

IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC

IEEE Power and Energy Society

Sponsored by the
Switchgear Committee

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IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC

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Abstract: The testing of fault current limiters (FCLs) operating on condition-based impedance increase for AC systems 1000 V and above is described in this guide. Constant impedance series reactors and single fuses are not included in this guide.

Keywords: asymmetrical short-circuit current, continuous current, electromagnetic compatibility, FCL testing, IEEE C37.302™, insertion impedance, insulation resistance, inter-turns insulation, lightning impulse/BIL, lightning impulse voltage, loss measurement, partial discharge, peak withstand current, power frequency voltage withstand, recovery, short-circuit current limitation, short-time withstand current, temperature rise.

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Introduction

This introduction is not part of IEEE Std C37.302-2015, IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC.

Significant developments in the area of fault current limiters (FCLs) operating on the principle of condition-based impedance increase have resulted in products emerging on the market in the last decade. There are, however, no guidelines on how to test these new FCL technologies. Therefore, in June 2010 the IEEE Switchgear Committee established WG PC37.302 to develop such a guide.

This Working Group was co-sponsored by the IEEE Power and Energy Society/Substations (PE/SUB) and the IEEE Power Electronics Society/Standards Committee (PEL/SC). This guide takes a technology-independent black-box approach and intentionally avoids stating any performance criteria. It provides, however, a newly developed set of parameters (not values) to fully describe the behavior of any FCL for testing purposes. Overall, this guide has been written to inform the stakeholder community about all the aspects of testing FCLs.

Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	2
2. Normative references.....	2
3. Definitions, acronyms, and abbreviations	3
3.1 General FCL definitions	3
3.2 Definitions related to voltages observed during fault current limitation	4
3.3 Definitions related to prospective short-circuit currents.....	5
3.4 Definitions related to initiation of CCL transition.....	5
3.5 Definitions related to currents without limitation by an FCL	6
3.6 Fault currents or over-currents with limitation by an FCL	6
3.7 FCL recovery processes and associated times	7
4. FCL technical principles.....	9
4.1 Type A FCLs	10
4.2 Type B FCLs	13
5. Sample specification parameters	16
5.1 Electrical performance.....	16
5.2 Rated fault current limitation voltage	18
5.3 Rated maximum prospective short-circuit current.....	18
5.4 Rated minimum prospective short-circuit current	18
5.5 Withstand current ratings in C mode	19
5.6 CCL Initiation criteria.....	19
5.7 Current ratings with FCL limitation	20
5.8 Insertion impedance.....	20
5.9 Physical and operational	21
5.10 Environmental	21
5.11 Safety.....	22
6. Design tests.....	22
6.1 Aspects of FCL behavior	22
6.2 Power frequency voltage withstand test	24
6.3 Lightning impulse voltage	25
6.4 Switching impulse voltage.....	26
6.5 Chopped-wave lightning impulse voltage	27
6.6 Surge current test (alternate).....	27
6.7 Partial discharge	27
6.8 Control circuit design test.....	28
6.9 Rated continuous current	28
6.10 Short-time withstand current and peak withstand current tests	30
6.11 Harmonic distortion.....	33
6.12 Short-circuit current limitation tests	33
6.13 Current interruption	38
6.14 Recovery.....	38
6.15 Electromagnetic compatibility EMC	39
6.16 Audible sound.....	39
6.17 Seismic tests	40
6.18 Visual inspection	40

6.19 FCL technology-specific tests	40
7. Production (routine) tests.....	41
7.1 Power frequency voltage withstand test	41
7.2 Other voltage withstand tests	42
7.3 Partial discharge	42
7.4 Control circuit voltage and wiring checks	42
7.5 Visual inspection	42
7.6 Considerations to assess essential FCL functionality	43
7.7 FCL technology-specific tests	43
8. Field inspection, testing, and commissioning of fault current limiter and ancillary systems	44
8.1 General	44
8.2 Field inspection and installation verification	44
Annex A (informative) Example of FCL ratings	46
Annex B (informative) List of variables.....	47
Annex C (informative) Bibliography.....	50

IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC

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1. Overview

1.1 Scope

This guide describes the testing of fault current limiters (FCLs) operating on condition-based impedance increase for AC systems 1000 V and above. This guide does not include constant impedance series reactors and single fuses. (For standards specific to these fault current limiting devices, see IEEE Std C57.16^{TM1,2,3} and IEEE Std C37.46TM [B14]⁴).

