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# Assessment of Protection on Transmission Lines with Fixed Series Capacitors (FSC) using Hardware-in-the-Loop Testing

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## SUMMARY

With the recent improvements in the topology and operations of transmission and distribution systems at Dominion Energy Virginia, existing protection schemes are experiencing different challenges and obstacles. For instance, fixed series capacitors (FSC) installed to increase the transfer capability and improve system stability can result in the maloperation of zone protection. This challenge becomes more prominent considering the nature of the dynamic response of FSC controllers, which would primarily change the line impedances. This paper aims to present a case study of coverage and security challenges for line protection using a hardware-in-the-loop (HIL) test setup on a series-compensated line. The implementation of the HIL includes the FSC controller and impedance protective relays. The study explored the impact of the dynamic response of the FSC controller on existing distance protection schemes. The study recommends maintaining series-compensation logic while ensuring proper operation of Zone 4 when the FSC is bypassed.

## KEYWORDS

Distance protection, electromagnetic transient simulation, fixed series capacitors, hardware-in-the-loop, line protection, real-time digital simulation, series-compensation.

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# I. INTRODUCTION

Dominion Energy Virginia (DEV) owns and operates a network of electric transmission and distribution systems in Virginia with an extensive and diverse generation portfolio. In recent years, the system topology and operational needs have significantly challenged line protections with the penetration of flexible AC transmission systems (FACTS). For example, fixed series capacitors are implemented across DEV's network to increase power transfer across the series-compensated lines.

However, the presence of fixed series capacitors (FSCs) on transmission lines imposes some challenges on the existing protection schemes across the transmission lines [1]. Currently, series-compensated lines are primarily protected using directional comparison blocking (DCB) schemes, where zone protection is assigned based on the line impedances, which change significantly based on the operational status of the FSCs. Thus, the most challenging part of protecting series-compensated lines is that the transient response of the capacitors is not easily predictable, as there are protective models that govern the FSC protection.

To better assess the transient response of the protection elements, real-time transient analysis and hardware-in-the-loop (HIL) tests are used since traditional short-circuit analysis tools cannot capture these events. The real-time digital simulator (RTDS) allows us to explore the impacts of capacitors transients on the implemented protection scheme for hundreds of faults on the network. RTDS has parallel, multi-core processors with digital cards that allow HIL tests to be implemented. This enables protection engineers to provide recommendations for enhancing line protection by connecting hardware devices such as impedance relays or controllers [2] [3].

This paper describes a case study of line protection for series-compensated lines with the presence of FSC controllers using RTDS. The study uses existing protection settings implemented in impedance relays with the series compensation logic ESERCMP set to be operational. The paper is organized as follows: Section II describes line protection in series-compensated lines, including relay settings. In Section III of the paper, the setup of the HIL tests is explained, as well as the testing procedure. Section IV presents the simulation results and the analysis of data. Finally, in Section V, some recommendations are provided along with suggestions for future work that can enhance line protection further.

# II. LINE PROTECTION IN SERIES-COMPENSATED LINES

The system considered in this study consists of a 52-mile 500 kV transmission line. Substation 1 is connected to a generation facility, and Substation 2 is connected to the rest of the grid. The line is compensated with an FSC located near Substation 2, with capacitance designed to provide 60 percent compensation of the line impedance. Fig.1 below illustrates the system's single-line diagram.

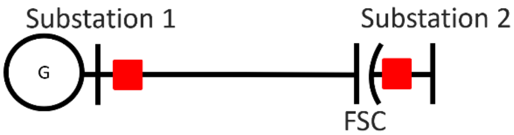


*Fig. 1: Single-line diagram for the series-compensated 500 kV transmission line.*

The line protection at the terminal with the FSC is shown in Fig. 2. The relays have underreaching, instantaneous protection in Zone 1 (21-1); the overreaching for Zone 2 is used for communications-assisted DCB scheme (21-2), the reverse reaching for Zone 3 for a blocking in DCB scheme (21-3), and when the FSC bypass breaker is closed, the instantaneous underreaching in Zone 4 is enabled with torque control (not shown in the figure).

