1

Introduction

1.1 Background

The intent of this textbook is to explain the origin and nature of the transients associated with fault and inductive and capacitive load current interruption. The transients in general have a power frequency and an oscillatory component. The oscillatory components have an RLC circuit basis with such a degree of commonality between the above current interruption cases that a generic calculation approach is possible. The power frequency component is either a balanced or momentarily unbalanced quantity and in some cases is the axis of oscillation for the oscillatory component. In overview, the following transients will be analyzed and the resulting equations applied to real current interruption cases:

- *Fault current interruption*: The transient of interest is the transient recovery voltage (TRV) that appears across the circuit breaker after current interruption. For terminal faults, that is, a fault at the circuit breaker, the power frequency component is dependent on the system earthing and the type of fault. The oscillatory component can be either overdamped or underdamped with travelling waves contributing to the former oscillation. The TRV may be on one side of the circuit breaker only, for example, a three-phase-to-earth fault on an effectively earthed system, or on both sides of the circuit breaker as for the out-of-phase switching and short-line fault cases.
- *Inductive current interruption*: The transients for consideration in this case are the TRV, which is the difference between the source power frequency and the load circuit oscillation, as well as the transients due to re-ignitions. The load circuit and re-ignition transient oscillations are underdamped.
- *Capacitive current interruption*: The transients in this case are related to both current and voltage. The transient currents to be considered are those due to inrush on switching in a single shunt capacitor bank or in back-to-back switching and outrush current when a bank discharges into a fault. At current interruption, the TRV is the difference between the source power frequency voltage and the trapped DC voltage on the capacitive load at current interruption. The voltage transient of issue is that due to re-striking.

Current Interruption Transients Calculation, First Edition. David F. Peelo.

The structure of the textbook is the following:

- Chapter 1: The short-circuit rating basis for high-voltage circuit breakers is described with reference to the IEC circuit breaker standard IEC 62271-100 followed by a review of current interruption terminology.
- Chapter 2: Oscillatory RLC circuits are treated using a generic solution approach without any recourse to the traditional Laplace transform method. An examination of all the various circuits involved in current interruption, re-ignitions or re-striking and making showed that by treating four basic circuit configurations, almost all switching cases can be covered. Some exceptions, of course, occur but, as readers will appreciate later, these are actually variations on a common theme. A basic knowledge of travelling waves is required later in the text, and an overview of basic considerations is included in this chapter.
- Chapter 3: Symmetrical component theory is applied to calculate the unbalanced power frequency voltage values, expressed as per-unit pole factors, that occur during fault and inductive and capacitive load current interruption.
- Chapter 4: The basis for the TRVs for terminal faults, that is, faults located at the terminals of the circuit breaker, is derived. This basis is then applied to the test duties required by IEC 62271-100 and further to show the effects of added capacitance, opening resistors and series reactors. The special cases of out-of-phase switching and double earth faults are then treated. This is followed by the derivation of asymmetrical current requirements and the relationship to time constants and so-called X/R values.
- Chapter 5: The short-line fault is a special case with the circuit breaker being stressed by the difference between TRVs on the source and line sides. The derivation of the line-side transient, which is not oscillatory in the usual sense but rather is travelling wave based, is described and related to standard requirements.
- Chapter 6: Inductive load current switching includes the switching out of unloaded transformers and shunt reactors. The former switching case is not onerous for circuit breakers but the same cannot be said for the latter case. The multiple variations of shunt reactor switching configurations are treated using the generic approach.
- Chapter 7: Capacitive load current switching involves both the switching in and switching out of shunt capacitor banks and unloaded cables and lines. The derivation of inrush and outrush currents, TRVs and re-striking events are treated in detail.
- Chapter 8: Circuit breaker type testing requirements for fault current interruption and load current switching are reviewed.

No chapter is stand-alone as such, and readers should note that Chapters 2 and 3 provide the basic theory for the calculations of Chapters 4–7.

Supporting calculations and information relating to the main text are provided in Appendices A–G. Finally, a brief history of how the understanding and appreciation of TRVs evolved and became standards is provided in Appendix H.

1.2 Short-Circuit Rating Basis for High-Voltage Circuit Breakers

High-voltage circuit breakers are rated on the basis of clearing three-phase faults. The most onerous case with respect to TRVs is for the first-pole-to-clear (FPTC or fptc). This is because after the first circuit breaker pole clears, the system becomes unbalanced, causing the AC recovery voltage across the pole to exceed its normal phase-to-earth value. Two cases can be distinguished based on the earthing of the power system:

Case 1: Power system effectively earthed.
An effectively earthed power system is one in which the ratio of the zero-sequence reactance to the positive-sequence reactance is positive and equal to 3 or less (neutrals solidly or low impedance earthed). Circuit breakers applied on such systems are rated on the basis of clearing a three-phase-to-earth fault. After the most onerous first pole clearing, this leaves a double-phase-to-earth fault and, in turn, after second pole clearing, leaves a single-phase-to-earth fault to be cleared by the third pole. This sequence is shown in Figure 3.6.

