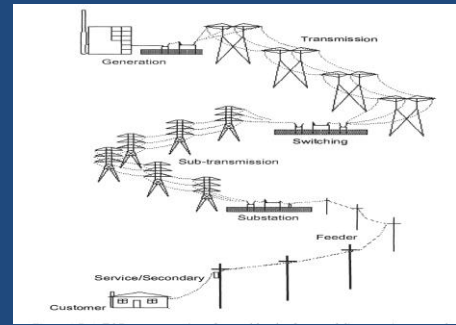

Insulation Coordination and Voltage Transients for Industrial Electrical Power Systems

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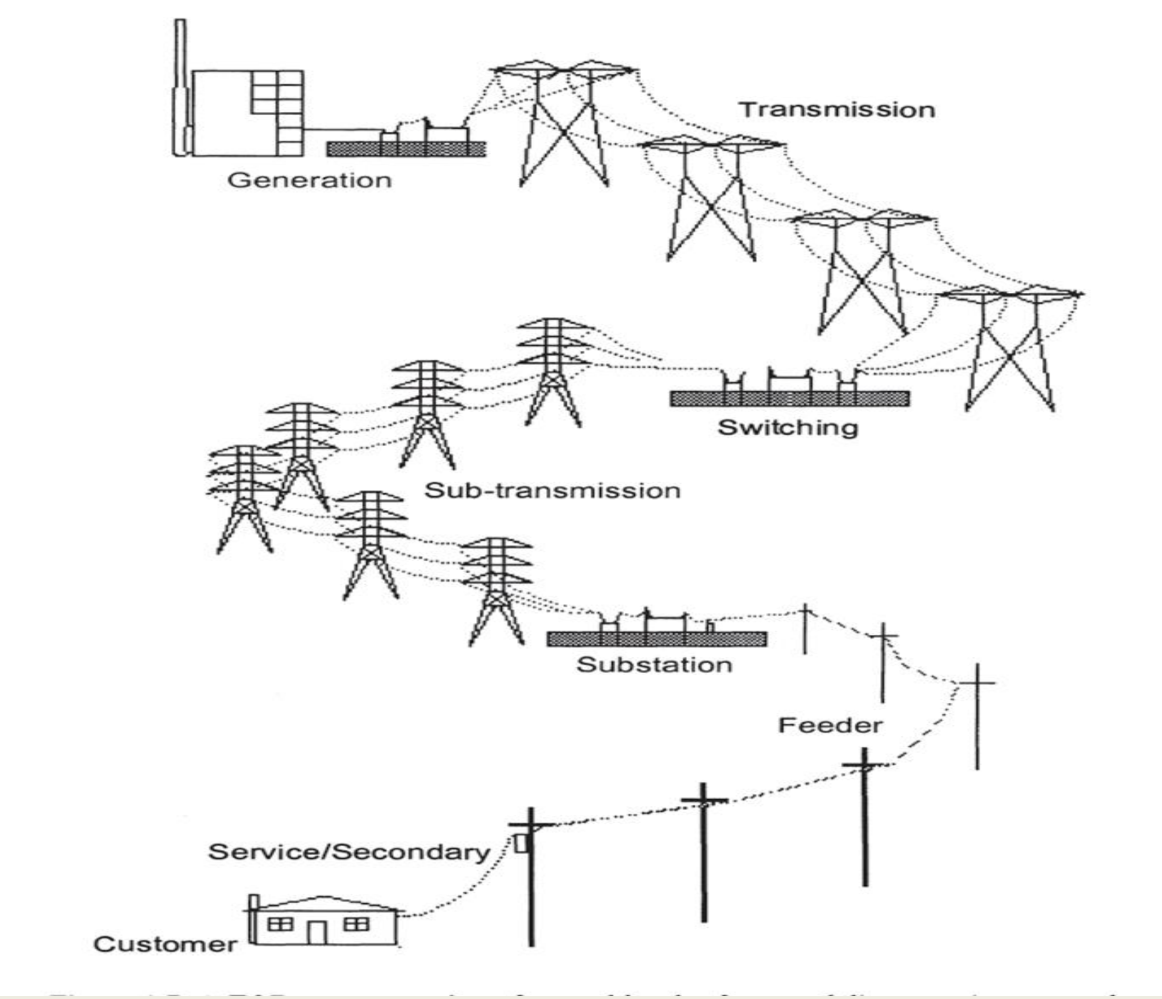
Contents:

Introduction

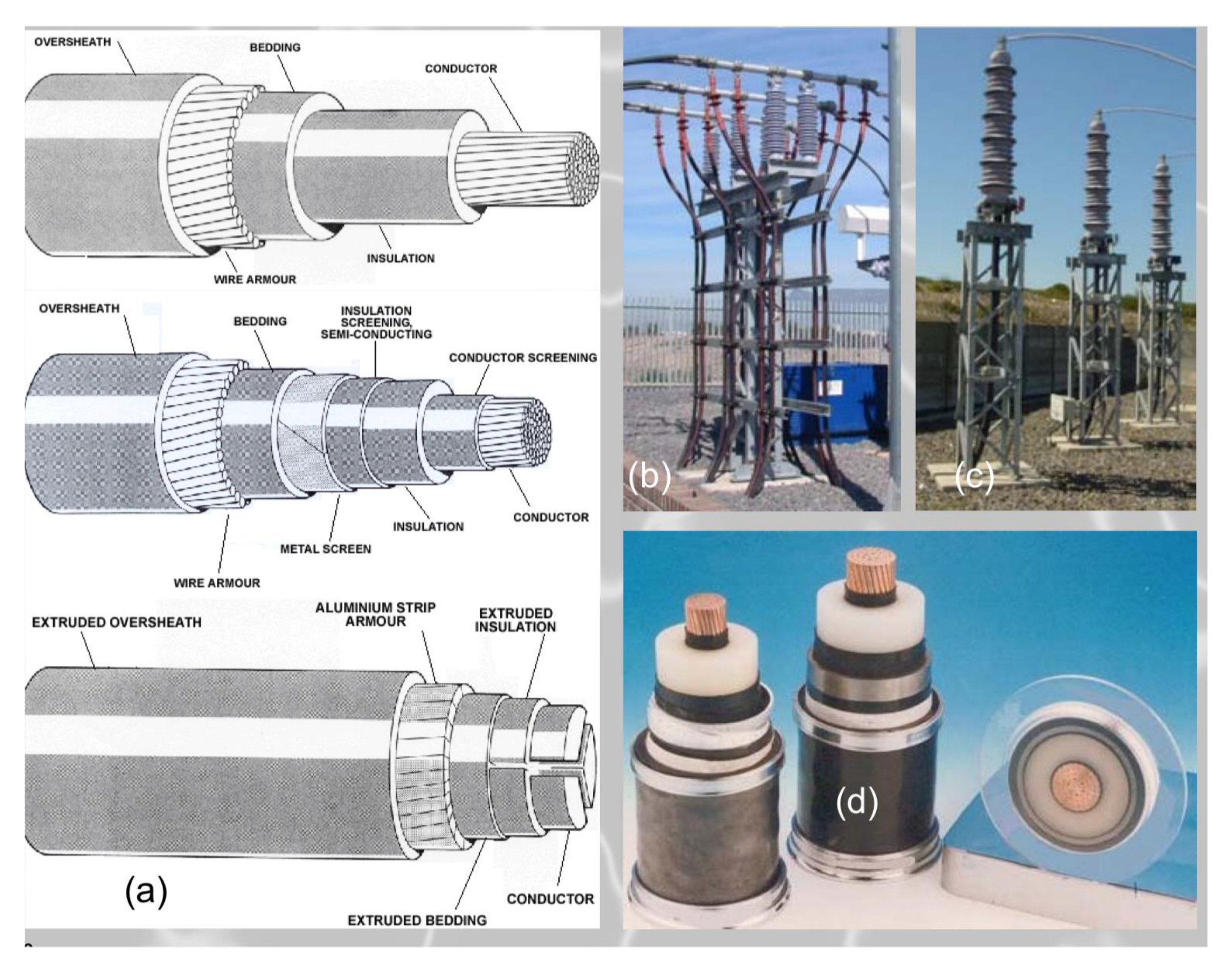
Main Sectors of the Electrical Power System



Insulation Material for Medium & High Voltage Systems

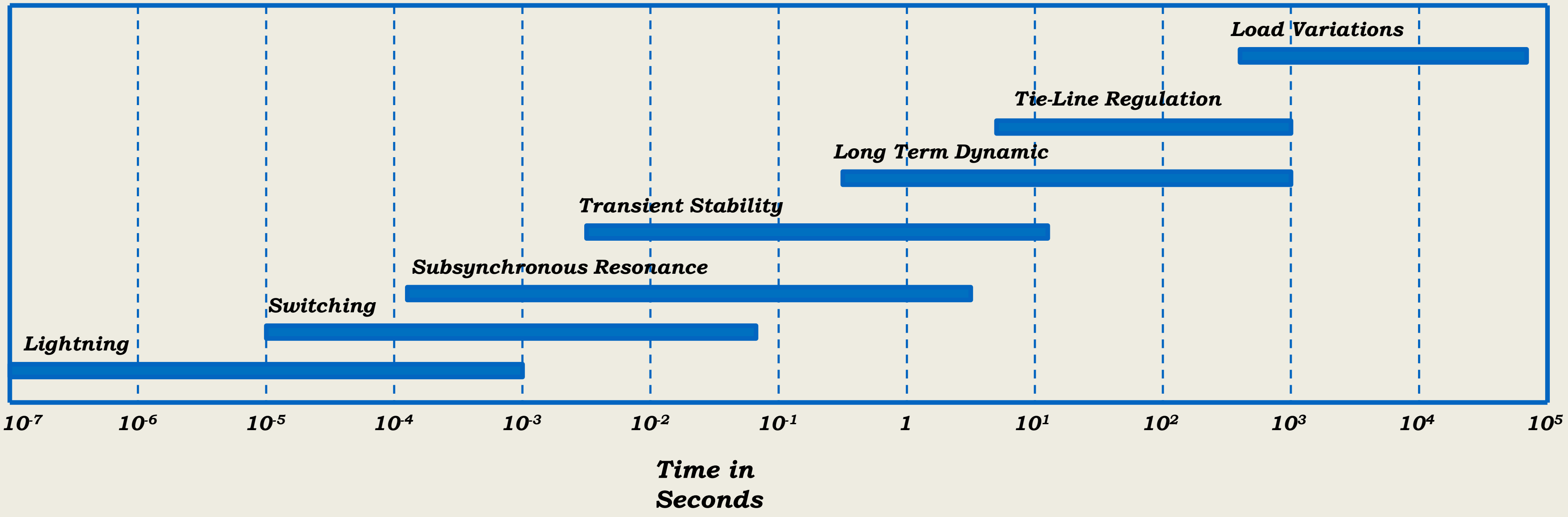
- Air
- Gas (i.e. SF_6 & GIS)
- Liquids (i.e. oil in transformers)
- Solids (i.e. paper, PVC in cables, plastics in switchgears)
- Failures in insulation cause safety risks for human, fires and system outages
- Failures may be due to insulation aging
- Failure also may be due to sudden increases in voltage (i.e. transients) beyond the ratings of the insulation material

