

A Solid State Current Limiter

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Abstract

Utility engineers faced with the challenges of integrating new generation into existing power systems, clearing faults more quickly or finding an alternative to SF6 breakers will soon have a new product to meet all of their needs: a solid state current limiting circuit breaker. Electric utilities have long wished for a practical, reasonably priced, solid state circuit breaker which could provide very reliable service with little maintenance. Closing can be timed so as to minimize transients. Adding the function of current limiting, also a long-held dream, enhances significantly to the value of the breaker. The largest challenge is to accomplish all this at a price which utilities can accept.

Advanced current interruption technology, utilizing high power solid-state components, has opened the door to high power control at a lower cost than ever before. The Solid State Current Limiter (SSCL), offers a viable solution to the transmission and distribution system problems caused by high available fault current. It appears that the time has now arrived when the selling price can be low enough to justify significant sales. By providing instantaneous (sub-cycle) current limiting, the SSCL alleviates the short circuit condition in both downstream and upstream devices by limiting fault currents coming from the sources of high short circuit capacity.

Introduction

Advanced current interruption technology, utilizing high power Solid-State Current Limiters (SSCL), offers a viable solution to the transmission and distribution system problems caused by high available fault current. Although the power industry has been interested in this concept for decades, it appears that the time has now arrived when the selling price can be low enough to justify significant sales. By providing almost instantaneous (sub-cycle) current limiting, the SSCL alleviates the short circuit condition in both downstream and upstream devices by limiting fault currents coming from the sources of high short circuit capacity. The advantages of added functions that a conventional circuit breaker cannot offer help to justify the higher cost associated with a solid state breaker.

To interrupt the current, the SSCL must rapidly insert an energy-absorbing element (e.g. resistor) into the circuit to limit the fault current. In addition to limiting the fault current, the SSCL can also limit the inrush current (soft start capability), even for capacitive loads, by gradually phasing in the switching device rather than making an abrupt transition from an open to a closed position.

A solid state breaker can offer the following advantages

- limited fault current
- limited inrush current (soft start), even for capacitive loads
- repeated operations with high reliability and without wear-out
- reduced switching surges
- improved power quality for unfaulted lines.

By limiting the current, we achieve fault isolation and better network protection, taking care of most of the distribution system situations that result in voltage sags, swells, and power outages. Thus the SSCL can substantially improve the power quality through fault current limiting and inrush current reduction.

High fault currents are known to be a factor in reducing transformer life, so it is expected that an advantage from the use of a current limiting breaker will be longer life with higher reliability for nearby transformers.

Switching Elements

There are different ways to implement the SSCL. Since we want to provide sub-half cycle current limiting, we need to either use semiconductor devices with turn-off capability (such as GTO, IGBT or IGCT) or to use an SCR switch together with a forced commutation circuit.

The former option offers the advantage of using a simple power circuit and very high speed operation. The current can be switched into an energy absorber in a few usecs. However these devices have both a lower voltage rating than SCRs have (4500 V vs. 8500 V) and a lower current carrying capability, the result of a more complex structure. Other effects of the structure, higher voltage drop and lower silicon utilization, further lessen the attractiveness of their selection. Actually, these devices in today's forms are an overkill for our application: they have low switching losses and therefore can operate at high frequency (1 kHz and up) while the SSCL requires only single infrequent operation. The selection of the SCR is settled when the cost factor is included. SCRs with ratings in the range of 5 to 7 kV and 1 to 4 kA are readily available from many vendors in a competitive market.

A number of circuit topologies have been examined for applications as a circuit breaker with current limiting and soft switching capabilities. These include projects sponsored by EPRI and commercial products from various vendors.

Circuit topologies using superconducting magnetic energy storage have also been proposed and evaluated. These seem to be limited by the reliability of the complex systems required and are also priced at levels that are not likely to achieve commercial success.

The topology proposed here is the first design that has the potential of achieving all of the goals for a solid state circuit breaker of interrupting faults at preset current levels, current limiting for downstream coordination, soft switching capabilities, and a sale price of 2.5 to 3 times that of conventional breakers. These operational goals for the breaker are key to the adoption of the breaker into critical circuits where these features add significant value.

Circuit Design

Since each phase of the breaker must withstand a high peak voltage, it is necessary to connect semiconductor devices in series. This has been done in many cases for applications such as ac to dc converter stations and the necessary precautions are well understood.

A modular approach offers important advantages during design, testing, manufacturing and service stages. Some of the more important are:

- Design is simplified because within the module we are dealing with comparatively low voltages and the individual module is much smaller than the whole breaker.
- Testing is also simplified because of the reduced voltage level. This will translate into substantial time and cost savings as prototype tests are iterated.
- During manufacturing we will save time and money by mass producing small modules, testing them and finally stacking them up to build breakers (like Liberty ships). The same modules can be applied to many different voltage ratings.
- During service we can have single modules as spares and then replace the failed module rather than repairing the valve itself by replacing a failed SCR. The module can then be sent to the shop or the factory for repairs.

