

TRANSIENT RECOVERY VOLTAGES FOR HIGH VOLTAGE CIRCUIT BREAKERS

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Abstract: Transient recovery voltages (TRVs) associated with short-circuit current interruption are presented, starting with general considerations that explain the different shapes of TRVs and how they are influenced by several parameters. TRVs are then presented in detail for terminal faults, short-line faults and out-of-phase breaking operations. The last part presents application considerations and the selection of circuit breakers for TRVs.

Keywords : TRV, Circuit breaker, High voltage, Terminal fault, Short-line fault, Out-of-phase, Transformer limited fault, Current limiting series reactor.

I. GENERAL CONSIDERATIONS ON TRV

The TRV is a decisive parameter that limits the interrupting capability of a high-voltage circuit breaker. Since the 1950's, the short-circuit breaking capability of gas blast circuit-breakers was found to be strongly dependent on TRV. This has led to the specification of TRVs and test circuits for short-circuit breaking test duties [1] [2]. [3] [4].

1.1 General

The recovery voltage is the voltage which appears across the terminals of a pole of a circuit breaker. This voltage may be considered in two successive time intervals: one during which a transient voltage exists, followed by a second one during which a power frequency voltage alone exists.

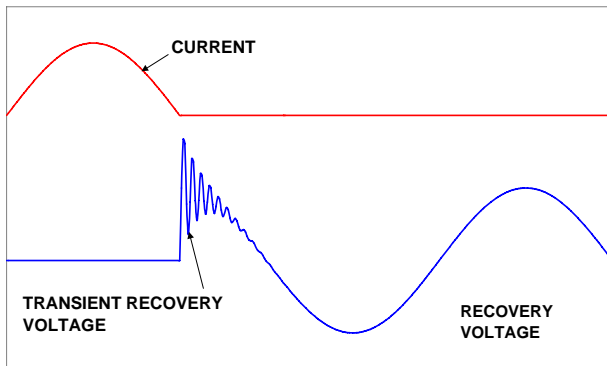


Figure 1 Current, TRV and Recovery Voltage

During the interruption process the arc rapidly loses conductivity as the instantaneous current approaches zero.

Within a few microseconds after current zero, current stops flowing in the circuit as arc resistance varies from a few hundred ohms at current zero to more than one million ohms.

The power system response to the current interruptions is what generates TRV. The difference in the power system response voltage between the source side and the load side of the circuit breaker is the TRV. The breaking operation is successful if the circuit breaker is able to withstand the TRV and the power frequency recovery voltage.

The nature of the TRV is dependent on the circuit being interrupted, whether primarily resistive, capacitive or inductive, (or some combination). Additionally, distributed and lumped circuit elements will produce different TRV wave-shapes.

When interrupting a fault at the circuit breaker terminal in an inductive circuit (terminal fault), the supply voltage at current zero is maximum. The circuit breaker interrupts at current zero, at a time when the power input is minimum, and the voltage on the supply side terminal reaches the supply voltage in a transient process called the transient recovery voltage. This is illustrated in Figure 2.

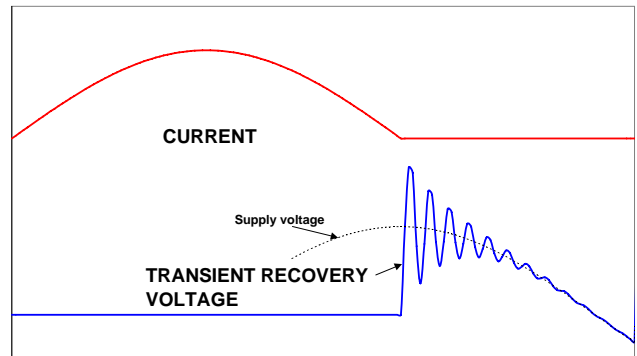


Figure 2 Current and TRV during interruption of inductive current

The TRV frequency is $\frac{1}{2\pi\sqrt{LC}}$, with L = short-circuit inductance, C = supply capacitance.

When switching capacitive loads, the load-side voltage keeps its instantaneous value at the instant of current interruption, neglecting losses, this gives a dc offset to the

TRV. In the simplest case, the TRV has then a 1-cosine waveshape at the power frequency, oscillating between 0 and 2 p.u.

Figure 3 illustrates three typical types of recovery voltages in resistive, inductive and capacitive circuit.

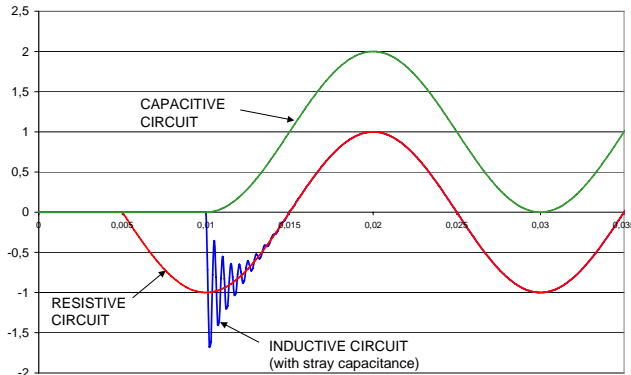


Figure 3 TRV and recovery voltage in resistive, inductive or capacitive circuits

Circuits for mainly active load current switching can be simulated by a combination of resistive and inductive elements. The recovery voltage is a combination of the shown in figure 3 for resistive and inductive circuits. It has initially a high frequency transient, due to the voltage drop in the transformer reactance, followed by a power frequency voltage, the amplitude of which is function of the load power factor.

In a similar way, interruption in a L-C series circuit produces initially a high frequency TRV of small amplitude (the voltage prior to interruption tends toward the supply voltage value) called the voltage jump, followed by the 1 - cos waveshape shown in Figure 3 for a capacitive circuit.

A short-circuited line will have a “ramp” voltage profile along the line. Upon interruption this ramp will “travel” and, depending on the electrical circuit discontinuities, there will be positive or negative reflections (see section 1.4).

Fault interruptions are often considered to produce the most onerous TRVs, shunt reactor switching is one of the exceptions (see separate chapter of the Tutorial).

TRVs can be oscillatory, triangular, or exponential and can occur as a combination of these forms. A dc offset may also be present as it is the case for lines with series capacitors. The highest peak TRVs are met during capacitive current and out-of-phase current breaking. TRVs associated with the highest short-circuit currents are obtained during terminal fault and short-line fault current breaking.

As shown in Annex A.1, a network can be reduced to the simple parallel RLC circuit of figure 4 for TRV calculations. This representation is reasonably valid for short-time frames until voltage reflections return from discontinuities in the network.

The TRV in the parallel RLC circuit is oscillatory (underdamped) if $R > \frac{1}{2}\sqrt{L/C}$

The TRV in the parallel RLC circuit is exponential (overdamped) if $R \leq \frac{1}{2}\sqrt{L/C}$

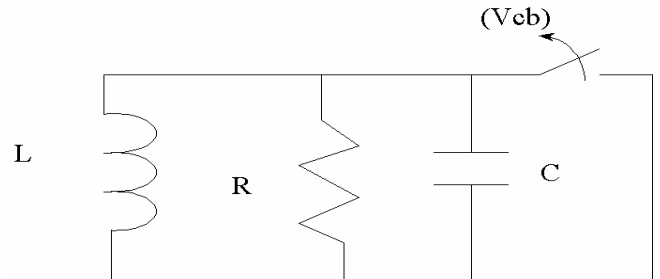


Figure 4 – Equivalent RLC circuit

Figure 5 shows the TRV shape as function of damping in an RLC circuit. From this figure, it can be seen that by lowering the resistance in the equivalent circuit, for example when adding a resistance of low ohmic value in parallel to the interrupting chamber(s), it is possible to effectively reduce the rate-of-rise of TRV (the TRV peak voltage is reduced as well). This method has been widely used for many years to assist current interruption by air-blast circuit breakers.

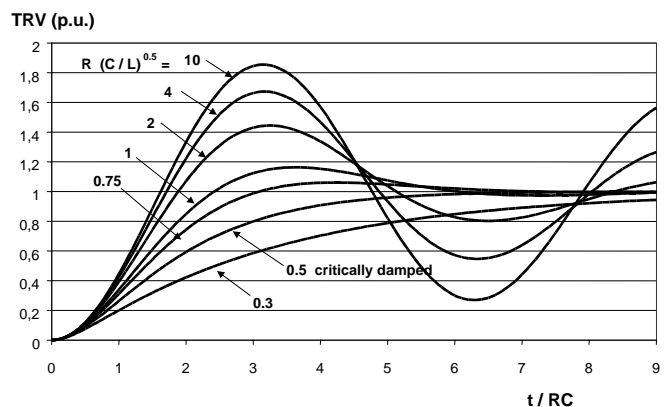


Figure 5 – TRV shape in RLC parallel circuit

When longer time frames are considered, typically several hundreds of micro-seconds, reflections on lines have to be taken into account. Lines or cables must then be treated as components with distributed elements on which voltage waves travel after current interruption. These traveling waves are reflected and refracted when reaching an open circuit or a discontinuity (see Annex A.3).

The most severe TRVs tend to occur across the first pole to clear of a circuit breaker interrupting a three-phase symmetrical fault at its terminal when the system voltage is

maximum.