NOTE—Testing of FCL load current interrupting capabilities are not addressed in this guide and may be discussed between user and manufacturer.⁵

¹ Information on normative references can be found in Clause 2.

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⁴ The numbers in brackets correspond to those of the bibliography in Annex C.

⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

1.2 Purpose

This guide provides guidelines for testing of fault current limiters (FCLs) operating on condition-based impedance increase for AC systems 1000 V and above.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C57.12.55, American National Standard for Transformers—Used in Unit Installations, Including Unit Substations-Conformance Standard.⁶

IEC 60060-1, High-voltage test techniques—Part 1: General definitions and test requirements.⁷

IEC 60076-3, Power transformers—Part 3: Insulation levels, dielectric tests and external clearances in air.

IEC 60076-4, Power transformers—Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors.

IEC 60076-6, Power transformers—Part 6: Reactors.

IEC 60255-26, Electrical relays—Part 26: Electromagnetic compatibility requirements for measuring relays and protection equipment.

IEC 60270-2000-12, High voltage test techniques—Partial discharge measurements.

IEC 60282-1, High-voltage fuses—Part 1: Current-limiting fuses.

IEC 62271-1, High-voltage switchgear and controlgear—Part 1: Common specifications.

IEC 62271-100, High-voltage switchgear and controlgear—Part 100: High-voltage alternating-current circuit-breakers.

IEEE Std 4™, IEEE Standard Techniques for High-Voltage Testing.

IEEE Std 118™, IEEE Standard Test Code for Resistance Measurement.

IEEE Std 693™, IEEE Recommended Practice for Seismic Design of Substations.

IEEE Std C37.09™, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.60™, IEEE High-voltage switchgear and controlgear—Part 111: Automatic circuit reclosers and fault interrupters for alternating current systems up to 38 kV.

IEEE Std C37.100.1™, IEEE Standard of Common Requirements for High Voltage Power Switchgear Rated Above 1000 V.

IEEE Std C37.122™, IEEE Standard for High Voltage Gas-Insulated Substations Rated Above 52 kV.

IEEE Std C37.301™, IEEE Standard for High-Voltage Switchgear (Above 1000 V) Test Techniques – Partial Discharge Measurements.

IEEE Std C57.12.00™, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

⁶ ANSI publications are available from the American National Standards Institute (<http://www.ansi.org/>).

⁷ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.91™, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

IEEE Std C57.16, IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

IEEE Std C62.11™, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (> 1 kV).

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁸

3.1 General FCL definitions

branches (of FCL): One or more intentional current paths through an FCL. Figure 1 illustrates “n” number of current branches through a single-phase FCL.

