Minimal Method to Solve By Testing of High Voltage Circuit Breaker By A Synthetic Test Circuit

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***Abstract*— Implementation in electrical power transmission system and higher voltage level operation & execution of power systems require circuit breakers required of higher interrupting capability Instantaneously. To make ensure that interrupting capability, circuit breakers must verify and prove the TRV withstand capability and specified according to standards. To test high voltage circuit breakers, a direct testing using power system network or a short-circuit alternators are not feasible and practical solution obtained. But synthetic testing is an one of the equivalent economical method and evaluated for testing of high voltage circuit breakers.**

In a synthetic test circuit, it is very quite complex to choose and make circuit components value for a desired TRV envelope. This paper purposes a synthesis process to design synthetic test circuit to generate four-parameter TRV envelope for circuit breaker testing. By using proposed approach a synthetic test circuit has been designed and simulated in MATLAB to generate a four-parameter TRV envelope for a 145 kV, 40 kA rating circuit breaker used.

Keywords— a Synthetic testing, and TRV rating concept, and Four-parameter TRV envelope

I. INTRODUCTION

The transient recovery voltage (TRV) is stated as the voltage across the open contacts of circuit breaker is just after the current interruption. Magnitude of TRV voltage starts from zero to TRV peak value in very short time i.e. 10's to 1000's of µseconds. The nature of TRV is depends on the circuit to be interrupted, means whether it is Firstly resistive, capacitive or inductive, or with their combination. The primary current interruption is possible only if the dielectric strength of medium between open contacts of circuit breaker increase with more slope or rapidly differentiated to TRV wave. Failure of circuit breaker to perform their duty when called upon can result in the loss of stability, and even collapse the system. The TRV peak amplitude is generally higher than the Power Frequency Recovery Voltage. But, these high value transients persist for very few µto milli seconds only. It is because the TRV across breaker contacts damped out in a very less time, and then becomes same as Power Frequency Recovery voltage.

To identify the switching performance, circuit breakers should be tested for all equal conditions of power systems. It could be possible by ideally using practical power supply or similar system in the test laboratory when a type test is conducted. Theoretically, it is possible in laboratory to build up a test circuit represents the power systems with all station equipments installed. This test method is defined as direct test. This method is preferred when both the test current and voltage are low. For high current and high voltage ratings of circuit breaker, this minimal method is not feasible because it require very high power rated testing facility laboratory. To increase testing capability of laboratory, parallel operation of number of alternators neither a practical nor an economical solution. Due to this reason, testing of ac circuit breaker by synthetic testing method is becoming popular .

Synthetic test technique can be adopted as extension of direct testing in various ways. It is combination of a current source, supplying the arc current instances the thermal stress on the test breaker, and a separate voltage source, supplying the transient recovery voltage which creates the dielectric stress. This arrangement is an economic way to cope up with the limitations of the direct testing in high-power laboratory.

The choice of components values are marked for each test duty is very complex. It is because of many test requirements & constraints have to be met and the complexity of circuit used. Usually, test circuits made on a trail and error basis by a person who is experienced on that particular circuit . To give reliable and required TRV waveform evenly for four parameter or double frequency TRV wave, this paper introduce a synthesis process or approach to design synthetic test circuit. The proposed synthesis process for design of synthetic circuit has been discussed and used to generate four parameter TRV envelope of 145 kV rated circuit breaker.

II. TYPES OF SYNTHETIC TEST CIRCUIT

Several synthetic testing methods have been investigated to connect the two or more sources together generally testing methods are classified on the basis of energy source used during the interaction interval. Interaction interval is the time from the start of the significant change in arc voltage, prior to current zero, to the time when the current including the post-arc current, if any, ceases to flow through the test circuit-breaker.

On the basis of energy source used during interaction interval, testing methods can be distinguished by two basic methods]:

1. Current injection method
2. Voltage injection method

Current injection method is one type synthetic circuit gives us the better numerical values especially in the arc-circuit interaction interval. Current injection methods can be further classified as series type and parallel type current injection method. In parallel current injection method, the voltage circuit is inserted in parallel with the test breaker always, while in series current injected method, it is inserted in series of circuit breakeralways. Parallel current injected type synthetic circuits also known as Weil-Dobke circuit. Weil-Dobke circuit shows the impedance to circuit breaker it is representative of the atmost reference system conditions .

