problems

Example 9.1 : *In short circuit test on a 3 pole, 132 kV circuit breaker, the following observations are made p.f. of fault 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillations of restriking voltage 16 kHz. Assume neutral is grounded and fault is not grounded. Determine average RRRV.*

Solution :

$$e = V_{ar}\left[1 - \cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

where $V_{ar} = K_1 K_2 K_3 E_m$

K_1(takes into account p.f. effect) $= \sin\phi$

K_2 (takes into account armature reaction effect) ≈ 0.9

K_3 (Phase factor or 1st pole to clear factor)

$= 1$ for both neutral and fault grounded

$= 1.5$ for any one of the two not grounded.

In the problem,

$$K_1 = \sin\phi = \sin[\cos^{-1} 0.4] = 0.9165$$

$$K_2 = 0.9 \qquad K_3 = 1.5$$

Peak value of voltage i.e. line to ground

$$E_m = \frac{132}{\sqrt{3}} \times \sqrt{2} = 107.77 \text{ kV}$$

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

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

$$= 2\pi \times 16 \times 10^3$$

$$= 1 \times 10^5$$

Time to reach maximum restriking voltage

$$\text{Maximum } t_m = \pi\sqrt{LC} = \frac{\pi}{1 \times 10^5}$$

Maximum restriking voltage,

$$= 2\,V_{ar}$$

$$= 2\,K_1 K_2 K_3 E_m = 2 \times 0.9165 \times 0.9 \times 1.5 \times 107.77 \times 10^3$$

$$= 2.66682 \times 10^5 \text{ V}$$

Average RRRV,

$$\frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}} = \frac{2.66682 \times 10^5}{\pi / 1 \times 10^5}$$

$$= 8.48 \times 10^9 \text{ V/sec} = 8.48 \times 10^6 \text{ kV/sec} = 8.48 \text{ kV/}\mu\text{sec}$$

Example 9.2 : *In a short circuit test on a 130 kV, 3 phase system, the breaker gave the following results : p.f. of fault 0.45, recovery voltage 0.95 times full line voltage, breaker current symmetrical, and restriking transient had a natural frequency 16 kHz. Determine average RRRV. Assume fault is grounded.*

Solution :

$$E_m = \frac{\sqrt{2} \times 130}{\sqrt{3}} = 106.144 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m \qquad \text{where } K_1 = \sin\phi = 0.8930$$

$$= 0.8930 \times 0.95 \times 1 \times 106.144 \qquad K_2 = 0.95$$

$$= 90.047262 \text{ kV} \qquad K_3 = 1$$

$$\therefore \quad \text{Maximum e} = 2\, V_{ar} = 180.09452 \text{ kV}$$

$$\text{Maximum time} = \pi\sqrt{LC} \quad \text{and} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum t} = \frac{1}{2 f_n} = \frac{1}{2 \times 16 \times 10^3}$$

$$\therefore \quad \text{Average RRRV} = \frac{\text{Maximum e}}{\text{Maximum t}} = \frac{180.09452}{1/2 \times 16 \times 10^3}$$

$$= 5.76302 \text{ kV}/\mu\text{sec}$$

Example 9.3 : *Calculate the RRRV of 132 kV circuit breaker with neutral earthed. S.C. data as follows: Broken current is symmetrical, restriking voltage has frequency 20 kHz, p.f. 0.15. Assume fault is also earthed.*

Solution :

$$K_1 = \sin\phi = \sin(\cos^{-1} 0.15) = 0.9886$$

$$K_2 = 1$$

$$K_3 = 1 \qquad \text{both grounded}$$

$$E_m = \frac{\sqrt{2} \times 132}{\sqrt{3}} = 107.77755 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m$$

$$= 106.54889 \text{ kV}$$

$$\therefore \quad \text{Maximum e} = 2\, V_{ar}$$

$$= 213.09778 \text{ kV}$$

$$t_m = \pi\sqrt{LC}$$

and

$$f_n = \frac{1}{2\pi\sqrt{LC}} \qquad \therefore \quad \pi\sqrt{LC} = t_m = \frac{1}{2 f_n} \text{ sec}$$

