Revision of IEEE C37.011 Guide for the Application of Transient Recovery Voltages for AC High-Voltage Circuit Breakers

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***Abstract*—A revision of IEEE C37.011 was done from 2008 to 2011 to improve the content of the 2005 edition on TRV interpolation for terminal fault, line fault, transformer limited fault and reactor limited fault. Another aim was to introduce class S1 and S2 circuit breakers for rated maximum voltages of less than 100 kV.**

***Index Terms*—Circuit breaker (CB), line fault, reactor fault, standard, terminal fault, transformer limited fault, transient recovery voltage (TRV).**

I. INTRODUCTION

THIS document presents and explains the main changes approved in 2011 to IEEE C37.011 Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers [1].

This application guide covers procedures and calculations necessary to apply the standard transient recovery voltage ratings for ac high-voltage circuit breakers (CBs) rated above 1000 V. The breaking capability limits of these CBs are determined to a great degree by the TRV. In this application guide, the TRV ratings are compared with typical system TRV duties. Examples of TRV calculation are given with suggested options if the TRV duty exceeds the TRV ratings of the CB.

IEEE C37.011 was revised from 2008 to 2011 to improve the content of the 2005 edition on the following items:

- transient recovery voltage interpolation for terminal fault;
- line fault including short line-fault;
- transformer limited fault;
- reactor limited fault.

Another objective was to introduce class S1 and S2 CBs for rated maximum voltages of less than 100 kV, respectively, for cable-connected systems and line-connected systems.

In addition, the informative Annex B "Typical capacitance values for various equipment" was revised to update the capacitance values of the capacitive voltage transformer.

To ease the understanding of this document, the following definitions are recalled:

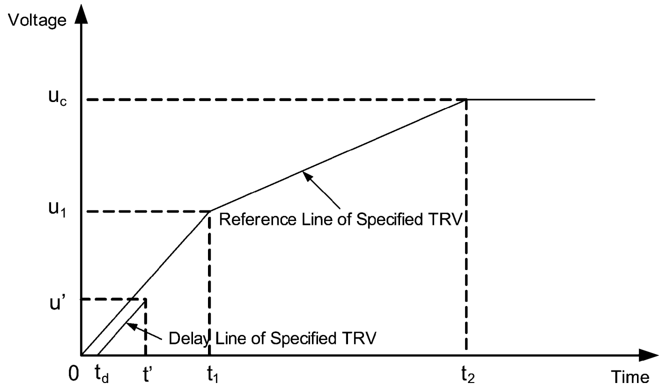

Fig. 1. IEEE specified four-parameter TRV envelope for the breaker rated above 100 kV and short circuit current more than 30% of rated short circuit current.

TRV Envelope: a CB TRV capability is defined by a two or four parameter envelope drawn with the rated parameters as specified in C37.06 (see T30 and T60 envelopes in Fig. 1).

System TRV: calculated TRV which is the difference in the power system response voltages on the source side and on the load sides of the CB.

Recovery voltage: the voltage that appears across the terminals of a pole of a CB after current interruption. This voltage may be considered in two successive time intervals: one during which a transient voltage exists (TRV), followed by a second, during which a power frequency voltage alone exists.

Rate of rise of recovery voltage (RRRV): the maximum slope of the tangent to the TRV waveform drawn from the instant of interruption.

Terminal fault test duties: T10, T30, T60, and T100 are the test duties performed at 10%, 30%, 60%, and 100% of rated short circuit interrupting current I_{sc} for the terminal faults.

II. TRV FOR TERMINAL FAULT

This section of IEEE C37.011 was revised to introduce the methodology to interpolate the CB TRV withstand capability for the fault currents between 30% and 60% of I_{sc}.

The parameters that define the CB TRV capabilities vary with the breaker voltage rating and short circuit current interrupting level. The CB TRV capabilities at 10%, 30%, 60%, and 100%

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of rated short circuit interrupting current, corresponding to terminal fault test duties T10, T30, T60, and T100 are given in IEEE Standard C37.06.