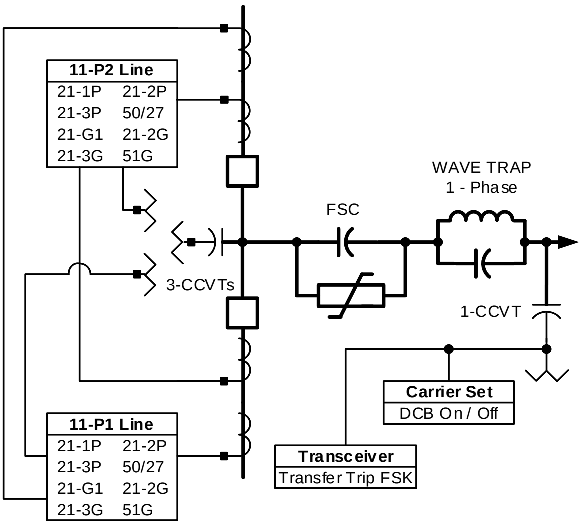


*Fig. 2: Line protection single-line diagram [1].*

In addition, directional inverse-time overcurrent (51) and instantaneous overcurrent elements (50) are supervised by an undervoltage element (27). However, this study did not include overcurrent elements results.

The impedance relays have special logic for series-compensated line protection. The logic enables or blocks Zone 1 tripping based on calculated voltage ($V_{CALC}$) and measured voltage ($V_{MEAS}$). For Zone 1 to operate, the ratio $V_{MEAS}$: $V_{CALC}$ should be greater than a threshold at a point in the line (usually around 20% from Substation 2). To enable series compensation logic, the option ESERCMP in impedance relays should be enabled.

Relay distance elements settings are based on the positive sequence impedance of the line and the zone allocation. For example, for this 52-mile line, the phase distance elements of Zone 1 are set to reach up to 20% of the uncompensated line. The line impedance is 4.35 in secondary ohms. Tables 1 through 3 summarize the relay settings.

*Table I*
*Series compensation settings.*

| | **ECVT** | **ESERCMP** | **XC** |
|---|---|---|---|
| **Substation 1** | Y | Y | OFF |
| **Substation 2** | Y | Y | OFF |

*Table II*
*Zone 1 and Zone 2 reach settings (impedances are in secondary ohms).*

| | Z1MP | XG1 | RG1 | Z2MP | XG2 | RG2 |
|---|---|---|---|---|---|---|
| **Substation 1** | 0.92 | 0.92 | 5.4 | 6.81 | 6.81 | 40 |
| **Substation 2** | 1.00 | 1.00 | 5.87 | 6.81 | 6.81 | 40 |

*Table III*
*Zone 3 and Zone 4 reach settings (impedances are in secondary ohms).*

| | Z3MP | XG3 | RG3 | Z4MP | XG4 | RG4 |
|---|---|---|---|---|---|---|
| **Substation 1** | 7.60 | 7.60 | 50.00 | N/A | N/A | N/A |
| **Substation 2** | 7.60 | 7.60 | 50.00 | 3.21 | 3.15 | 18.50 |

## III. HARDWARE-IN-THE-LOOP TEST SETUP

Dominion Energy Virginia (DEV) owns an advanced RTDS lab equipped with the FSC controller and impedance relays, connected to other auxiliary devices like the amplifiers. Digital simulation allows engineers to test protection and control equipment under virtually all possible faults. Furthermore, the real-time dynamic response of tripping and status signals is being captured and analysed.

Fig. 3 illustrates the HIL connection diagram. The system has four major hardware components: The RTDS computers, impedance relays, FSC controller, and amplifiers.

