Chapter-2

METHODS OF TESTING CIRCUIT-BREAKERS: A REVIEW

Short-circuit tests are conducted to prove the ratings of the circuit-breakers. The following short-circuit tests are conducted on circuit-breakers:

(1) Breaking capacity test

(2) Making capacity

(3) Duty cycle test

(4) Short Time Current Test

Short-circuit tests can be performed either by direct testing or indirect testing methods.

2.1 Direct Testing

IEC Standards definition of direct test is as follows:

" A test in which the applied voltage, the current and the transient and power-frequency recovery voltages are all obtained from a circuit having a single power source, which may be a power system or special alternators as used in short-circuit testing stations or a combination of both"[25].

A direct test is one where a three phase circuit-breaker is tested, on a three phase system, and at a short circuit MVA level equal to its full rating. In other words this is a test where a three phase circuit-breaker is tested on a 3-phase circuit at full current and full voltage. It should be obvious that testing a circuit-breaker under the same conditions at which it is going to be applied is the ultimate demonstration for its capability and naturally, whenever possible, this should be the preferred method of test. In direct testing, the circuit-breaker is tested under the conditions which actually exist on power systems and it is subjected to transient recovery voltage (TRV) which is expected in practical situations[1],[3].

In direct testing , the short circuit tests are conducted in short circuit testing stations and are mainly to prove the ratings of the circuit breaker. There are two types of short-circuit testing stations:

(1) Field type testing station

In this, the tests are conducted taking power directly from the system.

(2) Laboratory type testing stations

It has short-circuit generators to supply power for the short-circuit testing.

The short - circuit testing stations consists of the following equipments/components:

(i) Short circuit generator

(ii) Short-circuit transformer

(iii) Master circuit-breaker

(iv) Making switch

(v) Capacitors

(vi) Resistors and reactors

In direct testing, the circuit-breaker is tested under the conditions which actually exist on power systems. It is subjected to restriking voltage which is expected in practical situations. Fig.2.1 shows an arrangement for direct testing. The reactor L is to control short-circuits current. C, R_1 and R_2 are to adjust transient recovery voltage.

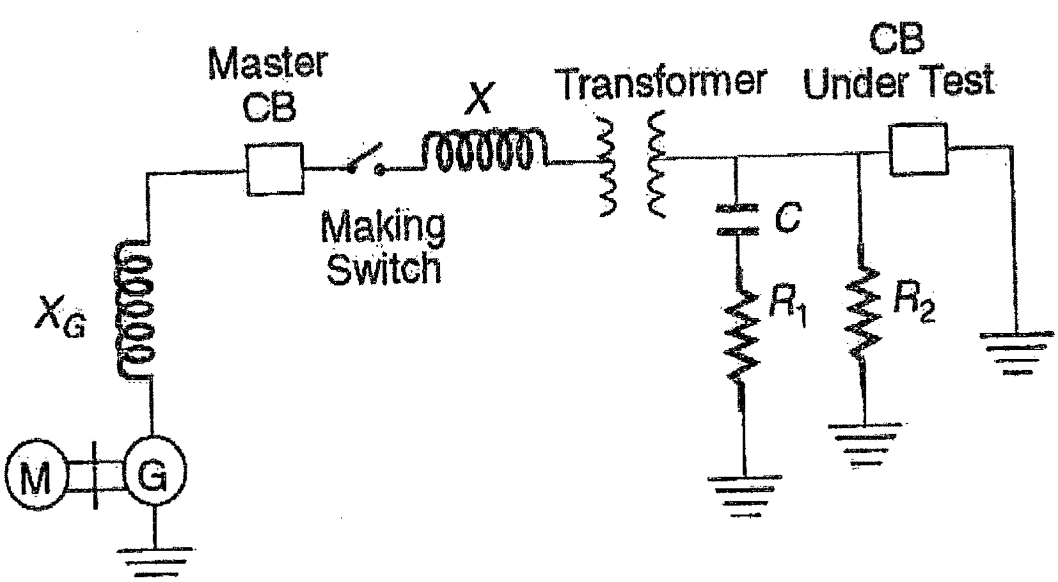


Fig.2.1 Circuit arrangement for direct testing

2.2 Necessity of Indirect Testing

Development in Electrical power transmission system requires the use of circuit-breakers with increasing breaking capacity. At present circuit-breakers are to be installed on 245kV to 1100kV power system with short-circuit ratings up to 120kA.

To test high voltage circuit-breakers, direct testing using the power system or short-circuit alternators are not feasible. The testing of high voltage circuit-breakers of larger capacity requires very large capacity of testing station. To increase testing plant power is neither an economical nor a very practical solution. Even a single pole of EHV circuit-breaker can not be tested by direct means.

The largest test facility in the world, KEMA high power laboratory, with a maximum short-circuit power of 8400MVA and a 145kV, 31.5kA, 3-phase direct test capability, is limited in its power to perform the direct tests. At the present time a complete pole of SF_6 circuit-breaker can consist of a single interrupting chamber with an interrupting power above the 10GVA level. Even KEMA'S high power laboratory can not verify the short-circuit interrupting capability by direct test methods[15],[18].

Direct testing facility available at CPRI high power laboratory in India is of 2500MVA capacity at 36/72.5kV in three phase and 1400MVA capacity, up to 245kV in single phase for testing of circuit-breakers[Appendix-A].