Case 2: Power system non-effectively earthed.
A non-effectively earthed power system is not defined by sequence reactances but rather as one where the neutral is isolated, high impedance or resonant earthed. Circuit breakers applied on such systems are rated on the basis of clearing a three-phase unearthed fault. First pole clearing leaves a phase-to-phase fault to be cleared simultaneously by the second and third poles in series. Before the second and third pole clearing, the fault-side neutral will shift by 0.5 pu and the AC recovery voltage for the first-pole-to-clear is 1.5 pu. This sequence is shown in Figure 3.7.

The standard TRV requirements for a 245 kV circuit breaker on an effectively earthed system and a 72.5 kV circuit breaker on a non-effectively earthed system are given in Tables 1.1 and 1.2, respectively.

Without going into detail at this point, the TRVs are based on the two components briefly discussed earlier: a power frequency component given by the first-pole-to-clear factor k_{pp} (Chapter 3) and an oscillatory component, which may actually be aperiodic, given by the amplitude factor k_{af} (Chapter 2).

The short-line fault and out-of-phase switching requirements are also shown in Tables 1.1 and 1.2.

In general, circuit breakers are designed to withstand voltage, carry load current and clear faults. However, circuit breakers are also required to interrupt load currents. Load currents at or around unity power factor present no difficulty, but at zero power factor leading or lagging,

Table 1.1 Standard transient recovery voltage values for 245 kV rated circuit breaker on an effectively earthed system.

Rated voltage, U_r (kV)	Test duty	First-pole-to-clear factor, k_{pp} (pu)	Amplitude factor, k_{af} (pu)	First reference voltage, u_1 (kV)	Time, t_1 (μs)	TRV peak value, u_c (kV)	Time, t_2 (μs)	Time delay, t_d (μs)	Voltage, u' (kV)	Time, t' (μs)	RRRV, u_1/t_1 (kV/μs)
245	Terminal fault	1.3	1.40	195	98	364	392	2	98	51	2
	Short-line fault	1	1.40	150	75	280	300	2	75	40	2
	Out-of-phase	2	1.25	300	196	500	392–784	2–20	150	117	1.54

RRRV: rate of rise of recovery voltage.

Table 1.2 Standard transient recovery voltage values for 72.5 kV rated circuit breaker on a non-effectively earthed system.

Rated voltage, U_r (kV)	Type of test	First-pole-to-clear factor, k_{pp} (pu)	Amplitude factor, k_{af} (pu)	TRV peak value, u_c (kV)	Time, t_3 (μs)	Time delay, t_d (μs)	Voltage, u' (kV)	Time, t' (μs)	RRRV, u_c/t_3 (kV/μs)
72.5	Terminal fault	1.5	1.54	137	93	5	45.6	36	1.47
	Short-line fault	1	1.54	91.2	93	5	30.4	36	0.98
	Out-of-phase	2.5	1.25	185	186	28	61.7	90	0.99

current interruption is an onerous duty. No rated interrupting current values are stated in the standards because in practice they are application dependent. Preferred capacitive current switching ratings are stated in the expectation that type testing to these values will cover a majority of actual applications.

1.3 Current Interruption Terminology

Current interruption terminology can be understood by considering an actual event. Figures 1.1–1.3 show the trace of a close–open (CO) three-phase unearthed fault current test on a vacuum circuit breaker. Taking each figure in turn, the terminology is as follows:

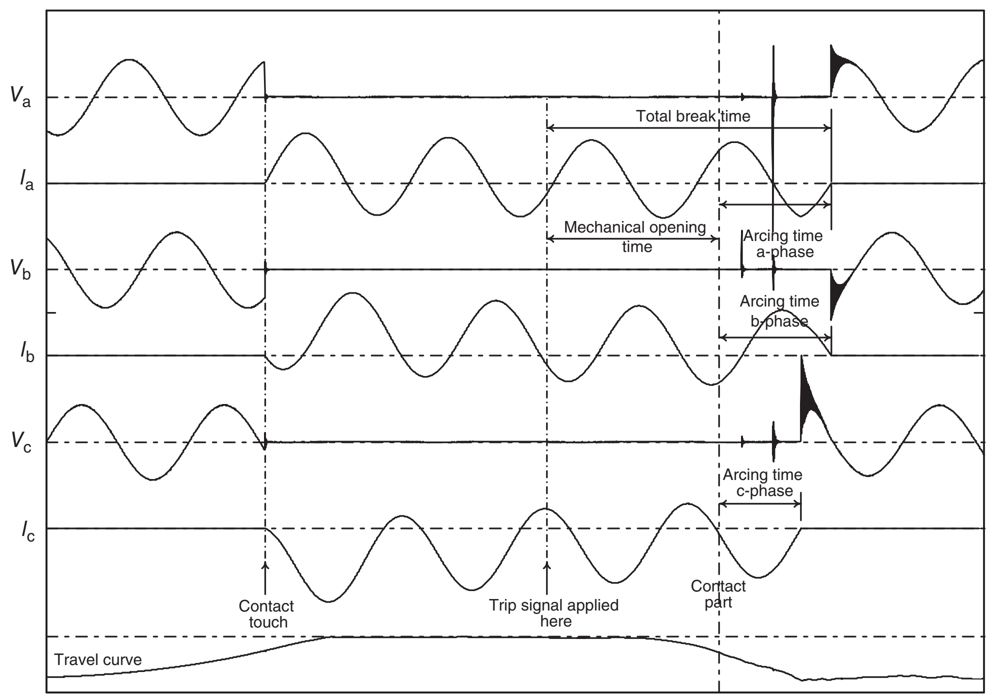

Figure 1.1 Current interruption terminology: timing-related quantities (trace courtesy of KEMA).

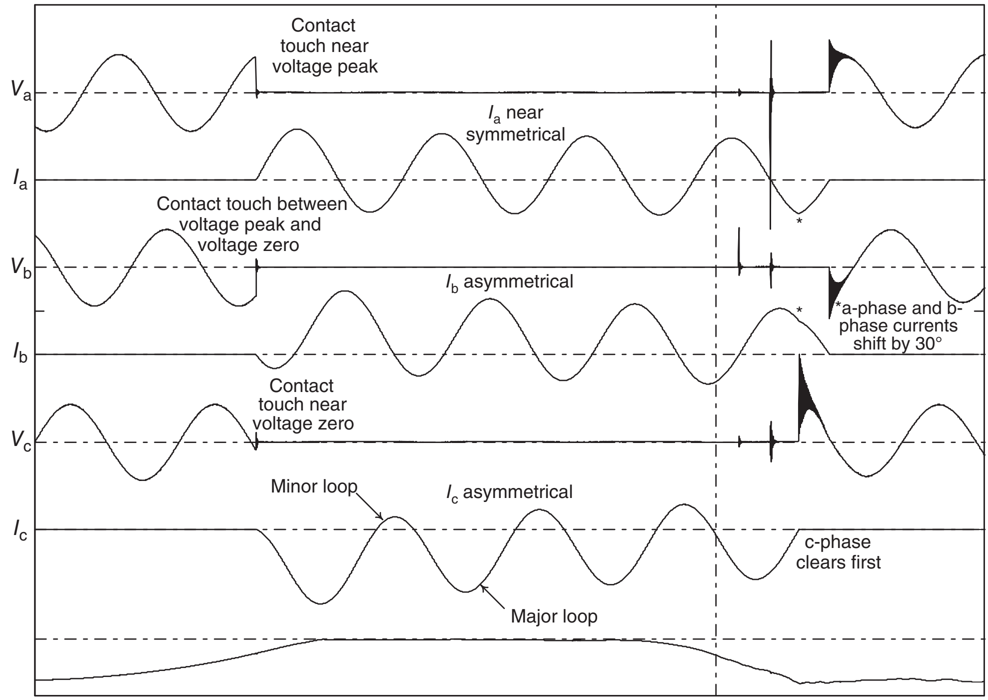

Figure 1.2 Current interruption terminology: current-related quantities (trace courtesy of KEMA).

Figure 1.1 (timing-related quantities):

- The circuit breaker is initially open, and a close signal is applied to the close coil to initiate closing.
- After a short electrical delay time, the moving contact starts in motion (travel curve at the bottom of the trace) and makes contact with the circuit breaker fixed contact. This instant is referred to as contact touch or contact make. In practice, actual electrical making of the circuit may precede mechanical contact because of a prestrike between the contacts. The time between application of the close signal and contact touch is the mechanical closing time of the circuit breaker.
- The circuit breaker is now closed and carrying fault current. A trip signal is applied to the trip coil initiating opening, also referred to as tripping, of the circuit breaker. After a short electrical time delay, the moving contact is set in motion and mechanical separation of the fixed and moving contacts occurs. This instant is referred to as contact part, contact parting or contact separation. The time between application of the trip signal and contact part is the mechanical opening time.
- An arc is drawn between the contacts, and current interruption attempts are made as the zero crossings occur, first on b-phase, then on a-phase and successfully on c-phase. c-phase is thus the first-pole-to-clear with an arcing time—time between contact part and current interruption—of about one half-cycle. The interrupting time, also referred to as the break time, on c-phase is the mechanical opening time plus the arcing time.

