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Fault Current Limiter Selection Considerations for Utility Engineers

K. TEKLETSADIK, P. LUBICKI, S. NICKERSON, J. LUDLUM, P. MURPHY
Applied Materials, Inc.
U.S.A.

SUMMARY

Several Fault Current Limiter (FCL) technologies have matured from R&D and demonstration projects into commercially available systems. So far, the technical knowledge about FCL systems, design parameters and impact analysis on utility equipment is primarily contained within the FCL manufacturer's technical expertise. The time has come to further disseminate the technical knowledge to utility engineers so that they can design fault current management systems with the technical expertise that enables them to specify FCLs for their applications. Applied Materials is developing Superconducting Fault Current Limiters (SCFCL) and Solid State Fault Current Limiters (SSFCL) for transmission and distribution voltage levels. Both FCL technologies are being subjected to testing and in-grid demonstration. This paper is aimed at describing how utility engineers may consider selecting a FCL for a specific location and application, based on the authors' experience. It is not intended as a manual or guide to be used or relied upon without independent testing or verification. It also discusses three FCL demonstration projects including SCFCLs in California and New York, and a SSFCL shipped to a utility site for installation.

KEYWORDS

Fault Current Limiter, Superconducting, Solid State, FCL, SCFCL, SSFCL.

Kasegn_Tekletsadik@amat.com

1. Introduction

As FCL technology transforms into a market-ready system, the design and specification of the system transitions from the manufacturer to the utility engineers. Applied Materials is taking a lead in this transformation and is developing an FCL family of systems based on SCFCL and SSFCL technologies. The main objective of this publication is to provide considerations for utility engineers in selecting the right FCL solution for a specific location and application. The FCL component has been developed for PSCAD, DigSilent, PSS/E, EMTP, and PSpice circuit simulation software packages. In general, any of the available software packages can be used with no or minimal loss of accuracy.

This paper will also discuss three FCL demonstration projects including SCFCLs in California and New York, and a SSFCL scheduled to be installed at a utility substation. Sharing our experiences in the design, manufacturing and installation of FCL demonstration systems is one of the main goals of this article. These demonstration units are installed and being evaluated over a period of one-to-two years in order to demonstrate the systems' reliability over longer-term operating conditions.

2. Benefits of Fault Current Limiters

The benefits of FCLs can be categorized based on two system types. The first one is related to existing systems where the main expected benefits of FCLs are increased asset utilization, equipment upgrade deferral, life extension, improved safety, improved reliability and operational flexibility, enabling interconnection of grids and avoiding major projects like splitting buses and building new substations.

