Nigerian Research Journal of Engineering and Environmental Sciences 6(1) 2021 pp. 176-187

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Effect of Circuit Breaker Arc on Faulted Inductive and Capacitive Circuit on a Transmission Line

Obi, P.I., *Amako, E.A. and Ezeonye, C.S.

Department of Electrical/Electronics Engineering, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria.
*ejikeamako@yahoo.com

ARTICLE INFORMATION

Article history:
Received 22 Apr, 2021
Revised 10 May, 2021
Accepted 11 May, 2021
Available online 30 June, 2021

Keywords:
Arc current
Arc voltage
PSCAD/EMTDC
MATLAB
Transient recovery voltage

ABSTRACT

This paper presents the effect of circuit breaker arc on transmission line comprising inductive and capacitive circuit with terminal faults and short line faults. This was realized with the aid of MATLAB and PSCAD/EMTDC software. The system voltage, current, arc current, arc voltage and transient recovery voltage during fault conditions were analyzed for all for four (4) cases. The analysis shows the respective system voltage and current plots as well as the breaker arc voltage and currents plots. The fault occurs at 0.2 seconds while breaker operation was between 0.3 seconds to 0.5 seconds. The circuit breaker separation was studied at t = 0 secs and t =0.009 seconds and the TRV and current zero-crossing were recorded. A TRV of 1.985×10^{-5} V and a zero crossing at $t = 3.24 \times 10^{-3}$ s were recorded with interruption of small inductive currents and current chopping. The transient recovery voltage was 1.59×10^{5} V and its breaker zero crossing at $t = 2.1 \times 10^{-2}$ s was recorded during interruption of capacitive currents. Also, the first transient recovery voltage was 2.66×10^{5} V and its zero crossing occurred at t = 0.0149 s with interruption of terminal faults. Similarly, the TRV was 1.59 $\times 10^{5}$ V and the breaker zero crossing occurred at $t = 2.1 \times 10^{-2}$ s from contact separation when fault was between a distance for of a few kilometers from the circuit breaker.

1. INTRODUCTION

A circuit breaker is a mechanical device for closing, carrying, and interrupting a circuit by means of parting the movable contacts under normal or abnormal condition and in addition performs the feature of a switch. Circuit breakers play an essential role in power transmission systems. They are one of the most important equipment in power system and without a circuit breaker, there is a high risk of electrical fires, electrocution and electrical shocks. They can clearly and rapidly isolate faulty sections on the system. They can equally be used for normal switching of loads and capacitors banks. High voltage circuit breakers are designed to interrupt current flow at natural current zero and withstand the stresses caused by dielectric on the process of interruption. They must additionally be in position to interrupt a wide variety of other currents at system voltage such as capacitive currents, small inductive currents, and load currents (Rao and Gajjar, 2008; Obi *et al.,* 2020). Circuit breakers insert a constantly increasing resistance in the circuit till the current to be interrupted drops to zero. When the current carrying contacts separate on an abnormal event, an arc is created in between them. This arc endures until its energy input ceases and it has a low resistance path which implies that the current in the circuit remains continuous as long as the arc is sustained (Van Lanen and Popov, 2007; Gupta, 2015).

Transient recovery voltage (TRV) occurs when current zero is reached and the high-frequency transient voltage which establishes an ample electrical strength appears across the breaker contacts. It is the instantaneous recovery voltage that appears across the terminals after current interruption at the instant of arc extinction which depends on the nature of the quenching gases, mode of interaction of arc strain and velocity, arc control devices, contact shape, and number of breaks per phase. TRV will continue to increase until a breakdown occurs, which will cause the voltage over the contacts to drop to the arc voltage. If no breakdown occurs, the TRV will continue to increase until it reaches the line voltage (Das, 2012; Gupta, 2015).

Arc extinguishing peak voltage is the maximum voltage that appears across the contacts of the circuit breaker during arcing period. The voltage that appears across the contacts during arcing is called arc voltage and it's generally low except for period of fault current. At current zero, the arc voltage rises rapidly to peak value and this period tends to maintain the current flow in the form of arc (Mehta and Mehta, 2008).

Some electrical devices or circuits start operation with the alternating current (AC) load voltage at close to zero volts in the AC cycle. The point where the AC line voltage is zero volts is the zero cross point and reverse of polarity additionally happens at the zero crossing voltage. By detection of the zero-crossing point, circuit breaker acts under the condition with a zero current and the arc becomes extinct, which leads to decrease in breaking capacity. This helps to determine the arc mode and the breaking ability of the circuit breaker (Xiang *et al.,* 2014; Yao *et al.,* 2018; Bansal, 2019).