The limitations of direct testing using the power system or short-circuit alternators are as follows :

- High cost of installation of testing stations
- Availability of limited power for testing of high voltage and Extra high voltage circuit-breakers
- Requires high power for testing circuit-breakers
- Flexibility of the system available is limited.

Therefore Indirect methods of testing are used for testing of large circuit-breakers. Synthetic testing is an alternative equivalent method for testing of high voltage circuit breakers and is accepted by the standards.

2.3 Indirect Testing Methods

The Indirect testing methods can be classified as Unit testing and synthetic testing

Unit Testing

The IEC standards definition of unit testing is as follows:

"The test made on a making or breaking unit or group of units at the making current or the breaking current, specified for the test on the complete pole of a circuit-breaker and at the appropriate fraction of the applied voltage, or the recovery voltage, specified for the test on the complete pole of the circuit-breaker"[25].

Unit testing means testing one or more units separately. Generally, high voltage circuit-breakers are designed with several arc interrupter units in series. Each unit can be tested separately. From the test results of one unit, the capacity of the complete breaker can be determined.

The unit testing method is used in laboratory to test Extra and ultra high voltage circuit-breakers at present. With this method, interrupting units are tested at a part of rated voltage of the complete breaker. This method is recognized by the IEC standard, but one major problem remains, namely the influence of the post-arc conductivity on the voltage distribution across the units. The trend of increasing the interrupting capability of a single interrupting unit will result in it being impossible to test a single unit in the high power laboratory[18].

Synthetic Testing Method

Synthetic testing is an alternative equivalent method for testing of high voltage circuit-breakers and is accepted by the various standards.

In synthetic testing, there are two sources of power supply for the testing:

(i) Current source

(ii) Voltage source

The current source is a high current, low voltage source. It supplies short-circuit current during the test.

The voltage source is a high voltage, low current source. It provides transient recovery voltage.

2.4 Principle and Advantages of Synthetic Testing

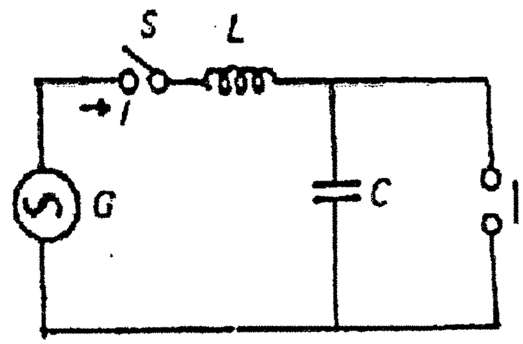


Fig.2.2. Basic circuit for testing Circuit-breaker

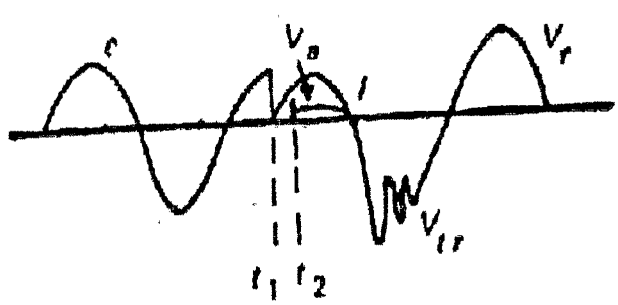


Fig. 2.3 Voltage waveforms across test Circuit-breaker

Fig.2.2 shows the basic circuit for testing circuit-breaker. When switch S is closed, short- circuit current I flows through the breaker B and when the test breaker B begins to open an arc voltage V_a appears across the breaker terminal as shown in Fig.2.3. At current zero when the arc is extinguished a transient voltage V_{tr} appears across the breaker, whose form is determined by the generator characteristics and the circuit constants L and C. The breaker has to withstand this transient recovery voltage if it is to clear the circuit.

So in actual practice, during the period of main short circuit current flow, there is comparatively small arc voltage appears across the breaker and that during the period of transient recovery voltage very little or no current flows through the breaker. Therefore there is no need to use a single high power source. Instead, the current can be supplied by a comparatively low voltage source, since the arc voltage is usually very small, 1 to 3% of the rated voltage of the breaker, and the voltage can be applied from low energy high Voltage, low current source at the point of current zero to simulate transient recovery voltage.

Main Advantages of synthetic testing are as follows:

- The breaker can be tested for desired TRV and R.R.R.V.
- The short-circuit generator has to supply current at a relatively less voltage as compared to direct testing.
- Both test current and test voltage can be independently varied. This gives flexibility to test.
- Very simple method of testing and can be applied to unit testing also.
- With this method a breaker of capacity (MVA) of five times that of the capacity (MVA) of the test plant can be tested.
- Synthetic testing is of a non-destructive nature and therefore they are ideal for development test purposes, where the ultimate limits of the device can be explored without destroying the test model [1].

2.5 Types of synthetic test circuits

Several synthetic testing methods have been developed and their performances have been studied in the past forty years [1],[3], [26], [28].

If the source of energy during the interaction interval is used to classify the methods adopted, they can be distinguished by two basic methods:

(i) Current injection and

(ii) Voltage injection method.

Depending on whether voltage circuit or source is switched on before or after current zero, the type of synthetic testing is known as current injection or voltage injection respectively.

Further the current injection method can be classified as parallel current injection and series current injection method.

