and can reduce the amplitude and the steepness or diminish the r.r.r.v. of a fast-rising wave (FOW) to a safe level, less than the turn-to-turn impulse withstand level of the coil, i.e. less than the steepness of a lightning surge ($t_1 > 1.2\ \mu$s). Normal practice is to tame it to 10 μs or so such as from a_1 to b_1 or a_2 to b_2, as illustrated in Figure 17.21, so that the surge is uniformly distributed over the entire windings and a normal surge arrester (when the amplitude is also higher than prescribed) in association with a surge capacitor, can protect it safely. Surge capacitors in the range of 0.1–0.25 μF (generally 0.25 μF) are ideal for neutral grounded machines and twice this level for the neutral isolated machines. The multiple reflections at the star point may almost double the voltage at the star point (neutral). They are connected between each motor terminal and ground or on the switching device within the interrupter housing. The size of surge capacitors can also be determined for specific applications if one knows the rate of rise (V_t/t_1) of the FOW and the level to which it is to be damped (V_{t1}/t_1') (Figure 17.21).

17.10.3 Application of surge protective devices (SPDs)

Surge arresters

A conventional gapped distribution class arrester will not offer adequate energy absorption capability, particularly for the long duration switching surges. The residual voltage (V_{res}) of such arresters is also usually high for the chosen arrester rated voltage (V_r) and may not offer adequate protection to the machine. For this purpose therefore either a station class surge arrester or a relatively new gap-less distribution class surge arrester, also known as metal oxide varistor (MOV) possessing high energy absorbtion capability (J) may be used for motor duty, subject to matching its V_{res} with the BIL of the motor. Data of a particular brand of these arresters is shown in Table 18.8(a) for a general reference. These arresters too are able to see only the amplitude and not the steepness of the surge. A surge capacitor in association with the MOV can overcome this drawback.

Surge capacitors

A surge capacitor offers a near-open circuit during normal operation (at or near the power frequencies) and a near short-circuit to the arriving surges at surge frequencies, f_s. While the inductance of the motor windings ($\propto f_s$) rises rapidly and offers a near-open circuit to the arriving surge. It thus attracts an arriving surge and reduces its steepness as well as amplitude due to high 'C' in the circuit parameters, which also reduces f_s and Z_s, as discussed earlier. The frequency of a surge can be determined by

$$f_s \simeq \frac{10^3}{4t_1} \text{ kHz } (t_1 \text{ is in } \mu\text{s}) \qquad (17.7)$$

The first peak being more relevant, we have therefore considered its rise time to determine the virtual frequency of the surge. This frequency, for a long-duration switching surge (high t_1), can be quite low for the surge capacitor to acquire enough reactance

$$\left(X_\mathrm{C} = \frac{1}{2\pi f_\mathrm{s} \cdot C_\mathrm{s}} \right)$$

such that the surge arrester alone may have to sustain the bulk of the surge. The surge capacitor providing only little support. The basic use of surge capacitors is to absorb only the FOWs and reduce their steepness and magnitude to make them safe for the turn insulation of the machine. At the commencement of switching operation it is a long duration surge of a moderate high frequency and the surge capacitor may not be conducting (or only partially conducting) and may not appreciably contribute in damping its (surge's) magnitude. Capacitor is fully conducting only after subsequent restrikes of the arc plasma when the surge frequency (f_s) assumes a high magnitude and the capacitor a low reactance and that is its basic purpose also. For all practical purposes, therefore, the arrester alone has to be suitable for handling such surges at the commencement of arc interruption, irrespective of whether it is supplemented by a surge capacitor or not. See also Example 17.5.

Arresters for such applications are therefore designed especially with low V_res at steep surges and a high energy absorption capability. Only a station class surge arrester or an MOV is usually preferred for such applications, and where steep fronted surges are envisaged, these arresters too may be supplemented with a surge capacitor. Table 18.8 provides data for motor protection station class surge arresters and Table 18.8(a) for MOVs. Since a surge arrester is normally an engineered item to suit a particular application, these data are only for general reference. For exact application and type of installation, it is always advisable to consult the manufacturer.

Example 17.4

Consider a surge capacitor of 0.25 μF. Then

$$Z_\mathrm{c} = \frac{1}{2\pi \cdot f \cdot C_\mathrm{s}}$$

where

Z_c = capacitor impedance in Ω, and

C_s = surge capacitance in F

at a power frequency (50 Hz)

$$Z_\mathrm{c} = \frac{1}{2\pi \times 50 \times 0.25 \times 10^{-6}}$$

$$= 12.73\ \mathrm{k}\Omega$$

which is large and will offer a near-open circuit to the power frequency voltage and remain unaffected under normal conditions. For a system voltage of 6.6 kV, it will draw a current of only

$$\frac{6.6}{\sqrt{3} \times 12.73} \quad \text{or} \quad < 0.3\ \mathrm{A}$$

while in the event of a surge voltage, say at 13 kHz, it will become

$$Z_\mathrm{c} = \frac{1}{2\pi \times 13 \times 10^3 \times 0.25 \times 10^{-6}}$$

$$= 48.95\ \Omega$$

which is quite low compared to a very high X_L of the windings and will share the bulk of the transient current and provide the required low effect of Z_c, to reduce the steepness of the TRV. Since they have high-energy ($\frac{1}{2}CV^2$) storing capability, capacitors when charged with d.c. can store high energy and also reduce the amplitude of the arriving surge. A surge has a d.c. component, hence the effectiveness of the surge capacitors. They absorb most of the energy of the arriving surge, reduce its amplitude (V_t) and also steepness and hence the rate of rise (r.r.r.v.), $V_\mathrm{t}/\mathrm{t}_1$.