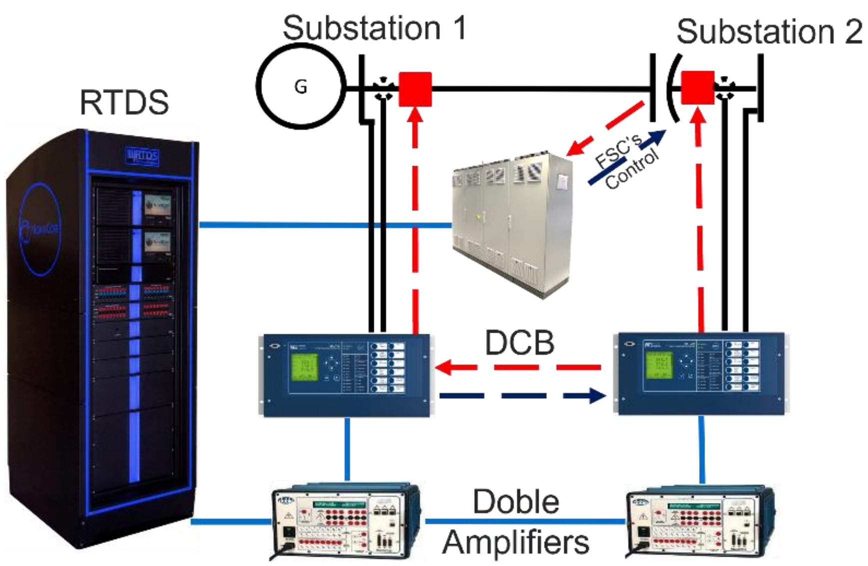


*Fig. 3: HIL signal flow diagram.*

### RSCAD® FX Model

The 500 kV line was modelled using RSCAD® FX software. The model consists of the boundary equivalent of DEV's power system including adjacent lines and buses. The generation facility was modelled using the IEEE Woodward Electric Hydro Governor Model (WEHGOV), and the exciter was modelled using the IEEE ST1A Exciter component model. Generator parameters were provided by the plant's operations at DEV. Transmission lines were modelled using the T-Line model with data provided by the Aspen OneLiner™ power system model. The FSC model consisted of two parallel capacitors, each with a capacitance of 71 μF, resulting in a total 142 μF capacitance.

### FSC Interface

The interface between RSCAD® FX model and the FSC controller utilized four Gigabit Transceiver Analogue Output (GTAO) cards, one Gigabit Transceiver Digital Input card, and one Gigabit Transceiver Digital Output card. All the connections were made using fiber optics cables.

### Relay Interface

Two impedance relays were receiving voltage and current signals using two amplifiers. Each amplifier was connected to a single GTAO. The trip signals were sent from impedance relay to the input side of Gigabit Transceiver Front Panel Interface (GTFPI) V2 card. The trip signal generated by the relays was used to open the two breakers to isolate the faults. The output of GTFPI V2 provided the FSC bypass breaker status, as it allows input/output configuration. Since GTFPI V2 output is only 5 V, another amplifier was used to bring the signal to 125 V to trigger the relay's input.

### Testing Procedure

After modelling and connecting the system, multiple faults were initiated to observe the response of the FSC controller and the relays. There were two cases: one when the FSC was in-service and the other when the FSC was bypassed. All types of faults were explored (SLG, LL, 2LG, 3L, and 3LG). The fault location percentages on the x-axis of the graphs below in Section IV are from 0% to 100%, with the Substation 1 terminal as the reference. To determine the fault location percentages from the Substation 2 terminal, 100% minus the percentages shown on the x-axis was used. The results shown in the report are for a fault incidence angle of 0 degrees; however, the results are comparable for incidence angles ranging from 0 to 90 degrees.

## IV. SIMULATION RESULTS AND ANALYSIS

### FSC In-Service (Compensated Line)

With FSC in-service, we ran the first batch of tests where two impedance relays were configured to record the response of the Substations 1 and 2 terminals. The underreaching Zone 1 elements in both terminals are shown in Fig. 4 and Fig. 5, respectively. The x-axis presents the distance from the relay at Substation 1, and the y-axis shows how much percentage of tests tripped at a certain zone for a fault located at a particular location. For the relay at Substation 1, the underreaching Zone 1 element reached up to 20% of the line. The overreaching Zone 2 element covered the remaining parts of the line. It should be noted that overreaching Zone 2 was designed to cover up to 150% of the line. On the other hand, the relay at Substation 2 terminal has shown a different response. Zone 1 reached up to 70%

of the line, with gaps, as it moved away from the FSC. The remaining part of the line was protected by Zone 2.