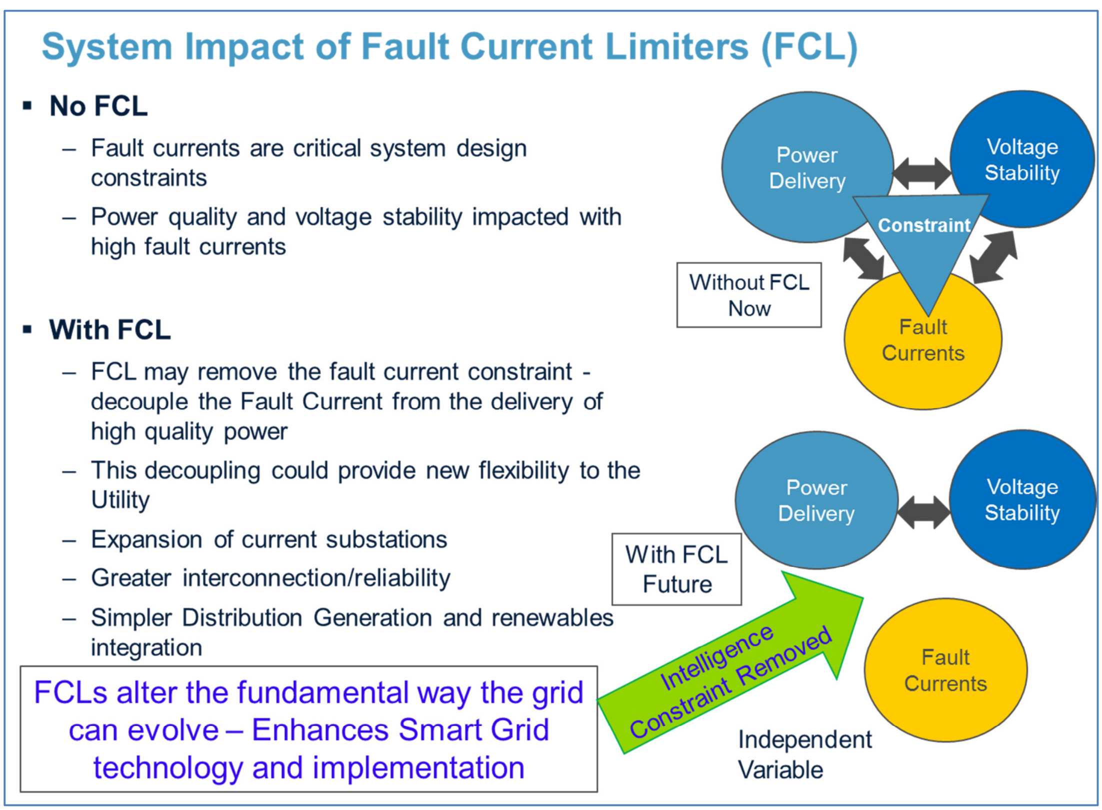


Figure 1 Impact of FCL on future Power System design

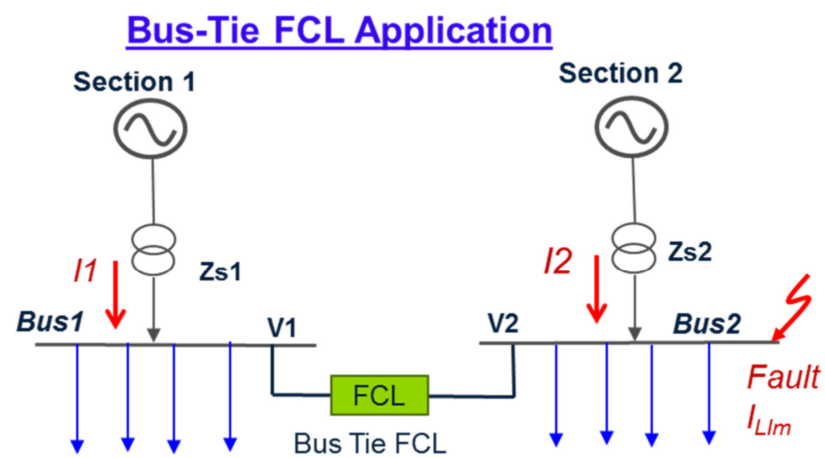
The second type of benefit is for new systems design where a fault current constraint is removed from the critical system design equation and all equipment is designed with low fault currents. As an example, a new system that uses FCLs could be designed for a maximum fault current of 50% or less than its equivalent old system. It can also mean power system equipment manufacturers build cost-effective and low-fault current rating equipment such as breakers, low impedance transformers, compact reactors, etc. With the FCL's new approach, a higher quality of power with stable systems can be designed. New systems can be designed for low fault current rating results with benefits of improved transient stability and voltage stability that improves the system resilience to power outages. Figure 1 shows how the FCL impacts the future generation, transmission and distribution systems by decoupling the fault current constraint from the system design. As the cost of FCLs continues to decrease and pilot projects move into deployment, FCLs have the potential to alter the way we design and plan the electrical grid.

3. FCL Technologies and Applications

Applied Materials is developing two types of FCL technologies, Superconducting (SCFCL) and Solid State (SSFCL). The FCL systems are based on a modular design platform that can be easily configured to meet various customer needs based on location, space availability and applications. The SCFCL is primarily for transmission voltage levels from 66 kV to 400 kV, whereas the SSFCL is targeting distribution voltage levels of up to 66 kV.

The application of FCLs may cover all sizes of utilities in their generation, transmission and distribution systems. Independent power producers and industrial customers also could benefit from FCLs. Based on the installation and configuration types, FCLs could be installed in-line with a feeder, in a bus-tie application or transformer neutral-to-ground connections. Generally, where there is a fault current problem that causes excessive electromagnetic forces and mechanical stress, thermal stress and high arc energy, FCLs could be used to eliminate or reduce the impact of excessive stress on equipment.

Figure 2 shows a typical bus-tie FCL application, where it is primarily used to interconnect buses. This application can also be extended to system interconnections of larger grids or substations to increase power availability and system reliability. The bus-tie application is also very useful for voltage sag improvement, where the voltage drop at the un-faulted (healthy) section can be maintained to a value that does not affect the customers connected to that section. This application improves grid interconnection and enables the addition of renewable energy generation with minimal impact on the existing system. The other type of FCL connection is in-line (shown in Figure 3) with a feeder or transformer to limit the fault current contribution from that line and protect it from fault currents from the rest of the system.



- Fault Current Limitation
  - FCL Fault Current Reduction, $cr = \frac{I_P - I_{Lim}}{I_P}$, where I_P = prospective fault current and I_{Lim} = limited fault current
  - Limited Fault Current , $I_{Lim} = (1 - cr).I1 + I2$
- Voltage Sag Improvement
  - V1 = cr.Vs, for example a system with an FCL of cr = 0.8, the voltage at the un-faulted Bus1 can be kept to 80% of the system voltage (Vs)

Figure 2 Typical Bus-tie FCL Application

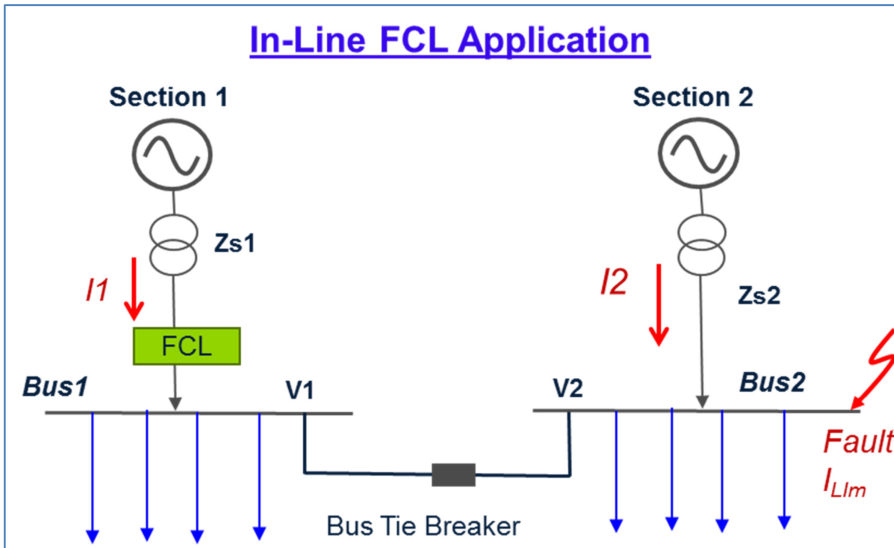


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Figure 3 Typical in-Line FCL Application

4. Installations

Figure 4 shows a distribution SCFCL installed in Santa Clara, CA. It is a 15 kV class, 1000 A 3 phase SCFCL and uses an active Liquid Nitrogen Supply. This system has been installed and running in the system for the last 12 months and has operated as designed to date. This technology could also be supplied with an optional bulk Liquid Nitrogen system which reduces the overall system complexity and cost.