The CB TRV withstand capability envelope at any other short circuit interrupting current below rated can be derived using the parameter values interpolated from rated parameters defined for 100% rated short circuit current using the multipliers as given in Table 1 of IEEE C37.011.

Usually, the TRV studies should be carried out to determine if a system TRV is covered by the CB TRV capability demonstrated by type tests, either when new CBs are to be installed or following a system change. It is not uncommon that the maximum short circuit current falls in between 30% and 60% of the CB rated short-circuit current. To allow comparison of system TRV and CB TRV capability and to avoid additional testing, a method of interpolation of TRV capabilities demonstrated by type tests was introduced in the former editions of this Guide.

Following the introduction of the two-parameter and four-parameter description of TRVs, this method of interpolation in the current range between T30 and T60 (terminal faults with, respectively, 30% and 60% of the CB rated short-circuit current) was not clearly stated in the 2005 edition of this Guide. Thus, the method of interpolation is further developed in this revision to define the breaker TRV withstand capability for short-circuit currents in this range and is explained in the following paragraphs.

In standards, it is considered that 30% of $I_{\rm sc}$ is the maximum short-circuit current for which a two-parameter TRV is applicable for CBs rated 100 kV and above. The related TRV capability for short-circuit currents between 30% of $I_{\rm sc}$ and 60% of $I_{\rm sc}$ is necessarily a four-parameter TRV as shown in Fig. 1.

The IEEE Working Group has defined that the TRV capability between T30 and T60 can be considered to have a rate-of-rise (u_1/t_1) and a first reference voltage (u_1) that have intermediate values between those of T30 and T60. TRV parameters $(u_1, t_1, u_{\rm c}, t_2)$ for any terminal fault current between 30% and 60% can be obtained as follows:

u_1 and t_1 are linearly interpolated between u_1 and t_1 of T60 and $u_{\rm c}$ and t_3 of T30;

$u_{\rm c}$ and t_2 are linearly interpolated between $u_{\rm c}$ and t_2 of T60 and $u_{\rm c}$ and t_3 of T30, where:

u_1	magnitude of the first reference voltage parameter;
t_1	time at which u_1 is reached;
$u_{\rm c}$	rated magnitude of the TRV peak;
t_2	rated time to reach the peak voltage parameter $U_{\rm c}$;
t_3	rated time to reach the peak voltage parameter $U_{\rm c}$ for test duties T10 and T30.

Fig. 2 shows an example of the TRV envelope for a terminal fault with 50% rated short-circuit current, interpolated between TRV envelopes for T30 and T60.

It can be seen in Fig. 2 that the TRV values at t_1 of T60 and t_3 of T30 are very close. In this time interval between t_1 and t_3, it can be considered that the CB voltage withstand increases as current decreases and a linear interpolation between 30% and 60% of $I_{\rm sc}$ is a reasonable estimation.

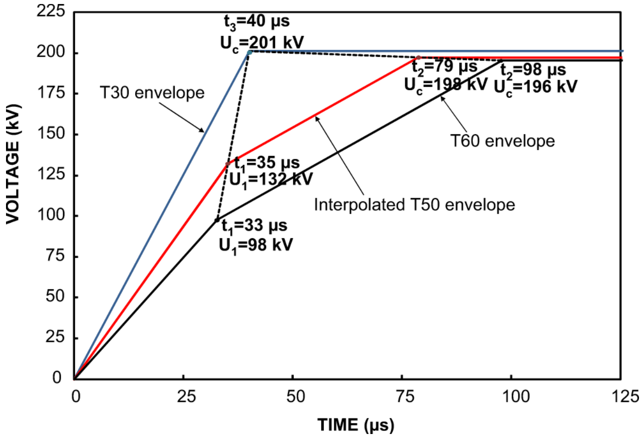

Fig. 2. Example of the TRV envelope for T50, interpolated between T30 and T60.

However, it shall be noted that this interpolation method is not applicable to CBs that have critical currents (i.e., if the minimum arcing time in any of the test-duties T10, T30, or T60 is 5 ms or more longer than the minimum arcing times in the adjacent test-duties).