By definition, all TRV values defined in the standards are inherent, i.e. the values that would be obtained during interruption of a fault at the circuit breaker terminals. This exponential part of TRV occurs when the equivalent surge impedance of the n connected lines in parallel ($Z_{eq} = \alpha \frac{Z_1}{n}$ where Z_1 is the positive sequence surge impedance of a line and α is a factor equal to 1.5 in the case of three-phase ungrounded faults and a function of Z_0/Z_1 in other cases) is lower than $0.5\sqrt{L_{eq}/C_{eq}}$ (L_{eq} = equivalent source inductance, C_{eq} = equivalent source capacitance). Detailed explanations are given in Annexes A.2 and A.3.

1.2 Exponential (overdamped) TRV

The exponential part of TRV, defined by equation $V_{cb} = V_o (1 - e^{-t/\tau})$ appears also as traveling waves on each of the transmission lines. Reflected wave(s) returning from open line(s) contribute also to the TRV as shown in Figures 6 and 8.

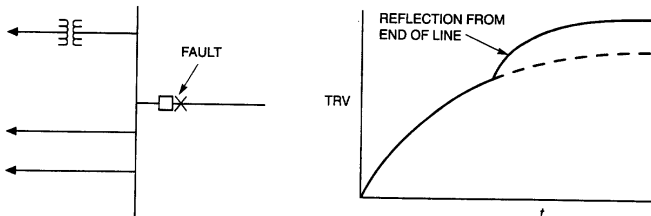


Figure 6 Exponential TRV characteristic

The initial rate-of-rise of recovery voltage is given by $RRRV = \frac{\alpha Z_1}{n} \times \frac{di}{dt}$. As higher short-circuit currents are associated with an increasing number of connected lines and the TRV is less influenced by the transformer natural frequency, the RRRV tends to decrease when the short-circuit current increases.

As an example, Figure 7 shows the one line diagram of a 550 kV substation. Figure 8 illustrates the TRV seen by circuit breaker A when clearing the three-phase fault shown in figure 7, circuit breaker B is open. This waveform is overdamped and exhibits an exponential waveshape. In figure 9, a reflection occurs from the end of the shortest line, causing a slight increase in the TRV crest. As the shortest line is 81 km long and the voltage wave travels at 300 000 km/s, the reflected wave is applied back on the

circuit breaker terminal after $2 \times \frac{81}{0.3} = 540 \mu s$.

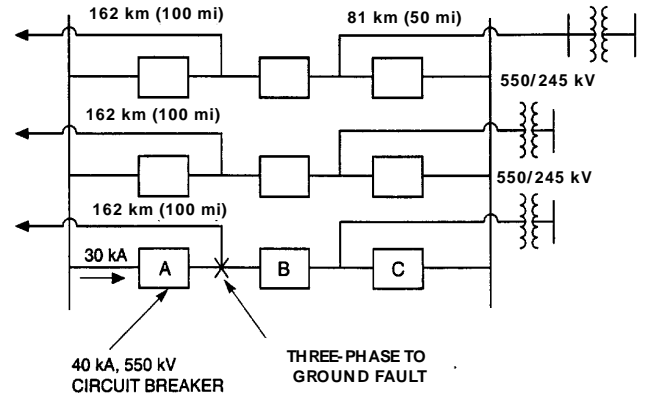


Figure 7- System configuration

Figure 8 also shows the TRV capability curve of a circuit breaker indicating that the breaker TRV capability exceeds system requirements.

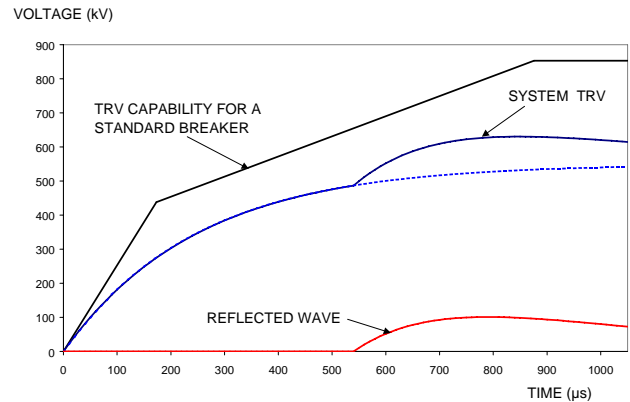


Figure 8 – Comparison of TRV capability for 550 kV circuit breaker and system TRV

1.3 Oscillatory (under-damped) TRV

The oscillatory TRV shown in Figure 9 occurs generally when a fault is limited by a transformer or a series reactor and no transmission line or cable surge impedance is present to provide damping.

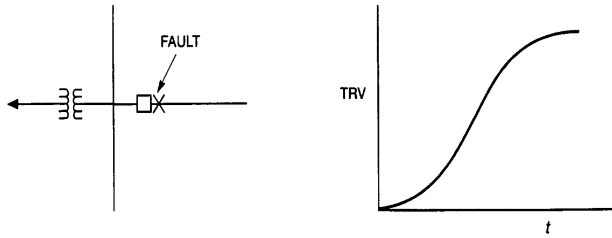


Figure 9 – Transformer limited fault and oscillatory TRV characteristic

Even when overhead lines are present, it is possible for the recovery voltage to be oscillatory. To be oscillatory, the surge impedance of a source side line has to be such that the equivalent surge impedance Z_{eq} is equal or higher than $0.5\sqrt{L_{eq}/C_{eq}}$ (L_{eq} = equivalent source inductance, C_{eq} = equivalent source capacitance). It follows that the number of lines connected is necessarily small and that the short-circuit current is generally low, up to 30% of rated short-circuit current.

Severe TRV conditions occur in some cases, for instance when short-circuit occurs immediately after a transformer without any appreciable additional capacitance between the transformer and the circuit breaker. In such cases, both the peak voltage and rate-of-rise of transient recovery voltage may exceed the values specified in ANSI/IEEE Std C37.06 (see section 3.1).

1.4 Triangular waveshape

Triangular-shaped TRVs are associated with short-line faults (SLF). After current interruption, the line side voltage exhibits the characteristic triangular waveshape shown in Figure 10 (see Annex A5.2 for justification). The rate-of-rise of the saw-tooth shaped TRV is a function of the line surge impedance. It is generally higher than that experienced with exponential or oscillatory TRVs, however the TRV peak is generally lower.

Because overhead lines have distributed electrical parameters (series resistance, shunt conductance, shunt capacitance and series inductance), the line side voltage oscillates in the form of a traveling wave with positive and negative reflections at the open breaker and at the fault, respectively.

The line side component of the recovery voltage has a sawtooth shape and a high rate of rise. Generally, the source recovery voltage rises much more slowly and only the line side triangular recovery voltage is important during the early portion of the TRV (see Figure 11). The closer the fault is to the circuit breaker, the higher the initial rate of rise of the line side recovery voltage due to the higher fault current,

while the crest magnitude of this line side triangular wave decreases due to the shorter time for the reflected wave to return.

The amplitude and rate-of-rise of TRVs for these short-line faults are determined on a single-phase basis during their early time periods (typically less than 20 μ s) when the source side voltage changes only slightly. Later in time, the TRV is less severe than for three-phase terminal faults.

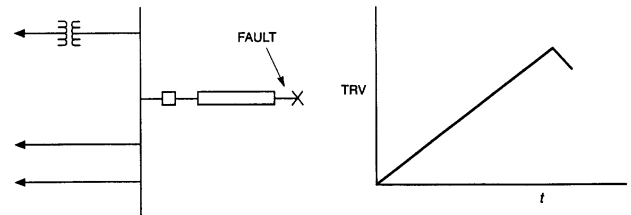


Figure 10 - Short-line fault TRV characteristic

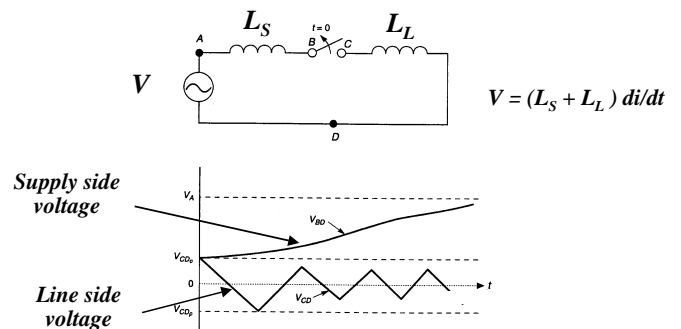


Figure 11 - TRV waveshape for short-line fault

The fault current for a line side fault is somewhat reduced from that obtained for a bus fault due to the additional reactance of the line. Let I_T be the fault current through the circuit breaker for a single-phase fault at the breaker terminal, and I_L be the reduced current for a line fault.

Figure 12 illustrates the case of a single-phase circuit where the fault current is limited by the source reactance (X_S) in series with the line reactance ($X_L \lambda$).

The fault current is given by :

$$I_L = \frac{V_{LG}}{X_L \lambda + X_S}$$

V_{LG} is the phase to ground voltage.

