Selection & Sizing of Fault Current Limiters

Sanjay Koul

Consultant Electrical Engineering Design

Abstract - This paper presents the overview of Fault Current Limiters including selection and sizing. The study can help the user give more insight to various factors to be considered for selection and sizing of fault current limiter. The paper reveals that FCL is crucial for limiting fault current and enhancing power system stability, reliability and safety.

Key Words: Fault Current Limiters, Resistive FCL, Inductive FCL, Superconducting FCL, Solid State FCL, Hybrid FCL, power system stability

1. INTRODUCTION

In the early days of electricity distribution, fault currents were not a major concern because the electrical networks were relatively small and the generation capacities were limited. The traditional protection devices such as fuses and circuit breakers were used to manage fault conditions. These devices were adequate for the smaller grids of the time but were not designed to handle the high fault currents that would come with the growth of larger interconnected grids.

As electrical grids expanded and the demand for energy grew, the size and complexity of power networks grew significantly which resulted in the need for a more reliable and effective method to manage and control fault currents became evident. To address the growing challenge of managing fault currents, Fault Current Limiters (FCLs) emerged as a vital technology to address increasing fault current levels in modern power systems. FCLs were developed to provide a solution that would protect critical infrastructure and improve the safety and reliability of power distribution networks and enabling the use of equipment with lower interrupting ratings. FCLs limit the peak fault current that could occur during a fault event, reducing the stress on system components and preventing potential damage.

Fault Current Limiters have evolved from early 20th century to present times, transitioning from traditional circuit breakers and fuses to sophisticated devices that utilize superconducting materials, solid state and hybrid technology.

Normal Operation: Under normal conditions, FCLs have very low impedance and do not significantly affect the operation of the power system.

Fault Condition: When a fault (e.g., short circuit, overload) occurs, the FCL quickly increases its impedance. This limits the magnitude of the fault current, protecting downstream equipment.

Post-Fault Recovery: After the fault is cleared, the FCL typically returns to its low-impedance state, restoring normal operation.

2. PLACEMENT AT UPSTREAM VS LOAD CENTER

The preferable location for installing a Fault Current Limiter (FCL) depends on the specific characteristics of the electrical network, but it is typically placed either at the upstream substation or at the load center, depending on the following considerations:

2.1 Upstream Substation Installation

Objective: Limit the fault current at the source to protect downstream equipment.

Advantages: Protects the entire downstream network, including transformers, circuit breakers, and cables, from high fault currents, Reduces the stress on the upstream substation and all downstream equipment, potentially allowing for the use of lower-rated equipment, Minimizes the overall fault current contribution to the grid, which can be crucial in interconnected systems.

Application: This is often preferred in high-voltage transmission networks or areas where the fault level is very high and must be reduced across a large portion of the grid. It's common in substations where large fault currents could affect multiple downstream feeders or systems.

2.2 Load Center Installation

Objective: Limit fault current closer to the point of consumption or specific sensitive equipment.

Advantages: Focuses protection on specific critical loads or equipment that may not be rated for high fault currents, Reduces the fault current locally, which can be important in industrial facilities or large commercial centers where sensitive machinery or processes need protection, Can help in reducing the required rating of local circuit breakers and other protection devices, offering cost savings.

Application: This is often used in low- or medium-voltage distribution networks or in industrial setups with sensitive loads. It is ideal for systems where localized protection is sufficient, and the fault level at the load center is more critical.

2.3 General Considerations

Network Configuration: In complex networks, fault current levels may vary significantly at different points. FCL placement should be based on an analysis of where the fault current exceeds the capability of existing protection devices.

Cost and Feasibility: Installing an FCL at an upstream substation might offer more comprehensive protection but can be more expensive due to the high voltage and fault levels involved. Conversely, installing FCLs at load centers may be more cost-effective but might not provide system-wide fault current reduction.

Grid Stability: In some cases, placing an FCL upstream can enhance overall grid stability by preventing excessive fault currents from propagating through interconnected systems.

In most cases, installing an FCL at the upstream substation is preferable when the goal is to protect a large portion of the grid and reduce fault currents system-wide. However, if the focus is on protecting specific loads or equipment, installation at the load center can be more appropriate.

