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

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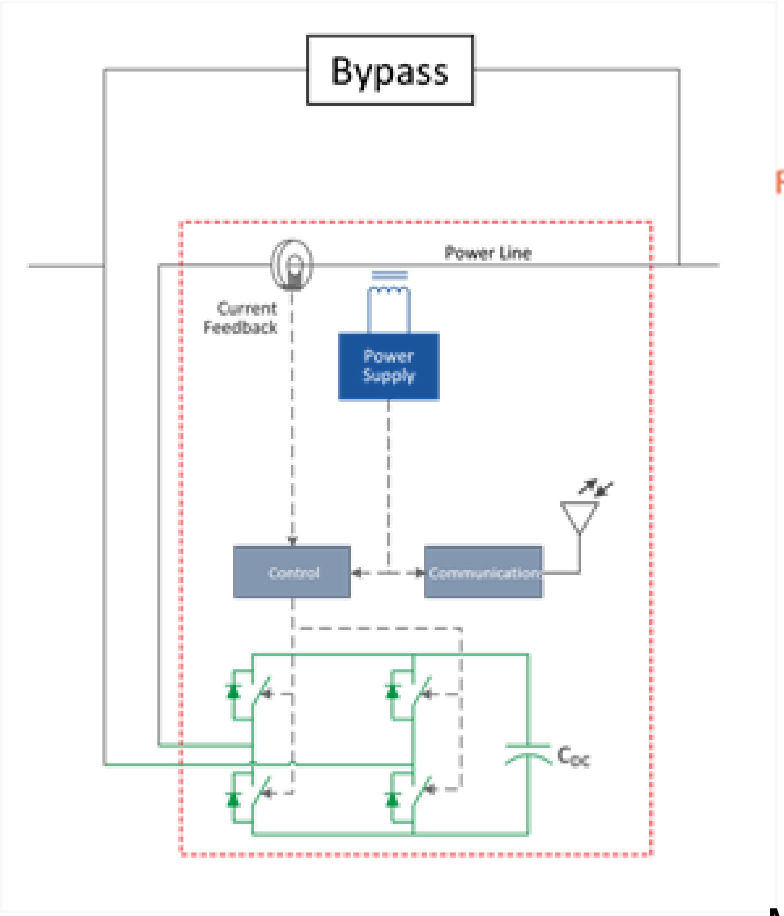
Introduction

- The 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. This requires protection engineering groups at utilities study the impact 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 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.
- 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.

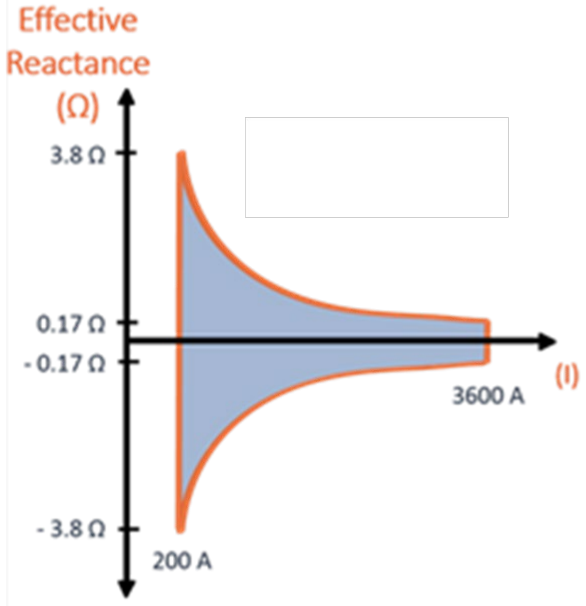
RTDS Study Methodology

- Develop RSCAD® models based on MATLAB® Simulink® models to represent the modular SSSC.
- 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



Modular SSSC Circuit



Modular SSSC Injection Characteristic

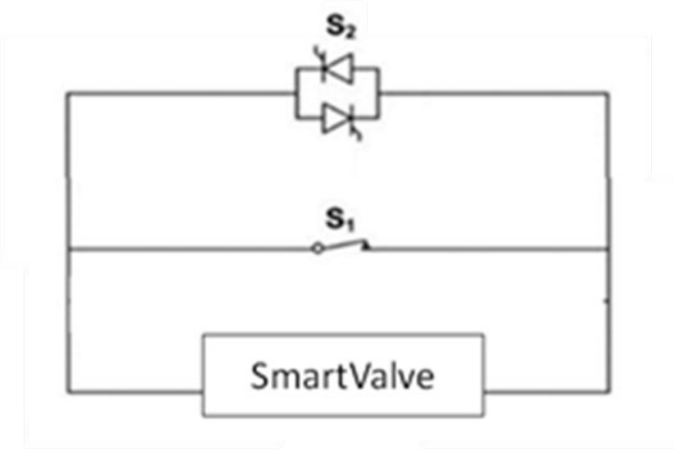
All power is harvested from the line to operate the control and communication circuits.