In parallel current injection method, the voltage circuit is inserted in parallel with the test breaker, while in series current injection method, it is inserted in series. The parallel current injection type synthetic testing is popular in Germany and is known as Weil - Dobke circuit. The series current injection type synthetic test circuit was suggested by Koplan Bashatyr (U.S.S.R) and is known as Russian circuit.

In voltage injection method, the voltage source is switched on after the current zero. This method was suggested by Siemens, Germany.

2.6 Current Injection Methods

In a synthetic test circuit using current injection, the superposition of the currents takes place shortly before the zero of the power-frequency, short-circuit current. A current of smaller amplitude but higher frequency, derived from the voltage circuit, is superimposed either in the test circuit breaker or in the auxiliary circuit-breaker.

These methods can be described in terms of general principles as follows:

- The current from the voltage circuit is superimposed on the power frequency current through the test circuit-breaker prior to the interaction interval;
- An auxiliary circuit-breaker interrupts the current from the current circuit prior to the interaction interval.

During the interaction interval, the test circuit-breaker is exposed to the voltage of the voltage circuit having an impedance which is representative of the reference system conditions. This explains the validity of current injection methods.

Several current injection methods are known but Parallel current injection is used by the majority of the test laboratories.

The following conditions shall be met:

(a) TRV wave shape circuit

- The shape and magnitude of the prospective TRV shall comply with the specified values
- The combination of the stray and lumped capacitance C_{dh} in parallel with Z_h gives rise to the delay time $t_d = Z_h \times C_{dh}$

(b) Frequency of the injected current and the injection timing

- The frequency of the injected current shall preferably be of the order of 500Hz with a lower limit of 250Hz and an upper limit of 1000 Hz.

- The initiation of the injected current shall be adjusted such that the time, during which the test circuit-breaker is fed only by the injected current, is not more than a quarter of the period of the injected current frequency with a maximum of 500μs.

2.6.1 Parallel current injection method synthetic test circuit [1], [2], [5]

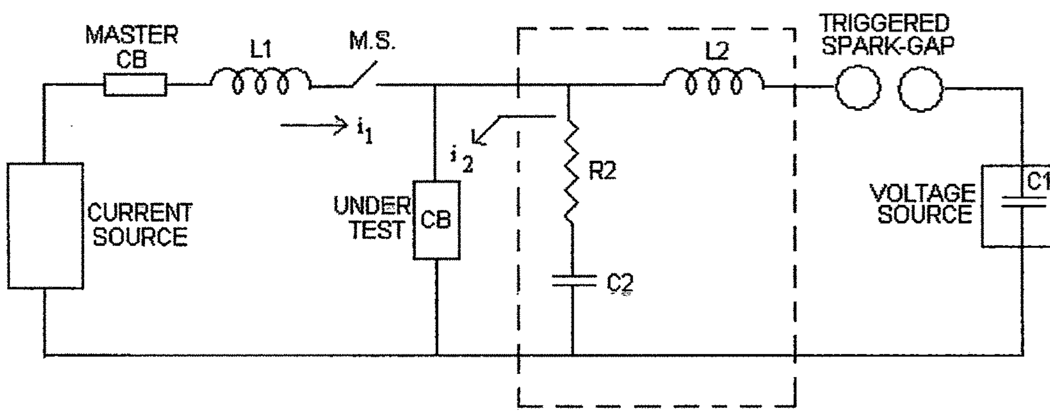


Fig.2.4 Schematic diagram of a parallel current injection method synthetic test circuit.

Fig.2.4 shows schematic diagram of a parallel current injection method synthetic test circuit. The high current source is a motor driven generator. It injects a high short-circuit current i_1 into the circuit-breaker under test at a relatively reduced voltage. The inductance L1 is to control the short-circuit current. The master circuit-breaker and the circuit-breaker under test are tripped before current i_1 reaches its natural zero. These circuit-breakers are fully opened by the time t_2.

The master CB (MB) is used as backup circuit breaker. If the CB under test (TB) fails to operate, the master CB opens. Also after every test, it isolates the CB under test from the supply source. Make switch (MS) is used to apply short circuit current at the desired moment during the test. For the operation of the circuit, first of all the MB and TB are closed. Then the short circuit current is passed by closing Make switch (MS).

The capacitor bank C1 is a high voltage source. It is charged to give the required recovery voltage. L2, R2 and C2 are to control transient recovery voltage and RRRV. The magnitude and frequency of transient recovery voltage (TRV) depend on the voltage to which the capacitor bank C1 is charged and the circuit parameters. The triggered spark gap is fired slightly before the short circuit current i_1 reaches its natural zero. There is a control circuit to fire the triggered spark gap at the desired moment. The closing and opening of the circuit breakers at the desired moment is done by the Automatic controller.

In Fig.2.5 and Fig.2.6, the relationship between the power frequency and the injected current is shown.

The test is initiated by closing the making switch (MS), which initiates the flow of the current i_1, from the high current source through the isolating breaker and test breaker(TB). As the current approaches its zero crossing the spark gap is triggered and at time t_1, the injected current i_2 begins to flow. The current $i_1 + i_2$ flow through the test breaker until the time t_2 is reached. This is the time when the main current i_1 goes to zero and when the isolation breaker separates the two power sources.

At time t_3 the injected current is interrupted and the high voltage supplied by the high voltage source provides the desired TRV which subsequently appears across the terminals of the circuit-breaker that is being tested.

