Transient Recovery Voltages (TRVs) for High Voltage Circuit Breakers

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Importance of TRV

- **The TRV is a decisive parameter that limits the interrupting capability of a circuit breaker.**
- The interrupting capability of a circuit breaker was found to be strongly dependent on TRV in the 1950's.
- Standard requirements for TRV were first **introduced in 1971**: in C37.072 (IEEE Std. 327) and IEC 56.
- When developing interrupting chambers, manufacturers must check and prove the withstand of TRVs specified in the standards for different test duties.
- Users must specify TRVs in accordance with their applications.
- Test laboratories must define test circuits that meet the TRV requirements.

Content

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  - TRV ratings
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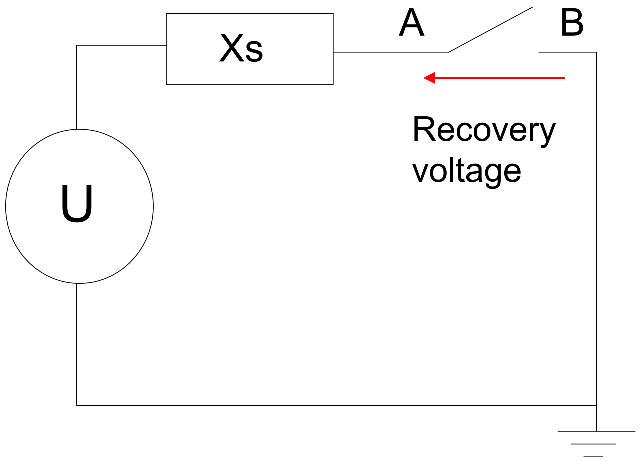
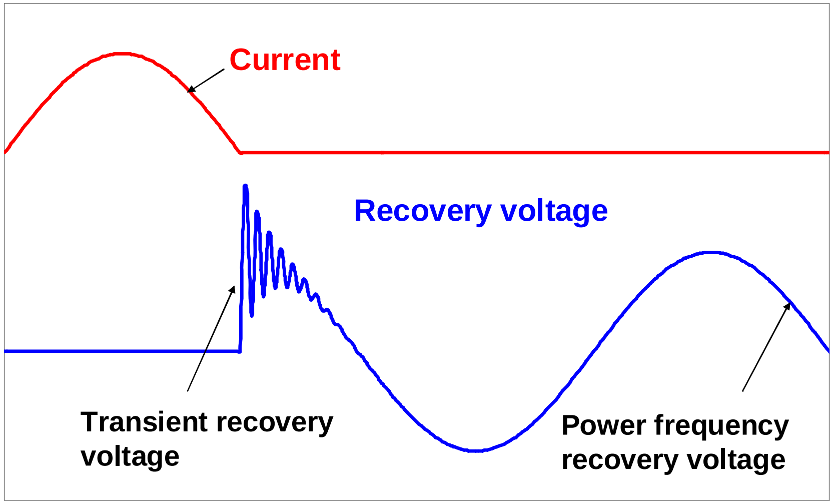
- **Short-line fault**
- **ITRV (Initial TRV)**
- **Out-of-phase**
- **(Long) Line faults**
- **Application considerations**
- **Selection of circuit breakers for TRV**

General considerations on Transient Recovery Voltages (TRVs)

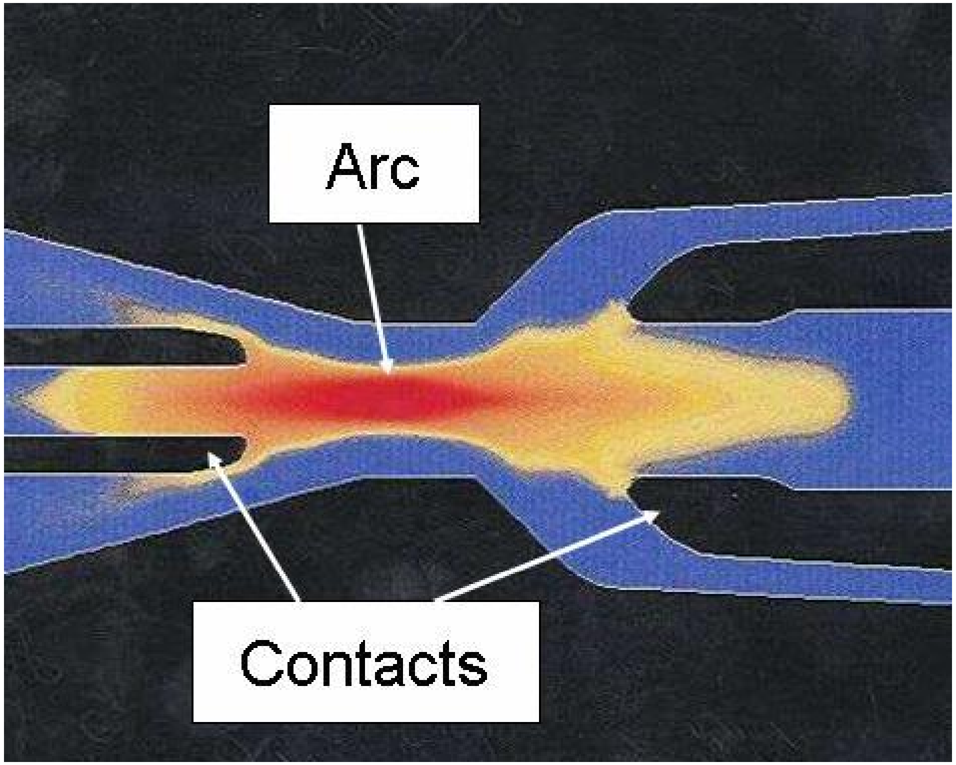
TRV for High-voltage Circuit Breakers

- The **recovery voltage** is the voltage which appears across the terminals of a pole of circuit breaker after current interruption.





Current Interruption Process (in gas blast circuit breakers)

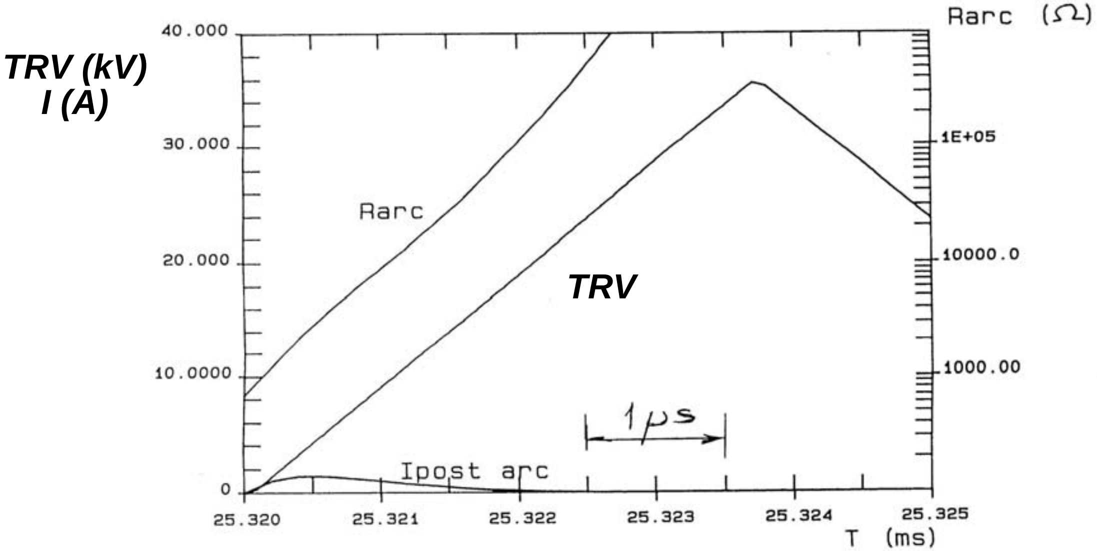


Two contacts are separated in each interrupting chamber.

An arc is generated, it is cooled and extinguished when current passes through zero.

TRV for High-voltage Circuit Breakers

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



Gas circuit breakers: within a few microseconds after current zero, arc resistance (R_{arc}) reaches 1 million ohms in a few microseconds and current stops flowing in the circuit.

- During the first microseconds after current zero, the TRV withstand is function of the energy balance in the arc: **thermal phase of interruption.**
- Later, the voltage withstand is function of the dielectric withstand between contacts: **dielectric phase of interruption**.
- The breaking operation is successful if the circuit breaker is able to withstand the TRV and the power frequency recovery voltage.
- The TRV is the difference between the voltages on the source side and on the load side of the circuit breaker.

Thermal Restrike

- During tens of microseconds around current zero, the evolution of arc resistance is function of the energy balance in the arc i.e. the difference over time between the power input (U_{arc} x I = R_{arc}. I^2) and the power loss by gas cooling.
- If the gas blast is not sufficient, the arc resistance stop increasing after current zero, it decreases to a low value, as a consequence the interval between contacts becomes conductive again.
- This type of restrike is called a thermal restrike.
- Arc model:

$$\frac{dR_{arc}}{dt} = \frac{R_{arc}}{\Theta} \times 1 - \frac{U_{arc} \times I}{P_{loss}}$$

R_{arc}= arc resistance P_{loss}= dissipated power

Θ = arc time constant U_{arc} = arc voltage   I = current

TRV for High-voltage Circuit Breakers

- The nature of the TRV is dependent on the circuit being interrupted, whether primarily resistive, capacitive or inductive, (or some combination).

- When interrupting a fault at the circuit breaker terminal (terminal fault) in an inductive circuit, the supply voltage at current zero is maximum.

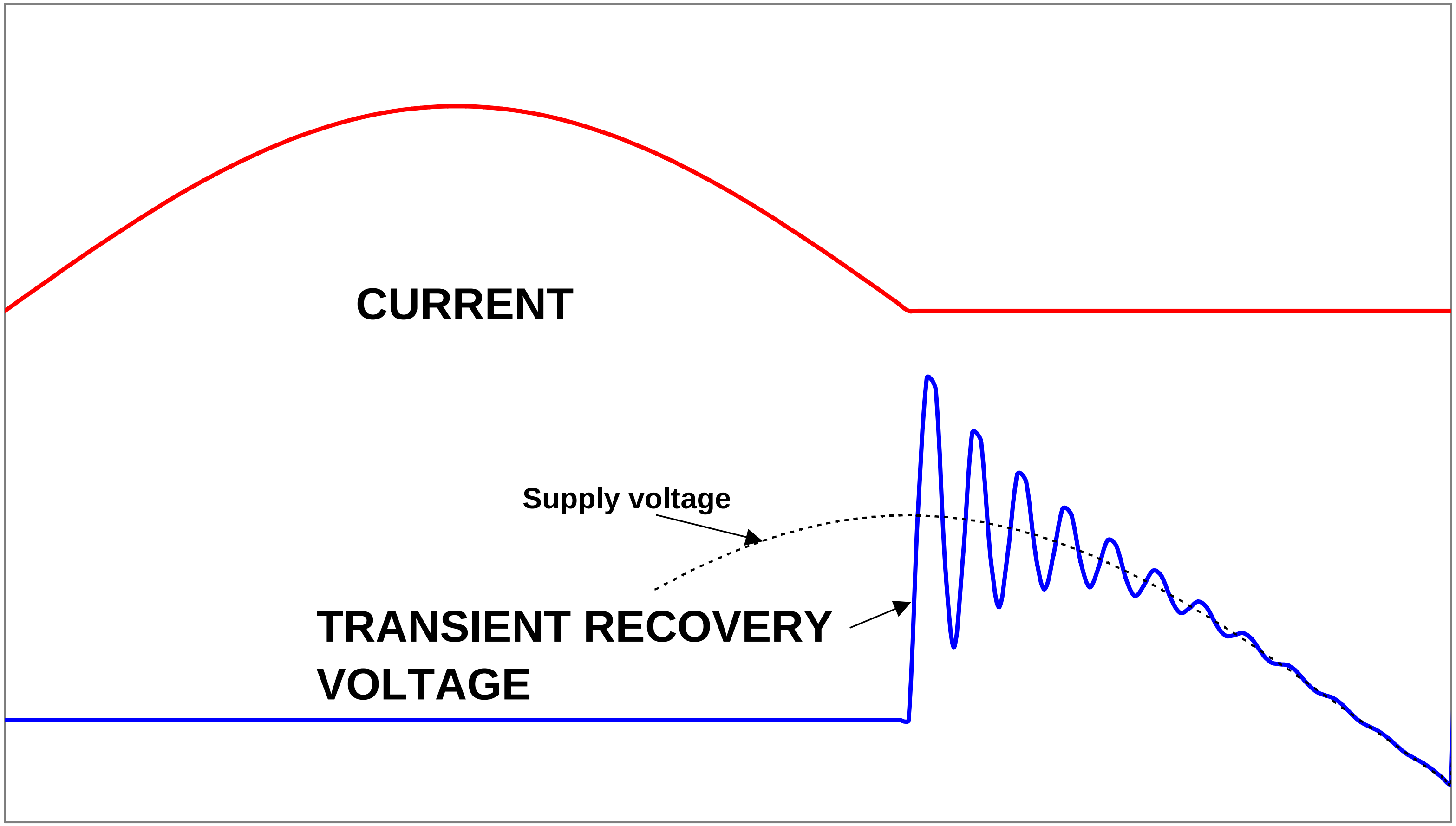
  The circuit breaker interrupts at current zero (at a time when the power input is minimum) the voltage on the supply side terminal meets the supply voltage in a transient process called the TRV.

  TRV frequency is $$\frac{1}{2\pi\sqrt{LC}}$$

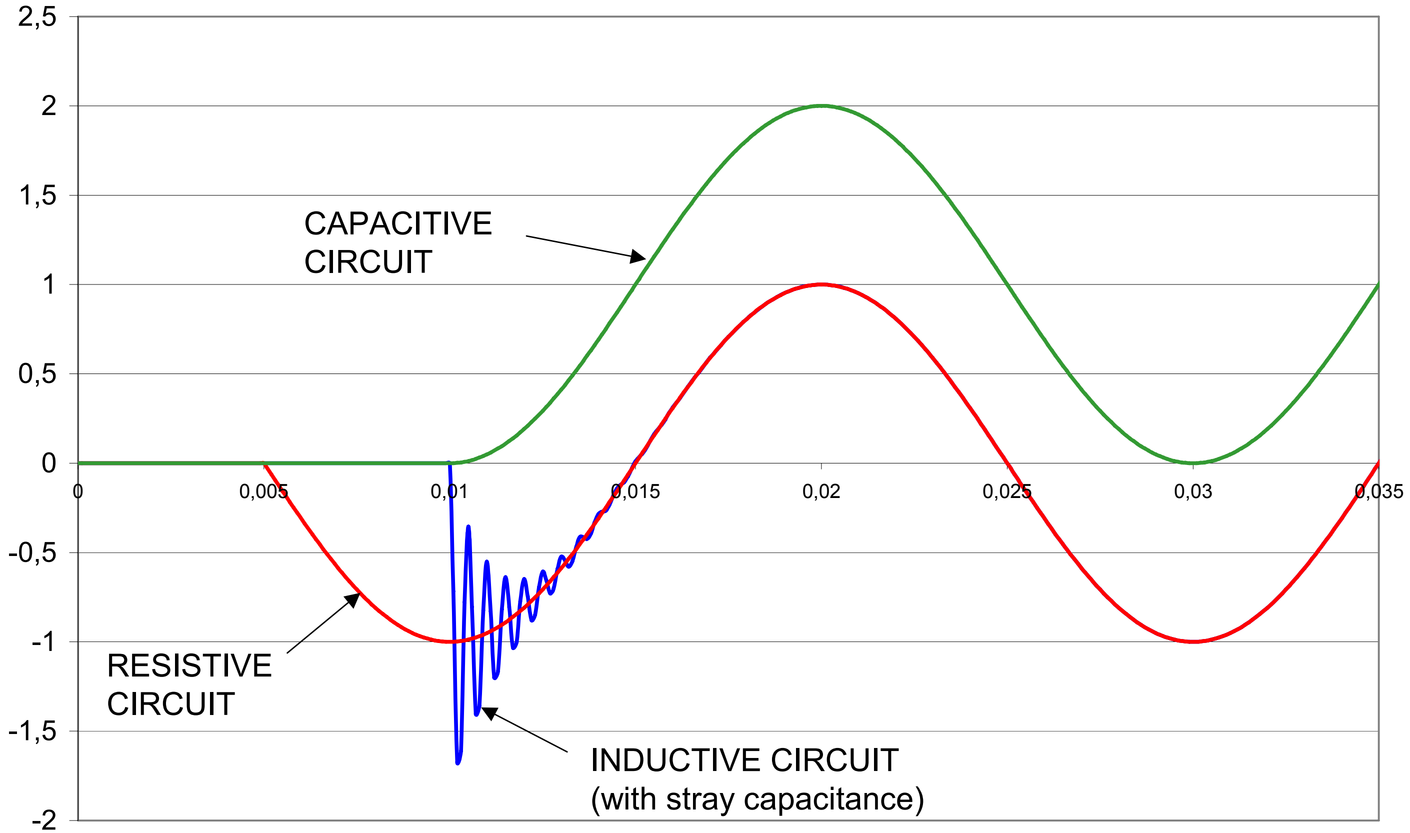
  with L = short-circuit inductance

  C = supply capacitance.

TRV for High-voltage Circuit Breakers



TRV for High-voltage Circuit Breakers

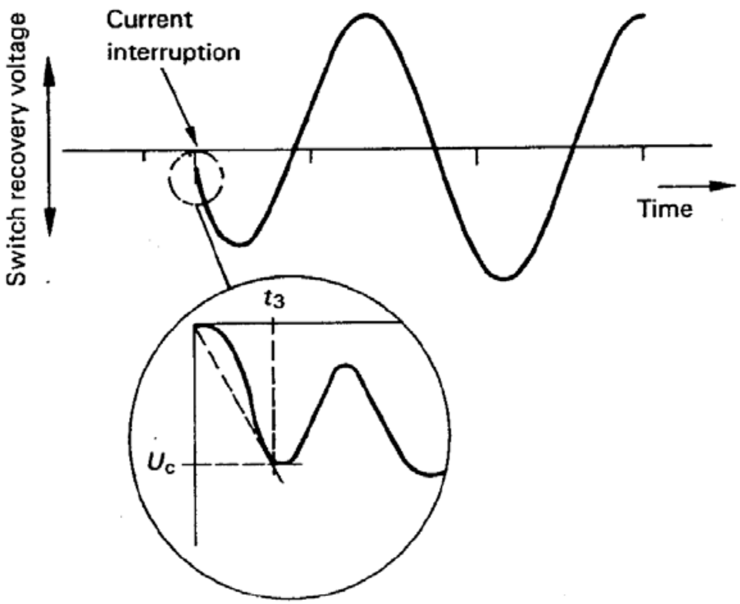


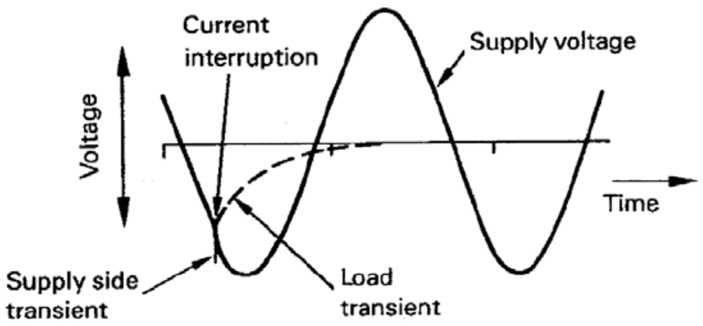
TRV and recovery voltage in resistive, inductive and capacitive circuits

- Combination of the former basic cases are possible

- Example #1: the TRV for mainly active load current breaking is a combination of TRVs associated with the inductive and resistive components of the circuit.

  They are specified for high-voltage switches only as circuit-breakers are able to interrupt with more severe TRVs (in inductive circuits).





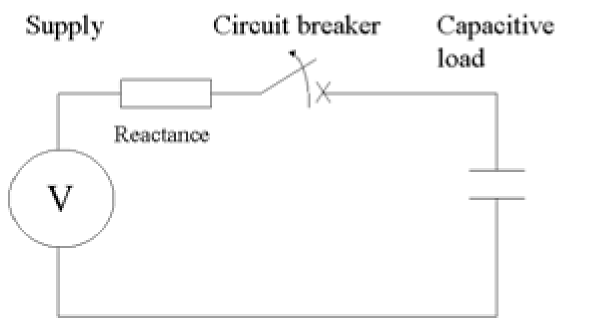
TRV for High-voltage Circuit Breakers

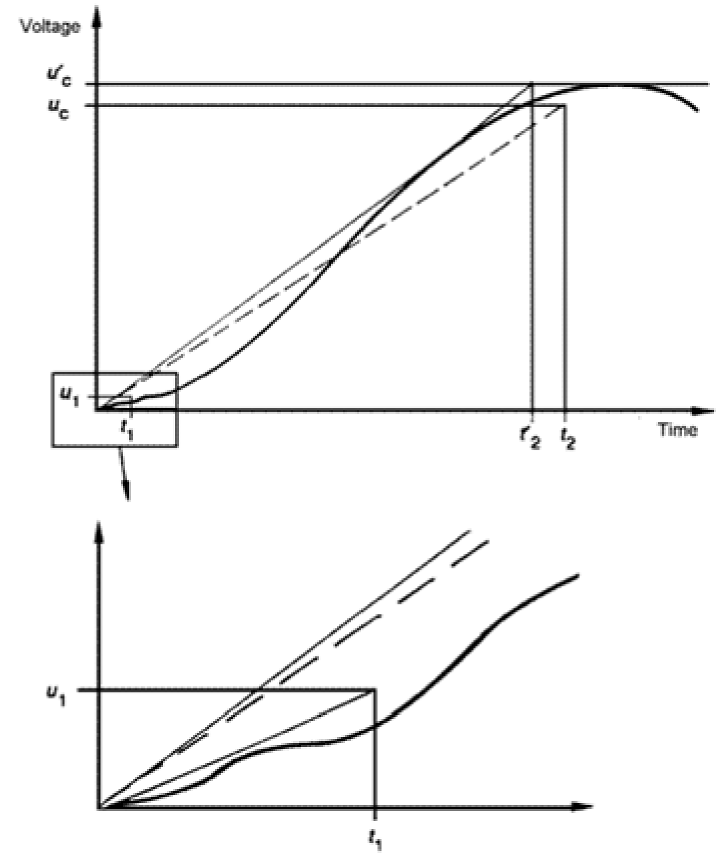
Example #2: circuit with capacitive and inductive components.

- In a circuit with a low short-circuit power, the recovery voltage during interruption of a capacitive load is the sum a (1– cos) wave-shape on the load side and a voltage oscillation on the supply side due a transient across the short-circuit (inductive) reactance at the time of interruption.

- The initial voltage jump tends to increase the minimum arcing time and therefore to increase the shortest duration between contact separation and the instant of peak recovery voltage.

In standards, the voltage jump is limited in amplitude in order to test with the more severe condition.

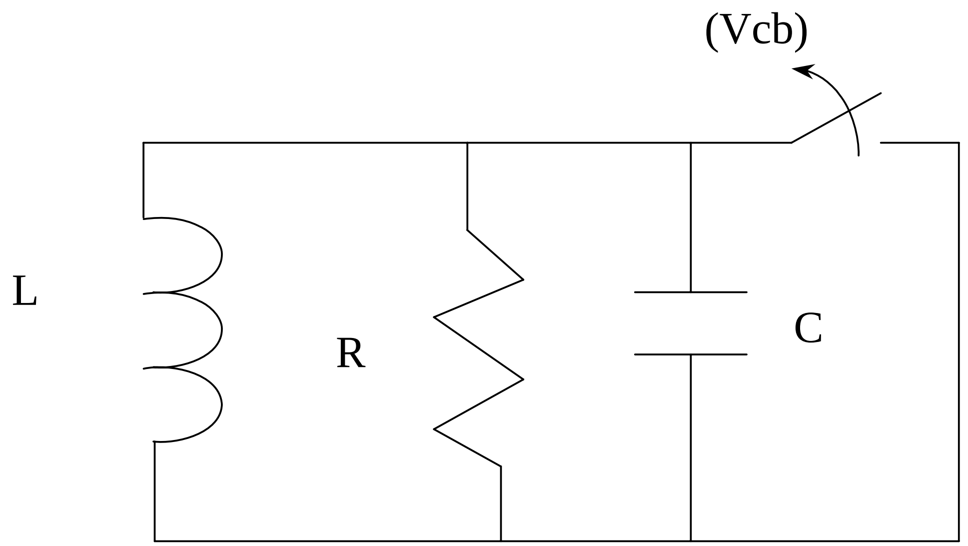




TRV for High-voltage Circuit Breakers

- Fault interruptions are often considered to produce the most onerous TRVs. Shunt reactor switching is one of the exceptions.
- TRVs can be oscillatory, triangular, or exponential and can occur as a combination of these forms.
- The highest TRV peaks are met during capacitive current and out-of-phase current interruption,
- TRVs associated with the highest short-circuit current are obtained during terminal fault and short-line-fault interruption.
- In general, a network can be reduced to a simple parallel RLC circuit for TRV calculations. This representation is valid for a short-time period until voltage reflections return from remote buses (see IEEE C37.011-2005)

TRV for High-voltage Circuit Breakers



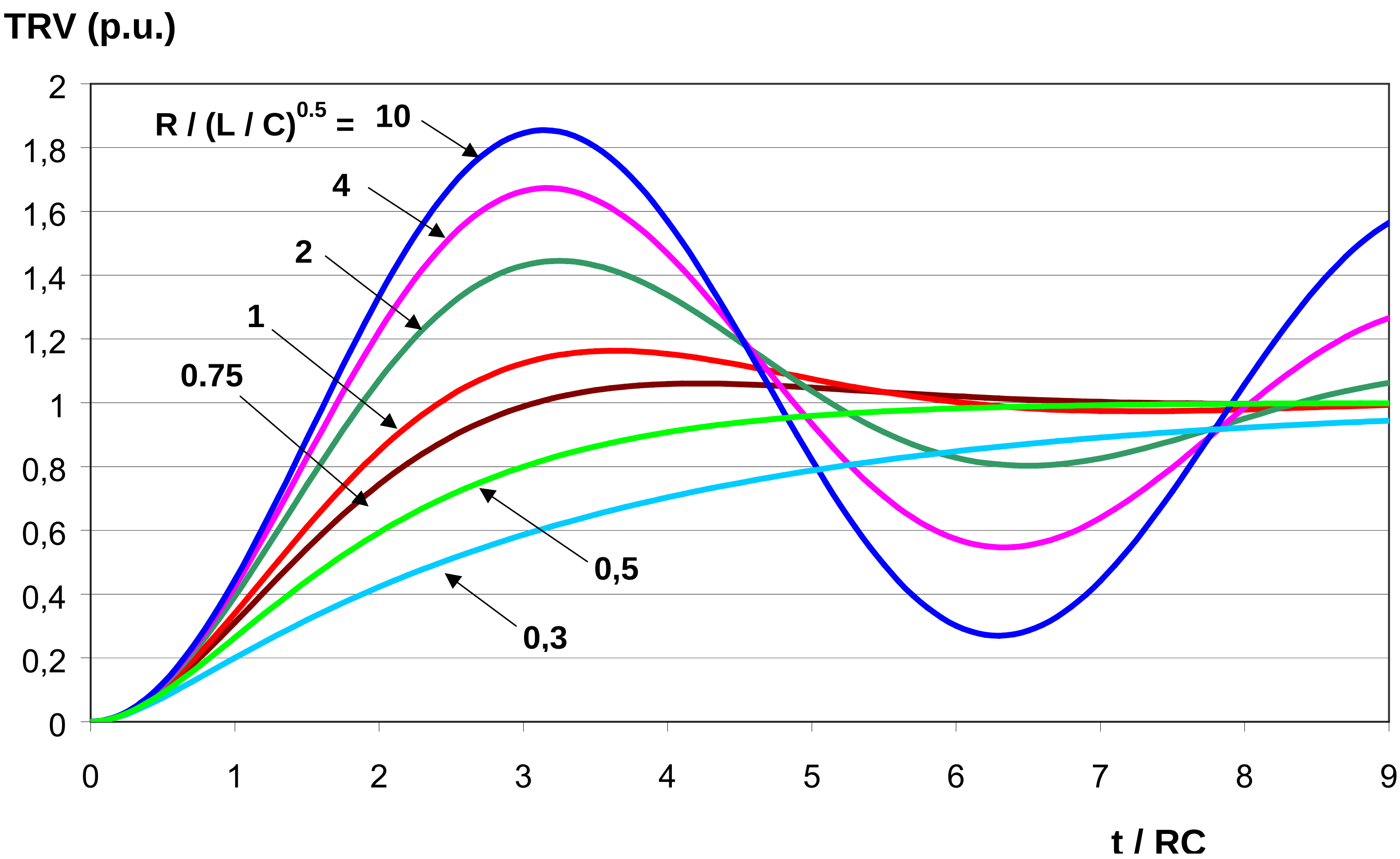
- The TRV in the parallel RLC circuit is oscillatory (under-damped) if

$$R \rangle \frac{1}{2}\sqrt{L/C}$$

- The TRV in the parallel RLC circuit is exponential (over-damped) if

$$R \leq \frac{1}{2}\sqrt{L/C}$$

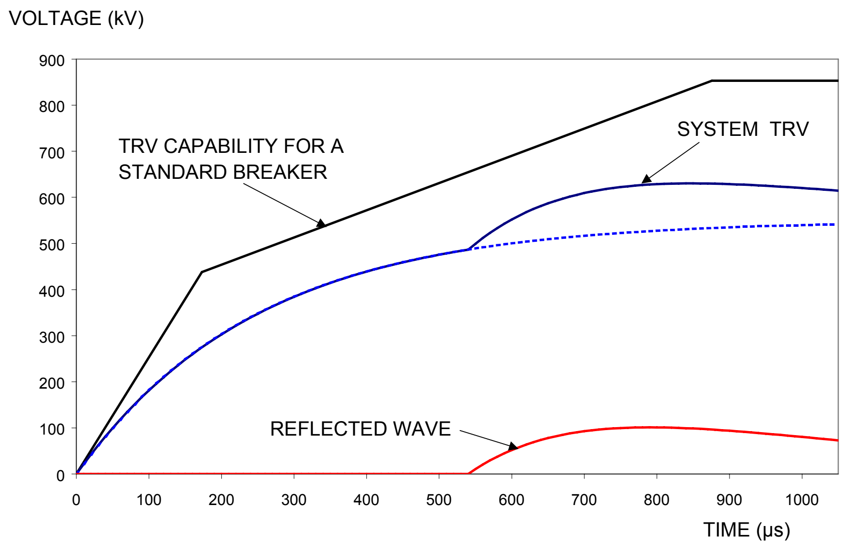
TRV for High-voltage Circuit Breakers



Note: damping of the oscillatory TRV is provided by R, as R is in parallel to L and C (parallel damping) the higher the value of R the lower the damping (the TRV peak increases when R increases).

