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Circuit Breaker Performance Analysis

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Abstract:- The problem of circuit breaking becomes complicated when voltages and currents in the range of kilovolt and kiloampere are involved. Circuit breaker (CB) is used in performing switching operations, and is a switch that can open live circuits. Circuit breakers are especially important in protective schemes where they have to interrupt fault currents, and isolate faulty section of the network. When the circuit breaker opens under fault condition many thousands of amperes pass through the contacts and the extinction of the arc and hence effective opening of the contacts of the CB are major engineering problems. When a circuit breaker opens, a high-frequency voltage, superimposed on the normal system voltage appears across the CB contacts. This voltage is known as transient recovery voltage (TRV) or restriking voltage, constituting a switching surge. Restriking delays arc quenching, and so it is detrimental to the circuit breaker as well as the entire system, since fault clearing may be delayed. This paper shows how resistance switching can be used to damp this surge and enable the CB to open before the magnitude of the voltage across the CB contacts reaches peak level, to prevent possible restriking of the arc.

Keyword:- *circuit breaker, arc, transient recovery voltage, restriking, resistance switching.*

I. INTRODUCTION

The circuit breaker is a major component of a protective scheme. The function of a circuit breaker is to provide switching and overcurrent protection functions - the dual functions of disconnect switch and short-circuit protection [1], [2]. They are to protect phase conductors downstream from damage due to current in excess of their ratings [3]. It is a mechanical device capable of breaking and reclosing a circuit under all conditions, including when the system is faulted and currents are at their greatest values. The forces needed to pull apart heavy contacts quickly are enormous and the energy required for this action is usually stored in springs or in compressed air tanks. The energy used in the interruption is $\int v(t)i(t)dt$ over the duration of interruption [4], [5]. A CB receives a signal from protective relay whenever fault clearance is necessary. Fig. 1 shows a synchronous generator under 3-phase short-circuit fault, and a CB to interrupt the fault current.

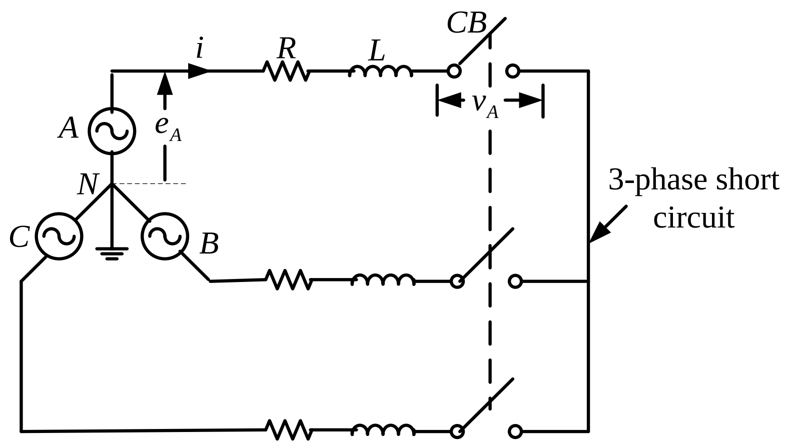

Fig 1:- Three-phase short-circuits and circuit breaking

The selection of a circuit breaker for a power system depends on the current the CB has to carry under normal operating conditions, and the maximum current it may have to carry momentarily when conditions are abnormal, as well as the current it may have to interrupt at the voltage of the line in which it is placed. The armature winding of a synchronous generator has resistance and inductance. Hence the current flowing when a generator is short-circuited is similar to that flowing when an alternating voltage is suddenly applied to a resistance and an inductance in series [6]. The applied voltage is given as:

$$e_A = V_m \sin(\omega t + \alpha) \qquad (1)$$

It is assumed that, the short-circuit occurs at time, $t = 0$ and so α determines the magnitude of the voltage at the occurrence of short-circuit. The waveform of the voltage is as shown in Fig. 2.