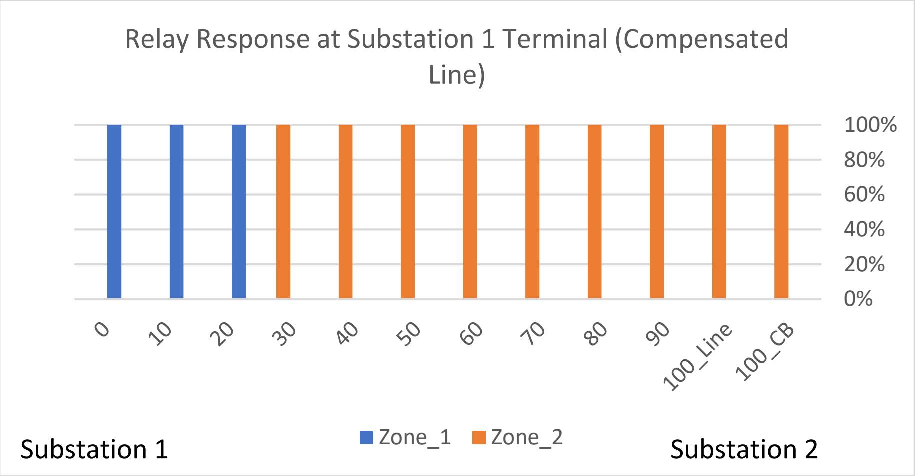


*Fig. 4: Percentage of Zone 1 and Zone 2 distance operations at terminal 1 – FSC in-service.*

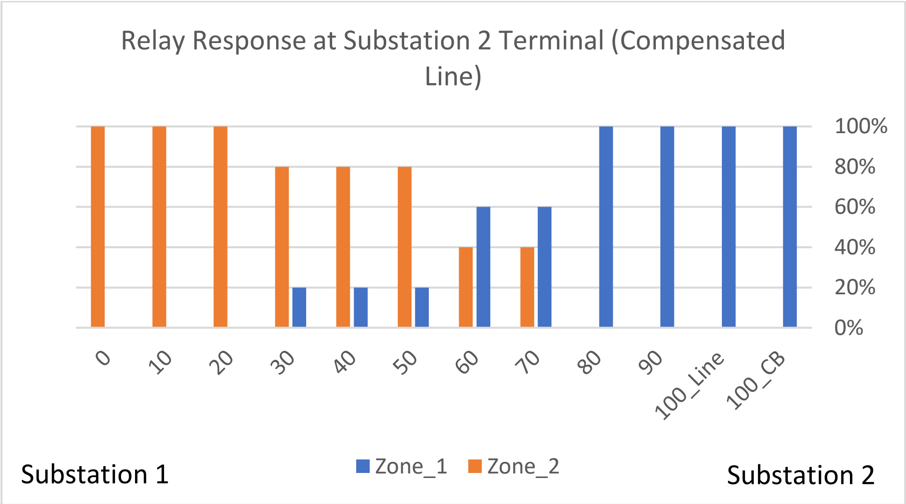


*Fig. 5: Percentage of Zone 1 and Zone 2 distance operations at terminal 2 – FSC in-service.*

The FSC controller's response is illustrated in Fig. 6, which shows that the FSC controller had a slower response time than the relays. This is because of the propagation delay of signals from the FSC controller. In addition, the figure illustrates that the relay at Substation 2 tripped at Zone 1, while the relay at Substation 1 tripped at Zone 2.