Reflection from end of lines

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.

TRV for High-voltage Circuit Breakers

- The most severe TRVs tend to occur across the first pole to clear of a circuit breaker interrupting a three-phase symmetrical current at its terminal and when the system voltage is maximum (see section on Terminal fault).
- By definition, all TRV values defined in the standards are inherent, i.e. the values that would be obtained during interruption by an ideal circuit breaker without arc voltage

  (arc resistance changes from zero to an infinite value at current zero).

Types of TRVs

Exponential (over-damped) TRV

- The exponential part of a TRV occurs when the equivalent resistance of the circuit with N connected lines in parallel

$$R_{eq} = \alpha \frac{Z_1}{N} \quad \text{is lower or equal to} \quad 0.5\sqrt{L_{eq}/C_{eq}}$$

where Z_1 = positive sequence surge impedance of a line

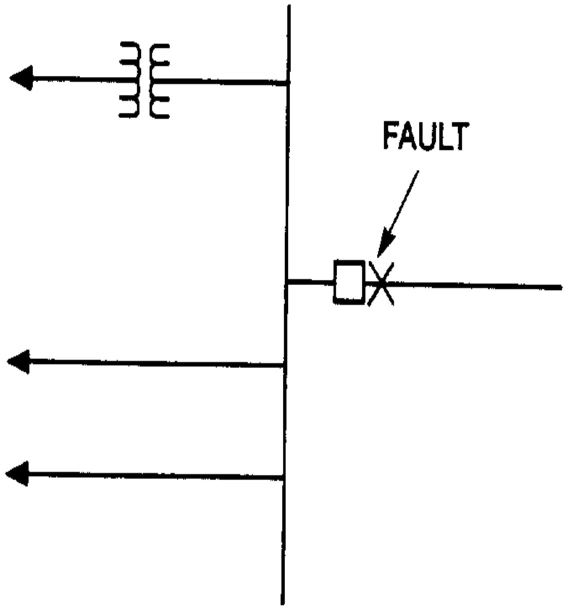
N = number of lines, α = coefficient

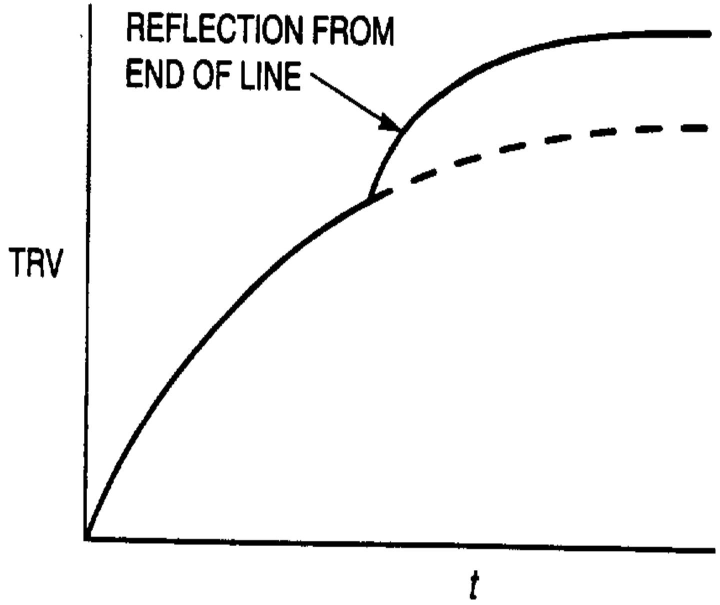
L_{eq} = source inductance, C_{eq} = source capacitance.

- It typically occurs when at least one transformer and one or several lines are on the unfaulted side of the circuit breaker and when a fault is cleared at the breaker terminals.

- This exponential part of TRV is transmitted as traveling waves on each of the transmission lines. Reflected wave(s) returning from open lines or discontinuities contribute also to the TRV.

TRV for High-voltage Circuit Breakers

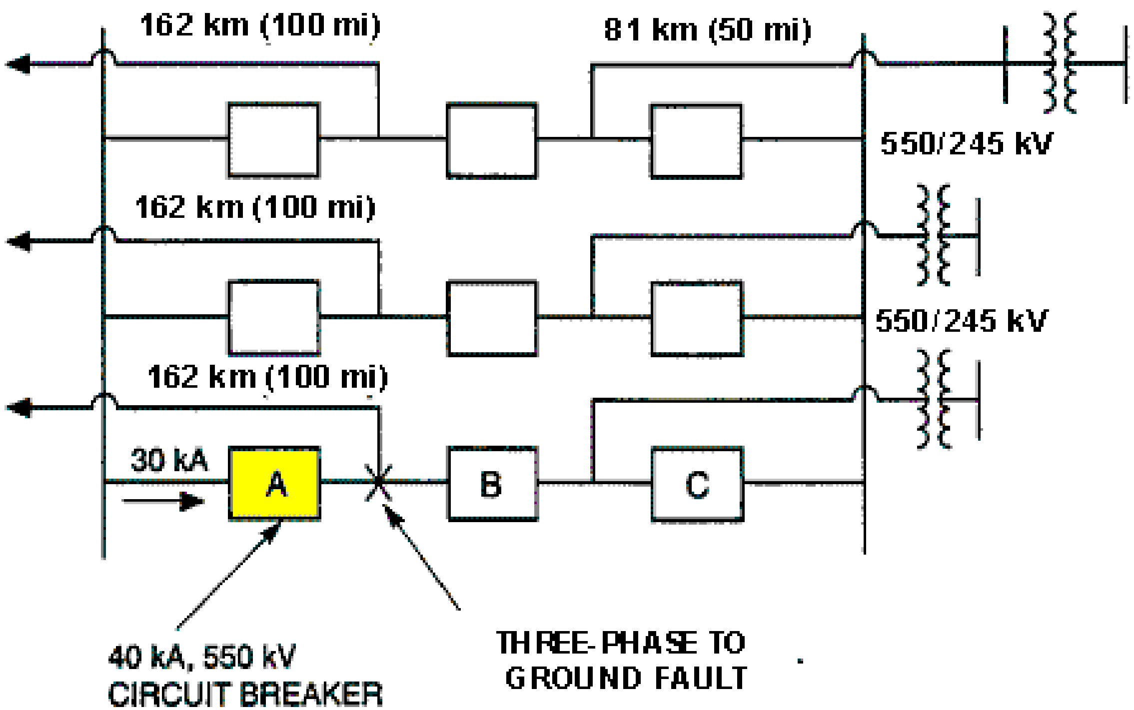




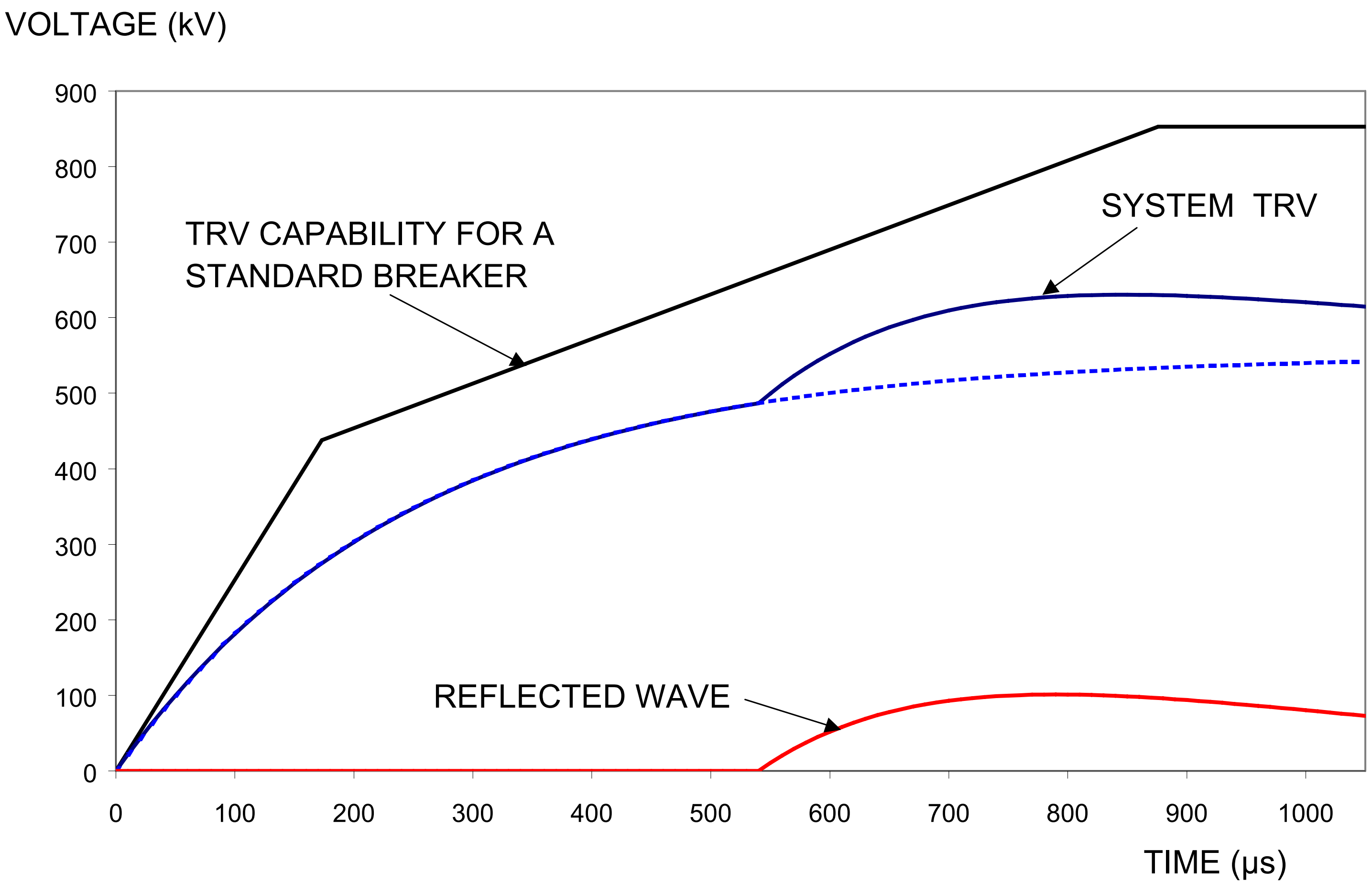
Exponential TRV characteristic

TRV for High-voltage Circuit Breakers

- As an example, the following figure shows the one line diagram of a 550kV substation. The TRV seen by circuit breaker (A) when clearing the three-phase fault is shown in the next slide. Circuit breaker (B) is open.



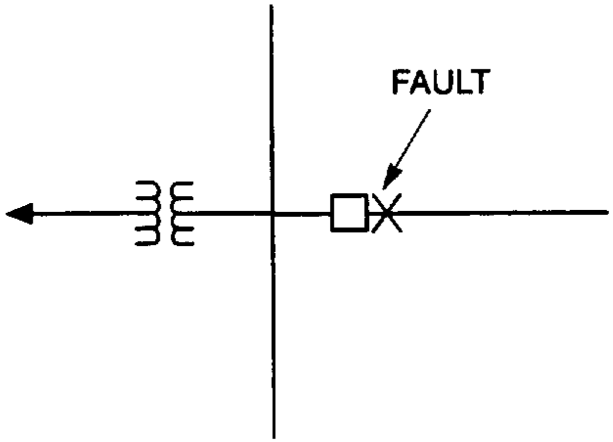
System TRV with reflected wave

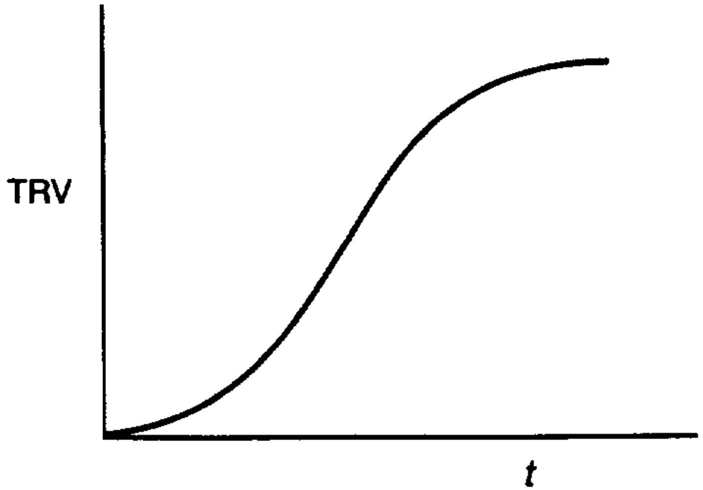


A reflection occurs from the end of the shortest line after 2 x 81 / 0.3 = 540 µs

Oscillatory (under-damped) TRV

- An oscillatory TRV 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.





TRV for High-voltage Circuit Breakers

- To be oscillatory, the equivalent resistance of the source side has to be such that

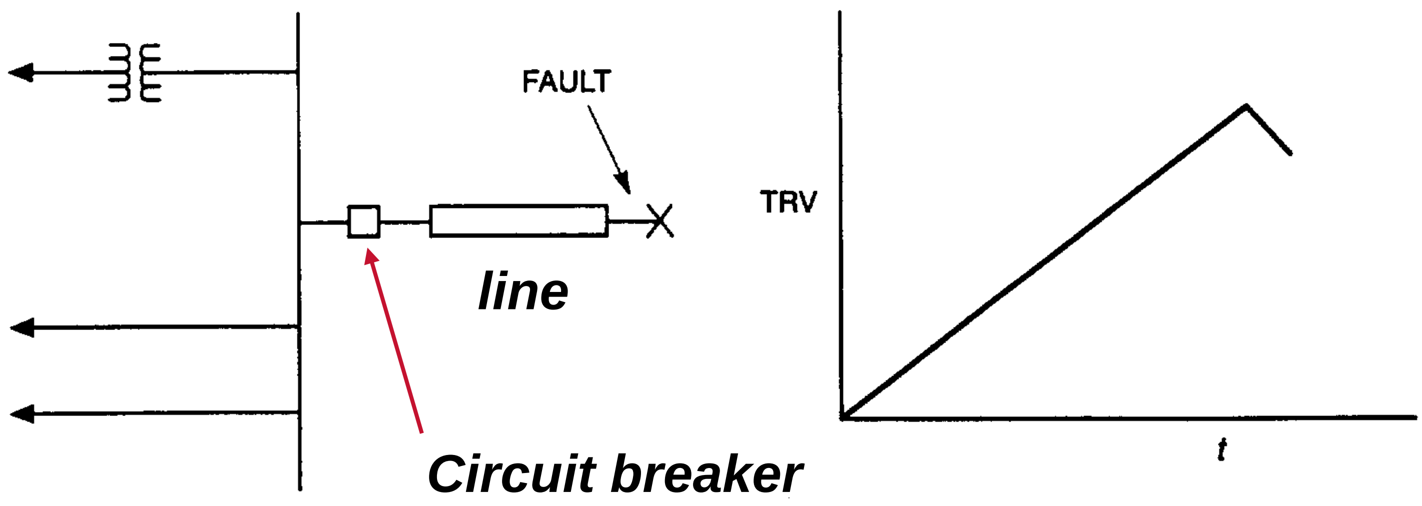
$$R_{eq} = \alpha \frac{Z}{n} > \quad 0.5\sqrt{\frac{L_{eq}}{C_{eq}}}$$

L_{eq} = equivalent source inductance, C_{eq} = equivalent source capacitance.

- To meet this requirement, only a low number of lines should be connected, therefore oscillatory TRVs are specified for
  - terminal fault test duties T10 and T30 for circuit breakers in transmission systems (Ur ≥ 100 kV),
  - all terminal fault test duties in the case of circuit breakers in distribution or sub-transmission systems (Ur < 100 kV).
- In the large majority of cases, TRV characteristics (peak value and rate-of-rise) are covered by the rated values defined in the standards for terminal faults at 10% or 30% of rated short-circuit current.

TRV with triangular wave-shape

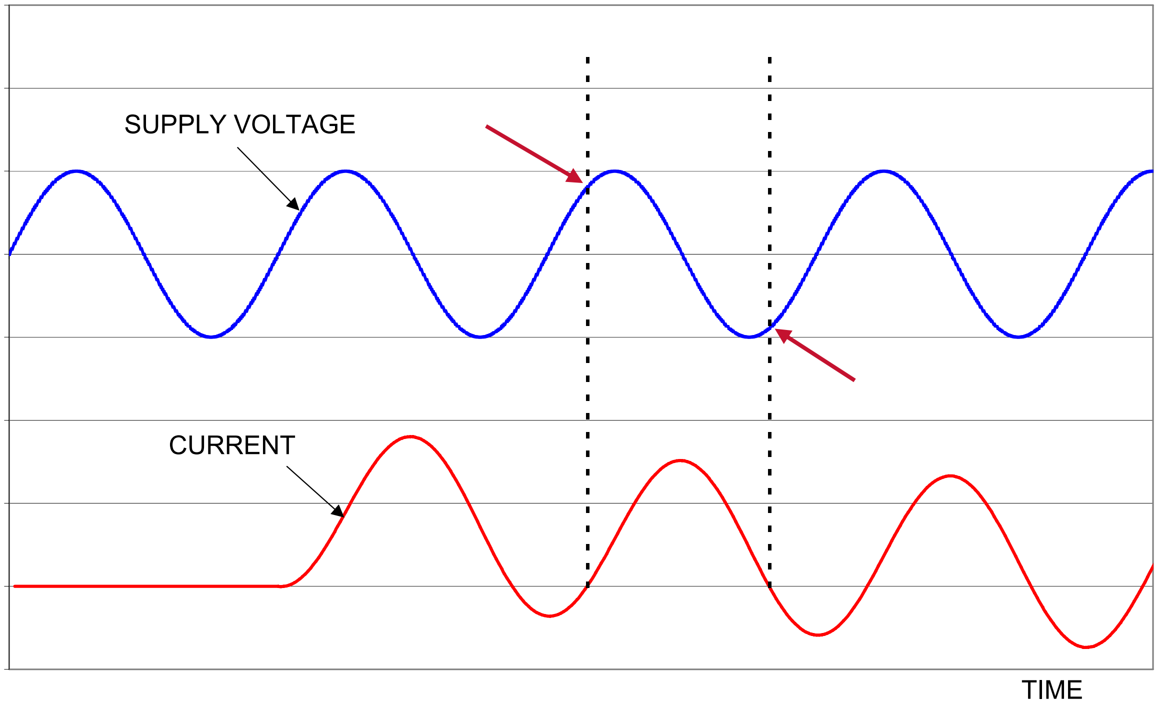
- Triangular-shaped TRVs are associated with **short-line faults** (see separate chapter).
- After current interruption, the line side voltage exhibits a characteristic triangular waveshape. The rate-of-rise of the saw-tooth shaped TRV is function of the line surge impedance. The rate-of rise is usually higher than that experienced with exponential or oscillatory TRVs (with the same current), however the TRV peak is generally low.



Asymmetry and circuit breaker influence on TRV

Effect of asymmetry on TRV

- The TRVs that occur when interrupting asymmetrical currents are less severe (lower RRRV and TRV peak) than when interrupting the related symmetrical current because the instantaneous value of the supply voltage at the time of interruption is less than the peak value.



Effect of asymmetry on TRV

- IEEE C37.081 and IEC 62271-100 give the reduction factors of the TRV peak and rate of rise of recovery voltage (RRRV) when interrupting asymmetrical currents.

Effect of a circuit breaker on TRV

- The circuit TRV can be modified by a circuit breaker. The TRV measured across the terminals of two different types of circuit breakers under identical conditions can be different.

- To simplify both rating and application, the power system TRV is defined / calculated ignoring the effect of the circuit breaker.

  An ideal circuit breaker has no modifying effects on the electrical characteristics of a system, when conducting its impedance is zero, at current zero its impedance changes from zero to infinity.

Effect of a circuit breaker on TRV

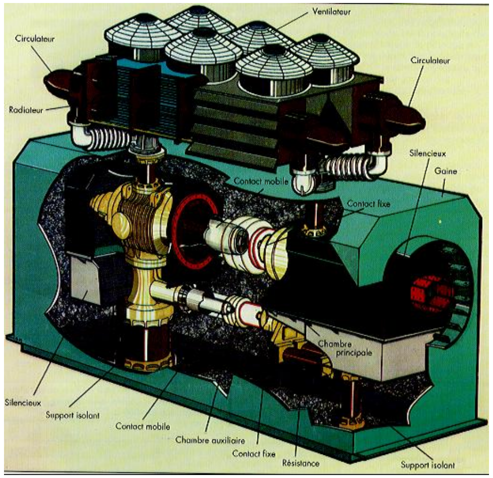
- When a circuit breaker is fitted with grading capacitors or with line-to-ground capacitors, these capacitors can reduce significantly the rate-of-rise of TRV during short-line faults.

- In the past, opening resistors (R) were used to assist interruption by air blast circuit breakers.

RRRV is reduced by this factor: $\frac{R}{R+Z}$

where Z is the surge impedance

of the system.

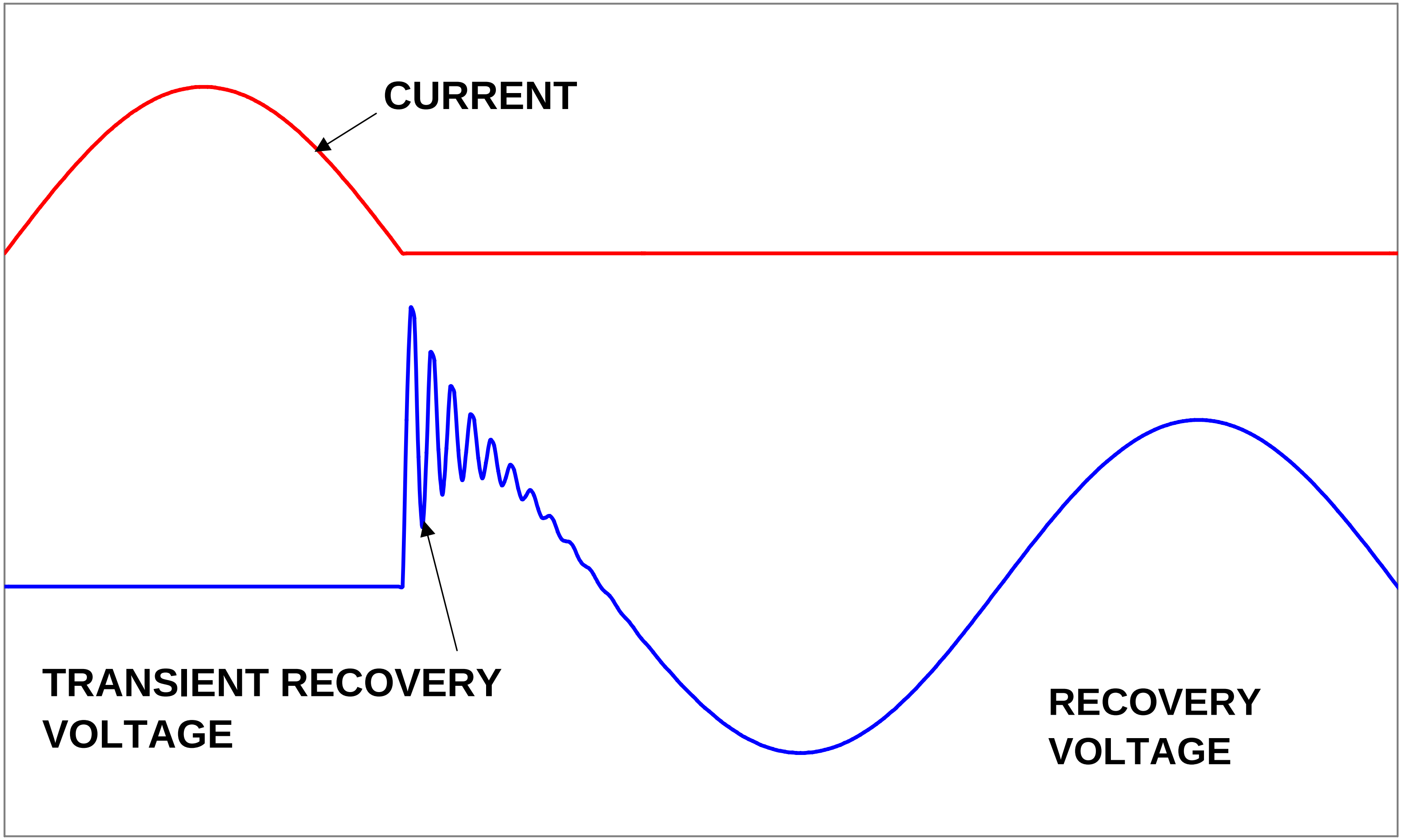


Air blast Generator Circuit Breaker with opening resistor

Terminal fault

Terminal fault TRV
First pole to clear factor

Terminal Fault TRV



The recovery voltage is function of the system grounding and the type of fault.

