21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2018 Grid of the Future Symposium

Study Results of the Impact of a Modular SSSC to Transmission Line Protection Schemes

L. J. KOVALSKY, H. KHALILINIA, G. CHAVAN
Smart Wires, Inc.
USA

S. NATTI, M. Y. XUE, A. BRAHMAN
DNV-GL
USA

SUMMARY

One method to control power flow on the transmission grid typically involves changing the series reactance of the line to either reduce or increase the circuit's total reactance. The introduction of series reactors or series capacitive compensation usually impacts the existing protection system, in particular, distance relays that rely on measuring changes in line reactance to detect faults. Before these devices can be added to a grid, protection engineering groups at utilities study the impact of network changes like adding power flow control and make the appropriate changes to the relays and settings.

This paper discusses a modular power flow control technology based on the Static Synchronous Series Compensator (SSSC) combined with a unique method for rapid bypass during line faults. The modular SSSC, a member of the modular FACTS (M-FACTS) family of devices, has a rapid bypass capability that allows for the detection and bypass of the injected voltage in 1 msec or less under fault scenarios. Since 1 msec is much faster than the response time of even the fastest relays, the inserted reactance of the modular SSSC is removed before relay action and typically does not impact the existing relays. This minimizes the effort required to integrate the modular SSSC power flow control solution into the utility's system.

This paper describes a series of tests that shows the existing line protection system's operation remains unaffected in most of the conditions with modular SSSC in service. A closed-loop Real-Time Digital Simulation (RTDS) test system was utilized to simulate various fault scenarios and capture the impact of the modular SSSCs on line protection. An equivalent 345 kV overhead line network was selected as a test system. The modular SSSCs were operated in capacitive mode as well as inductive mode.

Typical relay types were utilized from various manufacturers. The high-speed line protection schemes considered in this study include: Current Differential scheme (87L), Directional Comparison Blocking scheme (DCB) and Permissive Overreach Transfer Trip (POTT). In addition, a stand-alone relay was considered at one line terminal to provide step distance protection.

Len.Kovalsky@smartwires.com

Various test scenarios were selected based on several factors including but not limited to the inductive or capacitive series compensation level, protection scheme, fault type, fault location, fault inception angle, ground fault resistance and load condition before the fault.

Due to the ability of the modular SSSC to bypass in 1 msec or less, the study showed that it is unlikely that the modular SSSC could cause mis-operation of line protection under normal conditions, assuming the bypass settings are appropriate for the system. In summary, this paper concludes that the modular SSSC has minimal impact to line protection.

KEYWORDS

Power Flow Control, SSSC, Modular FACTS, Protective Relaying, Power System Protection, Distance Protection, Line Protection, Series Compensation, Series Capacitors, Series Reactors, Line Faults, RTDS

Introduction

The ability to control power flow helps utilities maximize the utilization of the existing transmission system. The Static Synchronous Series Compensator (SSSC) is one of the relevant technologies used for power flow control [1, 2]. The SSSC has been demonstrated in previous projects using bulk inverter systems [3]. Recent developments in the technology have enabled modular deployments of the SSSC to operate at line potential without a coupling transformer. The approach also has a bypass circuit for fast protection that operates at line potential. Smart Wires is a provider of a modular SSSC solution called SmartValve™.

A study was conducted to identify the impact of the modular SSSC with rapid bypass capability on transmission line protection schemes. The impetus for this study was inquiries from the system protection community to quantify the impact of the M-FACTs solutions on protection schemes [4].

A closed loop Real-Time Digital Simulation (RTDS) test system was developed to simulate various fault scenarios and capture the impact of the modular SSSC on the operation of line protection elements. The following technical approach was used to achieve the study objectives:

- Develop RSCAD® models based on MATLAB® Simulink® models to represent the modular SSSC. RSCAD is a user-friendly interface that allows the user to perform all necessary steps to prepare and run simulations, and to analyse simulation results with the RTDS.
- Develop an RTDS test system that includes overhead transmission lines of interest with the rest of the system being represented by an equivalent system
- Implement typical relay settings for multiple relay schemes within the system
- Develop test scenarios considering fault location, fault type, series inductive or series capacitive compensation level, protection scheme, load, system conditions, relay settings, the SSSC bypass settings and operating modes – capacitive or inductive.
- Perform RTDS testing and results analysis
- Summarize observations