III. LINE FAULT

The section on line fault has been largely expanded and updated, based on the work conducted by CIGRE Working Group A3–19 and published in CIGRE Technical Brochure 408 "Line fault phenomena and their implications for 3-phase short- and long-line fault clearing" [2]. It presents the basis of short-line fault rating as well as TRV parameters for single-phase and three-phase faults. The calculation of the first TRV peak ("d" factor) is done in two ways:

- using the effective surge impedances for the first (or last) clearing poles and the time-to-peak TRV that is equal to two times the travel time to the fault at distance;
- by physical considerations based on the effect of mutual inductance between phases.

In particular, it is shown that during a three-phase line fault, the rate of rise of recovery voltage (RRRV) for the first pole to clear is approximately 10% lower than for the last pole to clear and during single-phase line faults. Since the RRRV is the dominant TRV parameter in the thermal phase of interruption, the TRV stress is generally considered to be more severe for the last pole to clear a three-phase fault, and during single-phase faults, despite the fact that the initial TRV peak is 50% higher for the first pole to clear a three-phase line fault compared to the single-phase fault condition. Due to the coupling between phases, the line-side contribution to the TRV peak is increased by approximately 50% on the first pole to clear when it interrupts a three-phase fault. Detailed explanations on line faults can be found in [3].

IV. TRANSFORMER LIMITED FAULT

This section of IEEE C37.011 has been expanded to explain what could be done when it is not possible to test with the

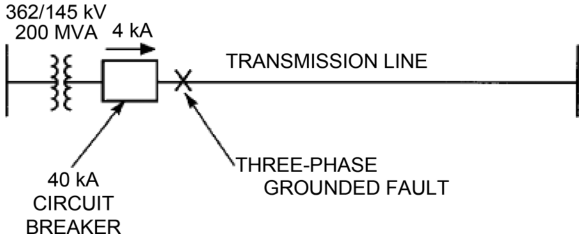

Fig. 3. Example of a transformer limited fault.

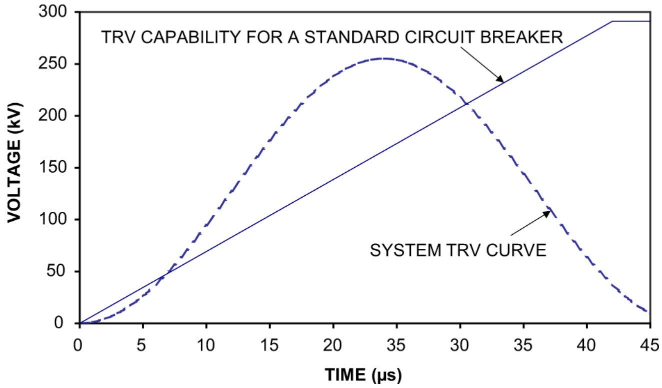

Fig. 4. Comparison of TRV capability for the 145 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV with the transformer limited fault.

TRV values for Definite Purpose CB for fast transient recovery voltage rise times in ANSI C37.06.1.

As illustrated in Fig. 3, a CB may have to clear a three-phase fault current mainly limited by the transformer impedance, without significant capacitance between the CBr and the transformer. The resulting TRV, as shown in Fig. 4, is determined by the inductance and surge capacitance of the transformer and the capacitance between the transformer and the CB. It is a high frequency transient that may exceed the TRV capability envelope as defined in standards ANSI/IEEE Standard C37.04 and IEEE Standard C37.06.

The system TRV curve can be modified by a capacitance and then be within the standard TRV capability envelope. Fig. 5 illustrates the modified system TRV for the condition of Fig. 4, but with the additional capacitance assumed between the transformer and the CB.

As an alternative, the user can choose to specify a Definite Purpose CB for fast transient recovery voltage rise times, as defined in ANSI C37.06.1. This standard is currently under revision by a Working Group of the IEEE High Voltage Circuit Breaker Subcommittee.