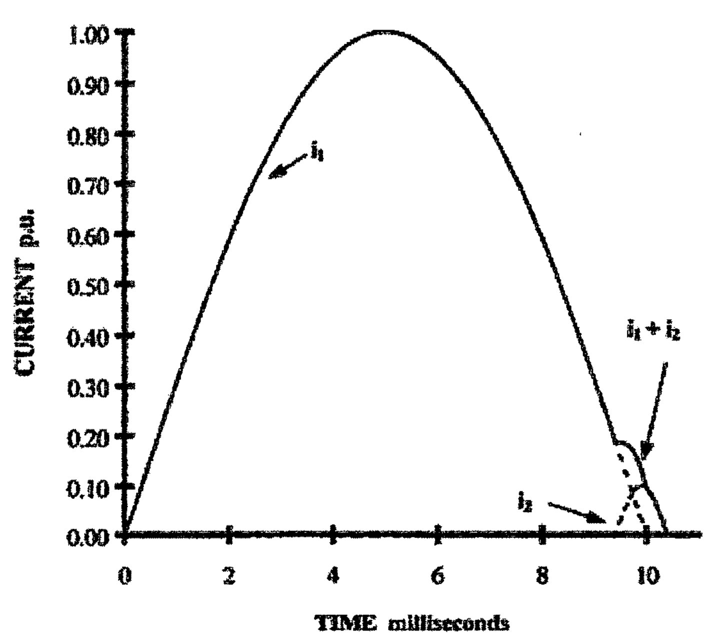


Fig.2.5 Relationship between primary current and injected current in a synthetic test parallel current injection scheme

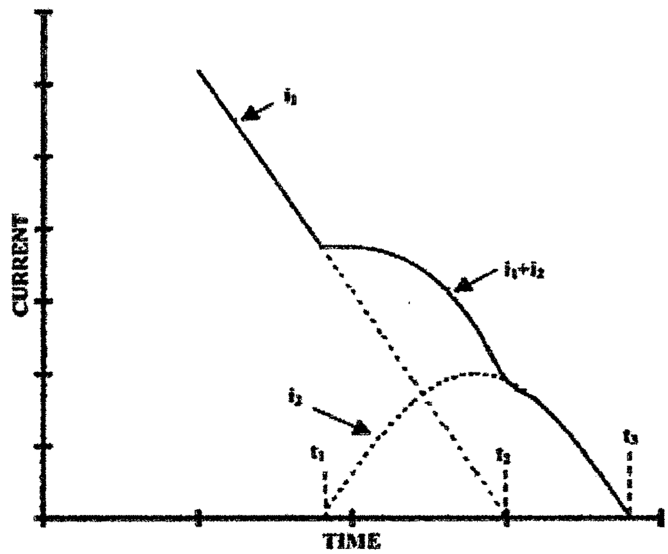


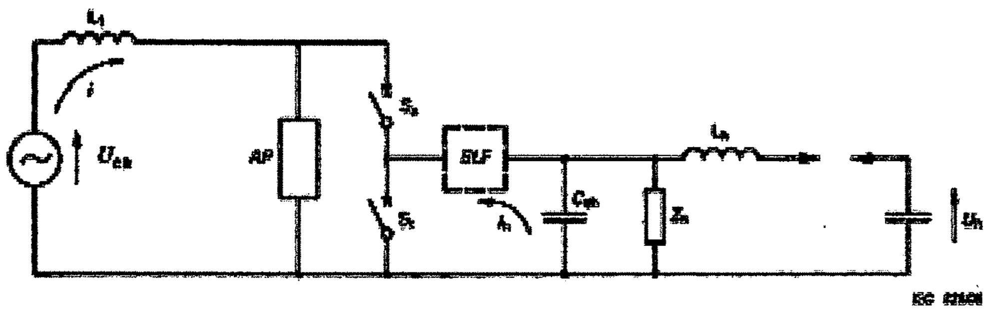
Fig.2.6 Expanded view of the parallel current injection near current zero

Sequence of operation

- At time t_0, the make switch M is closed and the normal power frequency current i_1 flows in the circuit-breaker under test.
- At time t_1, the spark gap S is fired and the current i_2 flows in the test breaker. The frequency of this current is determined by L_2 and C_2 so that peak approximately coincides with zero of current i_1.
- The current $i_1 + i_2$ flow through the test breaker until the time t_2 is reached. This is the time when the main current i_1 goes to zero and when the isolation breaker separates the two power sources.
- At time t_2, when the current i_1 becomes zero it is interrupted by the auxiliary breaker and the test breaker carries current i_2 from the voltage circuit.
- When this current becomes zero at time t_3, the transient recovery voltage (TRV) appears across the circuit-breaker under test. The magnitude and the frequency of this TRV depend on the voltage to which the capacitor C_1 is charged and the circuit parameters L_2 and C_2.

Breaking capacities up to ten or more times the short- circuit capacity of the short-circuit generator can be achieved.

