A Three-phase Test Circuit Design for High Voltage Circuit Breaker Based on Modeling

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الخلاصة

تعتمد أنظمة الطاقة الكهربائية الحديثة في أدائها الى حداً كبير على عمل قواطع الدورة الكهربائية. يستخدم قاطع الدورة الكهربائية في أكتشاف اضطرابات الشبكة الكهربائية و لحماية الاجهزة الحساسة و المعدات غالية الثمن مثل المولدات و المحولات و غيرها من الاجهزة. لذا فأنها يجب ان تعمل ضمن سماحية ضيقة جداً خصوصاً في الشبكة الكهربائية التي تعمل تحت شروط خطاء دائرة القصر . ان تقييم كفاءة عمل قاطع الدورة امر مهم لآثبات قدرته على ايقاف تيارات الخطأ، خصوصاً تيارات دائرة القصر و لتحسين موثوقية الشبكة. تهدف هذه الورقة الى تصميم دائرة اختبار ثلاثية الطور تستعمل لتقييم اداء قاطع الدورة ذات الفولتية العالية تحت شرط خطاء دائرة القصر بأستخدام المحاكاة. بهذه الطريقة سيتم التغلب على صعوبات الاختبارات العملية كونها لا تحتاج الى قدرة كهربائية عالي من مصادر حقيقية و لها مرونة غير محدودة لضبط قيم عناصر دائرة الاختبار و غير خطرة و اقتصادية.

الكلمات المفتاحية

تيار الدائرة القصيرة، تيار القطع، نظام التشغيل، تيار الحقن، الحقن.

Abstract

Modern electric power systems performance depend significantly on the operation of circuit breakers. Circuit breaker are used to detect disturbance in the electrical network and to protect the sensitive equipment and costly instruments such as: generators, transformers, and many more. So, they must operate within extremely tight tolerances especially at the electrical network that operate under a short circuit fault conditions. Evaluation of work efficiency for circuit breaker is an important procedure for demonstrating its ability to curb fault currents, especially short circuit currents and for optimizing reliability of network. This paper aims to design a three-phase test circuit used to evaluate the performance of high voltage circuit breaker under short circuit fault by simulation. By this method, the difficulties of practical tests will be overcome, where it doesn't need high electrical power of real sources, unlimited flexibility to adjust the elements value of test circuit, safe from the risks, and economic because it dependent on modeling.

Keywords

Short Circuit Current, Interrupting Current, power system (P.S.), Current Injection, Interruption.

1. Introduction:

The purpose of circuit breaker (C.B) is to close and open the system to prevent effects of fault and connect/disconnect components of the electrical grid. The circuit breaker is a part of the protection system of the major in the electrical network such as generators, transformers and transmission lines. In general it have to fulfil various requirements to meet the different electrical and mechanical stresses during their lifetime. In addition to capability of C.Bs to the switching, their capability to the switching at the short circuit represents the most essential duty. The short circuit currents occur as transient condition which may reach up to (5 - 20) times from rated current with in about (50) msec; [1]. The protective relay detects this fault while the trip impulse is sent to the C.B which operate to interrupts that current as soon as possible. But this interruption itself will produce additional transients, overlapped with the instantaneous conditions for the electrical system. On this basis, the interrupting devices must be capable of handling the transients of the currents produced in the electrical system in addition to the transients of the voltage produced in the interrupting device itself. As illustrated in **Fig. (1)**, for the short circuit current transients waveform**,** the total current (I_{Total}) component from direct current (I_{dc}) plus the symmetrical breaking current ($I_{sym.}$).