Modular SSSC Description

This study focuses on a modular, transformer-less version of the SSSC. It can inject a leading or lagging voltage in quadrature with the line current, providing the functionality of a series capacitor or series reactor respectively. However, unlike conventional series capacitors or reactors, the modular SSSC can inject the voltage independently of the line current, thus increasing the ohmic injection when operated below the rated value, as shown in the graph in Figure 1. The figure shows the response of a 2000 kVAr rated modular SSSC with a maximum continuous current rating of 3600 A RMS and with a maximum output voltage of ±566 V RMS of the fundamental. The figure shows the effective reactance injection as a function of line current. The orange boundary of the operating range reflects the maximum reactance available as a function of line current, which is achieved when the voltage output injection is kept at a constant ±566 V RMS. The grey area inside reflects the feasible range of operation if the output voltage is varied lower than ±566 V RMS of the fundamental.

Typically a fleet of modular SSSCs would be installed across all three phases. One mode of control is to maintain a fixed reactance by varying the injected voltage as a function of line current.

Since the modular SSSC can inject a voltage independent of the line current, it can provide capacitive series compensation without issues like sub-synchronous resonance (SSR). Modular SSSC solutions are connected in series with the utility facility, operate at line potential and have no connection to ground. This technology is particularly effective in highly meshed electric grids where spare system capacity can be utilized to resolve overload situations.

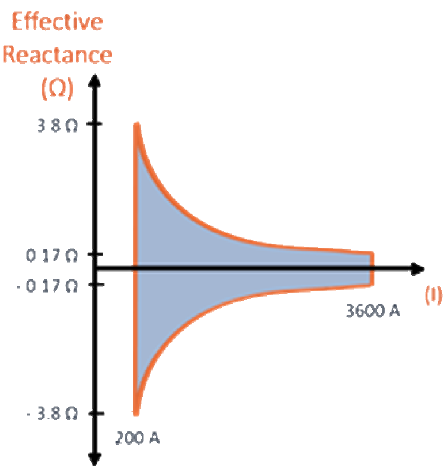

Figure 1 – Modular SSSC Injection Characteristic

Figure 2 illustrates the basic electrical configuration of the modular SSSC. The modular SSSC acts as a solid state synchronous voltage source, consisting of a voltage-sourced inverter as shown by the single-phase H-Bridge in Figure 2. The H-Bridge is controlled to inject a voltage directly into the transmission line to maintain a desired reactance. It does this by sensing the line current thru the Current Feedback transformer and determining the correct magnitude of the injection voltage such that the desired reactance is maintained. The modular SSSC harvests power directly from the transmission line to operate the control circuits.

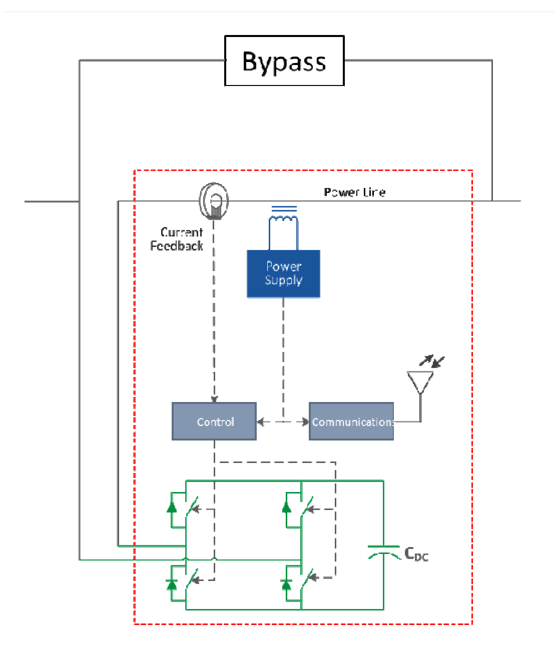

Figure 2 – Modular SSSC Circuit

The modular SSSC works in conjunction with a fast-acting bypass for protection and control, as shown in Figure 3. This fast-acting bypass is a switch connected in parallel with the modular SSSC and is either opened, allowing the modular SSSC to inject voltage, or closed, bypassing the modular SSSC. Under normal operation, it enables operators to switch a modular SSSC in series with the transmission line for power flow control. During fault conditions, the bypass provides rapid bypass of the modular SSSC in 1 msec or less. The bypass directly carries the transmission line current when the modular SSSC is bypassed. The bypass can operate at line currents of thousands of amps during normal operation and can withstand fault currents of up to 63 kA RMS for a duration of up to 1 second.

