An Innovative Simple Test Circuit for Single-Phase Short Circuit Making Test of High-Voltage Switching Devices

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Abstract:

Nowadays, high-voltage circuit breakers have reached such high short-circuit capabilities that testing them under the full rated voltage is generally not possible with direct tests, and they are conducted by using the synthetic test methods. Although the phenomena associated with making tests is of particular importance especially in case of load break switches, but making tests are rather disregarded in power studies. The aim of this paper is to present an innovative simple test circuit for single-phase short-circuit making test which can properly test the breaker at a reasonable cost, eliminating the need to large capacity power sources. The test circuit satisfies all relevant standard requirements and its results are conformable to those of reputable international testing laboratories.

Keywords: Circuit breaker testing, Making test, Switchgear testing, Synthetic test circuit.

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1. Introduction

Traditionally, The phenomena associated with the switching on, ”making”, of a short-circuit current in power systems have received much less attention than those accompanying the more critical interruption, “breaking”, of these currents. Nevertheless, the processes involved in making deserve appropriate attention from equipment designers, users of the apparatus, standardizing bodies and test laboratories. In the last decades it was well recognized, since the major international standards (IEC, ANSI) require full scale verification of the short circuit current making capability and thus, test laboratories need to have equipment to carry out such verification tests under realistic conditions [1].

One of the most important challenges that short circuit testing has always presented, is the development of appropriate test methods that can overcome the potential lack of sufficient available power at the test facility. One has to consider that the test laboratory should basically be able to supply the same short circuit capacity as that of the system for which the circuit breaker that is being tested is designed, however, this is not always possible, especially at the upper end of the power ratings [2].

Today it is impossible to conduct even unit tests under direct test methods. Thus, equivalent test methods are indispensable. Synthetic test methods are important equivalent methods that can be used for most tests of high-voltage circuit breakers [3].

The synthetic test method utilizes two independent sources, one, a current source, which provides the high current, similar to one used for direct tests, and second, a voltage source, which in most cases consists of a capacitor bank, charged to a certain high voltage that is dependent upon the rating of the circuit breaker being tested [4].

In this paper, a simple advantageous circuit for single phase testing of a three phase circuit breaker is introduced. The circuit can be categorized as a synthetic test circuit, taking advantage of a novel idea of using one other phase of the breaker under test as an auxiliary switch, for disconnecting the main switch from the high voltage source side.

The test set-up can be erected simply in any not advanced laboratory, eliminating the need to a high power specially designed short circuit generator, only available in few test stations among the world.

The test circuit is serviceable for a wide range of voltage and current ratings with no need to change the circuit component quantities. The only parameters to be changed will be the capacitor bank charge voltages, resulting in wide ranges of voltage and current applied to the breaker.

In the present study the conformity of the designed circuit with the standard test circuit requirements in terms of the applied thermal stress to the switching gap is discussed in more detail, concluding that this test set-up is much more severe than those using sinusoidal voltages. It must be taken into consideration that single-phase tests are naturally more severe than in the real situation where the highest recovery voltage is applied only on the first pole to clear [5].

Finally the theoretical and experimental results of the proposed test circuit are compared with those obtained from CESI Laboratories.

2. Standardization and Testing

It is now well recognized in the standards, that the verification of circuit breakers is an integral part of the certification procedure [1]. In the standard IEC 60265-1 and the new IEC 62271-100 (including reformed contents of IEC 60056 [6]) distinction is made between two extreme cases:

– Making at the peak of the voltage waveshape, leading to a symmetrical short-circuit current and the longest pre-striking arc;

– Making at the zero of the voltage wave, without pre-striking, leading to a fully asymmetrical short-circuit current.

The test procedure aims to demonstrate the ability of the circuit-breaker to fulfill the following two requirements:

a) The circuit-breaker can close against a symmetrical current as a result of the pre-arcing commencing at a peak of the applied voltage. This current shall be the symmetrical component of the rated short-circuit breaking current.

b) The circuit-breaker can close against a fully asymmetrical short-circuit current. This current shall be the rated short-circuit making current [7-8].