The final decision should be based on a detailed fault current study, considering factors such as fault current magnitudes, the sensitivity of the loads, the protection scheme, and economic factors.

3. SELECTION CRITER

Selecting a Fault Current Limiter (FCL) for a power distribution network involves several criteria to ensure it meets the technical, economic, and operational requirements of the network. Here's a detailed selection guide:

3.1 System Voltage and Current Levels

Operating Voltage: FCLs are designed to operate at specific voltage levels, such as low-voltage (LV < 1 kV), medium-voltage (MV < 1–33 kV**)**, or high-voltage (HV > 33 kV) systems. It is crucial to select an FCL rated for the voltage level of the network in which it will be installed.

Fault Current Levels: The maximum expected fault current level in the system determines the FCL's current rating. The device must be able to handle these fault currents without damage or malfunction.

Normal Load Current: The FCL should have low impedance during normal operation, allowing normal current flow without significant losses.

Peak Fault Current: The FCL must be rated to handle the maximum fault current and limit it to a value that can be managed by other protective devices (e.g., circuit breakers). Calculate the maximum prospective fault current and select an FCL that can limit it effectively.

Limit Reduction Capability: Verify the FCL's ability to reduce fault currents to acceptable levels, such as reducing from 60kA to 30kA.

3.2 Response Time

Fault Detection Time**:** The FCL must have a fast response time to detect and limit fault currents quickly, typically within a few milliseconds to prevent equipment damage. Different FCL technologies have varying response times:

Superconducting FCL (SFCL)**:** Millisecond-level response times, ideal for high-voltage and high-speed applications.

Solid-State FCL (SSFCL)**:** Microsecond-level response times, suitable for highly sensitive systems.

Resistive FCL (RFCL)**:** Relatively slower response times, though sufficient for many medium-voltage applications.

Restoration Time: After the fault is cleared, the FCL should quickly return to its low-impedance state. This is important to minimize downtime and restore normal operation promptly.

3.3 Impedance Characteristics

Low Impedance During Normal Operation**:** The FCL should exhibit very low impedance under normal load conditions to minimize energy losses and voltage drops.

High Impedance During Fault Conditions**:** During a fault, the FCL should quickly increase its impedance to limit the fault current. The level of impedance increase must be sufficient to protect downstream equipment and allow protective devices to operate effectively.

3.4 Fault Current Limiting Capability

Current Limiting Ratio**:** The ratio between the prospective fault current (the fault current that would flow without an FCL) and the limited fault current (the current that flows with the FCL installed) is an important parameter. The higher the limiting ratio, the more effective the FCL is.

Thermal Capability: The FCL must be able to absorb the thermal energy generated by high fault currents without overheating or degrading. This is particularly important for resistive and inductive FCLs, which dissipate energy as heat.

3.5 **Type of Fault Protection**

Single-Phase vs. Three-Phase Protection: Depending on the system design, the FCL may need to limit fault currents for single-phase, two-phase, or three-phase faults. Three-phase systems typically require more sophisticated FCLs.

Symmetrical vs. Asymmetrical Faults: The FCL must be able to handle both symmetrical (balanced) and asymmetrical (unbalanced) fault conditions, as both types of faults can occur in the system.

Transient Currents: The FCL must also handle transient over currents, which can occur during switching operations or capacitor bank energization.

3.6 **Coordination with Protective Devices**

Circuit Breaker Coordination: The FCL must be coordinated with circuit breakers to ensure that the breakers trip effectively during fault conditions. This includes ensuring that the fault current is reduced to a level that circuit breakers can safely interrupt.

Relay Coordination: Protective relays must be set appropriately to work with the FCL, ensuring that the relay settings account for the limited fault current.

3.7 **Physical Footprint and Space Availability**

Size of the FCL: The physical size and footprint of the FCL should fit within the available space in the substation, plant, or switchgear. Certain types of FCLs, such as inductive or resistive types, can be bulky, requiring careful consideration of space constraints.

Installation and Retrofitting: If the FCL is being installed as a retrofit in an existing system, compatibility with existing equipment and infrastructure must be ensured. The installation process should be manageable in terms of time and effort.

