Effect of Interrupted Current Magnitude on the Arc Produced in Medium and High Voltage Systems

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Abstract – **Interrupted current magnitude is the key parameter for arc production in medium and high voltage systems. The magnitude of the arc developed across a gap depends on the magnitude of the interrupted current. This means that keeping the anticipated arc to a low value can be achieved by reducing the anticipated interrupted current. The significance of this study is found in arc control in medium and high voltage systems where reduction in the interrupted current is shown to be the best technique. The method used was mathematical analysis of the key arc parameters. The major findings were that: the processes that result in electric arc production namely: field emission, thermionic emission and increase in mean free path, are current driven; by skin effect, effective conductor resistance is more for AC than for DC systems; proximity effect increases the effective conductor resistance; the system voltage is not responsible for re-establishing the arc during circuit breaker opening rather, it is the restriking voltage that is capable of doing this. The phenomena often misconstrued by many to be voltage driven, is therefore properly put in perspective in this paper as current driven.**

Keywords – **Electric Arc, Field Emission, Mean Free Path, Thermionic Emission, Skin Effect, Proximity Effect.**

I. Introduction

When reasonable high voltage is applied across an air gap, the air becomes ionized. The ionized gas conducts in form of a continuous spark or arc since it consists of molecules that have lost one or more electrons. The electrons which are negatively charged are attracted towards the anode with a high velocity, and by impact, detach more electrons on the way. The positive ions on the other hand are attracted towards the cathode [1, 2].

During circuit breaker opening under large currents interruption, the contact area reduces. This reduced contact area causes increased current density and hence a rise in the temperature. The heat produced in the medium in between the contacts is sufficient to cause ionization of the medium. This ionized medium acts as a conductor and arc is struck between the contacts of the circuit breaker. The arc provides a low resistance path to the current and also provides a gradual transition from the current-carrying to the voltage isolating states of the contacts but, it is dangerous on account of the energy generated in it in the form of heat which may result in explosive force. The circuit breaker should be capable of extinguishing the arc without causing any damage to the equipment or any danger to the operating personnel. Ionization of medium in between the contacts and potential difference across the contacts are responsible for the production and maintenance of arc. Reduction in the level of fault current being interrupted lowers the ionization process and thus is a good measure for controlling the arc [3].

For arc extinction, the separation between the contacts can be increased to such an extent that potential difference across the contacts is not sufficient enough to maintain the arc. But this philosophy is impractical as: in extra high voltage (EHV) systems, the separation between the contacts to extinguish the arc can be many meters which is not practically achievable [4].

The production of arc when reasonable voltage is applied across an air gap and/or when the contacts of a circuit breaker begin to separate in medium or high voltage systems are often misconstrued by many to mean that voltage is the driving force for electric arc production. This is however not true as electric arc production either by application of reasonable voltage across an air gap or during circuit breaker contacts separation in medium and high voltage systems is current driven. This is properly dealt with in this paper.

II. Electric Arc Production Processes

The processes that result in electric arc production namely are: field emission, thermionic emission and increase in mean free path. These processes may occur either one after another or almost simultaneously.

2.1 *Field Emission*

For surface voltage gradient above 10^6 V/cm, field emission occurs [3]. The contact area and pressure between the separating contacts decrease as the moving contact is withdrawn. The reduced contact area causes an increase in the resistance as shown in the expression:

$$R = \frac{\rho L}{A} \tag{1}$$

Where:

R = Contact resistance.

ρ = Resistivity.

L = Length.

A = Contact cross-sectional area.

The resistance between the separating contacts is quite small but due to large magnitude of fault current, a sufficiently high potential drop of the order 10^6V/cm is caused between the separating contacts so as to dislodge electrons from the cathode surface. This is field emission.

Electric arc welding is another scenario where voltage gradient produces arc utilized for welding. Arc welding is a type of welding that uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is usually protected by some type of shielding gas, vapor, or slag. Arc welding processes may be manual, semi-automatic, or fully automated. A typical arc welding circuit is shown in Figure 1 [5].