- We can use the same modules for different voltage breakers by stacking the appropriate number of modules depending on the voltage level of the breaker. This way we reap the benefits of mass production even further by:
 - Having the same building block for different voltage breakers, thus simplifying manufacturing, testing and repair costs.
 - Reducing maintenance expenses by needing only one type of spare module, thus reducing the cost of spare parts and simplifying training of field personnel.

Proposed Design

At the first look, a semiconductor with turn off capability seems very attractive - we can eliminate a forced commutation circuit, therefore simplifying the design. But on the other hand, we will need many devices in series to satisfy high voltage requirements and their cost is a significant contributor to the cost of the breaker. After a thorough costing exercise, we determined that at this time it remains less expensive to use SCRs and a commutation circuit than to use semiconductors with turn off capability.

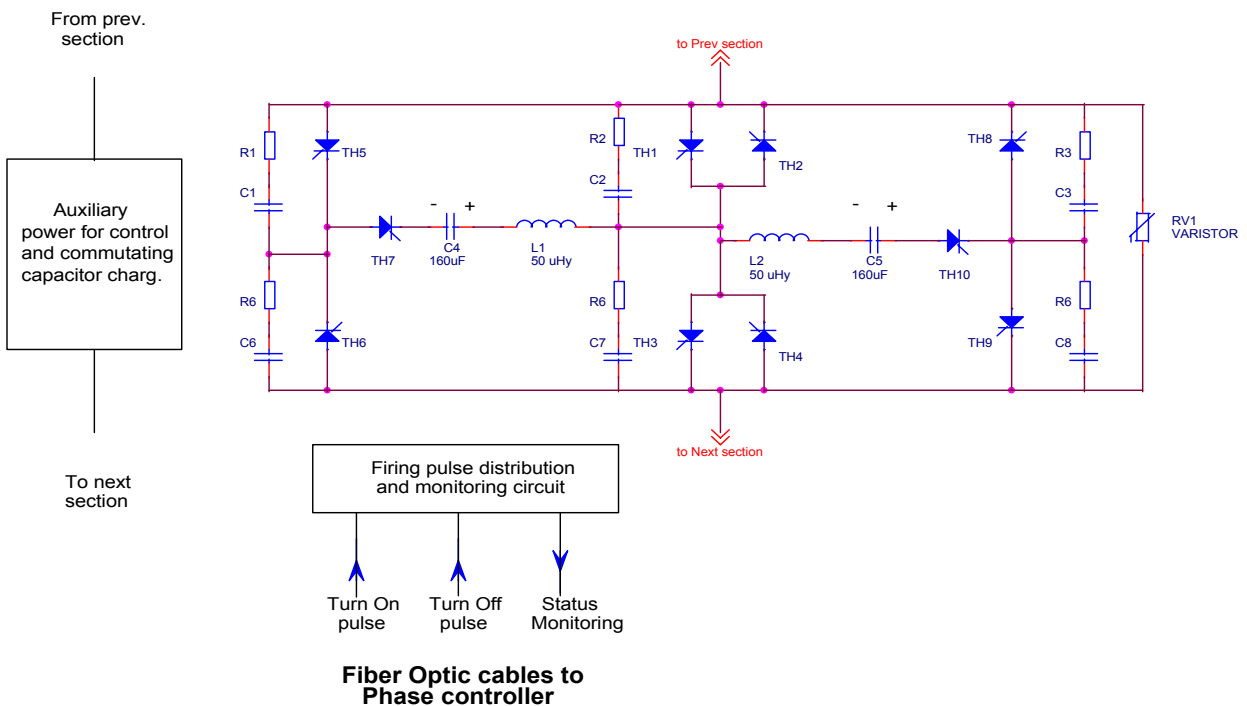


Figure 1

The circuit consists of four main SCRs, TH1 through TH4, and six commutating SCRs, TH5 – TH10. It also has energy absorbing varistor VR1, two commutating capacitors C4, C5 and two inductances L1, L2

The module is controlled by two fiber optic signals, one turning the switch on, the other turning it off. The module has its own controller which provides fiber signal to all SCRs, monitors relevant parameters and sends back information to the main controller (called the phase controller in Figure 2) about the module's status and other information. The module also has an auxiliary power circuit to provide power for the gate drives and charging current for the commutating capacitors

The current normally flows through TH1 and TH2 or TH3 and TH4, depending on the instantaneous polarity. By applying the proper control signals to SCRs TH1 through TH4, we can provide a soft start action through phase control action. The capacitors C4 and C5 are charged with the polarity shown.