Examples of Insulation in HV and MV Systems

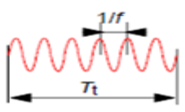
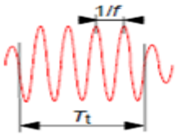
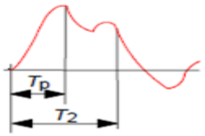
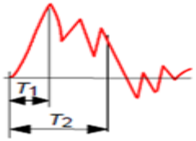
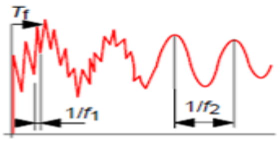
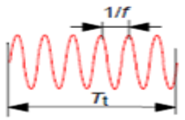
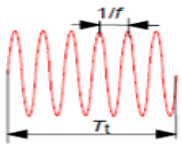
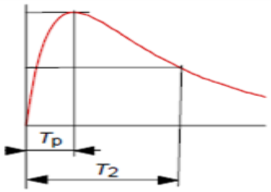
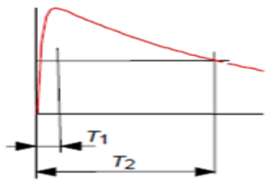


System Transient in Medium and High Voltage Systems

- External versus internal causes
- Deterministic versus statistical or stochastic based studies
- Transient phenomena have different time frames
- Studying transients is very important for power systems. This tutorial is an introduction to voltage transients



IEC 60071-1 Classes and Shapes of Over-Voltages

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz T_t ≥3 600s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t [a]	 48 Hz ≤ f ≤ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs	a
Standard withstand voltage test	a	Short-duration power frequency test	Switching impulse test	Lightning impulse test	a

[a] To be specified by the relevant apparatus committees.

Do We Need Transient Studies on Medium Voltage Systems?

- Transient studies may address:
  - Temporary Overvoltage (TOV)
  - Slow Front Overvoltage (SFO)
  - Fast Front Overvoltage (FFO)
  - Very Fast Transient Overvoltage (VFTO)
  - Transient Recovery Voltage (TRV)
  - Ferro-Resonance
- In general, insulation design in Medium Voltage (MV) Systems and typical industrial system has considerable safety margins. Elaborate lightning and switching transients studies are typically not conducted at early stages of design. However, more industrial systems include higher voltage components and special arrangements that may need transient studies

Do We Need Transient Studies on Medium Voltage and High Voltage Industrial Systems? (Cont'd)

- Systems with special configurations, ratings, or components may be subjected to transients beyond the capability of their typical insulation ratings. In such cases transient studies are recommended. Examples when we may need to examine system transients are:
  - Capacitors, and capacitor switching
  - Long run of cables
  - Potential and distribution transformers connected to long cables
  - Generator breakers
  - Some connections of current limiting reactors
  - When a system is un-grounded or un-effectively grounded, it may be subjected to transients during switching or energization.

Do We Need Transient Studies on Medium Voltage and High Voltage Industrial Systems? (Cont'd)

- When examining transients, indoor systems (switchgear, insulated cables, etc.) are different from outdoor installations (overhead lines to well pads etc.)
- If system configuration or components changed for an upgrading or improvement of capacity or for other reasons, the new configuration needs shall be assessed and the required studies shall be conducted as needed
- When a system is un-grounded or un-effectively grounded, it may be subjected to transients during switching or energization.

When Shall We Start Thinking about Insulation Coordination and Voltage Transients Studies?

- Examples:
  - Substation shield and lightning strike protection
  - Selecting surge arresters for protection of equipment
  - Transient Recovery Voltage (TRV), and specifying HV circuit breakers and other special cases of switching transients
  - Switching of high voltage and extra high voltage cables, and sheath grounding
  - GIS voltage transient protection (VFTO)
  - High resistance neutral grounded systems under fault conditions
  - Ferroresonance

What Tools Can Be Used for Typical Studies?

- Standards Methods as demonstrated in Guides and Recommended Practices (tools such as spreadsheets etc.)
- Transients software (mostly Time Domain)
  - Example is Electro-Magnetic Transient Programs (EMTP) such as ATP, PSCAD, EMTP-RV etc.
  - Correct modeling of equipment is critical when using software

Insulation Coordination

Definition for "Insulation Coordination"

- *Understanding the definition associated with "Insulation Coordination" is very important for performing relevant studies*
- *Definitions are listed in several references, and in this presentation we selected those listed in IEEE Std 62.82.1 as our referenced definitions*
- *For demonstration purposes, we selected definitions associated with our presentation topics. Other definitions are of an equal importance and must be consulted when performing studies.*

Definition of "Insulation Coordination" as per IEEE Std 62.82.1

"insulation coordination": The selection of the insulation strength of equipment in relation to the voltages, which can appear on the system for which equipment is intended and taking into account the service environment and the characteristics of the available protective devices.

NOTE—An acceptable risk of failure is considered when selecting the insulation strength of equipment (Why & How much??)

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1]:

- **atmospheric correction factor:** A factor applied to account for the difference between the atmospheric conditions in service and the standard atmospheric conditions. (NOTE—In terms of this standard, it applies to insulation exposed to the atmosphere only).
- **basic lightning impulse insulation level (BIL):** The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. BIL may be expressed as either statistical or conventional.
- **basic switching impulse insulation level (BSL):** The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. BSL may be expressed as either statistical or conventional.
- **conventional BIL (basic lightning impulse insulation level):** The crest value of a standard lightning impulse for which the insulation shall not exhibit disruptive discharge when subjected to a specific number of applications of this impulse under specified conditions, applicable specifically to non-self-restoring insulations.
- **conventional BSL (basic switching impulse insulation level):** The crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of impulses under specified conditions, applicable to non-self-restoring insulations.

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1] (continued):

- **conventional withstand voltage:** The voltage that an insulation system is capable of withstanding without failure or disruptive discharge under specified test conditions.
- **crest value (peak value):** The maximum absolute value of a function when such a maximum exists.
- **critical flashover (CFO) voltage:** The amplitude of voltage of a given wave shape that, under specified conditions, causes flashover through the surrounding medium on 50% of the voltage applications
- **front-of-wave lightning impulse voltage shape:** A voltage impulse, with a specified rate-of-rise, that is terminated intentionally by sparkover of a gap that occurs on the rising front of the voltage wave with a specified time to sparkover, and a specified minimum crest voltage
- **lightning overvoltage:** A type of transient overvoltage in which a fast front voltage is produced by lightning. Such overvoltage is usually unidirectional and of very short duration.

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1] (continued)

- **maximum system voltage, Vm:** The highest root-mean-square (rms) phase-to-phase voltage that occurs on the system under normal operating conditions, and the highest rms phase-to-phase voltage for which equipment and other system components are designed for satisfactory continuous operation without deterioration of any kind.
- **nominal system voltage:** The rms phase-to-phase voltage by which the system is designated and to which certain operating characteristics of the system are related. NOTE—The nominal system voltage is near the voltage level at which the system normally operates. To allow for operating contingencies, systems generally operate at voltage levels about 5% to 10% below the maximum system voltage for which systems components are designed.

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1] (continued)

- **overvoltage:** Voltage, between one phase and ground or between two phases, having a crest value exceeding the corresponding crest of the maximum system voltage. Overvoltage may be classified by shape and duration as either temporary or transient.

  NOTE 1— Unless otherwise indicated, such as for surge arresters, overvoltages are expressed in per unit with reference to peak phase-to-ground voltage at maximum system voltage, Vm × (√2) / (√3).

  NOTE 2— A general distinction may be made between highly damped overvoltages of relatively short duration (transient overvoltages) and undamped or only slightly damped overvoltages of relatively long duration (temporary overvoltages). The transition between these two groups cannot be clearly defined.

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1] (continued)

- **performance criterion:** The criterion upon which the insulation strength or withstand voltages and clearances are selected. The performance criterion is based on an acceptable probability of insulation failure and is determined by the consequence of failure, required level of reliability, expected life of equipment, economics, and operational requirements. The criterion is usually expressed in terms of an acceptable failure rate (number of failures per year, years between failures, risk of failure, etc.) of the insulation configuration.

Definitions Associated with Insulation Levels [Ref: IEEE Std 62.82.1] (continued)

- **protective margin (PM):** The value of the protective ratio (PR), minus one, expressed as a percentage. PM = (PR − 1) × 100.
- **protective ratio (PR):** The ratio of the insulation strength of the protected equipment to the overvoltages appearing across the insulation.
- **lightning impulse protective level of a surge-protective device:** The maximum lightning impulse voltage expected at the terminals of a surge-protective device under specified conditions of operation.
- NOTE—The lightning impulse protective levels are simulated by the following: 1) front-of-wave impulse sparkover or discharge voltage and 2) the higher of either a 1.2/50 impulse sparkover voltage or the discharge voltage for a specified current magnitude and wave shape.

Definitions Associated with Insulation Material & Configuration [Ref: IEEE Std 62.82.1]

- **external insulation:** The air insulation and the exposed surfaces of solid insulation of equipment, which are both subject to dielectric stresses and to the effects of atmospheric and other external conditions such as contamination, humidity, and vermin.
- **internal insulation:** Internal insulation comprises the internal solid, liquid, or gaseous elements of the insulation of equipment, which are protected from the effects of atmospheric and other external conditions such as contamination, humidity, and vermin.
- **non-self-restoring insulation:** An insulation that loses its insulating properties or does not recover them completely, after a disruptive discharge caused by the application of a test voltage; insulation of this kind is generally, but not necessarily, internal insulation.
- **self-restoring insulation:** Insulation that completely recovers its insulating properties after a disruptive discharge caused by the application of a test voltage; insulation of this kind is generally, but not necessarily, external insulation.
- **insulation configuration:** The complete geometric configuration of the insulation, including all elements (insulating and conducting) that influence its dielectric behavior. Examples of insulation configurations are phase-to-ground, phase-to-phase, and longitudinal.

Overvoltage Transients Protection & Applications of Surge Arresters

Introduction

What is a surge arrestor?

A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it limits the flow of power current to ground and is capable of repeating these functions as specified (Ref: IEEE Std. C62.22-2009).

Why do we need surge arrestors?

To provide protection to equipment insulation from abnormal overvoltage.