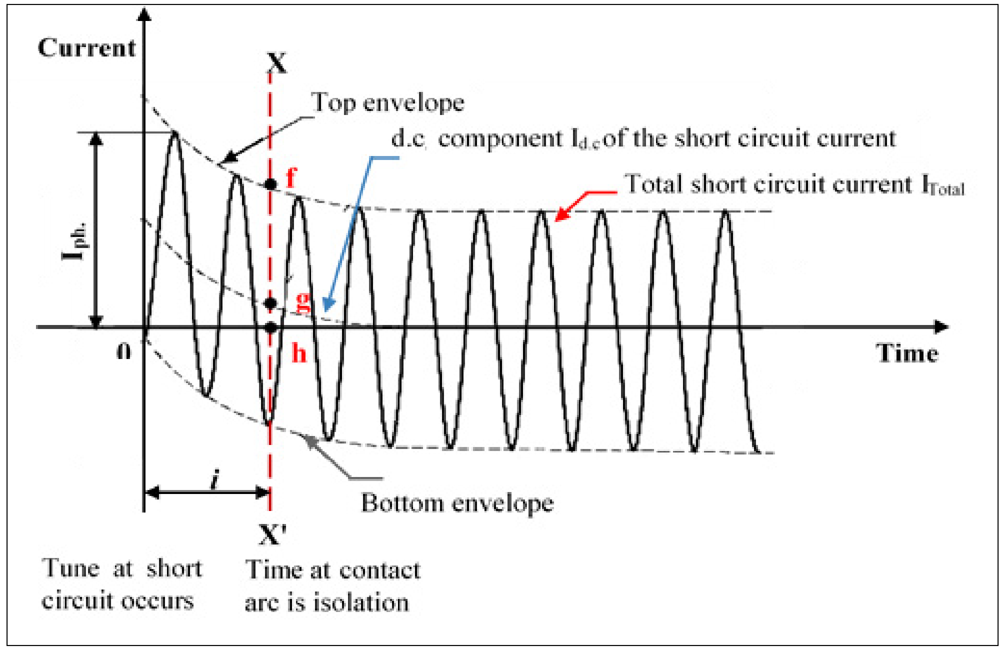

Fig. (1): Short circuit current transient's waveform [1].

Symmetrical and asymmetrical currents can be calculated based on the waveform of Fig. 1, Where, (X, X') a vertical line limited according to the arc isolation time and (*i*) the short circuit current in the limited period, while the points (**f**, **g**, and h) represent intersection points of line with top envelop, d.c component, and a time respectively.

$$I_{sym.} = \frac{fg}{\sqrt{2}} \qquad 1$$

$$I_{asy.} = \sqrt{\left(\frac{fg}{\sqrt{2}}\right)^2 + (gh)^2} \qquad 2$$

Where, ($I_{sym.}$) a root mean square (rms) value of alternating current in a time where the contact points been separated fully and ($I_{asy.}$) is (rms) value of asymmetrical breaking current. Therefore, the new developing in test of C.B have made it possible to improve and re-evaluate the conventional practical methods that sometimes require time and cumbersome steps [1, 2].

Many researches have been done in the performance evaluation, improving of the functions and in test of C.Bs. However, **Jamnani, et al.** [3] Designed and simulated a four- parameters Transient Recovery Voltage (TRV) synthetic test circuits by use Powersim Inc; (PSIM) simulator. **Jung, et al.** [4] developed several Laboratory tests to properly evaluate the three phase breaker performance. **Ebrahim, et al.** [5] simulated the generator-circuit-breaker (Gen. C.B) by use Alternative Transient Program- Electromagnetic Transient Programs ATP-EMTP and proposed a new technique to reduce a transient recovery voltage and a rate of rise of re-striking voltage during the switching period. **Mladen, et al.** [6] described a solution for automated analysis of circuit breaker operation based on advanced wavelet transforms and expert system for decision making. **David, et al.** [7] reviewed and simulate the transformer failures due to primary circuit breaker switching transients to indicate an effect of voltage surge, based on program of electromagnetic transients.

In this paper, the modeling of a test circuit (parallel current injection circuit) to evaluate the performance of a C.B in case of a short circuit occurrence accomplished. Phenomena which are related to test or behavior of the circuit breaker such as arc phenomena, a Transient Recovery Voltage (TRV), and Rate of Rise Re-striking Voltage (RRRV) are considered. Results of the simulation are showing the effect of interrupting current of short circuit and injection of high voltage through the tested C.B. Design of a circuit for short circuit test with their response to control on specification of (TRV and RRRV) wholly attained, according to International Electro technical Commission (IEC 62271-100) standards. Specifications of test circuit design with the two sources are: rated of a short circuit generator (230) kV AC and rated of a high voltage source with a capacitor bank (800) kV DC. While, specifications of the tested circuit breaker are: 3-phase, (195) kV rated voltage, (1.25) kA rated current, and (50) Hz line frequency.

2. The Injection Current:

The basic idea for this method is to produce a high current representing a short circuit current when the fault occurs. The proposed equivalent circuit of parallel current injection for test circuit of CB is illustrated in **Fig. (2).**