When the module receives “Turn Off” pulse and the current is flowing through TH1 and TH3, then SCRs TH5, TH7 and TH9, TH10 are fired. The current through the main SCRs goes down, main SCRs are turned off and the fault current is switched into commutation circuit TH5, TH7, C4, L1, L2, C5, TH10 and TH9. Providing that the external circuit has a much higher inductance than L1 and L2, the current stays constant and the capacitors first discharge and then are recharged with the opposite polarity. Once the voltage across the capacitor reaches the “knee” of the varistor, the current starts switching into it. Eventually the current switches into the varistor and commutating SCRs turn off.

After a pause, we fire the main SCRs with a high firing angle to provide the required let through current. There is a programmed number of pulses, then a programmed pause, probably repeating the sequence few times. If the fault clears we might reclose the breaker.

In the mean time the commutating capacitors are recharged to the initial polarity and the breaker is ready to close.

During the closing process we start firing the main SCRs with a high firing angle while monitoring the current. If a fault condition is detected, the breaker remains open.

In this circuit, the varistor performs dual functions – it assists in the commutations as described above and it also limits the transient voltages caused by the lightning strikes and other transient phenomena.

Modular Approach

Rather than building high voltage valves by series connection of 50 SCRs we propose to develop a self contained, forced commutation, 10 kV peak module with fiber optic control.

Each phase of the breaker is built up by connecting 26 such modules in series.

By working with a comparatively low voltage module during the design stage, we reduce costs by simplifying design and verification testing.

During the production stage the use of low voltage standard modules lowers the cost of manufacturing and testing.

To circumvent corona discharge problems we propose to put the switch into an oil tank.

Safety and electrical problems are addressed through the use of fiber optics for firing control and supervision.

Figure 2 shows a block diagram of the breaker.

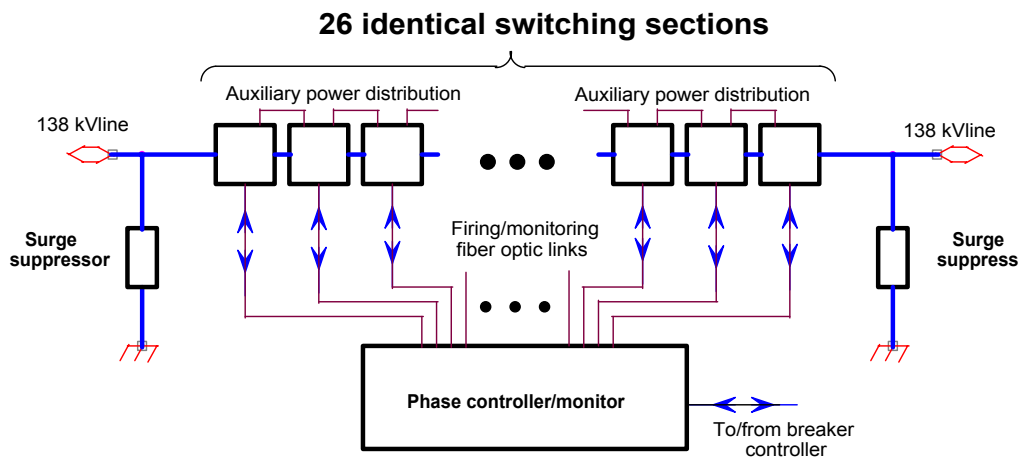


Figure 2, One phase of a 138 kV current limiter

Application Considerations

The following evaluations of the breakers operations in a variety of applications use computer simulations of circuit models to evaluate the operational features of the proposed solid state breaker. Simple models have been used.

Faults on a Distribution Feeder

Many of the power quality problems that customers experience are the result of faults and disturbances on adjacent feeders on the same distribution bus. The use of SSCLs on feeders can greatly alleviate this problem and enhance power quality in areas such as premium power parks.

The following results are derived from computer simulations for faulted conditions on the circuit shown in Figure 3. The circuit model is shown below the one line representation of the distribution feeder. This circuit was derived for simulation purposes to demonstrate the operational characteristics of the solid state breaker with current limiting proposed here.

The most common fault that occurs on a distribution feeder is the single line to ground fault. A fault is simulated for this circuit and is shown in Figure 4 for a single line to ground fault on phase A of this circuit. Figure 4 shows the fault as interrupted by a conventional breaker after approximately three cycles after the fault. The fault was imposed after a zero crossing of the rising waveforms to generate the maximum asymmetrical currents. The asymmetrical current here is approximately 34 kA with a symmetrical fault current of approximately 8 kA rms. The line to neutral voltage of a 13.8 kV feeder is shown in Figure 4 for reference purposes.