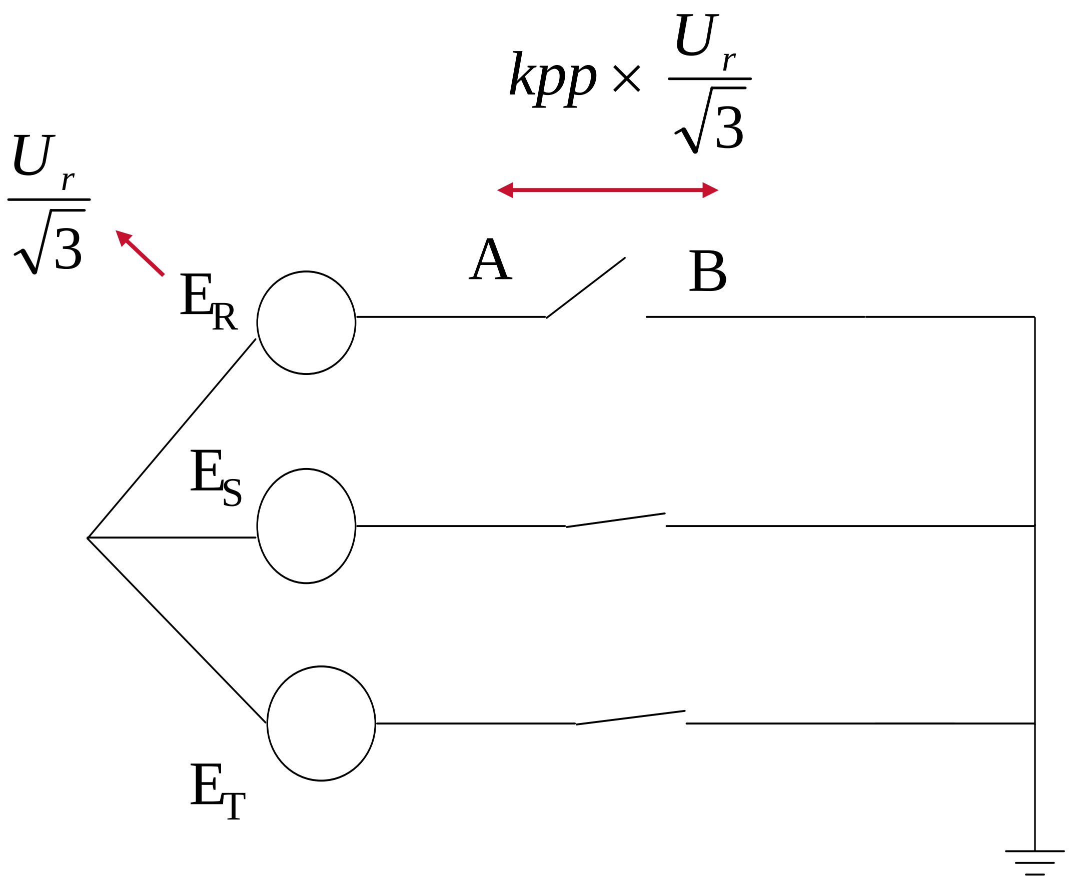
First Pole to Clear Factor (k_{pp})

- During 3-phase faults, the recovery voltage is higher on the first pole to clear.
- The first-pole-to clear factor is the ratio of the power frequency voltage across the first interrupting pole, before current interruption in the other poles, to the power frequency voltage occurring across the pole after interruption in all three poles.
- The ratio between the recovery voltage (RV) across the first pole to clear and the phase to earth voltage of the system

$$kpp = \frac{RV}{U_r / \sqrt{3}}$$

is called the first pole to clear factor.

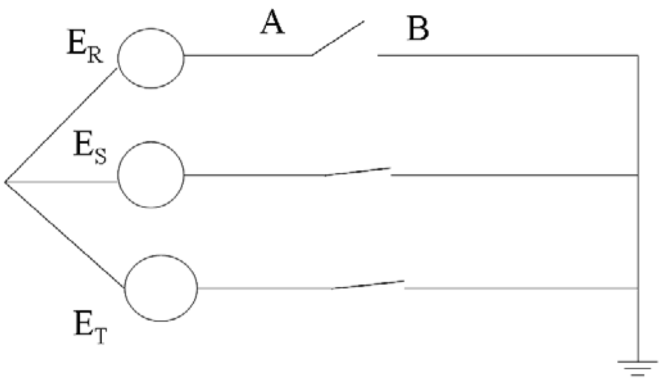
First Pole to Clear Factor (k_{pp})

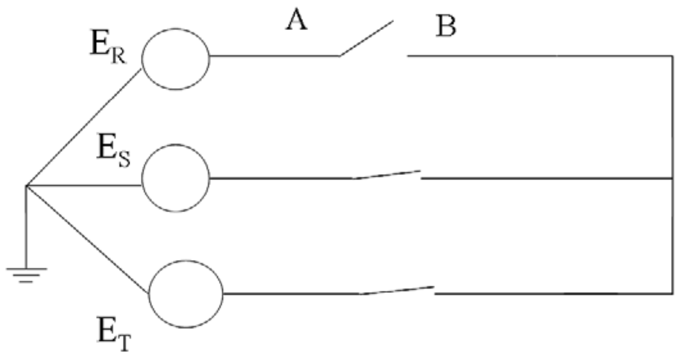


Terminal Fault TRV

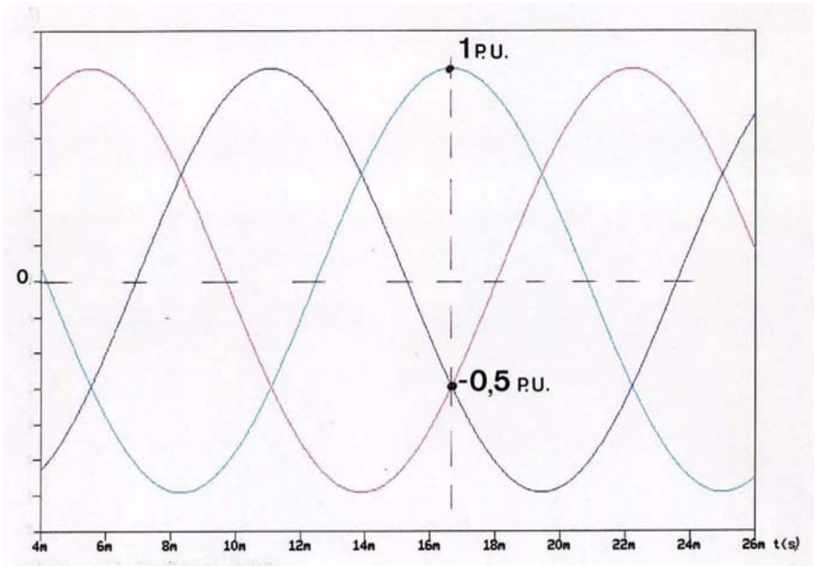
- When tests are performed single-phase, as substitution to three-phase tests, the supply voltage must be multiplied by k_{pp} in order to have the recovery voltage that would be met during three-phase tests.
- The first–pole–to-clear factor (k_{pp}) is a function of the grounding arrangements of the system and of the type of fault.
- For systems with non-effectively grounded neutral, k_{pp} is 1.5.
- For three-phase to ground faults in systems with effectively earthed neutral, k_{pp} is 1.3.
- For three-phase ungrounded faults, k_{pp} is 1.5.

Three-phase faults in non-effectively grounded systems or three-phase ungrounded faults





In these cases, kpp is 1.5



Three-phase faults to ground in effectively earthed neutral systems

- The value of k_{pp} is dependent upon the sequence impedances from the location of the fault to the various system neutral points: X_0 (zero sequence reactance of the system) and X_1 (positive sequence reactance of the system).

  For these systems the ratio X_0/X_1 is taken to be ≤ 3.0.

  Hence, for systems with effectively grounded neutral k_{pp} is 1.3.

Single-phase in an effectively grounded system

- In this case, k_{pp} is 1.0.

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

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

where

X_0 is the zero sequence reactance of the system,

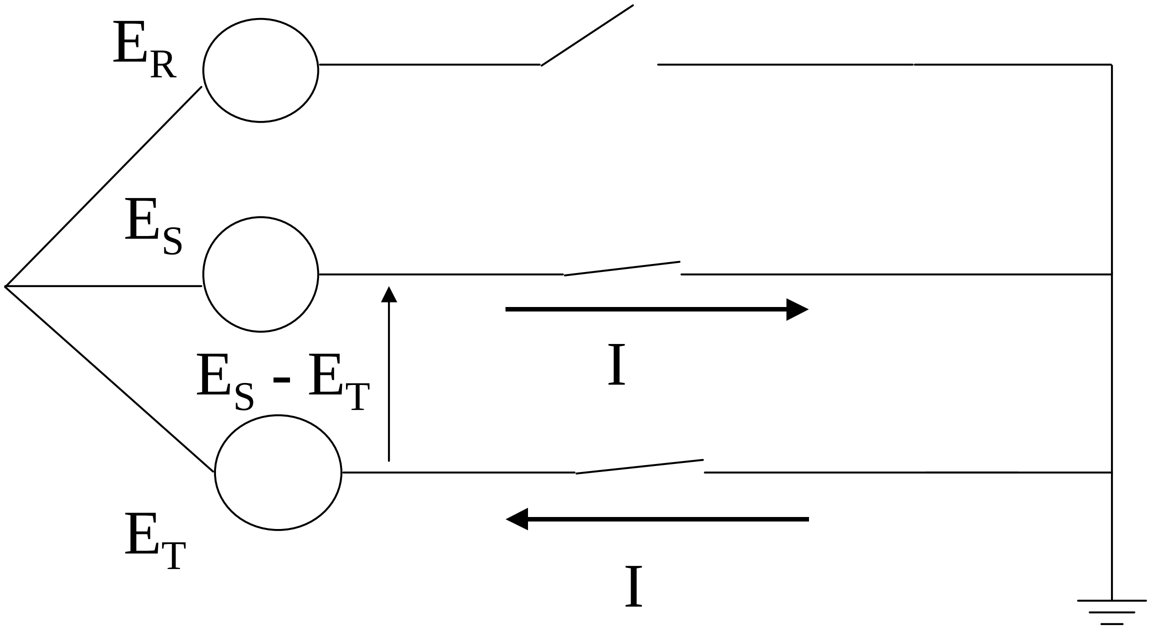
X_1 the positive sequence reactance of the system.

If $X_0 >> X_1$, $k_{pp} = 1.5$ as in non-effectively grounded systems

If $X_0 = 3.0\ X_1$: $k_{pp} = 1.3$ as in effectively grounded neutral systems (three-phase to ground faults)

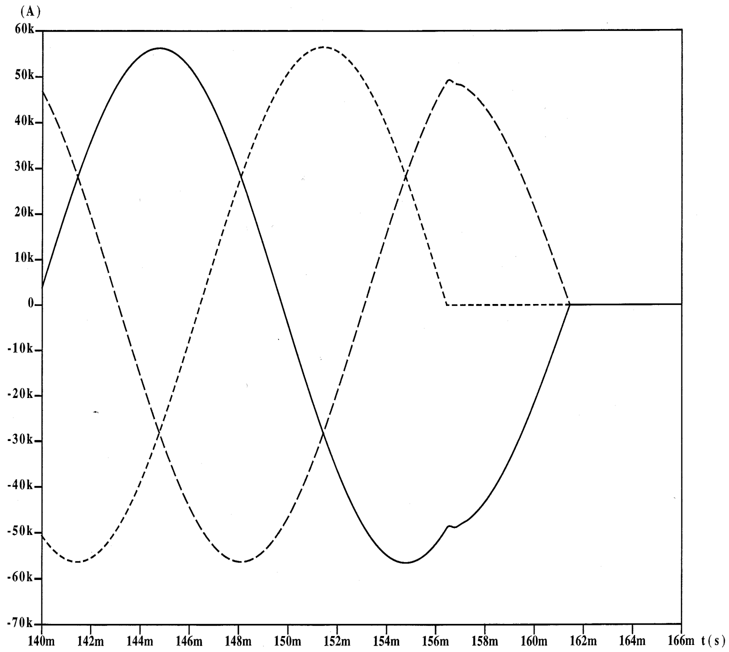
Equations for the other clearing poles

a) In systems with non-effectively grounded neutral, after interruption of the first phase (R), the current is interrupted by the last two poles in series under the phase-to-phase voltage (E_S – E_T) equal to $\sqrt{3}$ times the phase voltage

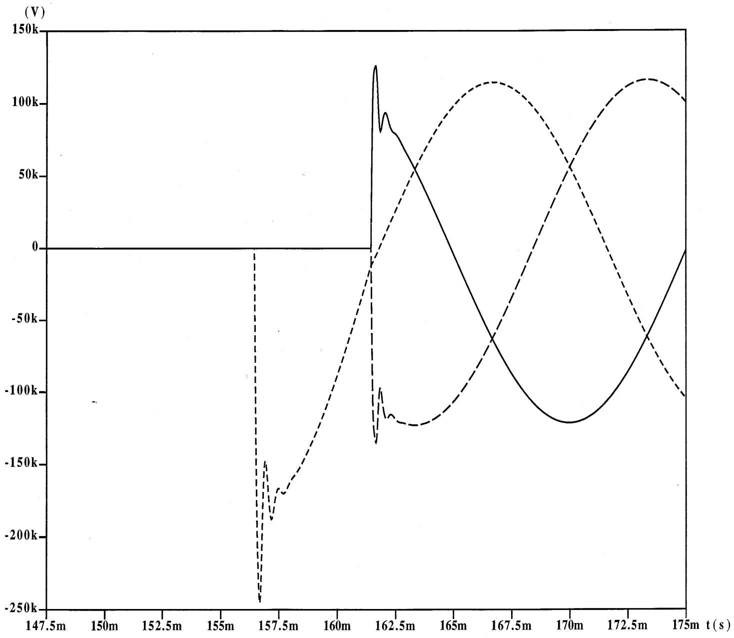


It follows that, in systems with non-effectively grounded neutral, for the second and third pole to clear:

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



Current in each phase



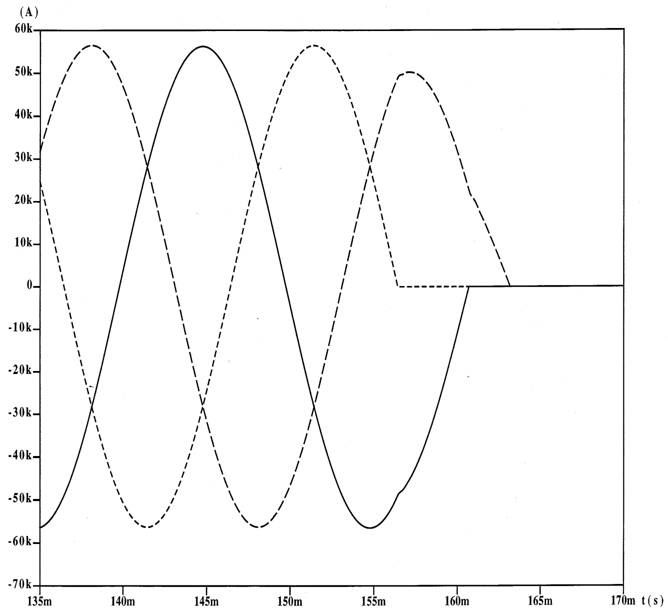
TRV in each phase

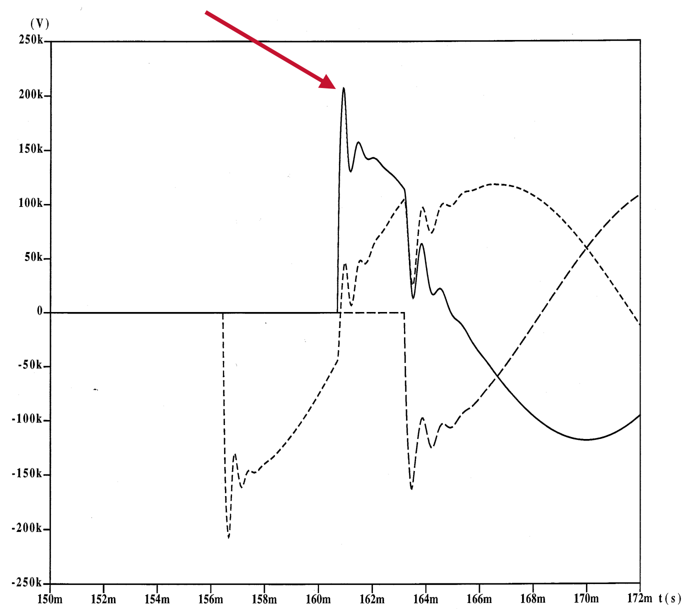
In systems with effectively grounded neutrals, the second pole clears a three-phase to ground fault

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

If $X_0 / X_1 = 3.0$ the second pole to clear factor is 1.27.

Currents

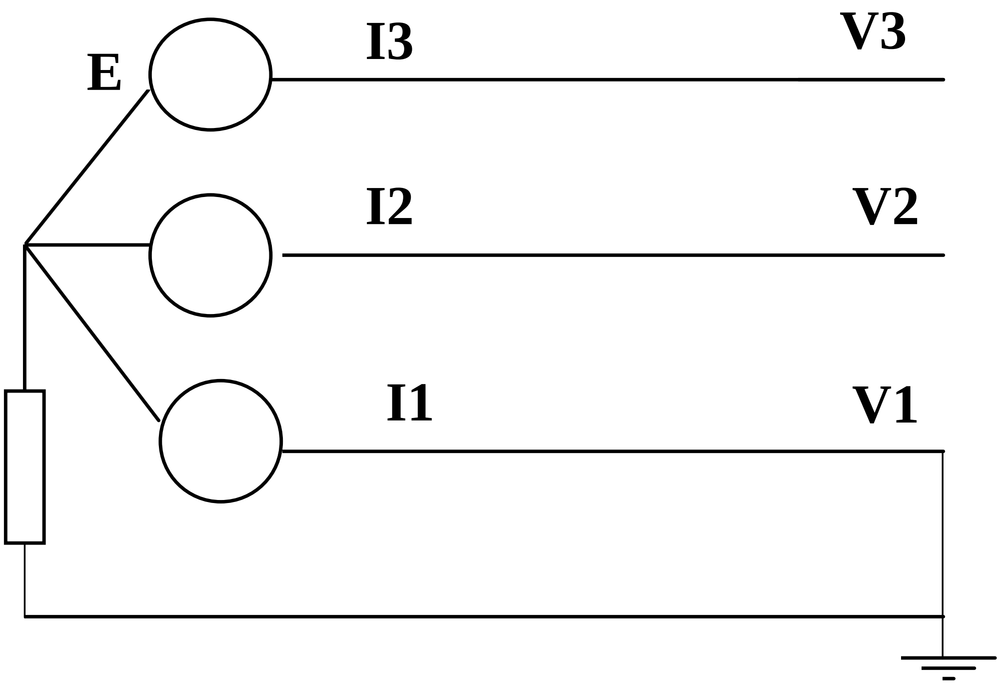




TRVs

In systems with effectively grounded neutral, for the third pole-to-clear:

$$k_{pp} = 1$$



Pole-to-clear factors (k_{pp}) for each clearing pole, 3-phase to ground case

Neutral	X0/X1	Pole to clear factor		
		first pole	2nd pole	3rd pole
isolated	infinite	1.5	0.87	0.87
effectively grounded	3.0	1.3	1.27	1.0
see note	1.0	1.0	1.0	1.0

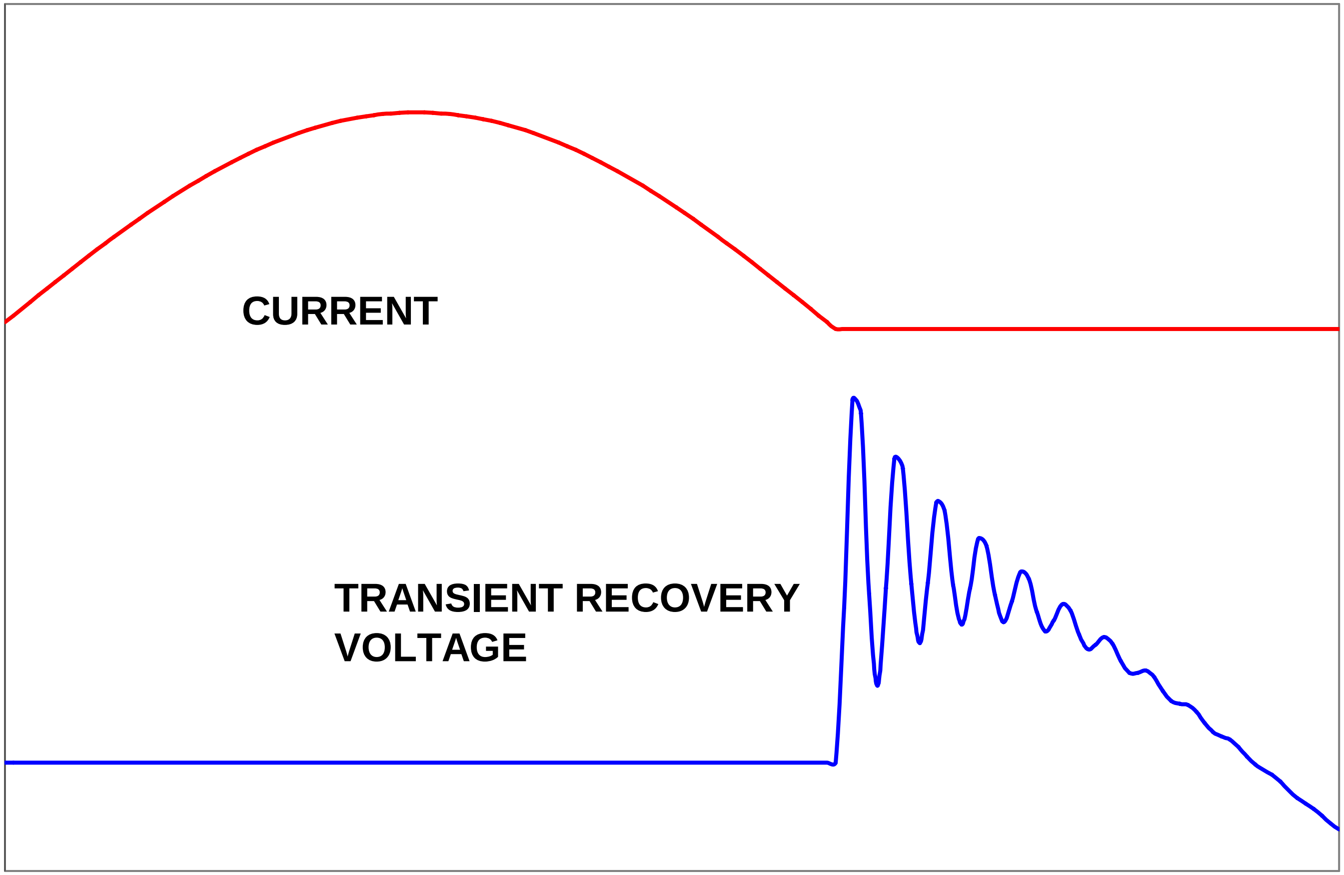
Note

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.

kpp= 1.5 is taken for all systems that are not effectively grounded, it includes (but is not limited to) systems with isolated neutral (it is also taken for three-phase ungrounded faults).

Terminal fault
TRV Ratings

Transient Recovery Voltage



Terminal Fault TRV Rating

- The TRV ratings for circuit breakers are applicable for interruption of three-phase faults
  - with a rated symmetrical short circuit current
  - at the rated voltage of the circuit breaker.
- For values of fault current other than rated and for line faults, related TRV capabilities are given in ANSI/IEEE C37.04 and IEEE C37.06.

Terminal Fault TRV Rating

- For circuit breakers applied on systems 72.5 kV and below, the TRV ratings assume that the systems can be non-effectively grounded.
- For circuit breakers applied on systems 245 kV and above, the TRV ratings assume that the systems are effectively grounded.
- Two-parameter and four-parameter envelopes have been introduced in order to facilitate the comparison between a TRV obtained during testing and a specified TRV.

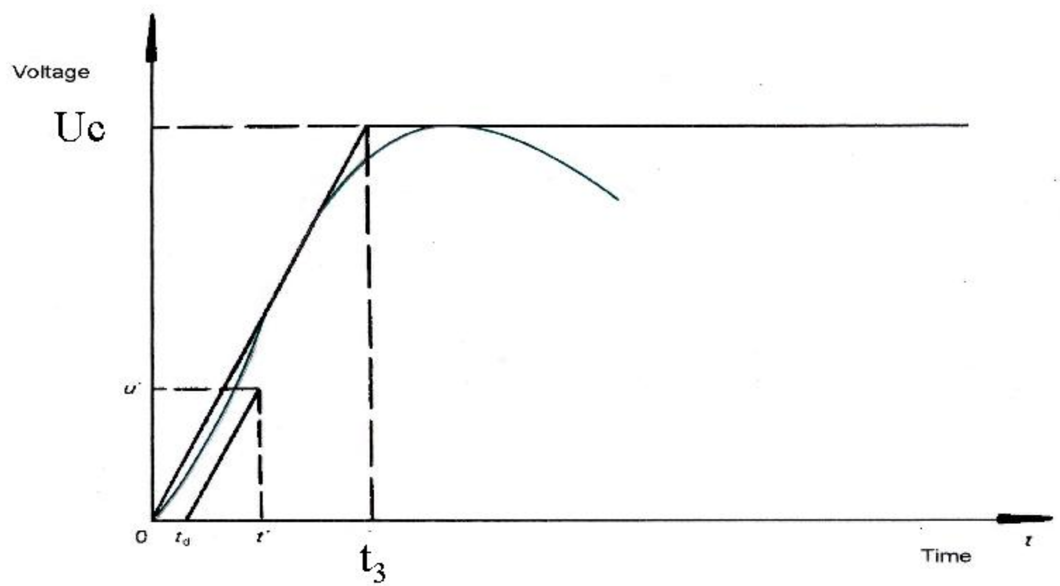
  In a similar way it is possible to compare a circuit-breaker specified TRV capability and a system TRV obtained by calculation.

Terminal Fault TRV Rating

- A two-parameter envelope is used for oscillatory (under-damped) TRVs.