X_L is the reactance of the line to the fault point per unit length

λ is the distance from the opening circuit-breaker to the fault

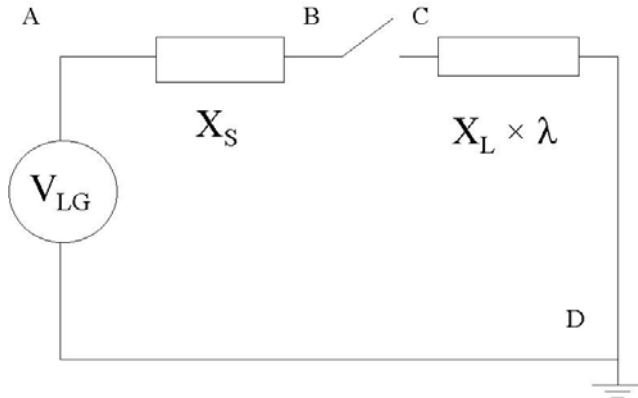


Figure 12 - Single-phase circuit with short-line fault

The source side reactance is given by

$$X_S = \frac{V_{LG}}{I_T}$$

The fault current is then

$$I_L = \frac{V_{LG}}{X_L \lambda + V_{LG} / I_T}$$

where

X_L is $(2 L_{1w} + L_{0w}) \omega / 3$

L_{1w} is the positive sequence power frequency line inductance per unit length

L_{0w} is the zero sequence power frequency line inductance per unit length

ω pulsation (2π times the system power frequency)

The TRV for SLF is specified in ANSI/IEEE Std C37.04 with transmission line parameters given in terms of the effective surge impedance, Z_{eff} , of the faulted line and a peak factor, d :

The rate of rise of recovery voltage on the line side (R_L) is given by the following formula, as function of the fault current (I_L) and the line surge impedance (Z):

$$R_L = \sqrt{2} \omega I_L Z$$

The first peak of TRV seen across the circuit-breaker terminals is the sum of a line-side contribution (e_L) and a source-side contribution (e_S):

$$e = e_L + e_S$$

$$e_L = d(1-M)\sqrt{2/3} E_{max} \text{ kV}$$

$$e_S = 2 M (T_L - t_d)$$

where

t_d is the time delay of TRV on the source side

T_L is the time to peak $T_L = \frac{e_L}{R_L}$

M is the ratio of the fault current to the rated short circuit current

E_{max} is the rated maximum voltage (kV)

This rate-of-rise during SLF is significantly higher than the values that are met during terminal fault interruption:

RRRV = 10.8 kV/ μ s for SLF with $I_L = 45$ kA $f = 60$ Hz

RRRV = 8.64 kV/ μ s for SLF with $I_L = 36$ kA $f = 60$ Hz

RRRV = 3 kV/ μ s for Terminal fault at 60 % of rated breaking current

RRRV = 2 kV/ μ s for Terminal fault at 100% of rated breaking current

The high rate-of-rise of SLF associated with high fault currents (of 45 kA or higher) can be difficult to withstand by circuit breakers. In order to assist the circuit breaker during the interruption, a phase to ground capacitor, or a capacitor(s) in parallel to the interrupting chamber(s), can be used to reduce the rate-of-rise of recovery voltage (RRRV).

When a phase-to-ground capacitor is used, the reduction of line side RRRV is given by

$$RRRV_L = \frac{Z \omega I_L \sqrt{2} \sqrt{C_L}}{\sqrt{C_L + 2.5 C_{add}}}$$

where

$$C_L = \frac{\lambda X_L}{\omega Z^2} \text{ is the total line capacitance}$$

C_{add} is the additional phase-to-ground capacitance

1.5 Pole-to-clear factor and TRV for each pole

The first-pole-to-clear factor (k_{pp}) is the ratio between the recovery voltage across the first pole to clear and the phase to ground voltage of the system. It is a function of the grounding arrangements of the system.

For systems with ungrounded neutral, k_{pp} is or tends towards 1.5. Such systems can be met with rated voltages less than 245 kV, however at transmission voltages, i.e. greater than 72.5 kV, it is increasingly rare and effective grounding is the norm.

For effectively grounded neutral systems, the realistic and practical value is dependent upon the sequence impedances of the actual earth paths from the location of the fault to the various system neutral points (ratio X_0/X_1). For these systems the ratio X_0/X_1 is taken to be less or equal to 3.0 and k_{pp} is 1.3.

For special applications in transmission systems with effectively grounded neutral where the probability of three-phase ungrounded faults cannot be disregarded, a first-pole-to-clear factor of 1.5 may be required.

In the case of single-phase faults in an effectively grounded system, k_{pp} is 1.0.

Generally it will not be necessary to consider alternative transient recovery voltages as the standard values specified cover the majority of practical cases.

- Equation for the first-pole-to-clear factor

$$k_{pp} = \frac{3X_0}{X_1 + 2X_0}$$

where X_0 is the zero sequence, and X_1 the positive sequence reactance of the system.

If $X_0 \gg X_1$, as in ungrounded systems then: $k_{pp} = 1.5$

If $X_0 = 3.0 X_1$, as in effectively grounded neutral systems then: $k_{pp} = 1.3$

- Equations for the other clearing poles

a) Systems with ungrounded neutrals

As illustrated in Figure 13, after interruption of the first phase (A), the same fault current is carried in phases B and C (but with opposite sign). This current is interrupted by the last two poles in series under the phase-to-phase voltage ($E_B - E_C$) equal to $\sqrt{3}$ times the phase-to-voltage. Each pole shares half of the phase-to phase voltage, so that for each pole:

$$k_{pp} = \frac{\sqrt{3}}{2} = 0.87$$

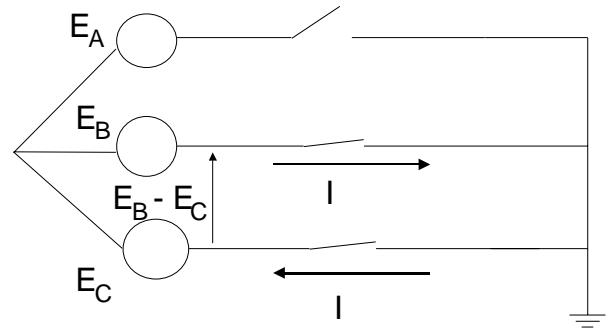


Figure 13 - Ungrounded system after interruption of the first phase

b) Systems with effectively grounded neutrals

In systems with effectively grounded neutrals, the second pole clears a three-phase to ground fault with a factor of

$$k_{pp} = \frac{\sqrt{3} \sqrt{X_0^2 + X_0 X_1 + X_1^2}}{X_0 + 2X_1}$$

This formula can be expressed as a function of the ratio X_0/X_1 :

$$k_{pp} = \frac{\sqrt{3} \sqrt{\alpha^2 + \alpha + 1}}{2 + \alpha}$$

where $\alpha = X_0/X_1$

If $\alpha = 3.0$, the second pole to clear factor is 1.25.

For the third pole-to-clear: $k_{pp} = 1$

Table 1 gives k_{pp} for each clearing pole as a function of X_0/X_1 as appropriate.

As the amplitude factor is the same for each pole, the multiplying factors of Table 1 are also applicable to the TRV on each pole.

In the special case of three-phase ungrounded faults, the pole-to-clear factors are as defined in a) for three-phase faults in ungrounded systems.

Table 1 - Pole-to-clear factors (k_{pp}) for each pole when clearing three-phase to ground faults

neutral	X_0/X_1	Pole-to-clear factor k_{pp}		
		Ratio	First	Second
ungrounded	Infinite	1.5	0.87	0.87
Effectively grounded	3.0	1.3	1.25	1.0
See note	1.00	1.0	1.00	1.0

Note: values of the pole-to-clear factor are given for $X_0/X_1 = 1.0$ to indicate the trend in the special case of networks with a ratio X_0/X_1 of less than 3.0.

- TRV on each pole to clear

Figure 14 shows the TRV on each pole to clear during interruption of a three-phase to ground terminal fault in an ungrounded system. The same TRV would be applied in the case of a three-phase ungrounded fault.

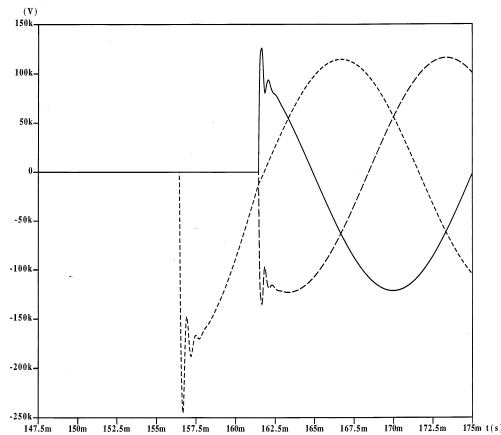


Figure 14 -TRV on each pole to clear during a three-phase to ground terminal fault in an ungrounded system.

Figure 15 shows the TRV on each pole to clear during interruption of a three-phase to ground terminal fault in an effectively grounded system.

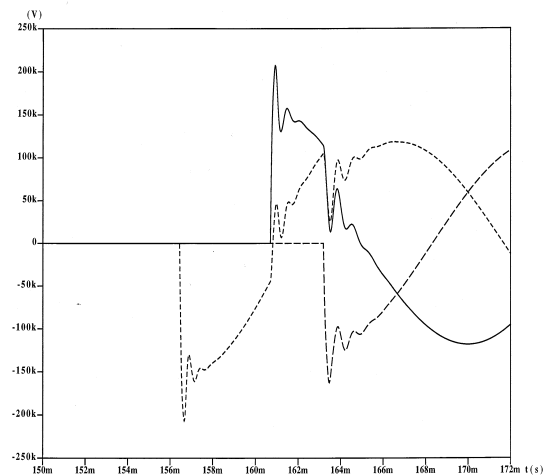


Figure 15 - TRV on each pole to clear during a three-phase to ground terminal fault in an effectively grounded system.

