



Improved Arc Interruption of High Voltage SF₆ Circuit Breakers Using Modified Mayr's Differential Equation

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Abstract: The study of arc interruption is very essential in high voltage circuit breakers since arc extinction must be achieved in the shortest possible time for effective protection of the power system. This paper presents some conventional arc models used in the research of interaction between switching arc and circuit during the interruption process of high voltage circuit breakers. It goes ahead to develop a model that is current dependent with a constant time parameter that helps to improve the process of arc interruption in high voltage SF₆ circuit breaker. The simulation results show that the model has the capability of reducing the arc interruption time by completely extinguishing the arc current almost instantaneously.

Keywords: Circuit Breakers, Switch, Switchgear, Dielectric Strength, Arc Extinction

1. Introduction

A circuit breaker is a device that do interrupt faults or abnormal currents and at the same time functions as a switch. Circuit breakers and fuses possess a time element of operation, whereby they operate practically instantaneously on short-circuits but with definite time lag on overloads [1]. Circuit breakers can be reset in less time and with less trouble that are required to replace blown fuses and spare parts are seldom required. For low voltage, fuses may be used to isolate the faulty circuits but for higher voltages, say from 3.3kV upwards, isolation is achieved by circuit breaker. Circuit breakers may also be preferred where continuity of service is an important consideration or where frequent fuse replacement may be expected.

Circuit breakers have to be accessible for inspection and maintenance, therefore it is required that there should be a provision for the separation of the breaker from the live parts by means of isolating switches. The disconnected element is usually separated from the live portion of the system by the use of isolating switches. They are to be employed only after the corresponding circuit breakers have been opened [1].

SF₆ is a heavy chemically inert non-toxic non-inflammable gas and it has good dielectric and good arc extinguishing properties. As pressure increase, the dielectric strength of SF₆

also increases. In addition, the dielectric strength of SF₆ is greater than the dielectric strength of oil. Nowadays, SF₆ gas is widely used in electrical equipment such as high voltage metal clad switchgear, voltage metal enclosed cables, circuit breakers, capacitors, bushings, current transformers, etc. It is liquefied at certain low temperature, liquefaction temperature increases with pressure [2].

During the arcing period in SF₆ circuit breakers, SF₆ gas is blown axially along the arc [2, 11]. The gas removes the heat from the arc by axial convection and radial dissipation [2, 11]. Consequently, the diameter of the arc becomes small during the current zero and the arc is extinguished. Due to its electro-negativity and given that the arc time constant is low, the SF₆ gas then regains its dielectric strength quickly after the current zero, the rate of rise of dielectric strength is very high and the time constant is very small [2, 11].

As regards SF₆ circuit-breaker, even after contact separation current will continue to flow. Specifically, at this point the current flows through the arc which has plasma that comprises of ionized SF₆ gas. For, as long as it is burning, the arc will become subjected to a constant flow of gas and it is the gas that extracts heat from arc. According to Ecsanyi [12], the arc is extinguished at current zero, when the heat is extracted by the falling current. As the gas continues to fall it eventually de-ionizes the contact gap, at which point the dielectric strength needed to avert a re-strike is established [3].

Mayr arc model was introduced in 1943 [6, 8]. Mayr assumed that power losses are caused by thermal conduction and the arc conductance is dependent on temperature. Mayr arc model is fit for currents near zero. Schwarz developed a modified Mayr arc model in 1971 [6, 9]. The cooling power and time constant in the model are function of the arc conductance [6]. The cooling power in the modified Mayr arc model is current-dependent [6, 10]. The arc models mentioned are black box models, that is, conventional arc models. They are usually used to simulate the interaction between switching arc and circuit during the interruption process of circuit breakers. The characteristics of the fault arc are different from the characteristics of the switching arc. The modified model

developed for his research is current dependent with a constant time parameter. The arc interruption is a function of the electrical power input.

2. Mayr's Mathematical Model of the Arc

Figure 1 shows a power system consisting of a short transmission line connected to a high voltage source through a transformer and an SF₆ circuit breaker where x_g , x_t and x_L represent the total resistance and inductive reactance of the conductors. Since the effect of shunt capacitance is neglected, the series resistance and reactance are taken as lumped.