NOTE – surge arrestor can only be activated by non-power frequency overvoltage (lightning or switching surge)

Definitions

Arrester Discharge Current:

The current that flows through an arrester resulting from an impinging surge (Ref: IEEE Std. C62.22-2009).

Arrester Discharge Voltage or Residual Voltage:

The voltage that appears across the terminals of an arrester during the passage of discharge current (Ref: IEEE Std. C62.22-2009).

General Considerations for Arrester's Applications

1. Arrester Class
2. Arrester MCOV
3. Temporary Over voltage (TOV) Capacity
4. Protection Ratio
5. Switching Impulse Energy Handling Capability
6. Arrester Pressure Relief Capability

Arrester Class:

The arrester class is designed base on the:

1. Required level of protection
2. Available voltage ratings
3. Pressure relief current limits (short circuit withstand)
4. Durability

Arrester Class (Cont'd)

- Station class arresters for heavy duty application, and most durable
- Intermediate class arresters for moderate-duty application (maximum system voltage 169kV)
- Distribution class arresters for lower voltage transformers, transmission and distribution lines

Class Applications

- Station class arresters for heavy duty application, and most durable
- Intermediate class arresters for moderate-duty application (maximum system voltage 169kV)
- Distribution class arresters for lower voltage transformers, transmission and distribution lines

General Considerations for Arrester Applications (Ref: IEEE Std C62.11-2012, Table C.1)

Class	Rated Voltage		Lightning impulse classifying current (kA)	Switching surge classifying current (A)	Minimum high-current short-duration withstand (kA)	Minimum low-current long-duration withstand (A.us)	High current pressure relief (kA)	Low current pressure relief (A)
	Duty Cycle	MCOV						
Station	3-48	2.55-39	10	500	65	-	40-65	400-800
	54-312	42-245	10	500-1000	65	-	40-65	400-800
	396-564	318-448	15	2000	65	-	40-65	400-800
	576-612	462-485	20	2000	65	-	40-65	400-800
Intermediate	3-144	3.55-115	5	500	65	-	16.1	400-800
Distribution heavy duty	3-36	2.55-29	10	-	100	250-2000	-	-
Distribution normal duty	3-36	2.55-29	5	-	65	250-2000	-	-
Distribution light duty	3-36	2.55-29	5	-	40	250-2000	-	-

Arrester's Maximum Continuous Over Voltage MCOV

- The maximum designed RMS value of power frequency voltage that may be applied continuously between terminals of the arresters (Ref: IEEE Std. C62.22-2009).

$$V_{L-G(Max)} = V_{L-L\ (Max,RMS)}/\sqrt{3}$$

$$MCOV \geq V_{L-G(Max)}$$

Where $V_{L-L\ (Max,RMS)}$ is the maximum system operating voltage

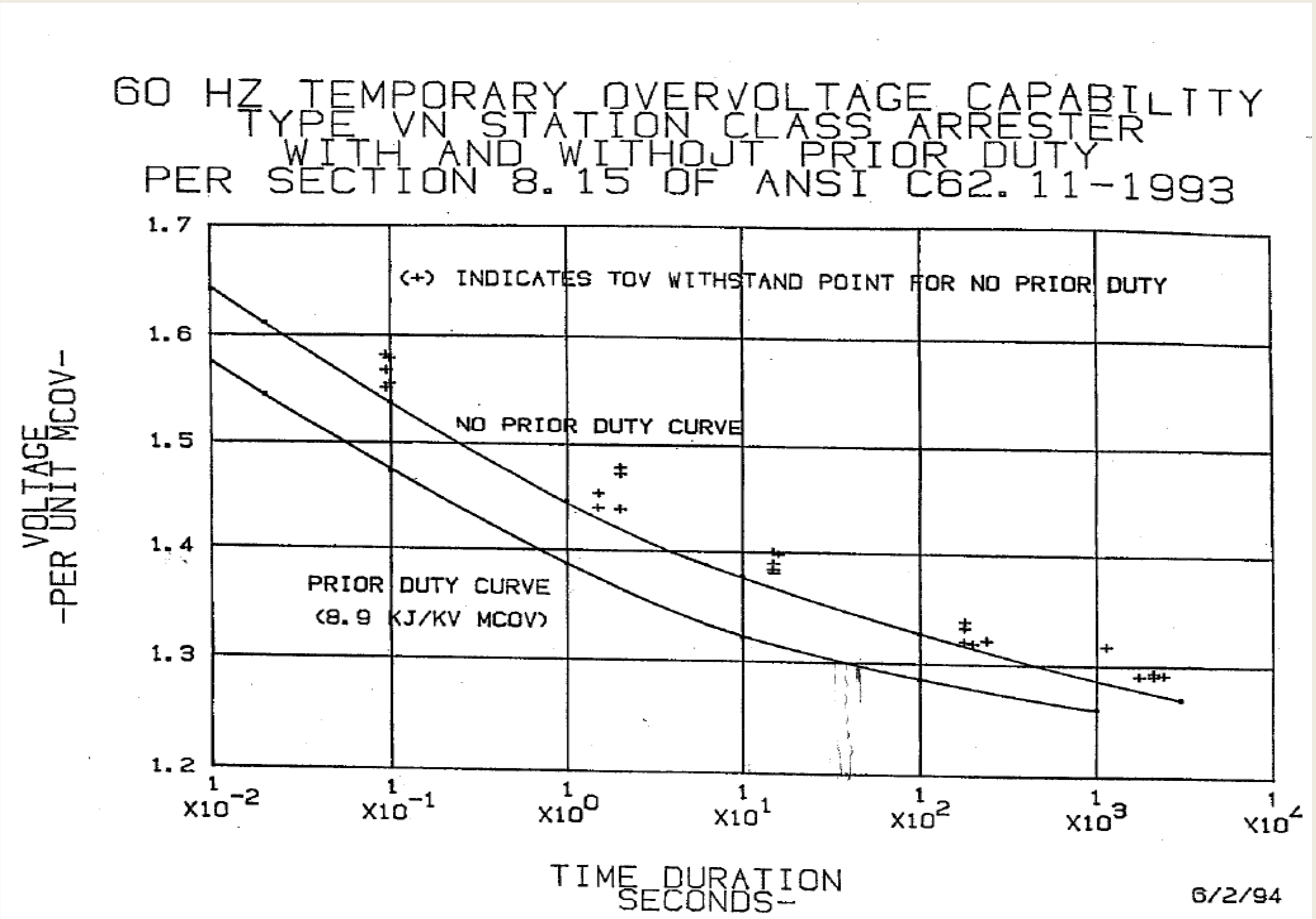
Arrester’s Maximum Temporary Over Voltage (TOV)

Temporary Over Voltage (TOV) Capability:

- Consist of lightly damped power frequency voltage oscillation, often with harmonics, usually lasting a period of hundreds of milliseconds or longer.
- Arrester is capable of operating for limited periods of time at voltage in excess of MCOV rating.

Temporary Over Voltage Capability (cont'd)

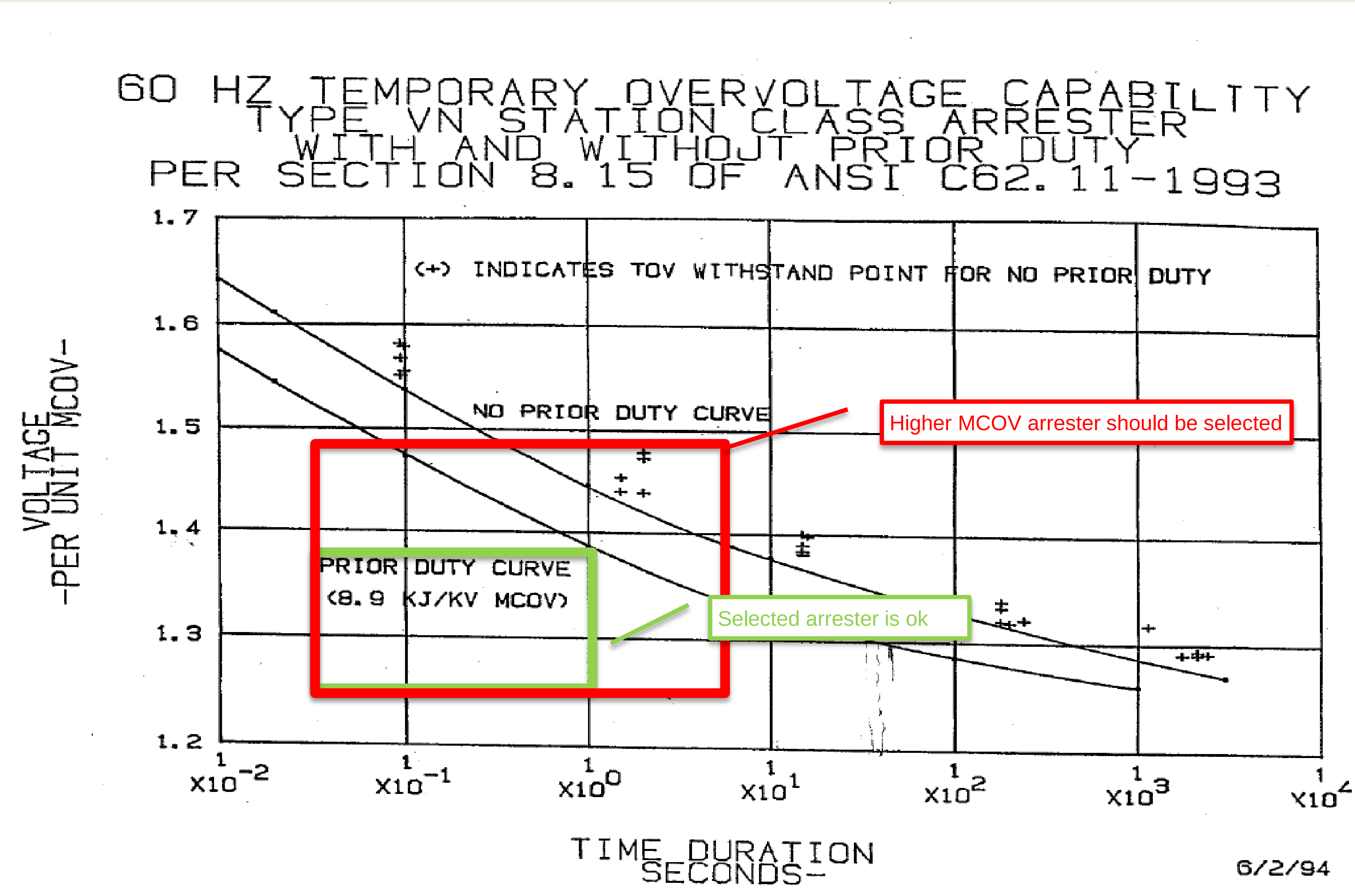
A typical arrester TOV capability curve



Temporary Over Voltage (TOV) Capability

- While selecting the arrester's MCOV, considerations need to be given to the arresters "TOV" capability
- The basic requirement is that the power frequency voltage versus time needs to be higher than the TOV amplitude versus duration characteristics.