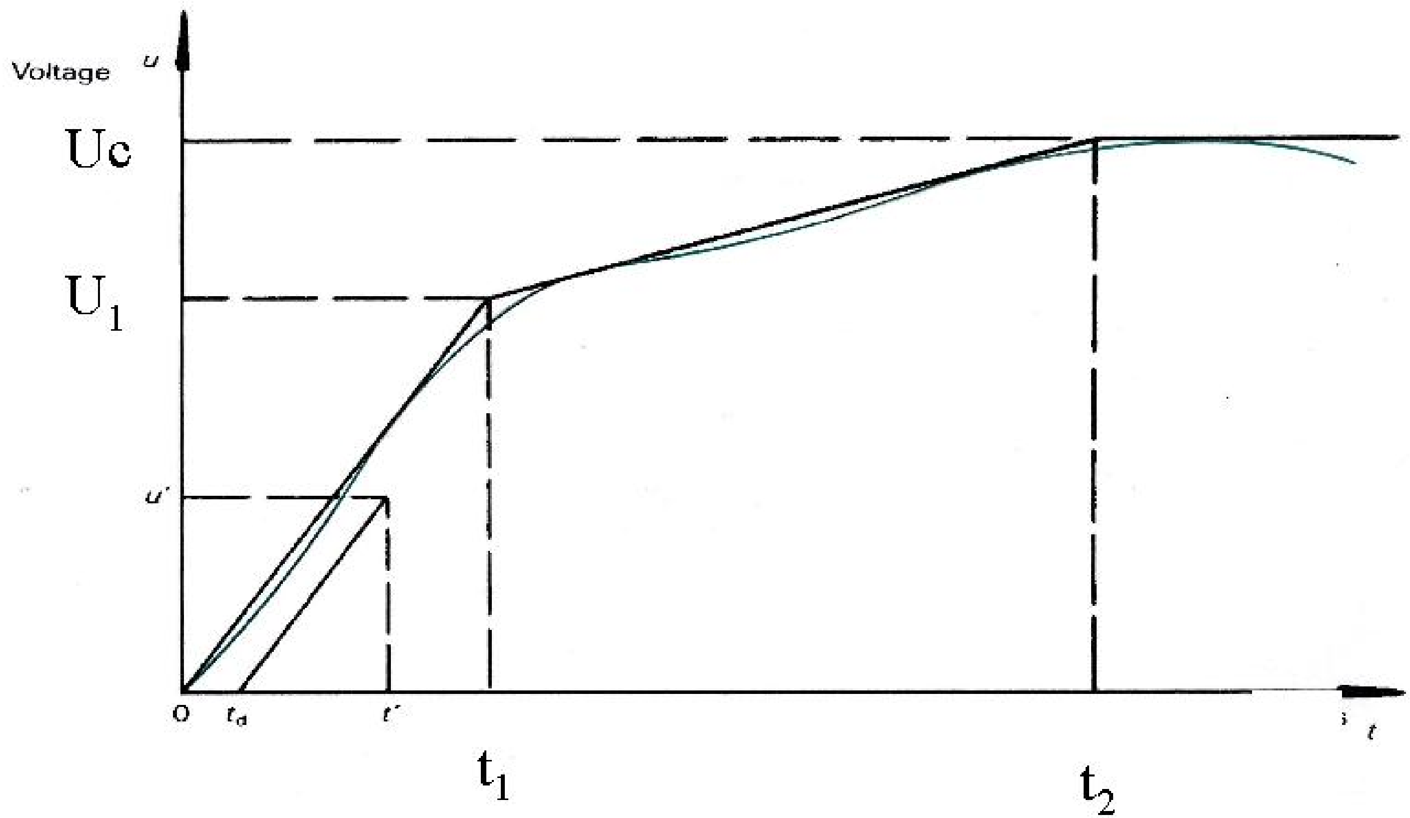
  For standardization purposes, two-parameter envelopes are specified

  - for circuit breakers rated less than 100kV, 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.



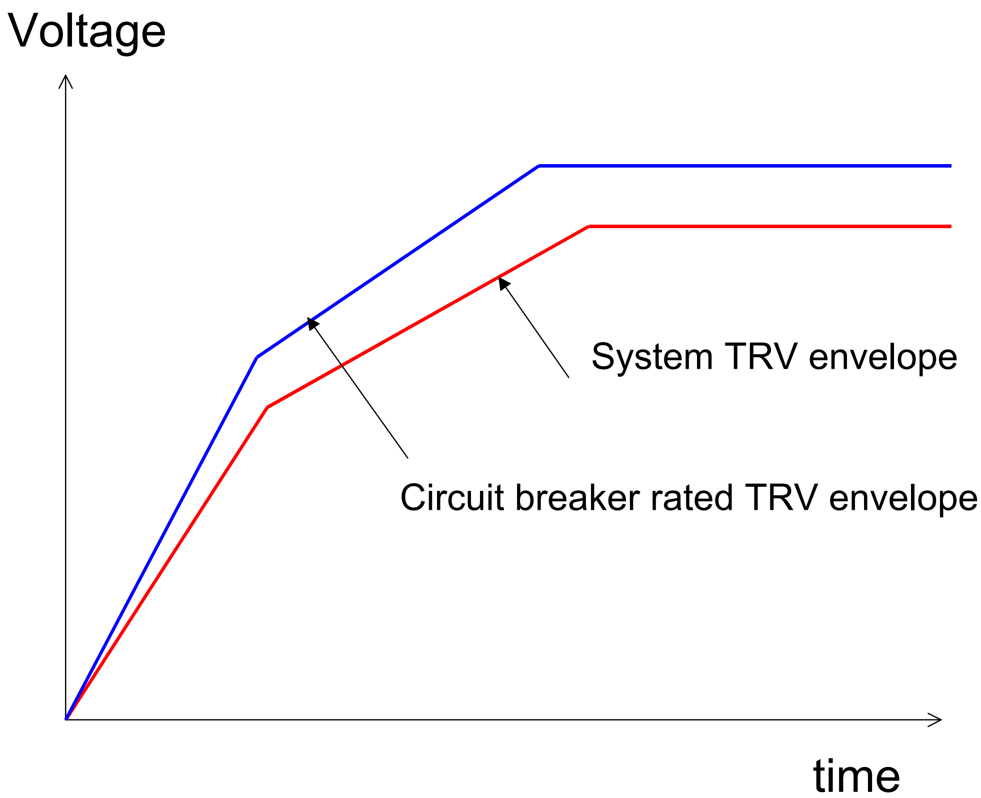
Terminal Fault TRV Rating

- A four-parameter envelope is specified for circuit breakers rated 100 kV and above if the short-circuit current is more than 30% of the rated breaking current.

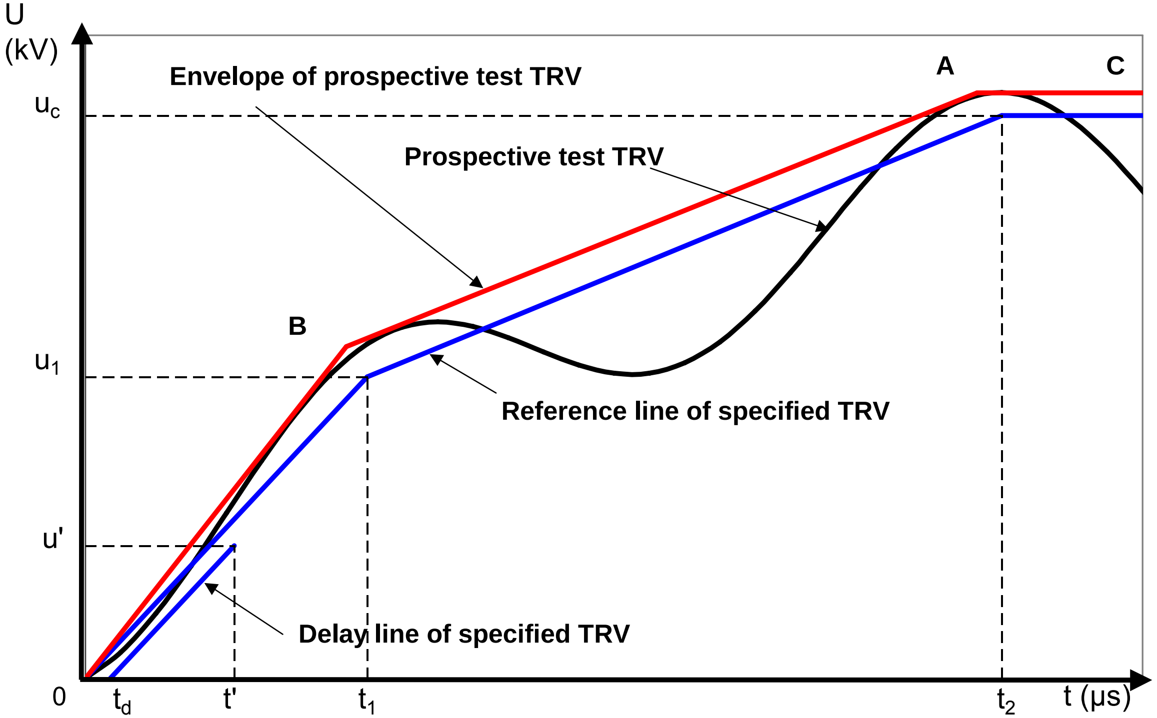


Terminal Fault TRV Rating

- A circuit breaker TRV capability is considered to be sufficient if the two or four parameter envelope drawn with rated parameters is equal or higher than the two or four parameter envelope of the system TRV.



- During testing, the envelope of the test TRV must be equal or higher than the specified two or four parameter envelope.



This procedure is justified as it allows to compare TRVs in the two regions where a restrike 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).

The peak value of TRV is defined as follows:

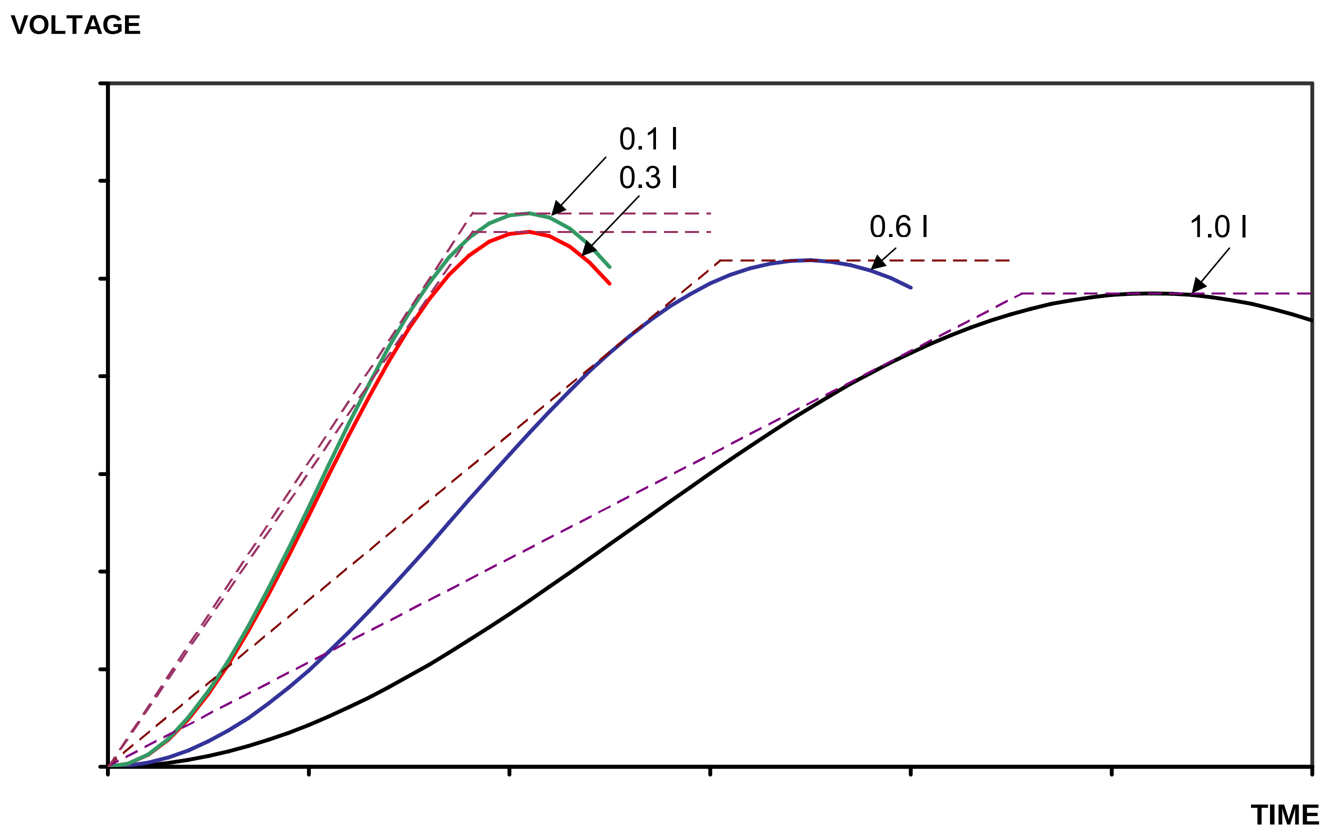
$$U_c = k_{af} \times k_{pp} \times \sqrt{2} \times \frac{U_r}{\sqrt{3}}$$

where

k_{pp} is the first pole to clear factor

k_{af} is the amplitude factor (ratio between the peak value of TRV and the peak value of the recovery voltage at power frequency). In IEEE C37.04, k_{af} is 1.4 at 100% rated breaking current.

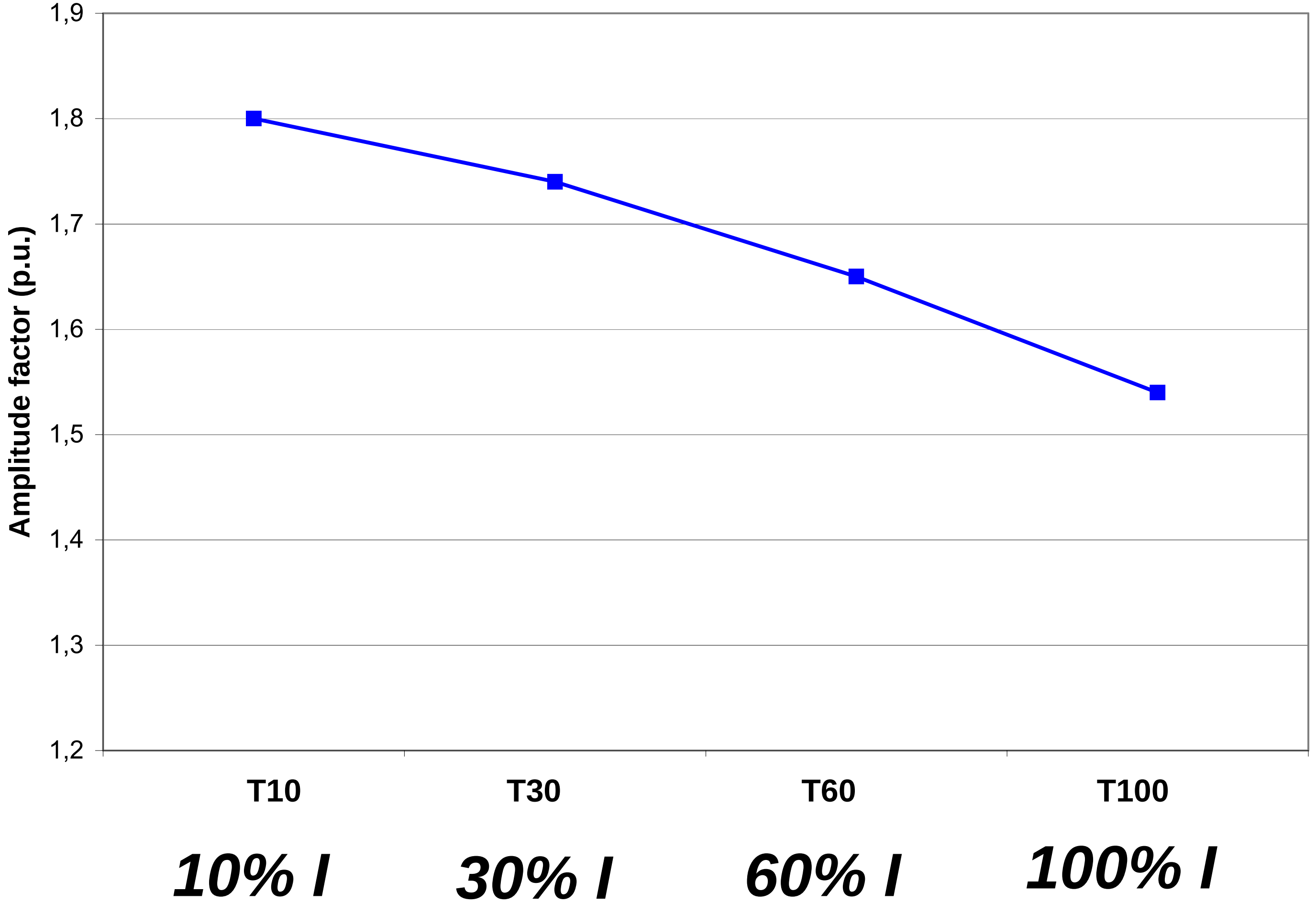
TRV envelopes for terminal fault (Ur < 100 kV)



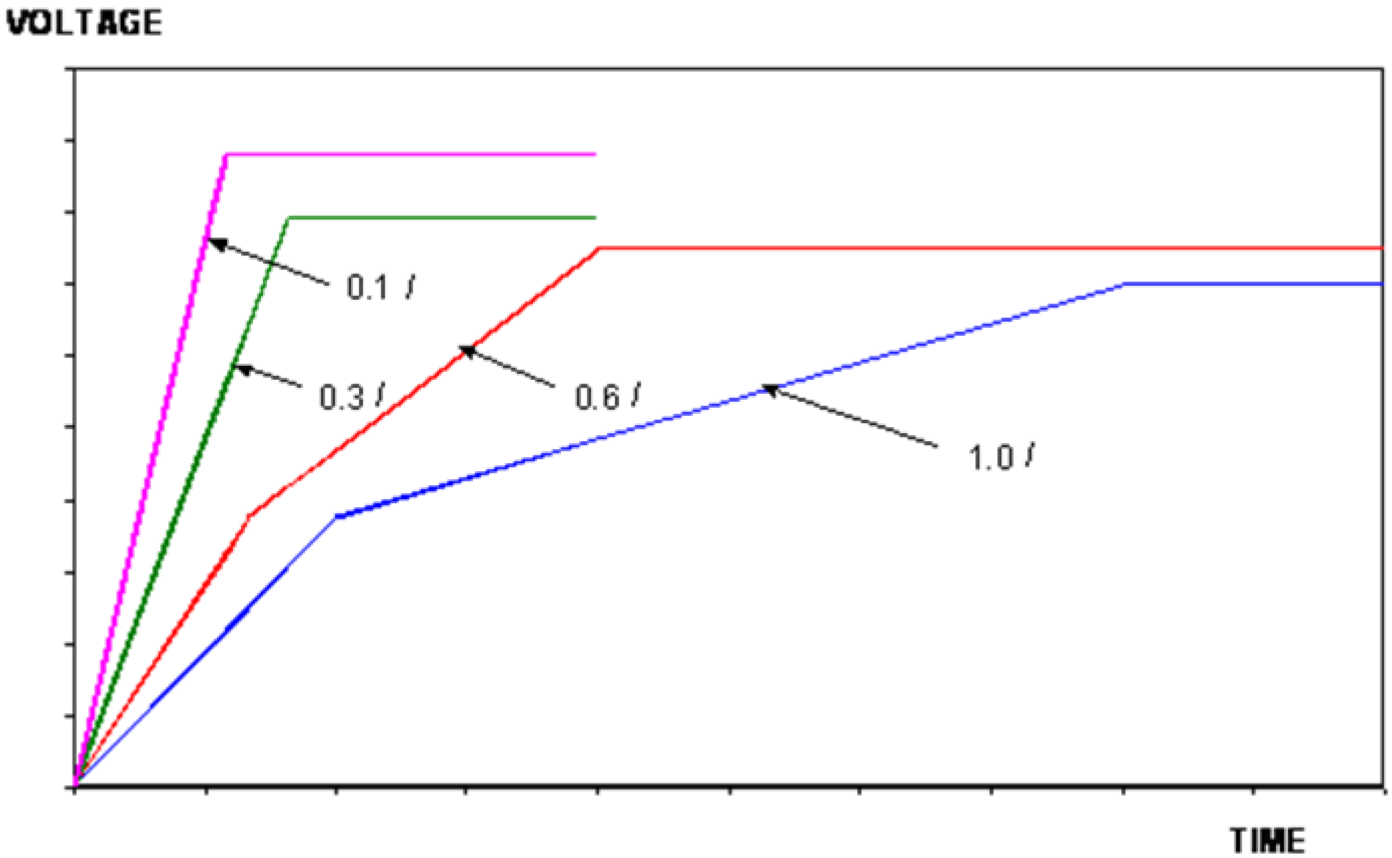
(I is the rated short-circuit current)

Amplitude factor for terminal fault (Ur < 100 kV)

Outdoor circuit breakers

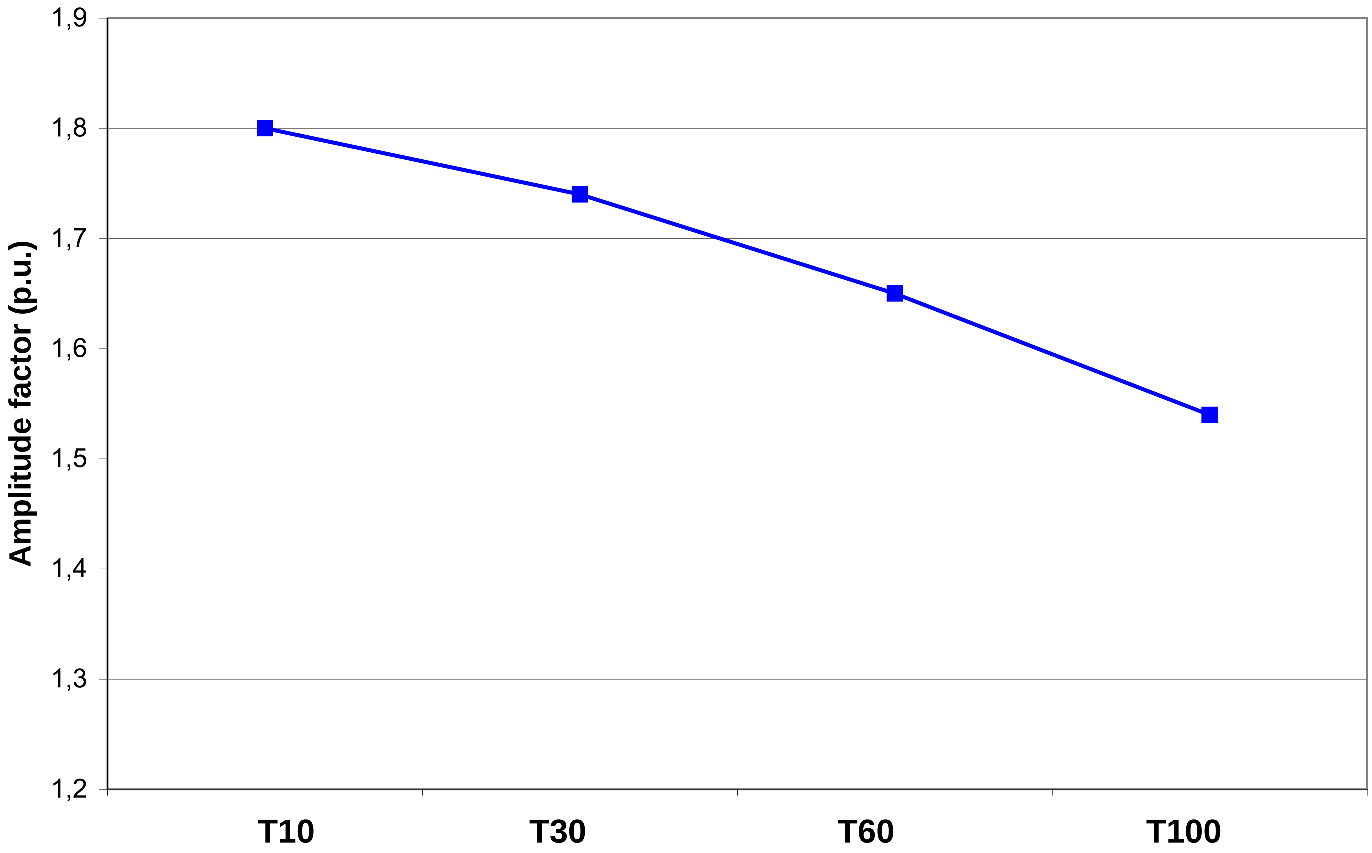


TRV envelopes for terminal fault (Ur ≥ 100 kV)

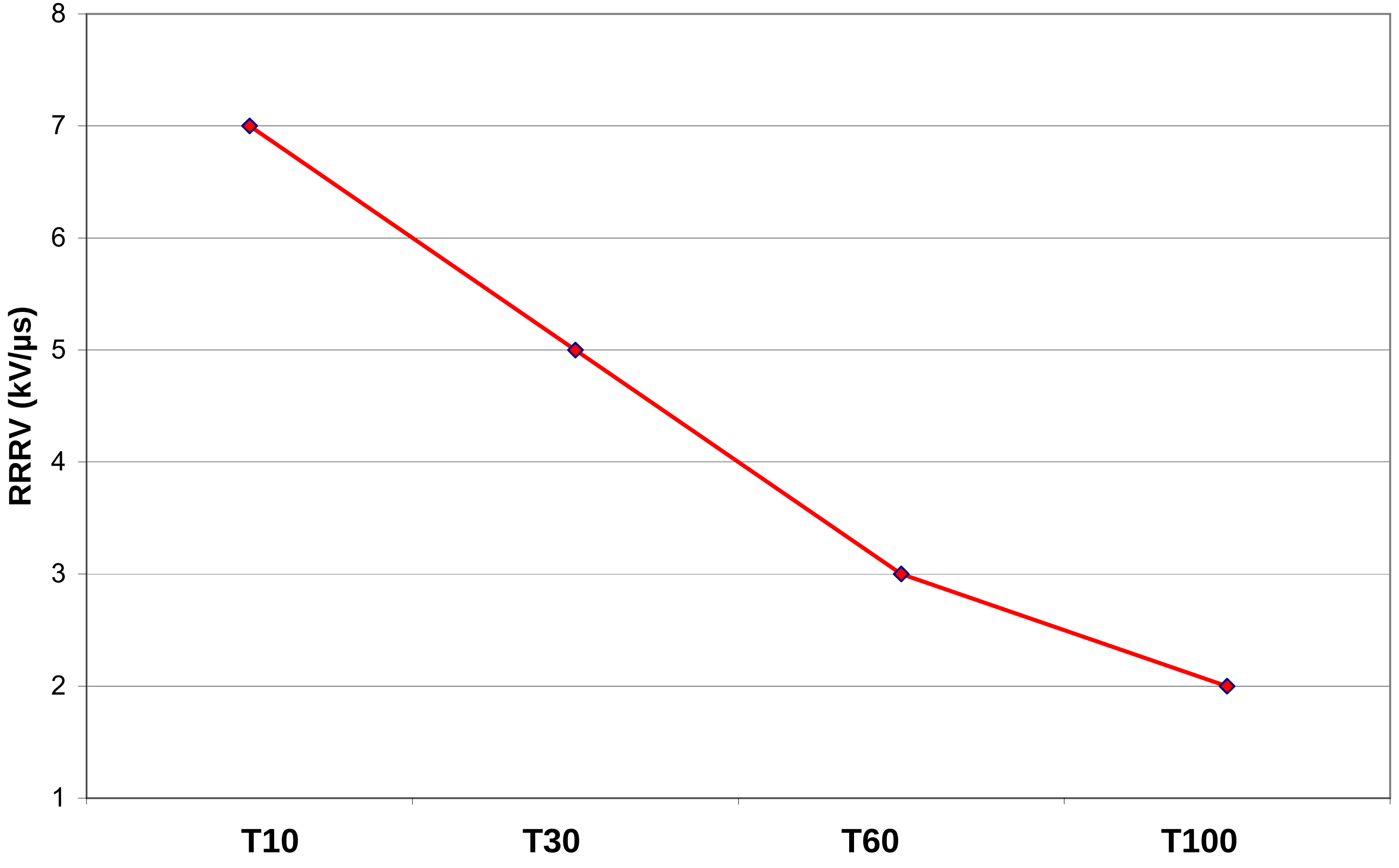


(I is the rated short-circuit current)

Amplitude factor for terminal fault (Ur ≥ 100 kV)



Rate-of-rise-of-recovery-voltage for terminal fault (Ur ≥ 100 kV)

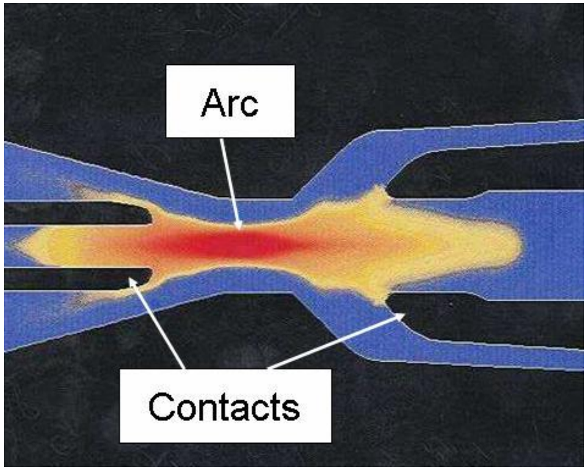


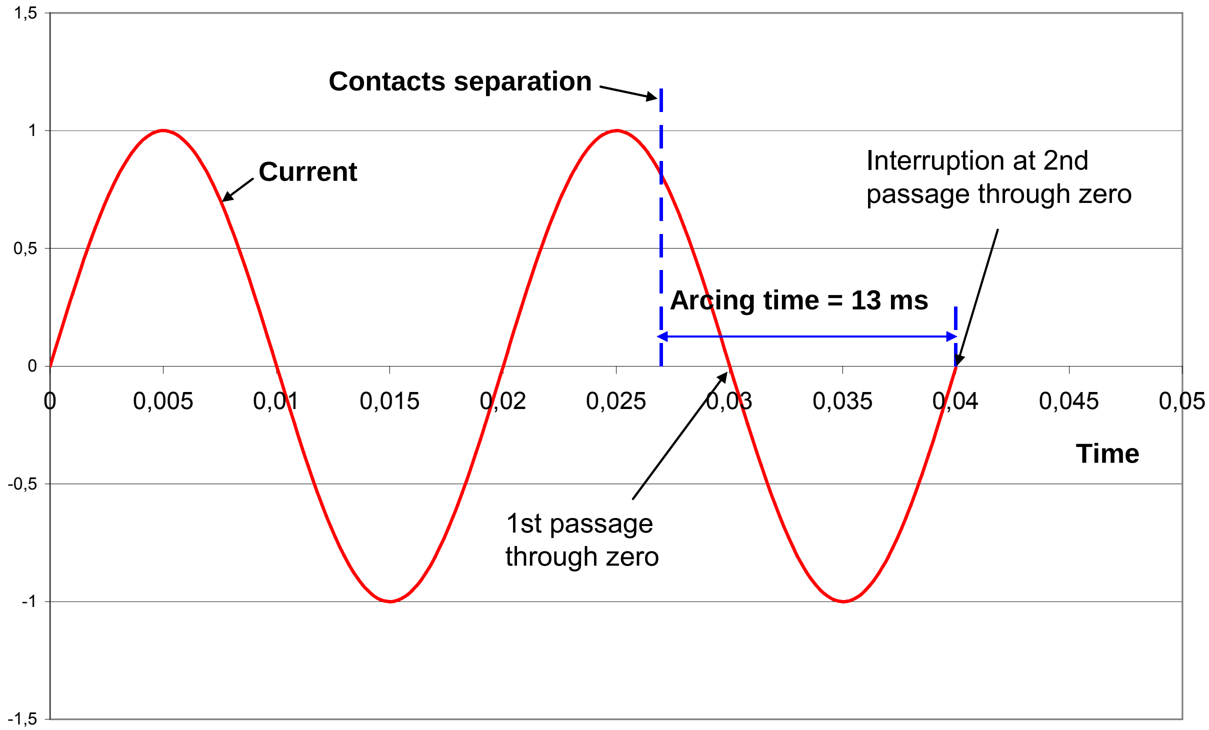
Terminal Fault TRV Rating

- Tests are required at 100% (T100), 60% (T60), 30% (T30) and 10% (T10) of rated short-circuit current with the corresponding TRVs and recovery voltages.
- 6 tests are required with 100% of rated short-circuit current, 3 tests with symmetrical currents and 3 tests with asymmetrical currents (when interrupting asymmetrical currents, the rate-of-rise and peak value of TRV are reduced but the energy in the arc is higher).
- In IEEE standards, for each test duty T10; T30, T60: 2 tests are required with symmetrical currents and 1 test with asymmetrical current. IEC requires 3 tests with symmetrical currents, considering that interruption with asymmetrical currents is covered by T100a (test duty with 100% rated short-circuit current and required asymmetry).
- 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 (see separate chapter).