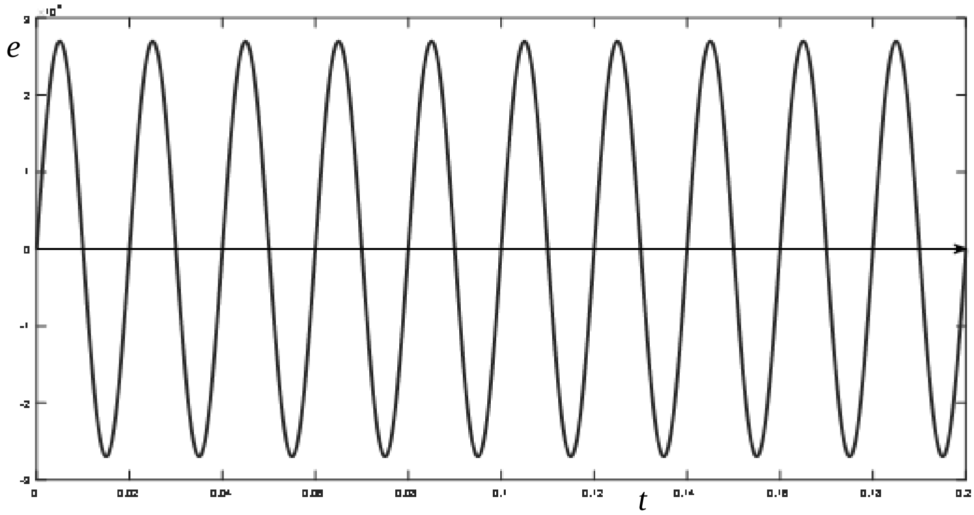

Fig 2:- System voltage

In per phase value, the differential equation relating the supply voltage and short-circuit current is:

$$Ri + L\frac{di}{dt} = V_m \sin(\omega t + \alpha) \quad (2)$$

The solution of equation (2) is:

$$i = \frac{V_m}{|Z|}\left[\sin(\omega t + \alpha - \theta) - e^{-\frac{R}{L}t}\sin(\alpha - \theta)\right] \quad (3)$$

Where $|Z| = \sqrt{R^2 + (\omega L)^2}$ and $\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$

Equation (3) is the current immediately after the fault occurs. It is called the **momentary current -** the maximum instantaneous current that the CB must carry without damage. It is the value of current whose disruptive force the breaker must withstand during the first half-cycle after the occurrence of fault. The short-circuit current is shown in Fig. 3.

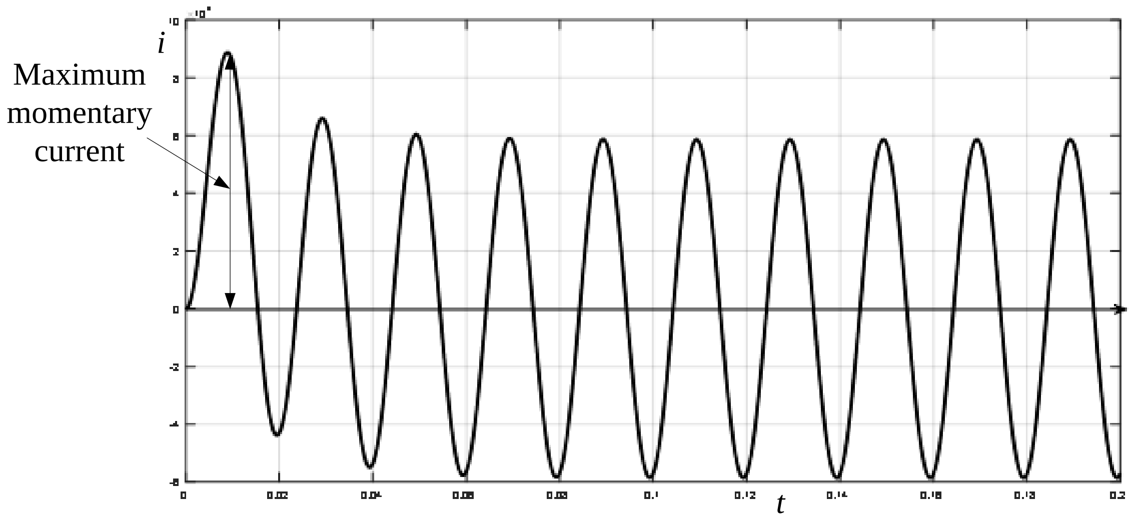

Fig. 3 Short-circuit current

It can be seen that the maximum momentary short-circuit current corresponds to the first peak. The short-circuit current comprises of two components: the ac symmetrical short-circuit current given by:

$$i_{ac} = \frac{V_m}{|Z|} \sin(\omega t + \alpha - \theta) \tag{4}$$

This is shown in Fig. 4

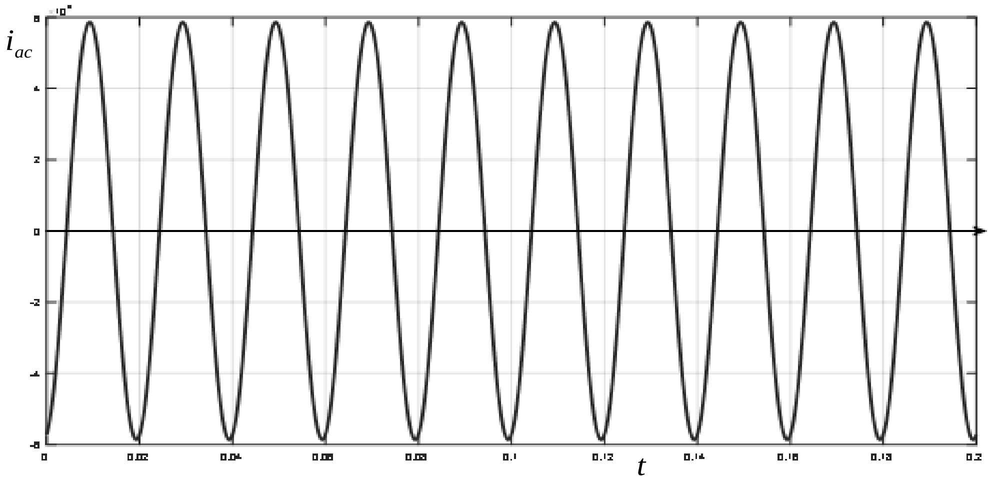

Fig 4:- ac symmetrical short-circuit current

The dc component current given by:

$$i_d = \frac{V_m}{|Z|} e^{-\frac{R}{L}t} \sin(\alpha - \theta) \tag{5}$$

It decays exponentially with time constant L/R. This is shown in Fig. 5

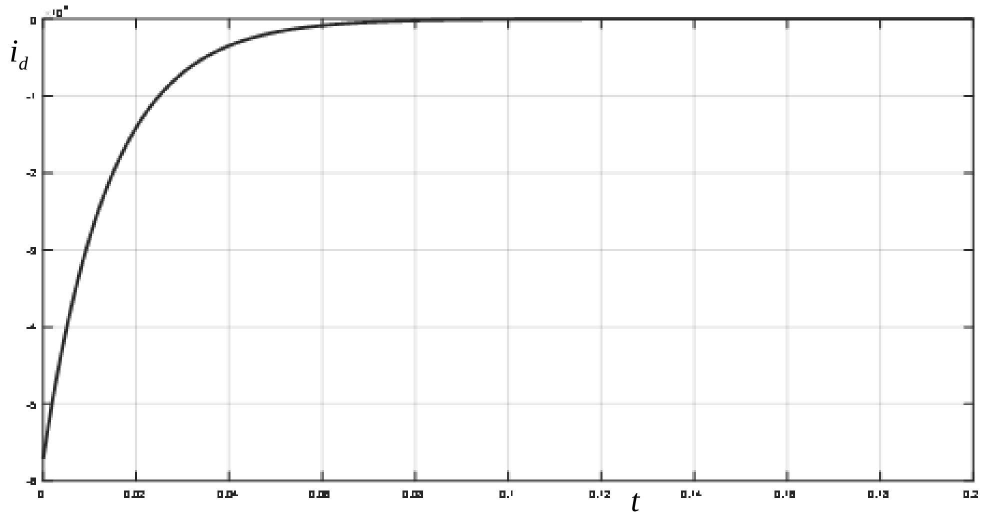

Fig 5:- Waveform of dc component of short-circuit current

After a fault occurs, the short-circuit current has decreasing magnitudes – subtransient, transient, and steady-state values. Excluding the dc component, we have the initial symmetrical short-circuit current, i_{ac} given by equation (4), and shown in Fig. 4. It is the ac component, and varies sinusoidally with time. Multiplying i_{ac} by 1.6 gives the momentary current. Multiplication by 1.6 takes care of the dc component [6]. In a large interconnected power system, heavy currents flowing during a fault must be interrupted well before the steady-state conditions are established. The **interrupting** current is thus higher than the symmetrical short-circuit current, but lower than the momentary current and depends on the speed of the CB. To allow for the dc component of the fault current, the symmetrical short-circuit current is modified by multiplying factors, such as the following: For 8-cycle CB opening time i_{ac} is multiplied by 1; for 3-cycle CB opening time, i_{ac} is multiplied by 1.2; and for 2-cycle CB opening time, i_{ac} is multiplied by 1.4 [7]. Thus, for CB opening time less than 8 cycles, the current, which a breaker must interrupt, is usually asymmetrical since it still contains some of the decaying dc component. Rating of CBs is given in terms the symmetrical short-circuit current. It is properly called rated symmetrical short-circuit current or simply, rated short-circuit current. The interrupting current take into account the dc component of the short-circuit current by multiplying the symmetrical short-circuit current by the aforementioned factors. Thus, the interrupting current is the total current when the CB contacts part to interrupt the circuit and it depends on the speed of the breaker, such as 8, 5, 3, or 2 cycles. The speed of the circuit breaker is a measure of the time from the occurrence of the fault to the extinction of the arc. The rated interrupting time of a CB is the period between the instant of energizing the trip circuit and the arc extinction on an opening operation. This period is preceded by the tripping delay time, which is usually assumed to be half cycle for relay to pick up.