1.6 Effect of current asymmetry on TRV

The TRVs that occur when interrupting asymmetrical current values are less severe than when interrupting the related symmetrical current. When the circuit breaker interrupts, at current zero, the instantaneous value of the supply voltage is less than the peak value supply voltage, due to the DC component of the asymmetrical current. Therefore, the TRV oscillates around a lower voltage value and is lower than in the symmetrical case (see also 3.3.2 in [7]).

IEEE Std C37.081a-1997 gives the reduction factors of TRV peak and rate of rise of recovery voltage (RRRV) when interrupting asymmetrical currents.

II. RATING AND TESTING

2.1 Terminal fault

The TRV ratings for circuit breakers are applicable for interrupting three-phase to ground faults at the rated symmetrical short circuit current and at the maximum rated voltage of the circuit breaker. For values of fault current other than rated and for line faults, related TRV capabilities are given. Rated and related TRV capabilities are described in ANSI/IEEE Std C37.04 and given in detail in ANSI C37.06.

While three-phase ungrounded faults produce the highest TRV peaks, the probability of their occurrence is very low. Therefore, as described in ANSI/IEEE Std C37.04, the TRV ratings are based on three-phase grounded faults with the TRV peaks established based on the grounding arrangements prevalent at the respective system voltages.

For circuit breakers applied on systems 72.5 kV and below, the TRV ratings assume that the systems can be operated ungrounded. The first pole-to-clear factor k_{pp} is 1.5.

For circuit breakers applied on systems 245 kV and above, the TRV ratings assume that the systems are all operated effectively grounded: the first pole-to-clear factor k_{pp} is 1.3. For systems 100 through 170 kV the systems can be operated either ungrounded or effectively grounded so two TRV ratings are available for these systems ($k_{pp} = 1.3$ or 1.5). In addition, for special applications in transmission systems where the probability of three-phase ungrounded faults cannot be disregarded, a first pole-to-clear factor of 1.5 may be required.

The two-parameter and four-parameter envelopes, illustrated in Figures 16 and 17, have been introduced in ANSI/IEEE Std C37.04 in order to facilitate the comparison of a TRV obtained during testing and a specified TRV. In a similar way it is possible to compare a circuit-breaker specified TRV capability and a system TRV obtained by calculation.

Two-parameter and four-parameter envelopes are used respectively for oscillatory (under-damped) and exponential (damped) TRVs. For standardization purposes, two-parameter envelopes are specified for circuit breakers rated less than 100 kV, at all values of breaking current, and for circuit breakers rated 100 kV and above if the short-circuit current is equal or less than 30% of the rated breaking current. Four-parameter envelopes are specified in other cases.

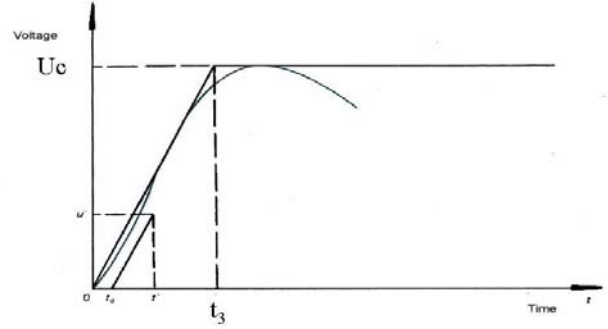


Figure 16 - Example of inherent test TRV with two-parameter envelope

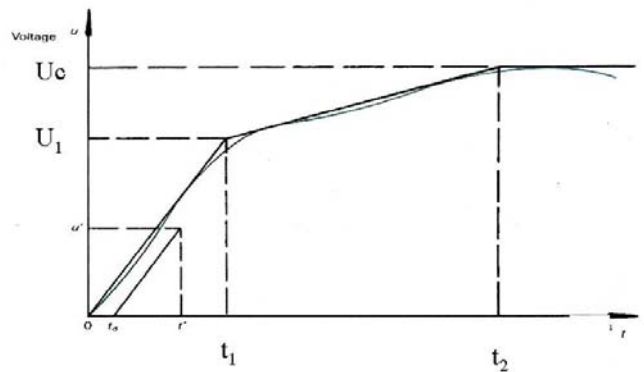


Figure 17 - Example of inherent test TRV with four-parameter envelope

The peak value of TRV is defined as follows

$$u_c = k_{pp} \times k_{af} \times \sqrt{2/3} \times U_r$$

where

k_{pp} is the first pole to clear factor (see section 7).

k_{af} is the amplitude factor (ratio between the peak value of TRV and the peak value of the recovery voltage at power frequency)

Typical values of k_{af} are 1.4 and 1.7 respectively at 100% and 10% of rated breaking current.

A circuit breaker TRV capability is considered to be sufficient if the two or four parameter envelope drawn with rated parameters is higher than the two or four parameter envelope of the system TRV. This procedure is justified as it allows comparison of the circuit breaker TRV capability and the system TRV in the two regions where a reignition is likely, i.e. during the initial part of the TRV where the RRRV is maximum and in the vicinity of the peak voltage (u_c). Generally, if the circuit breaker can withstand the initial TRV rate of rise, and the TRV peak, it will successfully interrupt. These are the most critical areas to check.

The general characteristics of the TRV envelopes defined by ANSI/IEEE Std C37.04 are illustrated in Figures 18 and 19 as a function of the fault current magnitude.

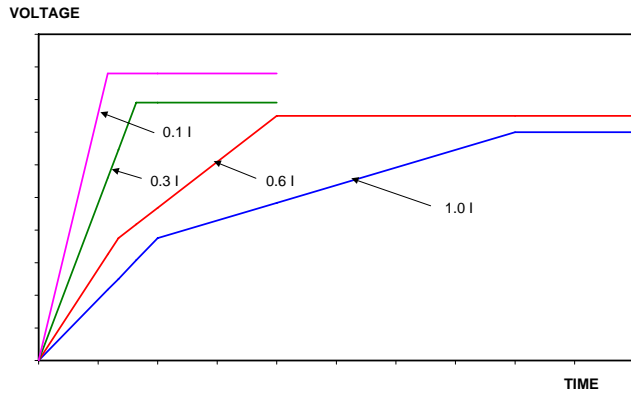


Figure 18 - TRV envelopes, 100 kV and above (I is the rated short-circuit current)

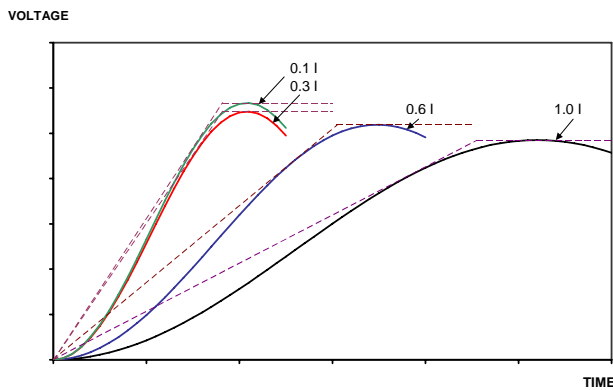


Figure 19 - TRV envelopes, 72.5 kV and below

As explained in section 1, the rate-of-rise of recovery voltage (RRRV) decreases when the short-circuit current is increased. For circuit-breakers rated 100 kV and above, standard values of RRRV are 2kV/μs and 3 kV/μs respectively for terminal fault tests at 100 % and 60 % of rated short-circuit current.

Tests are required at 100%, 60%, 30% and 10% of rated short-circuit current with the corresponding TRVs and recovery voltages [10].

Tests are generally performed with symmetrical and asymmetrical currents, as both conditions are possible in service. However when interrupting asymmetrical currents, the rate-of-rise and peak value of TRV are reduced (see 1.6).

In a network, the initial part of the TRV may have an initial oscillation of small amplitude, called ITRV, due to reflections from the first major discontinuity along the busbar. The ITRV is mainly determined by the busbar and line bay configuration of the substation. The ITRV is a physical phenomenon that is very

similar to the short-line fault (see 2.2). Compared with the short-line fault, the first voltage peak is rather low, but the time to the first peak is extremely short, within the first microseconds after current zero. If a circuit breaker has a short-line fault rating, the ITRV requirements are considered to be covered. Since the ITRV is proportional to the busbar surge impedance and to the current, the ITRV requirements can be neglected for all circuit-breakers with a rated short-circuit breaking current of less than 25 kA and for circuit-breakers with a rated voltage below 100 kV. In addition the ITRV requirements can be neglected for circuit-breakers installed in metal enclosed gas insulated switchgear (GIS) because of the low surge impedance

2.2 Short line fault

The rated values for the line surge impedance Z and the peak factor d are defined in ANSI/IEEE Std C37.04 as follows:

$$Z = 450 \Omega \quad d = 1.6$$

The line side contribution to the initial part of TRV is defined as a triangular wave in ANSI/IEEE Std C37.09 as follows:

$$e_L = d(1 - M)\sqrt{2/3} U_r \quad kV$$

$$R_L = \sqrt{2}\omega M I Z \cdot 10^{-6} \quad kV/\mu s$$

$$T_L = e_L / R_L \quad \mu s$$

where

- e_L is the peak value of TRV on the line side (kV)
- R_L is the rate-of-rise (kV/μs)
- T_L is the time to peak (μs)
- M is the ratio of the fault current to the rated short circuit current
- U_r is the rated maximum voltage (kV)
- I is the rated short circuit current (kA)

The TRV across the interrupter is in reality the difference between the transient recovery voltages on the supply and on the line side. As illustrated in Figure 20, the variation of the source side voltage increases the first peak value of TRV by e_s .

$$e_{total} = e_s + e_L$$

As a first approximation, the contribution from the source side voltage can be estimated by considering that the variation of the source side voltage is zero until time $td = 2 \mu s$ (standard value of time delay), and then changes with a slope of 2 kV/μs (standard value of RRRV for terminal fault) up to time T_L .