Figure 4 Silicon Valley Power, Santa Clara, California

Figure 5 shows a recent installation at Central Hudson Knapps Corner Substation in Poughkeepsie, New York. It is a 15 kV class neutral-to-ground SCFCL. This SCFCL has already experienced 2 faults and performed as expected.

A neutral–to-ground FCL is used where more than 80% of faults are phase-to-ground faults. In such applications, using a neutral-to-ground FCL seems to be a reasonable solution. It is understandable that 20% of faults that are phase-to-phase or balanced three phase faults are not limited with the neutral-to-ground FCL. The other concern with the application of neutral-to-ground FCL system, especially at higher voltage applications, is the overvoltage in the healthy phases.

$$Overvoltage = V_P . \sqrt{1 + \frac{V_{FCL}}{V_P} + \left(\frac{V_{FCL}}{V_P}\right)^2}$$

For example: for neutral-to-ground FCL with a 50% current reduction, the overvoltage on the healthy phases could go up to $1.32V_P$ (32% overvoltage). This may be acceptable at distribution systems but needs to be checked for insulation coordination purposes at transmission voltage levels.

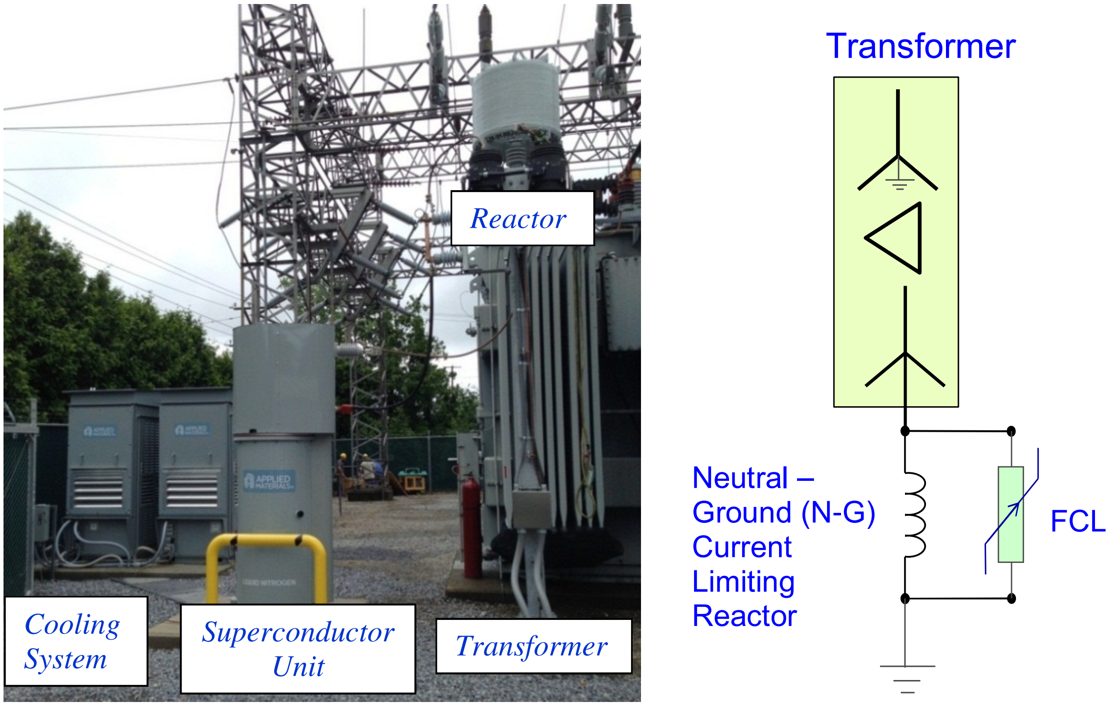

Figure 5 Central Hudson, Poughkeepsie, New York

Figure 6 shows a SSFCL being tested at a KEMA power test lab. This system is a 23 kV SSFCL built to limit fault currents from up to 26 kA symmetrical rms (65 kA peak) to as low as less than 6 A peak. We believe that one of the key benefits of the SSFCL is its flexibility in current-limiting performance where its application can cover a wide range of fault currents. For instance this SSFCL is designed to work for an application where the required limited fault current varies between 6 A peak (99.99% current reduction) to 40 kA peak (23% current reduction). SSFCL also has an added advantage of instant recovery for applications where instant recovery is critical, such as systems that are sensitive to voltage drops during recovery time.