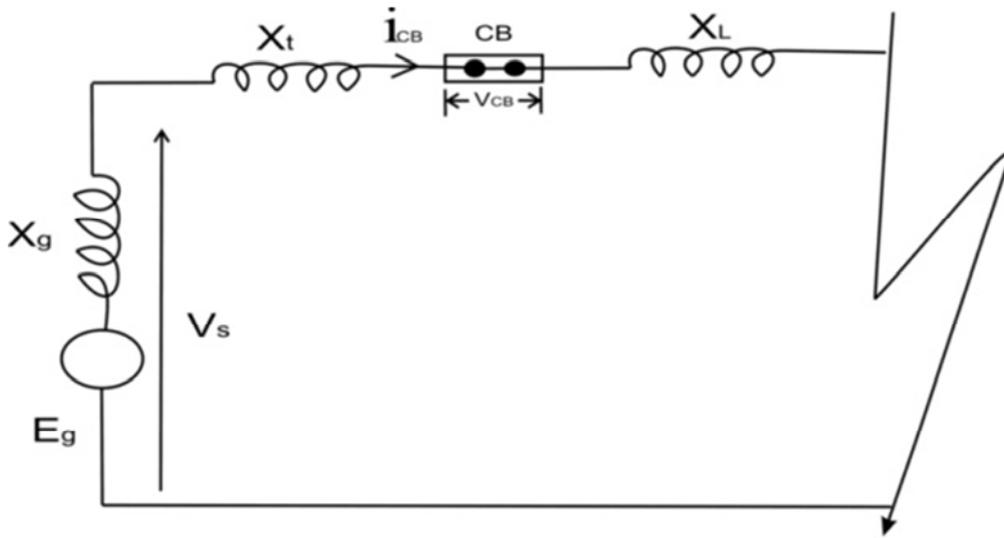


Figure 1. A Power System of a short transmission line with a fault at the end of the line.

The objective is to model the arc chamber to determine the arc voltage E_0 , load current and arc current i_{CB} . The model employs the non-linear modified Mayr's equation from when the arc conductance g_a reach the linearized solution value $g_0 = \frac{\omega \theta I}{E_0}$ till g_a reach a minimum value g_{min} before starting to increase.

The angular frequency of the supply voltage is ω , I is the root mean square (rms) value of interrupted current in amperes, E_0 is the near constant arc voltage just before its sudden drop as the falling current approaches zero and θ is arc time constant.

The electrical arc is the switching element of the circuit breaker, so the essential part of the circuit breaker model is the arc model. The model below was developed by Mayr [4]:

$$\frac{1}{G_m} \frac{dG_m}{dt} = \frac{1}{\theta} \left[\frac{e_a i_a}{N_0} - 1 \right] \quad (1)$$

G_m represents the conductance of the arc throughout the entire current range.

θ represents the ratio of a characteristic amount of stored energy to power loss which is referred to as arc time constant.

N_0 , e_a and i_a are the arc parameters.

3. Derivation of the Modified Mayr Model

Calculation of E_0 (Near-Constant Arc Voltage just before its sudden drop, as the falling current approaches zero):

The source voltage is at the peak value near the current zero. The rms voltage can be calculated thus:

$$E_m = \left[\frac{(x_L + x_T + x_G)}{\omega} \right] \frac{di}{dt} - E_0 \quad (2)$$

Therefore

$$\frac{di}{dt} = \frac{(E_m + E_0)\omega}{(x_L + x_T + x_G)} \quad (3)$$

The terminal voltage of the source v is expressed as:

$$V = \left[\frac{(x_L + x_T)}{\omega} \right] \frac{di}{dt} - E_0 \quad (4)$$

Eliminating $\frac{di}{dt}$ from (3) and (4),

$$V = E_m - (1 - F) - FE_0 \quad (5)$$

Where

$$F = \frac{x_G}{(x_L + x_G)} \tag{6}$$

$$i_{anew} = i_{aold} + di_a \tag{10}$$

Assume $v = 0.5E_m$ when the circuit breaker starts to open, then the initial arc voltage E_0 can be obtained from (5) as