Temporary Over Voltage (TOV) Capability (Cont'd)



Protection Ratio:

- Margin between the equipment's insulation strength and surge voltage at the equipment terminals. It is the basis for insulation coordination.
- Protection ratio takes into consideration of the location of the arrester, whether it is:
  - Mounted close / on the protected equipment (e.g. transformer)
  - Mounted away from the protected equipment

Protection Ratio (Cont'd)

When the arrester is mounted on or close to the protected equipment then the following equations and ratios are valid:

PRL1 = CWW / FOW

PRL2 = BIL / LPL

PRS = BSL / SPL

Where:

- CWW, BIL and BSL are protected equipment insulation level.
- FOW, LPL and SPL are arrester protective level.
- PRL1 & PRL2 ≥ 1.2 for non-self restoring equipment; 1.15 for self-restoring equipment
- PRS ≥ 1.15

Protection Ratio (Cont'd)

- How about cases where the arrester is not mounted close to the equipment?
- Arrester locating remotely from the equipment to be protected reduces the protective margin.
- To calculate allowable separation distance between arrester and equipment refer to IEEE C62.22-09 Annex C
  - It is used for 69 kV and above, with lightning surges entering into a shielded air-insulated substation.

Protection Ratio(Cont'd):

- For non-self restoring equipment, the maximum separation distance is calculated as:

$D_T = \frac{0.385cV_{sa}}{S}\frac{(0.870BIL)-V_{sa}}{2.92V_{sa}-0.870BIL}$ (time to crest at arrester voltage <2μs ,$V_T/V_{sa} \leq 1.10$, $PR_T = 1.15$) (Eq. C.3)

$D_T = \frac{0.385cV_{sa}}{S}\frac{(0.957BIL)-V_{sa}}{2.92V_{sa}-0.957BIL}$ (time to crest at arrester voltage <2μs ,$V_T/V_{sa} > 1.10$, $PR_T = 1.15$) (Eq. C.4)

$D_T = \frac{0.385cV_{sa}}{S}\frac{(0.870BIL)-V_{sa}}{2.92V_{sa}-0.870BIL}$ (time to crest at arrester voltage ≥2μs , $PR_T = 1.15$) (Eq. C.5)

- For self restoring equipment, the maximum separation distance is calculated as:

$D_B = \frac{c}{2S}\left[\frac{\delta BIL}{1.05} - V_{sa}\right]$ for $V_B/V_{SA} \leq 1.15$ and $PR_B = 1.05$ (eq. C.9)

$D_B = \frac{c}{2S}\left[\frac{1.15\delta BIL}{1.05} - V_{sa}\right]$ for $V_B/V_{SA} > 1.15$ and $PR_B = 1.05$ (eq. C.10)

$\delta = e^{-A/8.6}$ where A = 0.36576 km in Ft. McMurray (eq. C.11)

Protection Ratio (Cont'd) IEEE C62.22-09 Annex C

B	A piece of equipment that has self-restoring insulation (disconnecting switch, bus support, etc.) located in front of the surge arrester
BIL	Basic lightning impulse insulation level of the transformer or equipment *B* (kV)
c	Velocity of light, 300 m/µs
CWW	3-µs chopped-wave withstand of transformer or equipment B (kV) For transformer: CWW = 1.10 × BIL (IEEE Std C57.12.00-2000, Table 6) For circuit breaker: CWW = 1.15 × BIL (ANSI C37.06-2000, Table 4). This is also a conservative estimate for disconnecting switches and bus supports.
d'	Conductor length between junction *J* and surge arrester terminal (meters)
d''	Conductor length between surge arrester and ground (meters)
d	Total surge arrester lead, $d' + d''$ (meters)
d_m	Distance from station to flashover (kilometers)
δ	Relative air density factor used for derating air insulation for higher altitudes
D	Separation distance (meters)
D_B	Maximum allowable separation distance between junction *J* and equipment B (meters)
D_T	Maximum allowable separation distance between junction *J* and transformer terminal (meters)
di/dt	Rate of rise of surge current = $2\ S\ /\ Z$ (kA/µs)
FOR	Flashover rate of lines (flashovers/100 km-year)
J	Common point among transformer lead, surge arrester lead, and surged line
K_c	Corona constant that determines steepness of incoming surge (kV – km/µs)
L	Inductance of surge arrester lead *d* (µH) (Assume 1.3 µH/m)
MTBF	Mean time between failures (years). A failure in this context is an overvoltage event that exceeds the maximum voltage stress allowable (see V_B and V_T below), which includes a protective ratio.
N	Number of transmission lines, including the surged line, connected to a substation bus
n	1 for the equipment B case and for a nonsymmetrical substation layout case. Equal to *N* for the symmetrical substation layout case.
PR_T	Protective ratio of transformer. PR_T should be equal to or greater than 1.15.
PR_B	Protective ratio of equipment with self-restoring insulation and is either 1.00 or 1.05.
S'	Rate of rise (steepness) of incoming surge on the transmission line (kV/µs)
S	Rate of rise (steepness) of incoming surge at junction *J* (kV/µs)
V_a	Surge arrester FOW protective level at 0.5 µs (kV) (See Table 1)
V_{sa}	Voltage across the surge arrester, from junction *J* to ground (kV)
V_B	Maximum voltage stress allowable at self-restoring equipment B (kV)
V_T	Maximum voltage stress allowable at the transformer (kV)
Z	Surge impedance of line conductor or substation bus (Ω) (Refer to Z_L in Table 11 of IEEE Std C62.11-2005)

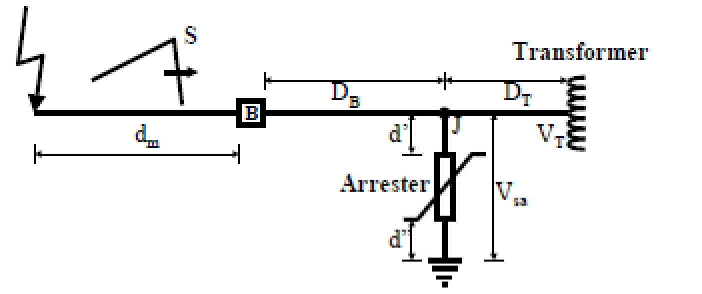
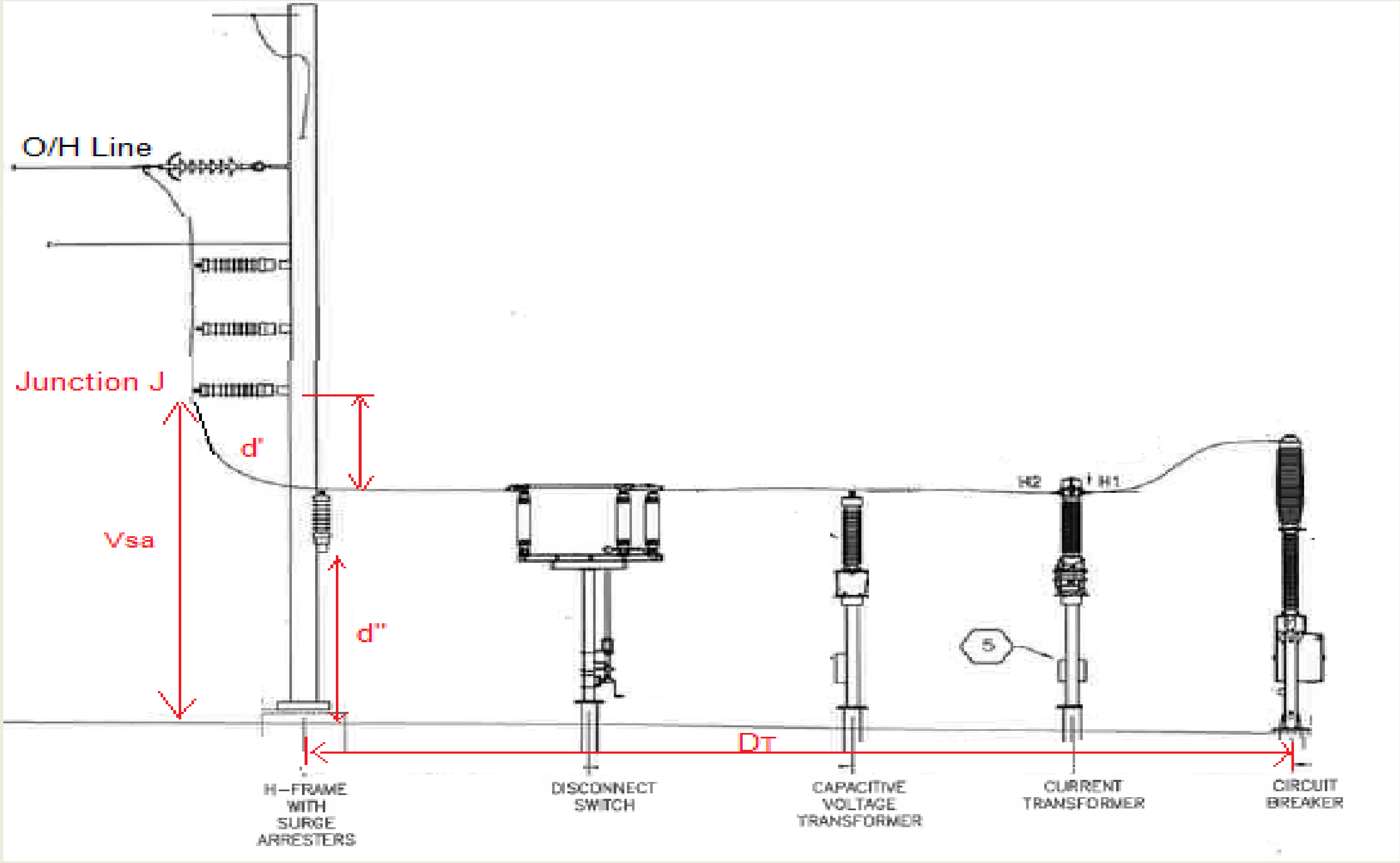


Figure C.1—Definition of symbols

Protection Ratio (Cont'd)



Switching Impulse Energy Handling Capabilities

- When the arrester is energized, it will absorb energy resulting in an increase in temperature. Under normal operating conditions, there is a balance between the heat generated in an arrester and the heat dissipated by the arrester. With such balance, a stable condition is maintained.
- During over voltage conditions (switching surge) the arrester absorbs more energy. If the temperature of the arrester is too high, the arrester can be driven into a state of thermal run away.