ANSI Guide C37.06.1 is assumed to cover the large majority of all cases for this switching duty. However, sometimes the required value of RRRV may not be used during testing either due to limitations of the test laboratory or because the switching capability of the CB is not sufficient. In such cases, the RRRV that has been withstood during testing should be compared with the RRRV obtained by calculation in the actual application considered. The calculation should take into account additional capacitances present in the substation (sum of stray capacitance, busbar, CVT, etc.). If the RRRV withstood during testing is higher than the value met in service, then the CB is suitable for the application.

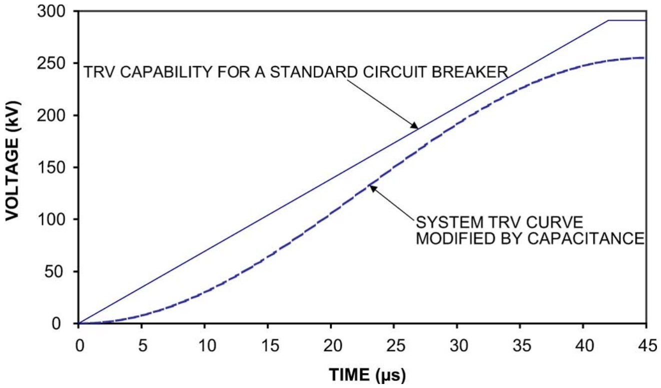

Fig. 5. Comparison of TRV capability for the 145-kV CB (at 10% of its rated interrupting current capability) and system TRV modified by additional capacitance between the CB and transformer.

V. REACTOR LIMITED FAULT

In some networks, a current limiting reactor (CLR) is used to reduce the fault current magnitude. It is also used as a damping reactor to limit inrush currents in capacitor bank applications. Due to the very small inherent stray capacitance of current limiting reactors, the natural frequency of transients involving these reactors can be very high. A CB installed immediately in series with this type of reactor will face a high frequency TRV when clearing a terminal fault (reactor at the supply side of the CB) or clearing a fault behind the reactor (reactor at the load side of the CB). The resulting TRV frequency generally exceeds the standard TRV values [4].

When the system TRV exceeds a standard breaker capability, the user has two possibilities:

1) add a capacitance in parallel to the reactor in order to reduce the TRV frequency and have a system TRV curve within the standard capability envelope; a phase-to-ground capacitance could also be added—it can be provided by a dedicated capacitor, a capacitive voltage transformer (CCVT), or by an HV cable;
2) specify a Definite Purpose CB for fast transient recovery voltage rise times, as defined in ANSI C37.06.1–2000.

The additional capacitance should be adequately sized to decrease the rate-of-rise of the TRV below the rated value defined for the CB utilized. In the case of CBs of rated voltages less than 100 kV, the RRRV can be reduced below the value specified for CBs class S2. If a shielded cable is used to connect a current limiting reactor to the CB, the cable capacitance to ground may be sufficient.

In the revised Guide, the section on reactor limited fault has been expanded to include examples of TRV calculations by system simulation using the equivalent circuit shown in Fig. 6. Where L_{s} is the short-circuit inductance of the source and R_{s} is a resistor so that the time constant of the source circuit is equal to the standard value of 45 ms, the branch $C_{\mathrm{add}} - R_{\mathrm{cadd}}$ represents a capacitor connected in parallel to the CLR and the resistance R_{cadd} gives a $\tan\delta$ of 0.01%.

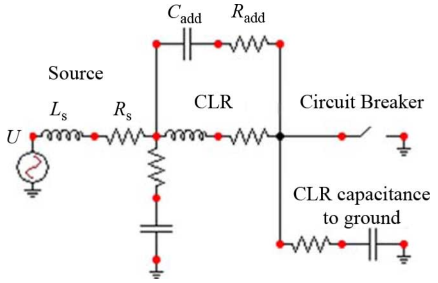

Fig. 6. Equivalent circuit for reactor limited fault TRV calculation.