3.8 **Environmental Conditions**

Ambient Temperature: The FCL must be capable of operating effectively within the environmental temperature range of the system.

Weather Conditions: In outdoor installations, the FCL must be weatherproof and resistant to environmental conditions like rain, snow, and humidity.

Cooling Requirements: Superconducting FCLs require cryogenic cooling systems to maintain the superconducting state. If such a system is chosen, the environmental and operational costs of cooling must be considered.

Disposal and Recycling: Evaluate options for the disposal and recycling of the FCL at the end of its lifecycle.

3.9 **Maintenance and Operational Costs**

Maintenance Frequency: Some FCLs, especially mechanical or superconducting types, require regular maintenance. Consider the ease of maintenance and the frequency of required checks and repairs.

Operational Costs: The long-term operational costs should be evaluated. For example, superconducting FCLs incur additional costs related to cooling systems, while resistive FCLs may lead to energy losses due to resistance.

3.10 **Technology Type**

The type of FCL technology chosen will significantly impact its performance, cost, and application suitability. Each type has different strengths and weaknesses, which should be considered:

Superconducting Fault Current Limiters (SFCL): Suitable for high-performance applications with the ability to handle large fault currents and provide high fault current reduction. Offers fast response times, requires cryogenic cooling.

Resistive Fault Current Limiters (RFCLs): Simple and cost-effective but less efficient due to energy losses, suitable for moderate fault current reduction.

Solid-State Fault Current Limiters (SSFCL): Fast response times and controllability but high initial costs due to semiconductor technology.

Inductive Fault Current Limiters (IFCL): Reliable and proven technology but can be bulky and slow in response.

Hybrid Fault Current Limiters (HFCLs): Combine features of different FCL technologies to balance performance and cost.

3.11 **Cost-Benefit Analysis**

Initial Investment: The upfront cost of purchasing and installing the FCL, including any necessary infrastructure modifications.

Lifecycle Costs: Consider the total cost of ownership, including installation, maintenance, operational costs (such as cooling systems for superconducting FCLs), and replacement parts.

System Enhancement vs. Cost: Evaluate whether the benefits of the FCL (e.g., improved system reliability, reduced fault current, extended equipment life) justify the investment.

3.12 Performance Criteria

Operational Reliability: The FCL should be reliable under various operating conditions and have a proven track record.

Durability: Ensure the FCL can withstand environmental conditions and operational stresses over its lifespan.

3.13 Impact on System Performance

System Stability: Evaluate how the FCL affects the stability and performance of the distribution network.

Voltage Regulation: Consider the FCL's impact on voltage regulation and overall power quality.

3.14 Application-Specific Considerations

Transmission Systems:

High Voltage Levels: Transmission systems often operate at high voltages, so SFCLs or hybrid FCLs are commonly used due to their fast response and high current-limiting capability.

Substation Integration: In large substations, space is often available for bulkier FCLs like inductive or resistive types. However, these systems must handle very high fault currents, requiring robust solutions.

Distribution Systems:

Medium Voltage Networks: In distribution networks, medium-voltage FCLs such as resistive or magnetic types are typically used. These networks often have lower fault currents but require reliable protection to avoid damage to transformers and switchgear.

Multiple Fault Conditions: Distribution systems can experience a variety of fault conditions (e.g., single-line-to-ground, double-line-to-ground), so FCLs must be versatile.

Industrial Applications:

Equipment Protection: Industrial systems often include sensitive equipment that needs protection from short circuits and over currents. FCLs with high precision and fast response times (e.g., solid-state or hybrid types) are typically preferred.

Space and Cost Constraints: In industrial plants, space may be limited, and cost constraints may lead to the selection of more cost-effective resistive or inductive FCLs.

Renewable Energy Integration:

Grid Stability: The intermittent nature of renewable energy sources like wind and solar can cause fluctuations in power flow and fault current levels. FCLs play a crucial role in maintaining grid stability.

Rapid Response Required: FCLs with fast response times, such as SFCLs or SSFCLs, are important for limiting fault currents in renewable energy applications, particularly where distributed generation is connected to the grid.

3.15 Compliance and Standards

Standards and Codes: Ensure the FCL complies with relevant standards and codes, such as IEC, IEEE, or local regulations.