II. SELECTION OF CIRCUIT BREAKERS

Manufacturing standards for high-voltage power circuit breakers are created primarily for the purpose of setting performance criteria of manufactured products. These performance criteria can also help users anticipate the need for refurbishment or replacement, especially if a history of significant in-service events, maintenance testing, and maintenance inspections have been kept [8]. Since the peak value of the short-circuit current is also related to the dc component, it is important to calculate it and to specify that the bracing of all electrical equipment is equal to or greater than this peak value. Circuit breakers are identified by the following ratings [5], [9], [10]:

- Nominal voltage- the breaker must be used in systems where the rms line voltage is not greater than this nominal value.
- Maximum voltage – This is the highest rms line voltage for which the CB is designed.

- Voltage range factor,

$$K = \frac{Rated \max imum\, voltage}{The\, lower \lim it\; of\; the\, range\, of\; operating\; voltage}$$

K determines the range of voltage over which the product:

$$rated\ short - circuit\ current\ x\ operating\ voltage$$

is a constant.

- Continuous current – Maximum continuous rms current the breaker can carry without exceeding the allowable temperature.
- Momentary current – Maximum rms asymmetrical short-circuit current that the breaker can withstand without damage. This is 1.6 times the interrupting rating.
- Interrupting rating – Maximum rms symmetrical short-circuit current that the CB can safely interrupt.
- Interrupting time – the period between the instant of energizing the trip circuit and the arc extinction.

In order to be selectively coordinated, distribution systems may require the application of circuit breakers with short-time-delay trip elements and no instantaneous trip element. A device with short-time current ratings can safely remain closed for a specified time interval under high fault conditions [11].

Ultimately, from current viewpoint two factors to be considered in the selection of circuit breakers are the momentary current, and the interrupting current. In selecting a CB, the maximum interrupting current must not be exceeded. This is given by:

Maximum interrupting current = K x rated symmetrical short-circuit current

The interrupting current is given by the symmetrical short-circuit current multiplied by α .

Interrupting current = $\alpha\ x$ rated symmetrical short-circuit current

Where

$$\alpha = \frac{rated \max imum\, voltage}{operating\ voltage}$$

Multiplying by α accounts for the dc component of the short-circuit current.

To specify a CB to be connected at a certain point in the utility, the symmetrical short-circuit current is computed, using subtransient reactances for synchronous generators and transient reactances for synchronous motors. Induction motors below 50 hp are neglected, and various multiplying factors are applied to the subtransient reactance of larger induction motors depending on their size. The electric power company normally informs the customer of the short-circuit megavoltamperes that can be expected at the point of connection, and is given as:

$$\sqrt{3}\, x \left(kV_b\right) x \left|I_b\right| x 10^{-3}$$

Short-circuit MVA = $\sqrt{3}\ x\,(\text{nominal kV})\, x \left|I_{SC}\right| x 10^{-3}$ (6)

I_{SC} in amperes is the rms magnitude of the short-circuit current in a three-phase fault at the connection point.

Base MVA = $\sqrt{3}\ x\,(\text{base kV})\, x \left|I_b\right| x 10^{-3}$ (7)

If base kV equals nominal kV,

Short-circuit MVA per unit =

$$\frac{Short - circuit\ MVA}{Base\ MVA} = \left|I_{SC}\right| \text{per unit} \quad (8)$$

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$$|Z_{TH}| = \frac{1.0}{|I_{SC}|} \text{ per unit} = \frac{1.0}{Short - circuit\ MVA} \text{ per unit}$$

(9)

Where $|Z_{TH}|$ and the emf, $1.0\angle 0^o$ make up the Thevenin equivalent circuit looking back into the system from the point of connection, at nominal voltage.

$Z_{TH} = X_{TH}$, since resistance and shunt capacitance are usually neglected.