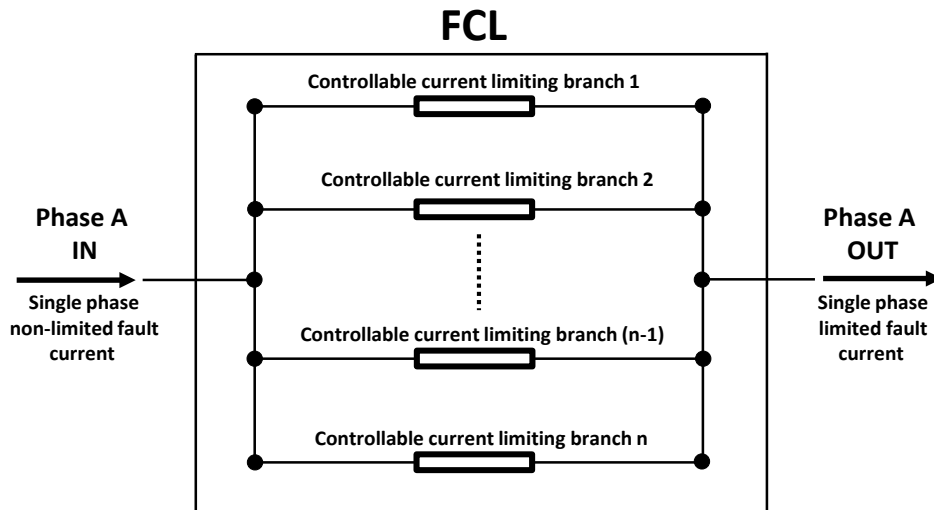


Figure 1—Current branches in an FCL

C mode: The (normal) conducting mode of an FCL (i.e., the FCL is in its low impedance state).

CCL transition: The transition from C mode to CL mode.

CL mode: The current limiting mode of an FCL (i.e., generally, the FCL is in its high impedance state while in CL mode. However, some technologies may transit back and forth between high and low impedance states during the current limiting phase in order to limit the fault current).

CLC transition: The transition from CL mode to C mode.

⁸ IEEE Standards Dictionary Online subscription is available at: <http://ieeexplore.ieee.org/xpls/dictionary.jsp>.

CLI transition: The transition from CL mode to Interrupting mode.

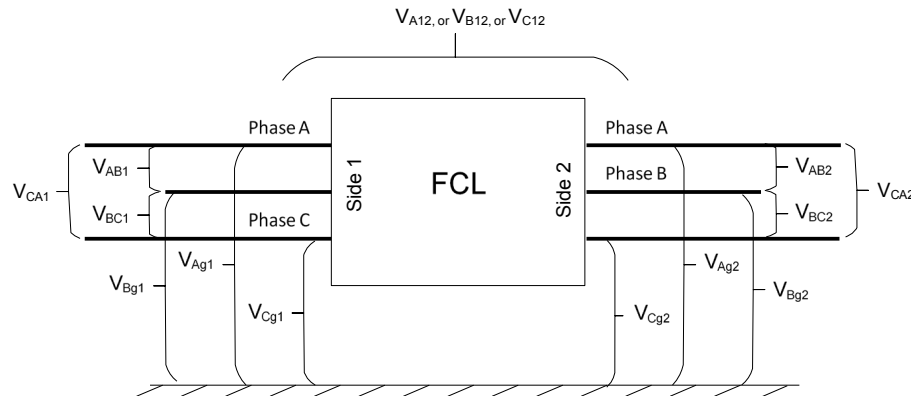
fault current limiter (FCL): A device or apparatus that limits the first peak and the subsequent rms short-circuit (i.e., fault) current in an alternating current power system to the specified value by providing a condition-based increase in resistive and/or reactive impedance between normal conducting mode and current limiting mode. The FCL may consist of discrete, functionally integrated, and spatially separated equipment.

IC transition: The transition from Interrupting mode to C mode.

insertion impedance: The impedance presented by the FCL in C mode at power frequency which may be constant or a current-dependent function.

interrupting mode: The interruption mode of an FCL (i.e., the FCL has interrupted the fault current flow). Not all FCLs have an Interrupting mode.

voltages across an FCL: The voltages across an FCL are defined in Figure 2. They include the voltage differences between the voltage on each phase terminal on one side of the FCL and the voltage on the terminal of the same phase on the other side of the FCL. The voltages across the FCL depend on the current flowing through each phase of the FCL and the impedance of the FCL in that phase.



V_{A12} , V_{B12} , or V_{C12} are the voltages across the FCL

Figure 2—FCL voltages

3.2 Definitions related to voltages observed during fault current limitation

For the purpose of characterizing the voltages observed across the FCL during fault current limitation, the following definitions apply.

fault current limitation voltage: The voltage across the terminals of the FCL from the beginning of the CL mode to fault interruption. This voltage may be considered in two successive intervals of time, one during which a transient voltage exists, followed by a second one during which the power frequency or the steady-state voltage alone exists. The voltage after the CLI transition should be less than or equal to the highest voltage that the FCL will be exposed to in the system.