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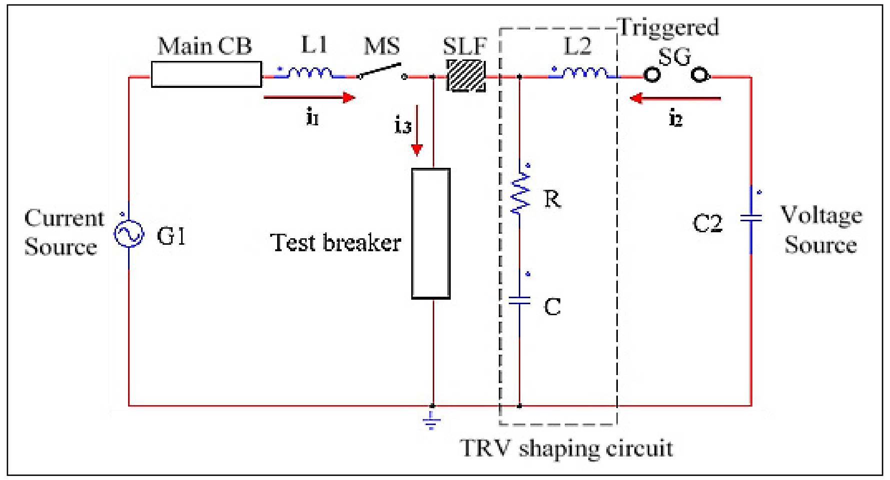

Fig. (2): Proposed circuit of parallel current injection for a CB test circuit.

The method is featured of this way by injecting a stream of current pulses, supplied from a high voltage source. The test circuit consists of two sources, the first for the high current and the second for a high voltage. The reactor (L1) is used to limit the current of short circuit, while the function of main C.B is to protecting the test Generator (G1). By using of the Making Switch (MS) the insulation between a current circuit and the voltage circuit is performed. (C2) represents a high voltage source with capacitor banks that is charged to the desired level of voltage. Voltage source with capacitor banks is connected in series from one side of Trigger Spark Gap (TSG), while the other side of the Trigger Gap (TG) is connected to group of (C, R and L2). A short line fault (SLF) and TRV shaping circuit are connect in series with (C, R and L2) reactors. This circuit consists of a combination of capacitors and reactors connected by (π) method. This group of frequency tuning reactors are used to control the TRV and RRRV. The relation between (i_1) the current of short circuit and (i_2) a current of DC source are illustrated in **Fig. (3).**

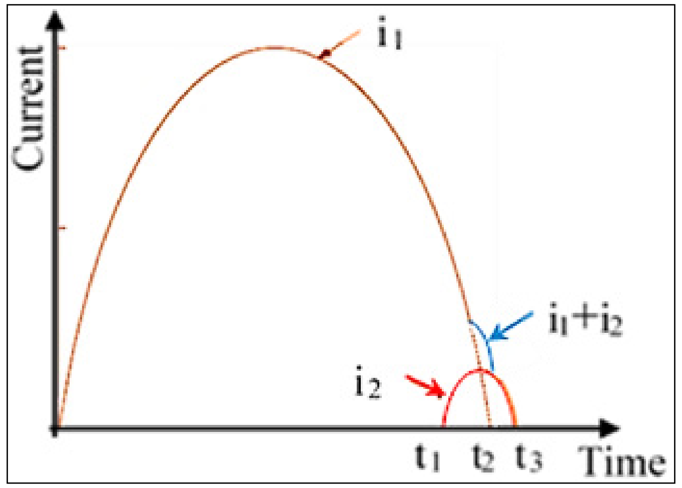

Fig. (3): The relation of the current at short circuit and the current flow from DC source [8].

However, a spark gap triggering when the current (i_1) is approaching from crossing zero at time (t_1), at the same time the injected current (i_2) begins flowing in test breaker. Now, two currents (i_1 plus i_2) are flowing through the tested circuit breaker until it reaches to t_2, where the current i_1 goes to zero. At t_2, the contact poles of tested breaker are separated and the injected current will be interrupting at t_3. The desired TRV will be appearing across the contacts of tested circuit breaker, during interrupting of high voltage that supplied from DC source [8, 9].

3. Simulink Model and Simulation Results

3.1 Simulink Model

In this model, the step up transformer is unused, where it is replaced by the voltage source which has the same required performance. The single-line diagram of proposed power system during the fault is illustrated in **Fig. (4).** One of the major regards that must be take in power system design, the short circuit currents and the suitable control on these currents. Location of faults occurrence is an important factor to compute, magnitude of a short circuit current.

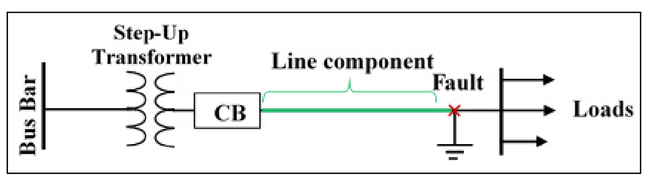

Fig. (4): Single-line diagram of the proposed power system during fault.