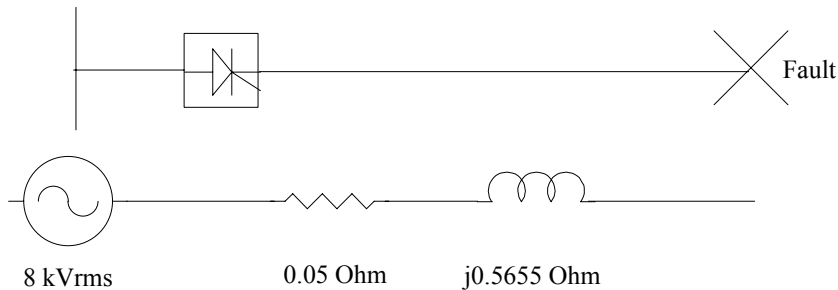


Figure 3, Radial Distribution Feeder Circuit

The operation of the solid state breaker with current limiting for the same fault conditions as shown in figures 3 and 4 is shown in Figure 5 using the same scale. An arbitrary selection for peak fault current limiting was made at 5 kA. Actual peak fault current limiting would depend on the circuit conditions.

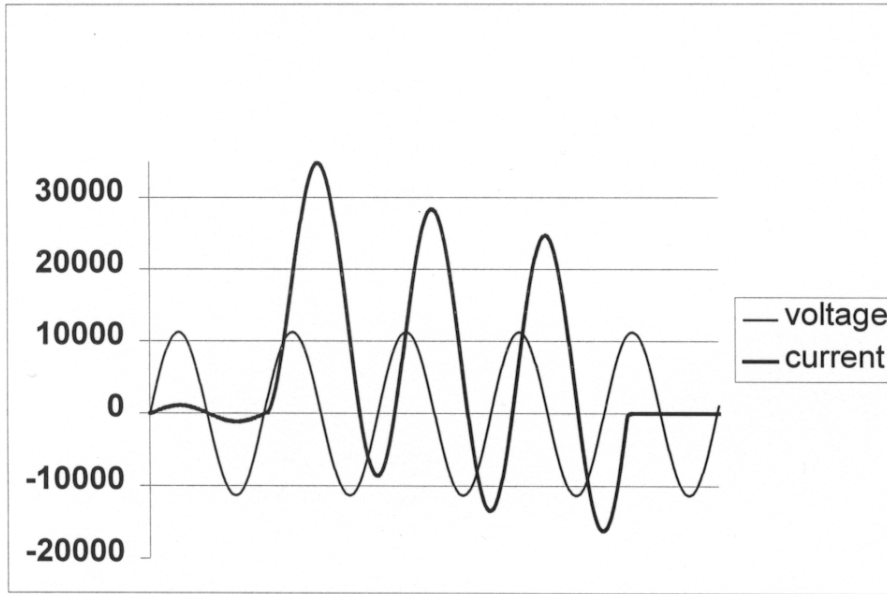


Figure 4, Single Line to Ground Fault, Phase A, Conventional Breaker

Shortly after the onset of the fault, when the current reaches the preset 5 kA level, the SCRs that are conducting the fault current are force commutated and a current limiting impedance is switched into the circuit until the first zero crossing of the current occurs. A current limited fault is then maintained for downstream coordination for some predetermined period by phase controlling the SCRs as shown in Figure 5.

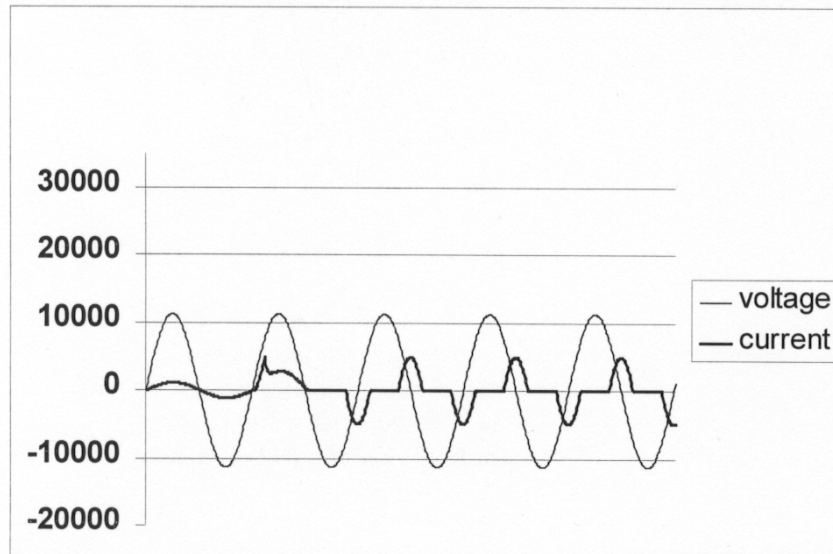


Figure 5, Single Line to Ground Fault, Phase A, SSCL with Current Limiting

Equipment in the fault current path will not experience the high asymmetrical and symmetrical fault currents that would be possible without the SSCL.

The SSCL operation may also be used in a zone protection philosophy. Figure 6 shows a radial feeder with two zones defined. A fault in zone 1 will be interrupted when the peak asymmetrical current reaches 5 kA in this example. Phase control of the SCRs for downstream coordination will be set so that the maximum current for a close in zero impedance fault will not exceed 5 kA. If the follow on current reaches these peak values, then the fault must be in zone 1 and the SSCL is the primary protection. Additional downstream coordination is not required, and the SSCL can lock out and terminate the fault as shown in Figure 7.