Advantage of synthetic testing:

- Reduced state of energy required.
- The breaker can be is tested for desired transient voltage, shape and slope of RRRV.
- Both of these test current and transient voltage across test breaker can be varied independently. This gives flexibility in testing.
- Synthetic testing allows well safer tests.
- Less damage to the test object in case of test failure atmost conditions.

III. IEC Four-Parameter TRV Envelope Concept explained here.

Before discussing the standards, a clear brief discussion about TRV wave form and circuit breaker response to TRV is in order. The TRV to which a circuit breaker is subjected depends on the type of fault, and the location of the fault, and the type of circuit switched (circuit configuration). The shape of TRV wave affects the circuit tripping process in two important areas. In the initial time (10-20µs), Known as the energy-balance region, failure to interrupt can be caused by thermal conditions of the system. When the contacts of circuit breaker separate, and a plasma arc developed. The product of current and arc voltage (input power to arc) expells high temperature of arc. To extinguish the arc, it must be cooled to such a level that the space between the contacts are act as an insulator. TRV is ultimate the response of power system to interruption of current. The nature of the TRV is dependent on the circuit being interrupted. Additionally, distributed and lumped circuit elements also produce various TRV wave shapes. Circuit breaker interruption capability can be assured only by successfully allowing all switching tests and test duties.

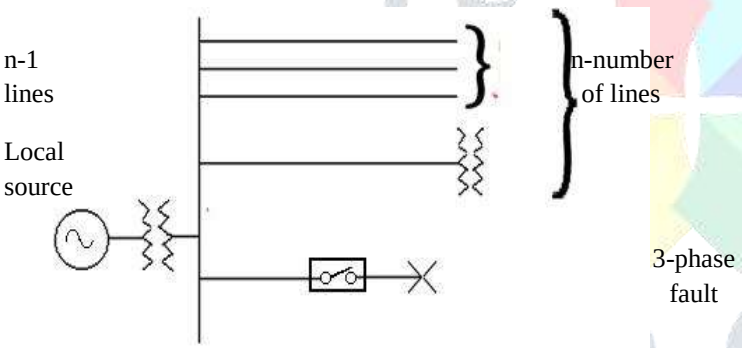


Fig. 1. Typical High Voltage station

Consider a typical high voltage station to explain the four-parameter TRV envelope concept. Circuit breakers 100kV and above are usually applied in composite circuits where the sources of fault currents are from transmission lines, as well as transformer. There is one local source and current from number of transmission lines feeding to the fault current.

During current interruption process, there is a strong interaction between the physical process between the circuit breaker contacts and the network connected with the terminals of circuit breaker. The transient recovery voltage (TRV) across breaker contacts after current interruption is formed by the local voltage oscillations and reflected voltage waves.

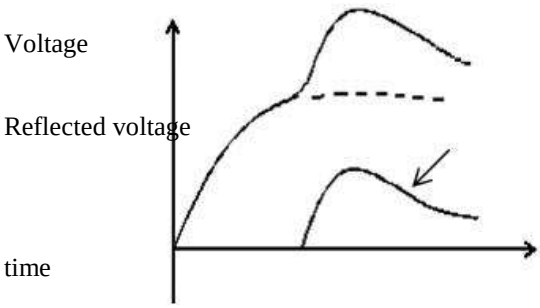


Fig. 2. TRV across breaker including first reflection

A. Four-parameter TRV envelope defined by IEC standards

Breaker rated for more than 100kV usually connects in system having number of transmission line (composite circuit) The surge impedance of these transmission line helps in damping fast the high frequency transient voltage across circuit breaker (sometimes reached over-damped condition due to surge impedance). Fig 2 shows TRV across the circuit breaker in a typical composite power system network. Later in time when over-damped (1-exp) wave that travelled as a wave out on the transmission system returns as a positive reflection from the first open circuit discontinuity and added to the over damped wave (1-exp) .. This analytical approach allows the TRV to be calculated for a given application condition and provides a base to describe the TRV envelope.