3.16 Type Test Certification

Product Certification: Check for certifications from recognized bodies that validate the FCL's performance and safety.

3.17 Integration and Compatibility

Compatibility: Ensure the FCL is compatible with existing network components and protection systems.

Integration Complexity: Evaluate the complexity of integrating the FCL into the existing network infrastructure.

3.18 Flexibility and Scalability

Future Expansion: Consider whether the FCL can be easily scaled or adapted for future network expansion or upgrades.

3.19 Safety and Risk Management

Safety Mechanisms: Verify that the FCL includes safety features to protect personnel and equipment.

Emergency Handling: Assess how the FCL handles emergency situations and fault conditions.

Operational Risks: Evaluate potential risks associated with the FCL's operation and the measures in place to mitigate them.

3.20 Vendor Support and Service

Experience and Expertise: Consider the vendor's experience and expertise in providing FCL solutions.

Customer Reviews: Check for customer feedback and case studies related to the vendor's FCL products.

Technical Support: Ensure the vendor provides adequate technical support and service.

Warranty: Review the warranty terms and conditions for the FCL.

Selecting the right Fault Current Limiter (FCL) is critical for ensuring the safety, reliability, and efficiency of power systems. The selection process involves a detailed analysis of system requirements, including fault current levels, voltage ratings, response times, impedance characteristics, and operational costs.

4. DATA SHEET

Below is a general structure of a Fault Current Limiter (FCL) datasheet that provides a detailed overview of key technical parameters and specifications. Actual datasheets can vary depending on the manufacturer and the type of FCL (e.g., Superconducting FCL, Resistive FCL, or Solid-State FCL), but they generally include the following types of information:

4.1 Product Overview

Product Name, Model Number, Type: (Superconducting/Resistive/Inductive/Magnetic/Solid-State/Hybrid), Application Transmission / Distribution / Industrial / Power Generation / Renewable Energy Integration), Rated Voltage (kV), Rated Current (A), Frequency 50/60 Hz.

4.2 Electrical Specifications

Nominal System Voltage (kV), Maximum Operating Voltage (kV), Normal Operating Current (A), Rated Short-Circuit Current (kA), Current Limiting Factor, Response Time (milliseconds/microseconds), Recovery Time (seconds), Steady-State Losses (watts/kW), Initial Impedance – Normal (ohms), Fault Impedance (ohms), Transient Overvoltage Limit (% of nominal voltage), Harmonic Distortion (%THD), Thermal Capacity (kJ), Peak Withstand Current (kA), Maximum Peak Fault Current (kA), Limiting Time Fault (mili seconds), Number of Fault Operations before maintenance.

4.3 Mechanical Specifications

Dimensions, Weight, Cooling Requirements (Air-cooled/Water-cooled/Cryogenic), Installation Type (Indoor/Outdoor), Mounting Requirements (Floor/Wall/Skid Mounting), Enclosure Protection Rating (IP Rating), Vibration Resistance (acceleration rating, e.g., G rating), Environmental Conditions (temperature and humidity limits), Grounding Requirements.

4.4 Operational Characteristics

Operating Voltage Range (e.g., 90% – 110% of rated voltage), Overload Capability (e.g., 150% for 10 seconds), Operating Temperature Range, Relative Humidity, Cooling System (e.g., liquid nitrogen for superconducting FCLs), Noise Level (Insert noise rating, e.g., dB at 1 meter).

4.5 Control and Communication

Control System (PLC/SCADA), Communication Protocols (e.g., Modbus, DNP3), Local/Remote Monitoring (Available/Not Available), Interface Type (e.g., RS485/Ethernet)

4.6 Protection Features

Overcurrent Protection, Over temperature Protection, Short-Circuit Protection, Thermal Monitoring, Ground Fault Detection

4.7 Standards and Certifications

Compliance (IEC / IEEE), Type Test Certifications

4.8 Installation and Maintenance

Installation Time, Maintenance Interval, Spare Parts Availability, Recommended Tools, Diagnostic Tools.

4.9 Warranty

Warranty Period, Extended Warranty, Warranty Coverage

4.10 Additional Features (Optional)

Programmable Control Features: Allows dynamic adjustment of current limiting behavior.