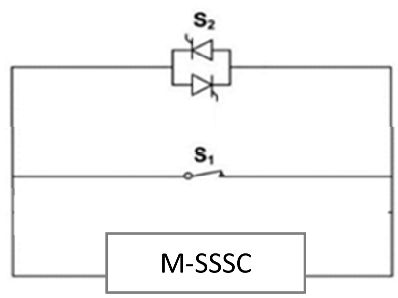

Figure 3 – Modular Bypass Circuit

The basic modes of operation of the bypass are as follows:

- Injection mode enabled: normally open contactor S1 is open, enabling injection of the modular SSSC voltage.
- Bypassed in steady state: S1 is closed. Fault protection: The bypass senses line overcurrent and automatically shorts with fast acting antiparallel SCR switches S2. S2 can also be activated by the internal protection mechanisms in the modular SSSC.

Note, whenever the state of contactor S1 changes, antiparallel SCR switch S2 is also engaged. This prevents arcing and prolongs the contactor service life.

The bypass is activated in one of two ways:

- Overcurrent protection: If any phase current is greater than a pre-programmed level indicative of a fault, the fast-acting bypass of the modular SSSCs will be triggered and bypass occurs within 1 msec or less. This current level is typically set considering the Short Term Emergency (STE) and Long Term Emergency (LTE) levels of the line so there is sufficient margin above those levels to distinguish a fault from an expected operating condition.
- Internal modular SSSC protection: The line fault may cause certain internal operational limits of the internal SSSC converter system to be exceeded. This will also trigger the bypass in 1 msec or less. These protection mechanisms are set to protect the modular SSSC and are not based on the system conditions.

Selected Transmission Network

DNV-GL and Smart Wires selected the transmission network based on the following criteria:

- Voltage level to cover broad range of the typical M-FACTS applications (e.g. no major difference between 230 kV or 345 kV from a protection and control standpoint)
- Ability to look at varying system conditions especially a weaker grid and low fault current conditions
- Ability to obtain detailed transmission facility and protection and control data for the system
- Use the same relays and settings on the selected system with the RTDS series compensated lines to facilitate the comparison of modular SSSC to conventional capacitor series compensation device performance
- Ability to demonstrate both inductive and capacitive applications of modular SSSCs on the test system.

Based on the above criteria, the following transmission lines were selected for the RTDS tests:

- 345 kV double circuit line ("Line 1") for the modular SSSCs capacitive application. The double circuit line is 50% series compensated and enables for direct comparison of modular SSSCs performance with series capacitive compensation.
- 345 kV double circuit line ("Line 2") for the modular SSSCs inductive application. The double circuit line is one of the major export paths in the region and possibly a good location for an inductive application of modular SSSCs to reroute the power to other export paths.

The selected study region is derived from a transmission operator's actual system. The system has a significant amount of wind generation exports and might be an appropriate location for a modular SSSC application. The series capacitors along the Line 1 are currently off-line because of sub-synchronous resonance (SSR) issues in that region. Addition of series capacitors in that region is not currently planned due to potential SSR issues even though the wind and solar generation is continuing to increase in that region.

Figure 4 shows the 345 kV equivalent test system that was created from the boundary equivalence of transmission network in the study region. The generator shown at each bus is the voltage source for system equivalence. The modular SSSCs in capacitive mode are deployed on the Line 1 (connected between Station 1 and Station 2), which is a 345 kV double-circuit line. The modular SSSCs in inductive mode are deployed on the Line 2 (connected between Station 3 and Station 4), which is a 345 kV double-circuit line. The symbol of capacitor and inductor are used to represent the modular SSSCs in capacitive mode and inductive mode respectively.