The second situation is only possible when closing speed is sufficiently high, causing the short circuit current initiate at voltage zero, thus providing the condition for maximum asymmetry, whereas slow contact approach inevitably leads to pre-strike near voltage maximum and symmetrical current. It can be understood easily that the pre-arcing stress due to the first situation is considerably higher than that in the second case.

Although the emphasis will be on circuit breakers, also some categories of high speed earthing switches and load breakers have to face the possibility of a closing-in into a short circuit. Due to their relatively low speed of making, pre-arcing times tend to be longer than those of circuit breakers, causing them to be subjected to a much larger pre-arc energy and symmetrical current, and so causing a significant building up of pressure by the pre-arc against which the mechanism must close and latch securely [1].

Taking all above into consideration, and also knowing that the severity of the making operation depends on the duration of the pre-arc, the proposed test circuit in this article will fulfill the first requirement, causing the test object to be subjected only to a symmetrical current.

3. Theoretical Considerations

3.1. Basic Test Circuit Principles

Figure 1 shows schematically the proposed test circuit. The circuit basically consists of 2 capacitors charged to certain voltage levels and a limiting reactor connected in series with the making switch. C_1 has small capacitance able to be charged to high voltages, where C_2 is a large capacitor charged to lower voltages. The sum of capacitor charge voltages is equal to the full rated phase to ground voltage to initiate pre-strike. The reactor main mission is to limit the magnitude of the test current to its required value. The values of L_1, C_1 and C_2 are selected to ensure a frequency equal to the rated frequency.

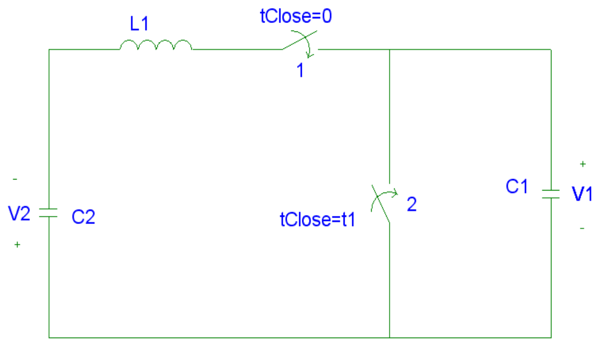

Fig. 1. Schematics of the proposed test circuit

Switch 1 is the main pole of three phase circuit breaker, subjected to test. While switch 2 in the proposed test circuit is another pole of the same three phase switch, just used for omitting the high impedance capacitor from the main switch current route, letting the short circuit making current flow through the test object.
The test sequence is started with capacitors charged to their required voltage levels and circuit breaker initially opened. When closing the three phase breaker, switch 1, the phase under test closes preceding switch 2 due to the larger voltage applied to its contacts. The instant of occurrence of pre-ignition in switch 1 is considered as time zero. Due to the high impedance of C_1, discharging of capacitors is negligible and so is the current amplitude flowing through switch.
After time of contact discrepancy between poles or jitter time, another pole of the switch pre-ignites (second switch in the proposed circuit closes), letting C_2 discharge through switches. This discharge creates a high-amplitude current passing through the test object with a first peak equal to the rated short circuit making current. The jitter time is a random variable depending on the type of the breaker. In following calculations jitter is considered as a Gaussian random variable with the standard deviation of 700 µs, this value has been derived from the mechanical tests of the switches used to perform the making tests with the proposed circuit. This means that for 99% of all cases the jitter is less than 2 ms.

3.2. Theoretical Results

In this section the test results of the test set-up designed for the testing of a disconnecting switch with following rated characteristics, are discussed:

Voltage	20 kV
Phase to earth voltage	11.55 kV
Frequency	50 Hz
Short-time withstand current	16 kA
Short-circuit making current	40 kA

The test set-up parameters resulting in a frequency of 50.3Hz, potential difference of 12 kV on test object sides and a first peak of making current of 45kA, is shown in figure 2. Where R_1 is the internal resistance of the reactor and R_2 and L_2 are the simulated resistance and inductance of the second switch.