*** Current injection circuit with the voltage circuit in parallel with test circuit-breaker (parallel circuit) as per IEC 62271-101** [26],[28]



Key

U_{ea}	voltage of current circuit	C_{dh}	capacitance for time delay of voltage circuit
L_1	inductance of current circuit	L_h	inductance of voltage circuit
AP	are prolonging circuit	U'_h	charging voltage of voltage circuit
S_a	auxiliary circuit-breaker	i	current of the current circuit
S_t	test circuit-breaker	i_h	injected current
Z_h	equivalent surge impedance of voltage circuit	SLF	short-line-fault circuit (for the corresponding tests)

Fig.2.7 simplified circuit diagram of a current injection circuit with the voltage circuit connected in parallel with the test circuit-breaker as per IEC 62271-101

Fig.2.7 shows the simplified circuit diagram of a current injection circuit with the voltage circuit connected in parallel with the test circuit-breaker. The voltage circuit is switched in shortly before the zero of the power-frequency short-circuit current, prior to the interaction interval. At this time the high frequency oscillatory current i_h is superimposed on the power-frequency short-circuit current i , with the same polarity to give a resultant test current in the test circuit-breaker.

After the auxiliary circuit-breaker interrupts the power-frequency short-circuit current i, the test circuit-breaker is connected only to the voltage circuit and i_h is the only remaining current. The voltage circuit also provides the recovery voltage across the test circuit-breaker after the current is interrupted.

Figure 2.8 shows an example of injection timing. The two points on inflection typically indicate the start of the current injection in the test circuit-breaker and the interruption of the power-frequency short-circuit current by the auxiliary circuit-breaker. The wave shape of the transient recovery voltage can be adjusted by varying Z_h and C_{dh} to obtain compliance with the requirements of IEC 62271-100.

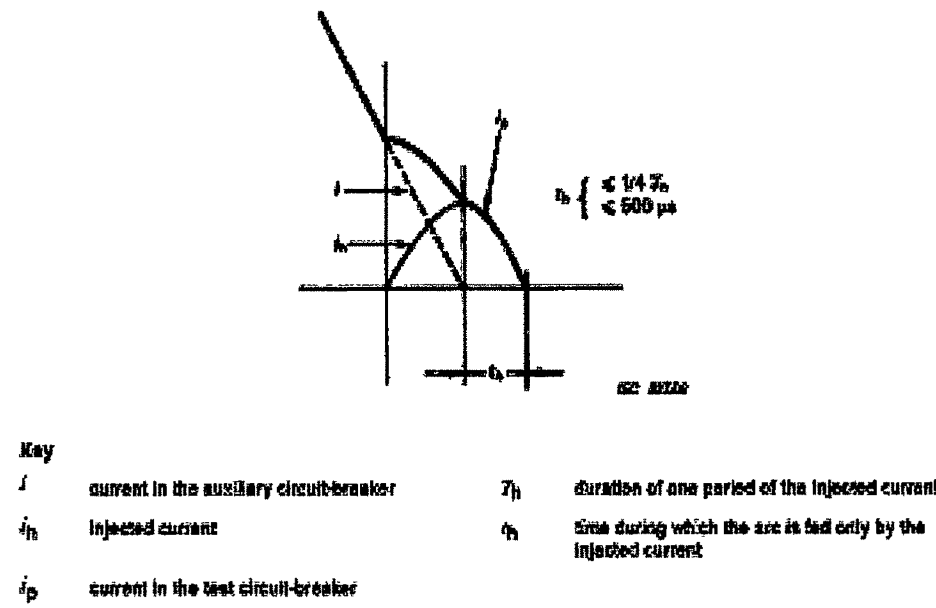


Figure 2.8 an example of injection timing.

2.6.2 Series Current Injection Method Synthetic Test Circuit [1], [3]

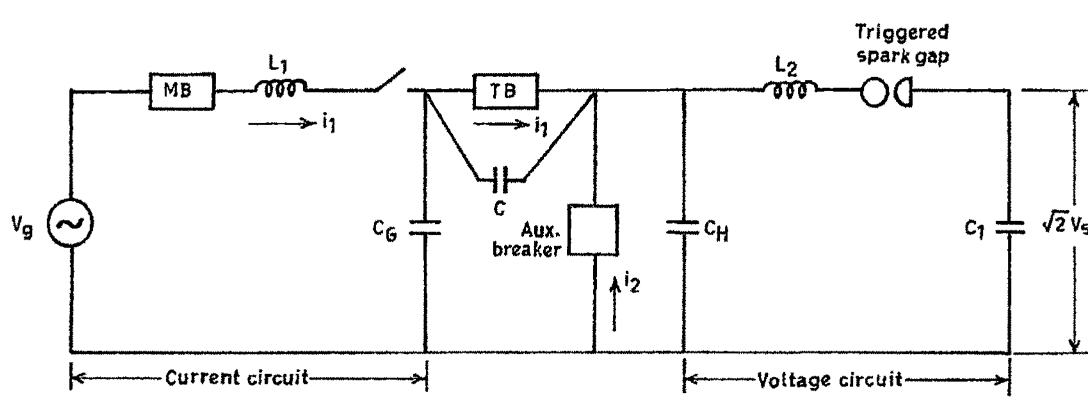


Fig.2.9 Schematic diagram of a series current injection method synthetic test circuit

Fig.2.9 shows schematic diagram of a series current injection method synthetic test circuit. In this method , the voltage circuit is connected across the auxiliary breaker, instead of the test breaker and the source capacitance. The voltage circuit is connected to current circuit in series before main current zero.

The capacitor C_1 is charged to the opposite polarity, so that injected current flows in the opposite direction to the power frequency (50Hz) current i_1 and thus subtracts from it.

As the current and voltage circuits are series connected, it is difficult to select circuit parameters to suit both the current and voltage circuits which would at the same time give the required transient recovery voltage.