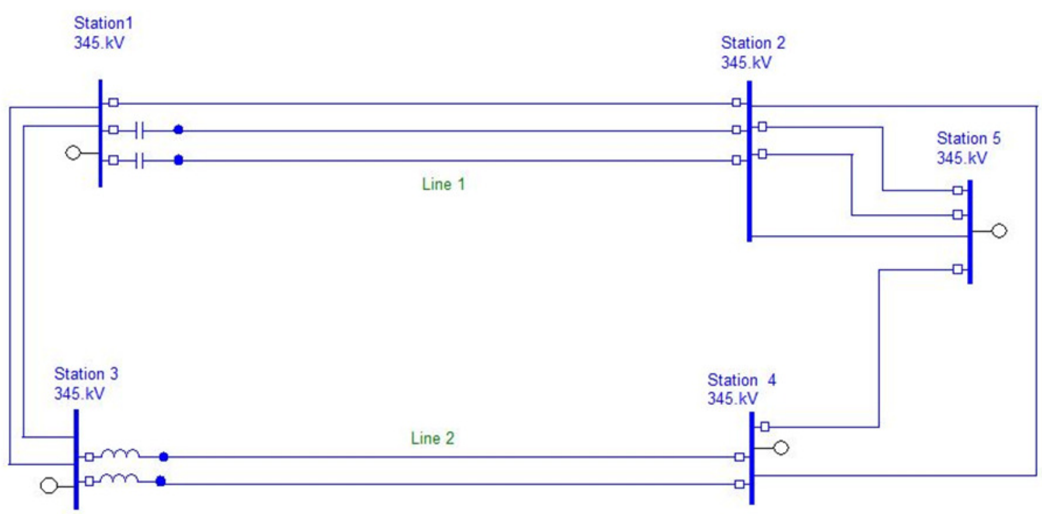

Figure 4 – Selected Study System

Figure 5 shows a simplified schematic representation of the RTDS system used for the closed loop protection tests with one transmission line for one type of protection scheme. As noted in Figure 4, the actual test system employed multiple lines, relays and protection schemes. The RTDS system includes parallel processors and peripheral boards. The processors compute the power system models and control schemes in real time. The peripheral boards are used to exchange analog & digital signals with relays in the test loop. The RSCAD software is the configuration tool used for RTDS tests.

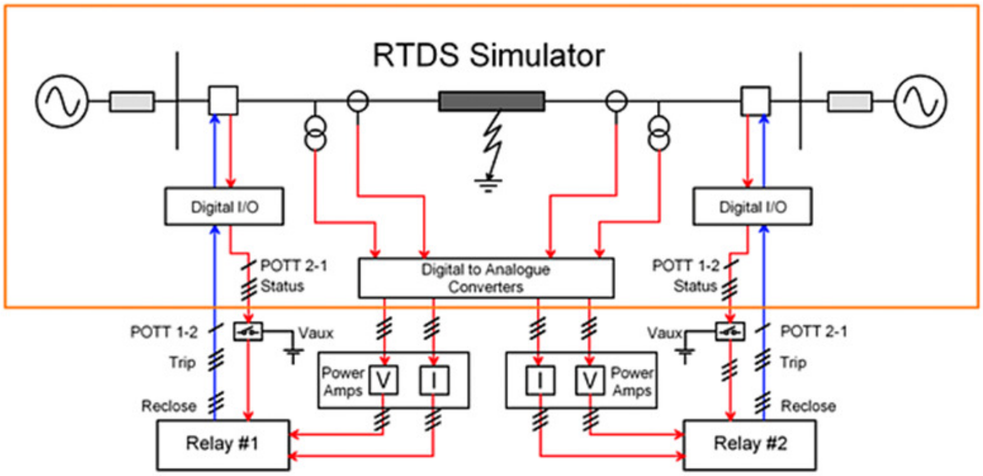

Figure 5 - Simplified RTDS System for Close-Loop Protection Tests

The modular SSSCs are modelled as controlled voltage source for each phase of the line. The bypass switch across the modular SSSCs is also modelled and it is controlled by protection logic. The modular SSSCs are modelled on three phases separately and each phase works independently.

The modular SSSC employs a multi-level waveform characteristic that was modelled to determine if that has any impact on protection. This was to determine if the harmonic content of the multi-level waveform would impact the relays.

If a fault occurs, the modular SSSC deployment will be bypassed to protect itself and to eliminate its impact to line protection. If any phase current is greater than a pre-set, programmable over-current level indicative of a fault, the modular SSSCs will be bypassed within 1 msec. The RTDS modelling also included a representation the internal protection mechanism of one of the modular SSSCs that results in a bypass in some fault scenarios.

Line Protection Schemes

The protection schemes evaluated for both Line 1 and Line 2 are shown in Table 1. The high-speed line protection schemes included: Current Differential scheme (87L), Directional Comparison Blocking scheme (DCB) and a Permissive Overreach Transfer Trip (POTT) scheme. In addition, Station 1 terminal had a stand-alone relay to provide step distance protection.