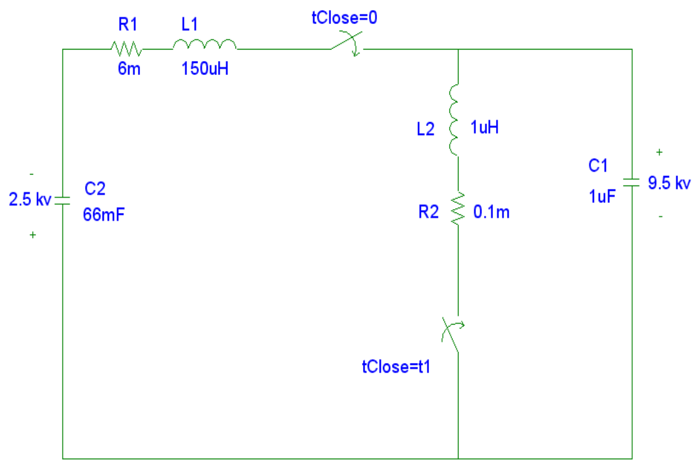

Fig. 2. Test circuit designed for testing 50 Hz breakers

This design can be used to test switches with rated frequency of 50 Hz and a wide range of rated voltage and rated short circuit making current, for this purpose the charge voltage of the capacitors has to be selected accordingly.
Figure 3 shows the current flowing through switch 1 while jitter time is equal to 2 milliseconds. The current can be determined by two time intervals.
Initially before closing of the second switch due to the high impedance of the equivalent capacitance of C_1 and C_2 in series, the current has a first peak of only 980 amperes and a frequency of 12995 Hz. The duration of

this current is maximum 2 milliseconds and so it can be disregarded in thermal stress considerations.

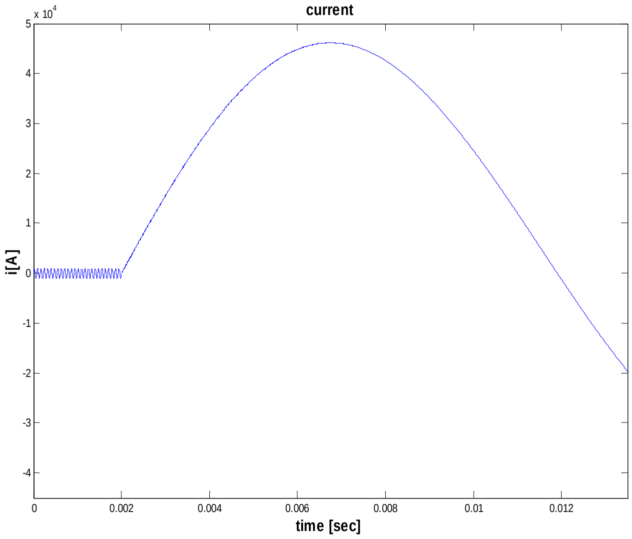

Fig. 3. Short-circuit making current passing through the test object

After this time span switch 2 closes and the capacitor C_2 is short circuited. This leads to an increase of the equivalent capacitance, consequently the current amplitude increases to 45 kA with a frequency of about 50 Hz.
The test characteristics such as frequency and voltage simply satisfy the standard requirements. The only requirement seems not to be satisfied is some current characteristics. Due to the standards for general purpose switches, the symmetrical rms value of current in each pole at 0.2s shall be at least 80 % of the rated short-time withstand current. Also the duration of the short-circuit current shall be at least 0.2s [8]. In some cases, where the total resistance of the test circuit is high, the current is damped rather fast and this condition can not be directly fulfilled. But the other parameters of the test circuit can be adjusted in such a way that the same stresses as indicated in standards are produced. This is discussed in detail in the next section.

3.3. Thermal Energy

High damping in designed circuit will cause the current amplitude in 0.2 second, to be less than 80% of first peak of current, as the result the thermal and mechanical stresses caused by current passing through the closed contacts are less than those recommended by standard requirements.
The thermal and mechanical stresses applied on the closed contact system are proportional to $\int i^2 . dt$, so in order to equalize these stresses caused by proposed test design with that of standard one, if there is no possibility to reduce the internal resistance of the reactor, the charge voltage of C_2 should be increased, resulting in an increase in the current amplitude and thermal energy, subsequently.