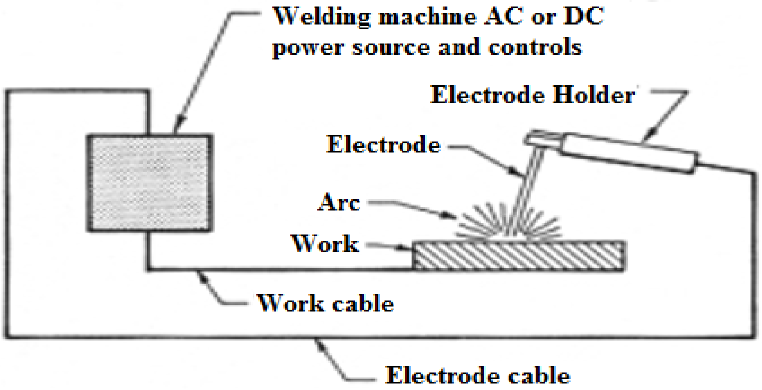

Fig. 1. A basic arc-welding circuit. Source: http://www.lincolnelectric.com

When a strong current jumps a gap between two electrodes arc is formed as shown in Figure 2 [6, 7]. The high current magnitude jumping the gap between the electrode and the work material as shown in Figure 1 causes the arc. It is the heat of this arc that melts the metals at the welding point. The temperature of the heat produced is of the order of 6000°C to 7000°C [8].

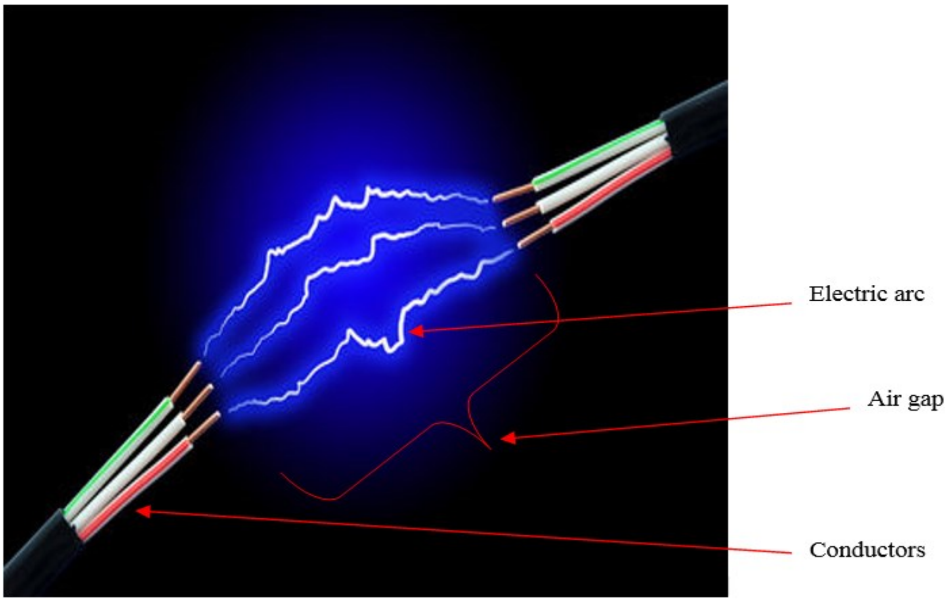

Fig. 2. Electric Arc. Source: www.scienceclarified.com

2.2 *Thermionic Emission*

For a medium of uniform cross section A, containing many free-to-move charged particles of volume density ρ, then these moving charges will form a current I in coulombs per second passing a given reference point as given below [9]:

$$I = v_d \rho A \text{ amperes} \tag{2}$$

Where:

I = current in amperes

v_d = drift velocity in ms^{-1}

ρ = charge density in coulombs/m^3

A = area of conducting medium in m^2

Electric Current Density is denoted by the vector symbol **J** [10]. The total electric current **I** can be related to the current density **J** by summing up (or integrating) the current density over the area where charge is flowing as:

$$I = \int J.ds \tag{3}$$

The current is as given in (3) because in an AC system, the current is non-uniformly distributed over the cross section. By *skin effect*, the current density is higher at the surface of the conductor compared to the current density at its centre. This effect becomes more pronounced as frequency is increased. This effect causes larger power losses for a given rms AC than the loss when the same value of DC is flowing through the conductor. Consequently, the effective conductor resistance is more for AC than for DC.

The explanation for this phenomenon is thus: For a solid round conductor composed of annular filaments of equal cross sectional area, the flux linking the filaments progressively decreases as we move towards the outer filaments. The simple reason for this being that the flux inside a filament does not link it [3]. The inductive reactance of the imaginary filaments therefore decreases outwards with the result that the outer filaments conduct more AC than the inner filaments (filaments being parallel). With increase in frequency, the non-uniformity of the inductive reactance of the filaments becomes more pronounced, so also the non-uniformity of current distribution. Skin effect is quite significant even at 50Hz, for large solid conductors.