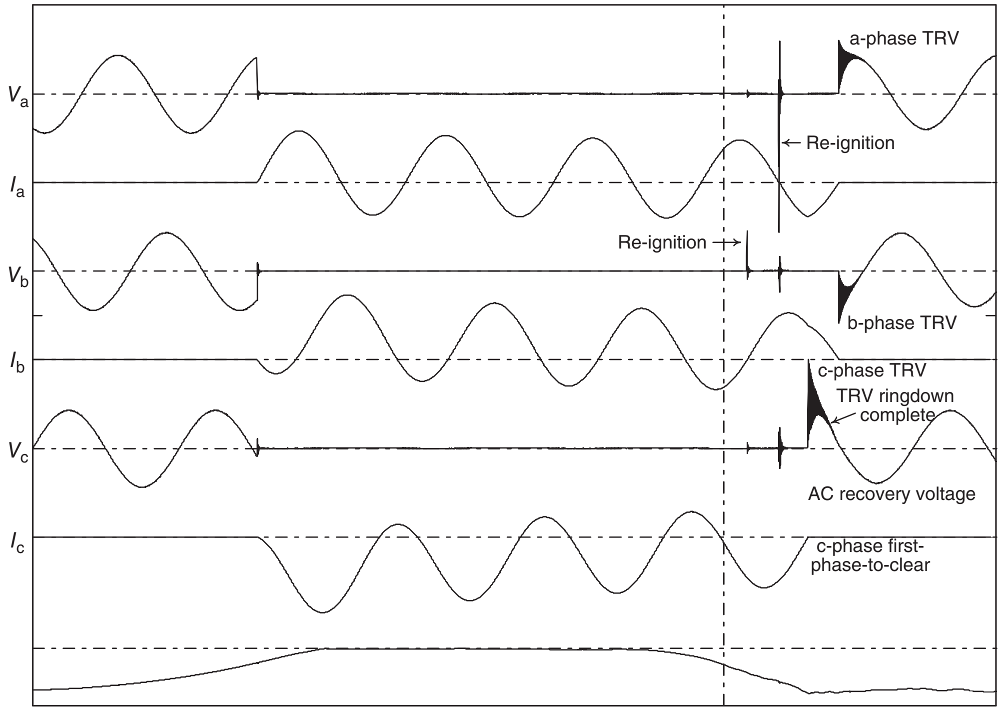

Figure 1.3 Current interruption terminology: voltage-related quantities (trace courtesy of KEMA).

- At current interruption in c-phase, the currents in a-phase and b-phase become equal in magnitude and opposite in polarity by means of a 30° shift, a shortened half-cycle in the former phase and a longer half-cycle in the latter. The total break time is the mechanical opening time plus the maximum arcing occurring in these two phases.

Figure 1.2 (current-related quantities):

- For a fault initiated at a voltage peak, the current will be symmetrical. Symmetrical means that the each half-cycle of the current, also referred to as a loop of current, will be identical to the preceding half-cycle of current. The current in a-phase is near symmetrical as a result of fault initiation just before the voltage peak.
- The currents in b-phase and c-phase are asymmetrical and consist of long and short loops of current referred to as major loops and minor loops, respectively. Maximum asymmetry occurs when the fault is initiated at a voltage zero crossing. Asymmetrical currents are discussed in detail in Section 4.7.

Figure 1.3 (voltage-related quantities):

- Current zeros occur every 60°, and the pole closest to a zero after contact part will make the first attempt to interrupt the current. The b-phase pole that is the closest to the first zero makes the attempt to interrupt the current but reignites because the contacts are too close to withstand the TRV. The a-phase pole in turn also makes an attempt but reignites followed by successful interruption on c-phase, that is, recovering against the TRV and AC recovery voltage.

- The TRV is a transient oscillation as the voltage on the source side of the circuit breaker recovers to the prefault system voltage. The TRV oscillates around the AC recovery voltage, its aiming point or axis of oscillation, reaching a peak value depending on the damping in the circuit. As the trace shows, the TRV rings down within a power frequency quarter cycle. The first-pole-to-clear is exposed to the highest TRV. The theory behind TRVs is discussed in Chapters 2 and 3 and applied in the later chapters.
- a-phase and b-phase poles clear 90° later, each with its own TRV of lower magnitude than for c-phase and of opposite polarity. The AC recovery voltage is the line voltage and is shared by both poles.

Bibliography

The following references are for the textbooks covering the broad range of circuit breaker types and related switching transients in high-voltage networks (see also Bibliography in Appendix H).

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