Switching Impulse Energy Handling Capabilities

The conservative energy discharge the arrester needs to handle is:

$$E = 2D_L E_A I_A / v$$

Where:

- D_L = Length of line (km) = Assume to be 300 km
- E_A = Arrester switching impulse discharge voltage for I_A
- E_S = Prospective switching surge voltage (kA) :

  $E_S = \sqrt{2} \times k_1 \times V_{LG}$ (k_1 is typical value per IEEE C62.22)
- I_A = Switching Impulse Current

  $I_A = (E_S - E_A)/Z$
- V = speed of light = 300 km/ms

The actual arrester's switching impulse energy capability must exceed the expected energy discharge

Arrester's Pressure Relief Capability

It is the short circuit rating of the arrester which should not be exceeded by the system's available short circuit current at the arrester location

Modeling Breakers for Studying Transient Recovery Voltage (TRV)

Transient Recovery Voltage (TRV)- An Introduction

- By definition TRV is the voltage appearing across the terminals of a circuit breaker after a switching event has occurred when interrupting:
  - **Fault Current,**
  - **Inductive Current,**
  - **Capacitive Current.**
- It represents the difference in the power system response voltage from line side to load side of the circuit breaker.

Transient Recovery Voltage (TRV)- An Introduction

- The concern:
  - **When current flow stops (after the initial few μsec) the power system response is a transient expressed as TRV.**
  - **With multiphase faults sequential interruption of fault current leads to power system recovery voltages higher than rated, which leads to circuit breaker restrike and non-interruption of current flow.**

Transient Recovery Voltage (TRV) Behavior Example

- In some cases the system response has an oscillatory and power frequency component. An example is a three phase to ground terminal fault at the circuit breaker. For this case the:
  - **Initial time interval consists of a transient voltage with an axis of oscillation around the recovery voltage.**
  - **Second interval represents the power frequency recovery voltage.**
- (do we have a plot from existing study that can be inserted here)

Transient Recovery Voltage (TRV)
Transient Analysis

- All transients have:
  - An initial condition which may be zero or a finite value,
  - An axis of oscillation that becomes the actual steady state value when the transient has died out,
  - A maximum value depending on the degree of damping,
  - A certain frequency determined by the values of L and C.
- Oscillatory components of TRV can be analyzed using RLC circuits and applying differential equations.
- Three of the RLC cases have a common 2nd order homogeneous differential solution of the form:
  - **$y = Ae^{r1x} + Be^{r2x}$;** where roots r1 and r2 are derived from the circuit RLC components and A and B from the initial boundary conditions.
- The fourth case uses a 2nd order non-homogeneous differential solution using lookup tables and the method of undetermined coefficients to solve the equation.

Transient Recovery Voltage (TRV) – Pole Factors

- For a circuit breaker opening under a fault there is sequential interruption of fault current. The first circuit breaker pole clears and the system becomes unbalanced causing the recovery voltage to exceed its normal phase to ground value.
- Under fault conditions two cases that affect recovery voltage levels can be considered:
  - **An Effectively Grounded system where the ratio of symmetrical reactance X_0 to X_1 is 3 or less,**
  - **A Non-Effectively Grounded system where the neutral is isolated, high impedance or resonant grounded.**
- For the cases listed above the TRV is based on a power frequency component determined by the first pole to clear factor (k_{pp}) and an oscillatory (or aperiodic) component based on the amplitude factor (k_{af}).
- Circuit breakers can interrupt rated fault levels at or near unity power factor with little or no problem, however at a zero power factor leading or lagging the TRV can impose a great challenge.

Transient Recovery Voltage (TRV) Pole Factors (cont'd)

- For an Effectively Grounded circuit the first and second pole to clear factor is derived from sequence components and calculated as:
  - **$k_{pp1} = 3\,(X_0/X_1) / (1 + 2\,(X_0/X_1))$**
  - **$k_{pp2} = (3^{0.5} / (2+(X_0/X_1)) / ((1 + (X_0/X_1) + (X_0/X_1)^2\,)^{0.5}$**
  - **k_{pp3} = 1 as the system is now balanced,**
- Amplitude Factor (k_{af}) is the ratio of the peak voltage value to the axis of oscillation with both being relative to the starting point.
  - **$k_{af} = 1 + \beta$ where $\beta = (B – A) / A$ (see graph below).**

- (reproduce graph from Peelo, page 25, Fig 2.9)

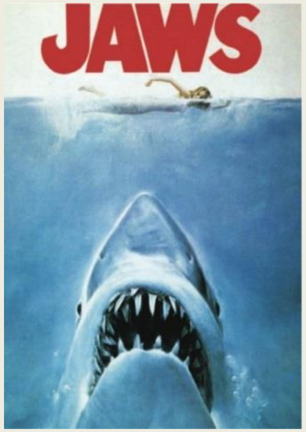
Transient Recovery Voltage (TRV) – Pole Factors (cont'd)

- For a Non-Effectively Grounded circuit the first and second pole to clear factor is derived from positive and negative sequence components but no zero sequence and calculated as:
  - $k_{pp1} = V_{cb} / V_{af}$
  - $k_{pp2} = |0.5 (V_b - V_c) / V_{af}|$
  - $k_{pp3} = |0.5 (V_b - V_c) / V_{af}|$

- (add table of eg's of first pole to clear factors for say a 72kv breaker)

Modelling Vacuum Breakers for Transient Analysis:

- Modelling is done to imitate real life. It has to be accurate especially for the intended purpose. How can we model an arc in a circuit breaker?



Modelling Vacuum Breakers for Transient Analysis:

- Three basic models with variants:
  - Physical arc models
  - Black box models
  - Formulas and calculations
- Models applications were described in CIGRE, Work Group 13.01 “Practical applications of arc physics in circuit breakers. Survey of calculation methods and application guide; Electra No.: 118, pages: 64-79, 1988
- CIGRE’s report shows the preferred modelling methods for:
  - Development
  - Testing
  - Operation

Modelling Guidelines for Arcs in Breakers

- For development and testing all three arc model types are used
- For Operation Black Box Type Models (BB) are used:
  - Influence of arc asymmetry and delayed current zero
  - Small inductive currents
  - Short line faults including TRV
- Formulas and calculations models are used for:
  - Description of dielectric recovery
  - Small inductive currents (alongside with BB)
  - Short line faults including TRV (Alongside with BB)

Modelling Vacuum Breakers During Closing and Opening Operations:

- Four categories of transients:
  - Low frequency
  - Slow front
  - Fast front
  - Very fast front
- Low frequency:
  - Closing: important for mechanical pole spread
  - Opening: high current interruption (interruption capability studies)

Modelling Vacuum Breakers During Closing and Opening Operations

(Continue)

- Slow front transients:
  - Closing:
    - Very important for mechanical pole spread
    - Important for pre-strikes studies
  - Opening, important only for:
    - Interruption capability studies
    - Small inductive currents where the following concerns:
      - Current chopping
      - Re-strikes and
      - High frequency current interruptions

Modelling Vacuum Breakers During Closing and Opening Operations

(Continue)

- Fast front transients:
  - Closing:
    - Important for pre-strikes studies
  - Opening, very important for:
    - Restrike characteristic
    - High frequency current interruptions
  - Opening, regarding current chopping important only for small inductive currents

Modelling Vacuum Breakers During Closing and Opening Operations (Continue)

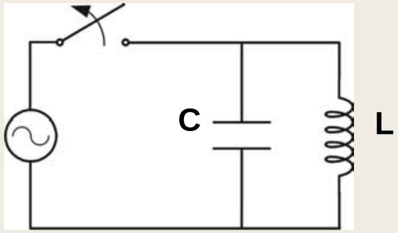
- Very fast front transients:
  - Closing:
    - Very important for pre-strikes studies
  - Opening, very important for:
    - Restrike characteristic
    - High frequency current interruptions

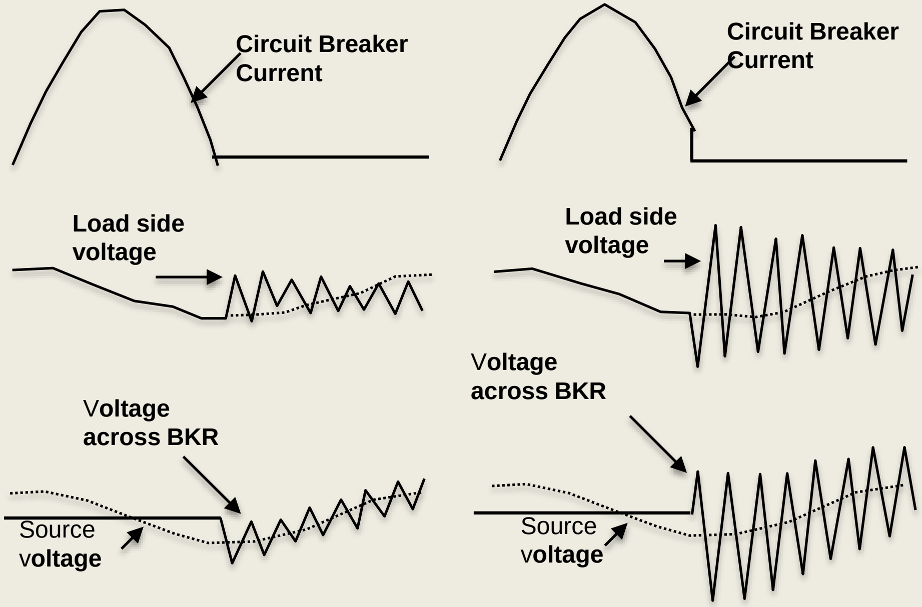
Current Chopping

- Vacuum Circuit Breaker interrupts the current before current zero is reached depending on
  - Contact material
  - Level of current
  - Form of current
- Current chopping is non-deterministic
- Overvoltage proportional to chopped current and surge impedance of load. As per Reference [B1]

$$V_{max} = \sqrt{\frac{L}{C} {I_o}^2 + {V_o}^2}$$

Current Chopping as Depicted in Reference B1





Current Chopping

- Estimation of current chopping level
  - $I_{ch} = (\omega \cdot i \cdot \alpha \cdot \beta)^q$