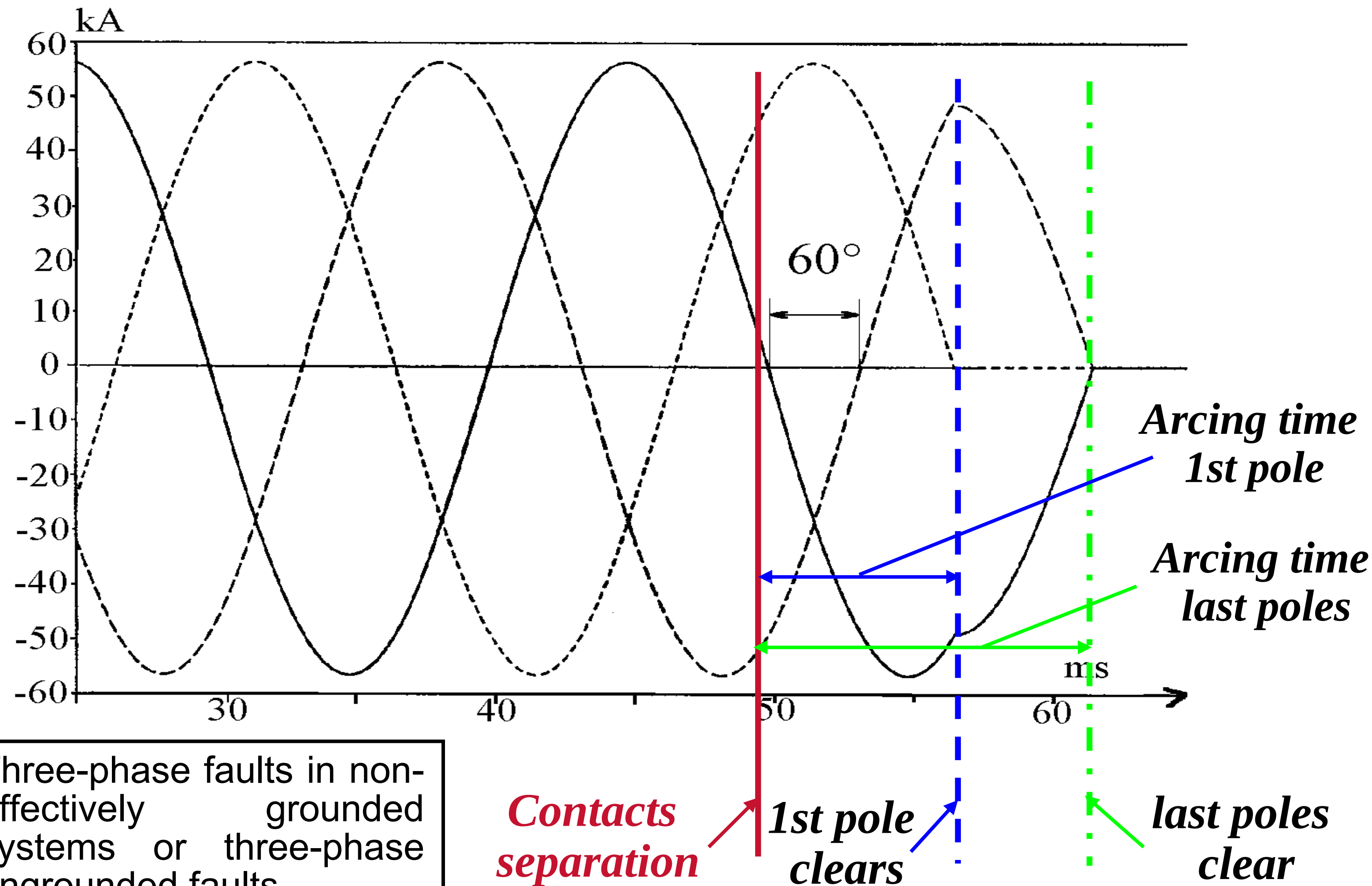
Terminal fault
TRV & Arcing times

Arcing time


Arc
Contacts


1,5
1
0,5
0
-0,5
-1
-1,5
0
0,005
0,01
0,015
0,02
0,025
0,03
0,035
0,04
0,045
0,05
Contacts separation
Current
Interruption at 2nd passage through zero
Arcing time = 13 ms
1st passage through zero
Time

Current interruption during three-phase fault breaking



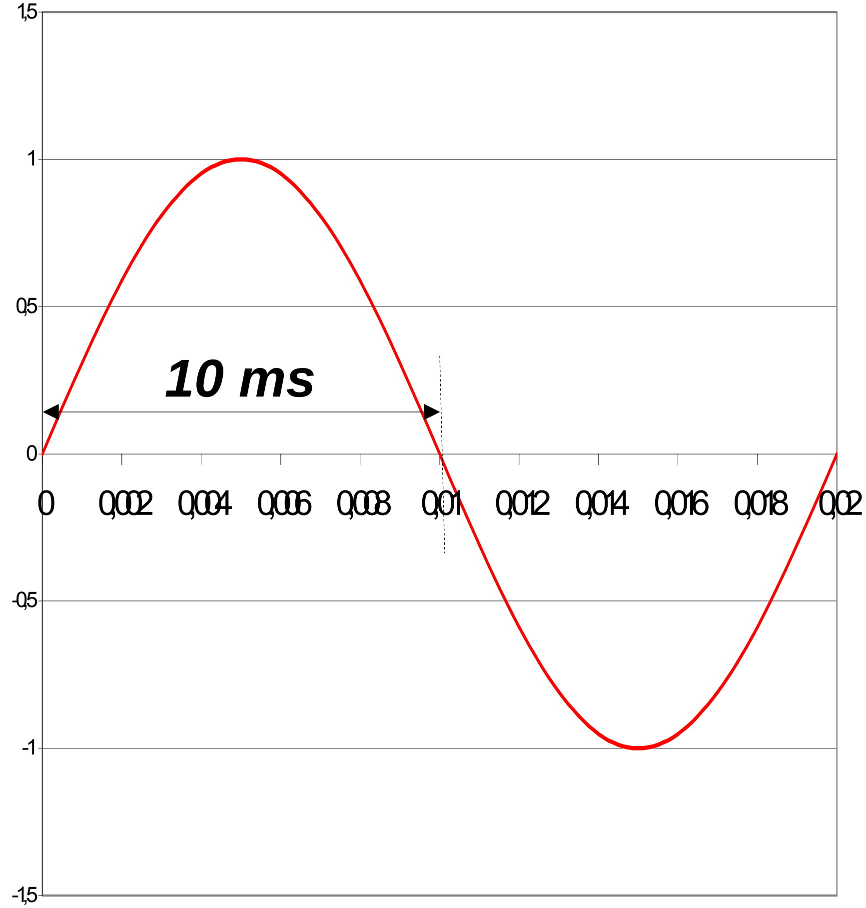
Three-phase faults in non-effectively grounded systems or three-phase ungrounded faults

Terminal Fault TRV & Arcing Times

In the case of periodic phenomena, durations can be expressed in milliseconds or in electrical degrees.

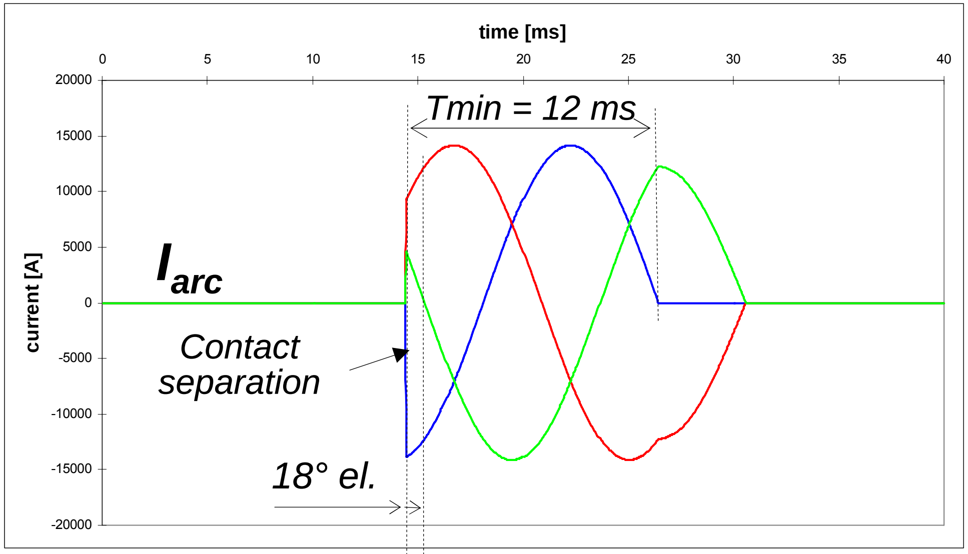
For a system frequency of 50 Hz, the duration of one current loop is 10 ms, it corresponds to 180° el. It follows that 18° el. = 1 ms

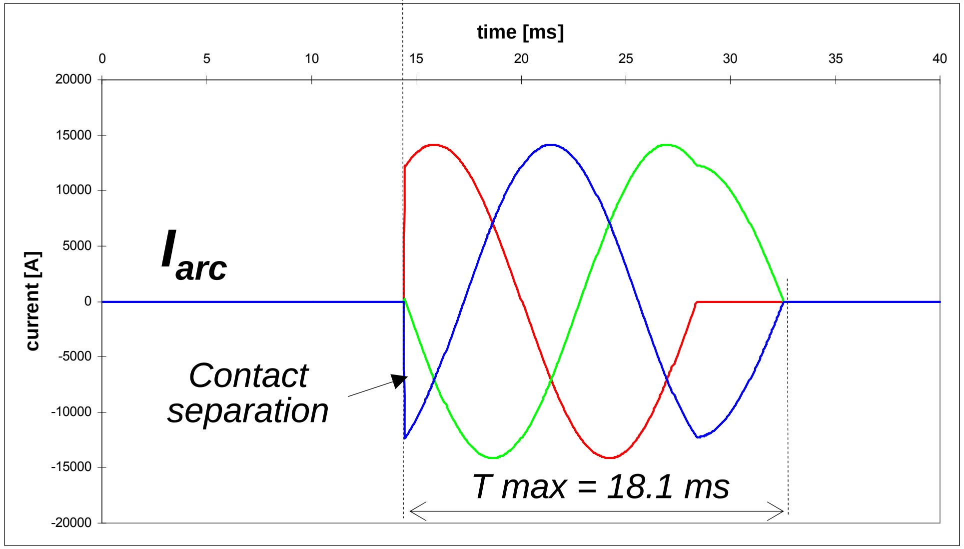
For a system frequency of 60 Hz: 18° el. = 0.83 ms



Example with f = 50 Hz

Minimum & maximum arcing times (60 Hz)





Three-phase faults in non-effectively grounded systems or three-phase ungrounded faults

Minimum arcing time (blue phase) Tmin = 12 ms

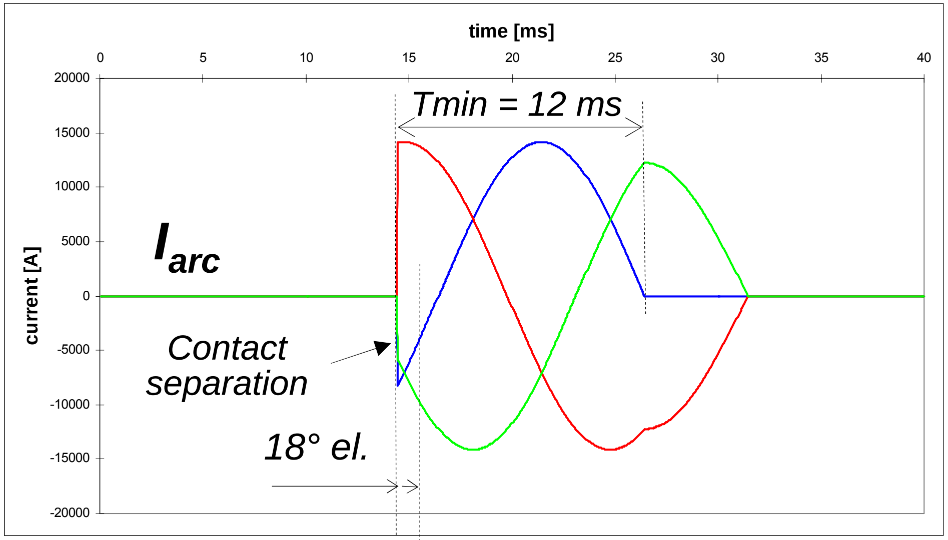
Contact separation delayed by 18° el. (or 0.83 ms)

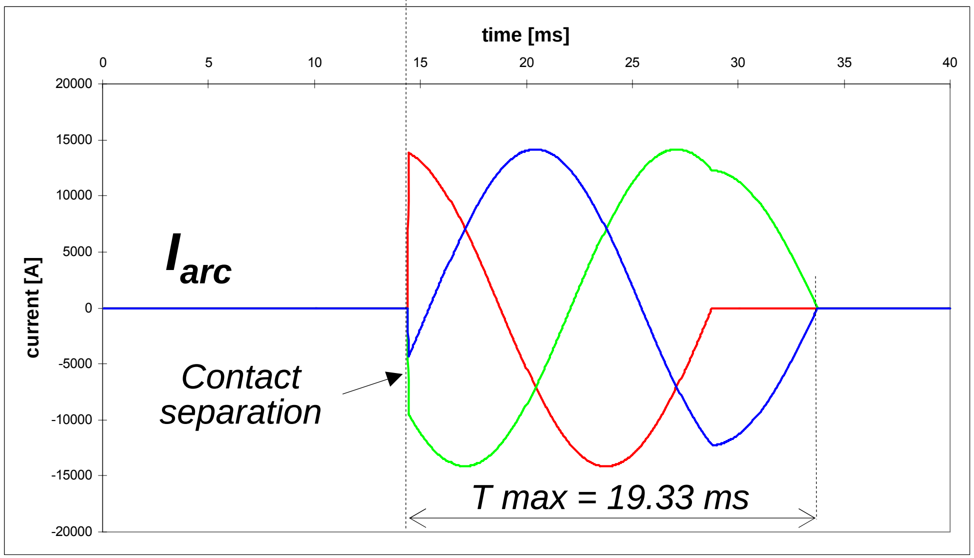
Arcing time 1st phase (red phase) = 13.94 ms (Tmin + 60° - 18° = Tmin + 42°)

Maximum arcing time (blue phase) = 18.1 ms (13.94 ms + 90° = Tmin + 132°)

Minimum & maximum arcing times (50 Hz)

Three-phase faults in non-effectively grounded systems or three-phase ungrounded faults





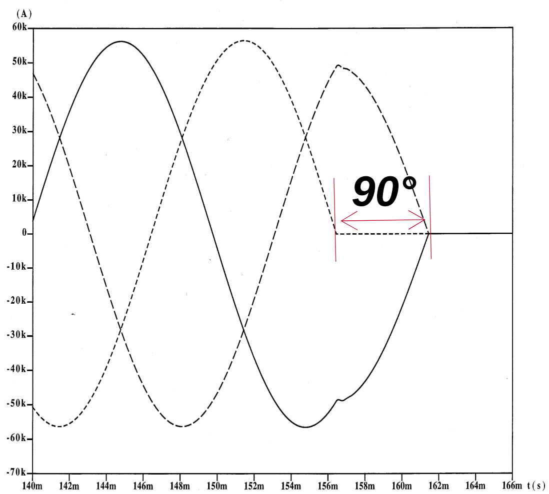
Minimum arcing time (blue phase) Tmin = 12 ms

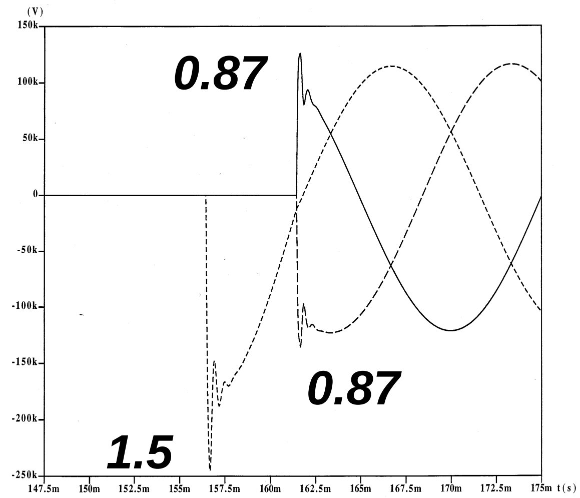
Contact separation delayed by 18° el. (or 1 ms)

Arcing time 1st phase (red phase) = 14.33 ms (Tmin + 60° - 18° = Tmin + 42°)

Maximum arcing time (blue phase) = 19.33 ms (14.33 ms + 90° = Tmin + 132°)

Three-phase fault currents & TRVs

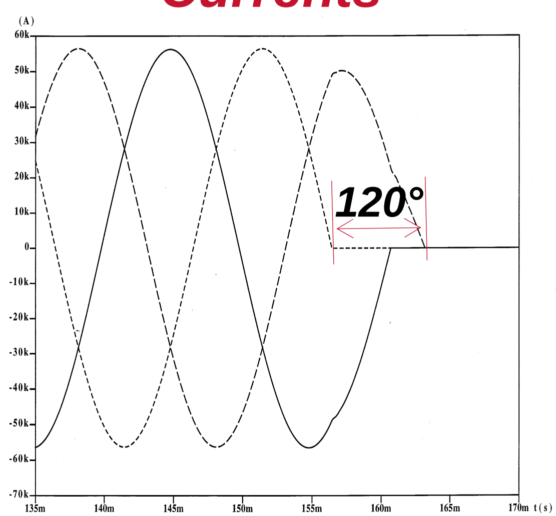


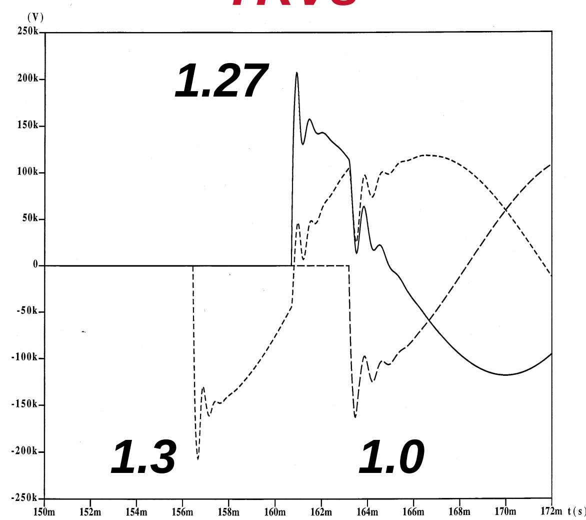


Three-phase faults in non-effectively grounded systems or three-phase ungrounded faults

Maximum arcing time = Tmin + 132°)

Currents **TRVs**



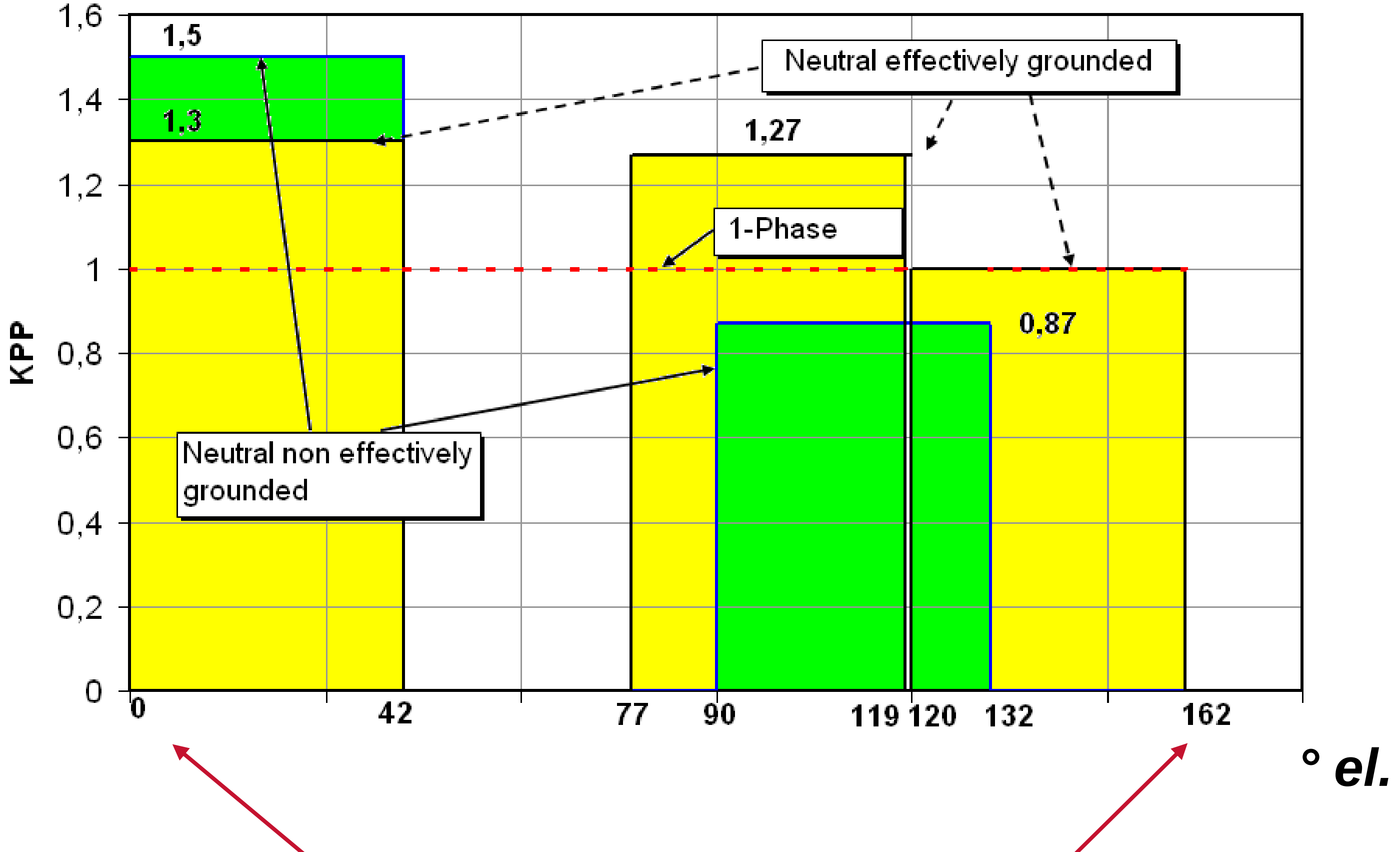


Three-phase faults in effectively grounded systems

Maximum arcing time = Tmin + 162°)

TRV & Arcing Times

Pole to clear factor



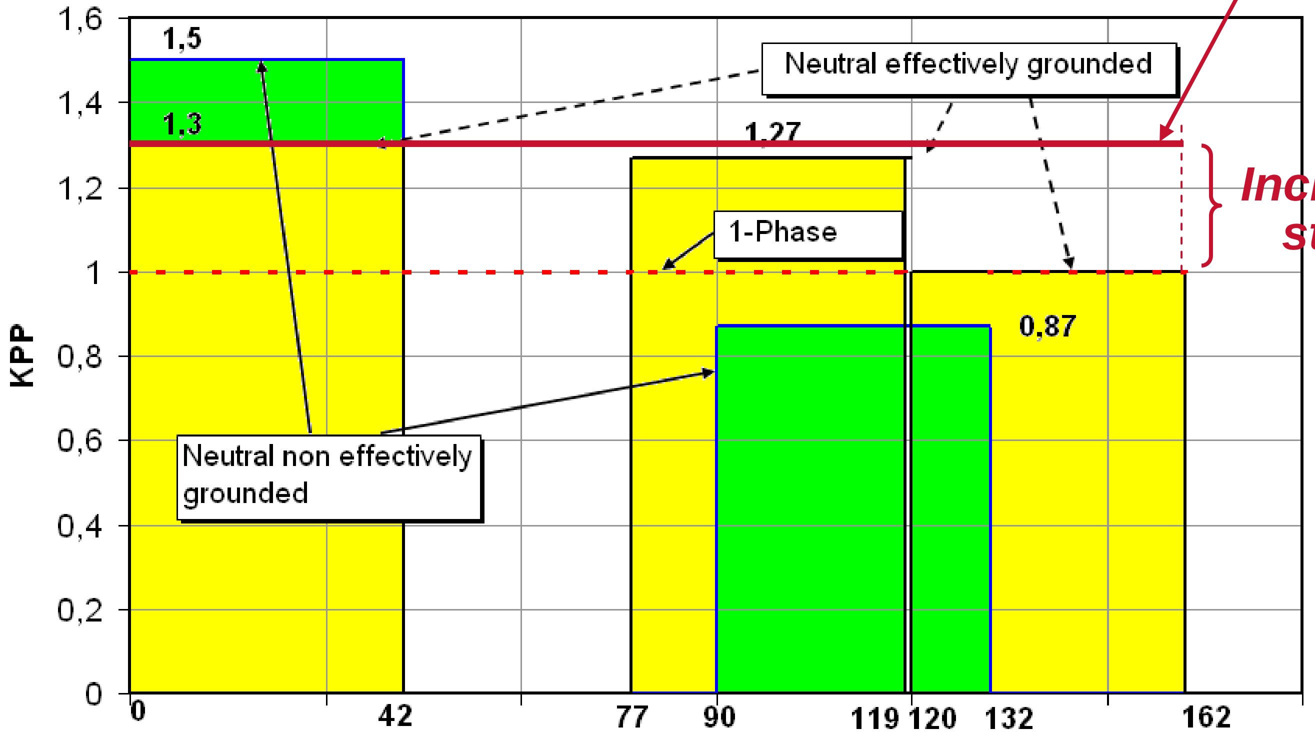
Reference: Minimum arcing time

Minimum arcing time + 180° -18°

TRV & Arcing Times

Pole to clear factor

Single-phase "umbrella" test with kpp=1.3



° el.