IEC used a four-parameter straight line description as shown in fig 3 which allows a TRV wave to be described in terms of simple straight lines. The four -parameter TRV does not correspond to the response of a circuit that can be analyzed.

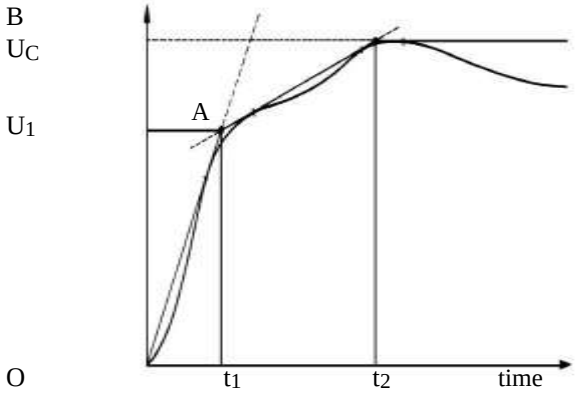


Fig. 3. Representation of four parameter TRV envelope

Four-parameter TRVs are ment as a function of rated voltage (U_r), first pole to clear(k_{pp}), and the amplitude factor (k_{af}) as indicated here :

$$U_1 = 0.75 \times k_{pp} \times U_r \times \sqrt{2/3}$$

$$U_c = k_{af} \times k_{pp} \times U_r \times \sqrt{2/3}$$

where, k_{af} = 1.4 for 100% terminal fault

k_{pp} =1.5 for non-effectively grounded fault

The time corresponding to U_1 is t_1 and time t_2 corresponds to U_c.

IV. Synthetic Testing Circuit for Test of HV Circuit Breaker

To produce four-parameter TRV, several TRV circuits have been implemented but parallel current injection method with a Weil-Dobke TRV circuit is the most popular used synthetic testing circuit in the high power laboratory. This circuit is able to produce RRRV and recovery voltage as obtained by various standards.

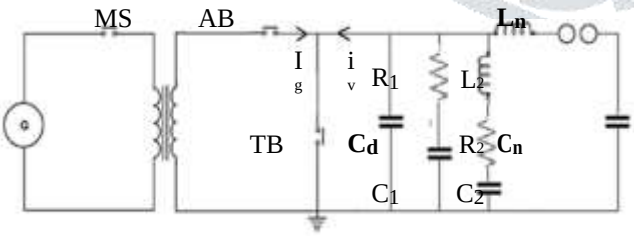


Fig. 4. Synthetic test circuit (Weil-Dobke Circuit)

Fig 4 shows the synthetic test circuit that is normally used for testing of circuit breaker. The current source is a high current low voltage source. The equivalent inductive reactance of source generator circuit is used to control the short circuit current during the test. Referring to the high voltage source side, C_n is a high voltage source. The capacitor bank, C_n has to be fully charged before starting the test. The test is initiated by switch off the making switch and the short circuit current starts to flow through the test circuit breaker. The triggered spark gap is fired slightly below the short circuit current reaches its natural current zero.

The main capacitor, C_n is charged to provide recovery voltage. It should be charged to a peak value of recovery voltage as per the following equation .

$$U_h = 0.95 \times k_{pp} \times U_r \sqrt{2/3} \qquad (3)$$

i.e. for 145 kV circuit breaker

$$U_h = 0.95 \times 1.5 \times 145 \times \sqrt{2/3} = 169kV \quad (4)$$

For 145 kV rated circuit breaker, main capacitor bank should be charged at least for 169 kV of voltage.

