Applications of Superconducting Fault Current Limiters in Electric Power Transmission Systems

Leonard Kovalsky, Xing Yuan, Kasegn Tekletsadik, Albert Keri, Joachim Bock, Frank Breuer

Abstract— **The introduction of new generating facilities by independent power producers and increasing load demand can result in fault-current over-duty on existing transmission system protective equipment. Conventional solutions to fault current over-duty such as major substation upgrades, splitting existing substation busses or multiple circuit breaker upgrades could be very expensive and require undesirable extended outages and result in lower power system reliability. Less expensive solutions such as current limiting reactors may have unwanted side effects, such as increase in system losses, voltage regulation problems or possibly could compromise system stability. This paper discusses the benefits of superconducting Fault Current Limiters (FCLs) which can be economically competitive with expensive conventional solutions. Superconducting FCLs are invisible in normal operation and do not introduce unwanted side effects. The performance of a particular type of limiter, the Matrix Fault Current Limiter (MFCL) is presented and examples are provided on how it could relieve fault current over-duty problems. The use of this device in a particular application in the American Electric Power (AEP) 138kV transmission grid is also discussed.**

Index Terms—**Circuit breakers, cryogenics, current limiting reactor, fault current, fault current limiter, high temperature superconductor**

I. INTRODUCTION

A fault condition may result in an electric power transmission system from events such as lightning striking a power line, or downed trees or utility poles shorting the power lines to ground. The fault creates a surge of current through the electric power system that can cause serious damage to grid equipment. Switchgears, such as circuit breakers, are deployed within transmission substations to protect substation equipment. When power delivery networks are upgraded or new generation is added, fault levels can increase beyond the capabilities of the existing equipment, with circuit breakers in an "over-duty" condition. This problem necessitates upgrades such as the modification of substations or replacement of multiple circuit breakers. Increased fault currents due to load growth and industry structural changes have become a significant factor in system planning and operation. Equipment and personnel safety, power quality, and overall system reliability are all at stake if techniques and tools are not found to mitigate the higher levels of fault current in today's grid.

This paper describes potential applications of a Fault Current Limiter (FCL) based on High Temperature Superconductor (HTS) presently under development by SuperPower, Inc. and Nexans SuperConductors GmbH for application in utility transmission networks. The Matrix Fault Current Limiter (MFCL) is targeted to address fault current over-duty problems at the transmission voltage level of 138kV and higher. The MFCL is expected to help utility transmission planners meet the threat of higher levels of fault duty in the grid cost-effectively and with no adverse side effects. A project is underway to design, fabricate and test the MFCL to qualify it as the world's first device capable of fault current limiting at transmission system voltages.[1] The MFCL will reduce the available fault current to a lower, safer level so the existing switchgear can still protect the grid.

II. CONVENTIONAL SOLUTIONS

The existing conventional solutions to transmission-level fault current over-duty resolve the problem with varying degrees of effectiveness. Some are costly and/or have negative impact on system reliability and integrity. Some of these solutions are:

1. Construction of new substations - Fault current over-duty coupled along with other factors may result in a utility selecting this solution, which will correct immediate problems, as well as providing for future growth. However, this is the most expensive of all the conventional solutions.
2. Bus splitting - This entails separation of sources that could possibly feed a fault by the opening of normally closed bus ties, or the splitting of existing busses. This effectively

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reduces the number of sources that can feed a fault, but also reduces the number of sources that supply load current during normal or contingency operating conditions. This may require additional changes in the operational philosophy and control methodology.

3. Multiple circuit breaker upgrades - When a fault duty problem occurs, usually more than one breaker will be affected. Upgrade of these breakers has the disadvantage of not reducing available fault currents and their associated hazards, as well as the often prohibitive expense of replacing the switchgear within a substation.
4. Current limiting reactors and high impedance transformers - Fault current limiting reactors limit fault current due to the voltage drop across their terminals, which increase during the fault. However, current limiting reactors also have a voltage drop under normal loading conditions and present a constant source of losses. They can interact with other system components and cause instability.
5. Sequential breaker tripping - A sequential tripping scheme prevents circuit breakers from interrupting excessive fault currents. If a fault is detected, a breaker upstream to the source of fault current is tripped first. This reduces the fault current seen by the breaker within the zone of protection at the location of the fault. This breaker can then open safely. A disadvantage of the sequential tripping scheme is that it adds a delay of one breaker operation before final fault clearing. Also, opening the breaker upstream to the fault affects zones that were not originally impacted by the fault.