Protection Schemes Evaluated for Line 1 (Between Stations 1 and 2) and for Line 2 (Between Stations 3 and 4)
87L & Step Distance – Both Lines 1 & 2
DCB & Step Distance - Line 1
POTT & Step Distance – Line 2
POTT & Fast Zone 1 – Both Lines 1 & 2
Step Distance – Both Lines 1 & 2

Table 1 – Protection Schemes Evaluated

Fault Simulation Scenarios

The study teams from DNV-GL and Smart Wires considered several aspects to select test scenarios for the RTDS simulations. As shown in Figure 6, a wide variety of test scenarios were implemented to cover as many possible system conditions.

Case Analysis

Based on the test scenarios in Figure 6, thousands of test cases from a combination of several factors were defined and simulated. In addition to different faults at different locations, numerous simulation variations such as inductive or series capacitive compensation levels, pilot scheme enable/disable, different relay settings, bypass protection scheme enabled/disabled, high/medium/low loading, parallel line in/out of service, etc. were simulated.

To interpret the results, the following definitions are used in this report to explain the normal or abnormal operation of the relays as applicable to line protection:

- Normal operation: refers to a condition when the relays trip for internal faults and do not instantaneously trip for external faults – the way the relays are intended to operate.
- Mis-operation: refers to a condition when the relays refuse to trip for internal faults or trip instantaneously for external faults – a way relays are not intended to operate.
- Over-reach: refers to a condition when a relay trips beyond its distance zone reach setting – mainly applicable to the distance element of line protection relays.
- Under-reach: refers to a condition when a relay trips less than its zone reach setting – mainly applicable to the distance element of line protection relays.

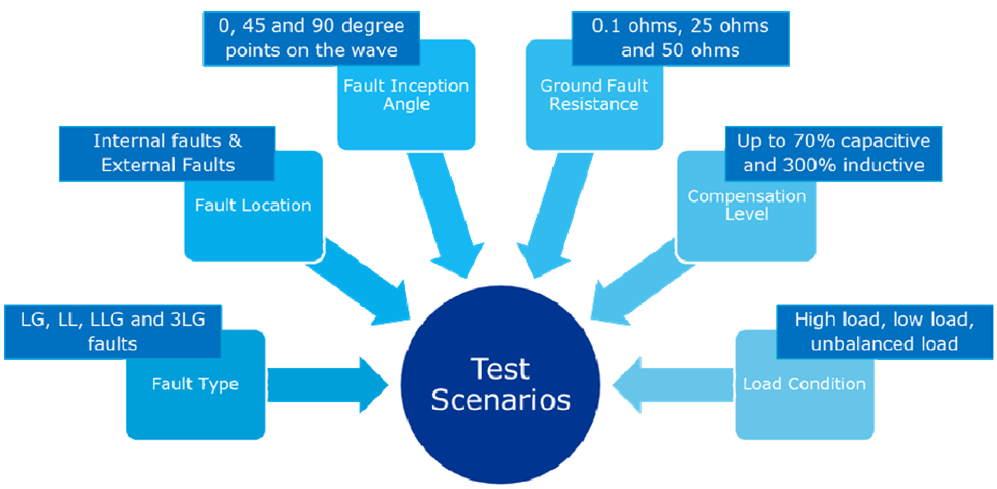

Figure 6 - Selection of Test Scenarios

Summary of Results

Tables 2 and 3 provide a summary of the RTDS tests performed on modular SSSCs operating in capacitive mode and inductive mode respectively. The tables show several conditions that were used in combination to develop test scenarios.

<table>
<tr><th colspan="2">Test Scenario Conditions</th><th>Result analysis</th></tr>
<tr><td>Fault type</td><td>SLG, LL, LLG and 3PH</td><td rowspan="6">The study results indicate there is no impact on the protection system operation under normal operating conditions.