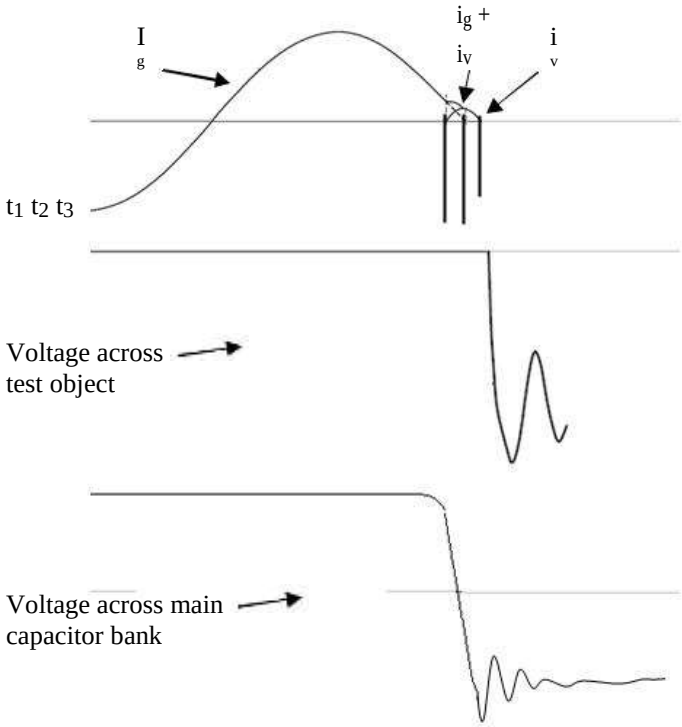


Fig. 5. Current through test breaker, voltage across test breaker and voltage of main capacitor bank

Fig 5 shows the relation between short circuit current and current from high voltage side. As the current approaches its zero crossing, the spark gap is triggered at time t_1 and current begins to flow. Now both currents flows through the test circuit breaker until time t_2 is reached. At this time, t_2, short circuit current will reach its natural current zero and it will be interrupted by auxiliary circuit breaker. Now the only injected current is flowing through test circuit breaker (will be interrupted at zero crossing).

V. Analysis of Synthetic Test Circuit (Weil-Dobke Circuit)

Several synthetic testing methods have been developed and their performances have been studied in the past forty years]. Weil-Dobke is one of the popular circuits of those.

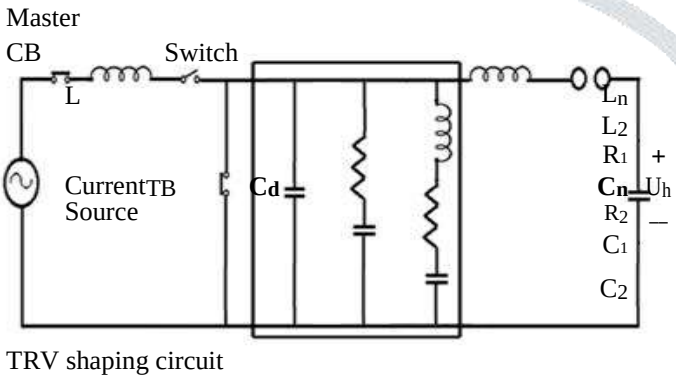


Fig. 6. Synthetic test circuit (Weil-Dobke Circuit)

Ignorance of delay capacitance makes it somewhat less complex to calculate equivalent transfer function of circuit. It shows its effect only for few microseconds of starting. So, most of the parameters of TRV will remain unaffected by delay capacitance existence.

sL_n

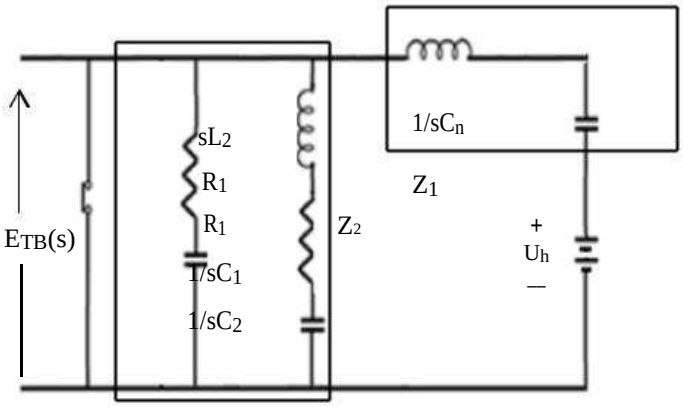


Fig. 7. Laplace circuit of synthetic test circuit (Weil-Dobke circuit)

Response $E_{TB}(t)$ of electrical system is related to the excitation input R(t) by a set of differential equations. The frequency dependent behavior of this circuit can be determined by system function as given in the relation,

$$E_{TB}(s) = R(s)H(s) \qquad (5)$$

Generally, system function may assume many forms and may have names like driving-point admittance, transfer impedance, voltage or current-ration transfers function. This is because the form of system function depends on whether the response and input is a specified current or voltage.