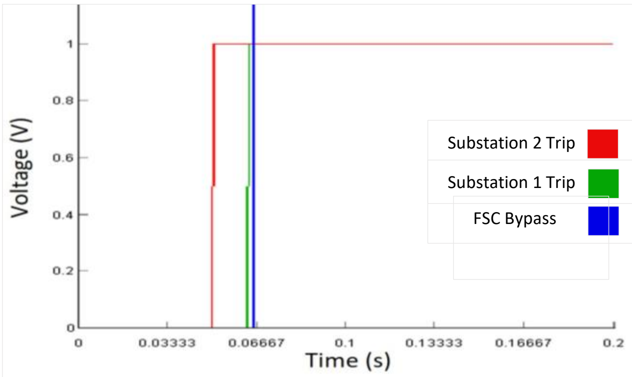

*Fig. 6: FSC controller and impedance relays responses.*

The FSC bypass controller protection covered all the faults from Substation 2 to 20% of the line (or 80% of the line from Substation 1). Most of the trips were temporary; there were very few permanent lockouts where the operator had to press a button to unlock the controller.

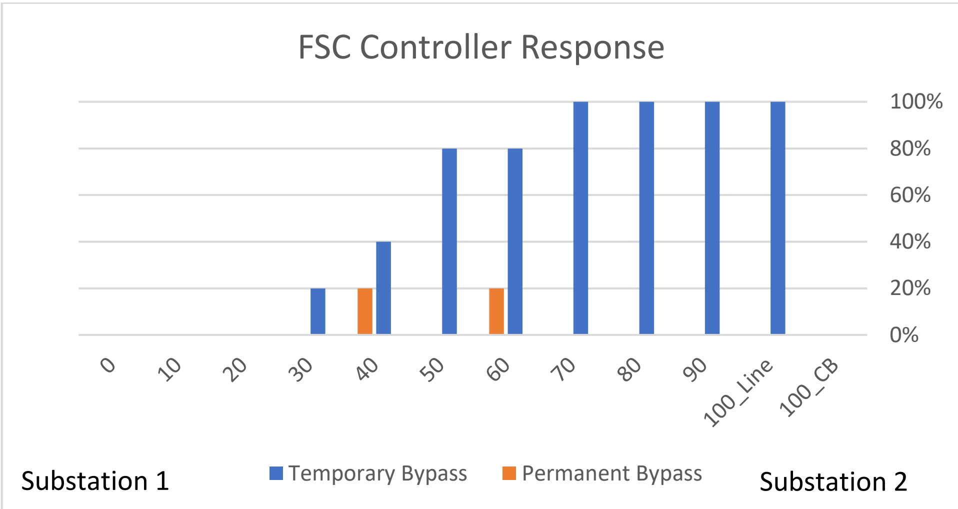


*Fig. 7: Percentage of FSC bypass protection near terminal 2 – FSC in-service.*

**FSC Offline (Uncompensated Line)**

With FSC offline, we ran the second batch of tests. The underreaching Zone 1 elements in Substations 1 and 2 terminals are shown in Fig. 8 and Fig. 9, respectively. For the relay at Substation 1, the underreaching Zone 1 element reached up to 30% of the line. The overreaching Zone 2 element covered the remaining parts of the line. The relay at the Substation 2 terminal showed a different response where Zone 1 reached up to 10% of the line with gaps, but the underreaching Zone 4 covered up to 80% of the line without gaps. The remaining part of the line was protected by Zone 2.