In this approximation, it is considered that the RRRV is the same as for three-phase terminal faults. In reality it is reduced by the factor M as RRRV is proportional to the fault current (on the source side $RRRV = 2 \times M$).

$$e_s = (T_L - 2\mu s) \times 2M$$

Tests are required at 90% and 75% of rated short-circuit current with the corresponding TRVs and recovery voltages [10].

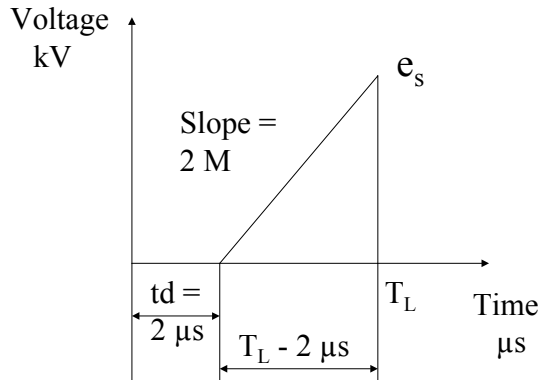


Figure 20 - Contribution of the source side voltage on TRV

2.3 Out-of-Phase

TRVs for out-of-phase conditions are specified as for terminal fault, except that the pole to clear factor is equal to 2.0 and 2.5 respectively for systems with effectively grounded neutral and for systems with ungrounded neutral.

Tests are required at 25% and 5-10% of rated short-circuit current with the specified TRV and recovery voltage [10].

III. APPLICATION CONSIDERATIONS

3.1 Transformer limited fault

TRVs associated with transformer limited faults are generally covered by the standard TRVs defined in ANSI/IEEE C37.06 for terminal fault test duties with 10% and 30% of rated short-circuit current. However, severe TRV conditions may occur when short-circuit occurs immediately after a transformer without any appreciable additional capacitance between the transformer and the circuit breaker. In such cases, both the peak voltage and rate-of-rise of transient recovery voltage may exceed the values specified in ANSI/IEEE Std C37.06.

As an example, Figure 21 shows the case of a 40 kA, 145 kV circuit breaker that has to clear a three-phase

fault at 10% of its rating. The resultant TRV is shown in Figure 22.

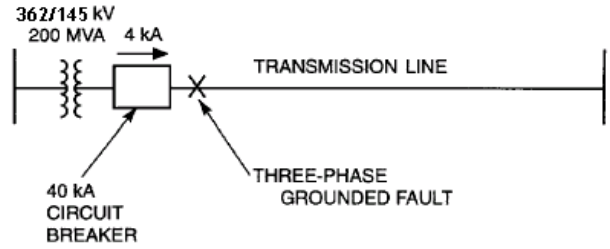


Figure 21 - Fault location

This TRV is determined by the inductance and capacitance of the transformer and by the capacitance between the transformer and the circuit breaker. In this particular case, the circuit breaker does not have the capability to withstand the imposed system TRV, unless the system is modified.

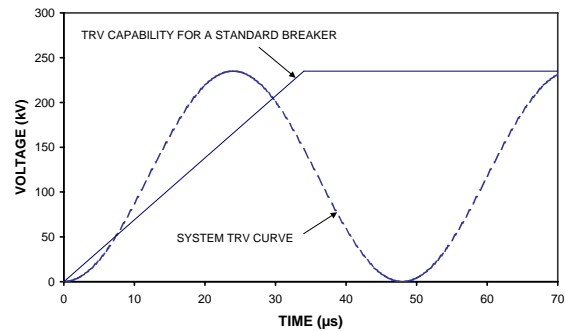


Figure 22 - Comparison of TRV capability for 145 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV

Guidance for such cases are given in IEEE C37.011-2005 [7] and in the ANSI Guide C37.06.1-2000 [8]. TRV values for Definite purpose circuit breakers could be specified when the rate of rise of the system TRV is higher than the rate of rise of the standard capability curve defined in ANSI C37.06, or, as an alternative, the system TRV curve can be modified by a capacitance and then be within the standard capability envelope.

Figure 23 illustrates the modified system TRV for the condition of Figure 21, but with additional capacitance assumed between the transformer and the circuit breaker.

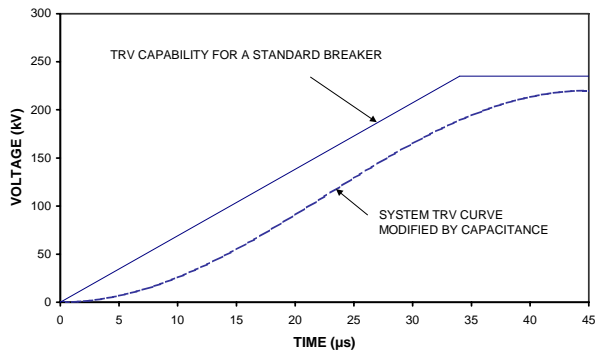


Figure 23 - Comparison of TRV capability for 145 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV modified by additional capacitance between circuit breaker and transformer

3.2 Series reactor limited fault

Series reactor are used to limit the short-circuit current in a line. When line side series reactors are used, high rate-of-rise TRVs can result in much the same ways as for transformer limited faults.

An example of a series reactor used on a 230 kV system is illustrated in Figure 24. The resultant TRV for the case described is shown in Figure 25. The same TRV is obtained if the reactor is on the bus side of the circuit breaker and the fault is on the line side of the circuit breaker.

This system TRV may exceed the standard capability curve, which is described by a two-parameter envelope where u_c and t_3 are defined in ANSI C37.06 for 10% short-circuit breaking capability, maximum voltage.

When the system TRV exceeds a standard breaker capability, the user has two possibilities

- either specify a Definite Purpose circuit breaker for fast transient recovery voltage rise times, as defined in ANSI C37.06.1-2000 [8]. In some cases their higher TRV withstand capability will be sufficient,
- or add a capacitance in parallel to the reactor in order to reduce the TRV frequency and have a system TRV curve within the standard capability envelope.

The available mitigation measures are very effective and cost efficient. It is therefore strongly recommended to use them, unless it can be demonstrated by tests that a circuit breaker can successfully clear faults with the required high frequency TRV.

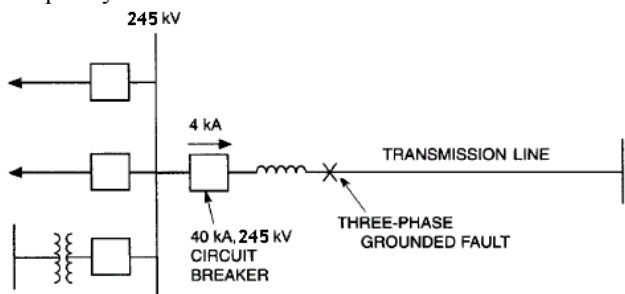


Figure 24 – Series reactor limited fault

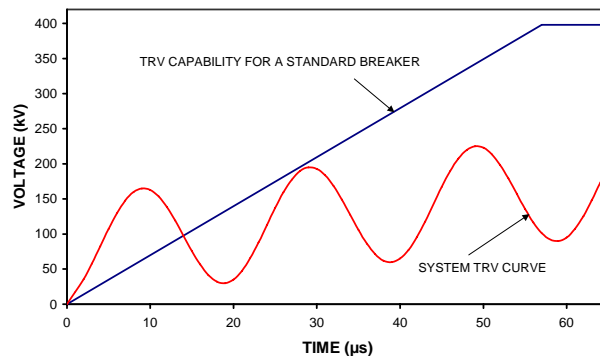


Figure 25 - Comparison of TRV capability for 245 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV

3.4 Long line faults

In the case of networks with long lines, even if they are effectively grounded, it may occur that the TRV for the first pole to clear is higher than the value that can be calculated with a first pole to clear factor of 1,3 and an amplitude factor of 1.5. This is due to the fact that during interruption of three-phase line faults, mutual coupling of lines between the first interrupted phase and the two other phases can increase the line side contribution of TRV on the first pole to clear.

Following studies made in Japan and in the USA by BPA, CIGRE Working Group A3-19 is investigating the matter and has already recommended to increase the peak value of TRV for test duty T10 (amplitude factor is 1.76 when the first pole to clear factor is 1.3) and reduce the time to peak for terminal fault test duty T60 and out-of-phase. These changes are taken into account in the current revision of IEEE C37.06.

IV. SPECIAL CASE OF GENERATOR CIRCUIT BREAKERS

Special TRV requirements are applicable for generator circuit breakers installed between a generator and a transformer.

As illustrated in Figure 26, two types of faults need to be considered.