The impedance characteristics for the generator and an electric utility system, feed short circuit current when the short circuit occur. This short circuit current ($I_{s.c.}$) is calculated as in Eq. 3.

$$I_{S.C.} = \frac{E}{Z_t} \qquad 3$$

Where, (E) is the system driving voltage and (Z_t) total impedance of the system. So, the impedance constitutes an important factor to limit the magnitude of short circuit current.

3.1.1. Design of Transient Recovery Voltage for HVCBs:

According to the definition of **[10]** to the (TRV) for a High Voltage Circuit Breakers (HVCBs). The voltage appears across a breaker terminals when the current is interruption. This voltage is distributing on the equivalent circuit components for a (TRV), so the short circuit which fed from a generator, transformer and the transmission line for a voltage greater than (72.5) kV, must be depends the double-frequency (TRV) circuit. The circuit parameters of double frequency TRV, are illustrated in **Fig. (5).**

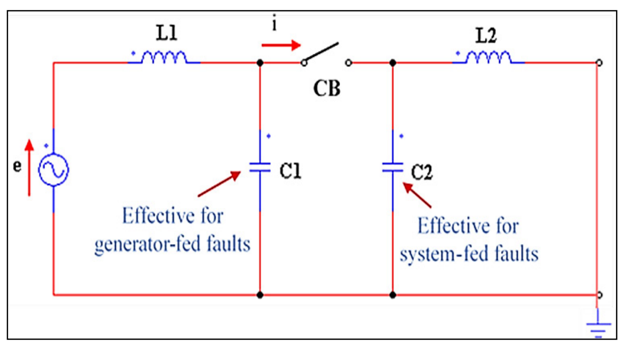

Fig. (5): The circuit of double frequency TRV [10].

The voltage source can be expressed as in Eq. 4:

$$e = E\cos\omega_s t \qquad 4$$

Where, **e** the voltage source of TRV circuit, **E** the system driving voltage, $\boldsymbol{\omega_s}$ system radian frequency, and **t** the time. When the C.B closed and be the inductance reactance is greater the resistance ($\boldsymbol{\omega_s L >> R}$) the current (i) as in Eq. 5:

$$i = \frac{E}{\omega_s L}\sin\omega_s t$$

So,

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt = E\cos\omega_s t$$

After solving the equation Eq. 6, can get an expression of single frequency (RV) across CB as in Eq. 7.

$$RV = E\left\{\cos w_s t - \exp^{\left(\frac{-Rt}{2L}\right)\cos\omega_n t}\right\} \qquad 7$$

Now, the frequency of oscillation for double frequency (TRV), according to the **Fig. (5)**; as in Eq. 8.

$$f_n = \frac{1}{2\pi\sqrt{L_n C_n}} \qquad 8$$

Where, **n** = 1, 2, $\mathbf{w_n}$ an input circuit natural radian frequency, and $\mathbf{w_s}$ the system radian frequency. The recovery voltage (**RV**) is calculated as in Eq. 9.

$$RV = E\left\{\frac{L_2}{L_1+L_2}\left(1-\cos\frac{1}{\sqrt{L_2C_2}}t\right) + \frac{L_1}{L_1+L_2}\left(1-\cos\frac{1}{\sqrt{L_1C_1}}t\right)\right\} \qquad 9$$

The natural frequency of the current in the capacitor calculate according to the value of inductance (L) and the value of capacitance (C). In many applications, frequency of inductance and capacitor circuit consider is greater than the system frequency. Because fault is a fully inductive mainly, the voltage of system will be shifting to (90°) from the phase of fault current. So, when the fault current approaching to zero, the system voltage will be approaching to the highest value [5, 11]. The relationship of TRV vs. voltage of system and current as illustrated in **Fig. 6**.

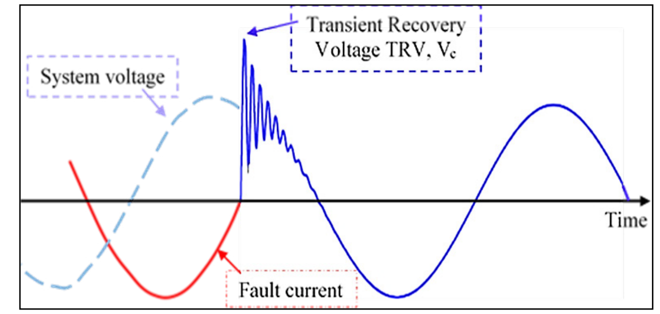

Fig (6): TRV vs. system voltage and current.

The response of the test circuit is specified to control the (TRV and RRRV) according to [11], which mention that the circuit breakers with a rated voltage above (100 kV), has TRV envelope defined by the four-parameter method. The TRV circuit for four parameters is illustrated in **Fig. 7**.