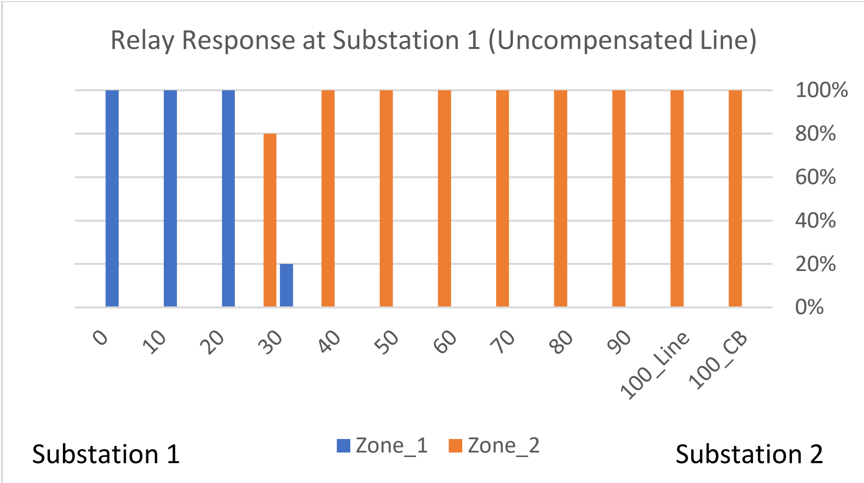


*Fig. 8: Percentage of Zone 1 and Zone 2 distance operations at terminal 1 – FSC offline.*

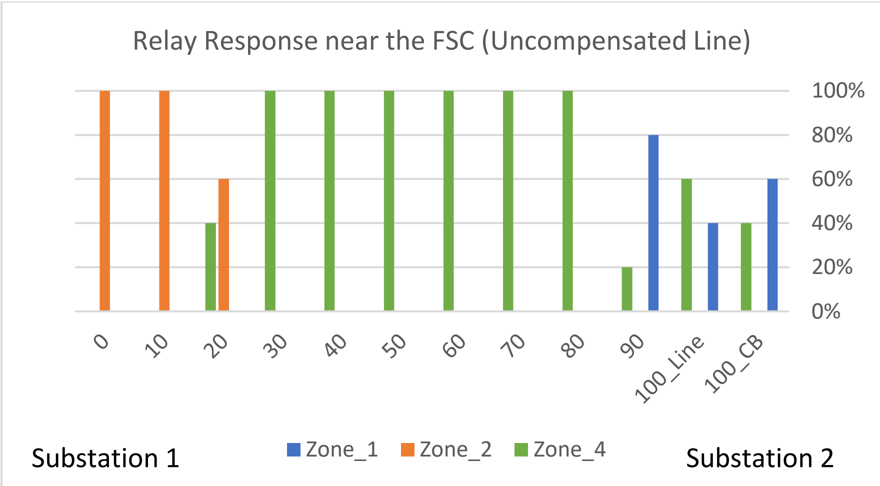


*Fig. 9: Percentage of Zone 1, Zone 2, and Zone 4 distance operations at terminal 2 – FSC offline.*

### Results Analysis

Since the FSC controller's response was slower than the relays' response, Zone 4 did not operate while the FSC was in-service. However, Zone 4 can be activated when the FSC is offline in the case of repetitive faults. We recommend maintaining the series-compensation logic ESERCMP with the options Y and XC = OFF selected to ensure fewer gaps in protection. In addition, Zone 4 protection (when the FSC was bypassed) provided more protection than Zone 1 (when FSC was in-service) as we moved away from the FSC towards Substation 1.

## V. CONCLUSION AND FUTURE WORK

Extensive HIL testing using RTDS was performed to determine relay response in the presence of the FSC controller for a critical series-compensated 500 kV line. All fault types were simulated at multiple locations across the line. The FSC controller was proven to have a slower response than the relays, which can assist engineers in designing zone operation and knowing the status of the breakers. The DCB communication-assisted typical Zone 2 and Zone 3 proved reliable and were used as delayed backup protection. However, the biggest concern is underreaching Zone 1, where protection gaps were observed moving away from the FSC. Furthermore, Zone 4 protection was more effective when the FSC was temporarily or permanently bypassed because the zone will reach up to 80% of the line. In other words, there are protection gaps when FSC is operational. We recommend maintaining series-compensation logic ESERCMP as Y and XC = OFF, since these settings have resulted in the safest output. Furthermore, Zone 1 operation should be backed up by other measures, such as the overcurrent protection currently operational in our system. In the future, we suggest adding Power Line Carriers in the HIL test for the DCB scheme and expanding the study for adjacent lines with the presence of FSC controller.

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