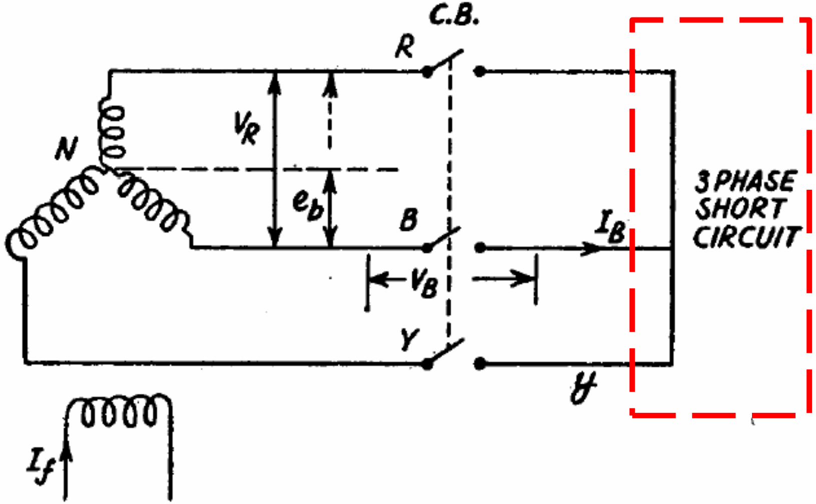
EEE4227: POWER SYSTEM PROTECTION

TERM: MID-TERM

Lecture 03
Transient recovery voltage(TRV) and Rate of rise of recovery voltage(RRRV)