It is possible that small motors are protected through the use of surge protective capacitors alone and only large motors are protected through both the surge arrester and the surge capacitor. They also help to damp the surge transferences due to electrostatic coupling from the higher voltage side of a power transformer to the lower voltage side of it, as a result of a reduced Z_c and a changed and reduced electrostatic ratio $\{C_\mathrm{p}/(C_\mathrm{p} + C_\mathrm{s} + C)\}$ (Section 18.5.2).

These capacitors differ from standard p.f. improvement capacitors, as they are designed to withstand higher test voltages and have a low internal inductance. They should preferably be non-inflammable, synthetic liquid impregnated and provided with a built-in discharge resistance. For specifications refer to VDE 0675 and VDE 0560 III.

Example 17.5

To illustrate the above, consider a surge capacitor of 0.25 μF being used in parallel with a 350 kW, 6.6 kV motor. If the likely FOW is presumed to have an amplitude up to 5 p.u., then the maximum energy this capacitor can absorb

$$= \frac{1}{2} \times 0.25 \times 10^{-6}\ [6.6 \times 10^3]^2\ \text{Joules}$$

$$= 5.4\ \text{Joules}$$

whereas the energy of the FOW will be

$$W_{(\mathrm{FOW})} = \frac{V_\mathrm{t}^2}{Z_\mathrm{s}} \cdot {}^{*}2T\ \text{Joules} \qquad (17.3)$$

where,

$$V_\mathrm{t} = 5 \times 5.39 = 26.95\ \mathrm{kV}$$

$$\left(1\ \text{p.u.} = \frac{\sqrt{2}}{\sqrt{3}} \times 6.6 = 5.39\ \mathrm{kV} \right)$$

$Z_\mathrm{s} \simeq 4000\ \Omega$ from Figure 17.7(c).

$T \simeq 20\ \mu$s for an FOW, Table 18.1

$$\therefore\ W_{(\mathrm{FOW})} = \frac{26.95^2}{4000} \times 2 \times 20$$

$$= 7.26\ \text{Joules}$$

that means the surge capacitor is capable of absorbing most part of the energy released by the FOW and damping its amplitude to a large extent and taming its steepness (r.r.r.v.) within safe limits. This (energy absorbed) is so much desired also as the arrester, during the FOW discharge, is capable of

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*Factor 2 is considered to account for reflection. For more details refer to Equation (18.10).

absorbing only a small energy as calculated below and most of it has to be absorbed by the capacitor only. When the machine is neutral isolated, the size of the capacitor may have to be doubled.

Since the amplitude of the FOW is more than permissible (16.2 kV for a normal design and 26.9 kV for a special design motor Table 11.6) it is advisable to damp the amplitude with the help of a surge arrester. Using a 6 kV station class surge arrester of Example 17.6,

$V_{\text{res(FOW)}} = 21.5$ kV from Table 18.8

(It is advisable to select another arrester with a $V_{\text{res}} < \dfrac{16.2}{1.15}$ say 14 kV (considering the protective margin for switching surges as 1.15 (Table 18.2)) to make use of a normal design motor.)

The FOW energy that will be absorbed by the arrester

$$W_{\text{(arrester)}} = \frac{V_t - V_{\text{res}}}{Z_s} \cdot V_{\text{res}} \cdot 2T \text{ Joules from Equation (18.10)}$$

$$= \frac{26.95 - 14}{4000} \times 14 \times 2 \times 20$$

$$= 1.81 \text{ Joules}$$

Total FOW energy absorbed by the arrester and the surge capacitor

$$= 1.81 + 5.4$$
$$= 7.21 \text{ Joules}$$

leaving only a small part (0.05 Joules) for the machine to absorb, which is too meagre for a motor having its own impulse voltage withstand capability at $V_{\text{res}} = 14$ kV.

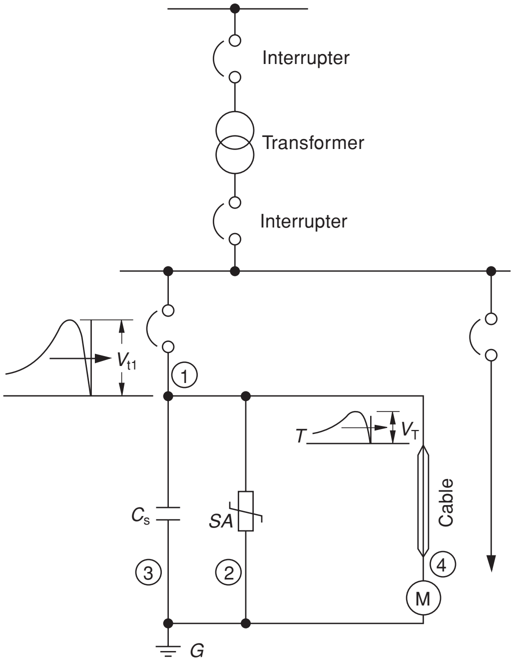
Note

The arrester has to be a MOV or a station class to absorb the long duration (250/2500 μs), high energy switching surges which it has to absorb first before the long duration surges (after restrikes) become steep fronted FOWs.

Illustration

1 Refer to Figure 17.21. Consider a steep fronted transient wave a_1 with a front time t_1, which has been damped to a moderate and less severe transient wave a_2 with a front time t_1'' by the use of a surge arrester. The resultant turn-to-turn voltage stress, et_1, for a given length ℓ of the machine windings will be limited to the maximum allowable voltage stress, et_2, of the windings' insulation (et_2 being a design parameter which may be obtained from the manufacturer). The damped intensity of the switching surge may even make up for an MV machine, having a low insulation level (less than 3 p.u., Table 11.6) suitable for operating on a system that could attain a transient voltage as high as 3–5 p.u. during normal switching, with an extremely low front time t_1. Figures 17.5(a) and (b), for instance, illustrate the oscillograms of a switching surge, with and without a surge arrester. The peak TRV, V_{t1}, in normal switching, which was of the order of 26 kV (4.8 p.u.) for a 6.6 kV system has been damped to a V_{t2} of only 13.5 kV (2.5 p.u.) with the application of a surge arrester.