The modular SSSC Voltage-Sourced Converter (VSC) consist of the four switches and the DC Link capacitor C_{DC}. The controls are operate the converter to maintain C_{DC} at a relatively constant voltage.

The Modular SSSC injects a voltage in quadrature with the line current such that it is capacitive or inductive. Unlike physical capacitors or inductors, the injected voltage is independent of the line current.

The curve shows the range of injected reactance as a function of the line current. The outer orange boundary is when the modular SSSC is injecting the full output voltage.

Bypass Circuit



Modular Bypass Circuit

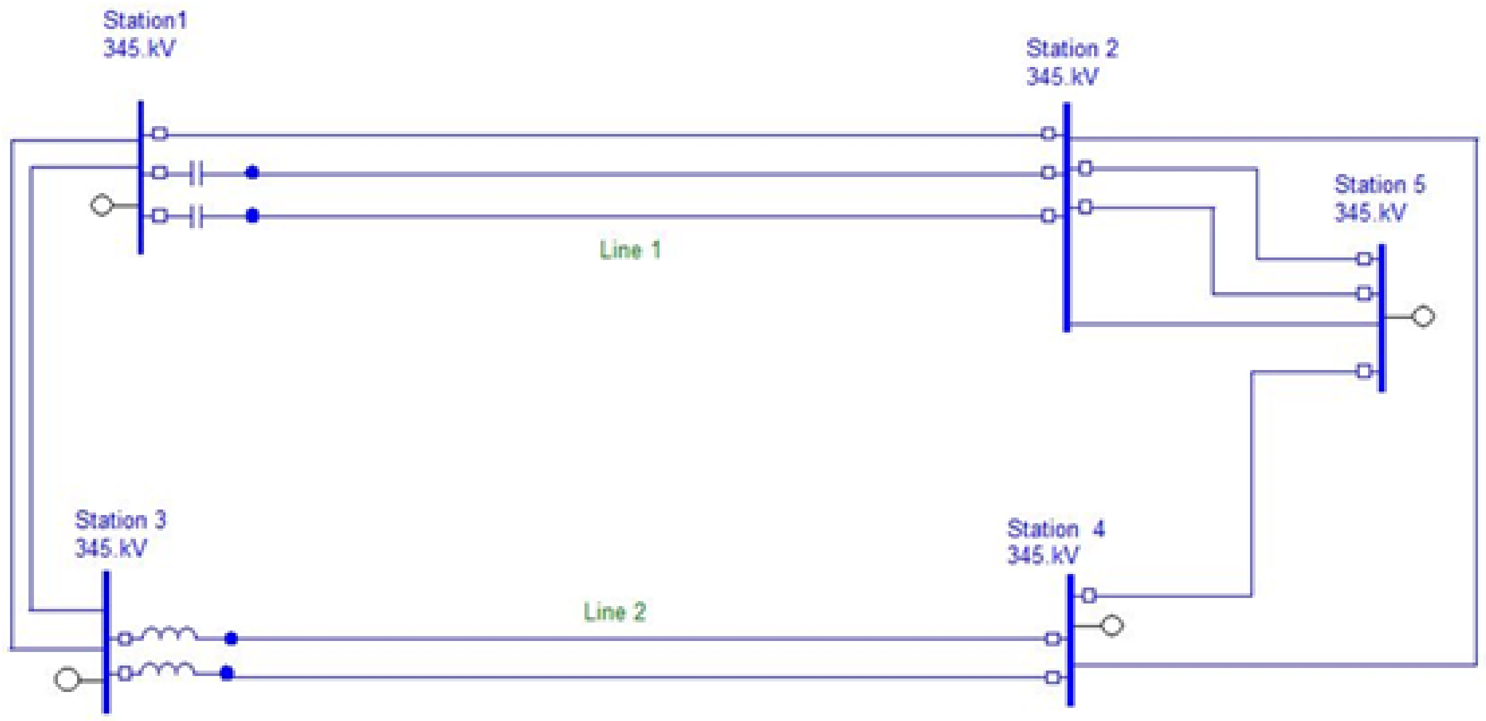
The basic modes of operation of the bypass are as follows:

- 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.