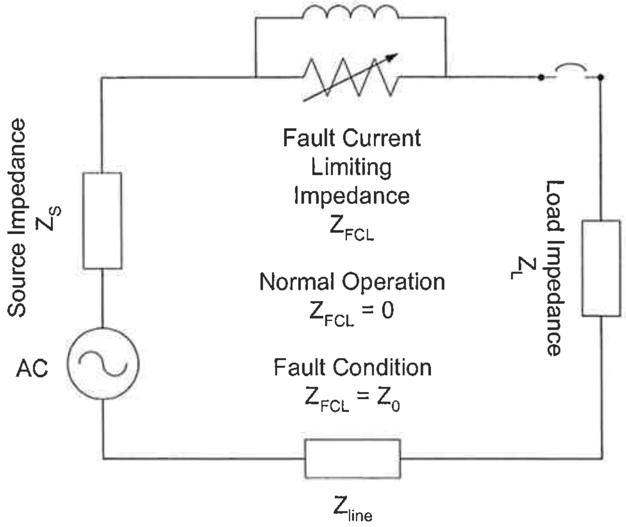

Fig. 1. Electrical Equivalent of MFCL in a Power System

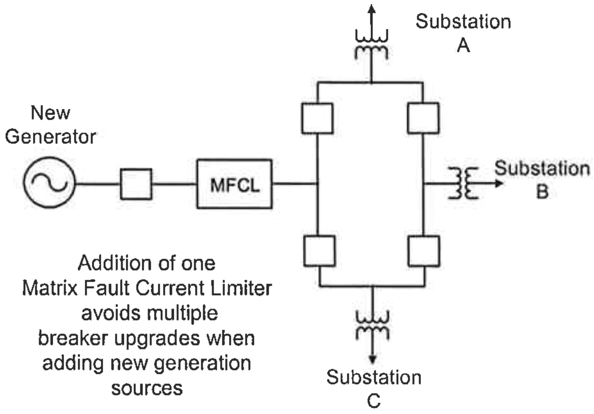

Fig. 2. Application of MFCL to Ease Introduction of New Generation

III. MFCL AS AN ALTERNATIVE SOLUTION

Figure 1 shows a simplified equivalent circuit representation of the MFCL in a transmission system. Here the MFCL is represented by an HTS element shown as variable resistance in parallel with a reactor. Under normal operating conditions, the peak of the AC current level of the power transmission network is always below the critical current level of the superconductor, therefore there is essentially not voltage drop across the device and there are no I^2R losses. The device is "invisible" to the grid. When the fault occurs, the fault current level exceeds the critical current level of the superconductor, creating a quench condition. The superconductor is forced to transition to the high resistive state and most of the fault current is shunted into the parallel inductor to introduce the current limiting impedance Z_0 into the grid to limit the fault current.

Figure 2 shows an example application of the MFCL to alleviate a fault duty problem when new generation sources are introduced. The introduction of the new generator could result in breaker over-duty problems on multiple breakers shown in the ring bus in the figure. Utilities are faced with extended outages and expense to upgrade all the affected breakers. An alternative approach is to use an MFCL to reduce the available fault current to a lower, safer level so the existing switchgear can still protect the grid. In the example of Figure 2, the MFCL is placed in series with the generator to reduce its contribution of fault current, avoiding the cost of upgrading the four breakers in the ring bus.

A pre-prototype MFCL device has been tested and it successfully demonstrated the expected current limiting performance.[1] The single-phase proof-of-concept prototype device has a nominal rating of 8.6kV line to ground at 800Arms. Figure 3 shows the typical current limiting response achieved in the proof-of-concept tests. With prospective asymmetric first peak fault current of 25.6kA, the device achieved the ratio of limited to prospective current of 84%. The ratio was 56% by the third cycle of the fault. This shows the fast dynamic resistance development before the first peak of the fault, as well as significant current limiting by the third cycle, which is the typical breaker opening time.