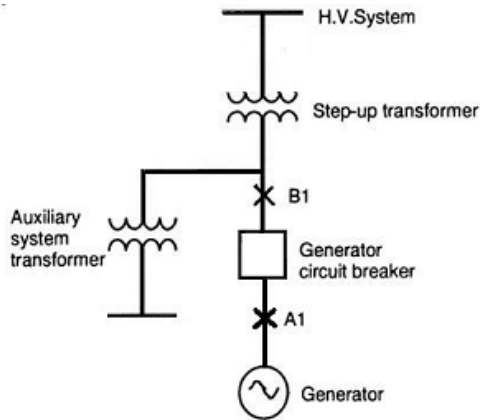


Figure 26 Fault conditions for Generator circuit breakers

A1 System-source fault B1 Generator-source fault

For the two types of fault, the TRV has an oscillatory waveshape and the first pole to clear factor is 1.5 in order to cover three-phase ungrounded faults. TRV parameters, i.e. peak voltage u_c , rate-of-rise (RRRV) and time delay, are listed in ANSI/IEEE C37.013.

- TRV for system-source faults

RRRV for system-source faults is 3-5 times higher than the values specified for distribution or sub-transmission circuit breakers. This is due to the fact that the TRV frequency is dominated by the natural frequency of step-up transformer if one considers the more severe case where the capacitance on the high side of the transformer can be neglected.

After reviewing the available transformer data of many power plants, the IEEE standardization group has defined TRV parameters in several ranges of transformer rated power.

The RRRV can be significantly reduced if a capacitor is

installed between the circuit breaker and the transformer. It is also reduced in the special cases where the connection between the circuit breaker and the transformer(s) is made by cable(s) [16]. This is covered in an amendment to ANSI/IEEE C37.013 [18].

Figure 27 RRRV for system-source faults – Transformers 50 MVA to 100 MVA

- TRV for generator-source faults

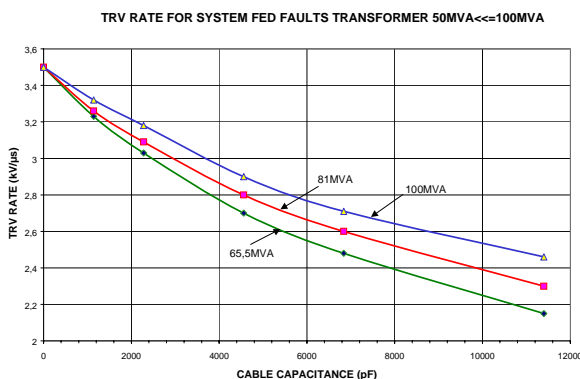
RRRV for generator-source faults is roughly two times higher than the values specified for distribution or sub-transmission circuit breakers. The values were defined after reviewing the data of many generators.

Due to the large time constants of generators and transformers (high X/R), Generator circuit breakers are required to interrupt currents with a high percentage of dc component (high asymmetry). The rate-of rise and peak value of TRV during interruption of currents with large asymmetry are reduced (see 1.6).

V. SELECTION OF A CIRCUIT BREAKER

The TRV ratings define a withstand boundary. A circuit TRV that exceeds this boundary at rated short circuit current, or the modified boundary for currents other than rated, is in excess of the circuit breaker's rated or related capability. Either a different circuit breaker should be used, or the system should be modified in such a manner as to change its transient recovery voltage characteristics when the withstand boundary is exceeded. The addition of capacitors to a bus or line is one method that can be used to improve the system's recovery voltage characteristics.

In special cases where the terminal fault TRV capability at 60% or 100% of short-circuit capability is higher than rated, a breaker with a higher rated interrupting capability could be used (see ANSI/IEEE C37.011 [7]).



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VII BIOGRAPHIES

Denis Dufournet graduated from ENSEM Nancy in Electrical engineering, in 1975. He joined AREVA T&D (then Delle Alsthom) in 1977 as a research engineer. He is currently Senior Expert, Head of research in AREVA T&D, Villeurbanne, France. Since 1983 he is member of Working groups and Technical Committees in IEC, IEEE and CIGRE. While participating in these activities, he received several awards from CIGRE: Distinguished Member in 2002, Diplôme d'Honneur from the Technical Committee in 2001.

He has been elected Fellow of the IEEE in 2005, and is chairman of IEEE WG C37.011 "Application Guide for TRV for High Voltage Circuit Breakers". He received the IEEE Standardization Association International Award in 2005.

In IEC, he is Chairman of IEC TC 17 (Switchgear and Controlgear) and SC17A (High Voltage Switchgear and Controlgear) since April, 2004, he is member of Maintenance teams 36 and 37.

In CIGRE, he is presently member of WG A3-19 and A3-22. Previously he has been a member of CIGRE WG 13-01 (Practical applications of arc physics), CIGRE-CIRED CC03 (TRV in Medium voltage networks) and CIGRE WG A3-11 (Application Guide for IEC 62271-100 and 62271-1)

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 Kirk Smith was born in Camden, New Jersey, USA in 1948. He received the B.S.E.E. ('70 degree in electrical engineering from Drexel University, Philadelphia, PA, and the M.S.E.E. ('71) and Ph.D. ('74) degrees in electrical engineering from the University of Pittsburgh, Pittsburgh, PA, with the specialization in electrical power engineering. Dr. Smith has 33 years of research and product development experience in a wide range of technologies in the switching of electric current. He is presently the Manager of the Power

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ANNEX A

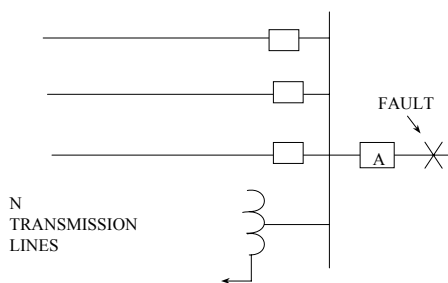
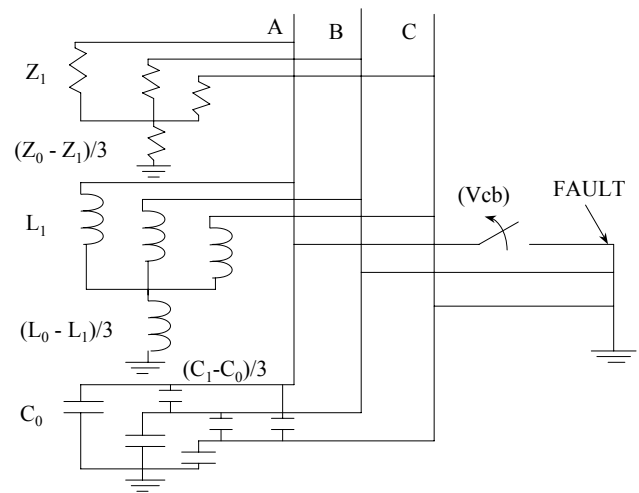
A.1 Three-phase terminal fault

During the interruption of a three-phase terminal fault, the circuit shown in Figure A.1 defines the general electrical equivalent network for the first phase to clear. The reduced circuits are valid for short time frames until reflections return from remote buses. Reflections are covered in A.4.

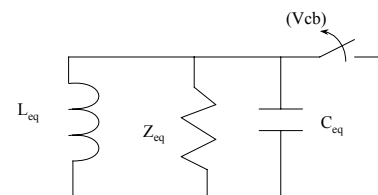
Figure A.1a) shows the corresponding one-line diagram representations, while Figure A.1b) indicates the three-phase representation.

The equivalent circuit given by Figure A.1c) shows that it is reduced to a simple parallel RLC circuit:

ANSI/IEEE C37.011 provides methods for the determination of parameters (such as L_1) and gives typical values of Z_1 , Z_0 and capacitances of various equipment.



a) Single line diagram



b) Three-phase diagram

c) Equivalent circuit

Figure A.1— Circuit definition for the interruption of a three-phase to ground fault

A.2 Exponential (overdamped) TRV

Current injection techniques can be used to solve for the circuit breaker TRV and, because the time span of interest is short (microseconds), the interrupted current can be represented by a ramp. The solution for the parallel RLC network as shown in Figure A.1c) is

$$V_{cb} = E_I (1 - e^{-\alpha t} (\cosh \beta t + \alpha/\beta \sinh \beta t)) \text{ kV} \quad (\text{A-3})$$

where

V_{cb} is the voltage across the open circuit breaker contacts

$$E_I \text{ is } \sqrt{2} I \omega L_{eq} \text{ in kV}$$

$$\omega \text{ is } 2 \pi f = 377 \text{ rads for 60 Hz systems}$$

$$I \text{ is short circuit current in kA, rms}$$

$$\alpha \text{ is } 1/(2Z_{eq}C_{eq})$$

$$\beta \text{ is } \sqrt{\alpha^2 - 1/(L_{eq}C_{eq})}$$

$$Z_{eq} \text{ is in ohms}$$

$$L_{eq} \text{ is in henrys}$$

$$C_{eq} \text{ is in farads}$$

For many systems the circuit will be overdamped by the parallel resistance of the line surge impedances, thus the capacitance can be neglected as a first approximation. The solution to the simple RL circuit is then

$$V_{cb} = EI (1 - e^{-t/\tau}) \text{ kV} \quad (\text{A-4})$$

where

$$\tau \text{ is } L_{eq} / Z_{eq} \text{ s}$$

The derivative of equation (A-4) at time zero is the rate of rise of the recovery voltage and is given by

$$dV_{cb}/dt = R = \sqrt{2} I \omega Z_{eq} 10^{-6} \text{ kV}/\mu\text{s} \quad (\text{A-5})$$

The above exponential expressions [see equations (A-3), (A-4), (A-5)] describe the component of the TRV until reflections return from remote stations associated with the transmission lines connected to the faulted station.