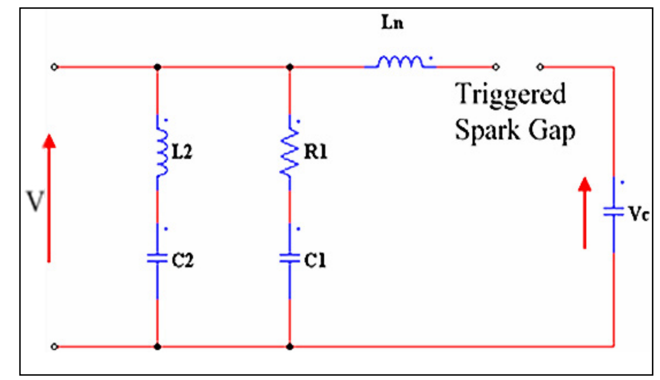

Fig. (7): Four parameters TRV circuit [12].

The envelope for four parameters circuit is illustrated in Fig. 8

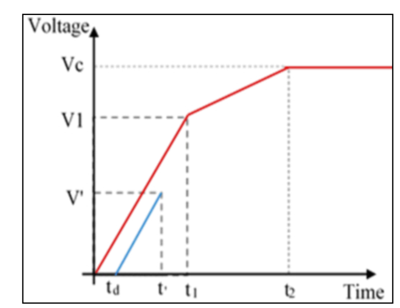

Fig. (8): Four Parameter TRV Envelope [12].

The TRV parameter is a function to rated voltage of the system (V_{rated}) in kV, so the first and second reference voltage, (V1) and (Vc) respectively are calculate as in Eq. below:

$$V_1 \text{ (First reference voltage)} = 0.75 \times k_{pp} \times V_{rated} \sqrt{\frac{2}{3}} \quad 10$$

Where, t_1 the time to reach (V_1) in μs, It is derived from (V_1) and the specified value of rate of rise re-striking voltage RRRV = V_1/t_1. Now, the time to reach (V_c) in μs, t_2 which is equal $4t_1$ for fault point closest to C.B and the fault of short line. In this case, the delay time ($t_d = 2\ \mu s$) because the rated voltage to the C.B is greater than to (100) kV.

$$V_c \text{ (TRV peak value)} = k_{af} \times k_{pp} \times V_{rated} \sqrt{\frac{2}{3}} \quad 11$$

And, $V' = 1/2\ V_1$

Where, (V_c) is (TRV peak value) or the charging voltage in kV. However, the power frequency component is given by factor called first-pole-to-clear (k_{pp}) that equals to (1.3) for fault point closest to C.B, while the oscillatory component which be aperiodic is given by amplitude factor (k_{af}) that equals (1.4) for fault point closest to C.B and fault of the short line according to [11].

3.1.2 Modeling of Short Circuit Generator

This type of generator have a special design where having very low reactance in order to give the maximum short circuit output. In this case, the Generator Circuit Breaker (GCB) is an essential to protect both of the generator and transformer. According to [11], the current of short circuit for the source system is generally greater than the source of short circuit current for the generator. So, the short circuit generator represented by the 3-phase AC voltage source. The parameter values of the generator model are (280) kV, (50) Hz, and an equivalent impedance for generator and transformer represented by a resistance (R=1Ω) and inductance (L=1mH), to obtain on desired performance for the voltage source.

3.1.3. Modeling of Charge Capacitor Bank

Use of large capacitor bank is required to the direct recovery voltage for any test method. The function of large capacitor bank is very necessary, for a wide range from the variable voltage. Therefore, the bank must be stored a sufficient energy, to supplying the injection current by the high frequency without distortion. In the practical tests for C.Bs, use of voltage source to fully charged the capacitor bank before it applying to test. However, modelling of capacitor bank achieved as a (DC) source is connect in a series with a capacitor from one side to the trigger spark gap (TG), this bank modeled to supplying (800) kV. To control on the frequency of circuit for short circuit tests, the other side from the (TG) connected to a group of reactors for tuning of frequency. Function of (TG) to control the injection instant in both current and voltage sources. While the purpose from utilizing of “trigger gap”, to make the electrodes capable to carry the injection currents repeatedly to a value above 5 kA. Modelling the work of the spark gap achieved by control of time switch.