IV. MFCL COMPARISION TO CONVENTIONAL SOLUTIONS

Table I summarizes the conventional solutions and their respective pros, cons and relative cost. The expected cost of the MFCL relative to the conventional solutions is also shown. Table I primarily considers the initial capital installation cost in the comparison. In the cases of multiple circuit breaker upgrades, the cost of bus work reinforcement must also be

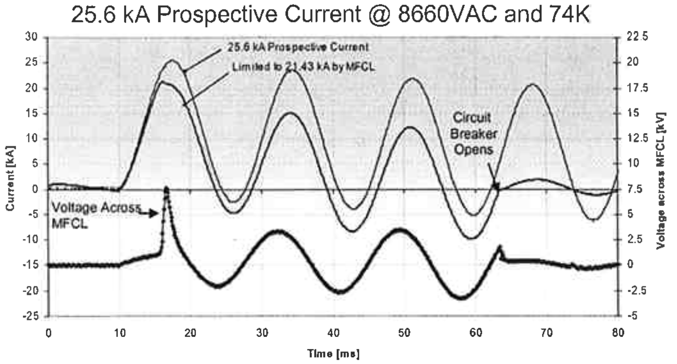

Fig. 3. Typical Proof-of-Concept Result

TABLE I
MFCL VS CONVENTIONAL SOLUTIONS

Solution	Advantage	Disadvantage	Relative Expense	Relative Expense to MFCL
New Substation	Provides for future growth	Expensive and lengthy to install	Most expensive of all solutions	MFCL less expensive
Bus Splitting	Separates sources of fault current	Separates sources of load current from load centers and undermines system reliability	High, if split bus not already installed	MFCL less expensive
Multiple Circuit Breaker Upgrades	Most direct solution with no adverse side effects	Difficult to schedule outages; Bus work reinforcement also required	High to medium, depending on # of breakers	MFCL less expensive than most multiple breaker upgrades
Current Limiting Reactors	Easy to install	Voltage drop and power losses; potentially cause instability	Medium to low	MFCL cost higher
Sequential Breaker Tripping	No major hardware installation involved	Expands impact of fault to wider range of the system	Low	MFCL cost higher

considered, since the level of fault current is not being reduced. This consideration makes the MFCL an attractive alternative, since it also minimizes the outage time. As shown in Table I, the MFCL is expected to be cost-competitive with all of the solutions with the exception of current limiting reactors and sequential breaker tripping. In these cases, a consideration of life-cycle costs and negative impact on system reliability may cause a utility consider the MFCL over these solutions. There is, furthermore, a limit to the effectiveness of adding current limiting reactors as more and more of these devices are added into the grid. One final consideration is that HTS FCLs may be essential for the application of other devices such as HTS cables in the grid. The very low impedance of HTS cables results in a high level of fault current, which could be mitigated by a device like the MFCL.