It must be noted that after closing and latching of the contacts to each other, the interrupter would be able to endure much more stresses without any serious damages such as welding and the must critical period in which the energy input to the breaker can result in melting and welding of contacts, is the period of pre-strike arc existence during a closing operation. The energy input to an interrupter during this period can be expressed in terms of current and the arc voltage as:

$$\mathrm{E}_{arc} = \int_{t\,arc} v_{arc} . i . dt \qquad (1)$$

The arc voltage (V_{arc}) in a given switching device is only a function of its contact distance, d, and is given by:

$$V_{arc} = V_0 + E_{plasma} . d \qquad (2)$$

Where V_0 is a constant value equal to the sum of cathode and anode voltage drops, approximately 15 – 20 V, and E_{plasma} is the plasma electric field.
It should be noted that the contact bouncing is not taken into consideration here, since the pre-strike arc vanishes by the first touch of contacts and the sum of energy of secondary arcs is negligible in comparison to the primary arc energy. The pre-ignition gap can be calculated as $d_{pre} = U_0 / E$, with U_0 being the sum of dc-charging voltages of C_1 and C_2, and E being the pre-ignition field strength [9]. With a nominal phase to ground test voltage of 12 kV and a constant pre-ignition field strength of 4kV/cm, a pre-ignition occurs on 3 cm contact distance, 15.3 milliseconds before galvanic contact touch.

The arc energy can be calculated as the sum of two terms:

$$\mathrm{E}_{arc} = \int_{t_{arc}} v_{arc} . i . dt = \int_0^{t1} v_{arc} . i . dt + \int_{t1}^{tend} v_{arc} . i . dt \qquad (3)$$

Where t_1 is the pre-ignition time of the second pole and t_{end} the instant of contact touch in the first pole. These two terms correspond to the contributions of the high frequency low amplitude current and low frequency high amplitude current as shown in figure 4, respectively. For the given waveform of figure 4, the energy is equal to 25.489 kJ; part of this energy is applied to the contact material resulting in its temperature rise.

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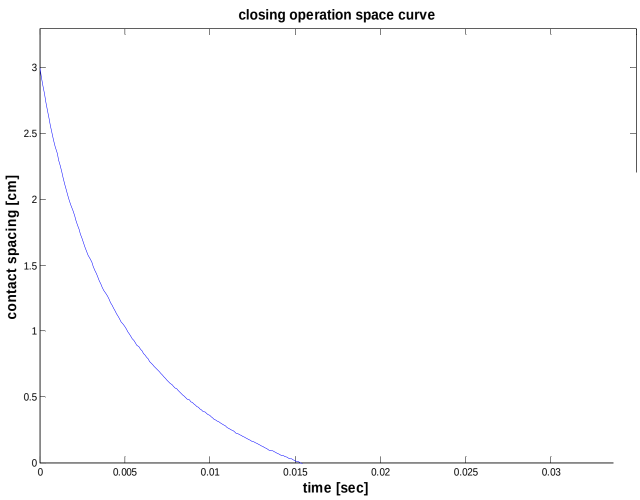
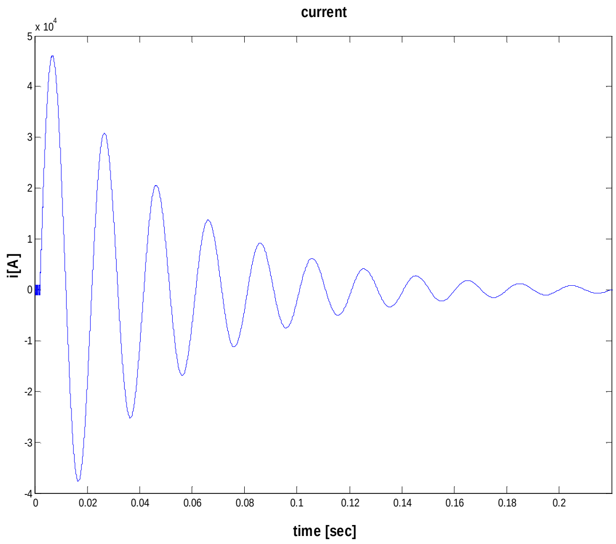


(a)



(b)

Fig. 4. (a) Contact distance and (b) making current with the same time zero. The time zero is the instant of occurrence of pre-ignition. Contact distance is a representative of arc energy

3.4. Pre-arcing Stress Probabilities

Because of the random nature of the closing time of the switches, the contacts can be closed at any point on the voltage waveshape [10]. So the voltage difference applied to contacts in the instant of closing the switch varies in interval of 0 to 1 pu, causing widely changes of arc energy quantity applied to contacts.