3.1.4. Short Line Fault (SLF)

To make successful simulation to the breaker test circuit, must simulate the real conditions of the power system when the fault occurs. The transmission line characterized through distribution (per-unit-length), it contains a combination of series inductance and the shunt admittance. The short transmission line adopted in this paper, so the shunt admittance, the values of other circuit impedances that associated with CB, and the bus structure will neglect in a short circuit calculations. The series inductance (X_s) is calculated as an influential only element in the work of the circuit. The line impedance determined with value (27) mH, according to desired short circuit current ($I_{S.C}$) and Eq. 12.

$$X_s = \frac{E}{I_{S.C}}$$

3.1.5. The Reactors

Purpose of reactors are to limits a short circuit test current to protect the equipment from overheating due to losses and to protect the parts of the system fully [13, 14]. Additional reactor (X_a) calculate as in Eq. 13.

$$X_a = \frac{E}{I_{desired}} - \frac{E}{I_{available}}$$

Where, $I_{available}$ the available short circuit current from a source and $I_{desired}$ the desired short circuit current after add the reactor.

3.1.6. Modeling of Circuit Breakers and Making Switch

The function of the main CB is isolate the breaker under test and other equipment within the testing circuit, from the consequences of failure of the C.B under test in interrupted the fault current. Therefore the main CB it has higher capacity than the breaker under test. While the auxiliary breaker is used to insulate the current circuit from voltage circuit at the moment of applying (TRV) [14, 15]. An auxiliary circuit breaker is connect in series CB under test, which receives the same trip open impulse at the same time as the circuit breaker of the under test. The control on breakers achieved by using timers, where the switching time of the main CB is (0.2) Sec. but the switching time for the auxiliary CB is (0.0937) Sec. Making switch connects in series with the main CB, this switch begins allow short circuit current flow from the generator via the main CB at a precise point of the voltage wave. So, it is must closed after closing both of main CB and CB under test. The pre-arcing during closing of switch must be very little value, because it affect the consistency of point on control wave. Therefore, the action in high speed essentially in permitting the C.B for precision exertion at the moment of closure.

3.2. Simulation Results

Complete Simulink model of a three phase test circuit illustrated in **Fig. (9)**. Two different sources are used in this circuit, a source of short circuit current and a (DC) voltage source. Where, high voltage source, TRV shaping circuit, and the short line fault (SLF) used to providing a re-striking voltage to the C.B under test.

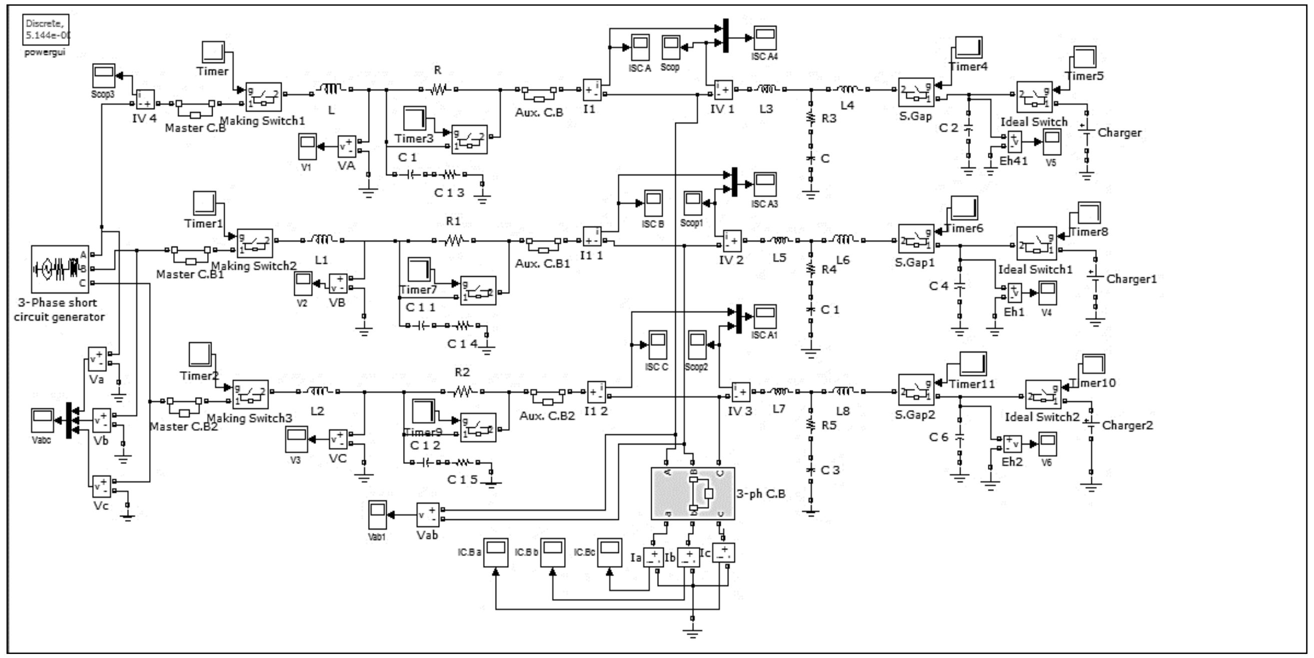

Fig. (9): The proposed design for a three-phase test circuit.