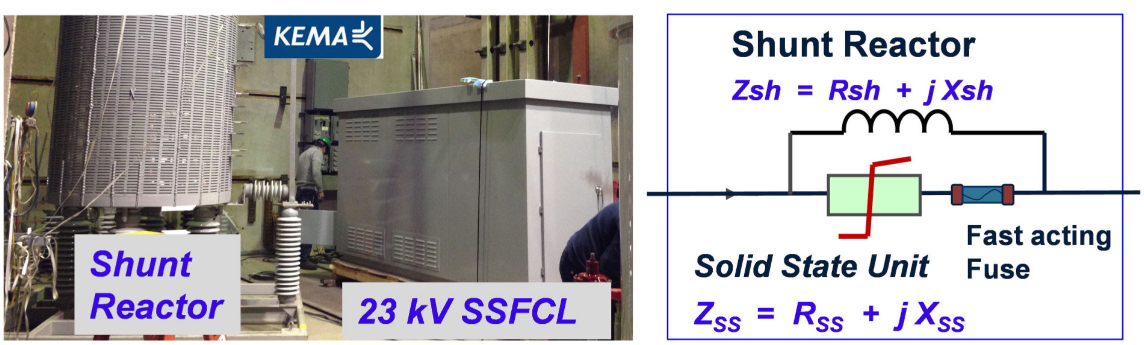

Figure 6 23 kV SSFCL tested at KEMA

Figure 7 shows a typical current-limiting performance of SSFCL tested at KEMA. The waveforms show a test set up at 23 kV system voltage (13.28 kV phase-to-ground) limiting 11.1 kA rms (30 kA peak) to 7.73 kA rms (21 kA peak), that is a 31.2% current reduction. This SSFCL has been tested to its design limits of up to 26 kA rms prospective fault currents and performed as expected.

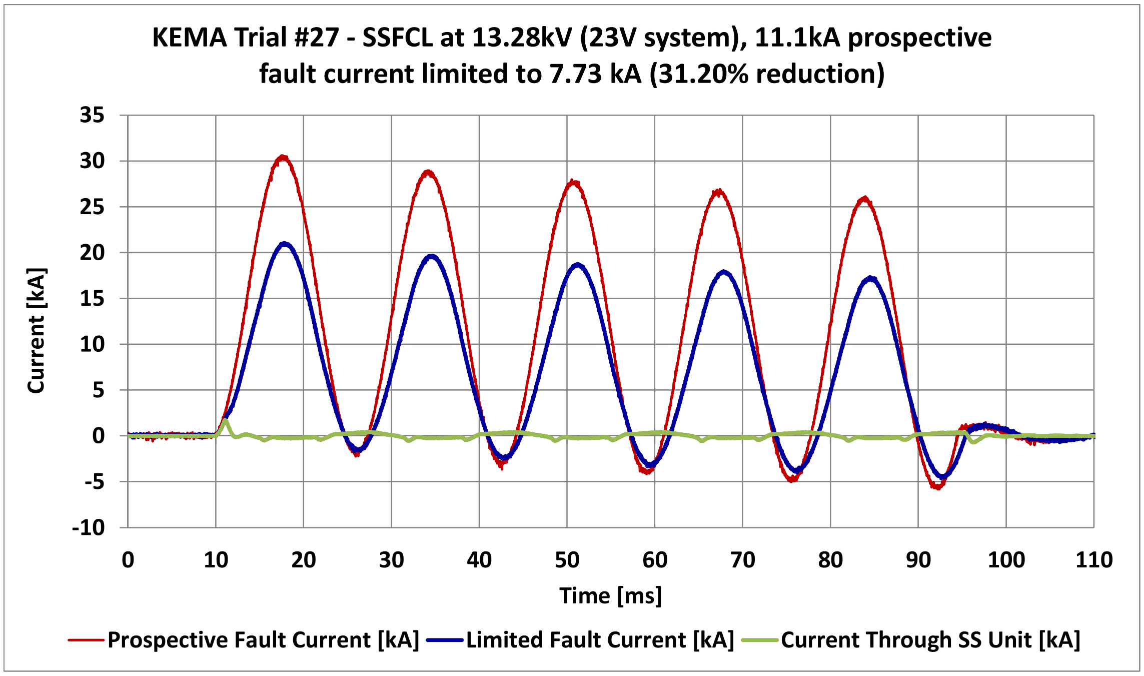

Figure 7 KEMA test results for a SSFCL fault current limitation test.

5. Cost Drivers

When looking for a FCL, engineers should be aware of the cost drivers for the FCL system they are planning to buy. The major cost drivers are the load current (I_L) and the fault current reduction required which is directly proportional to the voltage drop across the FCL during fault (V_{FCL}). It is therefore possible to get a cost factor (CF) related to the rating of the FCL as;

$$CF = k1.I_L.CR = k2.I_L.V_{FCL} = k2.I_L.I_{Lim}.Xsh$$

The cost factor constants k1 and k2 are FCL-type dependence and are expected to decrease as the FCL technology matures and the cost of the FCL decreases through materials performance improvements and as the cost of volume manufacturing decreases.

This equation shows that a higher the load current and current reduction results in higher cost of the FCL. The size and weight of the FCL is also linearly proportional to the cost factor. Understanding these factors helps the utility engineers to optimize the FCL location and application to get a cost-effective solution.

6. System Requirements

Table 1 below shows an FCL systems requirement table, where the most important system parameters required for selecting a FCL are listed. This table is intended as an example of how to calculate the FCL design parameters and provides a means to write a specification or rating of the selected FCL.