ω = Angular frequency

i = Amplitude of power frequency current

α, β, q = parameters dependent on contact material

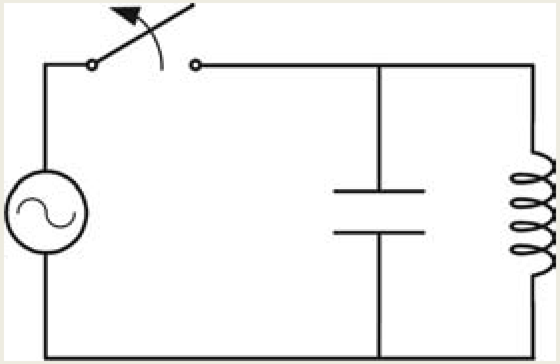
- Typical range 3 – 8A

High Frequency Current Quenching

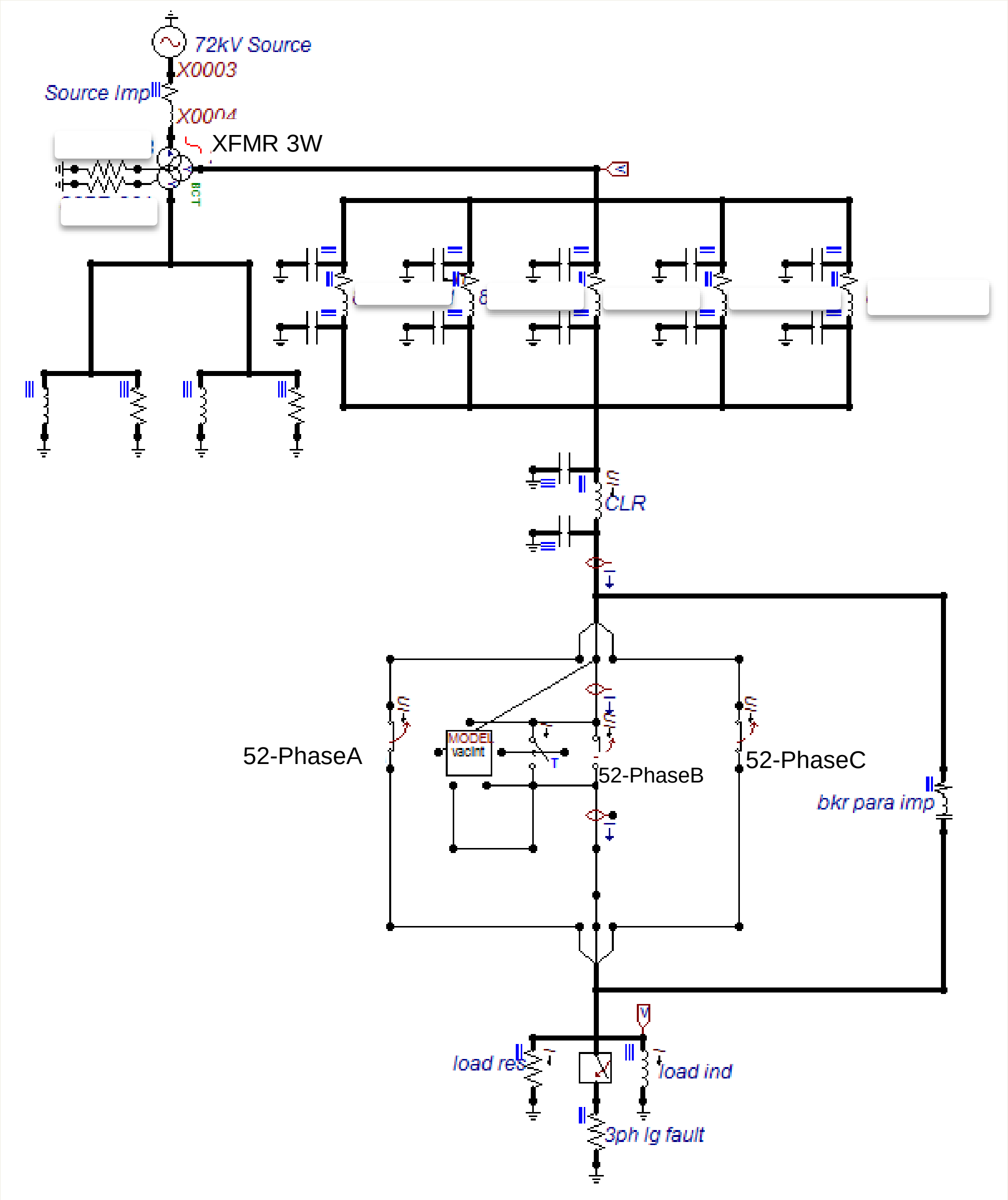
- Re-ignition in the VCB will appear in the form of a high frequency current superimposed on the power frequency current.
- Vacuum circuit breakers can quench high frequency currents in the range of several hundred A/μs when they cross current zero.

Multiple restrikes leading to Voltage Escalation

- Fast clearing of the restrike adds more stored energy into the inductor.
- New TRV across the breaker will be higher in magnitude, causing another restrike.
- This will continue until the contact gap withstand can handle the TRV. (Reference B2)



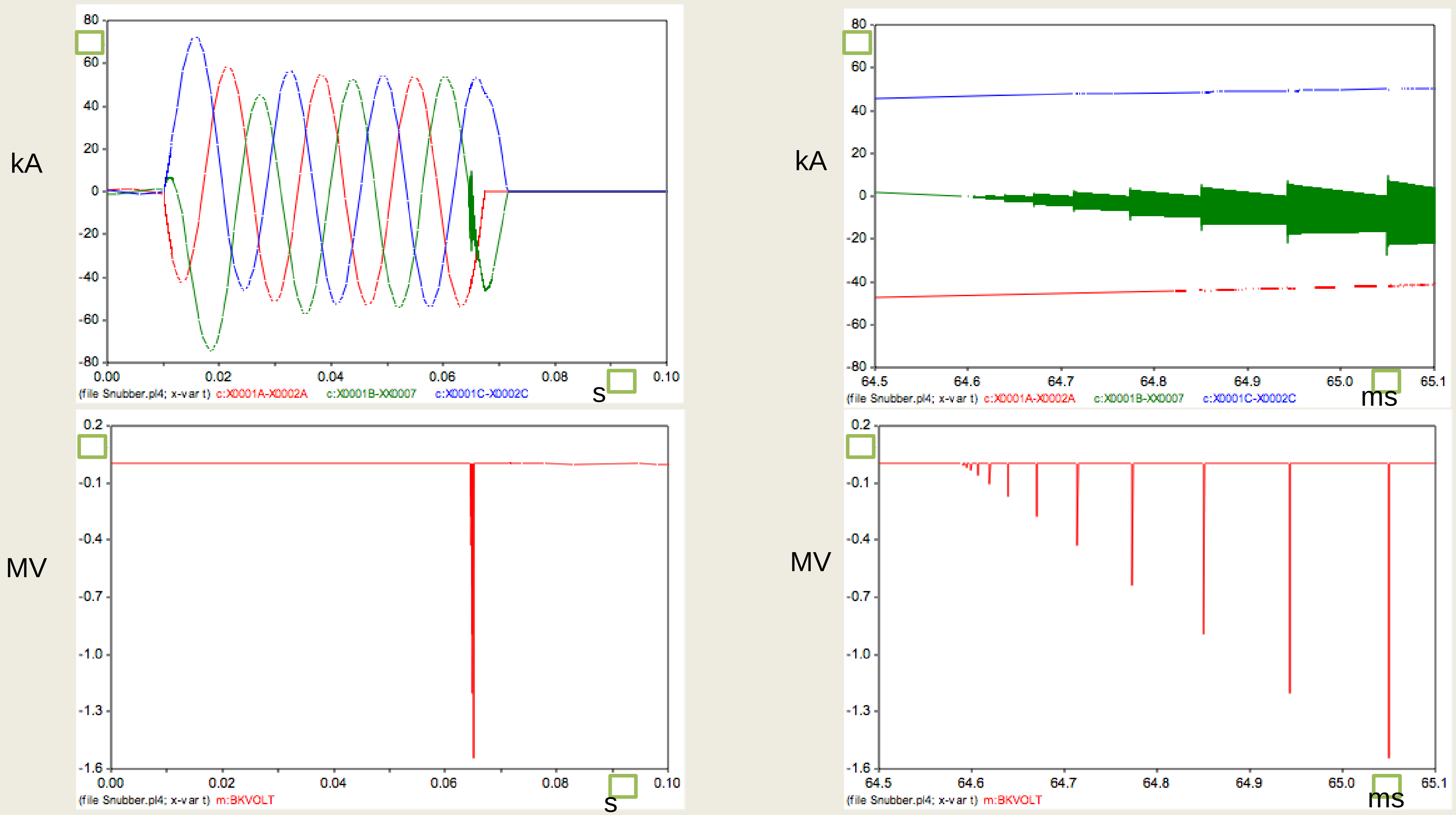
Model


72kV Source
X0003
Source Imp
X0004
XFMR 3W
CLR
52-PhaseA
52-PhaseB
52-PhaseC
bkr para imp
load res
load ind
3ph lg fault