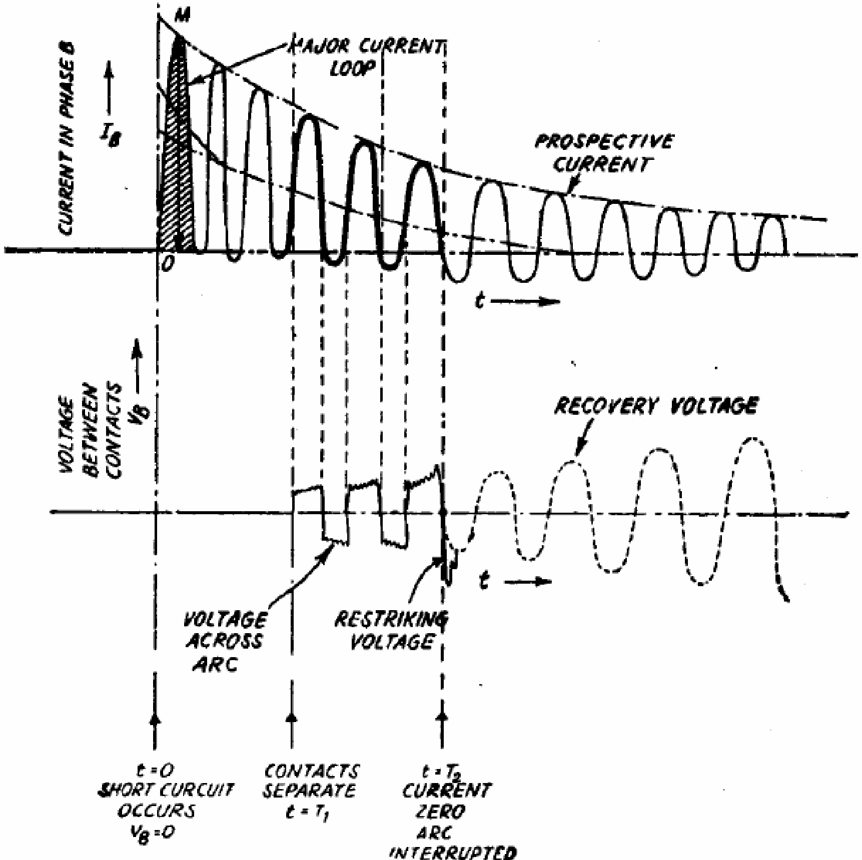
Transient recovery voltage, TRV

Scenario of 3-phase short circuit at the terminal of a synchronous generator

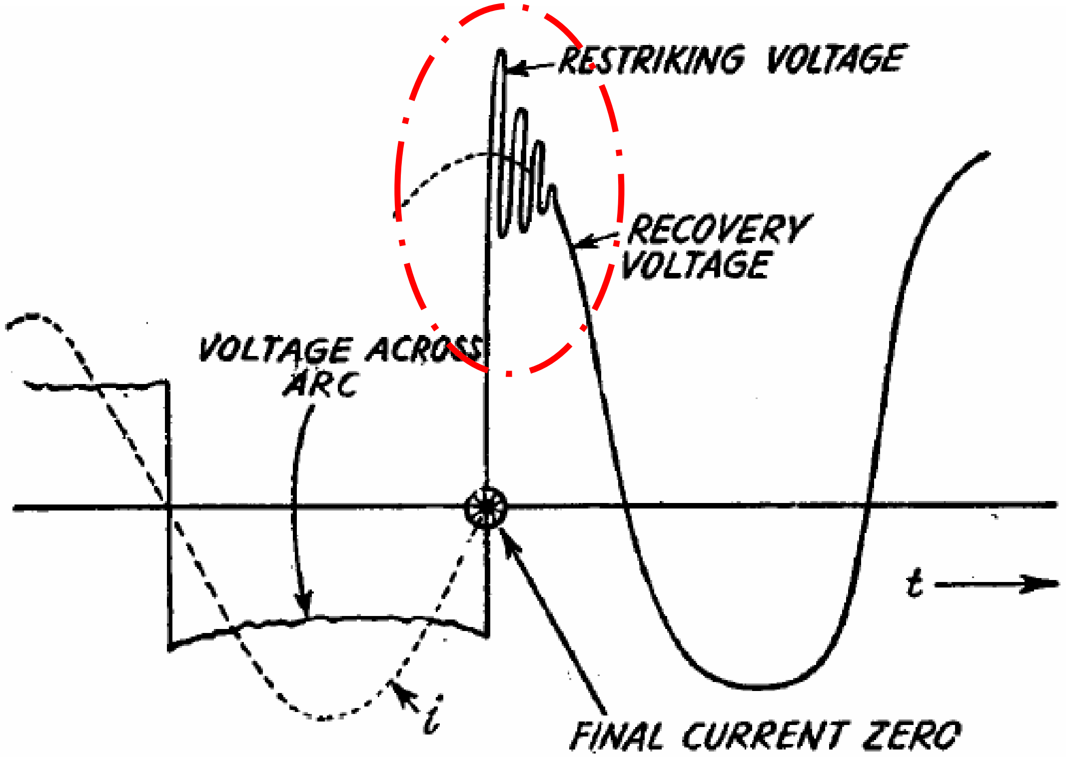


A 3 phase short circuit is applied on an unloaded alternator at the instant when the voltage of phase B with respect to neutral is zero. In such case the short circuit current in phase B will have the maximum dc component and the wave-form of Ib will be maximum unsymmetrical with respect to normal zero axis as shown in the figure