$$\therefore \quad \text{Maximum } t_m = \frac{1}{2 \times 20 \times 10^3} \text{ sec}$$

$$\therefore \quad \text{RRRV} = \frac{e_{max}}{t_{max}} = \frac{213.09778}{[1/(20 \times 10^3 \times 2)]}$$

$$= 8.52 \text{ kV}/\mu\text{sec}$$

Example 9.4 : *A 50 Hz generator has e.m.f. to neutral 7.5 kV (r.m.s.). The reactance of generator and the connected system is 4 Ω and distributed capacitance to neutral is 0.01 μF with resistance negligible . Find,*

i) maximum voltage across the circuit breaker contacts

ii) frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Solution :

$$X = 2\pi fL = 4\,\Omega$$

$$L = 4 / 2\pi \times 50 = 0.0127 \text{ H.}$$

$$E_m = \sqrt{2} \times 7.5 = 10.606 \text{ kV}$$

1) Maximum voltage $= 2 \times E_m$

$$= 2 \times 10.606 = 21.212 \text{ kV}$$

2)

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0127 \times 0.01 \times 10^{-6}}}$$

$$= 14.1227 \text{ kHz}$$

3) Maximum time to reach maximum voltage is,

$$t_m = \pi\sqrt{LC} = \frac{1}{2f_n} = \frac{1}{2 \times 14.1227 \times 10^3} \text{ sec}$$

$$\therefore \quad \text{Average RRRV} = \frac{\text{Maximum voltage}}{t_m}$$

$$= \frac{21.212}{[1/(2 \times 14.1227 \times 10^3)]}$$

$$= 0.599 \text{ kV}/\mu\text{ sec}$$

Example 9.5 : *In a system having 220 kV, the line to ground capacitance 0.015 μF, inductance 3.5 H. Determine voltage appearing across pole of circuit breaker if a magnetising current of 6.5 A instantaneous, is interrupted. Determine also the value of resistance to be used across the contacts to eliminate the restriking voltage.*

Solution :

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

$$\frac{1}{2} L\, i^2 = \frac{1}{2} C\, e^2$$

Energy stored in 'L' = energy given to capacitor

$$\therefore \quad e = i\sqrt{L/C} \qquad \text{where } i = \text{instantaneous value}$$

$$= 6.5\sqrt{\frac{3.5}{(0.015 \times 10^{-6})}}$$

$$= 99.3 \text{ kV}$$

To eliminate restriking voltage and critical damping condition,

$$R = 0.5\sqrt{L/C}$$

$$= 0.5\sqrt{\frac{3.5}{(0.015 \times 10^{-6})}} = 7.635 \text{ k}\Omega$$

Example 9.6 : *A 50 Hz, 3 ph alternator, has rated voltage 13.5 kV, connected to circuit breaker, inductive reactance 4 Ω/ph, C = 2 μF.*
Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

Solution :

$$E_m = \frac{\sqrt{2} \times 13.5}{\sqrt{3}} = 11.0227 \text{ kV}$$

$$X = 2\pi f L \qquad \therefore L = 0.0127323 \text{ H and } C = 2 \mu\text{F}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = 0.997 \text{ kHz}$$

$$\text{Maximum restriking voltage} = 2 E_m = 22.0454 \text{ kV}$$

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

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}} \quad \text{This is the expression of RRRV}$$

$$\therefore \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \quad \text{and} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum RRRV} = 2\pi f_n E_m$$

$$= \pi \times 0.997 \times 10^3 \times 22.0454 \text{ kV/sec}$$

$$= 0.06907 \text{ kV/}\mu\text{sec}$$

Example 9.7 : *In 132 kV transmission system, the phase to ground capacitance is 0.01 μF. The inductance being 6 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetizing current of 10 A is interrupted. Find the value of resistance to be used across contact space to eliminate the striking voltage transient.*