Reference: Minimum arcing time

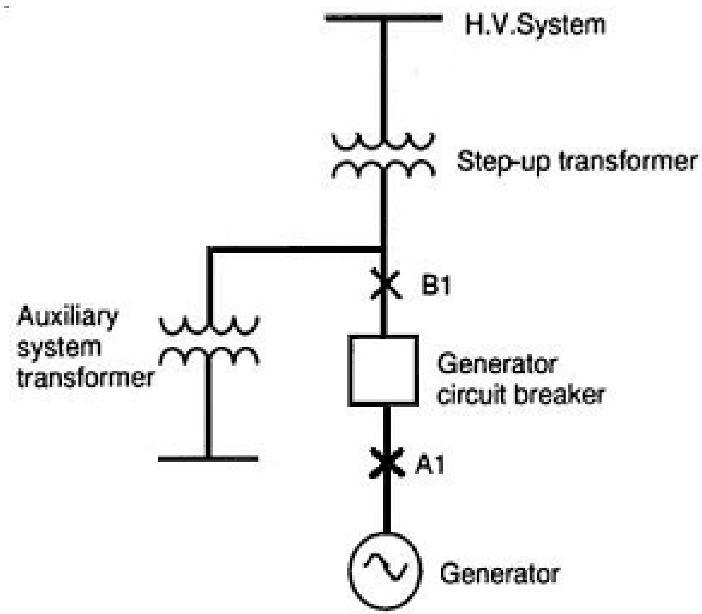
Minimum arcing time + 180° -18°

Terminal fault
Generator Circuit breakers

Special case of Generator circuit breakers

- Special TRV requirements are applicable for generator circuit breakers installed between a generator and a transformer. Two types of faults need to be considered

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 to 5 times higher than the value specified for distribution or sub-transmission circuit breakers ANSI/IEEE C37.04. This is due to the fact that the TRV frequency is dominated by the natural frequency of the step-up transformer.
- IEEE has defined TRV parameters in several ranges of transformer rated power.

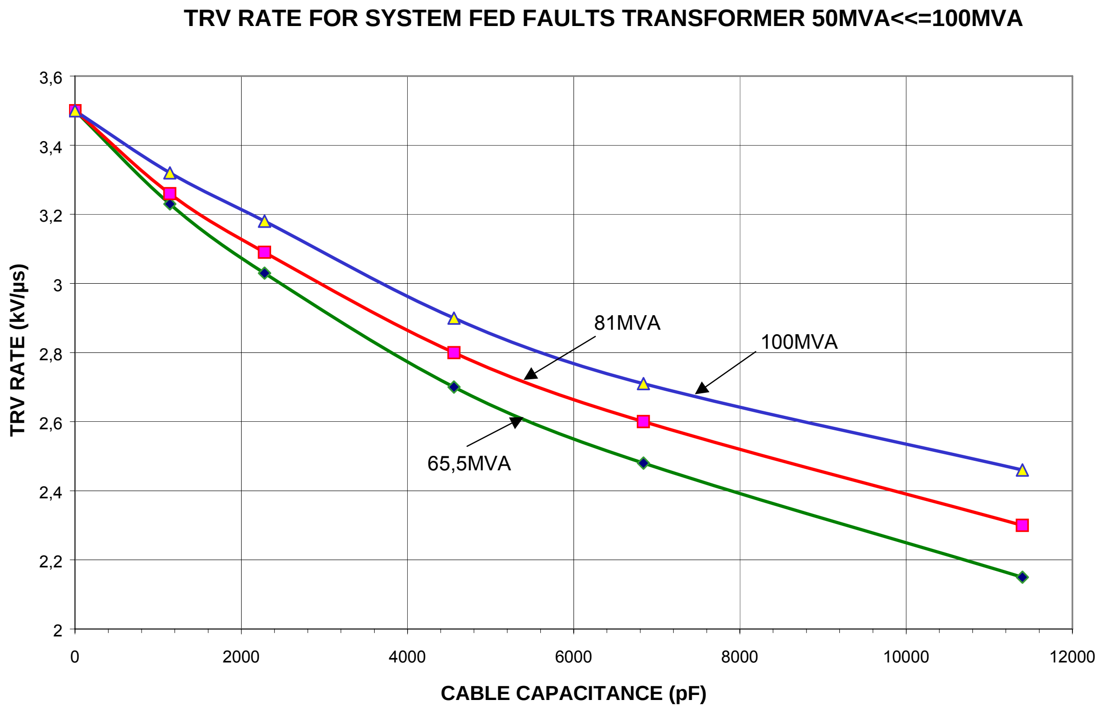
TRV parameters for System Source Faults

Table 5a– TRV parameters for system - source faults

Line	Transformer Rating (MVA)	Inherent TRV		
		T_2 -Time to - Peak (µs)	E_2 -Peak Voltage (kV)	TRV Rate (kV / µs)
	Column 1	Column 2	Column 3	Column 4
1	10 - 50	0.68 V	1.84 V	3.2
2	51 - 100	0.62 V	1.84 V	3.5
3	101 - 200	0.54 V	1.84 V	4.0
4	201 - 400	0.48 V	1.84 V	4.5
5	401 - 600	0.43 V	1.84 V	5.0
6	601 - 1000	0.39 V	1.84 V	5.5
7	1001 or more	0.36 V	1.84 V	6.0

TRV for system-source faults

- 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). This is covered in amendment 1 to ANSI/IEEE C37.013 (2007).



TRV for generator-source faults

- RRRV for generator-source faults is roughly 2 times the values specified for distribution or sub-transmission circuit breakers.

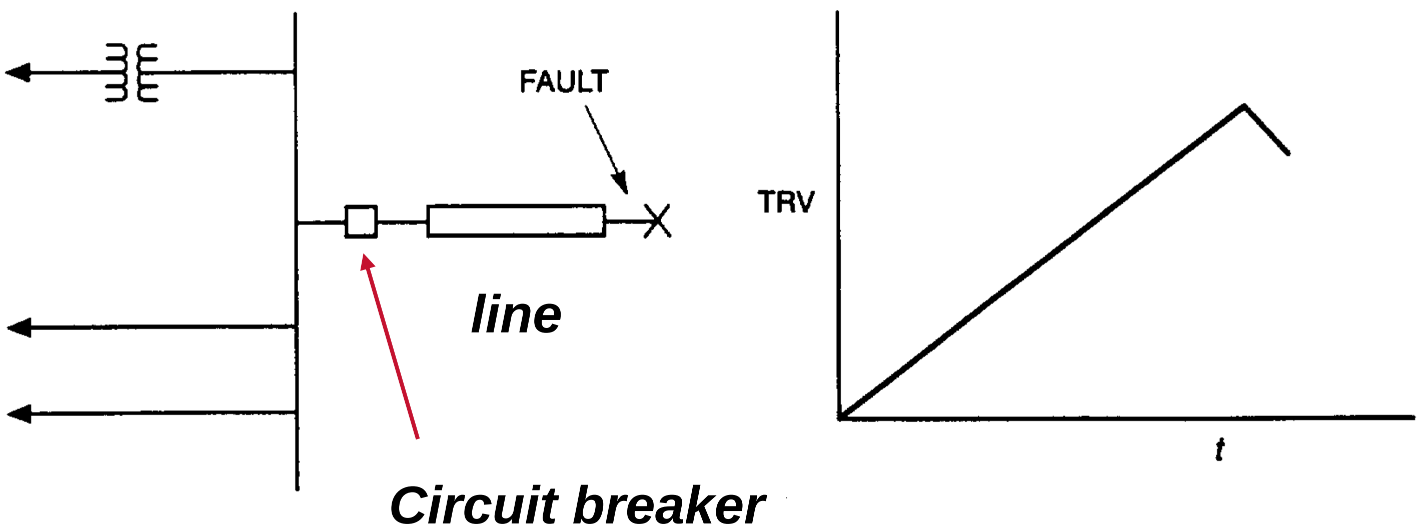
Asymmetrical currents

- 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 significantly reduced.

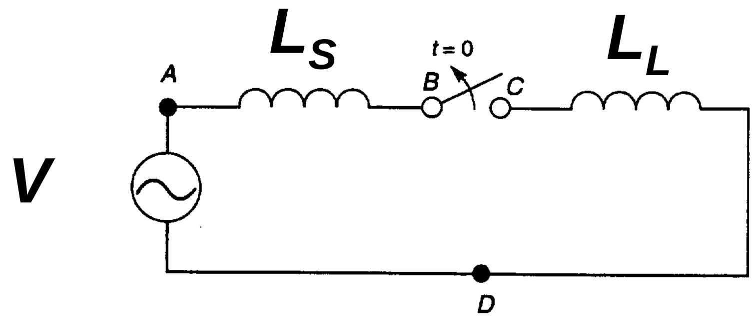
Short-line-fault (SLF)

Short-line-fault (SLF)

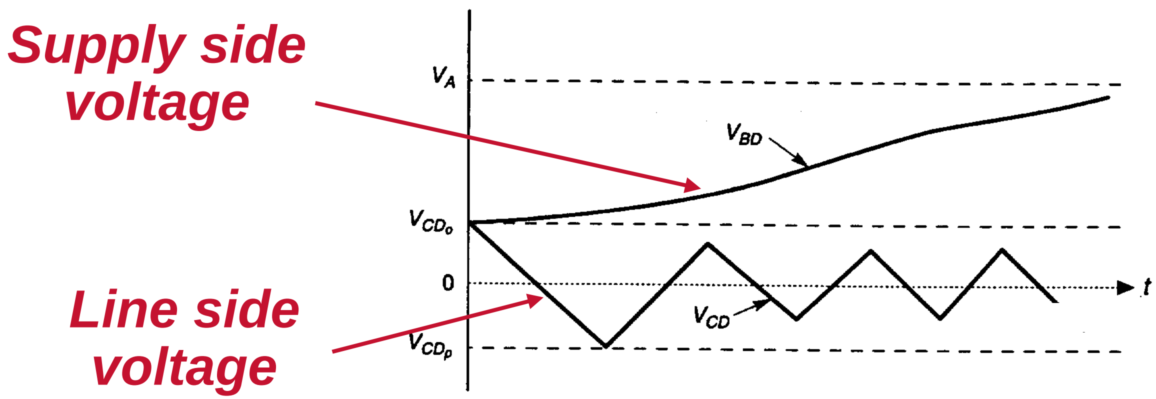
- Short-line faults occur from a few hundred meters up to several kilometers down the line.
- After current interruption, the line side voltage exhibits a characteristic triangular waveshape.



- The line side voltage oscillates as travelling waves are transmitted with positive and negative reflections at the open breaker and at the fault, respectively. The supply voltage rises much more slowly.

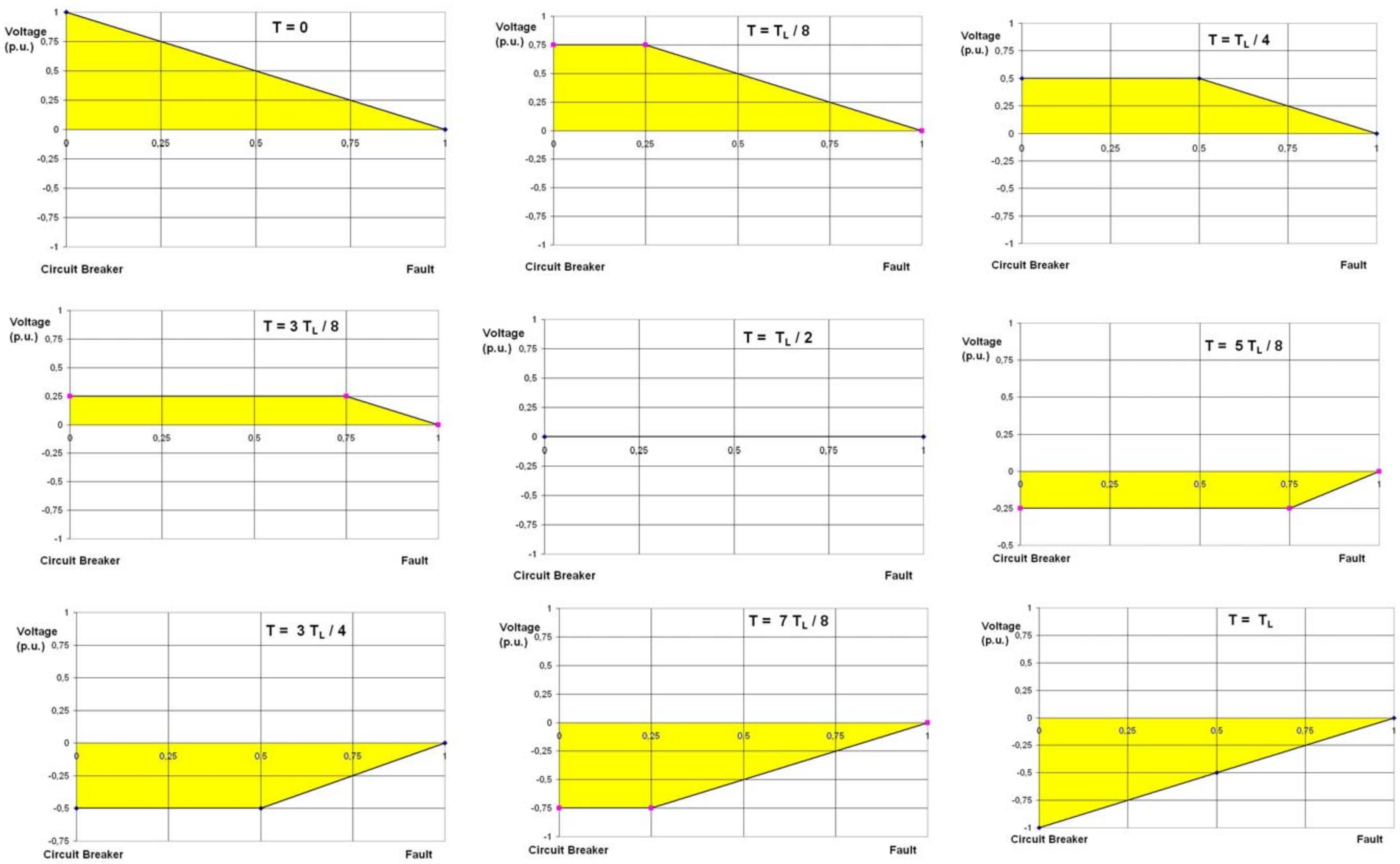


$$V = (L_S + L_L)\, di/dt$$



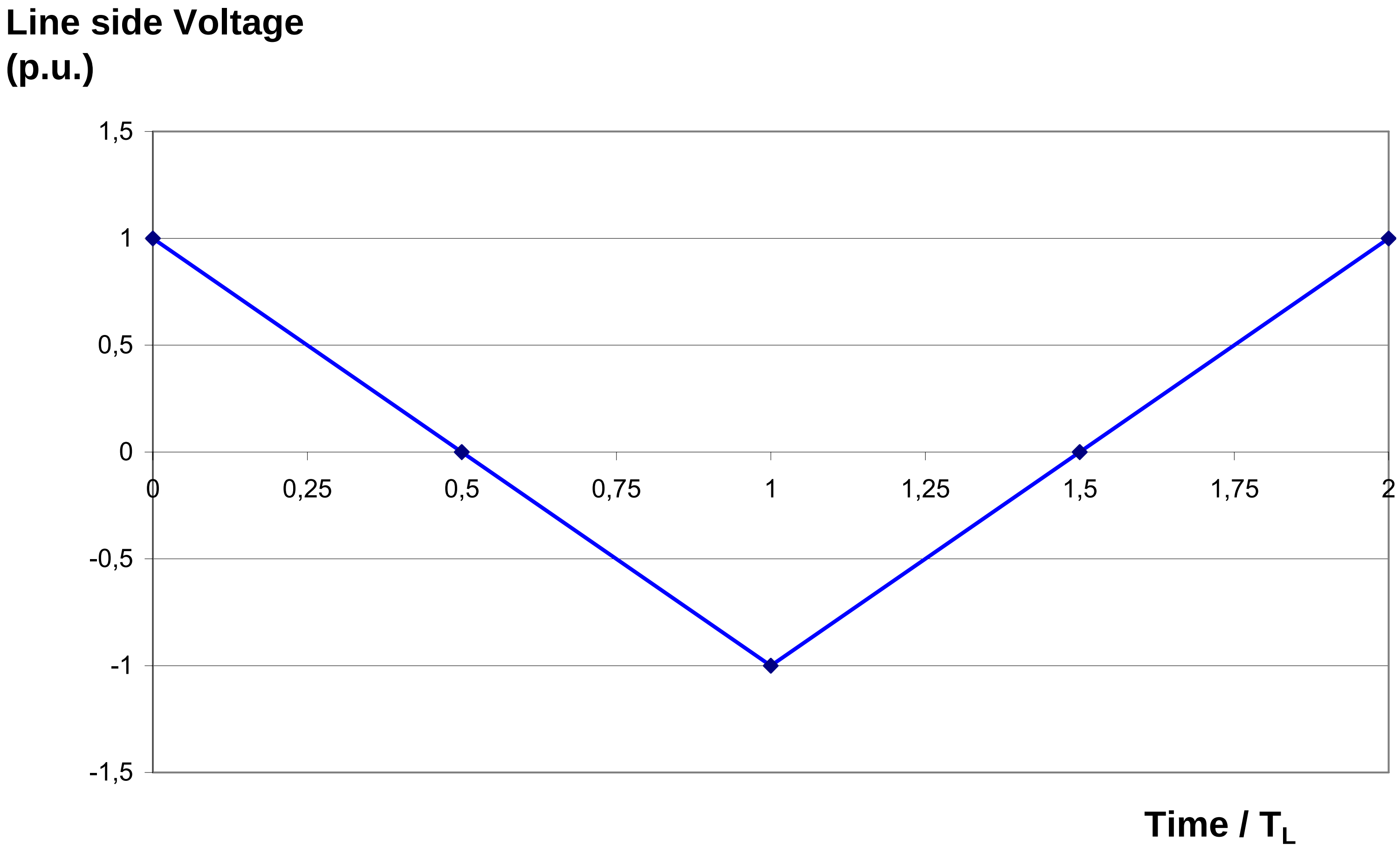
Short-line-fault (SLF)

Evolution of line voltage

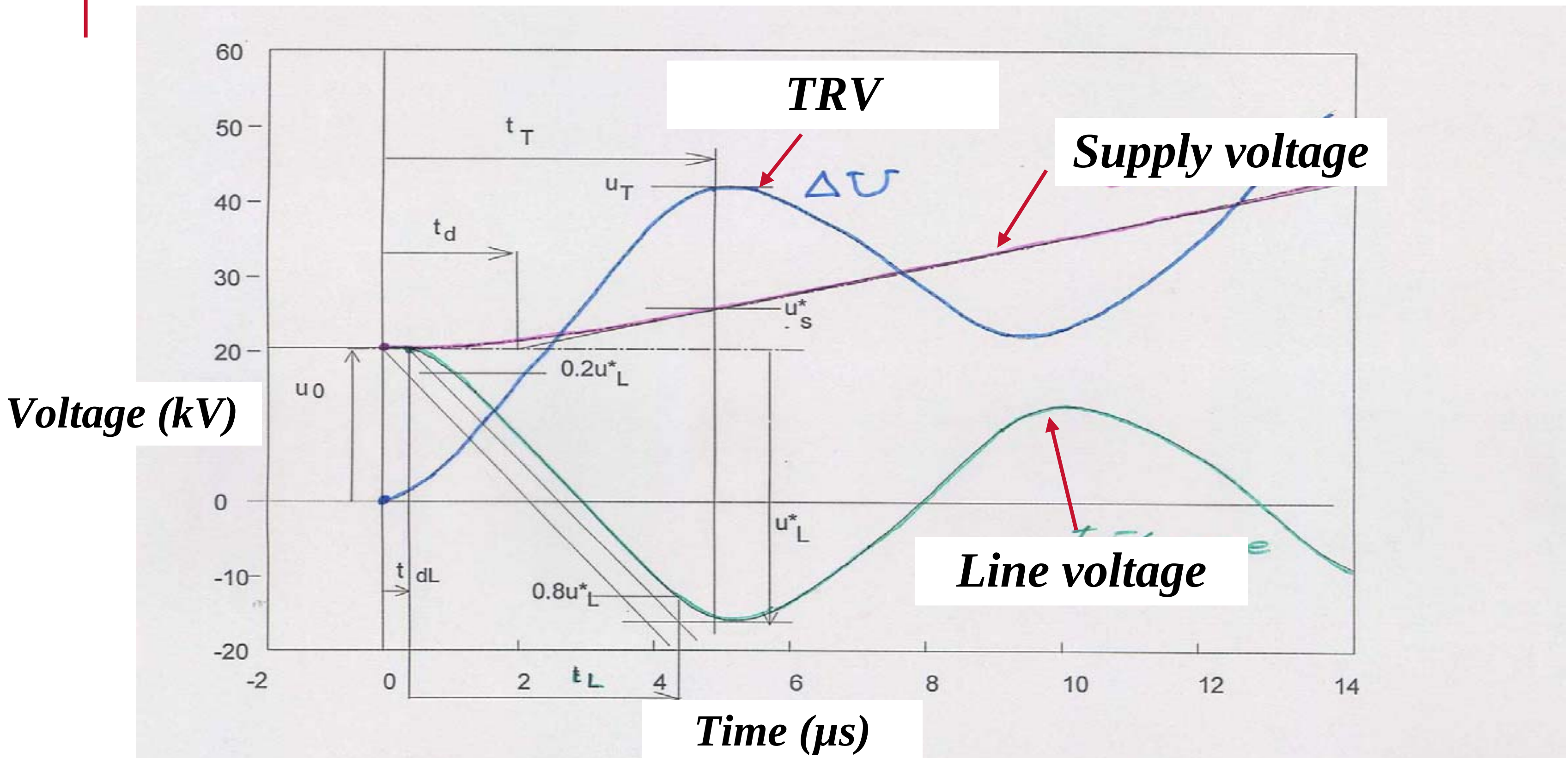


TL = Travel time for wave to travel from one end of line to the other and back.

Voltage on Circuit Breaker line-side terminal



Short-line Fault TRV



Short-line-fault (SLF)

- The rate of rise of voltage on the line side is function of the slope of current before interruption and of the surge impedance of the line:

$$\frac{du}{dt} = Z\frac{di}{dt} = Z\,\omega\,I\sqrt{2} = s\,I \quad (= s\,M\,I_{sc})$$

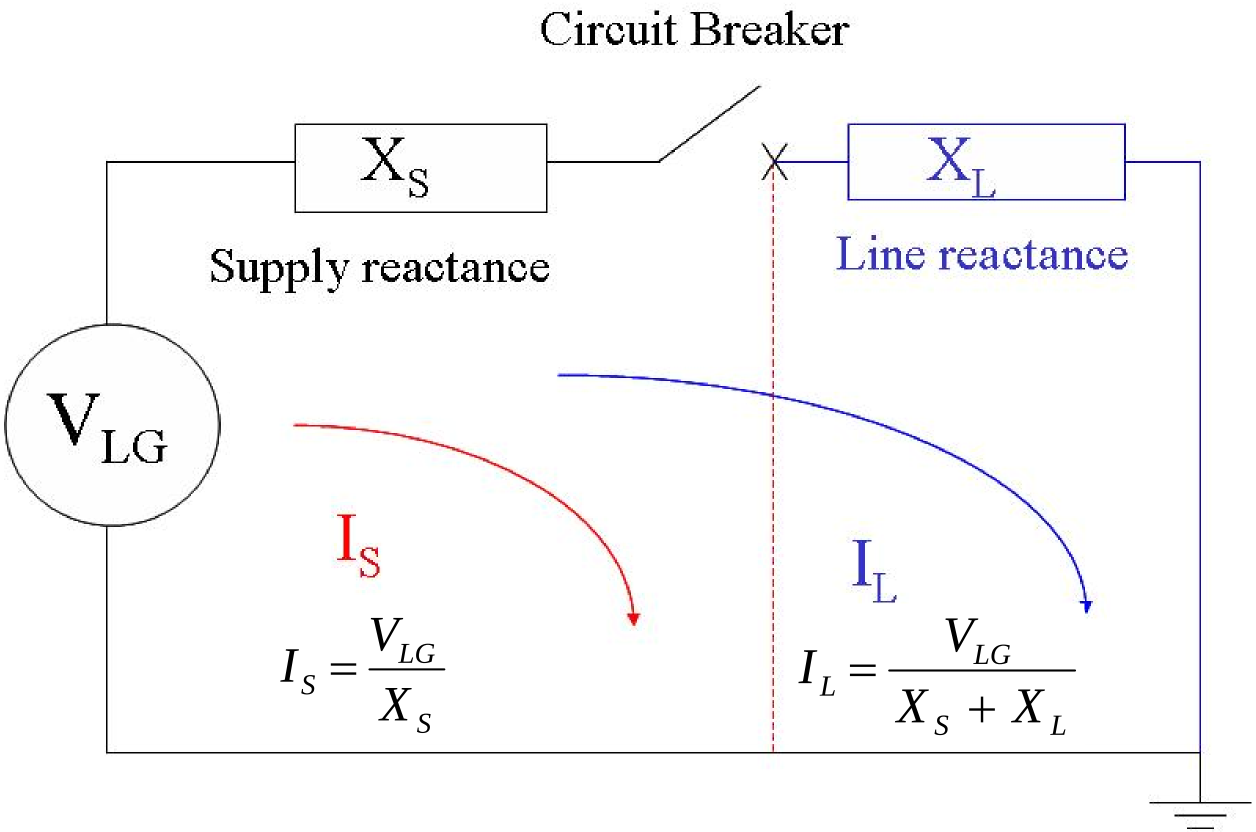
$$Z = \sqrt{\frac{L}{C}}$$ surge impedance of the line (450 ohm)

L et C are respectively the self inductance and the capacitance of the line per unit length

I	fault current (kA)
du/dt	rate of rise of recovery voltage (RRRV) (kV/µs)
ω	pulsation
s	multiplier = 0.20 (f = 50Hz) or 0.24 (f = 60 Hz)

The slope of TRV (du/dt) is proportional to the current

Percentage of SLF (or M)



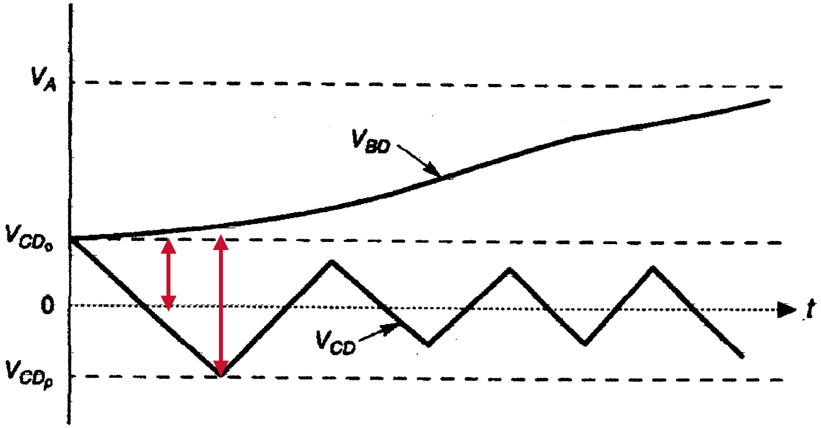
$$M = \frac{I_L}{I_S} = \frac{X_S}{X_S + X_L}$$

Short-line-fault (SLF)

- The transmission line parameters are given in terms of the effective surge impedance (Z) of the faulted line and a peak factor (*d*)

$$d = \frac{V_{CDo} + V_{CDp}}{V_{CDo}}$$

$$d = 2\omega \frac{Z_{eff}}{X_L v}$$



v is the velocity of light (0.3 km/μs)

ω is 2 π × system power frequency (377 rad/s for a 60 Hz system)

Short-line-fault (SLF)

- The rated values for the line surge impedance Z and the peak factor *d* are defined in IEEE C37-04 and IEC 62271-100 as follows:

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

- The line side voltage contribution to TRV is defined as a triangular wave as follows (where I is the rated short-circuit current) :

$$U_L = 1.6\,(1 - M)\sqrt{\frac{2}{3}}\,U_r \qquad du/dt = Z\,(\frac{di}{dt}) = \sqrt{2}\ Z\,\omega\,M\ I$$

the first peak of TRV decreases when M increases

the rate-of-rise of recovery voltage increases with M

- There is a critical value of short-line-fault for which the circuit-breaker has more difficulty to interrupt. This critical value of M is close to 90% for SF6 circuit-breakers, it is between 75% and 80% for air blast circuit-breakers.