2 If the turn-to-turn voltage, et_1, and the front time, t_1'' so achieved falls within the design parameters, no additional measures would be necessary to further reduce the TRV. However, if it is felt that the damped voltage, et_1, may exceed the required value of r.r.r.v. during operation, a surge capacitor may also be introduced in the circuit as illustrated in Figure 17.23 to tame the wave front a_2 to b_2, so that the front time is enhanced to a permissible t_1'''.



C_s: Surge capacitor 0.1–0.25 μF
SA: Surge arrester

① ② ③ ④: Represent amplitude and steepness of the arriving surge at different locations corresponding to curves of Figure 17.21.

Figure 17.23 Use of a surge capacitor in association with a surge arrester to provide taming as well as damping effects to a steep fronted TRV

Example 17.6

For the selection of an arrester:
Consider the same 6.6 kV motor having the following design parameters:

BIL – Lightning impulse 31 kV
FOW – For a front time 0.2–0.4 μs, the motor may be designed for 16.2 kV (3 p.u.). If a higher front of wave voltage withstand capability is required, the motor may be designed and insulated for 26.9 kV (5 p.u.) (Table 11.6, column 3).

Nominal system voltage = 6.6 kV (r.m.s.)
Maximum system voltage = 7.2 kV (r.m.s.)

$$1 \text{ p.u.} = \frac{7.2 \times \sqrt{2}}{\sqrt{3}} = 5.9 \text{ kV}$$

$$\text{Phase to ground voltage } V_g = \frac{7.2}{\sqrt{3}} = 4.2 \text{ kV}$$

The distribution system may be considered as solidly grounded having a GFF* of 1.4 and devoid of any other TOVs.†

Therefore, maximum rated ground voltage = 1.4 × 4.2

$$= 5.88 \text{ kV}$$

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*GFF = Ground fault factor (Section 20.6).
†TOV = Temporary over-voltage.

Select the nearest voltage rating of a station class surge arrester from the manufacturer's catalogue (Table 18.8), at 6 kV which has the following protective levels:

$V_{\text{res (max)}}$	*Protective level*	*BIL of motor*	*Protective margin available*
For a lightning impulse wave of 5 kA (8/20 μs)	17.7 kV	31 kV	175% ∴ OK
For a switching impulse wave of 1.0 kA (30/60 μs)	15.3 kV	[governed by the lightning impulse]	OK
For an FOW (1/2 μs) of 10 kA	21.5 kV	16.2 kV for normal design	Not suitable
		26.9 kV for special design	125% ∴ OK

With this particular arrester, the motor has to be specially designed for the higher level of FOW impulse voltage withstand. But the manufacturer can always modify the protective characteristics of the arrester, depending upon the system's requirements. The matter may therefore be referred to the manufacturer for recommendations. The arrester may be fitted with a 0.25 μF surge capacitor in parallel, to reduce the steepness of the FOW to a safe value (for the arrester of Example 17.5, it is 14/0.2 kV/μs).

Figure 17.24(a) *C–R*-type surge suppressor (*Courtesy:* Jyoti (Toshiba))

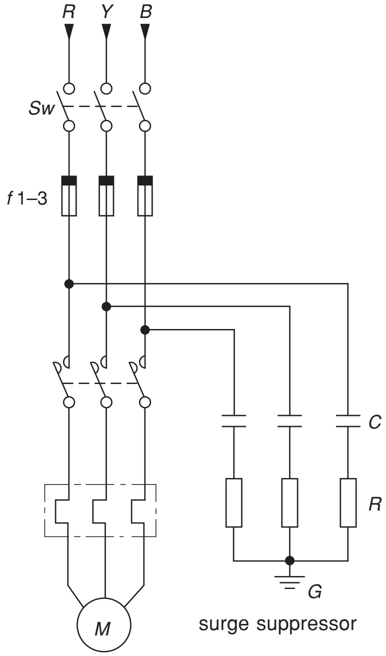


Figure 17.24(b) Typical power circuit of a *C–R*-type surge suppressor

17.10.4 Surge suppressors

A surge capacitor reduces the steepness and damps the amplitude of a surge. The use of a surge arrester to damp the amplitude of the surge, in association with a surge capacitor, may require more space, besides being a more expensive arrangement. This is particularly the case when an FOW switching surge in motor switching has only a moderate amount of energy to discharge. A compact and economical alternative is found in a surge suppressor, which makes use of a low-value damping resistance *R* in series with the surge capacitor *C*. The resistance can now absorb a part of the energy of a high-amplitude surge, damp it to a desired level and make the *C–R* unit suitable for taming as well as damping an FOW surge. The combination of *C* and *R* is appropriately termed a surge suppressor. Figure 17.24(a) shows a general arrangement of such a suppressor, while the power circuit diagram illustrated in Figure 17.24(b) is almost a replica of a non-linear resistor type surge arrester, discussed in Section 18.1.1 and shown in Figure 18.1(a). The non-linear resistor NR of Figure 18.1(a), is now replaced by *C*. The damping resistor *R* of the surge suppressor is able to provide the arriving surge, a low resistance path, and a means of absorbing the excess energy of the surge that the capacitor is not able to absorb to damp it to a required level while the surge capacitor absorbs bulk of the energy and arrests the steepness of the surge to a desired r.r.r.v. Use of *R* also prevents the reflections of the arriving surge at the motor terminals.