While in proposed circuit, using dc voltage equal to 1 pu, the arc energy is always equal to its maximum value.

Supposing that the closing time of the switch as a random variable has a uniform probability density function in the interval of one period of sinusoidal voltage waveshape, the probability density function of the voltage applied to the interrupter in the instant of closing are shown in figures 5.

As the figures depict the density of probability of happening the voltage in proposed circuit is an impulse on voltage 1 pu And the cumulative probability is a step function shifted by voltage 1 pu. In comparison with those of practical probabilities, it is obvious that the proposed test circuit is more severe than in practice.

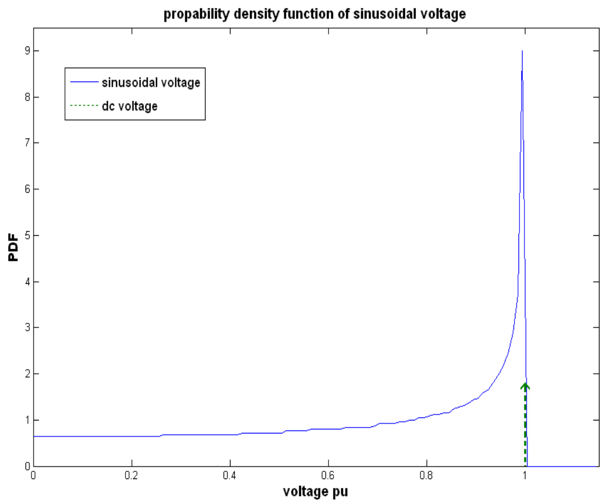


Fig. 5. Probability density functions of voltage applied to interrupter in instant of closing of contacts, for dc and ac voltage waves

The cumulative distribution functions of arc energy for AC and DC voltages are shown in figure 6. Because of jitter time variance, the cumulative probability of arc energy for dc voltage, is different from the corresponding probability of applied voltage, and is not a perfect step function. As we know the severity of the making operation depends on the duration of the pre-arc, and the energy applied to the test object [1], and so it can be concluded that this test method is more severe than those using ac voltages.

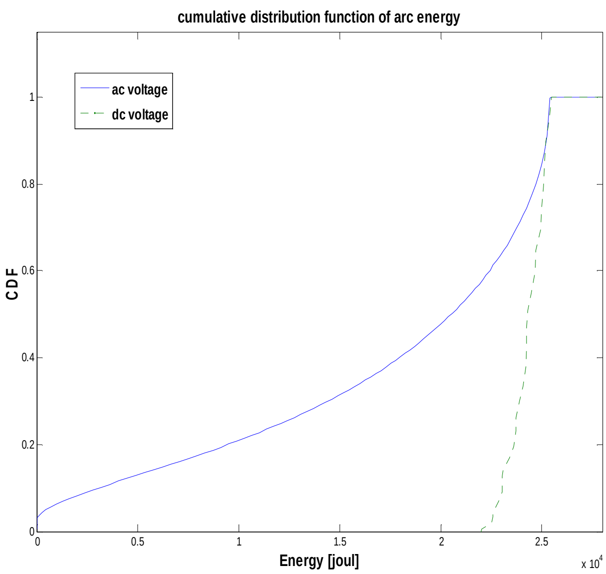


Fig. 6. Cumulative distribution functions of arc energy for ac and dc voltages

4. Experimental Results

In this section the results of short-circuit making tests carried out in CESI laboratories are compared with those obtained from short-circuit making tests of similar specimens using the proposed test circuit in this paper.

Two different load break switches were subjected to three-phase short-circuit making tests in CESI laboratories. The first breaker failed the tests while the second improved one, passed the tests successfully. Two resembling specimens of mentioned switches were subjected to single-phase short-circuit making tests by the proposed test circuit. The results were similar to those obtained in CESI laboratories. The rated characteristics of test objects are given below:

Voltage	24 kV
Frequency	50 Hz
Short-time withstand curren	16 kA
Short-circuit making current	40 kA

A travel curve for a closing operation of one of the test object during one of the single-phase making tests is shown in figure 7.