Proximity effect is another factor that causes non-uniformity of current distribution in conductors. When two current carrying conductors are arranged in parallel as shown in a two-wire line of Figure 3 below, with each line conductor divided into three sections of equal cross sectional area. Pairs AA, BB and CC form three loops in parallel. The flux linking loop AA (and hence its inductance) is the least. This increases for loops BB and CC. The density of the AC flowing through the conductors is therefore highest at the inner edges AA of the conductors and lowest at the outer edges CC [3]. The proximity effect becomes more pronounced with reduced distance between conductors. Proximity effect also increases the effective conductor resistance.

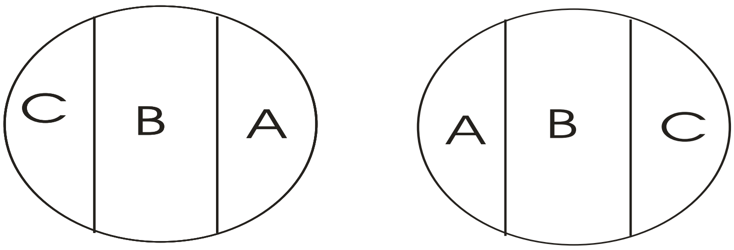

Fig. 3. A Two-Wire Line. Source: Nagrath and Kothari, (2004).

Under short circuit current interruption, the high current density at the surface of the conducting contacts drift to the contact tips leading to release of electrons from the cathode surface as explained in the next paragraph.

As the contacts of a circuit breaker move apart in medium and high voltage systems, the decrease in contact area causes increase in current density to very high values of the order of 10^6A/cm^2. These very high current densities raise the temperature of the contact (cathode) surface, resulting in release of electrons from this surface (i.e. thermionic emission).

2.3 *Increase in Mean Free Path*

The mean free path is the distance through which the electrons move freely during circuit breaker contacts separation. The electrons so emitted from the cathode make many collisions with the atoms and molecules of gases and vapors existing between the two contacts during their journey towards the anode. Such collisions cause ionization of atoms and molecules, thus dislodging more electrons. As the contacts separate, the mean path increases and the number of neutral molecules to get ionized increase as well.

III. Restriking Voltage

This is the voltage that tends to re-establish the arc in a circuit breaker when the circuit breaker is opened under fault condition. This is explained with Figure 4. A positive linear correlation exists between the magnitudes of the interrupted fault currents and transient restriking voltage, (TRV) [11, 12]. The rate of change of current ($\frac{di}{dt}$), when operating a CB plays a key role in the management of arc/heat energy generated. This is explained below:

When contacts of circuit breakers are opened in medium and high voltage systems, the voltage drop during arc formation is in phase with the arc current since the arc path is purely resistive. Current interruption at natural zero of current wave adopted in A.C. circuit breakers can be explained using the waveforms of Figure 4, whose equivalent circuit is shown in Figure 5.

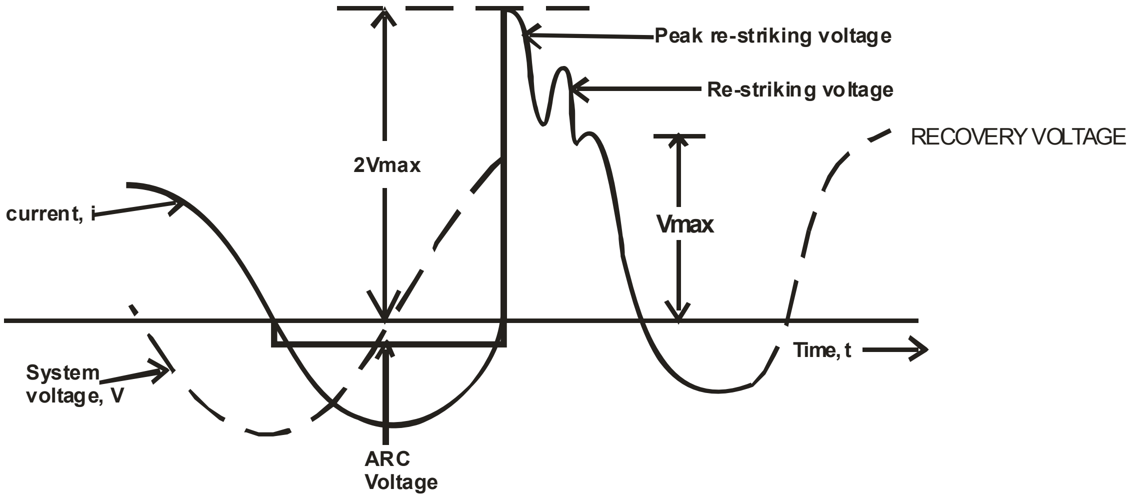

Fig. 4. Waveforms of short circuit current and system voltage when operating a Circuit Breaker. Source: Gupta (2012).