The design of the *C–R* combination maintains a negligible level of leakage current through the suppressor in healthy conditions (to contain resistance loss). It is easily achieved, as *C* provides a near-open circuit in these conditions and permits only a very small leakage current to flow through it.

A *C–R* suppressor also helps to reduce the surge impedance, Z_s, of the circuit and thus limits the amplitude of V_t as discussed in Section 17.8. They are therefore a good solution to protect equipment that are subject to steep rising switching surges during course of their normal operation such as an electric motor. With fine tuning between *C* and *R*, the surge suppressors available in the market are adequate by themselves to protect an electric motor from long duration to short duration steep fronted switching surges without the support of a surge arrester. These suppressors can be mounted on the switching device itself, rendering the significance of cable length also redundant as the surges are now diverted right at the source of their origin. For critical installations such as power generating station, however, a more pragmatic approach may be needed when it would be advisable to use a surge arrester in parallel with the surge capacitor to take care of long duration switching surges at the commencement of switching sequence until they build up into FOWs and the capacitor takes over.

Summary

The above analysis is more pertinent for old installations when the VCBs used to have high chopping current (3–5A) causing multiple restrikes of the arc plasma. With the availability of state-of-the-art VCBs and also vacuum contactors having very low chopping currents (Section 19.6) the possibility of a restrike is now rare and a surge capacitor alone is more than adequate, finely tuned to the improvised switching sequences mostly devoid of a restrike.

17.10.5 Setting fast-responding relays

No system is permitted to trip on the occurrence of a momentary disturbance, such as by travelling surges of any kind. To overcome this:

- The motor protection relay, as discussed in Section 12.5, is generally provided with a delay feature to bypass these transients and delay the tripping by two or three cycles.
- The same is true for an over-current or a ground fault relay when used in circuits that are prone to surges.

17.10.6 Conclusion

Switching of an induction motor was typical of all to illustrate the phenomenon of switching surges in an inductive circuit. The situation would remain the same when switching a power system, transformer or power cables also, in all conditions of loading (fully loaded, over-loaded or on no-load). Switching surges in a capacitor circuit is discussed in Section 23.5.1 with the likely levels of voltage surges. Below we discuss the insulation co-ordination and protection of other machines and systems.

17.11 Theory of surge protection (insulation co-ordination)

The insulation of a current-carrying system, machine or component is to provide it with the required insulation level (BIL) to withstand system voltages during normal operation, as well as temporary over-voltages (TOV) and momentary voltage surges, up to a certain level, during system disturbances. A safety margin is built into the equipment by the manufacturers according to Tables 11.6, 14.1, 32.1(a), or 13.2 and 13.3 as standard practice to sustain such voltages without failure or rupture of the insulating system. Repeated application of such voltages, even if they are below the BIL of the insulating system, or longer duration of over-voltages, may lead to failure or rupture of the insulating system as a result of insulation fatigue. It is possible that in operation, TOVs or voltage surges may exceed the safe (prescribed) power frequency or impulse withstand voltages (BIL) respectively, of the power system or the terminal equipment. For the recommended safe insulation levels of different equipment, refer to tables mentioned above.

For instance, when lightning of, say, a nominal discharge current of 10 kA strikes a 400 kV (r.m.s.) overhead line, having a surge impedance of 350 Ω, then two parallel waves will be produced each of amplitude 10 × 350/2 or 1750 kV which may be more than the impulse withstand level of the system and cause a flashover between the conductors and the ground, besides damaging the line insulators and the terminal equipment (Table 13.2). It is therefore imperative that the system is protected against such eventualities.

Surge protection, therefore, becomes essential when it is felt that the surges generated during an operation at a particular installation may rise beyond the permissible impulse withstand capacity (BIL) of the equipment or when a system is prone to frequent occurrences of temporary over-voltages. Induction motors for instance, which conform to the impulse withstand levels prescribed for this machine according to Table 11.6 may be supplemented by a surge arrester or suppressor, when it is felt that the amplitude or steepness (or both) of the surges in operation may exceed the prescribed levels. Coordination of insulation of the equipment to be protected with that of the protective level of the protective device, which may be a switchgear or a lightning arrester, is called insulation co-ordination. This would depend upon the type of installation, such as the type of switching device and the length of the inter-connecting cables. For an assessment of the possible magnitudes and durations of the TOVs and the prospective amplitudes and steepnesses of the lightning or switching surges, particularly at critical installations such as a generating station or a large switchyard, it is essential to carry out system transient network analysis (TNA) as noted later.

Where this is not necessary, it can be assessed by the equipment's exposure to such TOVs and surges and thus determine the appropriate level of BIL. IEC 60071-2 provides guidelines for the most appropriate surge protection scheme and is discussed in Section 18.6.

17.12 LV surge protection

The present chapter is basically dedicated to HV systems and equipment but surge protection of LV systems and equipment is no less important, irrespective of usually low severity of voltage surges on LV systems, as discussed in Sections 17.7.6 to 17.7.8. IEC-60664-2-2 lays emphasis on insulation co-ordination for low voltage systems and equipment also. IEC 60439-1 has defined clearances and creepage distances for low voltage equipment and devices to withstand different severities of voltage surges. LV surge protection is therefore also discussed here along with HV surge protection, to make the subject more comprehensive.