Several studies have been carried out on circuit breaker arc on transmission lines. Schavemaker and Sluis (2000) presented an improved Mayr-type arc model based on current-zero measurements. Their results showed that the Mayr-type arc models can be used to describe the arc behavior before current zero exactly. In Rao and Gajjar (2008), Mayr arc model with constant time parameter and cooling power was implemented to develop SF6 breaker model in PSCAD. From their results, it is observed that for the successful interruption of the arc, the fault location should be within the critical length, and cooling power should be optimal for the given fault location and the presence of the capacitances across the breaker is required. Andrea *et al.* (2010) presented a new direct current (DC) and AC arc fault electrical model with the aid of MATLAB, VHDL-AMS and PSICE. They compared the results which show that VHDL-AMS is most suitable for simulation of arc in circuit due to its direct description of impedance and Mayr hyperbolic form equations. Xi-xiu *et al.* (2011) investigated the implementation process of different kinds of black box arc model with different simulation software, which are MATLAB, EMTP-ATP and PSCAD/EMTDC. Their results show that compared with integral expression, arc model with differential expression is more accurate at current zero in electromagnetic transient simulation. Lezama *et al.* (2012) presented the modeling of a typical home electric installation with two typical loads (vacuum cleaner with universal motor and kettle) with the aid of MATLAB/SIMULINK. Their experimental results show good agreement with the simulation results. Yuan *et al.* (2013) investigated several conventional arc models for calculating the fault arcing current. Their results show that conventional arc models can be used to simulate the fault arc if the parameters of arc models are given properly. In Jing and Bing (2014), the electromagnetic properties of magnetic instantaneous acting trip in a low voltage molded case circuit breakers (MCCB) were analyzed using finite element analysis software ANSOFT. The simulation model of MCCB with respect to Cassie arc equations was built using power system simulation software PSCAD/EMTDC to describe the dynamic behavior of the breaker during fault. The results of short-circuit interruption demonstrates that the simulation model has good prospect in optimizing the design and protection performance of MCCB. Andrea and Bournat (2016) compared classical Mayr-type model with the mathematical model of an electric arc. Their results show that the proposed model provides a better description of the arc behavior in circuit than the Mayr-type model. Chen and Ke (2018) compared and analyzed two typical arc black box models on PSCAD. From their results, the voltage and current when the circuit breaker cuts different faults in different scenes were basically consistent. Saitwal and Khampariya (2018) studied and implemented Cassie-Mayr arc model of a high voltage circuit breaker as a black-box model in MATLAB/SIMULINK. Their results produced current and voltage waveforms which are very useful for studying complex current interrupting process in the circuit breakers without considering the underlying complex physical phenomenon.

From the reviewed literatures, it is seen that the effect of breaker arc on a faulted circuit comprising of inductive, capacitive, terminal faults and short-line faults was lacking in their studies. As a result, simulation of the circuit comprising of capacitive, inductive, terminal and short-line faults was done in this work in order to obtain system voltage and current, arc voltage, arc current and transient recovery voltage which was done with the aid of MATLAB and PSCAD.

2. METHODOLOGY

The materials used in this research are MATLAB Simulation software and PSCAD/EMTDC software. The method used for the analysis is the simulation of the circuit breaker arc model equations. The program was developed on the MATLAB platform based on the Mayr arc models which was modified to obtain the transient recovery voltage, arc voltage and current, and the system voltage and current during terminal and short-line fault.

The Mayr model and the arc behavior are primarily related with the variation of the arc conductance. The arc conductance is a function of the power transferred to the plasma channel.

In the Mayr model, the arc conductance is represented by:

$$\frac{1}{g_m}\frac{dg_m}{dt} = \frac{1}{\tau_m}\left(\frac{u_{arc}.i_{arc}}{p_o} - 1\right) \quad (1)$$

Where g_m is the arc conductance, τ_m is the arc time constant, p_o is the cooling power constant, u_{arc} is the arc voltage across the breaker and i_{arc} is the arc current.

The Mayr model is suited for modeling of the arc in the vicinity of current zero when the temperature of the plasma is below 8000 K (Schavemaker and Sluis, 2000).

Data for the analysis:

The following data were used in the analysis

- Transformer magnetizing current: 10 A
- Inductance of circuit: 100 H
- Capacitance of circuit: 0.004 μF
- System voltage and frequency: 220 kV/50 Hz
- Breaker arc separation starts at 0.009 s and at 0 s.

The circuit breaker parameters are:

- Current chopping limit: 5.0 kA
- Breaker open resistance: 1.0 x 10^{-6} ohms
- Breaker closed resistance: 0.005 ohms.