III. INTERRUPTION OF SHORT-CIRCUIT CURRENT

The heavy interrupting current is sensed by the protective relaying, which sends signal to energize the trip circuit of the CB, causing the moving contacts to separate from the fixed contact at high speed, say within a few milliseconds [3], [12]. This requires major engineering effort. As a circuit breaker senses the short circuit and begins to open the circuit, an arc will form between the fixed and moving contacts. An arc is defined as "a continuous luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes" [13], [14]. As the CB contacts part, large voltage gradient appears between them. This voltage gradient will cause ionization of the gas between the contacts surfaces, making it a gaseous conductor; current flow will continue, heating up the conduction path to extremely high temperatures with the radiation of intense heat and light known as electrical arc. Ionization of gas in this conduction path will be sustained by the heat generated, complicating .the interruption of current flow. The heat can also damage the CB. In large power systems, electric and magnetic fields effects cause switching transients close to the megavolt and kilo amperes range to be encountered. These provide enormous amounts of power for the creation of electrical arcs. Power interrupting devices must cope with these arcs, allowing for their formation and subsequent extinction. So, opening of a CB is followed by arc formation, which has to be extinguished in a very short time in the arc quenching chamber. The arc is elongated, cooled, and finally extinguished as it goes through a natural current zero. The arc can be quenched by air (air blast CB), oil (oil CB), sulphur hexafluoride (SF_6 CB), and magnetic field (magnetic blowout CB). When the arc between the CB contacts is extinguished, voltage known as transient recovery voltage (TRV) suddenly appears across the open gaps. This recovery voltage comprises of the system full voltage and a high-frequency voltage due to the generator inductance and stray capacitance – resulting in high frequency oscillations [7]. The single-phase equivalent circuit of the system is shown in Fig. 6. The TRV appears across the $R-L-C$ circuit, and across the CB contacts.

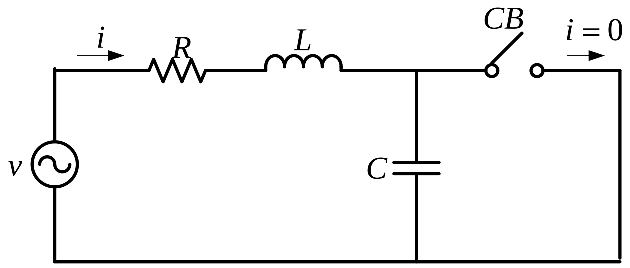

Fig 6:- System diagram

From Fig. 6:

$$Ri + L\frac{di}{dt} + v_C = v \qquad (10)$$

v_C is the capacitor voltage, and $v = V_m \cos \omega t$

v is assumed to remain constant at its instantaneous value of V_m when the CB opens at $t = 0$, and $i = 0$.

$$RC\frac{dv_C}{dt} + LC\frac{d^2 v_C}{dt^2} + v_C = V_m \qquad (11)$$

$$\frac{d^2 v_C}{dt^2} + \frac{R}{L}\frac{dv_C}{dt} + \frac{v_C}{LC} = \frac{V_m}{LC} \qquad (12)$$

Applying Laplace Transform we have:

$$s^2 V_C(s) + s\frac{R}{L}V_C(s) + \frac{1}{LC}V_C(s) = \frac{1}{LC}\frac{V_m}{s} \qquad (13)$$

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$$V_C(s)=\frac{V_m\omega_o^2}{s\left(s^2+s\frac{R}{L}+\omega_o^2\right)} \tag{14}$$

Where $\omega_o^2=\frac{1}{LC}$

In partial fraction, equation (10) becomes:

$$V_C(s)=V_m\omega_o^2\left[\frac{A}{s}+\frac{B}{s+\alpha-j\beta}+\frac{C}{s+\alpha+j\beta}\right] \tag{15}$$

$$v_C(t)=V_m\omega_o^2\left[A+Be^{-(\alpha-j\beta)t}+Ce^{-(\alpha+j\beta)t}\right] \tag{16}$$

Where

$$A=\frac{1}{\alpha^2+\beta^2};\ B=\frac{1}{-2\beta^2-j2\alpha\beta};\ C=\frac{1}{-2\beta^2+j2\alpha\beta};\ \alpha=\frac{R}{2L};\quad \beta=\frac{R}{j2L}\sqrt{1-\frac{4\omega_o^2L^2}{R^2}}$$