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.
- 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.

Selected Transmission Network

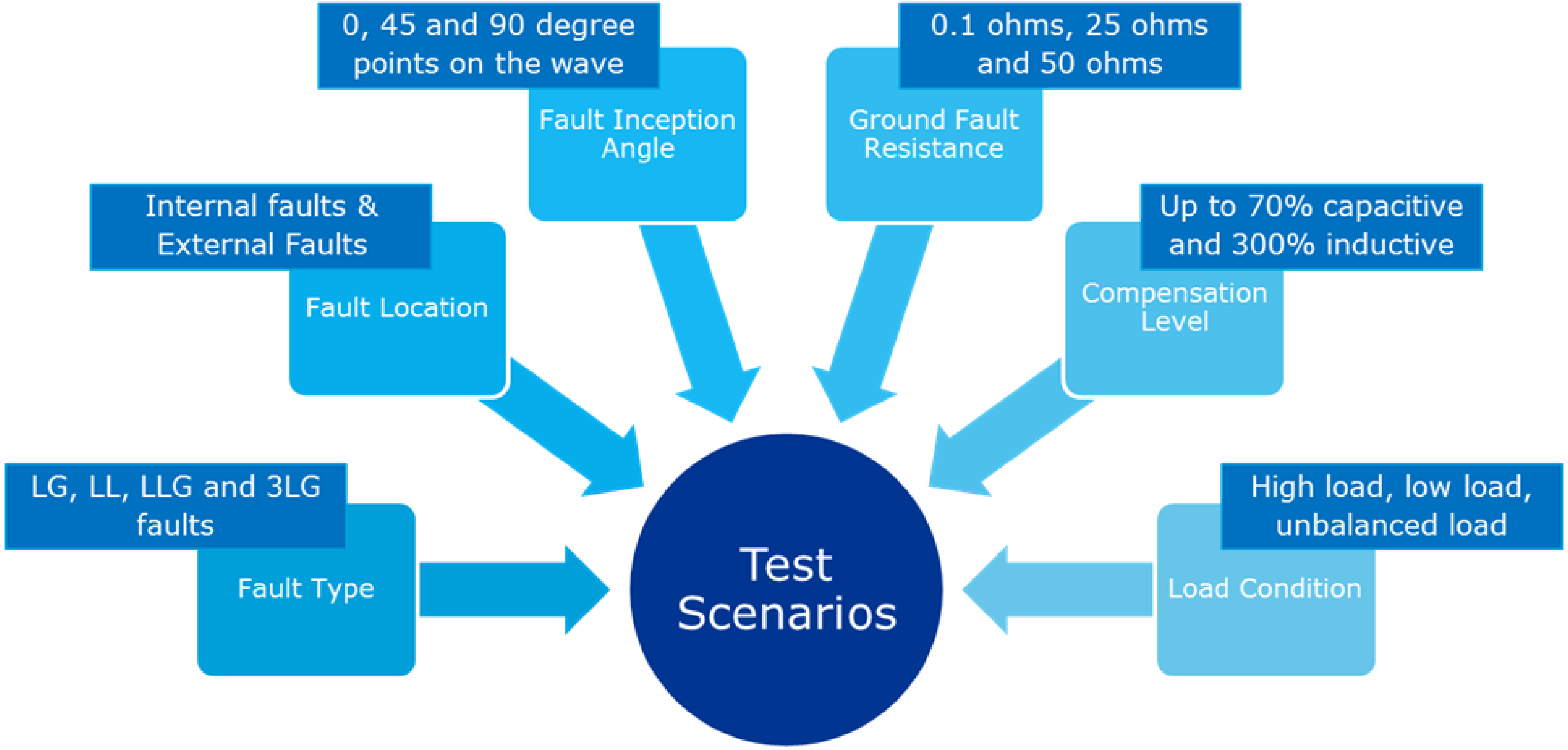


Protection Schemes Evaluated for Line 1 (Between Stations 1 and 2) and for Line 2 (Between Stations 3 and 4)
87L & Step Distance – Both Lines 1 & 2
DCB & Step Distance - Line 1
POTT & Step Distance – Line 2
POTT & Fast Zone 1 – Both Lines 1 & 2
Step Distance – Both Lines 1 & 2