The circuit breaker has a three-phase fault applied. The faults parameters are fault ON resistance as 0.01 ohms and fault OFF resistance as 1.0 x 10^{-6} ohms. In the Mayr arc model, the cooling power of the arc was considered as 309 kW, its arc conductance is 1.0 x10^{-4}s and the time constant (τ) is 0.3μs. The rated voltage of the supplied by the generator is 220 kV (peak). To validate the study of this model further, four (4) cases were analyzed in this research:

A. For interruption of small inductive currents and current chopping.
B. For interruption of capacitive currents – unloaded transmission line.
C. For interruption of terminal faults (faults very close to the terminal of the circuit breaker)
D. Fault occurring between a distance of a few kilometers to a few tens kilometers from the circuit breaker.

3. RESULTS AND DISCUSSION

3.1. Interruption of Small Inductive Currents and Current Chopping

A no load 220 kV/66 kV transformer of rating 250 MVA with leakage reactance of 0.1 pu was connected at the end of the circuit breaker as shown in Figure 1. The transformer on no –load produces no load currents i.e. magnetizing currents which are almost at zero power factor lag and the current is 1% which is smaller than normal current rating of the transformer. The system current and voltage plots over a period of 0.7 s is shown in Figures 2 and 3.

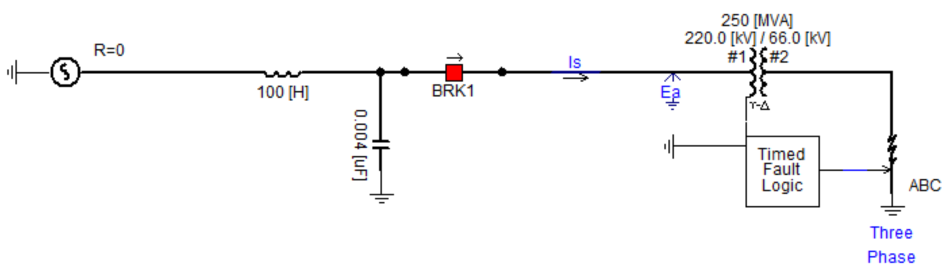

Figure 1: Circuit diagram for interruption of small inductive currents and current chopping

Figure 2: Plot of system current against time

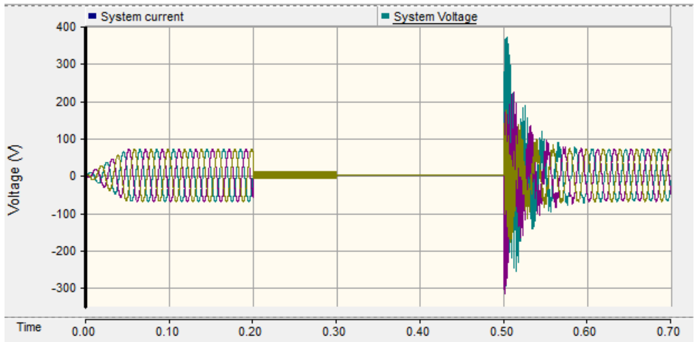

Figure 3: Plot of system voltage against time

In Figures 2 and 3, the voltage and current gradually builds up to 70 V and 0.004 A respectively due to the action of the capacitor. When the fault was introduced at t=0.2 s, the breaker action is delayed and acts at t=0.3 before the fault is cleared at t=0.5 s and the breaker recloses. The transient system voltage and current in Figures 2 and 3 were 371.1 V and 8 x 10^{-3} A respectively while the minimum values were -296.34 V and -3.4 x 10^{-3} respectively. Upon reclosing of the breaker the system stabilizes to a new voltage and current of 70.2 V and 0.0058 A respectively after about 0.11 s of reclosing of the breaker after the fault is extinguished and the circuit breaker returns to normalcy.

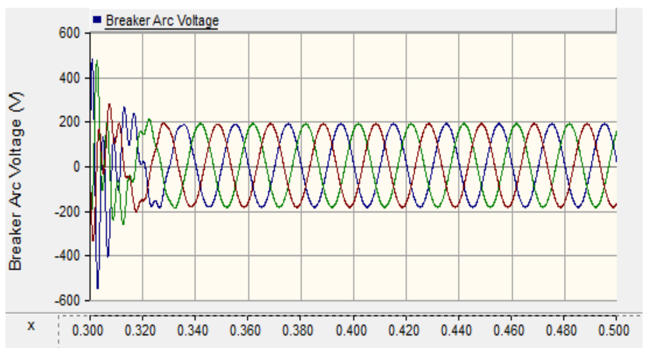

Figure 4: Plot of breaker arc voltage against time during breaker operation 0.3 s to 0.5 s

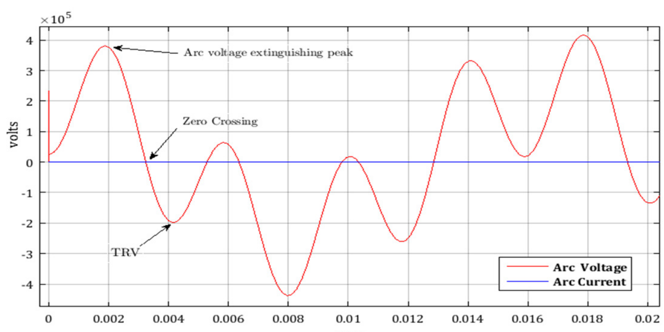

Figure 5: Plot of arc current and arc voltage when contact separation starts at t = 0 s