It can be seen that during the period of pre-arcing time this curve is similar to the typical travel curve used in section III.C. The pre-arcing time and distance are also similar, therefore the calculations of section III.B can be applied with good approximation to the real tests.

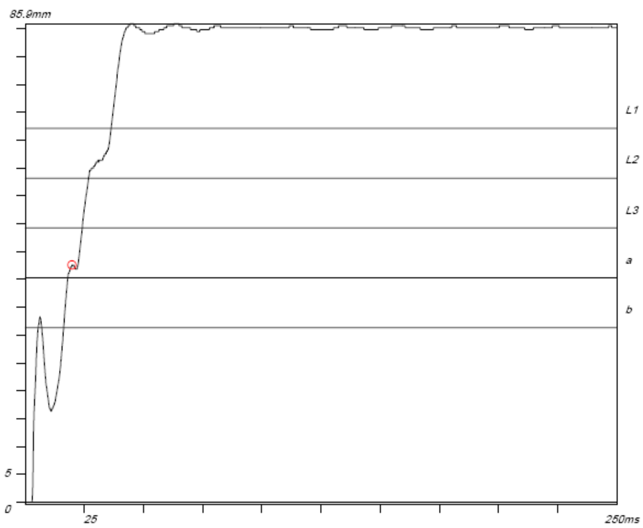


Fig. 7. Contact travel curve of a closing operation. The little circle shows the instant of pre-ignition

As it can be seen in fig. 7, after the contacts touch, the bouncing time and displacement of the contacts are small and therefore the arcing energy produced during the separation of the contacts after touching (secondary arc energy) is low compared to the pre-arcing period, therefore disregarding of the secondary arc energy in the calculation as stated in section III is justified.

In single-phase tests, the similar specimen to the first one tested in CESI laboratories, just failed the tests. Figure 8 and figure 9 show the failed specimens after direct making tests in CESI and indirect tests by the proposed circuit, respectively.

Fig. 8. Failed specimen in CESI laboratory direct tests

Fig. 9. Failed specimen in proposed single-phase test circuit

The resembling specimen of the second breaker, which successfully passed the CESI tests, similarly passed the single-phase tests using the proposed test circuit.

It should be noted that in order to fulfill the standard requirement of applying a symmetrical current to each pole of the test object directly, five three-phase making test procedures have been carried out on the test object.

While using the proposed test circuit in this article only one single-phase short-circuit making test for each pole will fulfill the standard requirement, applying a symmetrical current with the highest pre-arcing stress to the test object. It results to fewer numbers of tests and a limited number of circuit-breaker specimens for the entire series of type tests.

It must be taken into consideration that the proposed test method can be applied only if the right mechanical

operation of all three phases is assured and all three phases have the same making capabilities, these seem to be the case in all three phase switching devices, but nevertheless it must be noted that the proposed method can only be used to simplify the development tests and is not intended to replace the type tests in accredited laboratories needed to get the type test certificate.
Considering the fact that the whole investment for erecting the proposed test setup is less than one fifth of the sum necessary for using the high power laboratories for only one day, the proposed test circuit seems to be very cost efficient for development test purposes.

5. Conclusions

In this paper a new simple synthetic test circuit for making test of the high voltage switching devices is proposed. It has been shown that the parameters of the test circuit can be selected in such a way that all relevant standard requirements are fulfilled. Considering the probability of occurrence of the pre-strike during the making test, it has been shown that the proposed circuit applies the highest pre-arcing stress to the test object, this leads to the reduction of the number of necessary tests to meet the most severe condition for the switching device. Finally, the proposed circuit is used to perform making tests on two different load break switches and the results have been in good accordance to those obtained by direct making tests at a reputable test laboratory (CESI), Showing that the proposed test circuit, regardless of severity, is comparable with direct test circuits. Considering the very low cost of the proposed test set-up, it can be an ideal tool for switching device developers to easily ensure the performance of the switching devices by carrying out the making tests with stresses comparable to standard requirements before performing the rather high-cost direct tests at accredited laboratories.

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