NOTE 1—The corresponding voltage for a non-current limiting device with current interruption at current-zero is the TRV defined in IEEE Std C37.46 [B14].

NOTE 2—For FCL limitation of the rated symmetrical prospective fault current, refer to the circuit breaker standard IEEE Std C37.09.

maximum fault current limitation voltage: The maximum instantaneous value of fault current limitation voltage over any portion of its waveform, regardless whether it is periodic in nature or not. The symbol used for this value is $u_{k,CL,max}$.

RMS fault current limitation voltage: The rms fault current limitation voltage is defined by the two rms values of the fault current limitation voltage waveform that occur during its first- and last three half-cycles (i.e., $U_{k,CL,B}$ and $U_{k,CL,E}$).

NOTE—The first- and the last three half-cycles are each a period equal to the time required for three half-cycles of the power frequency symmetrical waveform. For voltages, the first period begins at the first zero crossing of the fault current limitation voltage after the CCL transition. The second period ends at the last zero crossing of the fault current limitation voltage before current interruption. For currents, the first period begins at the first zero crossing of the current after the CCL transition. The second period ends at current interruption. This concept is illustrated in Figure 6.

transient fault current limitation voltage (TLV) : The fault current limitation voltage during the time in which it has a significant transient component. It may be oscillatory or non-oscillatory or a combination of these depending on the characteristics of the circuit and the FCL.

3.3 Definitions related to prospective short-circuit currents

For FCLs, two prospective short-circuit current values are defined.

maximum prospective short-circuit current: The maximum prospective fault current for which the FCL has been designed. The two aspects are:

- peak short-circuit current, and
- symmetrical short-circuit rms current.

NOTE—The maximum symmetrical fault current may not be the most critical current for testing some FCL technologies. The most critical value should be discussed between the user and manufacturer.

minimum prospective short-circuit current for CCL transition: The minimum prospective fault current for which the FCL is designed to transition out of C mode.

NOTE—The minimum symmetrical fault current for CCL transition might not be the most critical current for testing some FCL technologies. The most critical value should be discussed between the user and manufacturer.

3.4 Definitions related to initiation of CCL transition

The CCL transition may be initiated by current magnitude, rate-of-current rise, external initiation signal, or other quantities.

CCL initiation criteria: The quantity which causes the CCL transition.

NOTE—For purposes of this testing guide, initiation criteria based on current, on rate-of-current rise, and on external initiation signals are considered. The user is invited to discuss testing of any other type of CCL initiation criterion with the manufacturer.

CCL initiation current: The instantaneous value of current which will initiate the CCL transition. It may need to be considered in combination with rate-of-current rise.

CCL initiation delay: The time delay from fault inception to reach the initiation criteria.

NOTE—CCL Initiation delay is a measured value of the test waveform or of the external initiation signal, not a characteristic of the FCL. The initiation delay includes system effects such as the time it takes the system fault current waveform to reach CL initiation conditions. The user is invited to consider that short-circuit conditions may arise at any time in the waveform. Therefore the measurements should include the point on the prospective fault current waveform when the short-circuit conditions are imposed and the time constant is of the prospective fault current. Accurately measuring this delay may be difficult for some FCLs.

CCL initiation rate-of-current rise: The initiation rate-of-current rise (i.e., gradient), is the rate-of-current rise which will initiate the CCL transition. It may need to be considered in combination with initiation current.

3.5 Definitions related to currents without limitation by an FCL

This clause pertains to currents at levels above the rated continuous current that do not meet the initiation criteria of an FCL.

branch short-time withstand current: The rms value of the current that a specific branch of the FCL can carry in the C mode, evaluated during the first- and last three full half-cycles under prescribed conditions of use and behavior without limitation by the FCL.