A.3 Oscillatory (underdamped) TRV

If there are no lines on the bus, then the resistance is removed from the equivalent circuit in Figure A.1c), and the TRV will be oscillatory. An approximate expression for the voltage is given in equation (A-6). The expression is approximate because of neglecting the source impedances behind the transformers.

$$V_{cb} = E_I [1 - \cos(t / \sqrt{L_{eq}C_{eq}})] \text{ kV} \quad (\text{A-6})$$

Even when lines are present, it is possible for the recovery voltage to be oscillatory. To be oscillatory, the surge impedance of a source side line has to be such that

$$Z_{eq} \geq 0.5 \sqrt{L_{eq} / C_{eq}}$$

With Z_{eq} , L_{eq} and C_{eq} as defined in A.1.

This formula shows that as the number of transmission lines is increased, the circuit is likely to be nonoscillatory, i.e., overdamped. In most cases, however, even $N=1$ makes the circuit overdamped.

A.4 Reflected waves

The initial wave that was calculated in equation (A-4) appears across the breaker pole. It also appears as traveling waves on each of the transmission lines. When one of these waves reaches a discontinuity on the line such as another bus or a transformer termination, a reflected wave is produced, which travels back towards the faulted bus. The time for a wave to go out and back to a discontinuity is

$$T = 6.65 l \sqrt{\mu k} \quad \mu\text{s} \quad (\text{A-7})$$

l is the distance to the first discontinuity (in kilometer)

μ is the magnetic permeability

k is the dielectric constant

for overhead lines

$$\sqrt{\mu k} = 1.0 \quad \text{and } Z_1 \text{ about 400 ohms (less for bundled conductor } 250 < Z_1 < 350)$$

for cables, typically

$$\text{Paper insulated fluid filled } k = 4, \mu = 1.0 \text{ and } \sqrt{\mu k} = 2$$

$$\text{PPP insulated fluid filled or EPR } k = 3, \mu = 1.0 \text{ and}$$

$$\sqrt{\mu k} = 1.73$$

$$\text{Polyethylene } k = 2.3, \mu = 1.0 \text{ and } \sqrt{\mu k} = 1.52$$

$$\text{Cable Surge Impedance (ohms) } 20 < Z_1 < 50$$

At a discontinuity transmitted and reflected waves can be described by equations (A-8) and (A-9) and Figure A.2.

Transmitted wave

$$e_t = e_i [2Z_b / (Z_a + Z_b)] \quad (\text{A-8})$$

Reflected wave

$$e_r = e_i [(Z_b - Z_a) / (Z_a + Z_b)] \quad (\text{A-9})$$

where

e_i is the incident wave

Z_a and Z_b are the equivalent surge impedances on either side of the discontinuity

Returning to the bus, the reflections are in turn reflected to begin the process again. A typical TRV, including the first reflection, is shown in Figure A.3. A reflected wave returning from an open ended line will contribute to the bus side TRV as follows:

$$E_{r1} = E_1 (2 Z_{eq} t / L_{eq}) e^{-Z_{eq} t / L_{eq}} \text{ kV} \quad (\text{A-10})$$

where $Z_{eq} = Z_a = 1.14 \frac{Z_1}{n}$ and $L_{eq} = \frac{3L_0L_1}{L_1 + 2L_0}$

From (A-10) it can be shown that the maximum reflected voltage is $E_{r1} \text{ max} = 0.7 E_1/n$. The more lines connected, the lower the magnitude of the reflected wave.

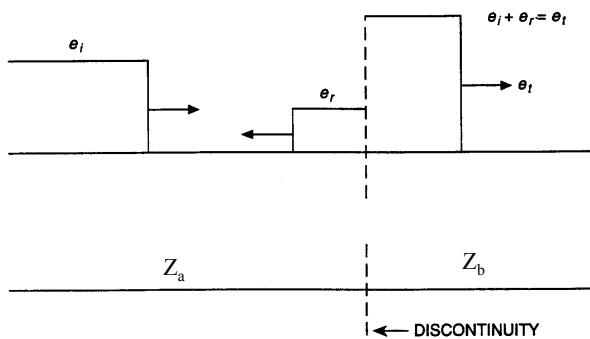


Figure A.2— Traveling waves at discontinuity

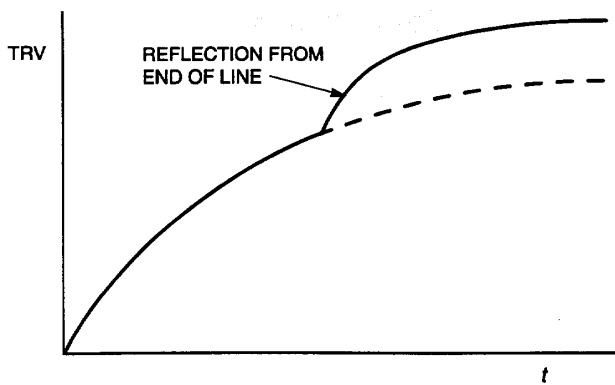


Figure A.3— Typical TRV including the first reflection

A.5 Short-line fault

A.5.1 General

Figure A.4 illustrates the single-phase circuit where the short-circuit current is limited by the source reactance (X_S) in series with the line reactance ($X_L \lambda$):

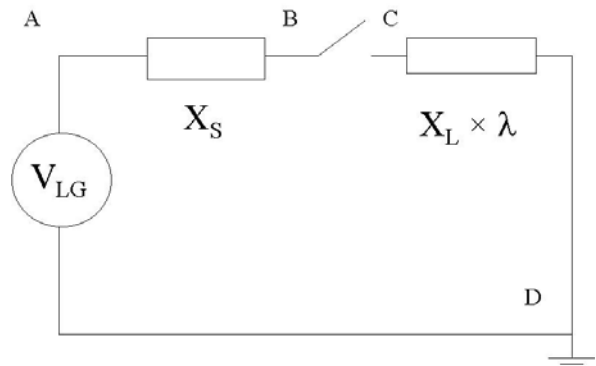


Figure A.4 - Single-phase circuit with short-line fault

The fault current is given by:

$$I_L = \frac{V_{LG}}{X_L \lambda + X_S}$$

The source side reactance is given by

$$X_S = \frac{V_{LG}}{I_T}$$

The fault current is then

$$I_L = \frac{V_{LG}}{X_L \lambda + V_{LG} / I_T} \quad (\text{A-11})$$

where

$$X_L \text{ is } (2 L_{1w} + L_{0w}) \omega / 3 \quad (\text{A-12})$$

X_L is the reactance of the line to the fault point per unit length

L_{1w} is the positive sequence power frequency line inductance per unit length

L_{0w} is the zero sequence power frequency line inductance per unit length

V_{LG} is the system line-ground voltage

λ is the distance from the opening circuit-breaker to the fault

A.5.2 Determination of line side voltage by traveling wave

Traveling wave theory can be applied theory can also be applied to the case of a line fault.

At the time of interruption ($t=0$) the instantaneous voltages on the circuit breaker terminals (points B and C in figure A.4) are at a maximum. The voltage decreases linearly along the line and is zero at the location of the fault (point D).

As shown on the upper part of Figure A.5, the voltage distribution can be considered as the sum of two waves, of equal amplitude, that are traveling in opposite directions.

In accordance with the theory given in A.4, when a traveling wave reaches the open circuit (Fig A.4 point B), the reflected wave is of same amplitude and with the same polarity. When a traveling wave reaches the short-circuit (fig A.4 point D), the reflected wave is of the same amplitude as the incident wave but of opposite polarity.

The application of these two basic rules leads to Figure A.5 which shows the distribution of voltages on the faulted line at times 0 , $t_L/4$, $3t_L/8$, $t_L/2$, $3t_L/4$ and t_L . Time t_L represents the time necessary for the traveling wave to reach the fault and be reflected back to the circuit breaker.

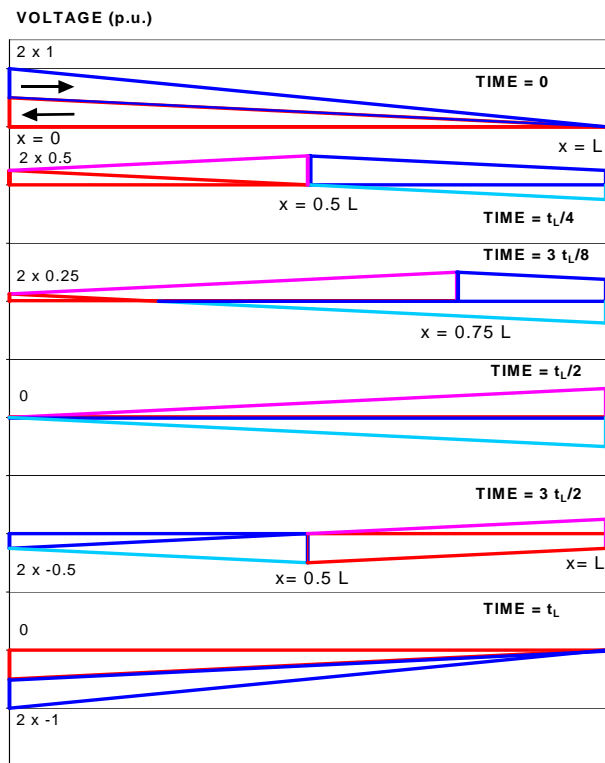


Figure A.5 - Traveling waves on a faulted line after current interruption

The total voltage at each point of the line, and at any given time, is the sum of all waves. Figure A.6 shows the resulting distribution of voltage on the line at several times after current interruption.