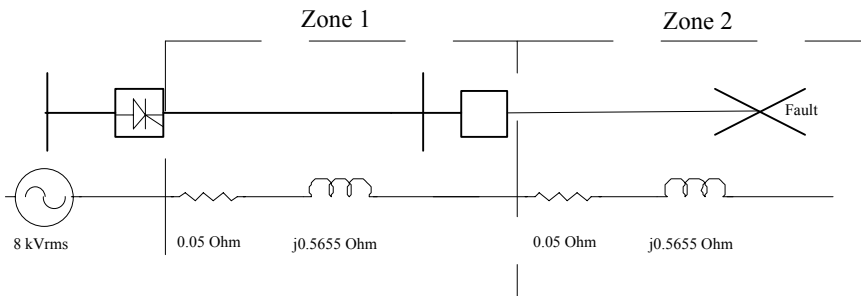


Figure 6, Protection Zones and the SSCL

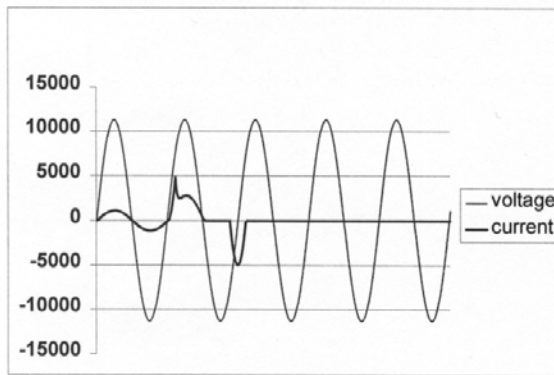


Figure 7, Zone 1 Fault

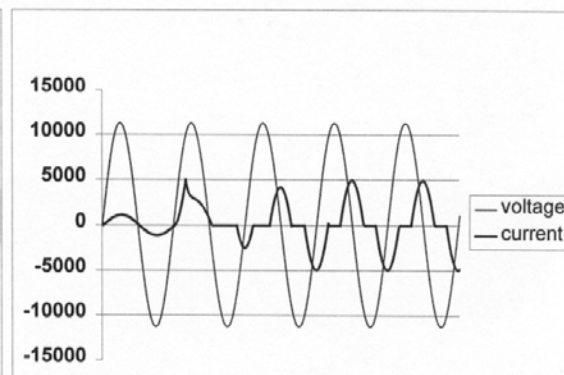


Figure 8, Zone 2 Fault

If the fault is in zone 2 as shown in Figure 8, then the first firing of the SCRs to allow follow on currents will let lower peak fault current through. The SCR phase angle for firing can then be adjusted for more conduction angle and more follow on current. The downstream breaker can then interrupt the fault and the SSCL will provide backup protection and only interrupt in the event of a breaker failure.

New Independent Generation

Deregulation of the electric energy system has opened the system to new independent energy providers. As the demand for new generation grows, market prices will create the incentive for new generation to be developed. The location and size of these new independent power providers will be market driven by many factors including the availability of fuel resources and access to the electrical network. New generation will increase the available fault current of the network as it is added and may result in existing equipment not being adequately rated to handle the new ratings. Upgrading the system to accommodate the new fault current ratings may be expensive and create excessively high prices and barriers to new generation. The SSCL with current limiting capabilities can be used to mitigate this situation.



Figure 9, Existing System Before New Independent Generator

To illustrate this situation, a computer simulation of an electrical network and the effect of new generation could have on it has been conducted. Figure 9 is a one line diagram of an electrical network to be analyzed for the effect of new generation and the SSCL application. The system consists of an infinite source, a transmission line, a substation bus, and a distribution feeder. Fault current for a fault on the distribution feeder is shown in Figure 10. Under existing conditions, fault current for the fault shown is approximately 25 kA, peak asymmetrical.

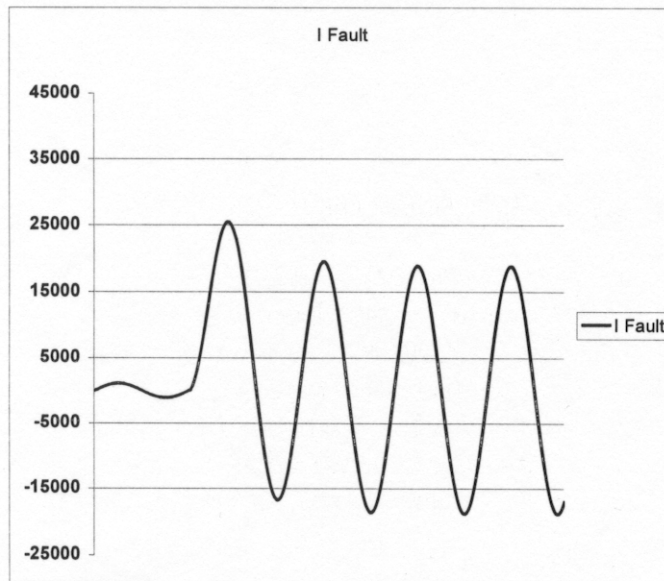


Figure 10, Fault Current Under Existing Conditions

In Figure 11, new generation has been installed near the substation bus using conventional breakers and providing additional available fault current for faults on any of the feeders that may be installed on the distribution bus.