Above circuit can be simplified in a series circuit having two impedances (Z_1 and Z_2) in series. By using voltage division rule, output voltage can be written as,

$$Z_2(s) = (sL_2 + R_2 + 1/sC_2) \parallel (R_1 + 1/sC_1)$$

Here, the system function represents the voltage-ration transfer function. Poles and zeros give a powerful graphical description of the behavior of a system. It should be noted that the difference in degree of denominator and numerator of impedance function, cannot exceed one.

$$E_{TB}(s) = R(s)Z(s) = R(s)[Z_N(s)/Z_D(s)] \qquad (8)$$

where,

$$Z_N(s) = s^3 L_2 R_1 C_n C_2 C_1 + s^2 C_n C_2 (k_1) + sC_n (k_2) + C_n \quad Z_D(s) = s^4 L_n C_n L_2 C_2 C_1 + s^3 C_1 C_2 C_n \{L_2 R_1 + L_n (R)\}$$

$$+ \quad s^2 [C_n \{L_n (C_1 + C_2) + C_2 (k_1)\} + L_2 C_2 C_1]$$

$$+ \quad s\{C_1 C_2 (R) + C_n (k_2)\} + (C_1 + C_2 + C_n)$$

$$k_1 = L_2 + C_1 R_1, \; k_2 = R_1 C_1 + R_2 C_2$$

and, $R = R_1 + R_2$

For step input response, $E_{TB}(s) = -(U_h/s) \times Z(s)$. Negative sign may confuse some people that why polarity has reversed. Actually, the high frequency current injected by this circuit, through test circuit breaker, interrupted after 180° electrical, in this span of time capacitor changes its voltage from positive potential to negative potential.

$$+ \quad s^2 [C_n \{L_n (C_1 + C_2) + C_2 (k_1)\} + L_2 C_2 C_1]$$

$$+ \quad s\{C_1 C_2 (R) + C_n (k_2)\} + (C_1 + C_2 + C_n)]$$

Calculating the Inverse Laplace Transform of such transfer function can be tricky. Point is a pole of the rational function, $E_{TB}(s) = -V\,[N(s)/D(s)]$, if $D(s_p)=0$

By looking denominator, D(s) of rational function $E_{TB}(s)$, we can say that it will have five poles including one at s = 0. It is convenient to write a rational function using its poles,

A rational function $E_{TB}(s) = -V*N(s)/D(s)$ is strictly proper because the degree of N(s) is less than the degree of D(s).

After study about the nature of required output TRV of synthetic test circuit, we can conclude that rational function will have real and/or complex poles, but not repeated poles. So, transfer function of circuit in fig 7 can be written in the pole-residue representation,

Poles, p_i may be real or complex

- Residues, r_i may also be real or complex Inverse Laplace will have the form,

It is clear that time response E_{TB} (t) not only depends on the complex frequencies, p_k, but also on the constant multipliers, r_k. These constants r_k are called residues when they are associated with first-order poles.

VI. SYNTHESIS PROCESS FOR FOUR PARAMETER SYNTHETIC TEST CIRCUIT

The synthetic (Weil-Dobke circuit) test circuit shown in fig 4 has been used to generate four-parameter TRV envelope. This circuit has eight degree of freedom (V_c, C_n, L_n, C_1, L_2, C_2, R_1, and R_2). The topology of this circuit is like that the modifying any one component affects all TRV parameters. In order to get converge result, an iterative process require that initialize and correct the all components value at each iteration and calculate the TRV for new set of component values.