Self-Healing Capability: Some advanced FCLs can self-recover after a fault.

Built-in Diagnostics: Integrated diagnostics for monitoring FCL health and performance.

5. SIZING CALCULATION

Correctly sizing a Fault Current Limiter (FCL) is crucial for ensuring that it can handle fault currents while maintaining system integrity. The sizing process involves determining the required ratings of the FCL based on the system's voltage, fault current levels, and the amount of fault current that needs to be limited. Below is a step-by-step guide to calculating the size and rating of an FCL.

5.1 System Parameters

Before sizing the FCL, you need to know the following key parameters of the electrical system:

System Voltage (V): The nominal voltage of the system (kV).

Nominal Load Current (I load): The current that flows during normal system operation (A).

Prospective Fault Current (I fault prospective): The expected fault current in the system without any current limiting device (kA).

Desired Fault Current Limiting Level (I fault limited): The maximum fault current that should be allowed to flow after the FCL is engaged (kA).

Fault Clearing Time (t clear): The time required for circuit breakers or protective relays to clear the fault (seconds).

X/R Ratio: The ratio of system reactance (X) to resistance (R), which affects the peak fault current.

5.2 Steps for Sizing Fault Current Limiters

Step 1: Determine System Voltage and Current

System Voltage (V system): The FCL must be rated for the nominal voltage of the system. Common voltage levels are 11 kV, 33 kV, 66 kV, or 132 kV in medium and high-voltage networks.

Normal Load Current (I load): This is the current that flows in the system under normal operation. The FCL must have a low impedance during this period to avoid voltage drop and power losses.

Step 2: Calculate Prospective Fault Current (I fault prospective)

The prospective fault current is the maximum current that could flow in the event of a fault without the FCL. This is usually provided by the utility or can be calculated based on system impedance:

I fault prospective = V system / Z system

Where:

V system = System voltage (in kV)

Z system = System impedance, which is dependent on the system's reactance and resistance. For high-voltage systems, reactance typically dominates.

Step 3: Choose Desired Limited Fault Current (I fault limited)

The desired fault current is typically chosen based on the fault current ratings of downstream protective devices (e.g., circuit breakers, relays, transformers). The FCL should limit the fault current to a value that the protective devices can handle safely.

For example, if the circuit breakers are rated to interrupt 25 kA, and the prospective fault current is 40 kA, you may want the FCL to limit the fault current to around 25 kA or less.

Step 4: Calculate Required Impedance of the FCL

The FCL operates by increasing the impedance in the circuit during a fault condition to limit the fault current. The required impedance can be calculated as follows:

Z FCL= V system / I fault limited – V system / I fault prospective

Where:

Z FCL = Impedance of the FCL during fault (in ohms)I fault limited = Desired fault current (in kA)

I fault prospective = Prospective fault current (in kA)

V system = System voltage (in kV)

Step 5: Determine FCL's Thermal Capacity

The FCL must absorb the energy from the fault without overheating. The **thermal energy** (W) dissipated in the FCL can be estimated by:

W = I^2 fault limited × ZFCL × t clear

Where:

I fault limited = Limited fault current (in kA)

Z FCL = FCL impedance during fault (in ohms)

T clear = Fault clearing time (in seconds)

The FCL must be designed to handle this amount of energy without damage.

Step 6: Calculate Peak Fault Current (I peak)

In systems with high X/R ratios, the peak fault current can be significantly higher than the RMS fault current due to the DC component of the fault current. The peak fault current is given by:

I peak = sq. rt. × I fault limited × $(1 + e^{-\pi/X/R})$

Where:

Ipeak = Peak fault current (in kA)

I fault limited = Limited fault current (in kA)

X/R = System X/R ratio

The FCL must be rated to withstand this peak current.

Step 7: Check Recovery Time and Repetition Rate

After the fault is cleared, the FCL should quickly recover to its low-impedance state to resume normal operation. The recovery time is particularly important for superconducting FCLs, which need time to return to their superconducting state after a fault.

Additionally, consider how often faults may occur in the system and whether the FCL can handle multiple fault events within a short period.

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