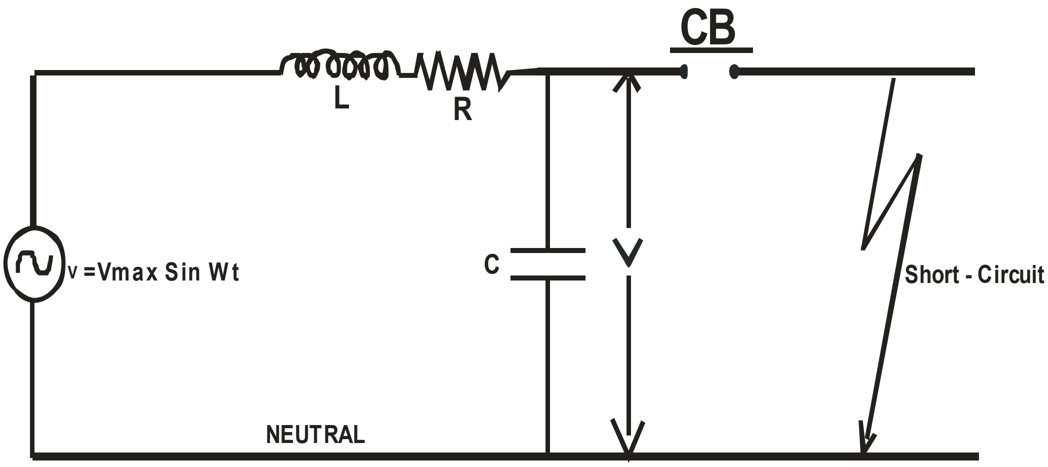

Fig. 5. Equivalent circuit diagram for figure 4. Source: Gupta, (2012).

The current passes through the zero point on the current wave shown in Figure 4 one hundred times per second for a 50Hz system. If the interruption is done when the current is at the zero point in the waveform, no arc shall be encountered. In between these zero limits in the current wave, the current rises to maximum and drops back to zero. Due to the restriking voltage, energy is generated between the two contacts of the circuit breaker. This energy is in the form of heat. Measures should be provided to take care of this heat either by cooling or by air blasting. If the rate of cooling is faster than the rate of heat generation, the arc is extinguished; otherwise, the arc re-strikes in another half cycle. The voltage across the circuit breaker contacts at the instant of an arc being extinguished is called the restriking voltage and is shown in Figure 4 [1].

Before opening the circuit breaker; The interrupted currents = 0, and t = 0, $v = V_{max}\,cos\,\omega t,\ I = \frac{V_{max}}{\omega L} sin\,\omega t$, $\frac{dI}{dt} = \frac{V_{max}}{\omega L}\omega\,cos\,\omega t$ and at t = 0:

$$\frac{dI}{dt} = \frac{V_{max}}{L} \quad (4)$$

From Figure 5, with the circuit breaker contacts opened and the arc broken, the current, I, is diverted through the capacitor C, so that the voltage, V, which has so far been effective only across the inductance, L, is suddenly applied to the inductance, L, and capacitance, C in series, which form an oscillatory circuit having a natural frequency:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}H_Z \quad (5)$$

The initial charging current surge tends to carry the voltage across the capacitor and therefore the circuit breaker contacts to double its equilibrium value, i.e. $2V_{max}$. This is the restriking voltage transient.