- As basic guidelines, distribution networks that are subject to excessive loadings or suffer from inadequate reactive power support are seen to be prone to frequent voltage fluctuations and breakdowns. Installations connected to such a system and supported by auto-mains failure supply source (captive generation) may be subject to severe voltage surges even on an LV system because of frequent switchings due to such breakdowns. This phenomenon is usually prevalent in countries having poor power management.
- LV systems feeding static drives, electronic appliances, furnaces and other non-linear loads (Sections 16.6.2 and 23.5) may also generate over-voltages and voltage surges, besides the causes discussed in Sections 6.13.2 and 17.7.6 to 17.7.8.

All this suggests that for the safety of LV equipment and devices surge protective devices (SPDs) must be used for all LV equipment and devices that are exposed to switching or transferred surges. SPDs are also recommended before and after a UPS (uninterrupted power supply) or wherever a step-down or step-up booster transformer is associated with an equipment or device such as, mobile phones (through their chargers), radios, music players, TVs, home appliances and all such devices associated with switchings or are exposed to surge transferences from their own built in transformers. Most of these devices are, however, fitted with a surge protective device by the manufacturers of these devices as a standard practice. Also see ANSI/IEEE C 62.11.

Based on this and discussions we have had so far, we can infer that an LV system, equipment or device may be exposed to the following kinds of system transients that may endanger its insulation and longevity,

- Indirect lightning strokes – through capacitive coupling of the transformer windings (Section 18.5.2)
- A lightning stroke in the vicinity of an LV installation causing high induced e.m.fs. (EMI effect) in the LV system also. This too is an indirect lightning effect
- Electromagnetic surge transferences – inductive coupling between the HV and the LV windings of the transformer
- Fault in the transformer windings itself
- Switching of non-linear loads
- Switching of power electronic circuits. They would call for a different kind of protection to suit continuous switchings (as in a PWM inverter circuit) and consequent switching surges demanding for high energy absorption capability requirements in the SPD. This aspect is discussed in Section 6.13.
- Resistive coupling – Lightning striking a ground may also raise the ground potential of another ground nearby (Section 23.18) and cause spurious ground currents in this ground also. This current may travel through the entire electrical network of this ground and damage many delicate devices enroute. Data or communication lines can be corrupted. If the line length is short it may also carry these dangerous voltages to the other end of it and damage equipment and devices there also. In all such cases it is advisable to provide an SPD between the neutral and the ground also to protect the LV system and the terminal equipment and devices from all such indirect ground disturbances.

17.13 LV Surge Protection Devices (SPDs) (or transient voltage surge suppressors (TVSSs))

When we talk of LV surge protection it is presumed that there is no direct lightning stroke on the LV system as noted above. The use of SPDs take care of over-voltages and transferred surges, prevents failures and enhances longevity of all connected equipment and devices, inter-connecting cables and wires. SPDs may be installed at the main power receiving point of the service connection at homes, industries, commercial complexes, residential buildings, colonies or wherever the main LV incoming power connection from the local supply agency terminates at the premises and at all load points as noted above that may be subject to any kind of switching operation or transferred surges. The SPDs can be of the following types,

i. Silicon avalanche diode suppressors (SAS) – They are semiconductor devices (diodes, thyristors, triacs), very fast acting but not high powered. Mostly used for dataline and communication system surge protection
ii. SCR suppressors – They too are semiconductor devices, slow acting but high powered
iii. RC–LC filters – Filter circuits also suppress switching and power frequency over-voltages. They are provided in combinations of R, L and C and arranged in shapes of L, T or π as shown in Figure 17.25. The shape of circuit and values of L, C or R components depend on protection criteria such as likely transient shape and protective level (impulse withstand capability) of the equipment or device to be protected.

Note
The above SPDs are usually not suitable for power electronic switching circuits such as the output side of a PWM inverter because SPDs being light duty devices are suitable to handle only transferred surges or small switching surges, while a PWM inverter is a heavy duty application with continuous switching transients.

iv. Conventional gapped discharge type
   – Expulsion type
   – Spark-gap type
   – Non-linear resistor (SiC) type
   These devices are dicussed briefly in Section 18.1.1
v. Non-conventional gapless metal oxide surge arresters (MOVs) as discussed in Section 18.1.

Non-linear resistor and metal oxide surge arresters are known as varistors and used extensively for the surge suppression and are discussed below.

Varistors too are semiconductor devices in the form of non-linear resistors and made of SiC (silicon carbide) or metal oxide compounds of bismuth, cobalt, antimony and manganese etc. Their non-linearity is expressed as in Equation (18.1). Under normal conditions a metal

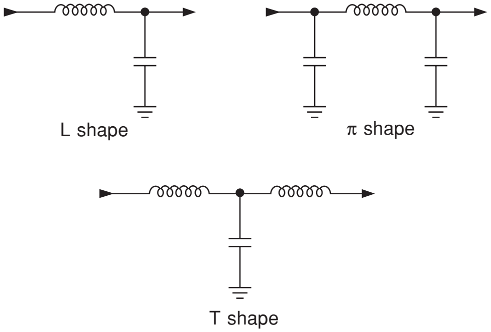


Figure 17.25 Sample circuits of L–C filters

oxide varistor (MOV) for instance draws a very small leakage current ($<10\ \mu$A) and offers a very high resistance (Figures 18.4(a) and (b). Under transient conditions this resistance diminishes to an extremely low conducting value and drains off the excess transient voltages to the ground limiting the amplitude of the transient voltages across the equipment or devices on which it is mounted within their permissible safe level. And quickly restoring its own normal condition for the next discharge.