Prospective breaker arc voltage is extremely high at as seen in Figure 5 as compared to the dielectric strength gain by the breaker gaps hence it restrikes several chops occur until a low enough current is interrupted that produces insufficient induced voltage to restrike across the breaker gap. These phenomena lead to high frequency oscillations through the arc channel, thus forcing a zero crossing. The resulting TRV has an

P.I. Obi et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(1) 2021 pp. 176-187

extremely high peak value as seen from 0.3 s to 0.33 s in Figure 4. A zoomed in view shown in Figure 5 shows that the first arc voltage extinguishing peak was 3.8 x 10^5 V and the first transient recovery voltage was 1.985 x 10^{-5} V while the breaker zero crossing occurs at t = 3.24 x 10^{-3} s from contact separation. When current is finally interrupted no further restrike takes place and the arc is completely deionized and reduced.

3.2. Interruption of Capacitive Currents

A cause of excessive transient voltage across the circuit breaker contacts is the interruption of capacitive currents like the opening of an unloaded long transmission line as such a line carry capacitive current. The source side capacitance provides the time delay prior to the initial rate of rise of the line side TRV, the load side capacitance is set at 0.004μF and a further 0.004μF is placed at the end as shown in Figure 6. The effect of the load capacitance was shown in Figure 6. When the current interruption was successful at current zero, the voltage across load capacitance is zero and the TRV builds up across the breaker contacts and charges the first the load capacitance which causes the time delay of the TRV waveform.

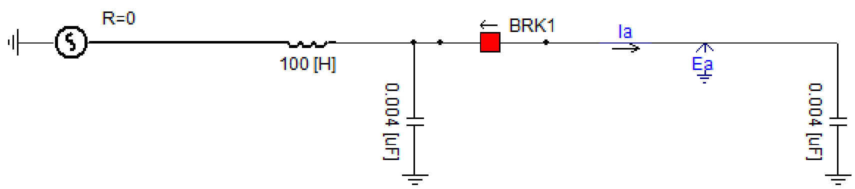

Figure 6: Circuit diagram for interruption of capacitive currents (unloaded transmission line)

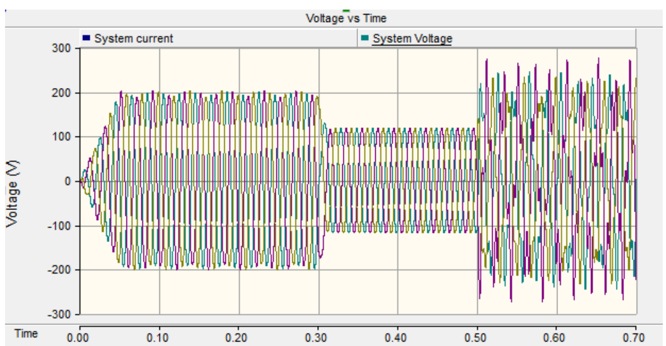

Figure 7: Plot of system voltage against time

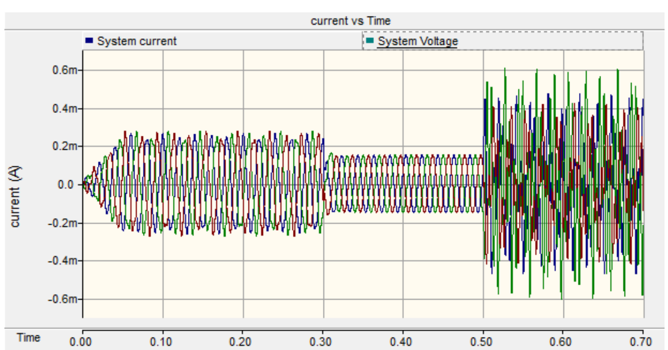

Figure 8: Plot of system current against time

In Figures 7 and 8, the voltage and current gradually builds up to 202 V and 0.00027 A respectively due to the action of the capacitor. When the fault was introduced at t=0.2 s, the breaker action is delayed and acts at t=0.3 s before switching of the unloaded transmission line at t=0.5 s and the breaker recloses. The transient system voltage and current are as high as 233.73 V and 4.7 x 10^{-4} A respectively as shown in Figures 7 and 8. Upon reclosing of the breaker the system currents and voltage become erratic and stabilize to a new voltage and current of 275 V and 0.0006 A respectively after about 0.167 s after reclosing of the breaker after the fault is extinguished and breaker terminal are closed. This erratic voltage is because of presence of capacitance at both end of the load source.