Transient recovery voltage, TRV



Transient recovery voltage, TRV



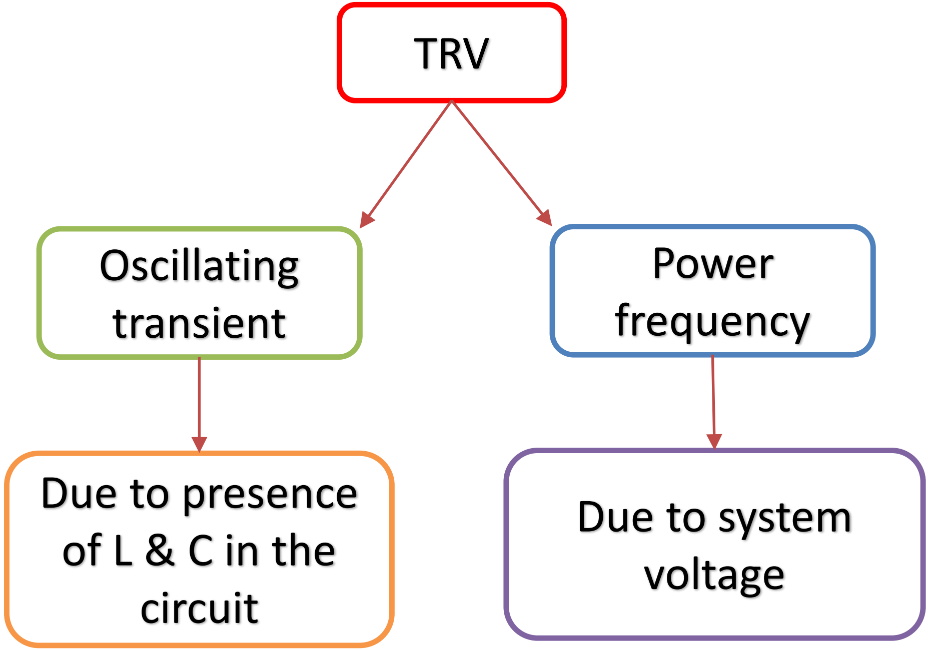
Important terms

- Transient recovery voltage/Restriking voltage/TRV
  - When the arc gets extinguished at fault current zero, a high frequency transient voltage appears across the contact. This transient vanishes within a very short time in the order of less than 0.001 sec. This high frequency transient voltage tries to ***re-strike*** the arc. This is called ***Restriking voltage or transient recovery voltage or TRV.***
- Prospective current
  - The current that would flow in the circuit if the CB were replaced by solid conductor is called ***Prospective Current.***
- Recovery voltage
  - The power frequency system voltage appearing between the poles after arc extinction is called ***Recovery Voltage.***

Important terms

- Reignition
  - Due to switching a capacitive current, a high voltage appearing across the contact can cause reignition of the arc after its final extinction. If the space breaks down within a period of 1/4 of a cycle from initial arc extinction, the phenomenon is called ***Reignition.***
- Restrike
  - If the break down occurs after 1/4 of a cycle of the initial arc extinction, the phenomenon is called ***Restrike.***

Factors affecting TRV



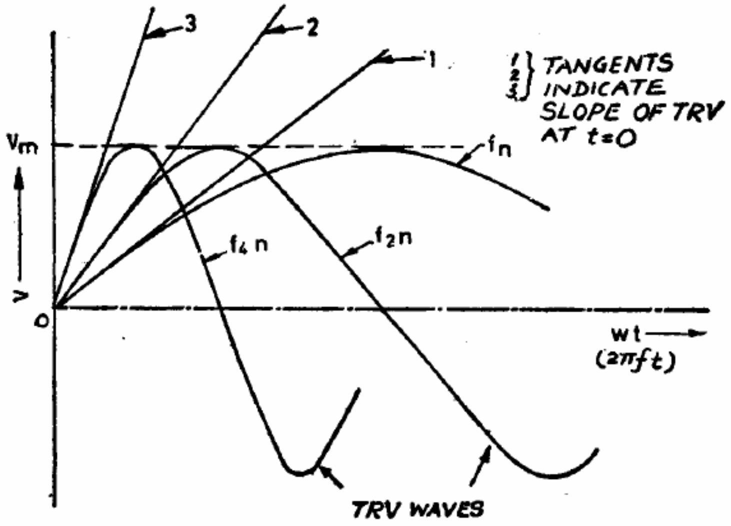
- the frequency of oscillating transient component is

$$f_n = \frac{1}{2\pi\sqrt{LC}} Hz$$

Where f_n = frequency of TRV
L = equivalent inductance
C = equivalent capacitance

Summary
Factors affecting TRV are-
- Line parameters L & C
- Natural frequency
- Power factor

Effect of natural frequency on TRV

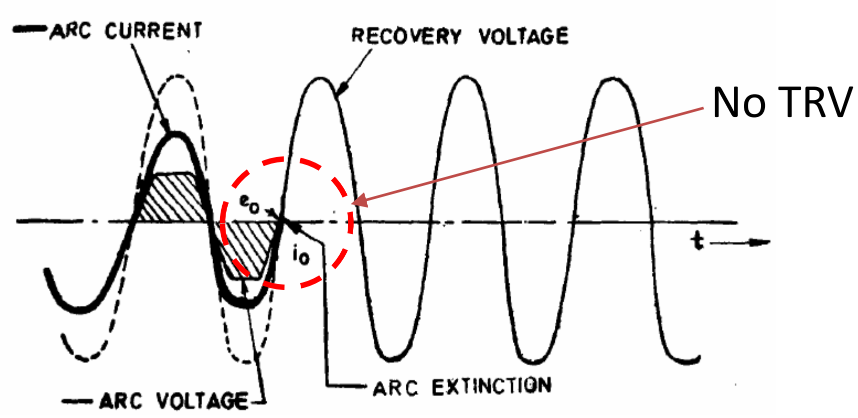


With the increase in the natural frequency, the rate of rise of TRV at current zero increase. The rate of rise of TRV across the CB pole causes voltage stress on the contact gap tending to continue the arc . With higher frequency, relatively less time is available for the building up of dielectric strength of the contact gap. Hence ***higher frequency*** is associated with ***greater stress***.