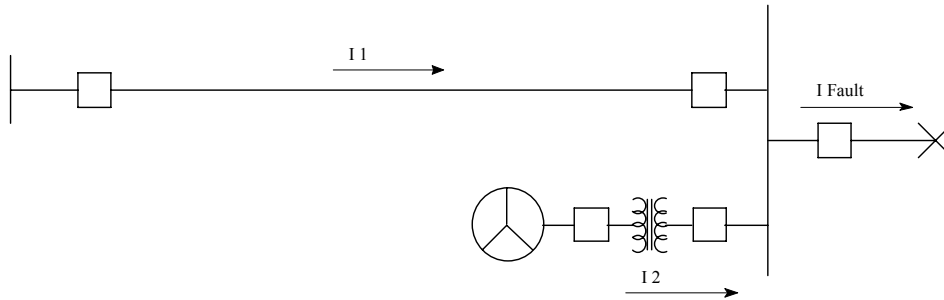


Figure 11, New Generation Using Conventional Breakers.

For purposes of illustrating the value of the current limiting breaker in this scenario, available fault currents have been simulated and are shown in Figure 12. The asymmetrical fault current has risen to 45 kA and could result in the feeder breakers and other equipment originally installed being considerably under rated and will need to be replaced with adequately rated equipment. Depending on the size of the network and the number of connections effected, this could be a substantial expense.

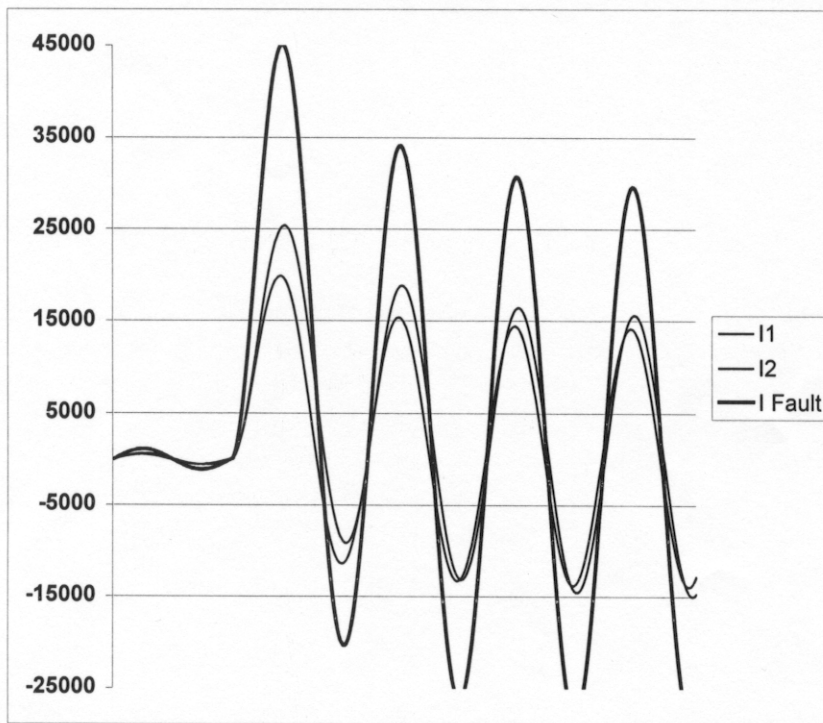


Figure 12, Fault Currents with New Generation and Conventional Breakers

An alternative solution to the problem of equipment fault current withstand capabilities after new generation is interconnected into the system in locations that were previously unplanned, is to install a SSCL with current limiting along with the new generation. Figure 13 is a one diagram of the same generation scenario but with a SSCL installed instead of a conventional breaker at the interconnection point.

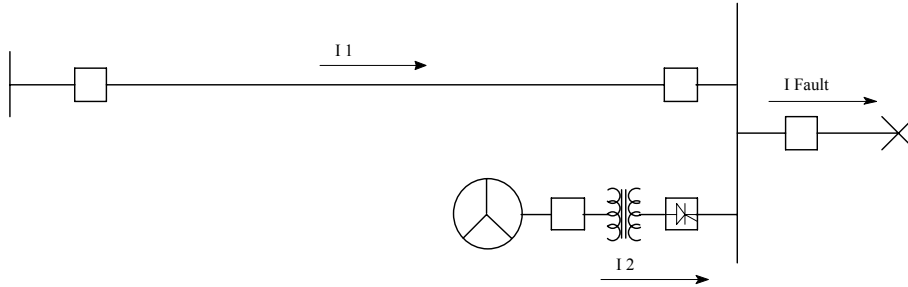


Figure 13, New Generation Using SSCL

The results of a computer simulation using the SSCL to current limit is shown in Figure 14. The asymmetrical component due to the new generation has been eliminated and the symmetrical component has increased by the current limit, which was arbitrarily set at 5 kA.