NOTE—The branch ID number is denoted by the value of the subscript “n”.

peak withstand branch current: The peak current associated with the first major loop of the short-time withstand current that a specific branch of the FCL can carry in the C mode.

peak withstand current: The peak current associated with the first major loop of the short-time withstand current.

short-time withstand current in C mode: The rms value of the current that the FCL can carry in the C mode.

NOTE—The actual current is expected to stay within the bounds of the two rated short-time withstand current values.

3.6 Fault currents or over-currents with limitation by an FCL

This clause pertains to currents at levels that meet the initiation criteria of an FCL.

limited short-circuit withstand branch current: The rms value of the current that a specific branch path of the FCL can carry with the FCL in CL mode, evaluated out of the first- and last three full half-cycles.

limited short-circuit withstand current: The rms value of the current that the FCL can carry in the CL mode, evaluated during the first- and last three full half-cycles, under prescribed conditions of use and behavior.

peak let-through current: The peak let-through current, $i_{p,LT}$ is the instantaneous value of the current attained during the fault current limitation operation of the FCL at the rated prospective fault current condition (rated power frequency, voltage, etc.). Figure 3 illustrates an FCLs peak let-through current relative to the unimpeded flow of fault current.

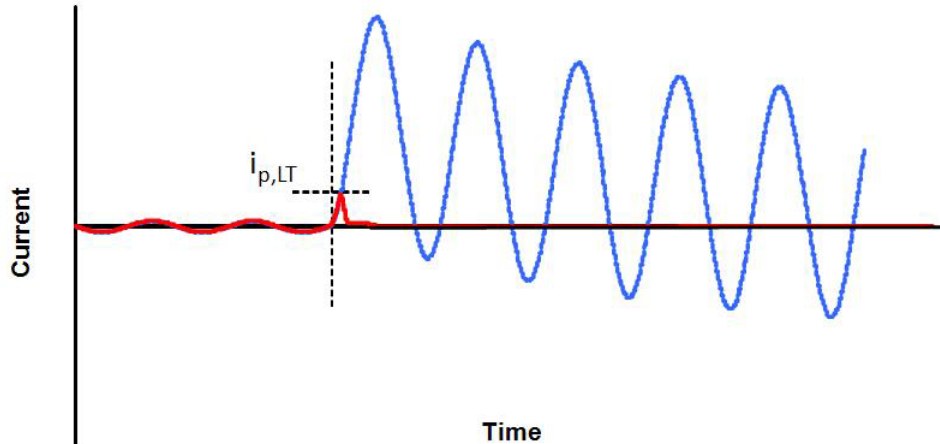


Figure 3—Peak let-through current

NOTE—For FCLs which result in a maximum value not during rated maximum prospective short-circuit current conditions, the user and the manufacturer should discuss this. The peak let-through current may depend on many parameters (e.g., prospective fault current, power frequency, power factor, settings or design of FCL, and others). Therefore, usually one FCL type has more than one value of peak let-through current. The manufacturer of the FCL usually performs tests to verify some representative peak let-through current values and derives all others by calculations in accordance with specified application data. As described above, it is not practical or necessary to perform FCL testing of all arrangements that exhibit a different value of peak let-through current.

peak let-through time: The time from fault inception to the instant when the current through the FCL reaches its specified value of peak let-through current, under specified conditions. This is a measured value, not a rating.

peak limited short-circuit withstand current: The peak value of the limited short-circuit withstand current through the FCL in CL mode.

peak limited, withstand short-circuit branch current: The peak value of the limited withstand short-circuit current for each FCL branch.

3.7 FCL recovery processes and associated times

C mode recovery status: The FCL being in C mode after a fault event and regaining rated current limiting but reduced continuous current carrying capability. *See also:* **FCL recovery process.**

NOTE—See Figure 4 in FCL recovery processes and associated times.

C mode recovery time: Δt_r is the amount of time required between the clearing of a rated fault event to the moment when the FCL regains C mode recovery status. *See also:* **FCL recovery process.**

NOTE—See Figure 4 in FCL recovery processes and associated times.