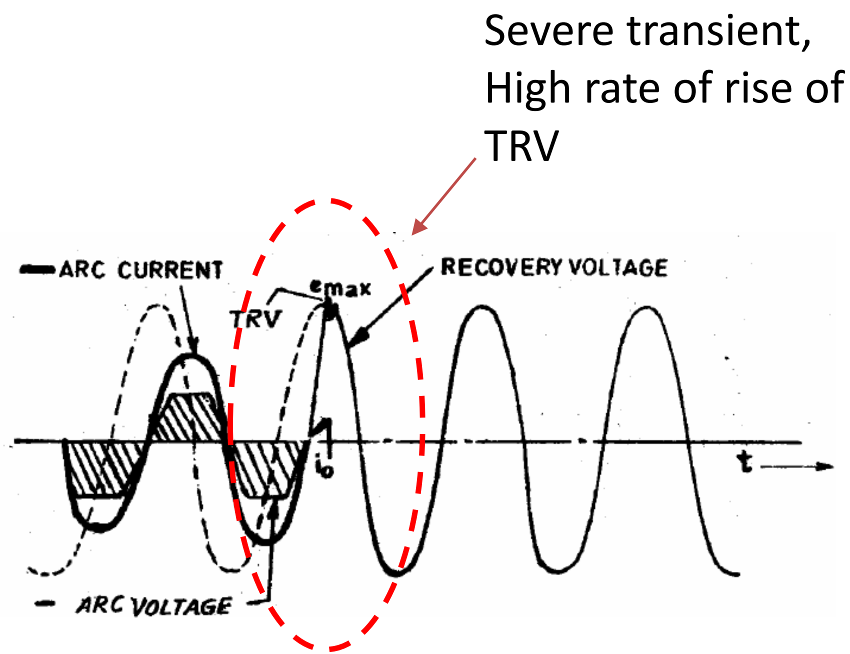
- Natural Frequency ↑
  Breaking capability ↓

So, dielectric stress has to be increased

Effect of power factor on TRV



Case 01: Unity power factor



Case 02: Low or zero power factor

Effect of power factor on TRV

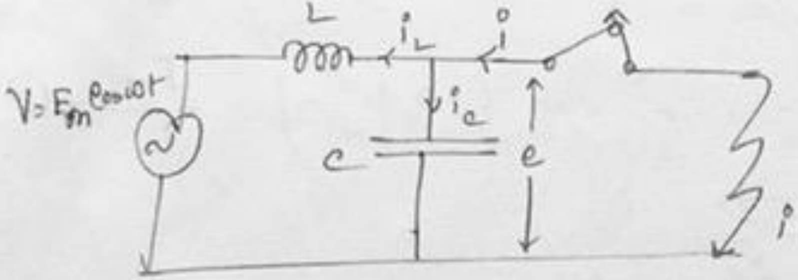
- The voltage appearing across the CB pole at the instant of current zero is influenced by the power factor of the current.
- The instantaneous value of the voltage developed across the pole at the instant of current zero (when the arc is extinguished) depends on the phase angle between the voltage and current i.e. power factor.
- For Unity power factor load, both current and voltage are in phase and both are zero at the instant of current zero, hence no TRV is generated.
- For zero power factor the peak value of the voltage ($emax$) is impressed across the pole at the instant of current zero. Such sudden application of voltage give rise to severe transient and has a high ate of rise of TRV.
- Hence interrupting current of low power factor is a difficult switching duty.

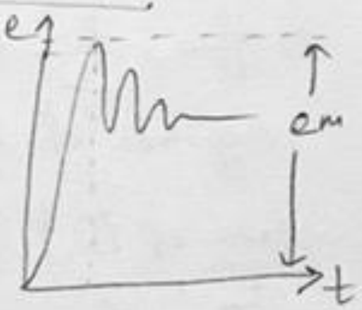
RRRV

- Rate of rise of ***Restriking voltage*** or TRV is usually abbreviated by R.R.R.V and is expressed in **volt/μsec.**
- Rate of rise of TRV and natural frequency of the TRV are closely associated. R.R.R.V. depends on the **system parameters**.
- The CB should be capable of interrupting its rated breaking current under the specific condition of TRV.
- The following characteristics of TRV are significant:
  - **Peak value of TRV**
  - **Time to reach the peak, hence the rate of rise**
  - **Frequency of TRV**
  - **Initial rate of rise**

Expression of TRV and RRRV

* Derivation of TRV or restriking voltage:





When the arc is extinguished, fault current will tend to flow in opposite direction & thereby will be divided into line inductance & shunt capacitance.

$$\therefore i = i_L + i_C$$

$$\Rightarrow i = \frac{1}{L}\int e\,dt + C\frac{de}{dt} \qquad [e = \text{restriking voltage}]$$

$$\Rightarrow i = \frac{e}{L}t + C\frac{de}{dt}$$

Expression of TRV and RRRV

$$\Rightarrow \frac{di}{dt} = \frac{e}{L}\frac{d}{dt}(t) + c\frac{d}{dt}\left(\frac{de}{dt}\right)$$

$$\Rightarrow \frac{di}{dt} = \frac{e}{L} + c\frac{d^2e}{dt^2} \quad \text{—— (i)}$$

Now, system voltage, $v = E_m \cos\omega t$

Since the load is inductive in nature, so current will lag system voltage by 90°.

$$\therefore i = \frac{E_m}{X_L}\cos(\omega t - 90^\circ)$$

$$i = \frac{E_m}{X_L}\sin\omega t$$

$$\Rightarrow \frac{di}{dt} = \frac{E_m}{\cancel{\omega} L} \times \cancel{\omega} \cos\omega t$$

$$\Rightarrow \frac{di}{dt} = \frac{E_m}{L}\cos\omega t$$

Magnitude of $\frac{di}{dt}$, i.e. when $t=0$, $\left.\frac{di}{dt}\right) = \frac{E_m}{L}$ —(

From eq^n (i) & (ii) $\Rightarrow$

$$\frac{E_m}{L} = \frac{e}{L} + c\frac{d^2e}{dt^2} \quad \text{—— (iii)}$$

Solving eq^n (iii) $\Rightarrow$ $\boxed{e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)}$ —— (iv)

Equation no (iv) is the equation of TRV or restriking voltage.

Now, restriking voltage will attain max or peak value when

$$\frac{de}{dt} = 0$$

$$\Rightarrow \frac{d}{dt}\left[E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)\right] = 0$$

$$\Rightarrow \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}} = 0$$

$$\Rightarrow \sin\frac{t}{\sqrt{LC}} = 0 = \sin\pi$$

Expression of TRV and RRRV

$\therefore \boxed{t = \pi\sqrt{LC}}$ ⇒ is the time for TRV to attain peak value

$\therefore$ Peak value of TRV or e_m or $e_{peak} = E_m\left(1 - \cos\frac{\pi\sqrt{LC}}{\sqrt{LC}}\right)$

$$\boxed{e_m = 2E_m} \text{ —— (V)}$$

Now, Restriking Voltage, $e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$

where, E_m = Peak value of recovery voltage (V)

L = Line inductance (H)

C = Shunt capacitance (F)

t = Time (sec)

$\therefore$ Rate of rise of restriking voltage, $RRRV = \frac{de}{dt}$

$$RRRV = \frac{d}{dt}\left[E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)\right]$$

$$\boxed{RRRV = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}} \text{ —— (VI)}$$

Now, RRRV will be max when $\frac{d}{dt}\left[\frac{de}{dt}\right] = 0$ i.e. when derivative of RRRV will be zero.

$$\therefore \frac{d}{dt}\left[\frac{de}{dt}\right] = 0$$

$$\Rightarrow \frac{d}{dt}\left[\frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}\right] = 0$$

$$\Rightarrow \frac{E_m}{\sqrt{LC}}\frac{1}{\sqrt{LC}}\cos\frac{t}{\sqrt{LC}} = 0 = \cos\frac{\pi}{2}$$

$$\Rightarrow \frac{E_m}{LC}\cos\frac{t}{\sqrt{LC}} = \cos\frac{\pi}{2} = 0$$

$\Rightarrow \boxed{t = \frac{\pi}{2}\sqrt{LC}}$ is the time when RRRV will be maximum.

Expression of TRV and RRRV

$$\therefore (RRRV)_{max} = \frac{E_m}{\sqrt{LC}} \sin \frac{\frac{\pi}{2}\sqrt{LC}}{\sqrt{LC}}$$

$$(RRRV)_{max} = \frac{E_m}{\sqrt{LC}} \sin \frac{\pi}{2}$$

$$\boxed{(RRRV)_{max} = \frac{E_m}{\sqrt{LC}}}$$

\# Now, frequency of TRV $f_n = \frac{1}{2\pi\sqrt{LC}}$

$$\Rightarrow 2\pi f_n = \frac{1}{\sqrt{LC}}$$

Again, $(RRRV)_{max} = \frac{E_m}{\sqrt{LC}} = 2\pi f_n \, E_m$

i.e. $\boxed{(RRRV)_{max} \propto f_n.}$

$\Rightarrow$ where f_n is the frequency of transient.