Table 1 FCL System Requirement Table

System Parameters - Provided by Utility		
System Voltage - Line-to-Line, *Vs*	220	KV rms
Maximum Load Current, I_L	1500	A rms
Prospective Fault Current, *Ip*	25	kA rms
Limited Fault Current, I_{Lim}	12.5	kA rms
Calculated System Parameters		
System Short Circuit Impedance, $Zs = \frac{Vs}{Ip.\sqrt{3}}$	5.08	Ω
Current Reduction, $CR = \frac{Ip-I_{Lim}}{Ip}$	50	%
Shunt Reactor Impedance, $Zsh = Zs\frac{CR}{1-CR}$	5.08	Ω
Voltage Drop Across FCL, $V_{FCL} = Zsh.I_{Lim}$	63.5	kV rms
Recovery time after Fault is cleared	2.0 - 3.5	sec
Fault Current Limiter Rating		
220 kV System Voltage, with 63.5 kV Voltage drop, 1500A, 5.08 Ω Shunt Reactor, Limits 25 kA to 12.5 kA (50% fault Current Reduction) and recovers to its normal operating mode within 3.5 seconds		

As shown in Table 1, a utility engineer can calculate the key system parameters for short circuit analysis. Based on these calculated parameters one could estimate the specifications or ratings for an FCL for that application. The example above describes this process for a 220 kV system. Since most short -circuit analysis is done with power system software packages, the next section describes the best approach a utility engineer could take to design an FCL of his or her choice.

7. FCL Simulation Models

This section addresses a key skill set for a utility engineer in how to incorporate FCLs into their short-circuit analysis. Applied Materials has developed several simulation models for both SCFCL and SSFCL systems. These models went through extensive revisions and were experimentally verified through extensive testing at component and system levels. In addition to the in-house test lab for component and module level testing, KEMA power test labs has been used extensively to characterize the performance properties of the FCL systems. FCLs have undergone over seven weeks of KEMA testing, exposing the system to thousands of high power faults, and have performed per design specifications and simulation results.

Figure 8 shows some of the basic simulation models developed for FCL systems. These models start from physics-based models that include transient electrical and thermal analysis and progress to simplified models with minimal or no loss of accuracy. Our in-house design software and PSCAD use the physics-based model. For some commercial software packages, like DIgSilent, ramped and step approximation functions are used to model the transition resistance of the Superconductor and Solid state units. Further simplification shows that the Superconductor unit can be represented by a fixed resistor with a value around 3 to 5 times the parallel shunt reactor. Even further simplification shows that a current limiting reactor model is accurate enough that the simulation has no loss of accuracy. Utilities that use frequency-based software, like PSS/E may be able to use the simplest model.

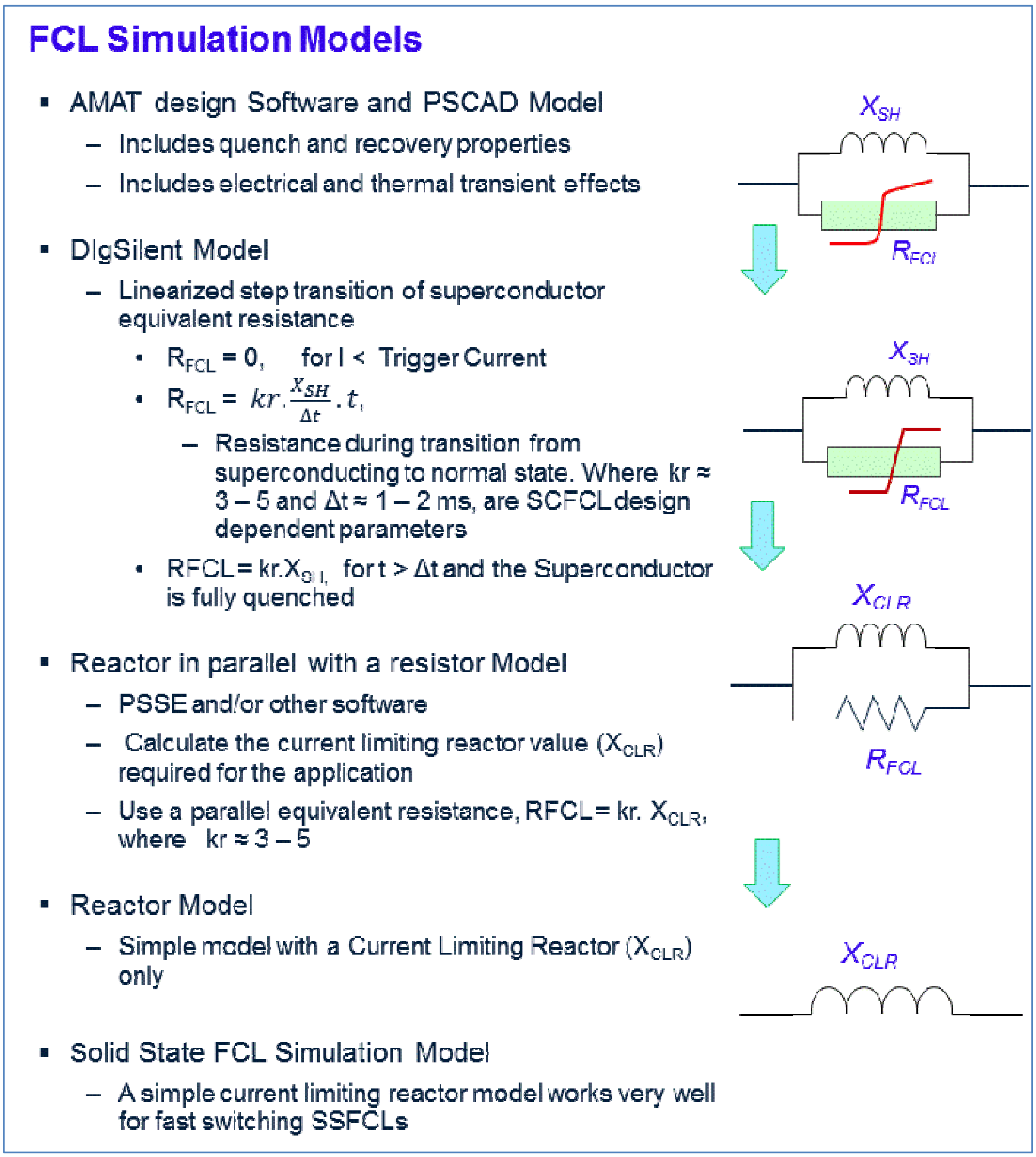

Figure 8 FCL Simulation Models

Figures 9 to 13 show simulation results for different types of FCL models. In general, since the fault current is much greater than the trigger current for the FCL, the FCL circuit in either the SCFCL or SSFCL introduces sufficient impedance within 1- 2 ms. Meanwhile, most of the current transfers to the current limiting shunt reactor. The difference between the physics-based simulation model and those approximations is negligible.