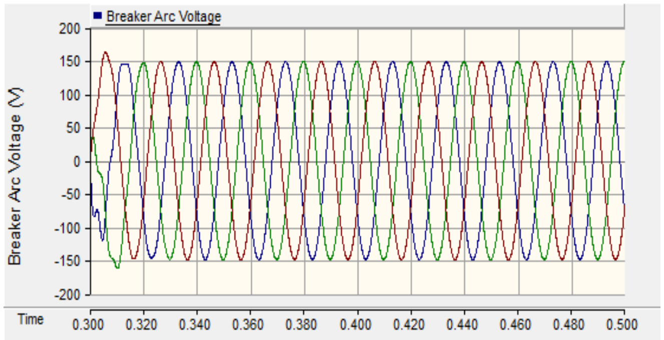

Figure 9: Plot of breaker arc voltage against time during breaker operation 0.3 s to 0.5 s

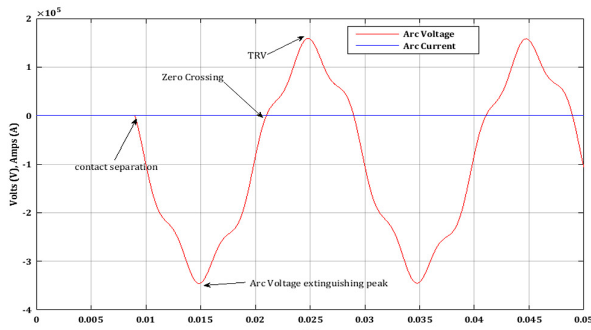

Figure 10: Plot of arc current and arc voltage when contact separation starts at t = 0.009 s

The breaker arc current reached a peak of 0.36 A before contact separation at t = 0.009 s as shown in Figure 8. The resulting TRV has an extremely high peak value as seen from 0.3 s to 0.315 s in Figure 9, and a more detailed in view shown in Figure 10, shows the first arc voltage extinguishing peak as -3.47 x 10^5 V and the first transient recovery voltage as 1.59 x 10^5 V while the breaker zero crossing occurred at t = 2.1 x 10^{-2} s after contact separation at t = 0.009 s. When current is finally interrupted no further restrike takes place, the arc is now completely deionized and reduced because the current is reduced to an insufficient value that does not cause further restrikes.

3.3. Interruption of Terminal Faults

When the fault occurs very close to the terminal of the circuit breaker as shown in Figure 11, it depends on the source voltage and its impedance. After the arc extinguishing peak voltage at the natural zero, the circuit recovers and the TRV appears accros the circuit beaker poles. In Figure 12 and 13 the voltage and current gradually ramp up to 185.43 V and 0.00074 A respectively in 0.05 s. when the fault was introduced at t=0.2 s, the breaker action begins and acts at t=0.3 s before the fault is cleared at t=0.5 s and the breaker recloses. The transient system current is as high as 0.0116 A respectively as shown in Figure 13. Upon reclosing of the breaker, the system currents and voltage become stabilized back to the pervious ramped up level as shown in Figures 12 and 13. This is normally a fault at the circuit breaker and is associated with a high current on introduction of fault. This high current is controlled by the relay setting which cuts off on exceeding the set value thereby clearing the fault and the system current and voltage return to normal levels. In Figure 14, the breaker arc voltage is extremely high at 0.3 s to 0.32 s by gaps hence it restrikes several chops occur until a low enough current is interrupted. The breaker arc current reaches a peak of 0.229 A before contact separation at t = 0.009 s. The resulting TRV has an extremely high peak value shown in Figure 14, and the more detailed in view shown in Figure 15 shows the first Arc Voltage extinguishing peak occurred at -2.66 x 10^5 V and the first transient recovery voltage at 2.66 x 10^5 V while the breaker zero crossing occurred at t = 0.0149 s upon breaker contact separation. This is because of the high current nature of terminal fault at point of fault introduction.