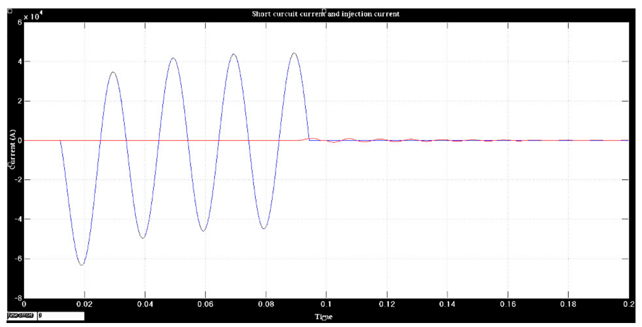

Fig. (10): The current of short circuit and the current of injection for one phase.

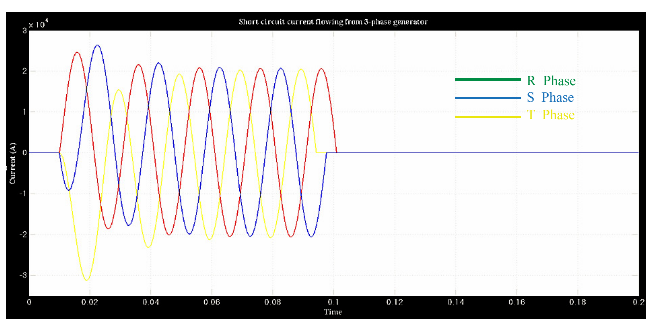

Fig. (11): Short circuit current flowing from short circuit generator.

Fig. (11), illustrate the current of short circuit supplied by 3-phase generator. Where, the waveform of short circuit current is affected by the (DC) and (AC) components that use in test circuit.

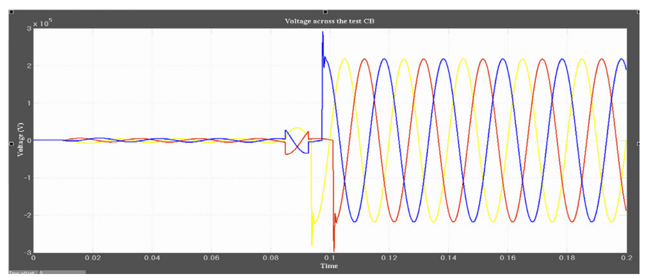

Fig. (12): Voltage waveform across the test C.B before and after the interrupting.

As illustrate in Fig. (12), the pole contacts for C.B are separating at (0.085) msec. so, effect of the arc voltage appears across the tested C.B when the value of the current becomes zero and be contacts of pole are opened fully.

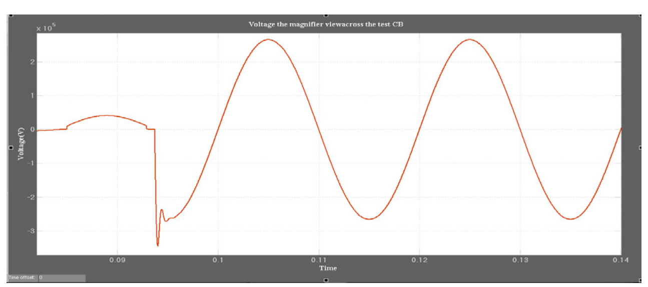

Fig. (13): The magnifier view to one phase for the arc, TRV and recovery voltage.

Fig. (13): illustrate the magnifier view for the effect of the arc, TRV and recovery voltage during the separation of the contacts of CB.

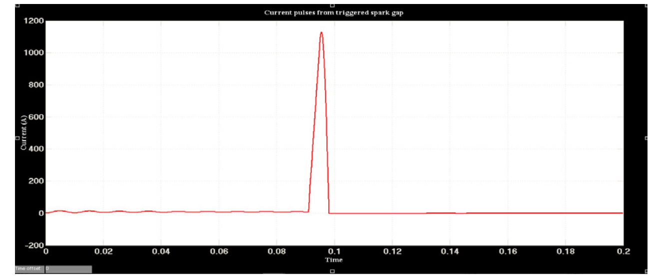

Fig. (14): Pulses of current from the triggered spark gap.