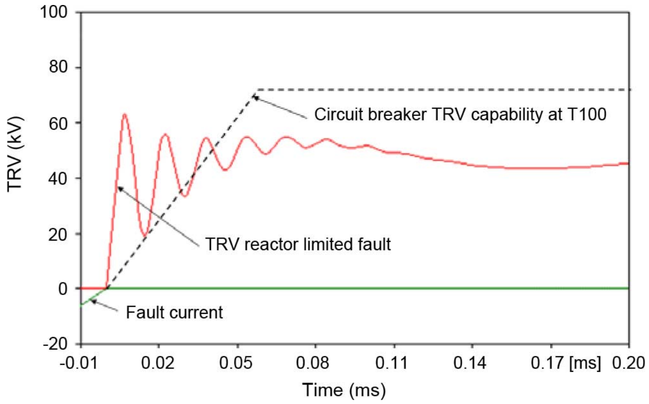

Fig. 7. Calculated TRV of the reactor limited fault without added capacitance, comparison with TRV capability for the class S2 CB 38 kV 12.5 kA. The fault current trace is indicative only to show its passage through zero.

Three-phase faults are generally considered as they lead to the highest TRV peak and RRRV, at least for the first pole to clear.

Fig. 7 shows an example of TRV calculated without the branch $C_{\text{add}} - R_{\text{cadd}}$ in parallel to the current-limiting reactor. The corresponding RRRV is 11.44 kV$/\mu$s, which greatly exceeds the standard value of RRRV for a class S2 CB with a rated short-circuit current of 12.5 kA (1.21 kV$/\mu$s in case of a fault with 100% rated short-circuit current).

When a capacitor C_{add} of 195 nF is added in parallel to the current-limiting reactor, the RRRV is reduced to 1.1 kV$/\mu$s (see Fig. 8). If a capacitor of 195 nF is connected phase-to-ground, the RRRV is reduced to 0.88 kV$/\mu$s. As can be seen in the example, the reduction of RRRV is more effective when the capacitance is connected phase-to-ground.

The addition of a capacitor increases the peak value of TRV, the value obtained in this example is higher than the TRV withstand specified for terminal fault T100 ($u_{\text{c}} =$ 71.7 kV for class S2 CBs). In these cases, a resistor connected in series with the additional capacitor will be necessary. Alternatively, a higher peak value of TRV may be specified or a CB with a higher rated voltage (48.3 kV) or a higher rated short-circuit current may be used.

Fig. 9 shows the TRV calculated with an additional phase-to-ground capacitance of 12 nF for the same reactor limited fault. It can be seen that this modified TRV is covered by the TRV capability of a 38-kV 40-kA CB interrupting a fault current (12.5 kA) that is approximately equal to 30% of its rated short-circuit current.

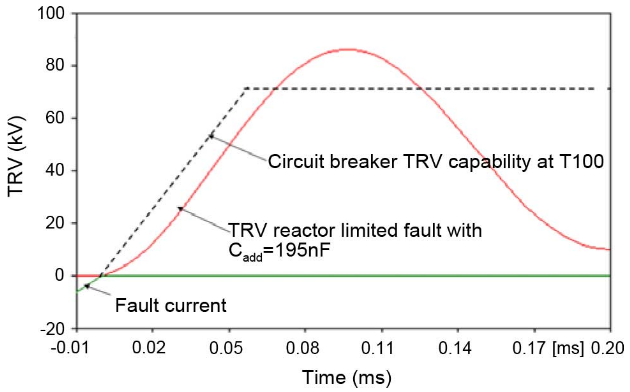

Fig. 8. Calculated TRV of the reactor limited fault with 195 nF added capacitance, comparison with TRV capability for the class S2 CB 38 kV 12.5 kA.

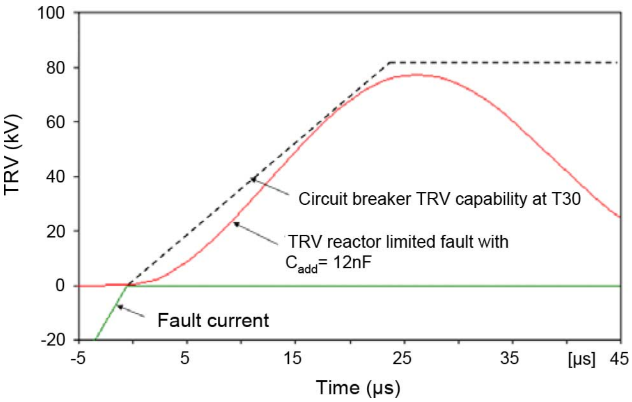

Fig. 9. Calculated TRV of the reactor limited fault with 12 nF added capacitance, compared with TRV capability for a class S2 CB 38 kV 40 kA at 30% of the rated short-circuit current.