- For selection of SPD generally the same consideration would apply as for the surge protection of HV systems and equipment discussed in Section 17.11. The safe protection level of SPD is chosen to be less than the impulse withstand capacity of the equipment or device to be protected. Such as for switchgear assemblies and busbar systems as per Table 14.3(a). For equipment and devices where impulse voltage withstand level is not prescribed, such as for LV motors[a] and capacitors[a], and also when no surge protection is available at the power receiving end, the preferable guideline for surge protection of such equipment and devices can be to choose the SPDs with a safe impulse level of less than the power frequency withstand voltage of the equipment or device. Such as for LV motors less than ($2V_r + 1000$) volts as per Table 11.4 and for power capacitors as per Table 26.3.
- – Similarly, one can choose safe over-voltages for light electronic circuits and devices, house-hold electrical appliances and speech communicating devices, mobile sets, telephony apparatus, TVs, music and voice recording systems etc. For delicate devices such as these this is usually provided within the device as a standard practice by the manufacturers.

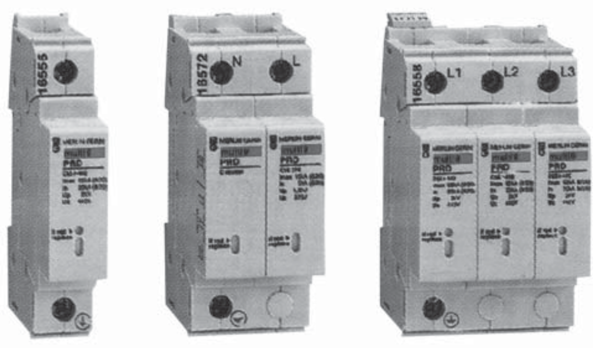
Note
An MOV is the basic ZnO element and is usually applied in association with a filter circuit (combination of R, L and C) to mitigate the severity of the arriving surge. Filter circuit also enhances life of the element remarkably.

SPDs in modular form

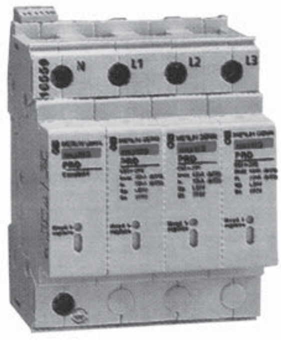
When MOVs are to be mounted as separate units (not inside a device) such as for houses and buildings to protect from surges, light and power circuits, household appliances and office equipment or LV industrial installations, the manufacturers usually enclose them in a casing to make it modular and easy to instal. With MOVs as noted above, is also built-in an inductor coil or a filter circuit in different configurations and values as shown in Figure 17.25 to achieve different characteristics to suit a particular application. The whole unit is conventionally called an SPD and is available in configurations of single to four poles. Figure17.26 shows a few varistors in housings ready for installation with a switching device in an LV switchgear assembly or a DB.

MOVs are of miniature sizes and vary in diameters and thicknesses according to their voltage rating and energy handling capabilities. Figure 17.27(a) shows a few typical miniature MOV elements and Figure 17.27(b) a graphical representation of its smoothing function. Figure 17.28 illustrates three typical V-I characteristic curves based on equation (18.1) of the same MOV for different energy handling (J) capacities as shown in Table 17.2. By making small adjustments in sizes of SiC resistors or metal oxide blocks numerous characteristics in V and I and energy handling capabilities (J) of the varistors can be achieved to suit an application. All manufacturers as standard, provide such technical data for their varistors, giving voltage rating, energy capability and peak transient current the device can withstand to enable the user make a proper choice of SPD for his application. They can also modify these characteristics to suit a particular application.

The SPDs can be installed with the switching device (one each between each pole and ground) feeding an installation, an individual equipment or device or a building, industry or a common load point controlling a group of loads depending upon their exposure to transient over-voltages. In most cases, SPDs at the receiving end



1-pole 2-pole 3-pole



4-pole

Figure 17.26 MOV SPDs in modular forms in different pole configurations (*Courtesy:* HPL (Moeller))

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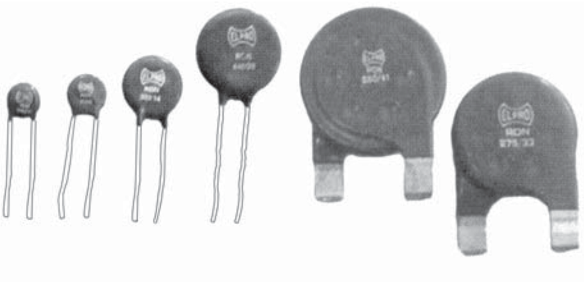
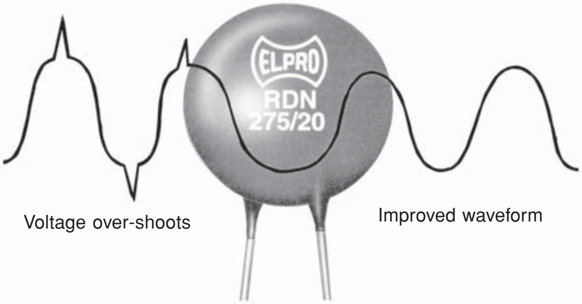
[a] *Notes*

1. No impulse test voltage is presently prescribed for these equipments, possibly because they are installed downstream in a distribution system and are automatically safeguarded against surges through the surge protection provided at power receiving end. Where it is not, the above procedure can be a good alternative.
2. SPDs are recommended in the switching circuit in any case for such equipment to safeguard them against internally generated switching surges such as during a switching operation.