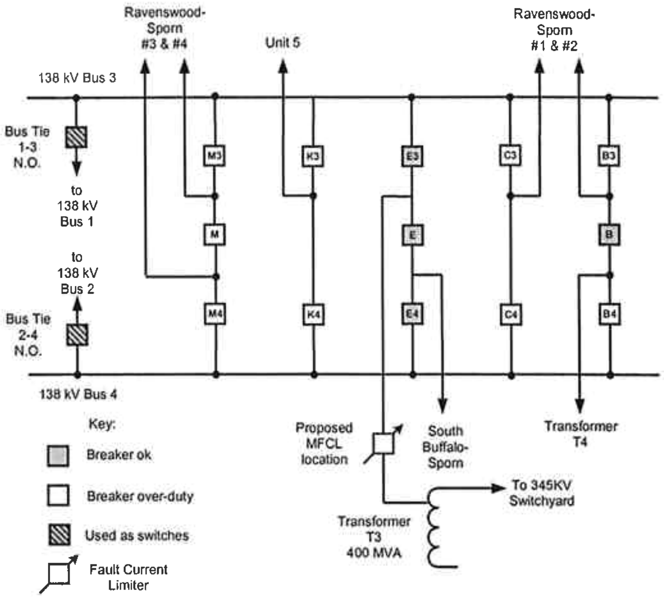

Fig. 4. Potential MFCL Application

V. EXAMPLE MFCL APPLICATION

The following is provided as an example of where an MFCL could possibly be used to provide a solution to a fault current over-duty problem. A thorough system study, required to study this case further, will be performed as part of the development program. Figure 4 illustrates an example of a substation in the American Electric Power (AEP) grid that currently employs a sequential tripping scheme to cope with high fault currents. Autotransformer T3 with a 400MVA rating ties the 345kV portion of the switchyard to the 138kV portion of the switchyard. This tie is beneficial to the operation of the system during normal operation, but the transformer contributes an additional 13kA at the 138kV buss during fault conditions. This puts 9 breakers, as indicted in the figure, in an over-duty situation. To resolve this problem, breakers E3 and E, which have sufficient rating, are tripped first if a fault is detected on Lines #1 to #4. This removes Transformer T3's contribution to the fault so that the affected over-duty breaker can safely open and isolate the fault. The sequential breaker scheme solves the problem, but has the disadvantage of delaying the fault clearing by the addition of E3 and E in the trip sequence. It also results in removing the normal T3 load current to portions of the system that were not affected by the fault.

Figure 4 shows how the addition of an MFCL in series with transformer T3 could resolve the problem without resorting to the sequential breaker trip scheme. During normal operation the MFCL is transparent to the system, and T3 supplies load current from the 345kV system to the 138kV system. Under fault conditions, the MFCL transitions to the high impedance state to limit the contribution of T3 to the fault, allowing the existing breakers to clear the fault without opening E3 or E first. The appropriate MFCL requirements have to be determined by additional system studies to finalize the feasibility of using an MFCL in this application. This particular application also presents a good opportunity to study the response of the MFCL at the onset of the fault. If the sequential breaker trip scheme is left in place with the MFCL installed in series with T3, then the response of the MFCL can be verified in the time before E3 and E are opened. This will help with the verification of the new MFCL technology before it is placed in a critical protection application.

VI. MFCL DEVELOPMENTS TO MEET TRANSMISSION-LEVEL APPLICATION REQUIREMENTS

A. Scale-Up to Transmission Voltage

As a result of the successful proof-of-concept demonstration, the next prototype development stage has been initiated to scale the design to the alpha prototype stage at 138kV. Most developments in HTS FCLs to date have focused on distribution-voltage level applications. The recent successful CURL 10 project successfully demonstrated a medium voltage (10kV, 10MVA) on the RWE grid near Siegen, Germany.[2,3] Previous HTS FCL approaches are also described in the extensive literature on the subject.[4, 5]

The scale-up to transmission-level voltages is particularly challenging, since there is not much prior art on the application of high voltage components in a cryogenic environment. In support of the high voltage work, a Cooperative Research and Development Agreement (CRADA) is being conducted on the MFCL program with Oak Ridge National Laboratory (ORNL) to utilize the available experience in this area. This will include the development of new high voltage design tools. Experimental and mock-up tests will be employed to develop the empirical formulas to predict breakdown voltages and perform evaluations of materials suitable for high voltage application in cryogenic environment.

B. Impact on Protection Schemes & Test Standards

The application of superconducting fault current limiters in the utility network will require new integration issues to be addressed. As devices like the MFCL come closer to commercial reality, these issues are now being considered by various industry groups. [6, 7] The characteristic of the MFCL impedance appearing only during the fault must be considered in the implementation of protective relay schemes. The development of testing standards and procedures also has to consider the variable impedance nature of the device. In particular, the method by which the BIL tests are applied to the terminals of the device must consider the variable impedance characteristic. These standards will be developed in conjunction with input from the utility industry.

C. Recovery Requirements

During the fault, the HTS material heats up and must cool back down to return to a superconducting state before the device is invisible to the system again. The time to return to a superconducting state is typically termed the "recovery" period. The cool-down period is proportional to the amount of time that the material was heating up during the fault, both in terms of the duration and the magnitude of fault current.

The length of the recovery period will also be a function of the conditions under which the recovery must take place. In some applications, the MFCL device will not be carrying any current during the recovery, which will result in the fastest recovery period. In some applications, the device will have to carry nominal load current during the recovery, which will provide some constant level of background heat generation in the device that will lengthen the recovery period. This would be the case for both applications shown in Figures 2 and 4. In this case, the HTS elements are not bypassing the parallel inductors, so the MFCL will present some impedance to the system during this recovery. As part of the future work, formal studies will be performed to determine acceptable recovery periods for the potential applications of the MFCL. Preliminary discussions with utilities have indicated that the presence of the MFCL impedance during the recovery may not be an issue of concern, since the device will typically be employed in strong systems, where the short circuit current level is high.

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