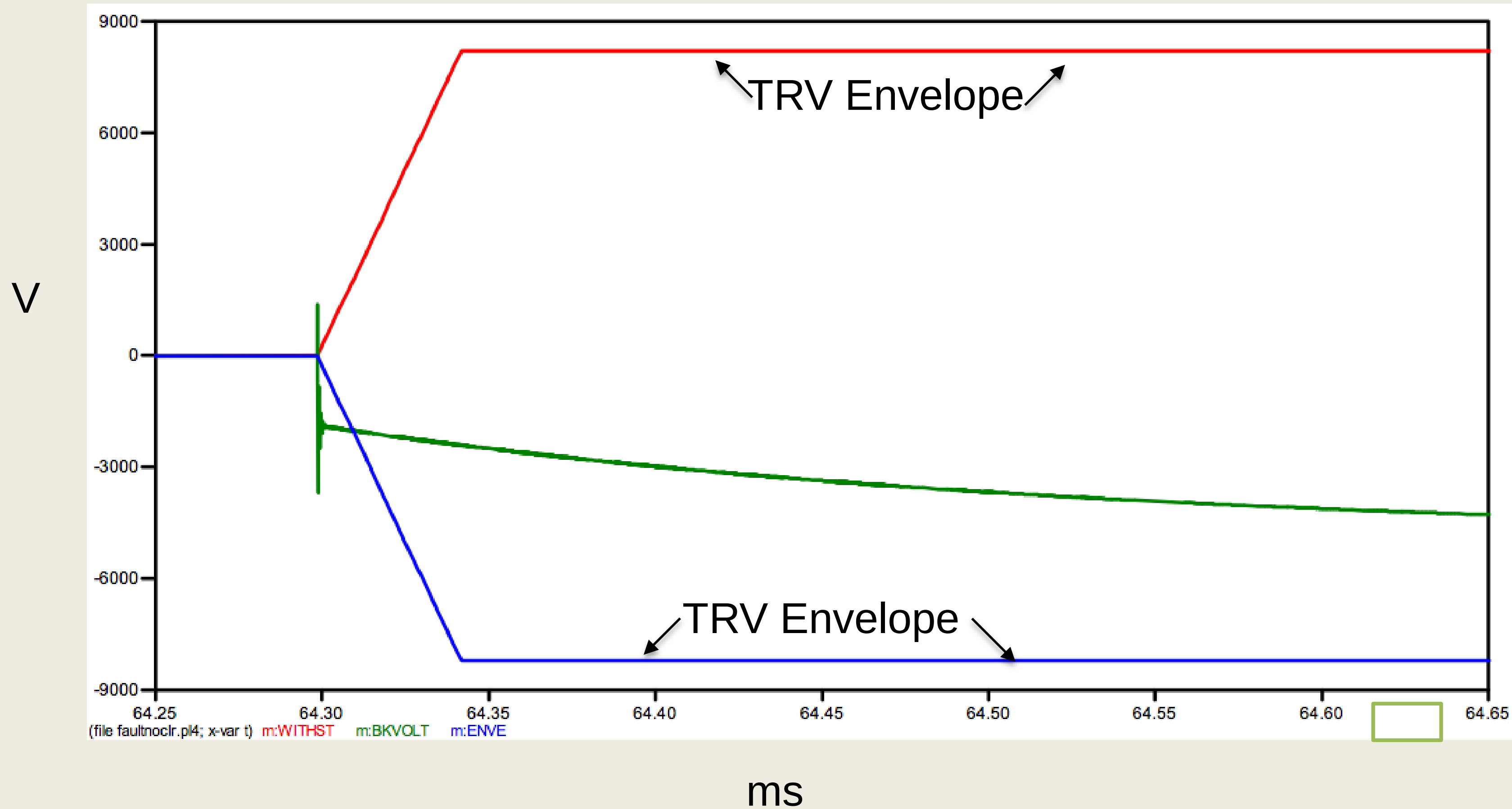
Model Parameters

- Current Chopping assumed to be 5A
- Opening of breaker occurs during short circuit of load
- Contact gap withstand is given by the TRV Envelope from IEEE C.37