When the arc finally extinguishes at some current zero in the current waveform shown in Figure 4 following the opening of the circuit breaker contacts, a voltage, v, is suddenly applied across the capacitor, and therefore across the circuit breaker contacts. The current, I, which would flow to the fault, is now injected in the capacitor and inductor [1]. Thus:$I = I_L + I_C$

or

$$I = \frac{1}{L}\int v dt + C\frac{dv}{dt}$$

$$\therefore \frac{dI}{dt} = \frac{v}{L} + C\frac{d^2V}{dt^2} \quad (6)$$

Substituting $\frac{V_{max}}{L}$ for $\frac{dI}{dt}$ as given in (4) into (6), gave $\frac{V_{max}}{L} = \frac{v}{L} + C\frac{d^2V}{dt^2}$

Or

$$V_{max} = v + LC\frac{d^2v}{dt^2} \quad (7)$$

Solving (7) by Laplace transforms [13], $LCS^2v(s) + v(s) = \frac{V_{max}}{S}$, $v(s)[LCS^2 + 1] = \frac{V_{max}}{S}$

Or $v(s) = \frac{V_{max}}{S[LCS^2+1]}$

Or

$$v(s) = \frac{V_{max}}{LCS\left(S^2+\frac{1}{LC}\right)} \quad (8)$$

But $\omega_n = \frac{1}{\sqrt{LC}}$

Such that: $\omega_n^2 = \frac{1}{LC}$

So that (8) is written as: $v(s) = \frac{\omega_n^2 V_{max}}{S(S^2+\omega_n^2)}$

Or

$$v(s) = \frac{\omega_n V_{max}}{S}\left(\frac{\omega_n}{S^2+\omega_n^2}\right) \tag{9}$$

The inverse Laplace transform of (9) is: $v(t) = \omega_n V_{max} \int_0^t \sin \omega_n t dt = \omega_n V_{max} \left[\frac{-\cos \omega_n t}{\omega_n}\right]_0^t = V_{max}\left[1 - \cos \frac{t}{\sqrt{LC}}\right]$

Or

$$v = V_{max}(1 - \cos \omega_n t) \tag{10}$$

This is the expression for restriking voltage, where:

$\omega_n = \frac{1}{\sqrt{LC}}$ = Angular natural frequency

V_{max} = Peak value of recovery voltage (phase-to-neutral),

t = Time in seconds,

L = Inductance in henries,

C = Capacitance in farads and,

v = Restriking voltage in volts.

IV. Discussion

One thing stands out in all the processes that lead to arc production outlined here.

Under the field emission, for a 132kV system, 40kA fault current requires the resistance between the contacts of as low as 25Ω/cm to give 10^6V/cm gradient that could cause field emission. The voltage developed for instance, when opening this circuit breaker at normal load current of say 500A at this 25Ω/cm is just 12.5kV/cm. The 132kV system voltage obviously cannot cause reasonable emission to produce worrisome arc.

Thermionic emission on the other hand happens thus: as the contacts of the circuit breaker move apart during opening operation, there is a decrease in the contact area. This decrease in the contact area causes increase in current density to very high values of the order of 10^6A/cm^2. These very high current densities raise the temperature of the contact (cathode) surface, resulting into the production of the electrons that initiate ionization of the gases in the air gap and in this way, the arc is struck.

For arc welding, a strong current (high current magnitude) jumps a gap between the electrode and work material. This high current magnitude jumping the gap between the electrode and work material causes ionization of the air mass between the electrodes before arc is formed.

By skin effect and proximity effect, there is heavy current drift to the tip of the parting contact. Increased current density here causes thermionic emission which has already been explained in the preceding paragraphs of this paper.

Under the increased mean free path process, the initiating electrons that collide with the atoms and molecules of gases and vapors existing between the two contacts during their journey towards the anode are products of field emission and thermionic emission which themselves are already shown here to be current driven.

Lastly, the system voltage is not responsible for re-establishing the arc during circuit breaker opening operation. It is the restriking voltage that is capable of doing this. Restriking voltage has a maximum value of $2V_{max}$ [1] and occurs at: $t = \frac{\pi}{\omega}$

Or

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

For restriking voltage having a maximum value of $2V_{max}$ means that examining (4), it can be inferred that with high value of the interrupted current, I, the restriking voltage will be high.

The restriking voltage has a positive correlation with the interrupted current, such that the important characteristics of restriking voltage transient namely:

- Amplitude factor given as:

$$\frac{\text{Peak Transient Restriking Voltage}}{\text{Peak System Voltage}}$$

- Rate of Rise of Restriking Voltage (RRRV), dv/dt, increase with increase in the interrupted current.

V. Conclusion

This paper provided detailed analysis that confirms that current is the key parameter for arc production in medium and high systems and not voltage. Measures for reducing the anticipated arc to easily manageable level should therefore be those that can lower the interrupted current.

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