(a) View of a few MOVs (they can be of any size depending upon their ratings)



(b) Smoothing function of a Metal Oxide Varistor

Figure 17.27 (Courtesy: Elpro International)

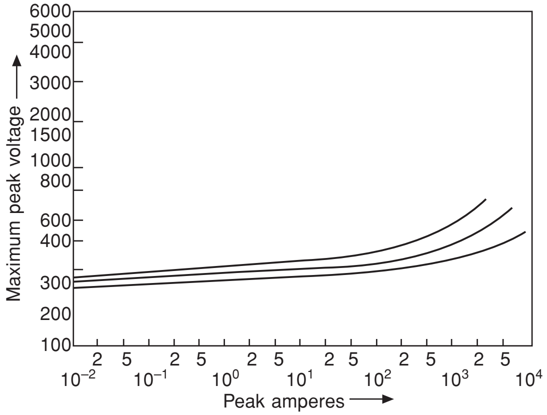


Figure 17.28 Transient V–I Characteristics of a typical MOV with different diameters (Courtesy: Elpro International)

controlling the whole installation would suffice and use of individual SPDs may be limited only to those equipment and devices that are subject to direct switching transients such as when fed through a step-down or step-up booster transformer (electronic devices and home appliances are typical examples) including electric motors which are fed through PWM inverters. Use of SPDs on the LV side of a distribution transformer is seen to be protecting its LV windings also, besides limiting the transferred voltages to other equipment and devices connected to it. It is seen that SPD on LV side also reduces the failure rate of distribution transformers and improves their longevity.

The SPDs can also be installed between the neutral and the ground of an installation where the ground is

Table 17.2 Typical data of the varistors of Figure 17.28 showing variation in diameter for different energy capabilities

Type Number	*Size Dia*	*Maximum Rating at 40°C*				*Characteristics*					*Typical capacitance*[a] *1 kHz*
		Continuous		*Transient*		*Varistor voltage @ 1 mA DC test current*			*Typical clamping voltage Vc @ 8 × 20 µs test pulse*		
		RMS	*DC*	*Energy 10 × 1000 µs Volts*	*Peak current 8 × 20 µs*						
	mm	*Vm(ac) (Volts)*	*Vm(dc) (Volts)*	*J (Joules)*	*Io (Amp)*	*Min (Volts)*	*Vn (Volts)*	*Max (Volts)*	*Vc (Volts)*	*Ip (Amps)*	*C (pF)*
RDN 130/9	09	130	175	15	2000	185	200	220	350	10	450
RDN 130/14	14	130	175	30	4500	185	200	220	340	50	1000
RDN 130/20	20	130	175	60	6500	185	200	220	340	100	2000

Courtesy: Elpro International

Nomenclature

- *Rated rms varistor voltage*: maximum continuous sinusoidal rms voltage.
- *Rated dc varistor voltage*: maximum continuous dc voltage.
- *Rated single pulse transient energy*: energy dissipated for a single impulse of maximum rated current at a specified wave shape, with voltage applied.
- *Rated peak single pulse transient current*: maximum peak current applied for a single 8 × 20 µs impulse, with rated line voltage.
- *Nominal varistor voltage*: voltage across the varistor at a specified pulse dc current.
- *Clamping voltage*: peak voltage across the varistor measured under conditions of a specified peak pulse current and specified waveform*.
- [a]*Capacitance*: between the two terminals of the varistor measured at a specified frequency.
- **Waveforms*: at high current and energy levels, varistor characteristics are measured with an impulse waveform. The 8 × 20 µs current wave (8 µs rise and 20 µs to 50% decay of peak value) is used as a standard for the varistor characteristics and ratings. One exception is the energy rating (J) in Joules (Watt × sec) where a longer waveform of 10 × 1000 µs is used. This condition is more representative of the high energy surges.

exposed to indirect lightning strokes. The actual lightning occurring elsewhere in the vicinity but influencing the grounds of this installation. Such a situation may arise at long open terrains having power lines and communication lines existing in close vicinity or electrical installations existing at less populated open fields.

Note
It is recommended to use a separate ground for SPDs than using the system ground, to prevent system ground potential rise during clearing of a surge.

Quick procedure to select an SPD

- Add about 10–20% in the rated voltage of the equipment or device to allow for voltage fluctuations and reducing unwanted discharges. This when it is not easy to assess the protective level of the equipment or device to be protected.
- Choose a safe clamping voltage (as per the safe over-voltage withstand capacity of the equipment or device).
- Select an appropriate surge energy capacity or consult the manufacturers or those in the field of surge protection who can guide for the right choice by their experiences. As a rule of thumb the protection level (clamping voltage) of the SPD should be chosen lower than the immunity level of the equipment or device being protected against transients (see IEC-61000-4-5). To make the choice of an SPD easy, Table 17.3 provides a brief comparison of various types of SPDs available in the market.

Monitoring the health of SPDs

Exploding of MOVs can be fire hazardous and dangerous for the personnel nearby. Every discharge of MOV, depending upon the severity of surge, affects its health and consequently its longevity. Measure of health of a MOV is its leakage current as noted in Section 18.1. This current is the cause of heating and deterioration of MOV. It is impractical to measure this current in service unlike in HV and EHV systems (Section 18.10). Therefore periodic inspections and checks of SPDs are mandatory. Since it is not easy to assess their health at site, the modern practice of many manufacturers is to provide an LED (light emitting device) indicator on each SPD itself to indicate its health.

It is provided in the MOV ground circuit. Typically green is indicative of a healthy and red a failed unit. The change from green to red is gradual and indicative of deteriorating health. One can assess the health through its colour change. There are no established guidelines to preventive maintenance, but based on site conditions, likely lightning strikes in the area, possible switchings of power loads (motors, capacitors and booster transformers) and transferred surges, one can frame his own norms and maintain a logbook for periodic checks. The duration of checks can be a month or more depending on site conditions and past experience on rate of failures. SPD must be replaced as soon as it glows its brighter red. Once again a matter of experience. In replacing the MOV one may be liberal rather than conservative.