At time t_2, when the currents i_1 and i_2 are equal and opposite, the current in the isolating breaker is interrupted and during the time from t_2 to t_3, the current flowing through the test breaker is i_3.

In Fig.2.10 and Fig.2.11, the relationship between the power frequency and the injected current is shown.

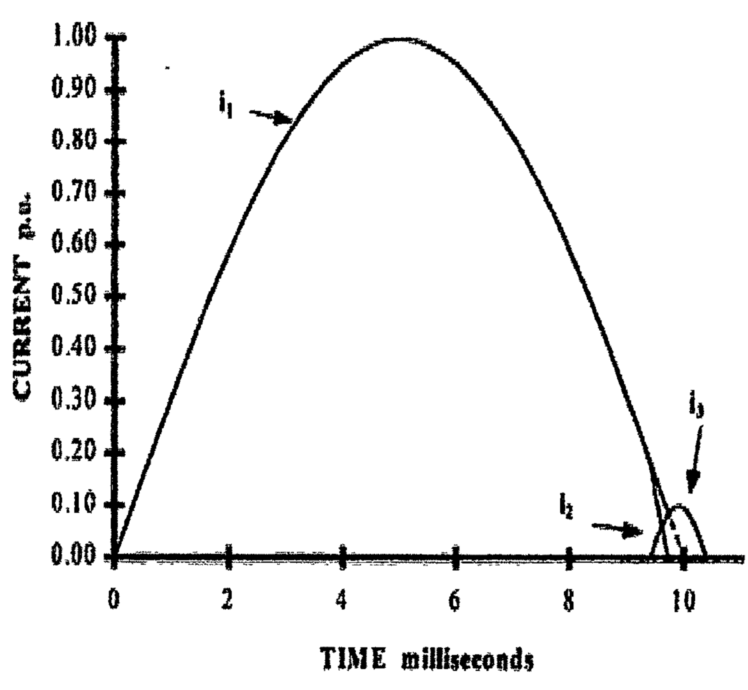


Fig.2.10 Relationship between primary current and injected current in a synthetic test series current injection scheme

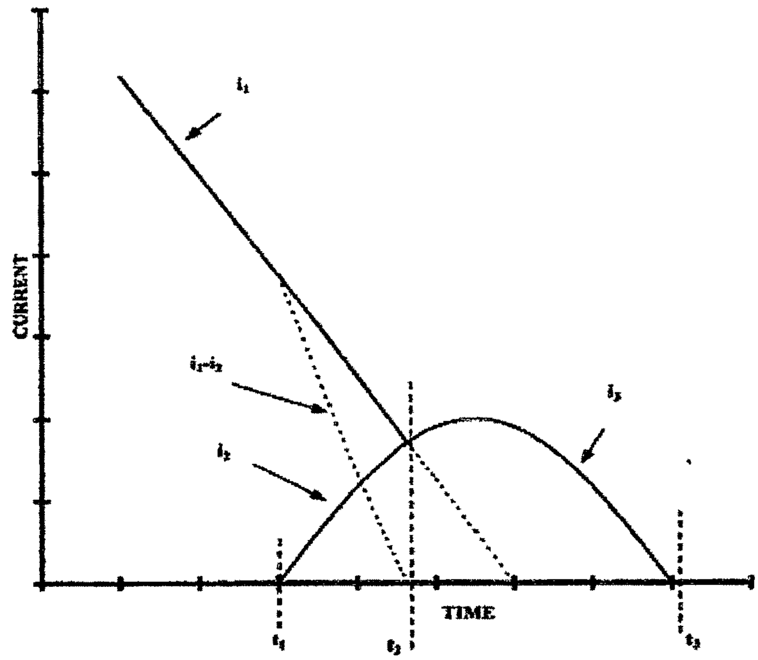
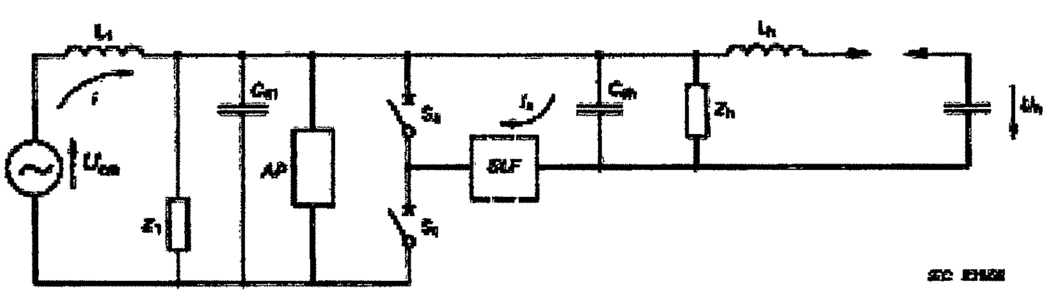


Fig.2.11 Expanded view of the series current injection near current zero

*** Current injection circuit with the voltage circuit in parallel with the auxiliary circuit- breaker (series circuit) as per IEC 62271-101** [26],[28]



Key

U_{os}	voltage of current circuit	U_h	charging voltage of voltage circuit
L_1	inductance of current circuit	i	current of the current circuit
AP	arc prolonging circuit	i_h	injected current
S_a	auxiliary circuit-breaker	Z_1	equivalent surge impedance of current circuit
S_i	test circuit-breaker	C_{d1}	capacitance for time delay of current circuit
Z_h	equivalent surge impedance of voltage circuit	SLF	short-line-fault circuit (for the corresponding tests)
C_{dh}	capacitance for time delay of voltage circuit	L_h	inductance of voltage circuit

Fig.2.12 simplified circuit diagram of a current injection circuit with the voltage circuit connected in parallel with the auxiliary circuit-breaker as per IEC 62271-101

Fig.2.12 shows the simplified circuit diagram of a current injection circuit with the voltage circuit connected in parallel with the auxiliary circuit-breaker. After switching in the voltage circuit, shortly before zero of the power-frequency, short-circuit current, the high-frequency oscillatory current i_h is superimposed, with opposing polarity, on the power-frequency short-circuit current i, in the auxiliary circuit-breaker.