The following transmission lines were selected for the RTDS tests:

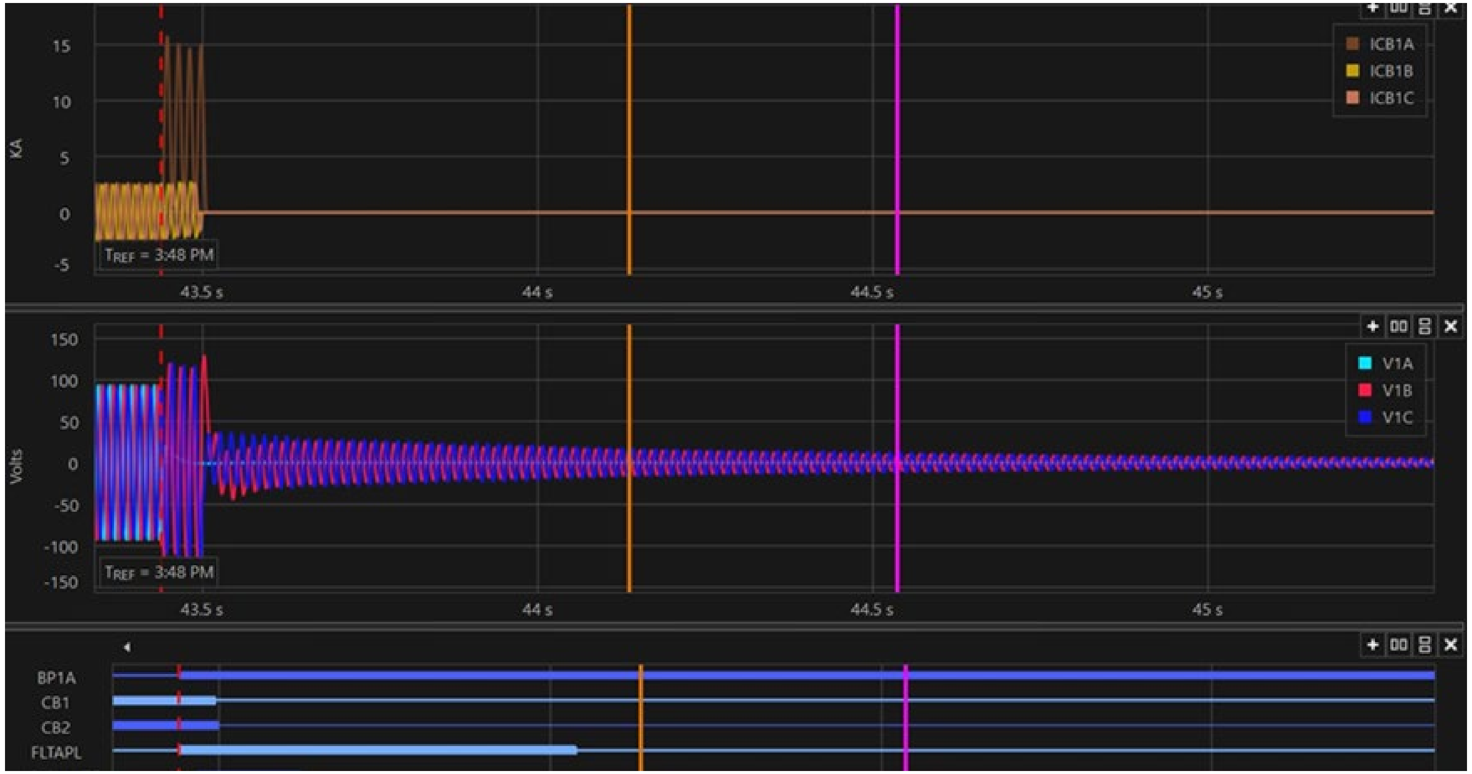
- 345 kV double circuit line ("Line 1") for the modular SSSCs capacitive application. The double circuit line is 50% series compensated and enables for direct comparison of modular SSSCs performance with series capacitive compensation.
- 345 kV double circuit line ("Line 2") for the modular SSSCs inductive 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.

Selection of Test Scenarios



- Based on these test scenarios, 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.

Example Test Case



- 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.

Summary of Results – 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 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>

Summary of Test Results – Inductive Mode

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

Study Conclusions

- 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 while the line current ramps 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.

Conclusions - Continued

- 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.

- 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.

- 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.