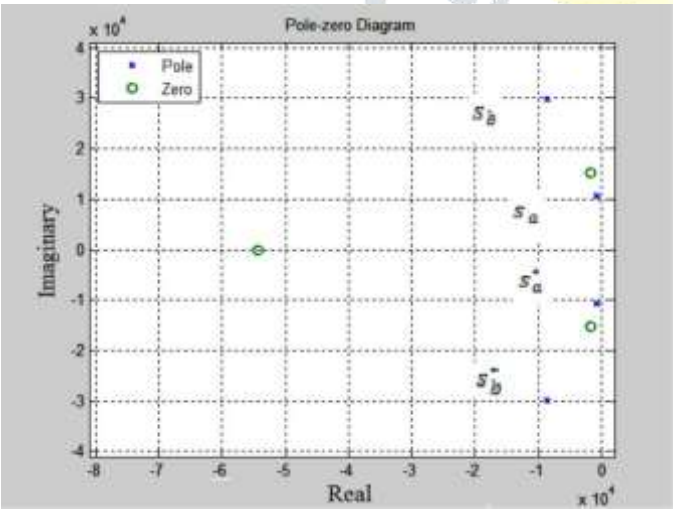
Desired Parameters of TRV i.e. U_C, t_2, U_1, and t_1
Desired injected current frequency
Desired accuracy

Enter the available range of elements value i.e. C_n, L_n, C_1, C_2, and L_2

Select the values of independent variables

Select initial value of dependent variables
Convert to laplace circuit
Determine transfer function / Frequency domain TRV expression
Change the value of test circuit component

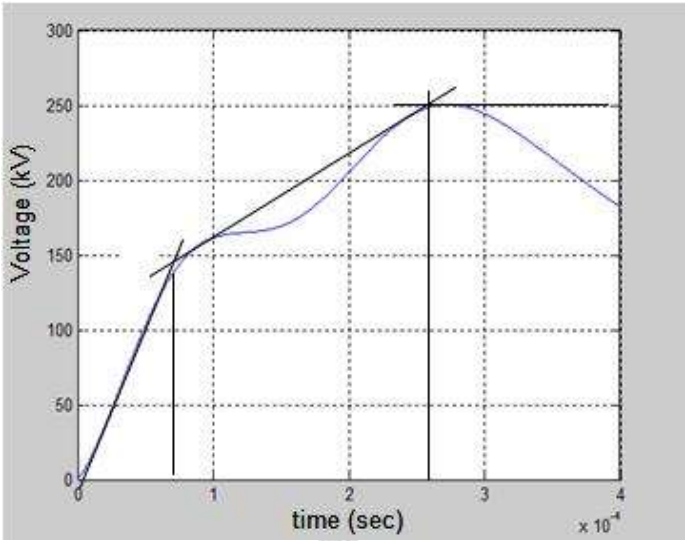
The circuit components value for the required TRV envelope according to IEC standards for a particular rating of circuit breaker will be calculated by the program developed by using MATLAB/Visual Basic 6 on the basis of proposed approach. The speed of convergence of the solution depends on the required accuracy of the result.



A B

Fig. 9. Pole-Zero plot of simulated synthetic test circuit

The pairs of pole s_a and s_a* and the pairs s_b and s_b* corresponds to oscillatory expressions in the time domain. The frequency of oscillation corresponding to s_a and s_a* is higher than that of s_b and s_b* just as the damping is less for s_a and s_a* than for s_b and s_b*.



VII. CONCLUSION

Application of high voltage circuit breakers in composite network intends multi-frequency TRVs across circuit breaker. To generate these TRV waves to test the circuit breaker for similar conditions, IEC standardized the parameters for each rating of circuit breaker. But about all these values are quite complex to directly link the defined TRV parameters with each component of synthetic test circuit.

The estimated and proposed synthesis process are approach to design synthetic test circuit (parallel current injection circuit) has been used to calculate the components value for synthetic test circuit which is then simulated to generate four-parameter TRV envelope according to the parameter stated by IEC for 145 kV rating circuit breaker. Time for convergence of solution depends on proper selection of initial values of dependent variables and required accuracy. Result obtained from the simulation of synthetic test circuit has been compared with the estimated result or standard defined by IEC. Result observed more appropriate and realistic.

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