Equation (16) is a high-frequency voltage, as shown in Fig. 7, where the system voltage, $V=33kV$ (line-to-line), $V_m=\sqrt{2}V$, $R=1.2\Omega$, $L=10mH$, $C=0.05\mu F$, $f=50Hz$. The natural frequency of oscillation is:

$$f_n=\frac{1}{2\pi\sqrt{LC}} \tag{17}$$

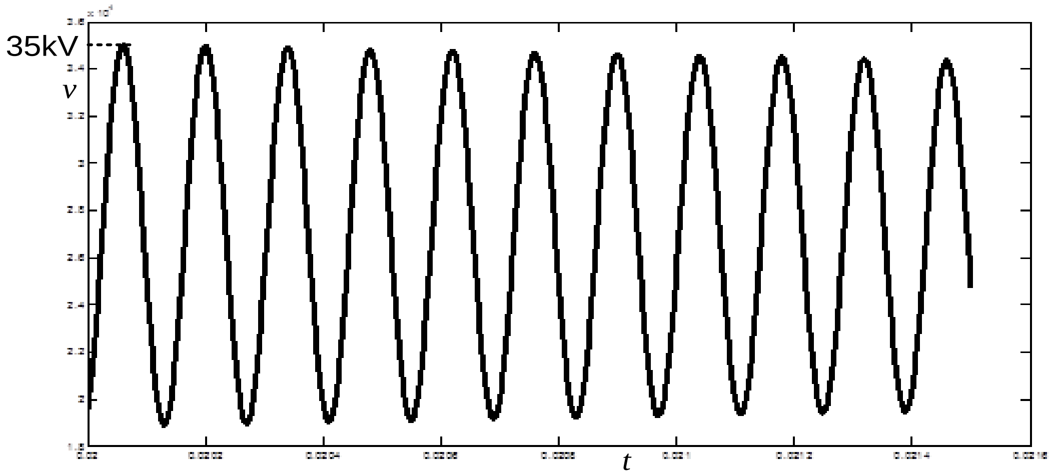

Fig 7:- High-frequency voltage

Fig. 7 shows that the line-to-line voltage across the breaker poles on fault interruption has risen to 60.6 kV. Differentiating equation (12) gives the rate of rise (RR) of this voltage. Thus:

$$RR=\frac{dv_c(t)}{dt}=V_m\omega_o^2\left[-(\alpha-j\beta)Be^{-(\alpha-j\beta)t}-(\alpha+j\beta)Ce^{-(\alpha+j\beta)t}\right] \tag{18}$$

The maximum rate of rise of this voltage is 364V/µs. Often, the resistance of lines is negligible compared with reactance. Therefore, neglecting *R*, the maximum value of this voltage is equal to $2V_m$, as shown in Fig. 8. In this case, the line-to-line voltage across the CB contacts is 93.5 kV, and the maximum value of rate of rise is 1211V/µs.

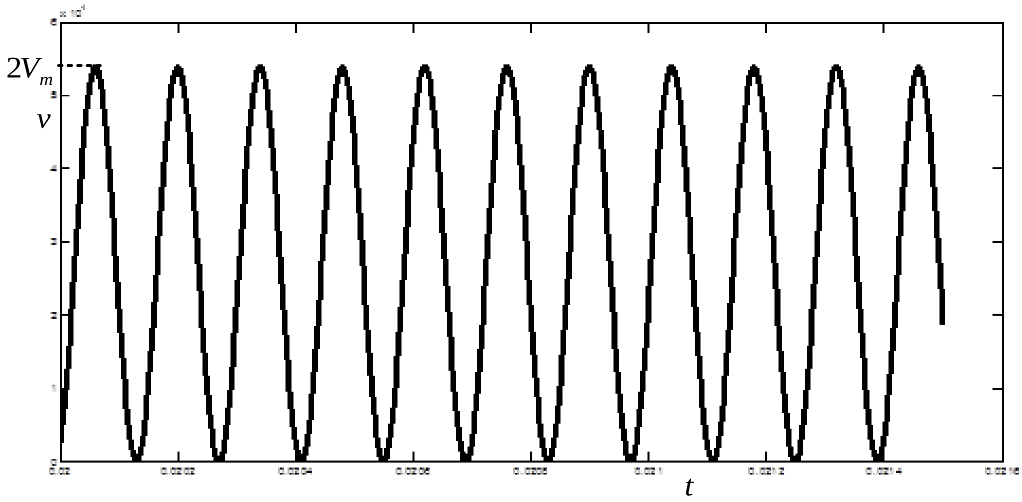

Fig 8:- High-frequency voltage, *R* neglected

This voltage superimposed on the normal system voltage is known as the transient recovery voltage (TRV) which appears across the CB contacts at the time of opening. This is shown in Fig. 9. The maximum value of the fault current is 6237A.