Table 17.3 Brief comparison of surge protective devices (SPDs)

Type of device	*Energy absorption capability*	*Response time*	*Leakage current*	*Features/Applications*
(i) Silicon avalanche diode suppressors (SAS)	1 J	100 n sec	1 µA	– Low energy handling capability – Low clamping voltage
(ii) SCR suppressors	High energy capability	Slow-acting	–	–
(iii) RC-LC filters	10 J	–	High charge current	– Not effective for lightning surges – To be tailor made for each application
(iv) Conventional gapped discharge type				
– Expulsion – Spark gap	–	1-3µ sec	–	– Suitable only for lightning surges
– Non-linear	100 J	100 n sec	1–100 mA	– High clamping voltage suitable for devices having high BIL
(v) Non-conventional gapless MOVs	100 J	<25 n sec	10 µA	– High energy handling capability – Fast response – Clamping voltage as desired – Suitable for both lightning and switching surges and all types of electrical and electronic equipment and devices in all LV ratings.

Source: Elpro International

Note
The values mentioned above are typical and may vary from manufacturer to manufacturer.

In case of MOV elements (usually installed with a filter circuit) inside an electronic device or household appliance, it is impracticable to assess its health in the above fashion. But as these devices and appliances are usually installed at the far end as referred to a power distribution network, the severity of surges and over-voltages by the time they arrive the device or appliance is quite feeble and may not unduly stress the MOV element. Some manufacturers therefore claim that MOV elements used such are capable of millions of discharges and therefore adequate for a lifetime of the device and appliance it is protecting.

Relevant Standards

IEC	*Title*	*IS*	*BS*	
60060-1/1989	High voltage test techniques. General definitions and test requirements.	2071-1/1999	BS 923-1/1990	–
60071-1/1993	Insulation coordination phase to earth – Principles and rules. Insulation coordination phase to phase – Principles and rules.	2165-1/2001, 2165-2/2001	BS EN 60071-1/1997	–
60071-2/1996	Insulation coordination – Application guide.	3716/2001	BS EN 60071-2/1997	–
60470/2000	A.C. contactors for voltages above 1 kV and up to and including 12 kV.	9046/2002	BS EN 60470/2001	–
60664-1	Insulation coordination for equipment within low-voltage systems – Part 1 – Principles, requirements and tests.	–	–	–
TR 60664-2-2	Insulation coordination for equipment within low voltage systems. Part 2-2 Application guide	–	–	–
60947-4-1/2001	Low voltage switchgear and controlgear. Electromechanical contactors and motor starters including rheostatic rotor starters.	13947-4-1/ 1998	BS EN 60947-4-1/ 2001	–
61024-1/1990	Protection of structures against lightning – General principles.	2309/2000	BS 6651/1999, DD ENV 61024-1/1995	–
TS 61312-3/2000	Protection against lightning electromagnetic impulse – Part 3 – Requirements of surge protective devices (SPDs)	–	–	–
61643-1	Surge protective devices connected to low-voltage power distribution systems – Part I – Performance requirements and testing methods.	–	–	–
61643-12/2000	Surge protective devices connected to low voltage power distribution systems – Part 12 – Selection and application principles	–	–	–
TR 62066/2002	General basic information regarding surge over-voltages and surge protection in low-votlage a.c. power systems.	–	–	–
–	Capacitors for surge protection for systems 0.65 kV to 33 kV.	11548/2001	–	–

Relevant US Standards ANSI/NEMA and IEEE

ANSI/IEEE-1313.1/1996	Insulation coordination – Definitions, principles and rules.
ANSI/IEEE-C62.11/1999	Metal oxide surge arresters for a.c. power circuits >1 kV.
IEEE C62.45/2002	Guide on surge testing for equipment connected to LV power a.c. circuits.

Notes

1 In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.

2 Some of the BS or IS Standards mentioned against IEC may not be identical.

3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

List of formulae used

Rate of rise of recovery voltage

$$\text{r.r.r.v.} = \frac{V_t}{t_1}\ \text{kV}/\mu\text{s} \qquad (17.0)$$

V_t = peak value of the voltage surge in kV
t_1 = rise time in μs

Surge frequency

$$f_s = \frac{1}{2\pi\sqrt{LC}}\ \text{in Hz} \qquad (17.1)$$

f_s = surge frequency in Hz
L = leakage inductance of the circuit in henry (H)
C = lumped leakage capacitance of the circuit in farad (F)

Surge impedance

$$Z_s = \sqrt{\frac{L}{C}}\ \Omega \tag{17.2}$$

Surge energy

$$W = \frac{V_t^2}{Z_s} \times t \times 10^3 \text{ kW-s or kJ} \tag{17.3}$$

W = energy released in kW-s or kJ
V_t = prospective crest of the surge in kV
Z_s = surge impedance of the power system and the terminal equipment in Ω
t = duration for which the surge exists (in seconds)

Velocity of propagation

$$U = \frac{1}{\sqrt{L_0 C_0}} \text{ km/s} \tag{17.4}$$

U = velocity of propagation in km/s
L_0 = line or conductor mutual inductance in H/km
C_0 = leakage capacitance of the same medium in F/km

Per unit voltage

$$1 \text{ p.u.} = \sqrt{2} \cdot \frac{V_1}{\sqrt{3}} \tag{17.5}$$

Current zero

This is defined by $i = 0$, where

$$i = I_{\max} \sin \omega t \tag{17.6}$$

i = instantaneous current component at any instant on the current wave
$I_{\max}$ = peak value of the current
ω = angular velocity = $2 \pi f$
t = time

Surge protection of motors

For surges,

$$\text{Surge frequency}, f_s \simeq \frac{10^3}{4 t_1} \text{ kHz} \tag{17.7}$$

t_1 = rise time of the surge in μs

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