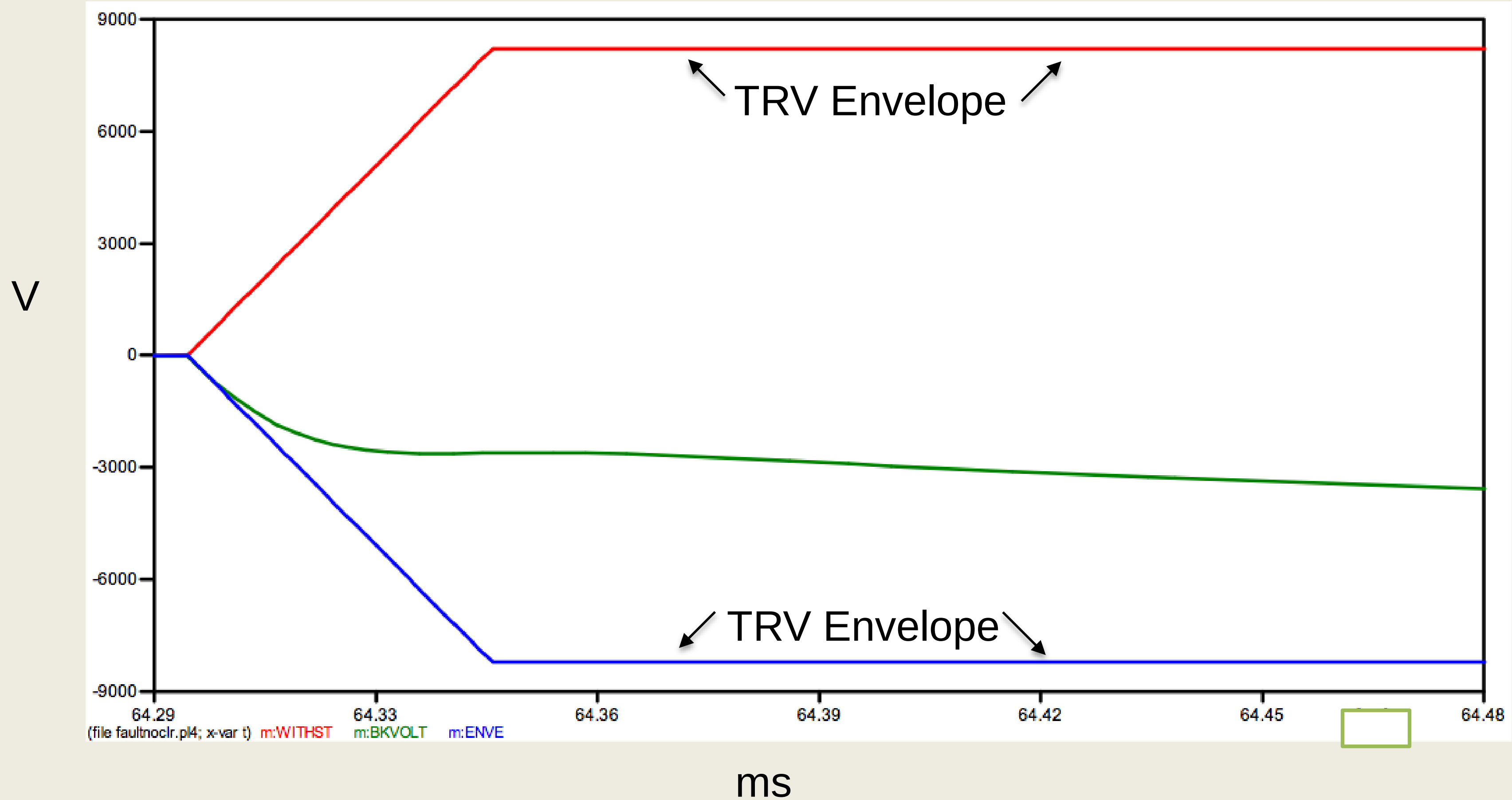
EMTP Results – Multiple Reignitions



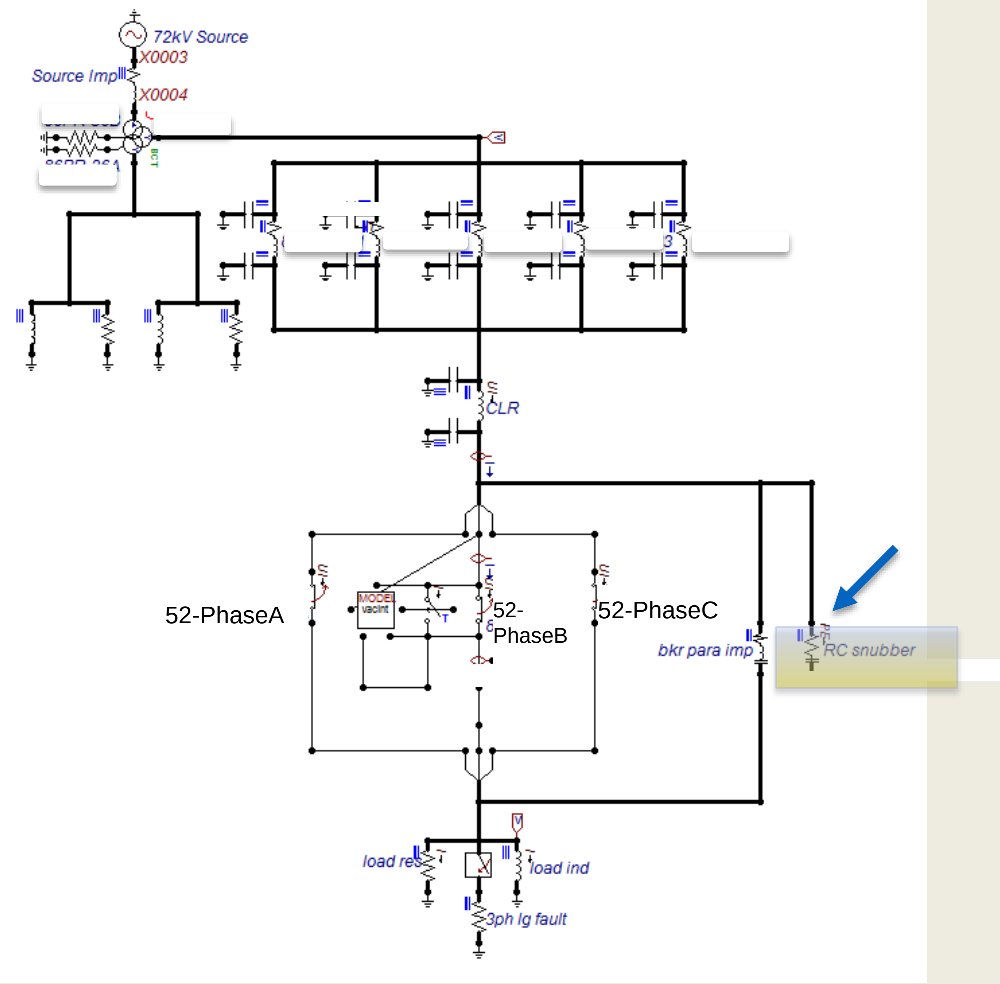
Simplification – TRV envelope



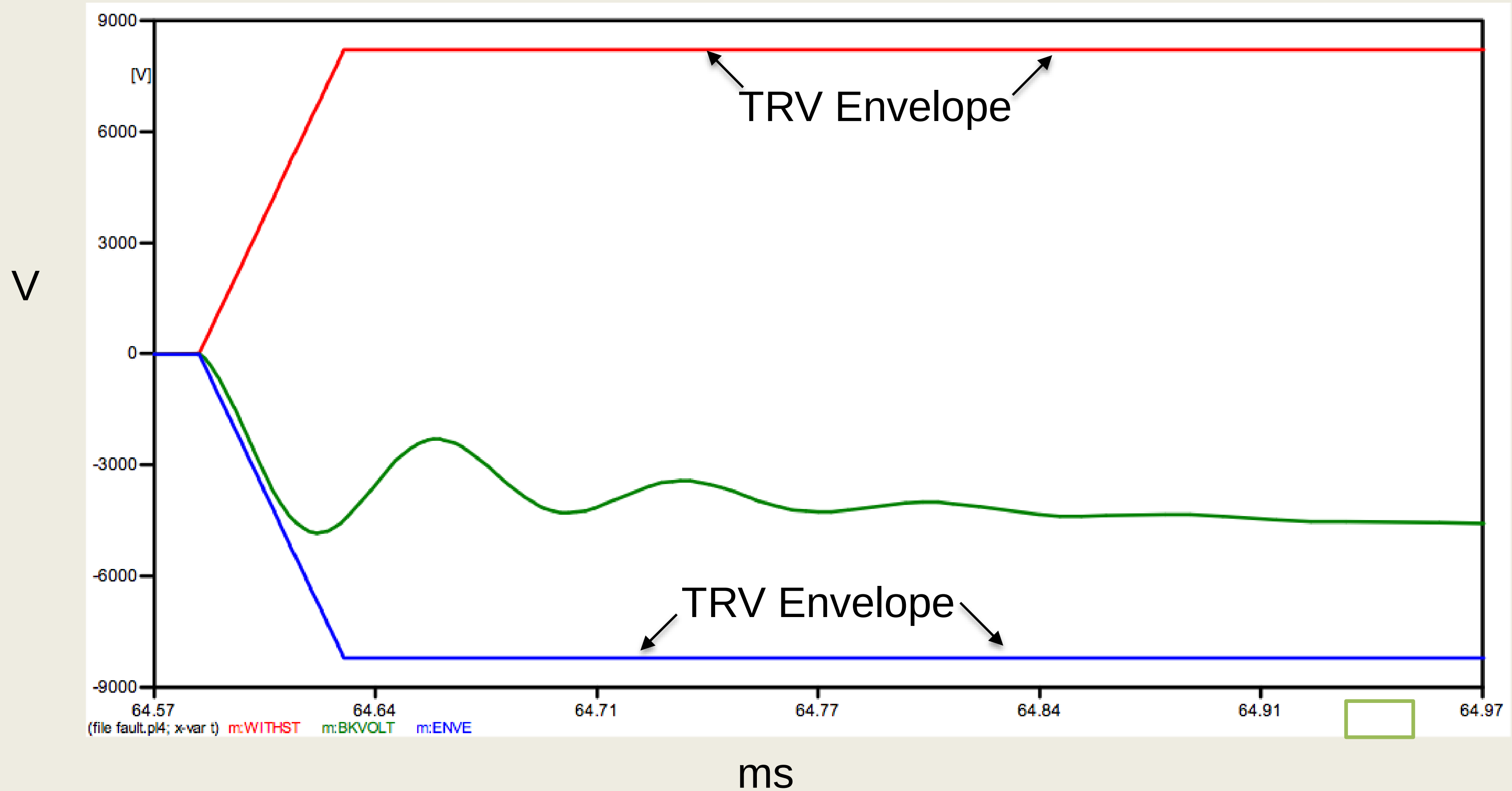
No Current Chopping



Addition of RC Snubber



Addition of RC Snubber



Conclusion:

When system configuration is altered, transient recovery voltage (TRV) on breaker may considerably change such that it becomes outside the acceptable limits. To establish vacuum breaker's TRV in a modified system, the Electromagnetic Transient Program (EMTP) could be used to model the system and the vacuum breaker and to perform the necessary calculations. Modelling vacuum circuit breakers shall address current chopping phenomena as necessary. Current chopping could introduce high frequency voltage transients which cause the TRV to have high rate of rise and could bring it out of allowable IEEE established limits. If required, remedial actions can be taken to bring the TRV of the breaker to the allowable zone as given by the Standards

Transient Recovery Voltage (TRV) Special Case (Short Line Fault)

- A special case is the short line fault where the circuit breaker is stressed by the difference between TRV's on the line and load side.
  - …

Case Study – FCLD - Introduction

- In medium voltage (MV) industrial distribution systems power requirements may change over time.
  - Eg: An equipment is operating more than what it was initially designed for. If a fault was to occur there's a possibility that:
    - TRV is greater than the equipment's design
    - Fault occurred on an important equipment, which can result to major outages
- Regardless of the reasoning, short circuit current needs to be restricted to something more manageable

FCLD Introduction (Cont.)

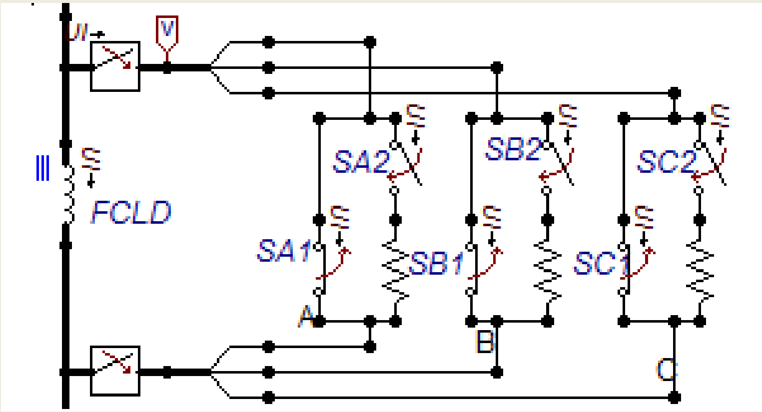
- As short circuit current in MV systems are a function of voltage and inductive reactance a way to limit the fault is to increase inductive reactance at fault location.
  - One way of doing so is using a current limiting reactor
- Current limiting Reactors:
  - Limits short-circuit current and voltage to a level suitable for installed electrical system
  - Can be used to allow continuous operation without having to open the circuit

Study and Analysis Approach

- Important to study the Switching Transient and Transient Recovery Voltage (TRV) of how the electrical equipment characteristics.
- EMTP / ATPdraw is a useful program to simulate transient studies. In this case we used it to study the characteristics of the current limiting reactor and its' affect on the overall system.
  - However, EMTP is not as user-friendly as other power system programs. Need to model current limiting reactors as individual components

Current Limiting Reactor modelled in EMTP

- Pre-fault: SA1, SB1 and SC1 are closed whereas SA2, SB2, SC2 are open.
- Fault: SA1, SB1 and SC1 are open whereas SA2, SB2, SC2 are closed.
- As the current across the fuse (represented as a resistor) approaches current-zero point, current across the reactor (represented as inductor) increases, which reduces the transient voltage across the FCLD.



Results

- The transient voltage across the current limiting reactor is much smaller than the transient voltage across a fuse/breaker without current limiting reactor.
- If sized properly the current limiting reactor can:
  - Ensure that the TRV will be within equipment's limitations
  - Allow continuous operation without having to break the circuit due to a fault.

Lightning Protection for A Distribution OH Line Case Study

Part II:

Overhead industrial distribution MV lines subjected to lightning strikes

- **This section discusses**
  - OH distribution lines subjected to Lightning strikes
  - Flashovers caused by direct strikes and induced voltages
  - Possible solutions that can be implemented to reduce outages caused by lightning strikes
  - Economics i-e criticality of load vs cost of implementing these solutions.

Case Study

- **System Description:**
    a. 25kV distribution line located in Northern Alberta feeding critical facility loads.
    b. Feeder passing through flat land with no buildings and trees in surroundings.
    c. Line Configuration: Horizontal arrangement with no shield wire and surge arresters for lightning protection.
    d. System have experienced outages due to lightning strikes.

Lightning Flashovers

- Lightning flashovers are caused by either Direct lightning strikes or induced voltages produced by lightning strikes on nearby building, trees etc.
- For our 25kV feeder located in Fort McMuarry, direct-stroke flashovers and induced flashovers in Fort McMuarry area are estimated (based on methods described in IEEE STD 1410-2010) to be around 68 Flashovers/100km/year and 2 Flashovers/100km/yr. Assuming all flashovers cause faults , Total faults= 70 faults/100km/yr.

System Improvement Options

(I) Shielding: Extend pole and add shield wire

(II) Lightning Arresters: Add lightning arrestors every second pole?

(III) Replace insulators with higher BIL (which would also help for system that does not have effectively grounded neutral)

Shield Wire

i. Addition of shield wire provides one of the best solutions to mitigate outages against direct lightning strikes.

ii. Use of shield wire with shielding angle less than 30 degree and structure CFO of 225kV (typical 25kV tangent) and ground resistance of 10 ohms, number of direct hits causing flashover can be reduced down to 80% (Figure 8, IEEE STD 1410-2010)

iii. However,

- Assumption of 10ohm grounding resistance may not be accurate. Figure 8 of IEEE STD 1410 maybe used to evaluate the reduction in shield wire performance due to ground resistance.
- Back Flashovers

Surge arresters

i. The use of arresters only to protect against direct strokes is not very effective economically.
ii. However arresters prove to be very effective in reducing the induced voltage flashovers especially when used to protect pole with lower insulation levels.
iii. When used in conjunction with an OHSW, the overhead ground wires divert most of the lightning energy away from phase conductors and connected equipment, and the arresters limit peak insulator voltages and reduce back flashover rates more effectively than improved grounding at every pole, hence, making OHSW design less dependent on insulation level and grounding.

Summary and Conclusions

- From above analysis:
  - Direct lightning strikes are major source of flashovers based on line vicinity and structure configuration.
  - Adding the shielding wire with ground lead grounded at every pole provides the best possible protection against the lightning flashovers. However to counter the effects of back flashovers and induced voltage strikes further steps shall be taken.
  - Use of longer crossarm or fiberglass standoff for downlead may be used to provide more insulation between center phase and ground downlead.
  - Use of guy strain insulators may be considered.

Summary and Conclusion (continued)

- In cases where the footing resistance at the pole is higher and improving structure insulation is not possible the use to surge arresters is recommended
- Pole structures with electrical equipment like cable terminations, transformers, fuse cut-outs and disconnect switches shall be protected with surge arresters.

A Brief Discussion on Slow Front Over-voltage (SFO), Fast Front Over-voltages (FFO), Very Fast Transient Over-voltages (VFTO) and Ferro Resonance

Standards, Books and Key References

Standards References

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- IEEE Std Draft PC62.82.2™/D3 Draft Guide for the Application of Insulation Coordination
- IEEE Std 1313.2™-1999 (Reaff 2005), IEEE Guide for the Application of Insulation Coordination
- ANSI C84.1-2006, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz)
- IEEE Std C62.11-2012: Standards for Metal Oxide Surge Arresters for AC Circuits (>1kV)
- IEEE Std C62.22-2009 (Reaffirmed 2003): IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
- IEEE Std C62.22.1 (Reaffirmed 2003): IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems

Standards References

- IEEE Std C62.82.1- 2010; Standard for Insulation Coordination—Definitions, Principles, and Rules
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- IEEE Std C62.22.1 (Reaffirmed 2003): IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems

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- IEEE Application Guide for Transient Recovery Voltage for AC High Voltage Circuit Breakers, IEEE Std C37.011
- IEEE Standard Rating Structure for AC High Voltage Circuit Breakers, IEEE Std. C37.04b
- IEEE AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis- Preferred Ratings and Related Required Capabilities, IEEE Std C37.06
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- Abdel-Salam, Anis, El-Morshedy & Radwan “High-Voltage Engineering; Theory & Practice” Second Edition, CRS 2000
- Ametani, Nagaoka, Baba & Ohno “Power System Transients; Theory and Applications” CRC 2014
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