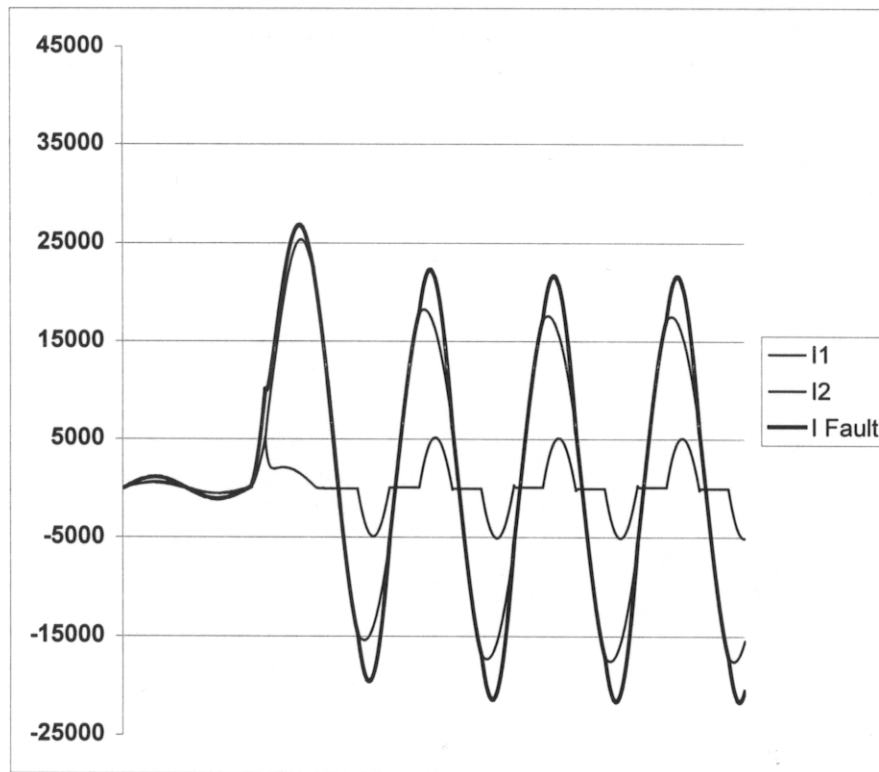


Figure 14, Fault Currents with New Generation and SSCL

Bus Tie Breaker

Current limiting can have significant value in many applications. Another application that is sometimes considered important for this approach is in a bus tie breaker joining two radial distribution busses. A one line diagram for this application is shown in Figure 15. Faults on any of the radial distribution feeders will see currents from both sources as long as the tie breaker is closed. This greatly increases the available fault current for any disturbances on any of the feeders.

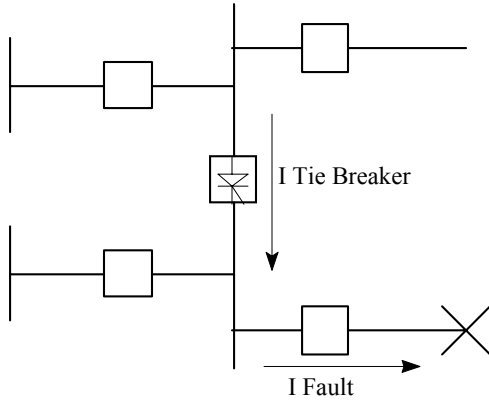


Figure 15, Bus Tie Breaker

Limiting the current through the tie breaker will reduce the fault current on the faulted feeder and the disturbance that would impact adjacent feeders. Figure 16 shows the fault currents that resulted from simulations on the circuit in Figure 15 without any current limiting breaker. Figure 17 shows the same result but with a current limiting bus tie breaker. The reduced fault contribution will reduce the disturbance on the adjacent bus and the feeders attached to it. This will greatly improve the overall power quality of all of the feeders on the busses.