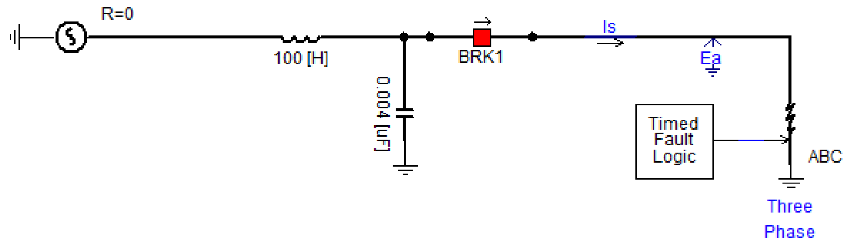

Figure 11: Circuit diagram for interruption of terminal faults

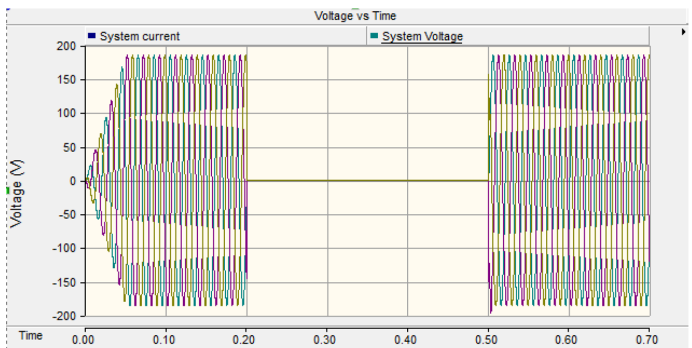

Figure 12: Plot of system voltage against time

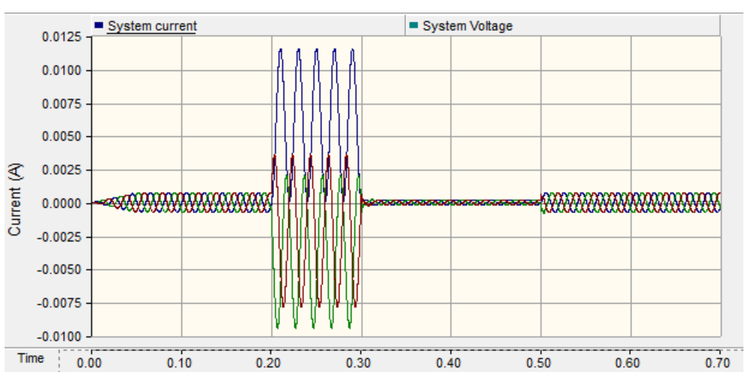

Figure 13: Plot of system current against time

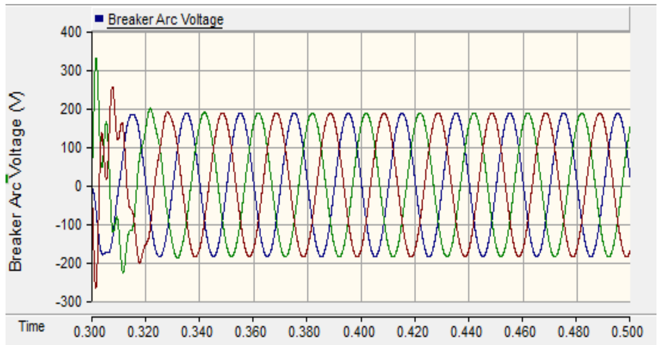

Figure 14: Plot of breaker arc voltage against time during breaker operation 0.3 s to 0.5 s

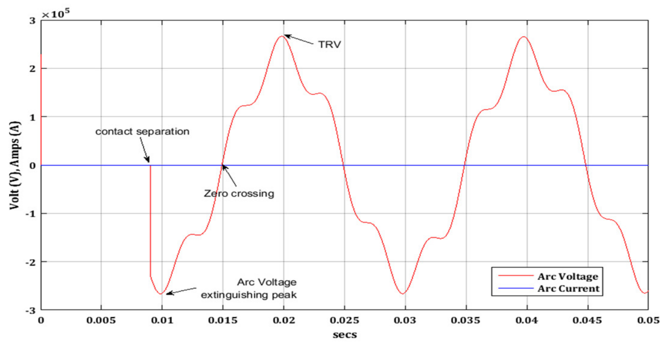

Figure 15: Plot of arc current and arc voltage when contact separation starts at t = 0.009 s

3.4. Fault Occurring between a Distance of a Few Kilometers to a few tens Kilometers from the Circuit Breaker

The length of the line has been set as 50 km in this case called short- line or kilometeric faults as shown in Figure 16. The TRV across the breaker terminals is accompained by a high frequency line side component and the reduction in fault current is only slightly less than the previous case.