FCL recovery process: The process between clearing of the fault and the FCL regaining fault current limitation capability as illustrated in Figure 4 along with additional transitions until the FCL is back in C mode and able to carry full rated current.

NOTE 1—Each of the specific times identified in the Figure 4, and defined in the text that follows, may be negated depending on the technology employed.

NOTE 2—The recovery process may occur with or without load current flow. If the FCL has to be isolated from the system to recover, it either needs a manual service (human intervention) before returning to service or it recovers automatically.

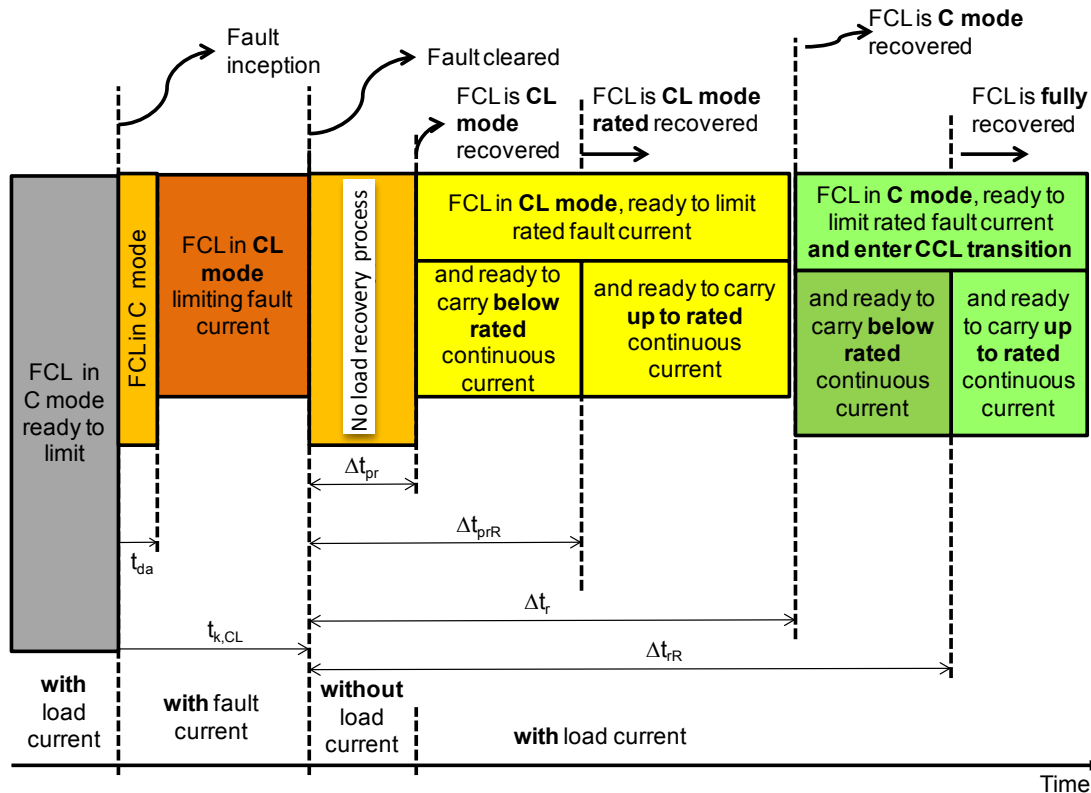


Figure 4—Summary of FCL recovery process and subsequent transitions

full recovery status: The FCL being in C mode after a fault event and regaining continuous current capability and full rated short-circuit current limitation capability. *See also:* **FCL recovery process.**

NOTE—See Figure 4 in FCL recovery processes and associated times.

partial recovery time: Δt_{pr} is the time from the clearing of a fault event to the end of the no load recovery process. *See also:* **FCL recovery process.**

NOTE—See Figure 4 in FCL recovery processes and associated times.

rated full recovery time: Δt_{rR} is the time from the clearing of a rated fault event to the moment when the FCL regains full recovery status. *See also:* **FCL recovery process.**

NOTE—See Figure 4 in FCL recovery processes and associated times.