It is important to note that the way both SCFCLs and SSFCLs are designed, the transient overvoltage across the parallel connection of the shunt reactor and the Superconductor or Solid State unit is controlled with voltage control circuits and the simulation models should be used with no concern about the transient overvoltage. The impact of the FCL on Transient Recovery Voltage for breakers is therefore negligible.

Figure 9 shows how the Superconductor senses fault current, quenches, introduces high resistance and current transfers to the parallel shunt reactor and hence fault current is limited by the reactor. This simulation model is based on a 220 kV transmission SCFCL with a prospective fault current of 25 kA (symmetrical rms) and designed to limit the fault current to 12.5 kA, a 50% current reduction including the first peak.

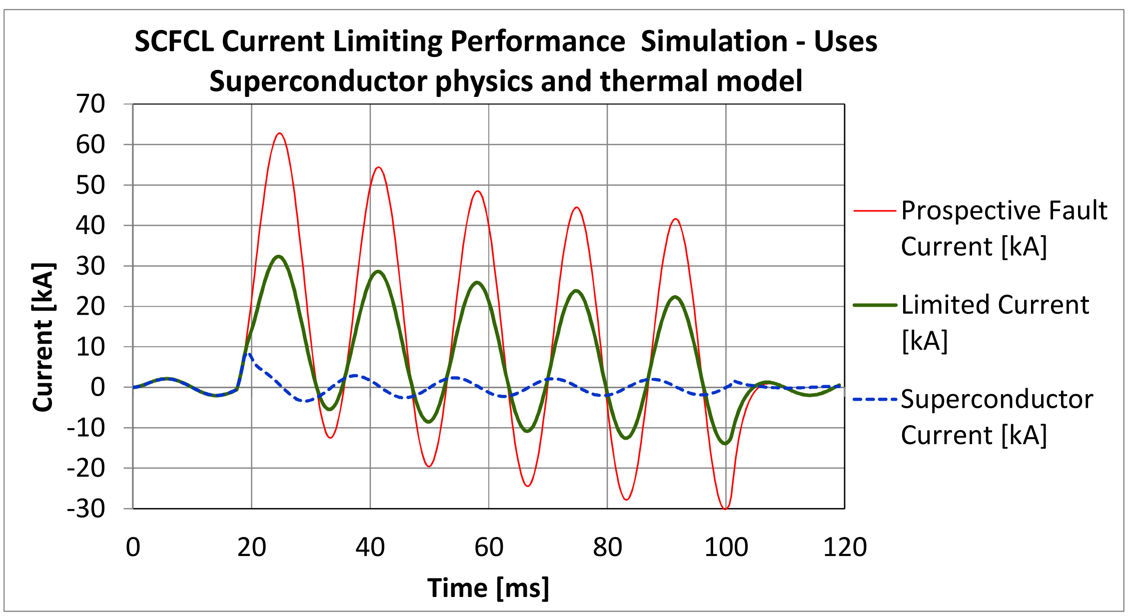

Figure 9 SCFCL current limiting performance simulation using superconductor physics and thermal model

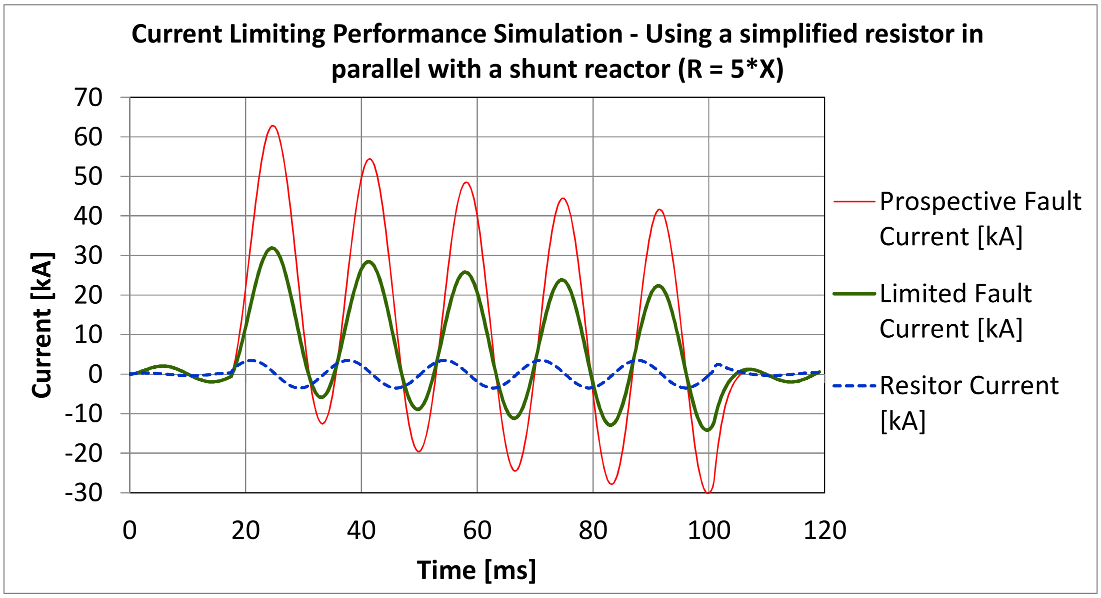

Figure 10 SCFCL model using a reactor in parallel with a fixed resistor

As seen on Figure 10, using a simplified parallel reactor and resistor model misses the transient effects of the Superconductor heating at the start of the fault for around 1 to 2 ms. Neglecting this effect did not affect the overall limited fault current waveform shape of amplitude.