From (9), the change of arc current di_a in the time interval dt is

$$E_0 = \frac{[E_m(1-F) - 0.5E_m]}{F} \tag{7}$$

$$di_a = \frac{E_m - V}{\frac{x_G}{\omega} dt} \tag{11}$$

According to Mayr [5] initial condition values:

So the updated arc conductance is:

$$i_a = 0$$

$$g_{anew} = g_{aold} + dg_a \tag{12}$$

$$v_a = 0$$

The change of the arc conductance dg_a in the time interval dt is determined as:

$$g_a = g_o$$

$$dG_m = \left(\frac{G_m}{\theta}\right) \left[\left(\frac{e_a^{2i_a}}{N_o}\right) - 1\right] \tag{13}$$

$$V = v_{new}$$

$$v_{new} = E_m - \left(\frac{x_G}{\omega}\right) \left(\frac{di_a}{dt}\right) \tag{8}$$

Dividing and multiplying both sides of the equation by dt and $\frac{1}{G_m}$ respectively, (13) becomes

The arc voltage is determined as:

$$\left(\frac{1}{G_m}\right) \frac{dG_m}{dt} = \frac{1}{\theta} \left(\frac{e_a^{2i_a}}{N_o} - 1\right) \tag{14}$$

$$v_{mnew} = \frac{i_{anew}}{g_{mnew}} \tag{9}$$

Simulation Results and Discussion

So the updated value of the arc current is

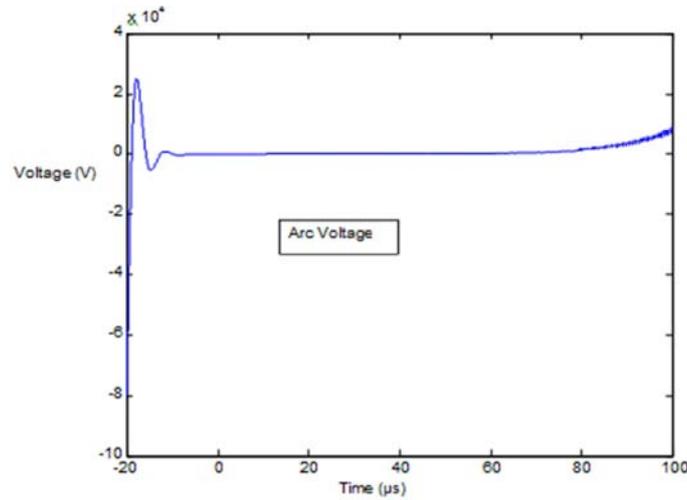


Figure 2. Arc Voltage plotted against Time.

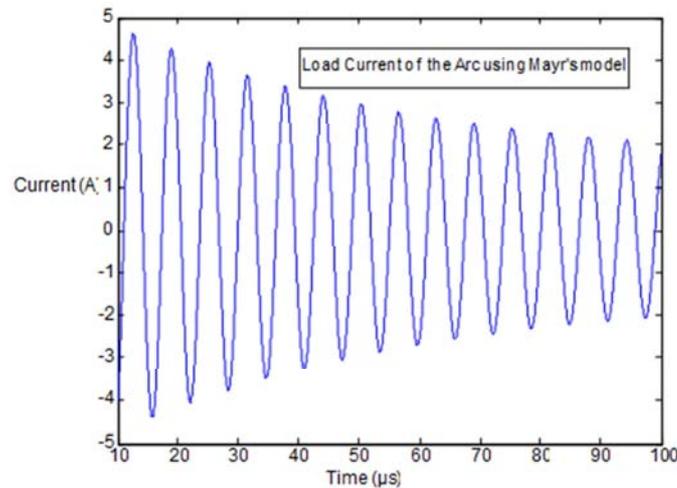


Figure 3. Load Current plotted against time.