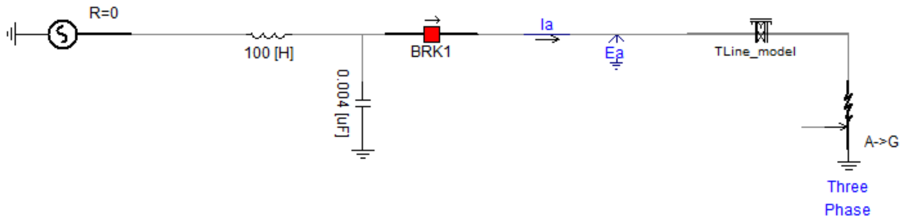

Figure 16: Circuit diagram for interruption of terminal faults

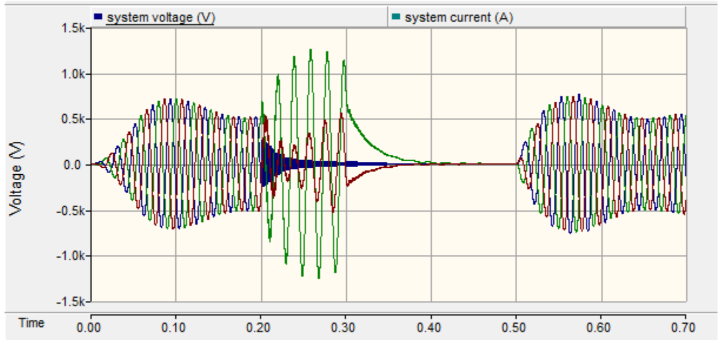

Figure 17: Plot of system voltage against time

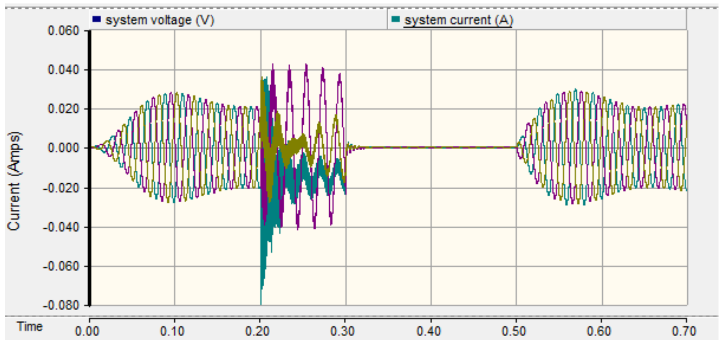

Figure 18: Plot of system current against time

In Figures 17 and 18, the voltage and current gradually builds up to 202 V and 0.00027 A respectively, due to the action of the capacitor. When the fault is introduced at t=0.2 s, the breaker action is delayed and acts at t=0.3 s before switching of the unloaded transmission line at t=0.5 s and the breaker recloses. The transient system voltage and current were as high as 233.73 V and 4.7 x 10^{-4} A respectively as shown in Figures 17 and 18 respectively. Upon reclosing of the breaker the system currents and voltage build up and stabilize to a new voltage and current of 275 V and 0.0006 A respectively after about 0.167 s after reclosing of the breaker after the fault was extinguished and breaker terminal are closed.

.

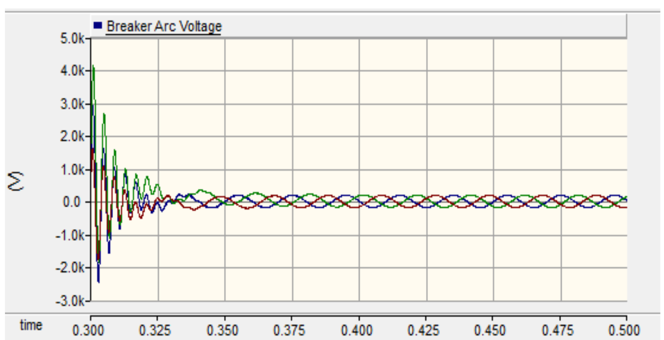

Figure 19: Plot of breaker arc voltage against time during breaker operation 0.3 s to 0.5 s

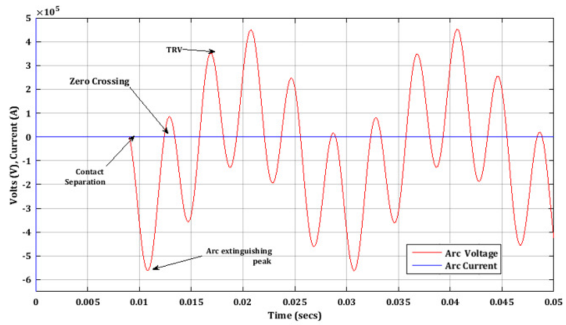

Figure 20: Plot of arc current, arc voltage and TRV when contact separation starts at t = 0.009 s

The breaker arc current reached a peak of 0.36 A before contact separation at t = 0.009 s. The resulting TRV has an extremely high peak value as seen from 0.3 s to 0.35 s in Figure 19, and in the more detailed in view shown in Figure 20, which shows the first arc voltage extinguishing peak as -3.47 x 10^5 V and the first transient recovery voltage as 1.59 x 10^5 V while the breaker zero crossing occurred at t = 2.1 x 10^{-2} s after contact separation at t = 0.009 s. When current is finally interrupted no further restrike takes place is the arc is completely deionized now and its dielectric strength of the arc is completely reduced. The results in Figures 19 and 20 really show characteristics of short line fault since rate of rise of recovery voltage (RRRV) is normally high depending on the surge impedance of the line.