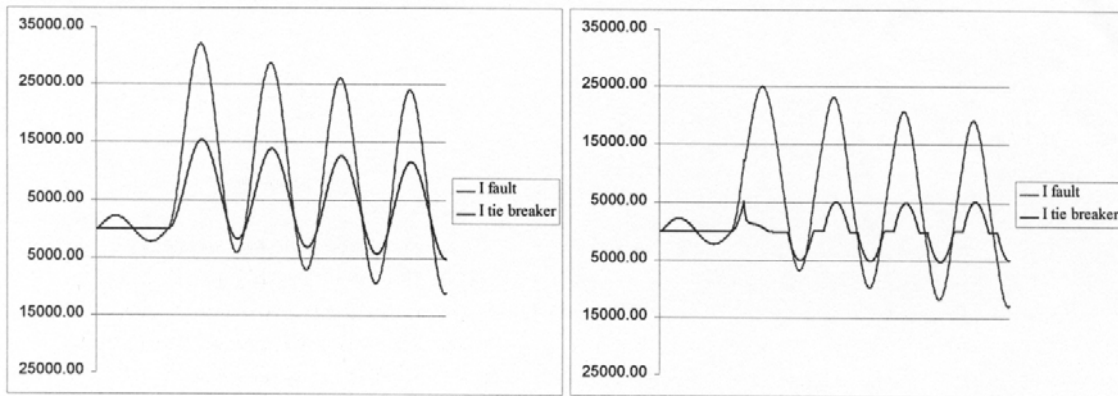


Figure 16, Without Current Limiting Figure 17, With Current Limiting

Load Control

The ability to control current levels through phase control of the conducting SCRs creates the opportunity for other operational modes that do not involve fault conditions. Limiting a customer's ability to draw more than the rated load current during normal daily operations may have value in some circumstances. Figure 18 shows a computer simulation for load currents that exceed their 600 A rms rating and then the SCRs are phased back in order to curtail the load and not exceed the rms rating on the fundamental component. The harmonic content of the phase controlled load current is shown in Figure 19. For underground feeders that are in danger of overheating from excessive load, this operational mode may have significant value.

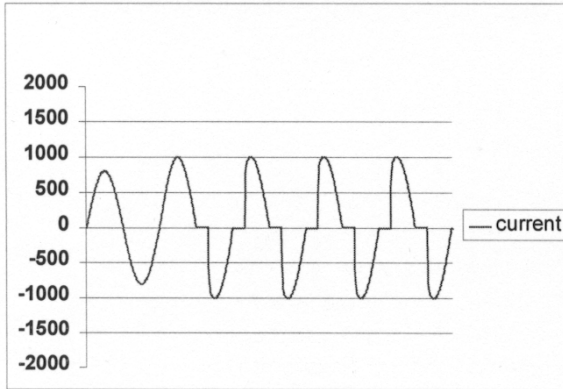


Figure 18, Load Current Limiting

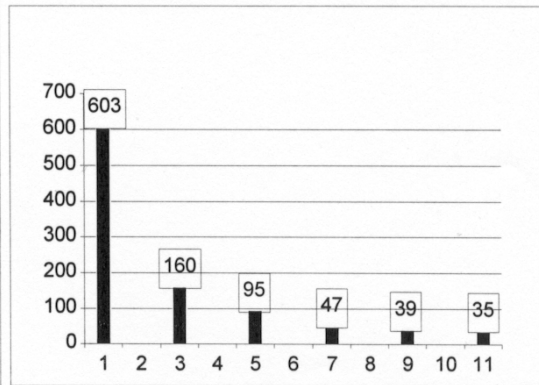


Figure 19, RMS Currents

Soft Switching

Many power quality disturbances are the result of switching transients. These can be from capacitor switching, transformer inrush, motor starting, reclosures, or other transient condition resulting from closing a breaker. The SSCL can be operated to alleviate the effects from these switching transients. Where load characteristics are known, such as a capacitor bank, the breaker can be closed at a zero voltage crossing to eliminate the transient. In other circumstances, where the load conditions are unknown, such as reclosing after a fault, the SSCL can be phased on as shown in Figure 20 to reduce the transient effects.

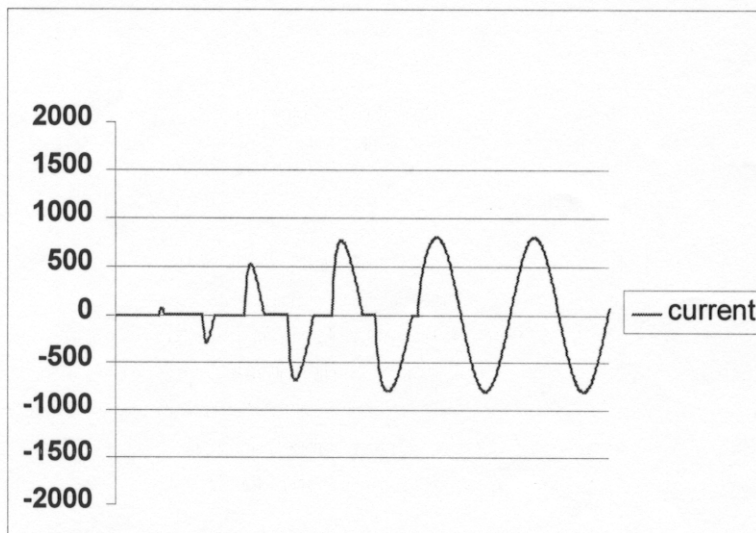


Figure 20, Soft Switching