As illustrate in Fig. (14), the trigger time for the current pulse is setting at 0.085 msec; with the peak value is equal to (1180) V. During this time the arc voltage is fed to the tested CB by injection.

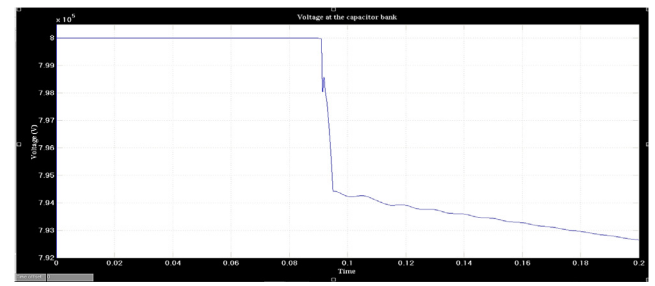

Fig. (15): Voltage at the capacitor banks.

As in Fig. (15), for the capacitor banks at a charge and discharge. Maximum charge value for a capacitor bank is (8×10^5) V, Where bank is fully charging before it use to supply the injection current at time (0.085) msec.

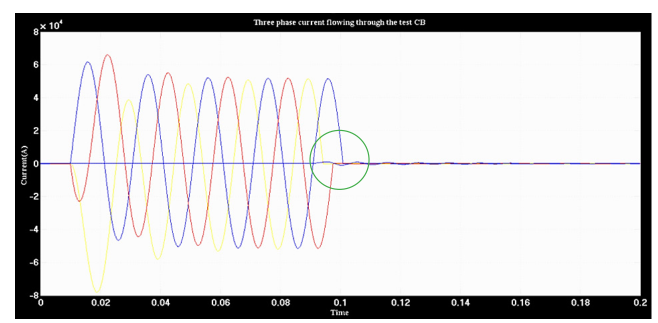

Fig. (16): Current of short circuit, the injection current, and the current will flowing through the tested C.B.

As shown in Fig. (16), a three-phase short circuit current with an effect of injection current which is indicated by the green circle.

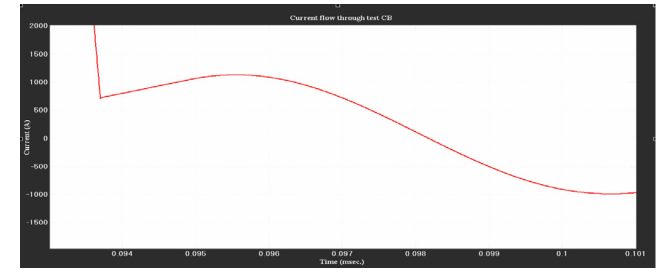

Fig. (17): The magnifier view for injection current flow through tested CB.

As illustrated in Fig. (17), peak value of injection current for a one phase (1.150) kA with time of (6) msec. the frequency of injection current before and after current zero is (667) Hz, this is compatible with a standard specifications which state "the frequency of injected current must be kept within the range of (300 - 1000) Hz".

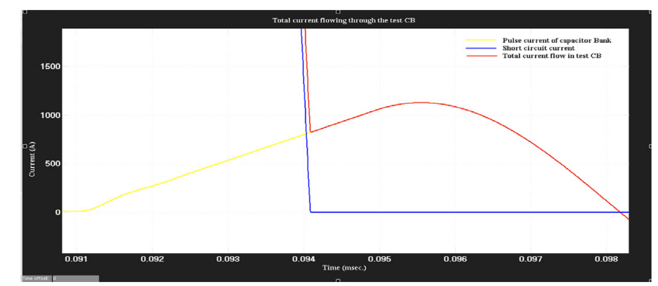

Fig. (18): The magnifier graphic for injected current, short circuit current and the total current flow through tested CB.

As illustrated in Fig. (18), three types of currents flowing in the tested CB. These currents are represents: current pulse from capacitor bank, short circuit current from short circuit generator and the total current which is value about (1.150) kA.

4. Conclusion

Current injection method is adopted in a design of a test circuit for a three-phase high voltage circuit breaker based on simulation. All the values of components which used in the simulation circuit attained in accordance with the standards of IEC, ANSI and IEEE. The proposed circuit, applied the full voltage test system for level of (230/200) kV kA. Accurate computations of circuit components TRV circuit, a short line fault, current limiting reactors, and the other components, gives realistic results. The control elements that used to regulate a time of injection current, have a significant role to make this procedures of the test asymptotic of truth. Circuit breakers have capability to interrupting this type of fault currents, provided that apply within their ratings. The simulation aspects of the test circuit that designed are: an inclusive, an adjustable, and very simple for the application.

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