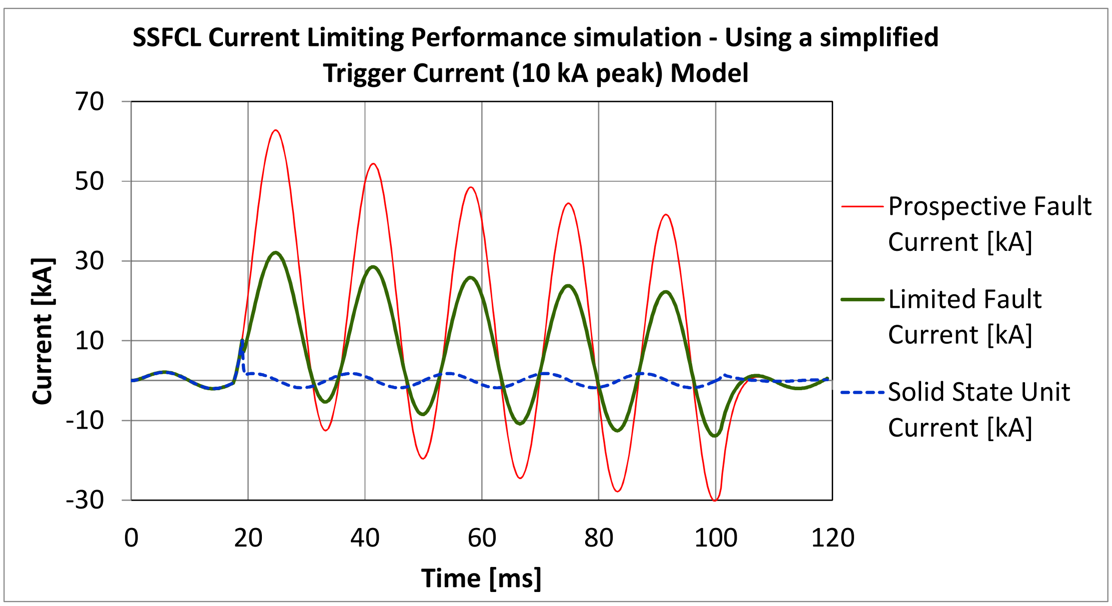

Figure 11 SSFCL Current limiting simulation

Figure 11 shows a simulation of a SSFCL using a pre-set trigger current. This simulation model is based on a SSFCL with a prospective fault current of 25 kA (symmetrical rms) and is designed to limit the fault current to 12.5 kA, a 50% current reduction including the first peak. Compared with the SCFCL, SSFCL simulation is even more suitable for further simplification because of negligible or extremely low current flowing through the SS unit after it triggers the unit and almost all the fault current transfers to the parallel shunt reactor.

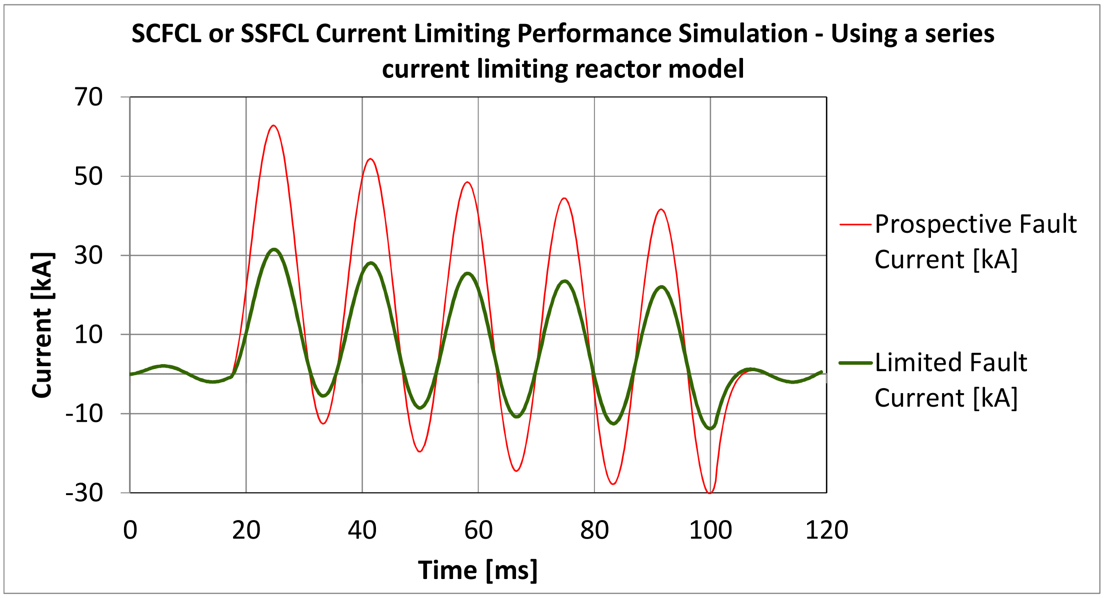

Figure 12 FCL Simulation using a series current limiting reactor

Even with further simplification using a series current limiting reactor, as shown in Figure 12, there is no loss of accuracy on the limited fault current waveform or amplitude.
Figure 13 shows a comparison of four different models described above. For the purpose of short-circuit analysis, utility engineers can use even the simplest model with negligible or no loss of accuracy. The key takeaway here is the FCL knowledge is now available to utility engineers in the form of a simplified simulation model. Utility engineers can design their own FCL and ask the manufactures to make their selected system. It is as simple as selecting the value of a series current limiting reactor.