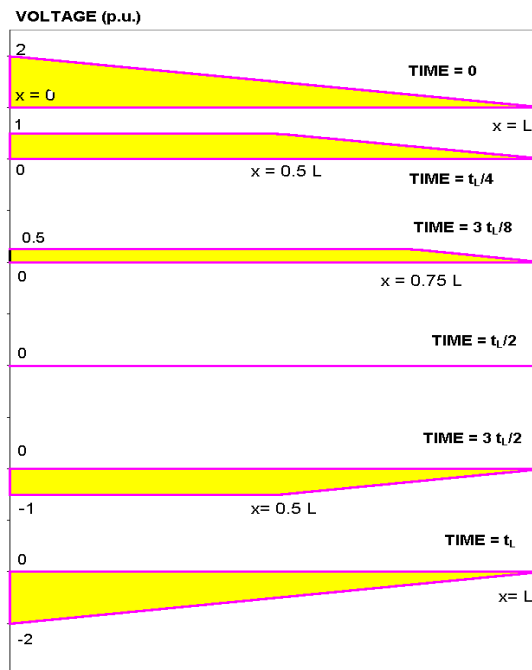


Figure A.6 - Voltage distribution on the line at different times after current interruption

Figure A.7 shows the corresponding time-variation of voltages at different locations on the line: at the circuit breaker terminal (fig A.4 point C, ($x=0$)), half-way to the fault ($x=0.5L$) and three-quarters of the way to the fault ($x=0.75L$). It can be verified that the voltage on the line side terminal of the circuit breaker varies with a triangular shape, it is assumed here that there is no damping.

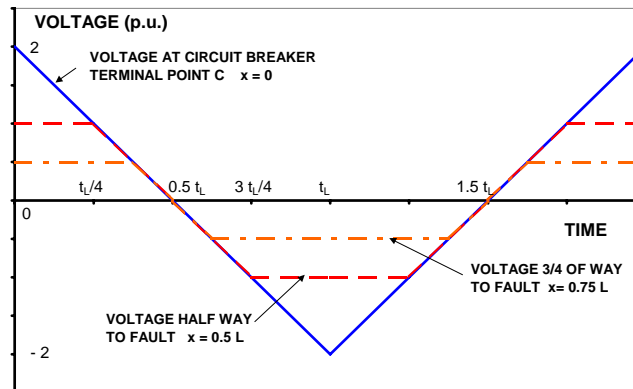


Figure A.7 - Time variations of voltages at three locations on the faulted line

A.5.3 Calculation of Short-line fault quantities

In this sub-clause we give practical applications of the theory developed in sections 4 and 6.2.

We consider the case of a 245 kV circuit breaker application in a network with a single-phase short-circuit current of 40 kA and a power frequency of 60 Hz.

According to the notations in 4 and 6.2, we have

$$V_{LG} = \frac{U_r}{\sqrt{3}} = \frac{245}{\sqrt{3}} = 141.5 \text{ kV}$$

$$I = I_T = 40 \text{ kA}$$

A.5.2.1 Calculation of the line length corresponding to a fault with 90% of rated short-circuit current

$$M = 0.9$$

$$I_L = 0.9 I_T = 0.9 \times 40 = 36 \text{ kA}$$

Source side reactance

$$X_S = \frac{V_{LG}}{I_T} = \frac{245}{\sqrt{3} \cdot 40} = 3.536 \Omega$$

As explained in section 4 :

$$I = 36 = \frac{V_{LG}}{X_L \lambda + X_S} = \frac{245/\sqrt{3}}{X_L \lambda + 3.536}$$

it follows that

$$X_L \lambda = \frac{245}{36\sqrt{3}} - 3.536 = 3.929 - 3.536 = 0.393 \Omega \quad (1)$$

where

X_L is the reactance of the line to the fault point per unit length

X_L is $(2L_1\omega + L_0\omega) / 3$

L_1 is the positive sequence power frequency line inductance per unit length

L_0 is the zero sequence power frequency line inductance per unit length

V_{LG} is the system line-ground voltage

λ is the distance from the opening circuit-breaker to the fault

ω is $2\pi \times$ system power frequency (377 rad/s for a 60 Hz system)

$$X_L = (2L_1 + L_0) \frac{\omega}{3} = \frac{2X_1 + X_0}{3}$$

with

$$X_1 = L_1 \omega = 0.5 \Omega / \text{km}$$

$$X_0 = L_0 \omega = 1.2 \Omega / \text{km}$$

$$X_L = \frac{2 \times 0.5 + 1.2}{3} = \frac{2.2}{3} \Omega / \text{km} \quad (2)$$

From (1) and (2)

$$\lambda = \frac{0.393}{2.2/3} = \frac{3 \times 0.393}{2.2} = 0.536 \text{ km}$$

A.5.2.2 Calculation of the fault current corresponding to a length of faulted line

In this second example of calculation we consider the case of a fault 1.5 km away on the line.

$$X_L \lambda = \frac{2.2}{3} \cdot 1.5 = 1.1 \Omega$$

$$I = \frac{245 / \sqrt{3}}{1.1 + 3.536} = \frac{141.45}{4.636} = 30.5 \text{ kA}$$

$$\text{It follows that } M = \frac{30.5}{40} = 0.76$$

The fault current is 76% of the maximum (single-phase) short-circuit current.

A.5.2.3 Calculation of the first peak of TRV

In the example A.5.3.1, M is 0.9 i.e. the fault current is 90% of the rated short-circuit current.

a) Contribution of the line side voltage (e)

$$e = d (1 - M) \sqrt{2/3} U_r$$

$$e = 1.6 \times 0.1 \times \sqrt{2/3} \times 245 = 32 \text{ kV}$$

b) Contribution of source side voltage (e_S)

As explained in sub-clause 6.2, the contribution of the source side voltage is:

$$e_S = 2 \times M (T_L - 2) \quad (3)$$

The time to peak T_L is determined as follows:

$$R_L = \sqrt{2} \omega Z M I$$

$$R_L = \sqrt{2} \times 377 \times 450 \times 0.9 \times 40 \cdot 10^{-6} \text{ kV} / \mu\text{s}$$

$$= 0.24 \times 0.9 \times 40 = 8.64 \text{ kV} / \mu\text{s}$$

$$T_L = \frac{e}{R_L} = \frac{32}{8.64} = 3.7 \mu\text{s} \quad (4)$$

From (3) and (4):

$$e_S = 2 \times 0.9 \times (3.7 - 2) = 3 \text{ kV}$$

The first peak of TRV across the circuit breaker terminals is then

$$e_T = e + e_S = 32 + 3 = 35 \text{ kV}$$

The rate-of-rise of recovery voltage is

$$RRRV = \frac{e_T}{T_L} = \frac{35}{3.7} = 9.46 \text{ kV}/\mu\text{s}$$

Figure A.8 shows the time variations of the TRV and supply voltage obtained by calculation of transients in a 245 kV network with the same short-line fault conditions. These curves have been determined by a digital transient program. It can be verified the same values of peak TRV (e_T) and RRRV are obtained by the computer program and the simplified method of calculation.

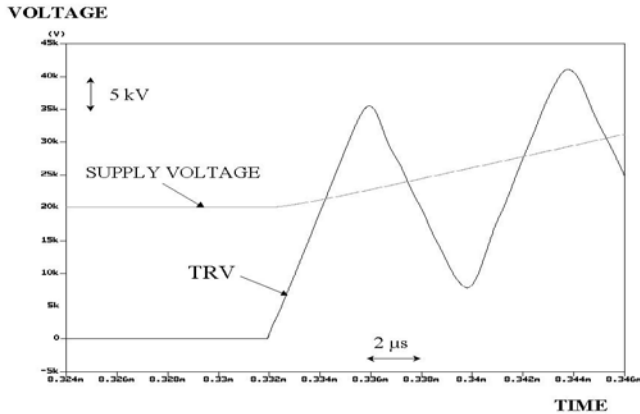


Figure A.8 - TRV and supply voltage during SLF 90% 40 kA 60 Hz 245 kV

Some engineers confuse the voltage peak that can be calculated from the peak factor defined in the standards, and the TRV peak (as shown in figure A.8) that is by definition the peak value of voltage across the circuit-breaker terminals. For this particular case, we have

- contribution of the line side voltage :

$$e = 1.6 \times 0.1 \times \sqrt{2/3} \times 245 = 32 \text{ kV}$$

with peak factor = 1.6 p.u.

- inherent TRV seen by the circuit breaker

$$e_T = e + e_S = 32 + 3 = 35 \text{ kV}$$

- ratio of TRV to the crest value of the steady state voltage at the circuit breaker before interruption

$$\frac{35}{0.1 \times \sqrt{2/3} \times 245} = 1.75 \text{ p.u.}$$

The example A.5.3.3 shows that in many cases simple calculations, using the equations in this document, can be done to determine the main characteristics of a TRV, at least approximate values of parameters, and to check the validity of complex digital simulations.