The examples illustrated by Figs. 8 and 9 show that a CB with a higher short-circuit rating enables reducing the value of the added capacitance, an optimum choice of CB rating, and the value of added capacitance can be found on a case-by-case basis.

VI. CBs CLASS S1 AND S2

The content of IEEE C37.011 was revised to include the two classes of circuit breakers (S1 and S2) that are defined in ANSI/IEEE Standard C37.04b for rated voltages higher than 1 kV and less than 100 kV. The specification of classes S1 and S2 is dependent on the type of application:

- a CB class S1 is intended to be used in a cable system;
- a CB class S2 is intended to be used in a line system, or in a cable system with direct connection (without cable) to overhead lines.

A cable system is a system where the TRV during interruption of the terminal fault at 100% of short-circuit interrupting current does not exceed the two-parameter envelope derived from Column 5 of Table 2A in ANSI/IEEE Standard C37.04b.

CBs located in indoor substations with cable connections are generally in cable systems. A CB in an outdoor substation is considered to be in a cable system if the total length of cable (or equivalent length when capacitors are also present) connected on the supply side of the CB is at least 100 m. The capacitance

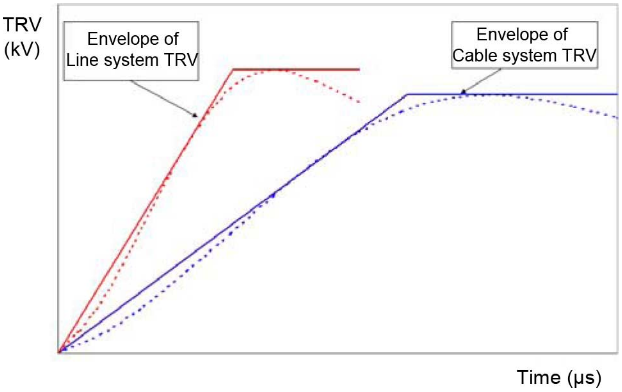

Fig. 10. Comparison of line-system and cable-system rated TRVs.

of cable systems on the supply side of CBs is provided by cables and/or capacitors and/or insulated bus.

A line system is a system where the TRV during the interruption of a terminal fault at 100% of short-circuit interrupting current is covered by the two-parameter envelope derived from Column 4 of Table 2A in ANSI/IEEE Standard C37.04b and exceeds the two-parameter envelope derived from Column 5 of Table 2A.

This definition of line systems normally applies to systems of rated voltages equal to or higher than 15 kV and less than 100 kV. In line systems, no cable is connected on the supply side of the CB, with the possible exception of a total length of cable up to 100 m between the CB and the supply transformer(s). Systems with transmission lines directly connected to a busbar (without intervening cable connections) are typical examples of line systems.

The two-parameter envelopes of TRVs for line and cable systems are illustrated by Fig. 10. The RRRV for class S2 CBs is approximately two times higher than that for class S1 and the peak TRV is also higher for class S2 (the amplitude factor of rated TRV is 1.54 for class S2 and 1.4 for class S1).

The definitions of classes S1 and S2 CBs and the corresponding TRV parameters are identical to those introduced at the same time by IEC.

VII. CONCLUSION

The draft revision of IEEE C37.011 was successfully balloted in August 2011 by the IEEE Switchgear Committee and was published in November 2011.

IEEE C37.011 was revised to improve the content of the 2005 edition on TRV interpolation for terminal fault, single-phase and three-phase line faults, transformer limited fault, and reactor limited fault.

The authors believe that the content of the revised Guide represents a significant improvement of the 2005 edition and that it will give a better understanding of TRV obtained in different fault conditions and help users decide whether the TRV capability demonstrated during type tests is covered in particular cases of application.

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