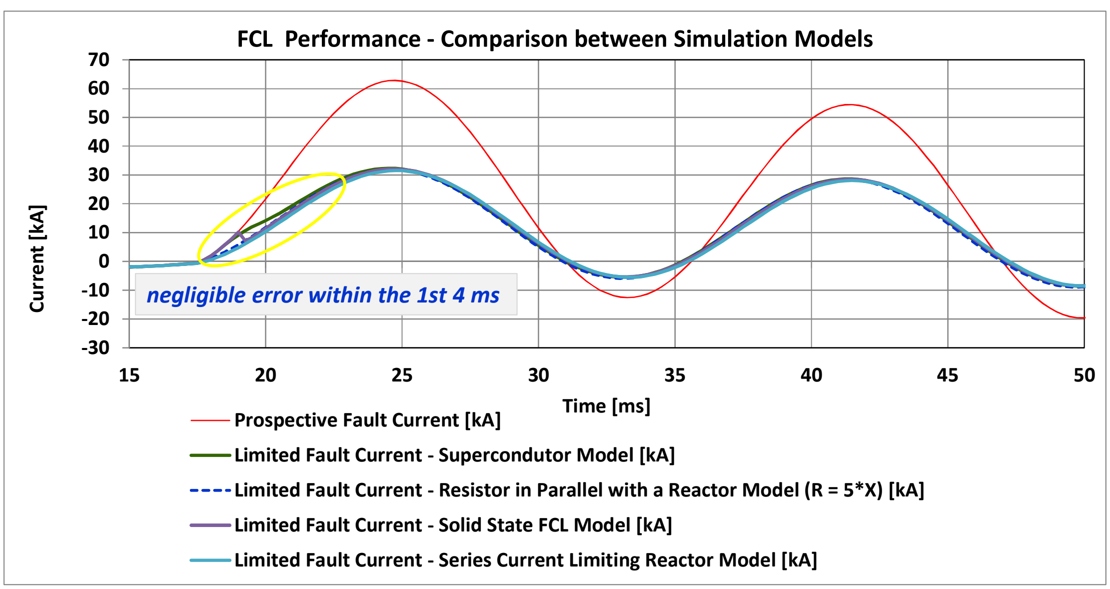

Figure 13 A comparison of four different models described above

One additional FCL performance parameter is the recovery time after the fault clears. Recovery time is mostly associated with SCFCL for obvious reasons, as the superconductor heated and transitioned to non-superconducting state by the fault requires time to cool and return to the superconducting state. The Applied Materials SCFCL is designed to recover within 2 to 3.5 seconds after the fault is cleared. Figure14 shows the typical recovery time is takes a superconductor unit to recover at around 2.2 seconds.

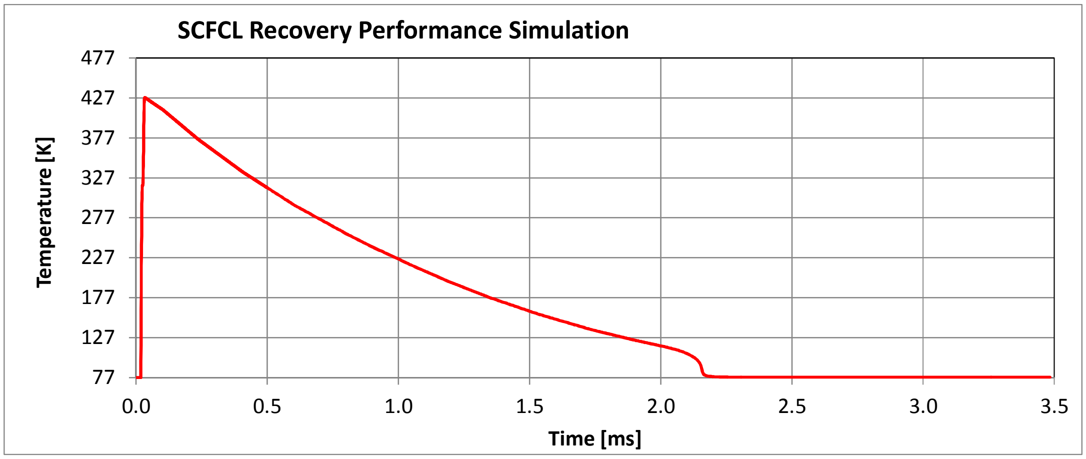

Figure 14 SCFCL Recovery Performance Simulation result

SSFCL can be designed to recover instantly, since there is no component that changes temperature as quickly during the fault. For applications where the recovery time has high impact on the system performance, such as transient stability, voltage stability and protection issues, SSFCL appears to give a clear advantage over SCFCL.

8. Conclusion

As the cost of FCLs continues to decrease and pilot projects move into deployment, FCLs have the potential to alter the way we design and plan the electrical grid. This smart technology can improve safety and reliability, defer capital and offer operational flexibility. Utility engineers may wish to consider adding FCL technologies and systems to the utility toolbox and using them to design a cost-effective fault current management system for existing or future systems.

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