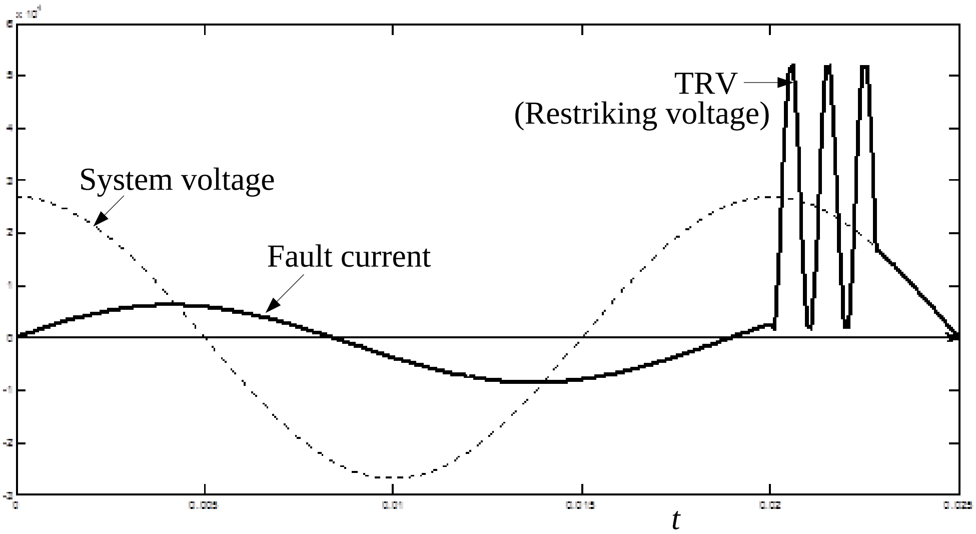

Fig 9:- Waveforms of voltage and current of the system on fault interruption.

The transient recovery voltage constitutes a switching surge and tends to restrike the arc and prevent the opening of the CB until the next current zero. Restriking occurs if the value of the dielectric strength of the contact space is not enough to withstand the potential gradient across it. This is detrimental to the CB since it can damage the poles, and also delay fault clearance in the system. The rate of rise of the surge must be limited so that the CB can open before the surge reaches maximum value, in order to prevent retriking.

IV. RESISTANCE SWITCHING

A resistor connected across the contacts of the CB, will damp the oscillation and reduce the severity of the transient at the time of opening the CB. Fig. 10 shows a resistor connected in parallel with the poles of the circuit breaker. The resistance is switched into the circuit automatically by closing of the auxiliary resistor break before the main break opens. Resistance switching lowers the current to be broken and raises the power factor so that the voltage is not at peak value at opening. It opens after the main break.

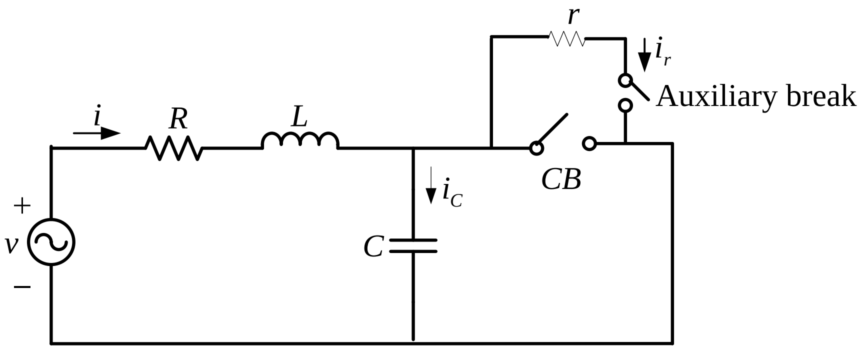

Fig 10:- Resistance switching

From Fig. 10 we form the equations:

$$Ri + L\frac{di}{dt} + \frac{1}{C}\int\left(i_C - i_r\right)dt = v \tag{19}$$

$$ri_r + \frac{1}{C}\int\left(i_r - i_C\right)dt = 0 \tag{20}$$

$$i = i_C + i_r \tag{21}$$

$$ri_r = \frac{1}{C}\int i_C\,dt \tag{22}$$

Summing equations (14) and (15) results in:

$$L\frac{di}{dt} + Ri + ri_r = v \tag{23}$$

Substituting (17) and (18) into (20) gives:

$$L\frac{di_C}{dt} + \left(\frac{R+r}{rC}\right)\int i_C\,dt + \left(\frac{rRC+L}{rC}\right)i_C = V_m \tag{24}$$

Neglecting *R*, we have:

$$L\frac{di_C}{dt} + \left(\frac{1}{C}\right)\int i_C\,dt + \left(\frac{L}{rC}\right)i_C = V_m \tag{25}$$