Short-line-fault (SLF)

- The TRV seen by the circuit breaker is the sum of a contribution from the line side (e_L) and a contribution from the supply side (e_S):

$$e = e_L + e_S$$

with (in a first approximation)

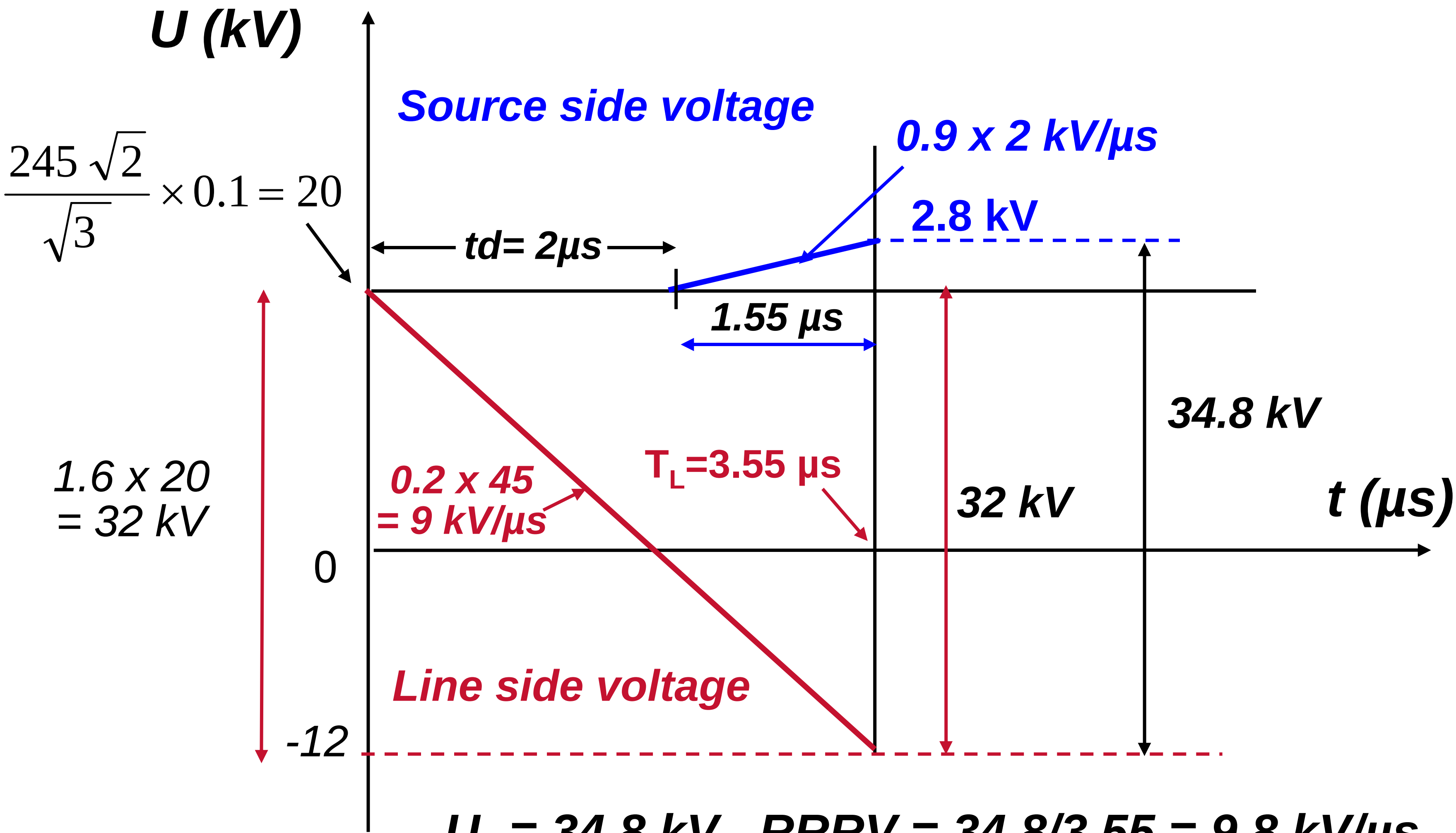
$$e_S = 2\,M\,(T_L - t_d)$$

where

T_L is the time to peak of the line side TRV

td is the time delay of TRV on the source side

- Example of calculation of SLF TRV : **L90 245 kV 50 kA 50 Hz**
  Fault current = 0.9 x 50 = 45 kA



U_T = 34.8 kV RRRV = 34.8/3.55 = 9.8 kV/µs

Short-line-fault (SLF)

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

Test duty	RRRV (kV/µs)	I (kA)	F (Hz)
SLF L90 50 kA	10.8	45	60
SLF L90 50 kA	9	45	50
SLF L90 40 kA	8.64	36	60
Terminal fault T60	3	30	50/60
Terminal fault T100	2	50	50/60

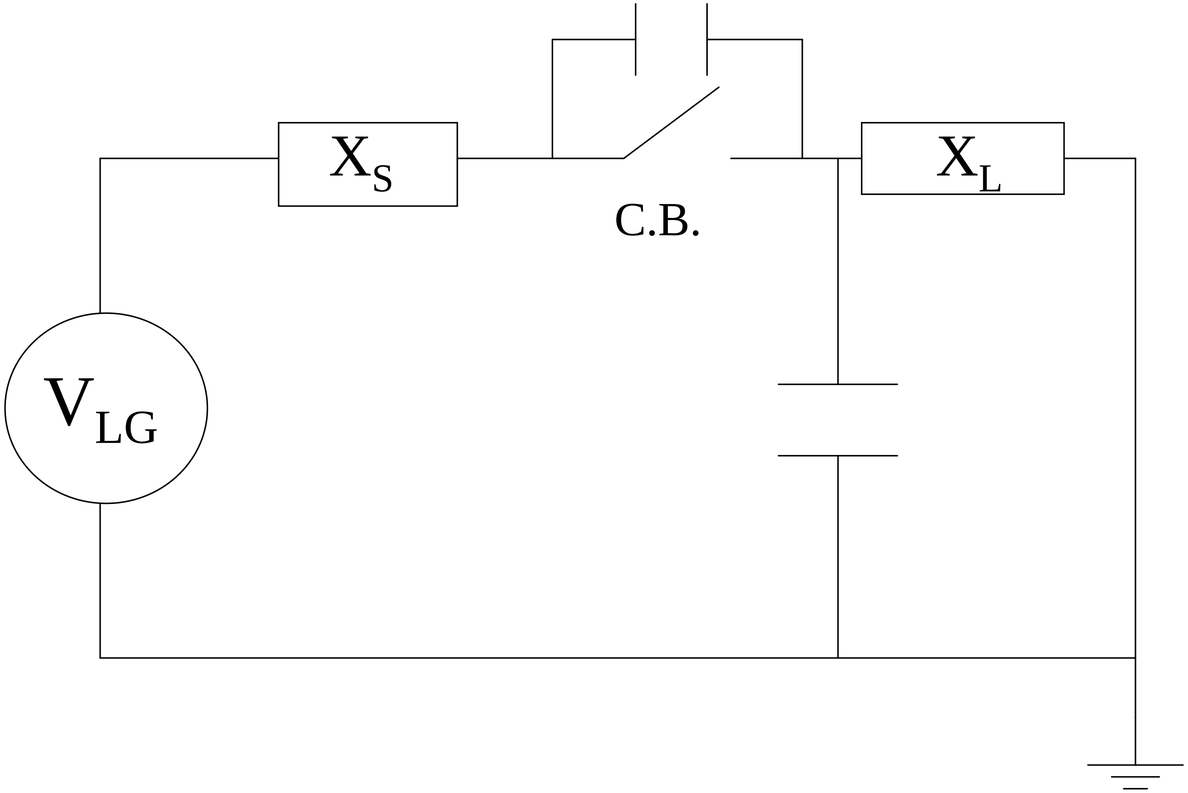
For SLF, this table gives the RRRV of the line side voltage

Short-line-fault (SLF)

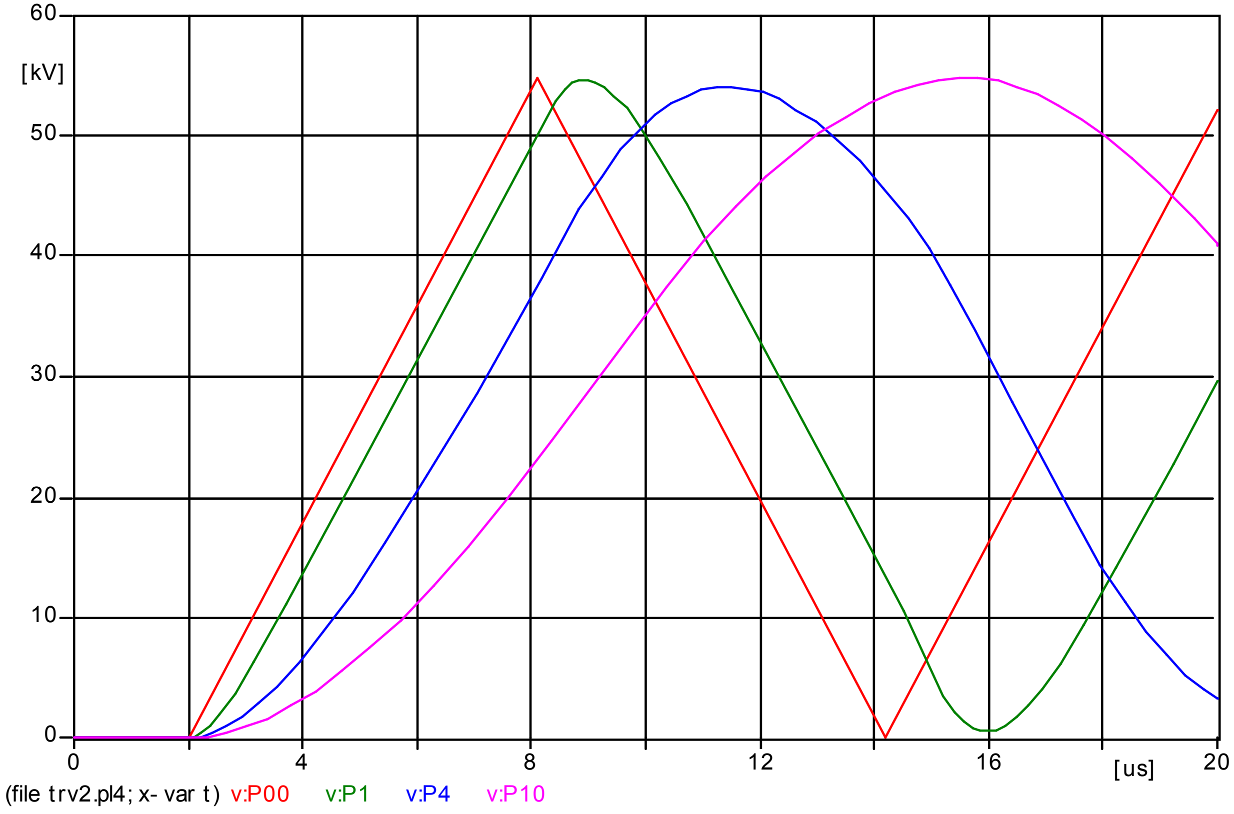
- The high rate-of-rise of SLF associated with high fault currents (e.g. 57 kA at 60 Hz) can be difficult to withstand by circuit breakers.

  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), may be used to reduce the rate-of-rise of recovery voltage (RRRV).

Possible Connections of Capacitors



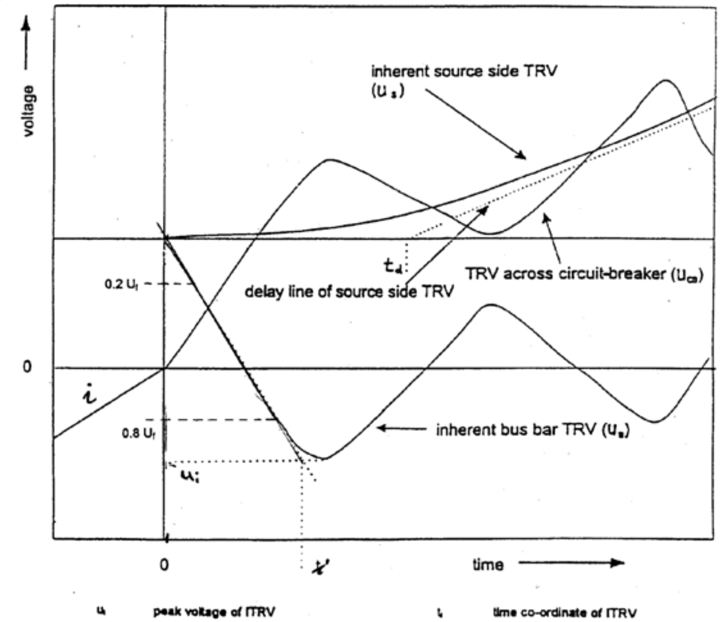
Reduction of TRV slope by Capacitors



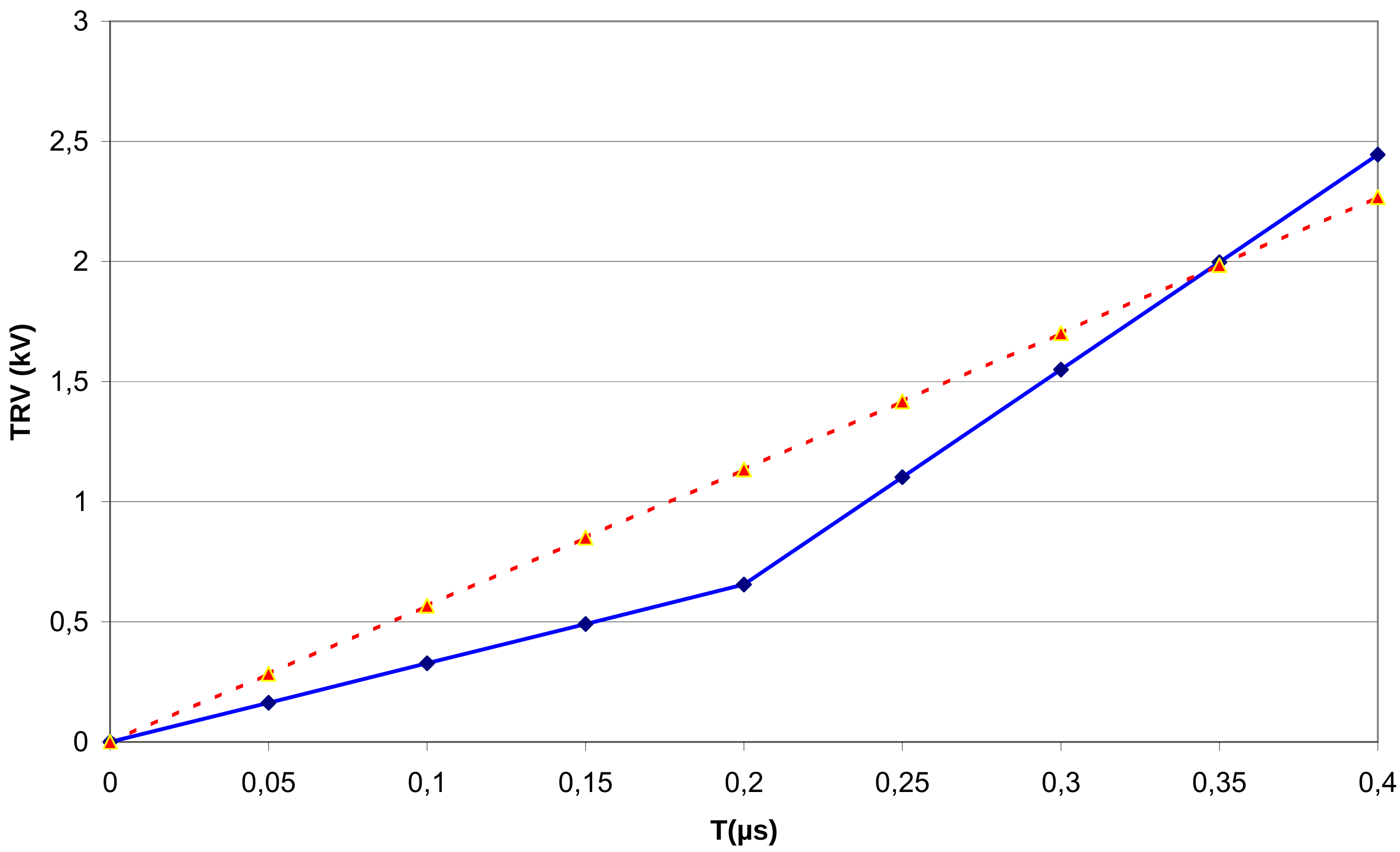
Line side voltage with different values of line to ground capacitors

ITRV (Initial transient recovery voltage)

- Due to travelling waves on the busbar and their reflections, a high-frequency oscillation occurs which is similar to the one observed on a faulted line under short -line fault conditions.
- As the busbar is usually on the supply side of the circuit-breaker, this oscillation, which is called **"Initial Transient Recovery Voltage (ITRV)"** is superimposed to the very beginning of the terminal fault TRV.
- Compared with the short-line fault, the first voltage peak is much lower, and the time to the first peak is shorter, within the first microseconds after current zero.



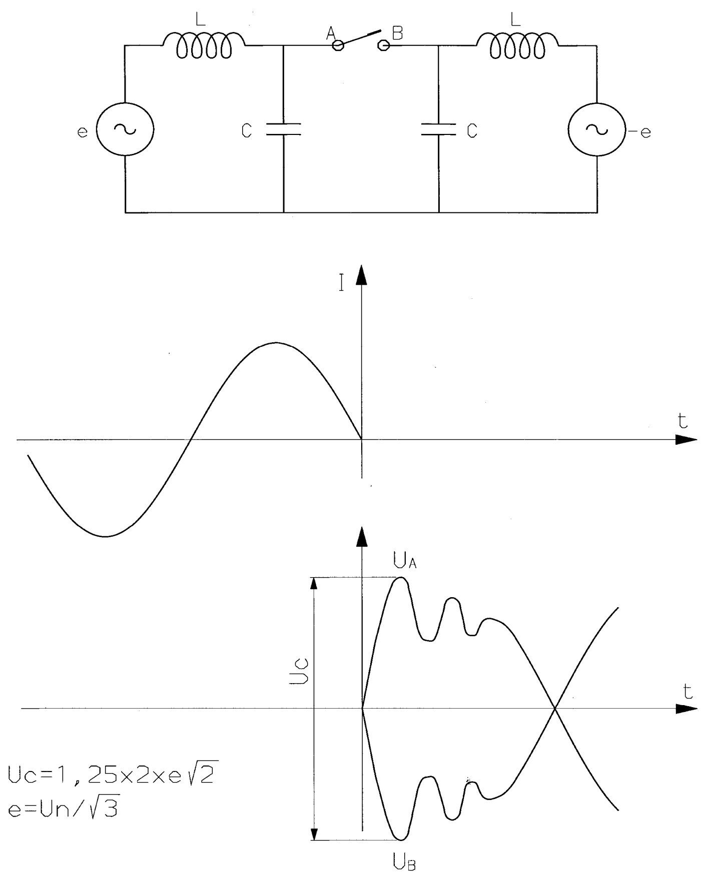
- **If a circuit breaker has a short-line fault rating and SLF tests are performed with a line having an insignificant time delay ("zero time delay"), the ITRV requirements are considered to be covered.**
- Since the ITRV is proportional to the busbar surge impedance and to the current, the ITRV requirements 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.



Comparison of **TRV for SLF with time delay (0.2 µs) and ITRV (solid line)** and **TRV for SLF with insignificant time delay and without ITRV (dotted line).**

Out-of-Phase

Out-of-Phase

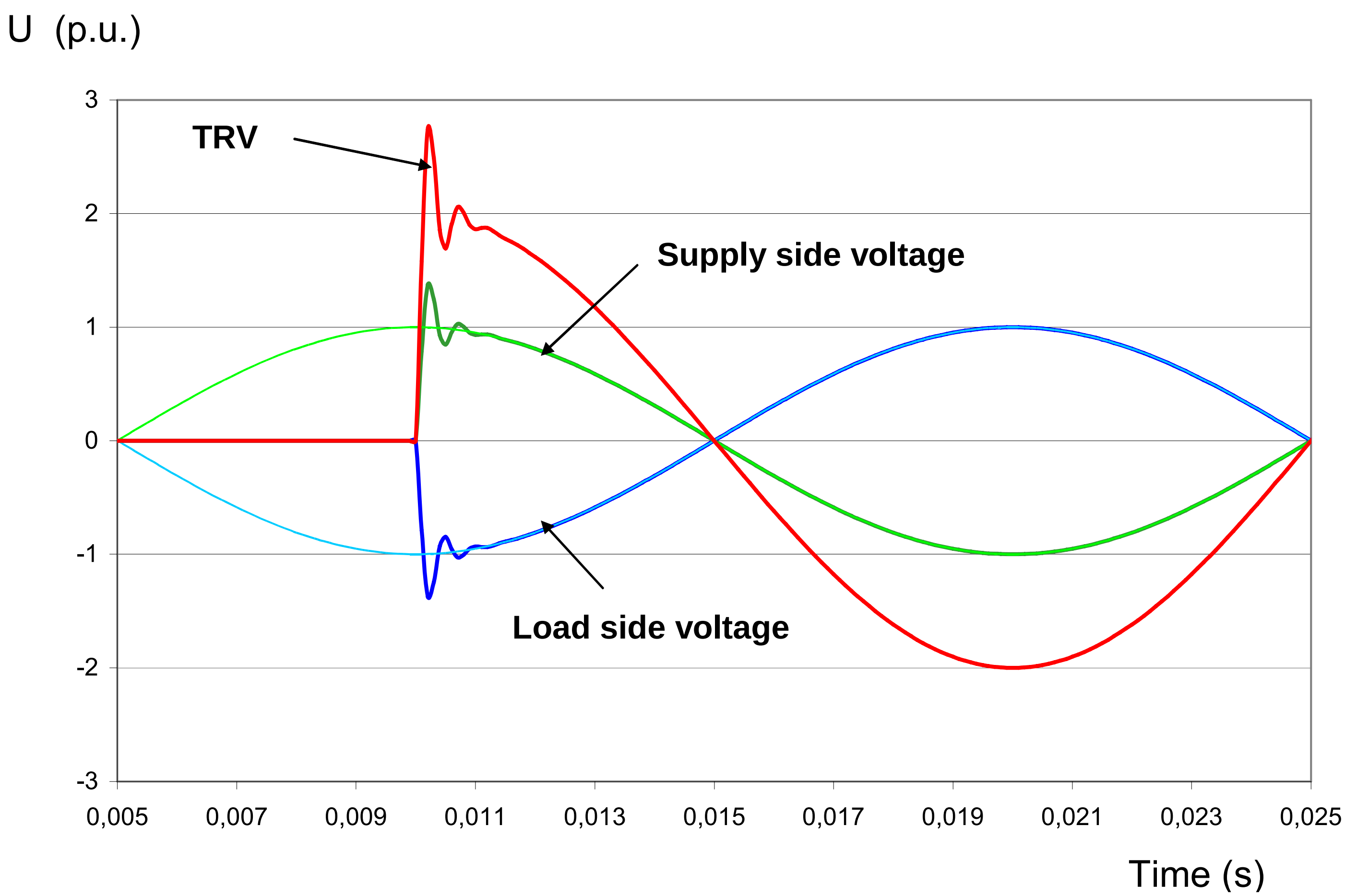


Some circuit-breakers may have to interrupt faults that occur when two systems are connected in out-of-phase conditions.

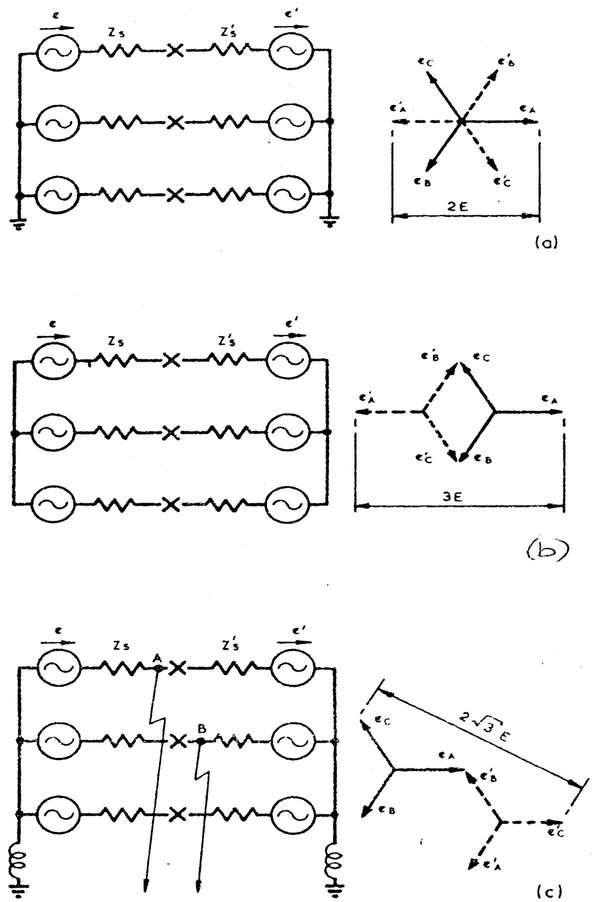
At current interruption, the voltage on each side of the circuit-breaker meets the voltage of the supply, with a transient voltage similar to that of terminal fault. The resulting peak TRV is 37% to 48% higher than for terminal fault T100.

However the current is only 25% of the rated short-circuit breaking current.