In figure 2, transient overvoltage occurs during arc interruption, the voltage comes down in less than 5μs, then increases gradually till it becomes steady. These activities occur in less than 80μs. Figure 3 shows how the load current diminishes immediately the movable portion of the breaker contact leaves the immovable part and SF6 blown axially along the arc. Figure 4 shows arc current completely extinguished after a successful arc interruption in less than 100μs.

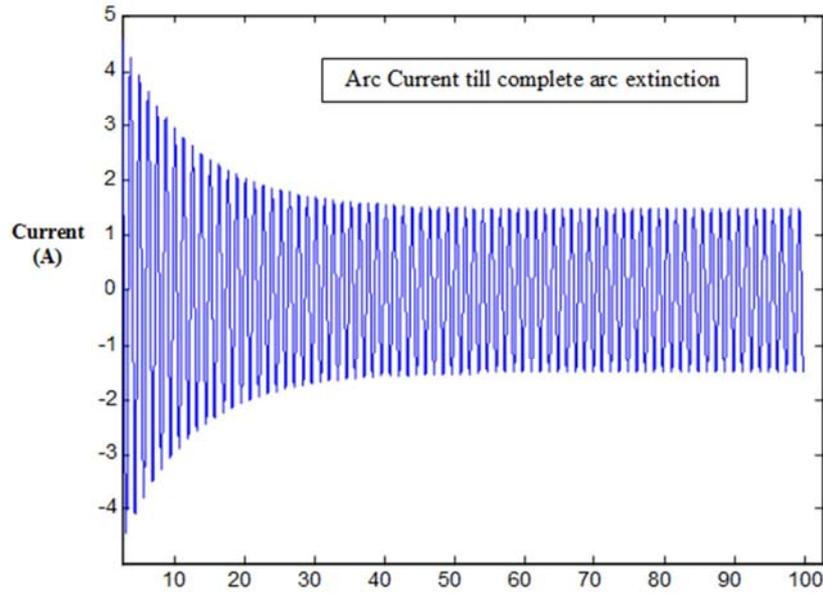


Figure 4. Arc Current plotted against Time.

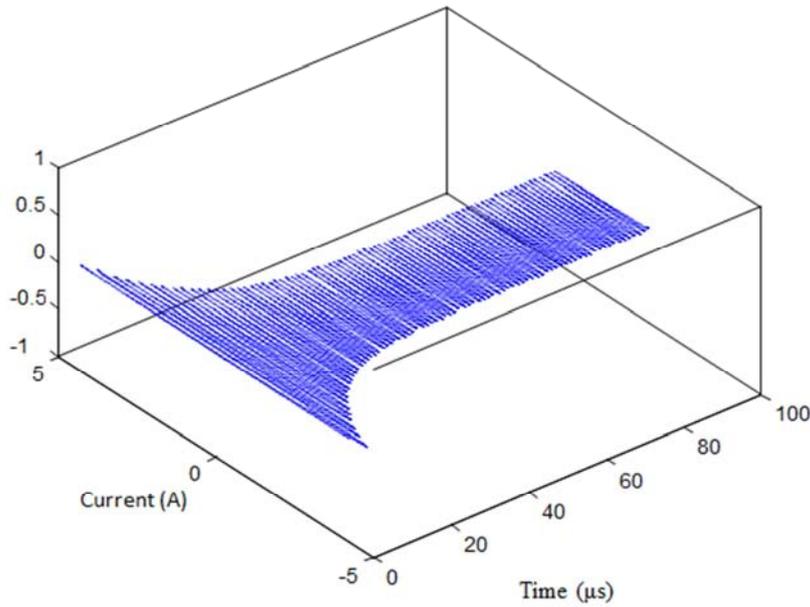


Figure 5. 3-D Plane of the Arc current.

4. Conclusion

A model that is current dependent with a constant time parameter is developed after studying Mayr's model. The main advantage of this model is that it diminishes the value of the load current almost instantaneously during arc interruption of high voltage SF₆ circuit breaker which protects the transmission line. The model can be used for the determination of the current interruption in high voltage SF₆ circuit breaker under specific circumstances defined by the

surrounding network. With the simulation results obtained, the model has sufficient performing ability for effective arc interruption.

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