Applying Laplace Transform to (22)

$$sLI_C(s) + \frac{1}{sC}I_C(s) + \frac{L}{rC}I_C(s) = \frac{V_m}{s} \tag{26}$$

$$I_C(s) = \frac{V_m}{L}\left[\frac{1}{s^2 + \frac{1}{rC}s + \frac{1}{LC}}\right] \tag{27}$$

$$V_C(s)=\frac{I_C(s)}{sC}=V_m\left[\frac{\omega_o^2}{s\left(s^2+\frac{1}{rC}s+\omega_o^2\right)}\right] \tag{28}$$

$$V_C(s)=V_m\omega_o^2\left[\frac{A}{s}+\frac{B}{s+\alpha-j\beta}+\frac{C}{s+\alpha+j\beta}\right] \tag{29}$$

$$v_C(t)=V_m\omega_o^2\left[A+Be^{-(\alpha-j\beta)t}+Ce^{-(\alpha+j\beta)t}\right] \tag{30}$$

Where

$$A=\frac{1}{\alpha^2+\beta^2};\ B=\frac{1}{-2\beta^2-j2\alpha\beta};\ C=\frac{1}{-2\beta^2+j2\alpha\beta};\ \alpha=\frac{1}{2rC};\ \ \beta=\frac{1}{j2rC}\sqrt{1-4r^2C^2\omega_o^2}$$

With resistance switching, equation (30) is the voltage that appears across the CB contacts on fault interruption. This is shown in Fig. 11 for various values of *r*. The maximum value of this voltage is equal to V_m. Differentiating equation (30), we have:

$$RR=\frac{dv_C(t)}{dt}=V_m\omega_o^2\left[-(\alpha-j\beta)Be^{-(\alpha-j\beta)t}-(\alpha+j\beta)Ce^{-(\alpha+j\beta)t}\right] \tag{31}$$

It can be observed that the rate of rise (RR) of this voltage decreases with decrease in *r*. For example, for $r=100\Omega$, RR = 240V/µs, while for $r=10\Omega$, RR=27V/µs. Consequently, the CB can be opened before peak voltage is reached. In addition, the current to be broken decreases as the magnitude of *r* decreases. Hence, the value of the resistance *r* controls the voltage across the CB contacts, and the breaking current.

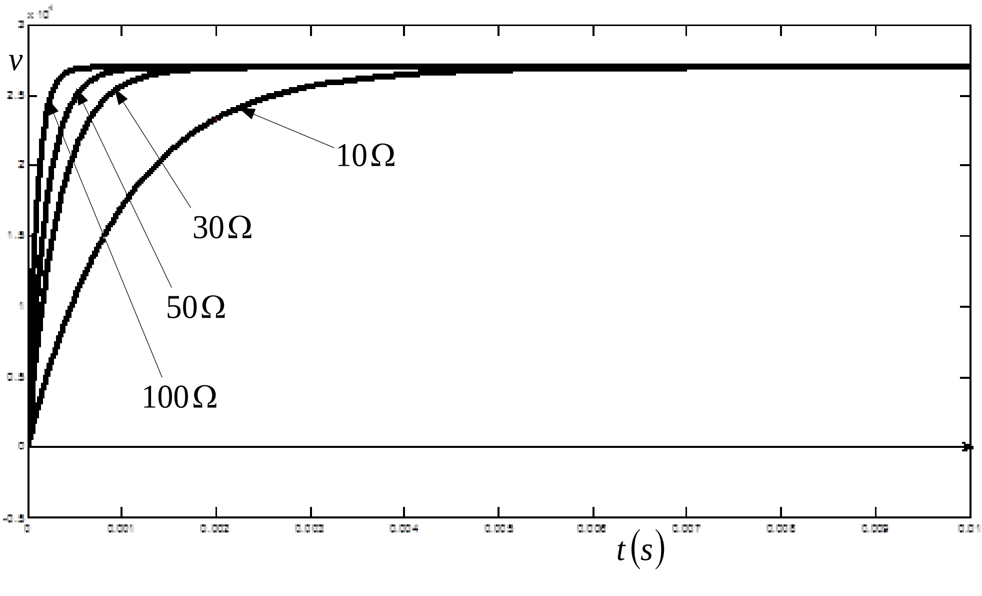

Fig 11:- TRV for resistance switching

V. CONCLUSION

This paper shows the formation of high-frequency voltage surge across the contacts of a circuit breaker as they part. This surge can restrike, and delay the opening of the CB, leading to some dire consequences. The CB could be damaged, and the whole system could suffer from sustained fault. It has been shown that, with resistance switching, this surge will be greatly attenuated. Voltage will not be at its peak value at opening. The less the value of resistance r, the lower the voltage at opening since the rate of rise of voltage becomes less. The current to be broken will also be lowered, while the power factor is raised. Eventually, the CB poles are safeguarded, and speedy clearance of fault ensured.

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