After the resulting current in the auxiliary circuit-breaker has ceased to flow, the oscillatory current commutates into the test circuit-breaker and the current circuit. The test circuit-breaker is now part of a circuit which comprises the series connected current circuit and the voltage circuit. After the extinction of the resulting the resulting current in the test circuit-breaker, the transient recovery voltage is supplied both by the voltage circuit and the current circuit.

Fig.2.13 shows an example of injection timing. The single point of inflection corresponds to the interruption of current in the auxiliary circuit-breaker. The wave shape of the transient recovery voltage can be adjusted by varying Z_h and C_{dh} as well as Z_1 and C_{d1} to obtain compliance with the requirements of IEC 62271-100.

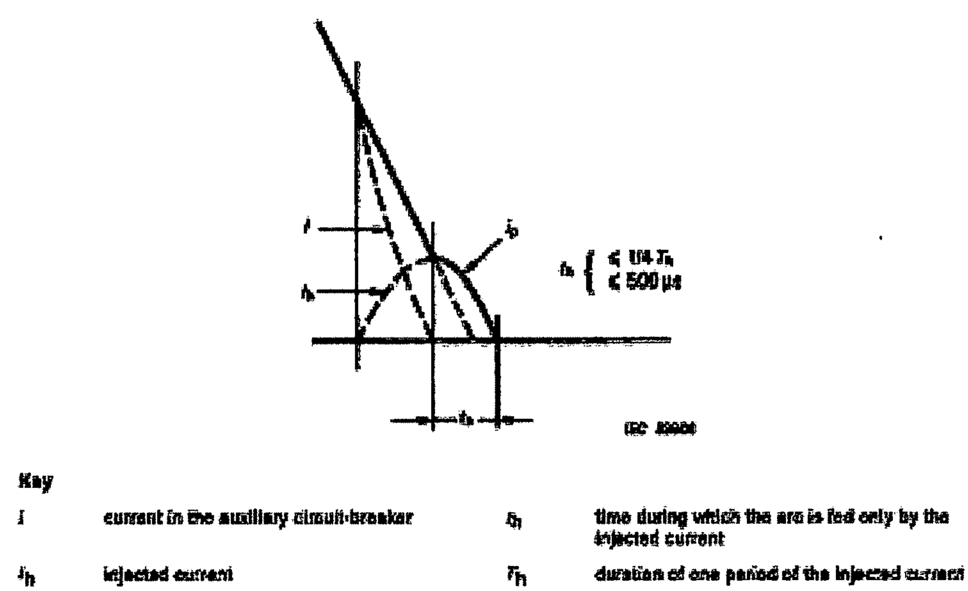


Figure 2.13 an example of injection timing

2.7 Voltage Injection Methods as per IEC 62271-101 [26], [28]

In a synthetic test circuit using voltage injection, the current circuit provides the entire short-circuit current for the test circuit-breaker and also, after current zero, the first part of the transient recovery voltage.

By suitable choices of its voltage and natural frequency, the correct values of the power factor, current and first part of the TRV can be obtained.

About the time of the first peak of the transient recovery voltage of the current circuit, the voltage circuit is switched in by means of a voltage-dependent control circuit in such a way that the specified transient recovery voltage is continued and so that there will be no delay between the current stress and the voltage stress.

In these methods,

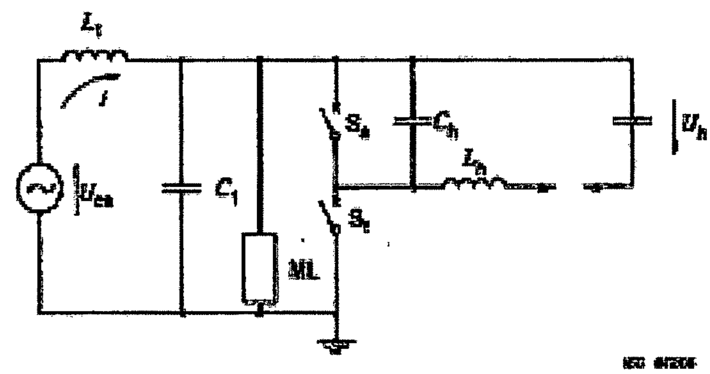
- The voltage from the voltage circuit is applied to the test circuit-breaker after the interaction interval;
- A capacitor in parallel with the auxiliary circuit-breaker is used to apply the recovery voltage to the test circuit-breaker;
- During the high current and interaction intervals, the test circuit-breaker is exposed to the current circuit only.

Several voltage injection methods are known but only Series voltage injection method is used by the test laboratories.