4. CONCLUSION

The switching action, is the basic function of the circuit breaker, this refers to the change from conductor to insulator at a certain voltage level. Before current interruption, the fault current flows through the arc channel between the breaker contacts as shown in the system voltage and current against time plots from time 0.2 to 0.3 s. All faults occur at 0.2 s while the breaker opens at 0.3 s and then breaker closes at 0.5 s when fault is cleared for all 4 cases studies above. The breaker arc component demonstrates the impacts of the Mayr arc model on the arc behavior describing the arc characteristic during current zero-crossing. The TRV oscillation frequency depends on the inductance and capacitance (LC) parameters of source side circuit. It is observed that there is successful interruption of the arc in all scenarios.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Andrea, J. and Bournat, M. (2016). Model of an Electric Arc for Circuit Analysis. *28th International Conference on Electric Contacts, Edinburgh, United Kingdom,* 6th – 9th June 2016, pp. 361-366.

Andrea, J., Schweitzer, P., and Tisserand, E. (2010). A New DC and AC Arc Fault Electrical Model. *Proceedings of the 56th IEEE Holm Conference on Electrical Contacts (HOLM 2010), Charleston, South Carolina, USA,* 4th – 7th October 2010, pp. 1-6.

Bansal, R. (2019). *Power System Protection in Smart Grid Environment.* New York: CRC Press, p. 624.

Chen, T. and Ke, H. (2018). Modeling and Simulation of High Voltage Circuit Breaker Based on PSCAD. *Advances in Computer Science Research,* 65, pp. 155-159.

Das, J. C. (2012). *Power System Analysis.* 2nd Ed., New York: CRC Press, p. 1031.

Gupta, J. B. (2015). *A Course in Electrical Power.* 15th Ed., New Delhi: S. K. Kataria & Sons Publishers.

Jing, H. and Bing, S. (2014). Simulation Analysis on Dynamic Protection Characteristics of Low Voltage Circuit Molded Case Breakers Based on PSCAD/EMTDC. *Proceedings of the 33rd Chinese Control Conference, Nanjing, China,* July 28-30, 2014, pp. 6293-6297.

Lezama, J., Schweitzer, P., Weber, S., Tisserand, E., and Joyeux, P. (2012). Modeling of a Domestic Electrical Installation to Arc Fault Detection. *IEEE 58th Holm Conference on Electrical Contacts, Portland, OR, USA,* 23rd – 26th September 2012, pp. 1-7.

Mehta, V. K. and Mehta, R. (2008). *Principles of Power Systems. 4th Ed.,* New Delhi: S. Chand & Company Ltd, p. 608.

Obi, P. I., Okoro, C. K. and Okonkwo, I. I. (2020). Electrocution, Accidents and Electrical Injuries in Nigeria Homes and work sites – Causes, Effects and Remedies. *IOSR Journal of Electrical/Electronic Engineering (IOSR – JEEE),* 15(2), pp. 53-61.

Rao, B. K. and Gajjar, G. (2008). Modelling of SF6 Circuit Breaker Arc Quenching Phenomena in PSCAD. *Swicon Papers,* pp. 163-168.

Saitwal, K. V. and Khampariya, P. (2018). Research of Electric Arc Model for High Voltage Circuit Breaker Based on Matlab. *International Journal of Advance Engineering and Research Development (IJAERD),* 5(7), pp. 43-48.

Schavemaker, P. H. and Sluis, L. V. D. (2000). An Improved Mayr-Type Arc Model Based on Current-Zero Measurements. *IEEE Transactions on Power Delivery*, 15(2), pp. 580-584.

Van Lanen, P. A. and Popov, M. (2007). Vaccum Circuit Breakers Post Arc Current Modelling based on the theory of Langmuir probes. *IEEE Transactions on Plasma Science,* 35, pp. 925 – 932.

Xiang, W., Hua, Y., Wen, J., Yao, M. and Li, N. (2014). Research on Fast Solid State DC Breaker Based on a Natural Current Zero-Crossing Point. *Journal of Modern Power Systems and Clean Energy,* 2(1), pp. 30–38.

Xi-xiu, W., Zhen-Biao, L., Yun, T., Wenjun, M. and Xun, X. (2011). Investigate on the Simulation of Black-box Arc Model. *1st International Conference on Electric Power Equipment - Switching Technology, Xi'an, China,* 23rd – 27th October 2011, pp. 629-636.

Yao, F., Zhao, W., Wang, J. and Li, Z. (2019). Arc Extinction of DC Side Low-Voltage Breaker of Charging Device for Battery Pack in Power Plant Based on Insulated-Gate Bipolar Transistor Module Series Technology. *Journal of Engineering,* 2019(16), pp. 2312-2317.

Yuan, L., Sun, L. and Wu, H. (2013). Simulation of Fault Arc Using Conventional Arc Models. *Journal of Energy and Power Engineering*, 5, pp. 833-837.