Voltages during Out-of-Phase Interruption



Out-of-Phase Factor for 3-phase faults



In standards the out-of-phase factor for interruption tests performed single-phase is

2.0 for effectively earthed systems

2.5 for non-effectively earthed systems

The factor for making operations is 2.0

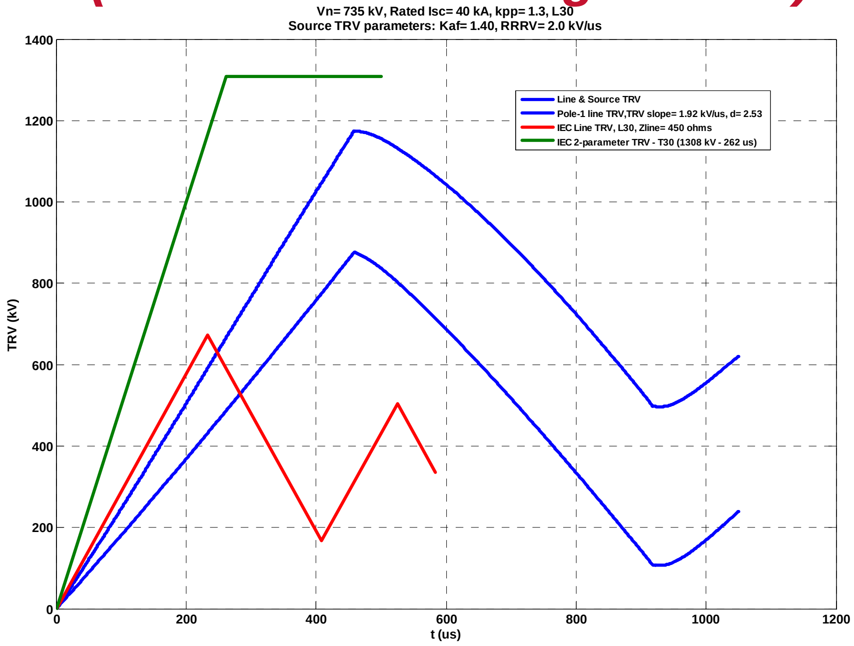
(Long) Line Faults

(Long) Line Faults

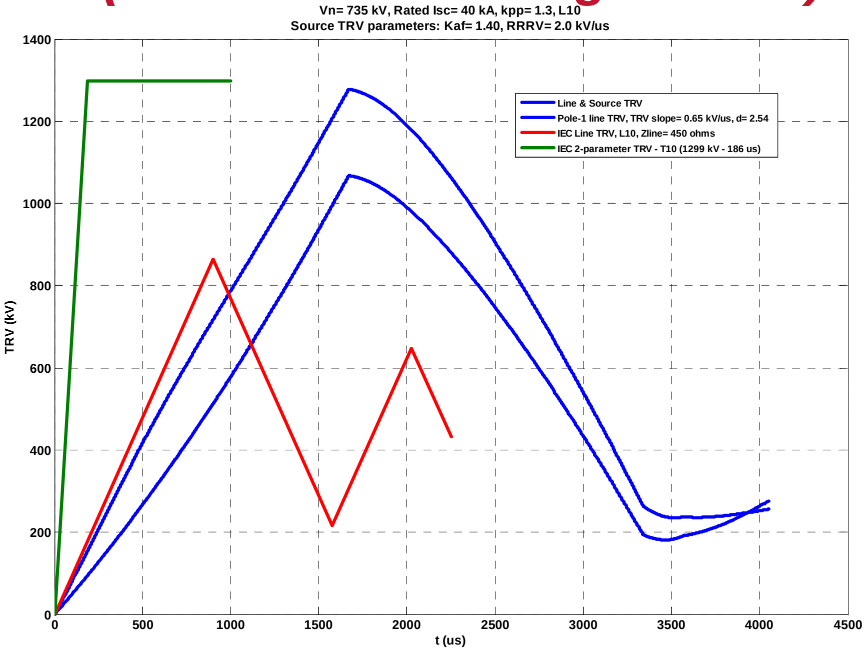
- With some line faults conditions it may occur that the TRV is not covered by the standard TRV withstand capability defined for terminal fault and short-line fault.
- Such situations can occur, depending on the actual short-circuit power of the source, during interruption of some three-phase line faults (higher TRV peak on the first-pole-to-clear).
- Mutual coupling of lines between the first interrupted phase and the two other phases can increase the line side contribution to TRV on the first pole to clear.
- The matter has been studied extensively by CIGRE WG A3-19, a Technical Brochure will be published by the end of 2008. Examples of TRV calculations by CIGRE WG A3-19 are given in the following.
- The TRV withstand capability demonstrated by terminal fault test duties T10, T30, T60 and out-of-phase OP2 usually cover line fault TRVs (a revision of the TRV for T60 is in progress).

▶ Example 1: L30 and L10 in 735kV/40kA network

L30
(30% rated breaking current)



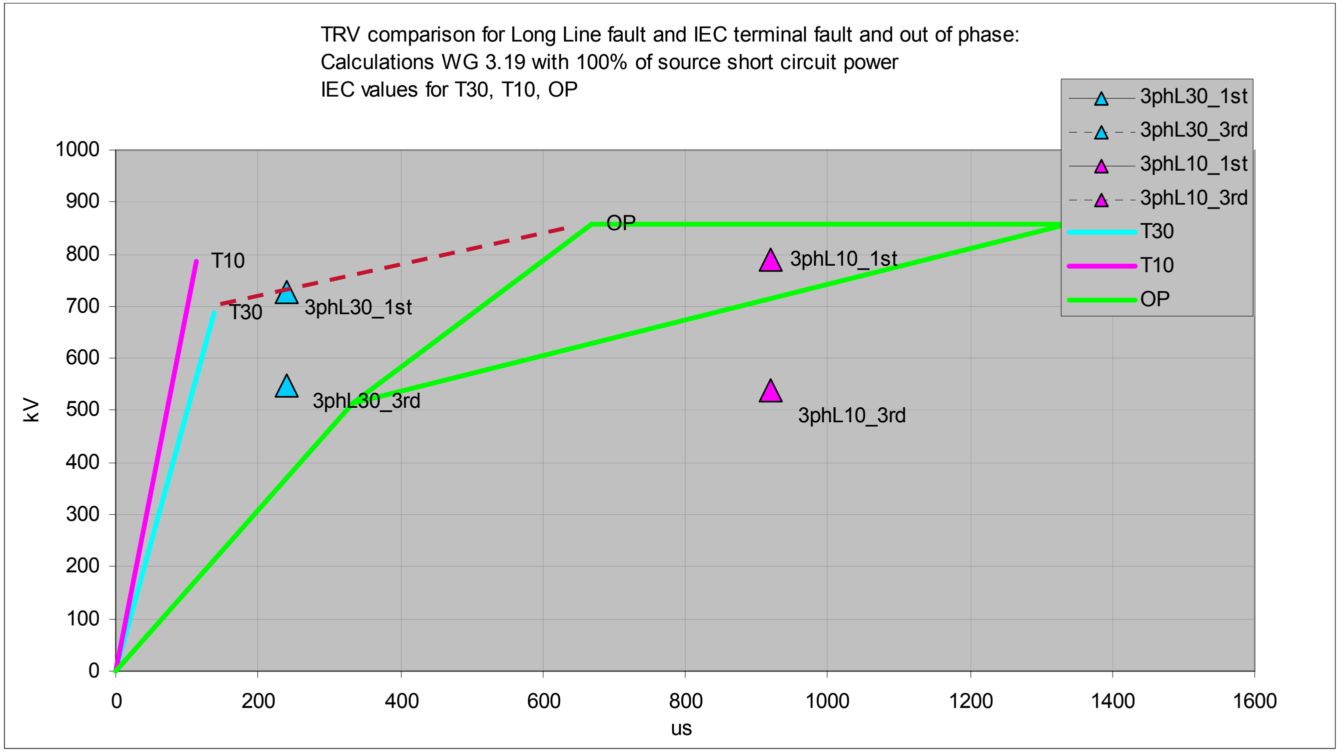
L10
(10% rated breaking current)



Comparison of first (dotted blue) and last (dotted red) clearing pole TRVs for three-phase L30 and L10, with total TRV for first pole (blue)

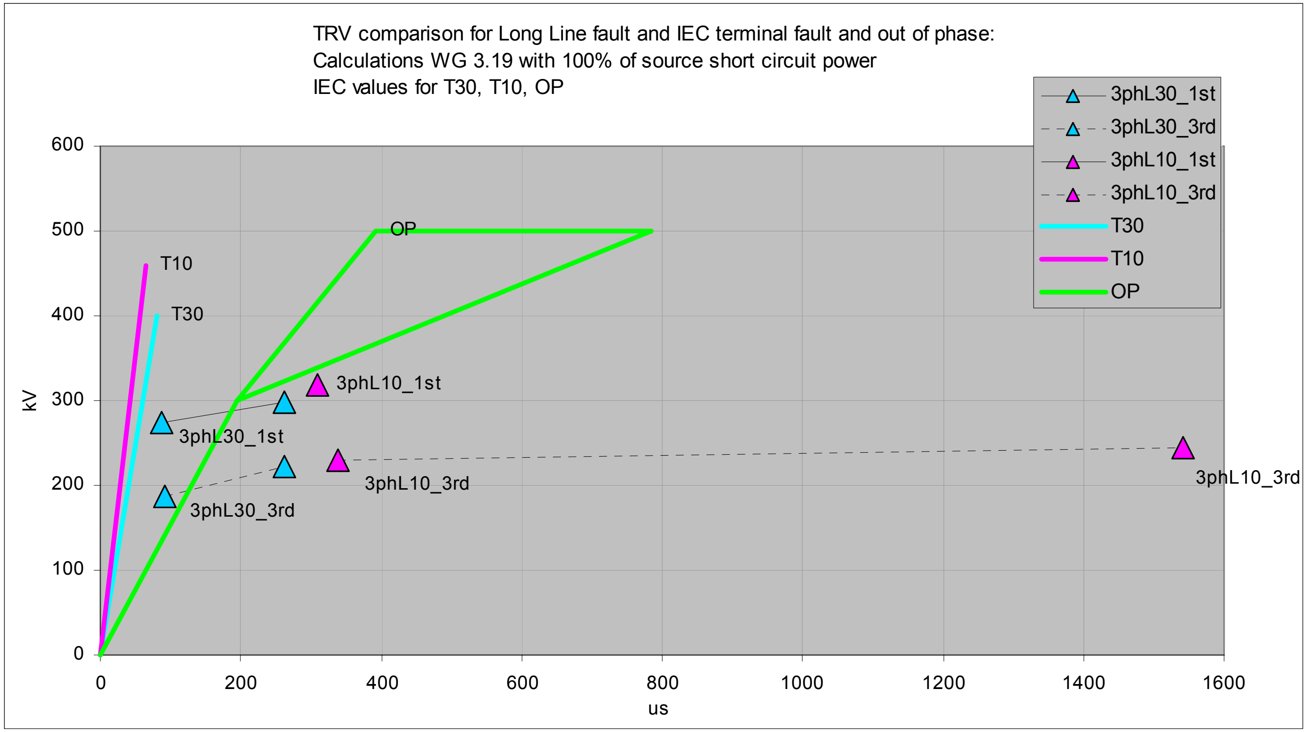
Note: the standard 2 parameter TRV with kpp=1.3 is shown in green. In edition 2.0 of IEC 62271-100 and the draft revision of IEEE C37.06, kpp has been increased to 1.5 for test duty T10.

Example 2: L30 and L10 in 420kV/63kA network



Comparison with TRV withstand capability demonstrated by T10, T30 and OP (out-of-phase, with shorter time t_2)

Example 3: L30 and L10 in 245kV/50kA network

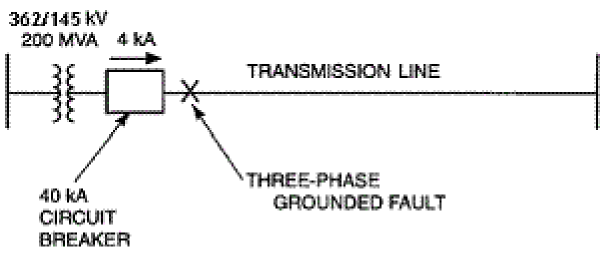


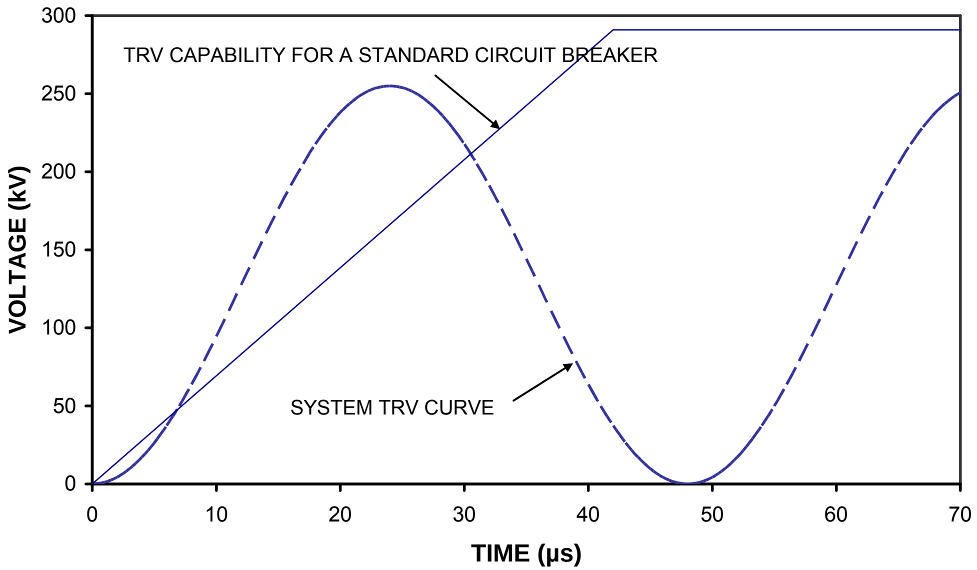
Comparison with TRV withstand capability demonstrated by T10, T30 and OP (out-of-phase)

Application Considerations

Transformer Limited Faults

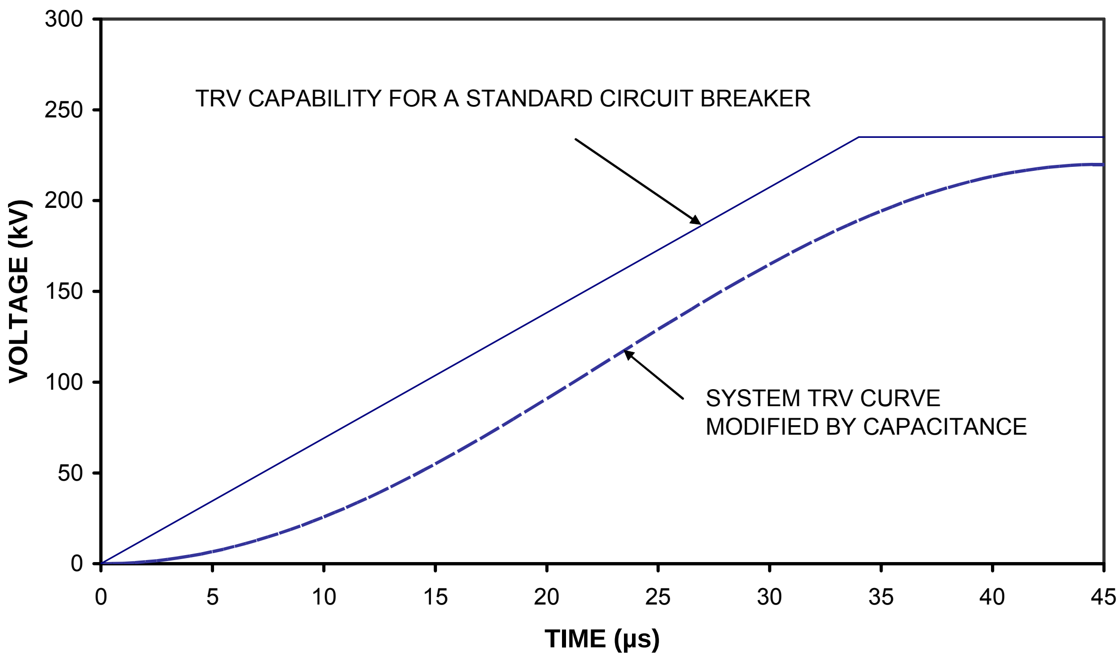
- Severe TRV conditions may occur in some cases, for instance when short-circuit occurs immediately after a transformer without any appreciable additional capacitance between the transformer and the circuit breaker.





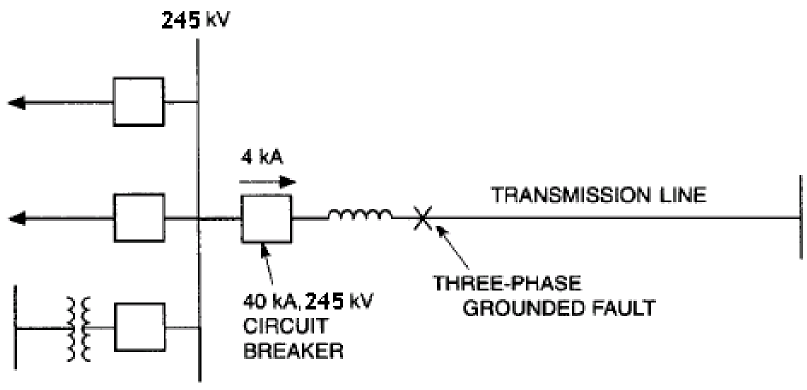
Transformer Limited Faults

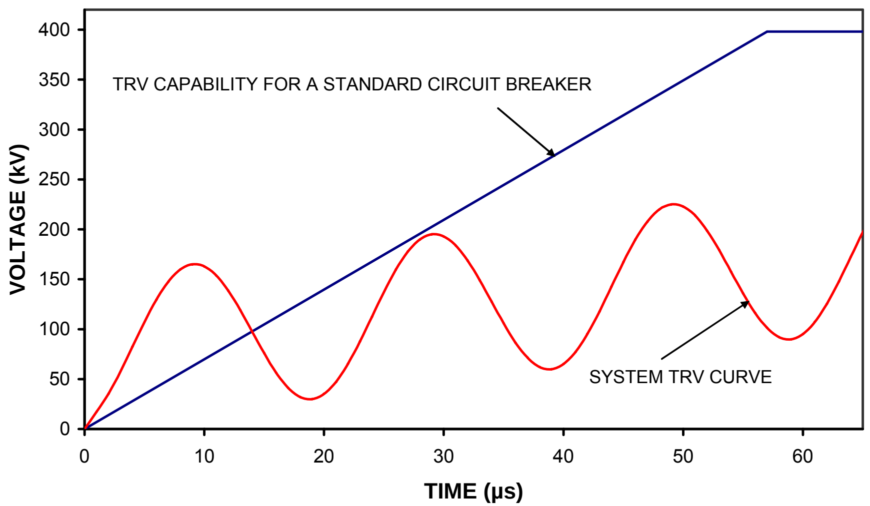
- Such cases are covered in IEEE C37.011-2005 and ANSI Guide C37.06.1-2000 “Guide for HV circuit breakers designated Definite purpose for fast TRV rise time” (the content is included in a draft revision of IEEE C37.06).
- Definite purpose circuit breakers could be specified or the system TRV can be modified by adding a capacitance, and then be within the standard capability envelope.



Series Reactor Limited Faults

- Series reactor are used to limit the short-circuit current in a line.
- A high rate-of-rise TRV is obtained in case of fault with a series reactor on the line side or the bus side of the circuit breaker.





Series Reactor Limited Faults

- If the system TRV exceeds a standard breaker capability, a capacitance can be added in parallel to the reactor in order to reduce the TRV frequency and have a system TRV curve within the standard capability envelope.
- This mitigation measure is very effective and cost efficient.
- It is therefore strongly recommended to add a capacitance in parallel, unless it can be demonstrated by tests that a circuit breaker can successfully clear faults with the required high frequency TRV.

Selection of circuit breaker for TRV

Selection of circuit breaker for TRV

- The TRV ratings define a withstand boundary. A circuit TRV that exceeds this boundary is in excess of the circuit breaker’s rated or related capability.

- When the withstand boundary is exceeded:

  - either a different circuit breaker should be used,

  - or the system should be modified in such a manner as to change its TRV characteristics.

- The addition of capacitors (e.g. to a bus or line) is one method that can be used to improve the system’s recovery voltage characteristics.

  A typical example is the addition of a capacitor in parallel to a series reactor in order to reduce the RRRV to a value covered by the standard (i.e. by test duty T30).

References

Main References

- ANSI/IEEE C37.04, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.
- IEEE Std C37.06-200x, Draft AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-Preferred Ratings and Related Required Capabilities
- ANSI/IEEE Std C37.09-1999, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.
- IEEE C37.011 Application Guide for TRV for AC High-Voltage Circuit Breakers" (2005).
- IEEE C37.013, IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis.
- A.Greenwood, Electrical Transients in Power Systems. (book) 2nd edition, John Wiley & Sons (1991).
- R.Alexander, D.Dufournet, IEEE Tutorial on TRVs : www.ewh.ieee.org/soc/pes/switchgear/TRVTutorial (2005).

Other papers of interest on TRV

- [1] Hochrainer (A.). Proposition relative à la détermination d'une tension transitoire de rétablissement équivalente pour les disjoncteurs (méthode des quatre paramètres). CIGRE session 1958, rapport 151. Das Vier-Parameter-Verfahren zur Kennzeichnung der Einschwingspannung in Netzen. ETZ 78. (1957-10).
- [2] Pouard (M.). Nouvelles notions sur les vitesses de rétablissement de la tension aux bornes de disjoncteurs à haute tension. Bulletin Société Française des Electriciens N°95 (1958-11).
- [3] Baltensperger (P.). Définition de la tension transitoire de rétablissement aux bornes d'un disjoncteur par quatre paramètres, possibilités des stations d'essais de court-circuit. Bulletin de l'Association Suisse des électriciens N°3 (1960).
- [4] Bolton (E.), Ehrenberg (A.C.) et al. Etudes britanniques sur les phénomènes du défaut kilométrique. CIGRE Session 1964, Rapport 109 (1964-06).
- [5] Beehler (J.E.), Naef (0.), Zimmerman (C.P.). Proposed transient recovery voltage ratings for power circuit breakers. IEEE Transactions on Power Apparatus and systems N°84 (1965).
- [6] Catenacci (G.), Paris (L.), Couvreux (J.P.), Pouard (M.). Transient recovery Voltage in French and Italian High-Voltage Networks. IEEE Transactions on Power Apparatus and Systems, N°11 (1967-11).

Other papers of interest on TRV

- [7] Catenacci (G.), Paris (L.), Couvreux (J.P.), Pouard (M.). Transient Recovery Voltages in French and Italian High-Voltage Networks. IEEE Transactions on Power Apparatus and Systems, vol. PAS-86, N°11 (1967).
- [8] CIGRE WG 3.1. Transient Recovery Voltage in High Voltage Networks – Terminal faults. CIGRE Session 1968, Report 13-10 (1968).
- [9] Baltensperger (P.), Cassie (A.M.), Catenacci (G.), Hochrainer (A.), Johansen (O.S.), Pouard (M.). Tensions transitoires de rétablissement dans les réseaux à haute tension - Défauts aux bornes. CIGRE Session 1968, Rapport 13-10 (1968).
- [10] Dienne (G.), Frisson (J.M.). Contribution à l'étude expérimentale des tensions de rétablissement lors de la coupure de transformateurs court-circuités au secondaire. CIGRE Session 1968, rapport 13-07 (1968).
- [11] Colclaser (R.G.), Buettner (D.E.). The Traveling-wave Approach to Transient Recovery Voltage. . IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, N°7 (1969-07).
- [12] Petitpierre (R.), Watschinger (H.). Transient Recovery Voltage Conditions to be Expected when Interrupting Short-circuit Currents Limited by Transformers. CIGRE Session 1970, Paper 13-07 (1970).

Other papers of interest on TRV

- **[13] Harner (R.), Rodriguez (J.). Transient Recovery Voltages Associated with Power system, Three-phase transformer secondary Faults. IEEE Power Engineering Society (1971-02).**
- **[14] Dubanton (Ch.), Gervais (G.), Van Nielsen. Surge impedance of overhead lines with bundle conductors during short-line fault. Electra N°17 (1971-04).**
- **[15] Calvino (B.). Quelques aspects des contraintes supportées par les disjoncteurs haute-tension à la coupure d'un court-circuit. CIGRE Session 1974, Rapport 13-08 (1974).**
- **[16] Catenacci (G.), CIGRE WG13-01. Contribution on the study of the initial part of the transient recovery voltage. Electra N°46 (1976).**
- **[17] Braun (A.), Hinterthür (K.H.), Lipken (H.), Stein (B.), Völcker (O.). Characteristics values of the transient recovery voltage for different types of short-circuits in an extensive 420 kV system. ETZa, vol.97 (1976).**
- **[18] Braun (A.), Suiter (H.). Détermination des tensions transitoires de rétablissement apparaissant aux bornes des disjoncteurs de groupes dans les grandes centrales modernes. CIGRE Session 1976, Rapport 13-03 (1976).**

Other papers of interest on TRV

- [19] Hedman (D. E.), Lambert (S. R.). Power Circuit Breaker Transient Recovery Voltage. IEEE Transactions on Power Apparatus and Systems, vol. PAS-95, pp. 197–207, (1976 -01)
- [20] Colclaser (R.G.), Reckleff (J.G.). Investigations of inherent transient recovery voltage for Generator Circuit breakers. IEEE Transactions on Power Apparatus and Systems, vol. PAS-102, N°19 (1983-9).
- [21] Wagner (C.L.), Smith (H.M.). Analysis of Transient Recovery Voltage (TRV) rating concepts. IEEE Transactions on Power Apparatus and Systems, vol. PAS-103, N°11 (1984-11).
- [22] Haginomori (E.). Performance of circuit-breakers related to high rate of rise of TRV in high power, high density networks. IEEE Paper 85 W172-2 (1985).
- [23] Parrott (P.G.). A review of Transformer TRV Conditions. Electra N°102 (1985-10)
- [24] Bonfanti (I.), Colombo (E.). A contribution to the assessment of TRVs in MV distribution systems and circuit breaker performances. Colloquium CIGRE SC13, Florianopolis (1995-09).
- [25] CIGRE-CIRED WG CC03. TRV in Medium Voltage Networks. Electra N°181 and Technical Brochure N°134 (1998-12)

Other papers of interest on TRV

- [26] Dufournet (D.), Willième (J.M.). Disjoncteurs de générateur : Chambre de coupure SF6- Coupure de courants avec passages par zéro retardés- Influence des connections par câbles sur la TTR en coupure de défauts alimentés par le réseau. CIGRE Session 2002, Rapport 13-101 (2002).
- [27] Hamade (H.), Kasahara (Y.) et al. Severe duties on high-voltage circuit breakers observed in recent power systems. CIGRE Session 2002, Rapport 13-103 (2002).
- [28] Smeets (R.P.P.), Peelo (D.F.) et al. Evolution of stresses in distribution networks and their impact on testing and certification of medium voltage switchgear. CIGRE Session 2002, Rapport 13-106 (2002).
- [29] Iliceto (F.), Dilli (B.). TRVs across circuit breakers of series compensated lines. Analysis, design and operation experience in the 420kV Turkish grid. CIGRE Session 2002, Rapport 13-109 (2002).
- [30] Dufournet (D.), Montillet (G.). TRV Requirements for System Source Fault Interrupting by Small Generator Circuit Breakers. IEEE Transactions on Power Delivery, vol. 17, N°2 (2002-04).
- [31] Johnson (Anders), Analysis of Circuit Breaker Transient Recovery Voltages Resulting from Transmission Line Faults, Thesis Master of Science in Electrical Engineering, University of Washington (2003)
- [32] M.Steurer, W.Hribernik, J.Brunke. Calculating the TRV Associated with Clearing Transformer Determined Faults by Means of Frequency Response Analysis. IEEE Transactions on Power Delivery, vol. 19, N°1 (2004-01).

Thank you for your attention
Questions ?