(1) Voltage injection circuit with the voltage circuit in parallel with the auxiliary circuit-breaker (Series circuit)

Fig.2.14 shows the simplified diagram of a voltage injection circuit with the voltage circuit connected in parallel with the auxiliary circuit-breaker. The current circuit supplies the entire short-circuit current stress.

A capacitor of suitable value is connected in parallel with the auxiliary circuit-breaker. After the current zero of the power-frequency short-circuit current, this capacitor transmits the entire transient recovery voltage of the current circuit to the test circuit-breaker, passing the necessary energy for the post-arc current.



Key

U_{ca}	voltage of current circuit	S_t	test circuit-breaker
L_1	inductance of current circuit	C_h	capacitance of voltage circuit which together with L_h controls the major part of the TRV
C_1	capacitance of current circuit which together with L_1 controls the first part of the TRV	L_h	inductance of voltage circuit
ML	multi-loop re-ignition circuit	U_h	charging voltage of voltage circuit
S_a	auxiliary circuit-breaker		

Fig. 2.14 Simplified diagram of a voltage injection circuit with the voltage circuit connected in parallel with the auxiliary circuit-breaker

About the time of the first peak of this transient voltage, the voltage circuit will be switched in and from this moment onwards the transient recovery voltages of both circuits are added together to form the transient recovery voltage across the test circuit-breaker. The auxiliary circuit-breaker is stressed only by the voltage of the voltage circuit. Both components of the voltage across the test circuit-breaker are superimposed to produce the transient recovery voltage, the wave shape of which can be adjusted by varying C_h and C_l in conjunction with additional components to obtain compliance with requirements of IEC 62271-100.

(2) Voltage injection circuit with the voltage circuit in parallel with the test circuit-breaker (Parallel circuit)

This voltage injection circuit is similar to the one described above except that the voltage circuit is in parallel with the test circuit-breaker instead of the auxiliary circuit-breaker. It is not in common usage [26].

2.8 Comparison of Various Synthetic Test Circuits

In synthetic testing circuits, an AB (auxiliary breaker) is necessary to separate the current source and the voltage source. The insertion of the AB in a synthetic test circuit introduces an extra arc voltage in the test circuit and makes the arc-circuit interaction of the TB different from the interaction in the direct test circuit[15],[26],[28].

In synthetic test circuits, the ratio of the driving voltage of the current source with respect to the arc voltages is low, because the driving voltage is a fraction of the rated voltage and the arc voltages of TB and AB add up. As a result, the duration of the first current loop and also the arc energy in the TB is reduced. The arc energy reduction in the TB varies with the arc duration i.e. the arcing time of the TB[15].

For the synthetic test circuit, the total arc energy input in the TB is less than in the direct test circuit, but just before the current zero the dI/dt and subsequently the arc energy input in the TB is higher. It is demonstrated that the arc-circuit interaction plays an important role for TB to clear the fault.

For SF_6 circuit-breakers with an arc voltage with significant extinguishing peak, the voltage injection synthetic test circuit produces an overstress for the TB[15].

Presently two types of synthetic test circuits, based on the injection method of a high voltage circuit are in use, the parallel current injection circuit and the series voltage injection circuit[15]. For both the circuits, the insertion of AB gives the same influence on the TB in the high current interval. However, in the interaction period around current zero, the influence is different. The arc voltages of TB and AB shorten the first current loop and extend the second current loop. The arc voltages of the AB and TB have an influence such that the dI/dt before the first current zero is higher than the dI/dt in the corresponding direct test circuit. A higher dI/dt means for the TB **in the series voltage injection synthetic test circuit, although the total arc energy input is lower, the arc energy input per time unit just before current zero is higher**[15].

Arc voltage influence during the current zero periods:

For a small arc time constant, as in SF_6, the arc voltage just before current zero is important for the breakers. The arc voltage can influence the arc-circuit interaction and this can affect the interrupting capability of the breaker.

From the calculations performed, it is concluded that, **the voltage injection synthetic test** circuit puts more stress on the TB than the direct and current injection circuits do during the current zero period. The AB in the voltage injection synthetic test circuit causes the overstress on the TB during current zero period. The higher the extinguishing peak in the AB, the more difficult it is for the TB to clear the fault[15].

Depending on the interrupter design, there are several shapes of arc voltage waveforms for a breaker when it clears a fault current, one shape is the arc voltage with an extinguishing peak, another shape is the arc voltage with a less significant extinguishing peak or an arc voltage without extinguishing peak.

Also **Voltage injection method requires** a very accurate timing for the voltage injection. This timing becomes a critical parameter which in most cases is rather difficult to control. Therefore this method is not very popular [1].

In series current injection method, as the current and voltage circuits are series connected, it is rather difficult to select circuit parameters to suit both the current and voltage circuits which would at the same time give required restriking voltage transient. This circuit arrangement is particularly suited for low frequency circuit[3].

More than forty years of synthetic testing experience shows that the current injection method has better equivalence than the voltage injection method. To produce four-parameter TRV, several TRV circuits have been developed but parallel current injection method with a Weil-Dobke TRV control circuit is the most popular used synthetic testing circuit in the high power laboratories as it is capable of providing RRRV and recovery voltage as required by various standards. Weil-Dobke circuit has a low capacity requirement on the main capacitor bank as compared to other TRV control circuits and is easy to design the various components. However, special attention should be paid on the insulation coordination of TRV branches[14],[15],[17],[18],[19].