Solution :

$$L = 6 \text{ H}$$

$$C = 0.01 \mu\text{F} = 0.01 \times 10^{-6} \text{ F}$$

$$i = 10 \text{ A}$$

Voltage appearing across poles of circuit breaker, is given by,

$$V = i\sqrt{\frac{L}{C}}$$

$$= 10\sqrt{\frac{6}{0.01 \times 10^{-6}}}$$

$$= 10 \ (24494.89)$$

$$\therefore \quad V = 245 \text{ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= \frac{1}{2}\sqrt{\frac{6}{0.01 \times 10^{-6}}}$$

$$= \frac{1}{2} (24494.89)$$

$$\therefore \quad R = 12.24 \text{ k}\Omega$$

Example 9.8 : *A 50 cycles, 3 phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit breaker. The capacitance to earth between the alternator and circuit breaker is 0.003 μF per phase. The circuit breaker opens when rms value of current is 7500 A. Determine the following:*

i) Maximum rate of rise of restriking voltage.

ii) Time for maximum rate of rise of restriking voltage.

iii) Frequency of oscillations

Neglect first pole to clear factor.

Solution :

i = 7500 A, L = 1.6 mH, C = 0.003 μF

$$X_L = 2\pi f L = 2\pi \times 50 \times 1.6 \times 10^{-3} = 0.50265\ \Omega$$

Peak value of active recovery voltage (Phase to neutral) i.e.

$$E_m = (i \times X_L) \times \sqrt{2} = (7500 \times 0.50265) \times \sqrt{2}$$

$$= 5331.4083\ V$$

$$f_n = \text{frequency of oscillations} = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}$$

$$= 72643.96\ Hz$$

Maximum RRRV $= 2\pi f_n E_m = 2\pi \times 72643.96 \times 5331.4083$

$$= 2433443822\ V/sec$$

$$= 2433.4438\ V/\mu sec$$

Time for maximum RRRV

$$= \frac{\pi\sqrt{LC}}{2}$$

$$= 3.4414\ \mu sec$$

Example 9.9 : *In a short circuit test on a 132 kV, 3-phase system the breaker gave the following results p.f. of the fault 0.4, recovery voltage 0.95 of full line value, breaking current is symmetrical and the restriking transient had a natural frequency of 16 kHz. Determine RRRV assuming that the fault is grounded.* **[AU-May-2004]**

Solution :

$$E_m = \frac{\sqrt{2}\times132}{\sqrt{3}} = 107.77\ kV$$

$$V_{ar} = K_1 K_2 K_3 E_m, \quad \text{where } K_1 = \sin\phi$$

Here $\phi = \cos^{-1} 0.4 = 66.42°$

$\therefore$ $K_1 = \sin(66.42°) = 0.9165$

$K_2 = 0.95$

$K_3 = 1$

$\therefore$ $V_{ar} = (0.9165)(0.95)(1)(107.77) = 93.83\ kV$

$\therefore$ Maximum $e = 2V_{ar} = 2(93.83) = 187.66\ kV$

Maximum time $= \pi\sqrt{LC}$, $\quad f_n = \frac{1}{2\pi\sqrt{LC}}$

$\therefore$ Maximum $t = \frac{1}{2 f_n} = \frac{1}{2\times16\times10^3} = 3.125\times10^{-5}$ sec

Average RRRV $= \frac{\text{Maximum e}}{\text{Maximum t}} = \frac{187.66}{3.125\times10^{-5}} = 6.0051 \approx$ **6 kV/μsec.**

Example 9.10 : *What is the prospective voltage e across the stray capacitance of 0.0023 μF, when the instantaneous current chopped by circuit breaker is 7 A. The value of the inductance in the circuit is 35.2 H ?* **[AU, Dec.-2004]**