$\rightarrow$ Maximum Rate of Rise of Restriking voltage is proportional to the natural frequency of the circuit.

Mathematical problem

Problem 01-

A 50 Hz 3ϕ alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to bus bar through a CB. The capacitance to earth between the alternator and the CB is 0.003μF per phase. The CB opens when r.m.s value of the current is 7500A.

Determine:

a) Frequency of oscillation
b) The expression of T.R.V
c) Maximum R.R.R.V.
d) Time for maximum R.R.R.V.
e) Maximum voltage across the contents of the CB after the instant when the arc extinction takes place.
f) Average rate of rise of voltage up to the first peak of the oscillation.

Mathematical problem

Solution:

a) $f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}$ Hz ≡ 72644 Hz

b) I= 7500A

ωL $=2\pi f \times 1.6\times10^{-3}$

E= IωL $=7500\times314\times1.6\times10^{-3} = 3768\, Volts\,(r.m.s)$

$$E_m = \sqrt{2}E = \sqrt{2}\times3768 = 5328\, Volts$$

$$Restriking\ Voltage, e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$= 5328 \times \left(1-\cos\frac{t}{\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}\right)$$

$$=5328 \times \left(1-\cos\frac{t}{2.2\times10^{-6}}\right.$$

Mathematical problem

c) $(R.R.R.V)_{max} = \frac{E_m}{\sqrt{LC}} = \frac{5328}{2.2\times10^{-6}}$

d) $Time\ for\ (R.R.R.V)_{max}, t = \frac{\pi}{2}\sqrt{LC} = 2.2 \times 10^{-6} \times \frac{3.14159}{2} = 3.45\ \mu sec$

e) $e_{max} = e_{peak} = 2\ E_m = 2 \times 5328\ V = 10.656\ kV$

f) $Avg. rate\ of\ rise = \frac{e_{peak}}{t}$ where t is the time to reach the e_{peak}

$$= \frac{e_{peak}}{\pi\sqrt{LC}} = \frac{10.656}{3.14\times2.2} = 1.543\ kv/\mu sec$$

Mathematical problem

Problem 02-

A 50 Hz, 66kV, 3ϕ generator has an earthed neutral. The inductance & capacitance per phase of the system are 7.5mH and 0.015μF respectively. In a short circuit test the p.f. of the fault current was 0.25 and the fault current was symmetrical and the recovery voltage was observed as 90% of the full line voltage. Calculate the rate of rise of restriking voltage (phase to neutral value). Assume that fault is isolated from the ground.

Mathematical problem

Solution:

$$V_{L-L} = 66\ KV$$

$$\therefore phase\ voltage = \frac{66}{\sqrt{3}} KV$$

$$\therefore peak\ recovery\ voltage = \frac{66}{\sqrt{3}} * \sqrt{2} = 54\ KV$$

$$Active\ recovery\ voltage = K_1 K_2 K_3 E_m \sin\theta$$

$$here, K_1 = demagnetisation\ factor = \frac{recovery\ voltage}{system\ voltage} = 90\% = 0.9$$

$$K_2 = \begin{Bmatrix} 1.5 \rightarrow when\ symmetrical\ fault\ is\ not\ grounded \\ 1 \rightarrow when\ symmetrical\ fault\ is\ grounded \end{Bmatrix}$$

$$K_3 = \begin{Bmatrix} 1 \rightarrow Active\ recovery\ voltage\ between\ phase\ and\ neutral \\ \sqrt{3} \rightarrow Active\ recovery\ voltage\ between\ two\ line \end{Bmatrix}$$

Mathematical problem

In this case, active recovery voltage, $E = 0.9 * 1.5 * 1 * \sin(\cos^{-1} 0.25) * 54\ KV$

$$= 70.58\ KV$$

$$\therefore Restriking\ voltage_{max} = 2 * 70.58$$

$$= 141.16\ KV$$

$$\therefore Rate\ of\ rise\ of\ restriking\ voltage = \frac{Restriking\ voltage_{max}}{\pi\sqrt{LC}}$$

$$= \frac{141.16}{33.3}\ KV/\mu s$$

- Reference-
- Topic 3.7,3.10/ Chapter 03/ Switchgear protection and power systems/Sunil S. Rao

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