In most cases, the overcurrent threshold is sufficient to result in a bypass for normal operation. Overreach of distance protection was observed in a few cases where the modular SSSC bypass scheme did not operate due to the fault currents lower than modular SSSC's overcurrent protection threshold. However, when those cases were re-run with the internal protection features of the modular SSSC activated in these low level fault cases, a bypass resulted. The overreach caused by bypass protection not being triggered can also be addressed by adjusting the relay settings.</td></tr>
<tr><td>Fault location</td><td>Internal and External</td></tr>
<tr><td>Point on Wave</td><td>0°, 45° and 90°</td></tr>
<tr><td>Compensation</td><td>50% and 75%</td></tr>
<tr><td>Loading</td><td>Medium and High</td></tr>
<tr><td>Modular SSSC Bypass Protection</td><td>Overcurrent protection in-service.</td></tr>
</table>

Table 2 - Summary of RTDS Tests on Modular SSSC – Capacitive Mode

<table>
<tr><th colspan="2">Test Scenario Conditions</th><th>Result analysis</th></tr>
<tr><td>Fault type</td><td>SLG, LL, LLG and 3PH</td><td rowspan="6">The study results indicate no impact on the protection system operation under normal operating conditions.</td></tr>
<tr><td>Fault location</td><td>Internal and External</td></tr>
<tr><td>Point on Wave</td><td>0°, 45° and 90°</td></tr>
<tr><td>Compensation</td><td>100%, 200% and 300%</td></tr>
<tr><td>Loading</td><td>High</td></tr>
<tr><td>Modular SSSC Bypass Protection</td><td>Overcurrent protection in-service.</td></tr>
</table>

Table 3 - Summary of RTDS Tests on Modular SSSC – Inductive Mode

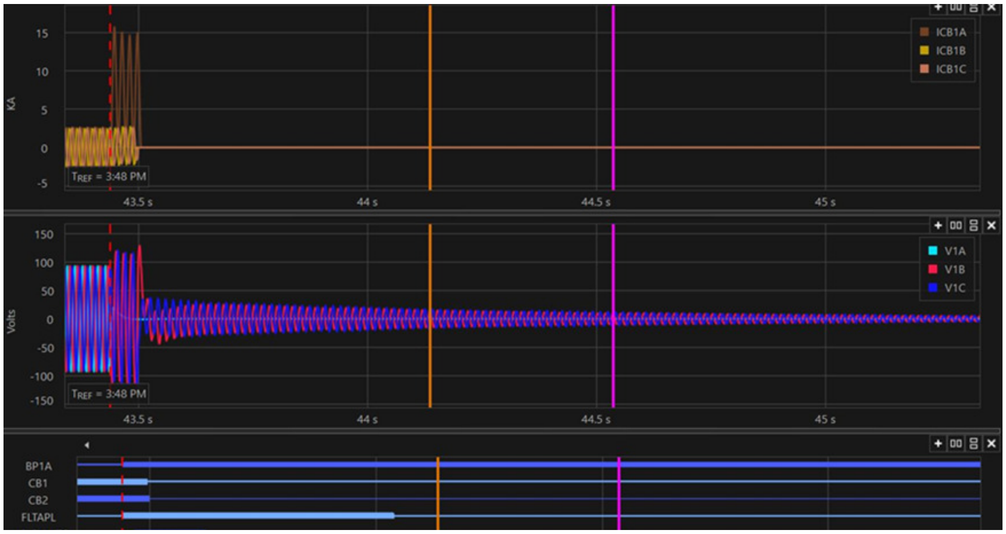

Figure 7 – Example Test Case

Figure 7 provides an illustrative example of one of the plots of an example test scenario. The top plot in the figure shows the primary currents (ICB1A, ICB1B and ICB1C) flowing through the terminal breaker. The middle plot of the figure shows the secondary voltages (V1A, V1B and V1C) from the line CVT of the terminal. The bottom plot of the figure shows the circuit breaker status signal (CB1, CB2), a signal indicating the simulated fault applied (FLTAPL), and the bypass status for Phase A (BP1A). This is a scenario where a single-line-to-ground fault was applied on Phase A. In this case, the bypass protection system bypasses the modular SSSC Phase A, however the Phase B and Phase C (un-faulted phases) were not bypassed. All relays operated normally and no mis-operation was observed.

Conclusions

Based on RTDS simulations of several thousands of test cases on a 345 kV line system, the impacts of modular SSSC to line protection were evaluated.

The modular SSSC employs the use of a bypass switch that is activated in two types of scenarios during a fault. It primarily is activated within 1 msec when a pre-programmed overcurrent protection limit is exceeded, indicative that a fault has occurred. In some cases, particularly for lower level faults, the modular SSSC internal converter protection mechanism is activated to result in a system bypass.