Solution : Prospective voltage appearing across C.B. is given by,

$$e = i\sqrt{\frac{L}{C}}$$

$$L = 35.2 \text{ H}$$

$$C = 0.0023 \ \mu F = 0.0023 \times 10^{-6} \text{ F}$$

$$i = 7 \text{ A}$$

$$\therefore \quad e = 7\sqrt{\frac{35.2}{0.0023 \times 10^{-6}}}$$

$$= 7(123710.74)$$

$$\therefore \quad e = \mathbf{865.97 \ kV}$$

Example 9.11 : *A circuit breaker is rated at 1200 A, 1500 MVA, 33 kV, 3 sec, 3-phase. What are its rated breaking current and making current ?* **[AU, Dec.-2004]**

Solution :

$$\text{Rated symmetrical breaking current (rms)} = \frac{MVA}{\sqrt{3} \times kV}$$

$$= \frac{1500 \times 10^6}{\sqrt{3} \times 33 \times 10^3}$$

$$= \mathbf{26.24 \ kA}$$

$$\text{Rated making current} = 2.55 \times 26.24$$

$$= 66.92 \text{ kA}$$

Short time rating = **26.24 kA for 3 sec.**

Example 9.12 : *A 3-phase alternator has the line voltage of 11 kV. The generator is connected to a circuit breaker. The inductive reactance upto the circuit breaker is 5 Ω / phase. The distributed capacitance upto circuit breaker between phase and neutral is 0.001 μF. Determine peak restriking voltage across the CB, frequency of restriking voltage transients, average rate of restriking voltage upto peak restriking voltage, maximum RRRV.* **[AU, Dec.-2004]**

Solution :

$$E_m = \frac{\sqrt{2} \times 11}{\sqrt{3}} = 8.98 \text{ kV}$$

$$X = 2 \pi f L$$

$$L = \frac{X}{2\pi f} = \frac{5}{2\pi(50)} = 0.01591 \text{ H}$$

$$C = 0.001 \ \mu F$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(0.01591)(0.001 \times 10^{-6})}} = \mathbf{39901.11 \ Hz.}$$

Maximum restriking voltage = $2 E_m = 2(8.98) = 17.96$ kV

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

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin\frac{t}{LC}$$

This is the expression of RRRV

$$\therefore \quad \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} = \frac{8.98}{\sqrt{(0.01591)(0.001 \times 10^{-6})}}$$

Example 9.13 : *In a system of 132 kV, the circuit phase to ground capacitance is 0.02 microfarad, the inductance is 5H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetic circuit of 8 A is interrupted instantaneously. Calculate the value of the pre-insertion resistor to be used across the contact space.* **[AU, May-2005]**

Solution : $L = 5$ H, $C = 0.02\ \mu F = 0.02 \times 10^{-6}$ F

$i = 8$ A

Voltage appearing across poles of circuit breaker is given by,

$$V = i\sqrt{\frac{L}{C}} = 8\sqrt{\frac{5}{0.02 \times 10^{-6}}} = 8\sqrt{250 \times 10^{6}}$$

$$\therefore \quad \mathbf{V = 126.491\ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= \frac{1}{2}\sqrt{\frac{5}{0.02 \times 10^{-6}}}$$

$$= \frac{1}{2}(\sqrt{250 \times 10^{6}})$$

$$\therefore \quad \mathbf{R = 7.9056\ k\Omega}$$

Example 9.14 : *In a short circuit test on a circuit breaker the following readings were observed on a single frequency transient time to reach the peak recovery voltage 40 μsec and the peak restriking voltage 100 kV. Determine the average RRRV and the frequency of oscillations.* **[AU, May-2005]**

Solution : Average RRRV is given as,

$$\text{Average RRRV} = \frac{\text{Peak restriking voltage } (E_m)}{\text{Time to reach the peak } (t_m)}$$

$$= \frac{100 \times 10^{3}}{40} = 2500$$

$$\therefore \quad \textbf{Average RRRV = 2500 V/μsec}$$

Natural frequency f_n is given by,

$$f_n = \frac{1}{2 \cdot t_m} = \frac{1}{2(40 \times 10^{-6})}$$

$$= \frac{1}{80 \times 10^{-6}} = 12500 \text{ Hz}$$

$$\therefore \quad \mathbf{f_n = 12.5\ kHz.}$$