The operation of either scheme will actuate the bypass SCR to bypass the modular SSSC. If the fault current exceeds the programmed current threshold, the SCR bypass operation happens in 1 msec or less, which is faster than any line relays. If the modular SSSCs are bypassed, the line relay will respond per protection settings properly i.e., there is no under-reach or over-reach.

Because of the fast operation of the bypass SCR, it is unlikely that a modular SSSC could cause mis-operations of line protection under normal conditions, assuming the bypass overcurrent settings are appropriate for the system. In a system where the fault current is much higher than load current for fault on the line or near the line, the modular SSSC's overcurrent protection alone is sufficient to bypass the modular SSSC units instantly. In a weaker system where the fault current is close to load current, the internal protection system of the modular SSSC supplements the overcurrent protection to bypass the modular SSSC quickly.

The bypass was purposely disabled to simulate a failure in some of the study cases to assess the impact on line relay mis-operation in capacitive mode. Without the bypass, the modular SSSC will continue injecting voltage during the fault. This causes the line voltage to ramp down and the line current to ramp up, which consequently may cause line relay elements such as Z1P or Z1G to trip for external faults. However, if the Z1P and Z1G reach settings are reduced, the mis-operation can be avoided. Since this is only for the case where the bypass is disabled, this action is not required for normal operation. The reduction of Z1P and Z1G reach depends on the line impedance and series capacitive compensation level. Note that under the bypass disabled condition and for the same series capacitive compensation level, the over-reach caused by the modular SSSC is less than the series capacitor. Therefore, if the series capacitive compensation level is 50% of line impedance, the setting of 50% of line impedance for Z1P or Z1G would be secure for the modular SSSC.

When the modular SSSC is installed on transmission lines where pilot schemes are already in use, it is very unlikely that the modular SSSC can cause line relay mis-operation even under the worst condition such as if the bypass were disabled. For transmission lines with high speed pilot schemes such as 87L, DCB or POTT, the communication-aided scheme will operate as the primary line protection, and the relay's under-reaching element (Z1P, Z1G, etc.) will become backup protection such that they can be set towards providing additional security.

Another way to eliminate the modular SSSCs impact to line protection one option is to install the CVT or PT on the line side of modular SSSC. This way, the modular SSSC will be excluded from line protection zone. The CT can be placed either on the bus side or the line side of the modular SSSC. However, the results of this study show that this is not needed since the bypass operates as expected in normal operation.

When the modular SSSC is set in inductive mode, the under-reach of zone 1 protection is not significant, which is different from a series reactor application. Even if the modular SSSC is not bypassed during the fault (to simulate a bypass failure), the line protection's Z1P and Z1G reach would be minimally affected. The zone 2 protection could reach less than the settings in the bypass-disabled condition, since the modular SSSC would continue injecting voltage that will effectively increase line voltage and lower line current. However, since zone 2 protection is backup protection and can be set with more margins, extended zone 2 reach settings can avoid this problem. A conservative approach is to set zone 2 reach per compensated line impedance. As per the capacitive case above, this is only for the case where the bypass is disabled to simulate a failure, and this action is not required for normal operation.

The modular SSSC injected voltage has harmonics, but the harmonics have only minor impact to the line voltage under heavy load conditions. The RTDS study results show that relay performance will not be affected.

In conclusion, the study has shown that under fault conditions, the modular SSSCs are rapidly bypassed and the line relays will respond per protection settings properly i.e., there is no under-reach or over-reach. This minimizes the impact on the existing relay system and simplifies the integration of the modular SSSC.

BIBLIOGRAPHY

[1] L. Gyugyi et al, "Static Synchronous Series Compensator: A Solid State Approach to the Series Compensation of Transmission Line," IEEE PES Winter Power Meeting, Paper 96, WM 120-6 PWRD, 1996.

[2] Working Group B4.40 22-12, CIGRE "Static Synchronous Series Compensator (SSSC) – February 2009.

[3] N. Hingorani and L. Gyugyi, "Understanding FACTS" – Concepts and Technology of Flexible AC Transmission Systems," IEEE Pres ISBN 0-7803-3455-8 1999.

[4] J. L. Blackburn and T. Domin, "Protective Relaying – Principles and Applications," 4th Edition, CRC Press, ISBN 13:978-1-4398-8811-7 2014.