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MODULAR STATIC SYNCHRONOUS SERIES COMPENSATOR (M-SSSC): EMT MODELING FOR REAL-TIME AND OFFLINE SIMULATIONS

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Abstract *– The objective of this paper is to present a Modular Static Synchronous Series Compensator (M-SSSC), and particularly its Electromagnetic Transient (EMT) model structure, its behavior in response to setpoint changes and certain transient events in power system, its main operational characteristics and modes, and its possible use in several platforms, as non-real-time power systems software, as real-time application by using Model-in-the-loop approach.*

Key Words: FACTS, series-compensation, real-time simulation, M-SSSC, power flow control, EMT simulation, EMT modeling, Phase-Locked Loop (PLL), Multilevel Modular Converter (MMC).

1 INTRODUCTION

The increasing share of distributed generation from renewable energy sources and growth in dispersed charging infrastructure for electric vehicles lead to increasing load-flow dynamics. The behavior on the grid user side creates challenges in planning and operation of power systems. And for a safe, secure and dynamic operation, system operators have increasingly used Dynamic Line Rating (DLR) and Flexible AC Transmission Systems (FACTS) as tools to manage system voltage and load-flows more effectively and maximize the use of existing infrastructure.

The paper presents a Modular Static Synchronous Series Compensators (M-SSSC). By using power electronics, the M-SSSC effectively increases or decreases the reactance of a given transmission circuit, enabling real-time power flow control. As a modular device, these FACTS allow for easy deployment or re-deployment and allows the solution size to be scaled up or down to support the changing needs of transmission and distribution grids. Given the fast response of the unit's power electronics, the unit's set-point can be changed remotely at any given time to actively control power flow with no degradation in unit life.

The M-SSSC enables utilities to get more from their existing grid by:

- Pushing power away from overloaded facilities or pulling power onto underutilized facilities
- Addressing short-duration and emergency needs with rapidly deployable and easily re-deployable solutions
- Accommodating changes in generation and load by deploying this FACTS in as little as weeks, when using a mobile deployment
- Avoiding or minimizing the use of valuable substation space
- Providing high availability via a modular, redundant solution

Utilities and system operators are increasingly interested in how M-SSSC impacts the power system, its dynamic performance during system disturbances and its interaction with protections, other devices, or grid users. The dynamic performance with those functionalities, its ramping response, operation in different modes, and response to different type of disturbances are presented and discussed in this article. In section 2, the M-

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SSSC technology is presented, while in section 3 the EMT model is described extensively, including protection schemes and control system. Section 4 presents some simulations using the described model. Finally, main conclusions are included in section 5.

2 M-SSSC TECHNOLOGY

M-SSSC enables dynamic power flow control and real-time congestion management, supporting grid development and operational strategies in both the short-term and the long-term. M-SSSC utilize a single-phase, series-connected, multi-level Voltage-Source Converter (VSC) configuration that injects a leading or lagging voltage in quadrature with the line current. This causes an increase or decrease of the power flowing through the circuits they are installed and nearby circuits as well, providing an equivalent functionality of a series capacitor or series reactor respectively [1]. However, unlike conventional series capacitors or reactors, the M-SSSC can inject the voltage independently of the magnitude of line current, thus modifying the effective reactance injection when operated below the rated current.

State of the art M-SSSC solutions leverage on a redundant design and use a fast-acting bypass for protection against system faults. The bypass can isolate the VSCs in the event of a fault in less than 1 ms after fault detection and can withstand fault currents of up to 63 kA for 1 s. Since the M-SSSC operates at line potential, there is no requirement for an insertion transformer, introducing a compact solution that can be installed within space-constrained substations. M-SSSC mainly injects voltage at the fundamental frequency, thus introducing a minimal risk of initiating Sub-Synchronous Resonance (SSR) or Sub-Synchronous Control Interaction (SSCI) related events. ENTSO-E’s Technopedia has ranked the technology readiness level as mature and proven (TLR 7) [2].

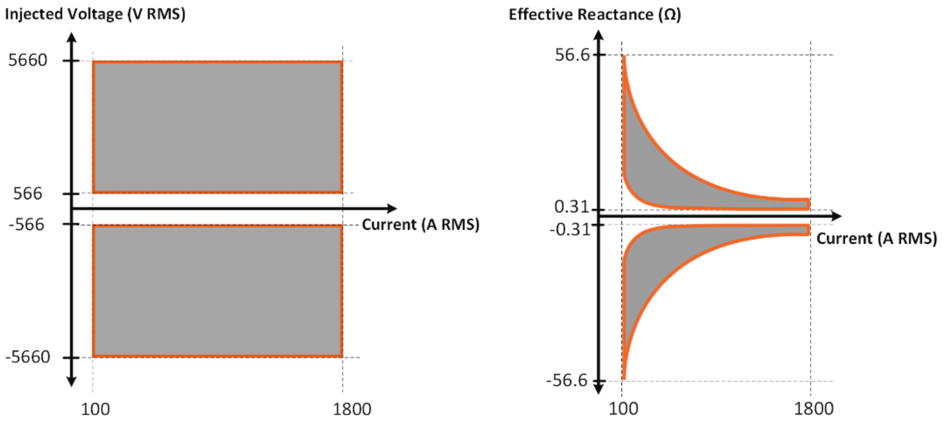
A commercially available M-SSSC solution is depicted in Fig. 1-(a). It has a set of 10 VSCs, whose reactive power rating is 1 MVAr respectively and a maximum continuous current rating of 1800 A RMS. A typical M-SSSC installation is shown in Fig. 1-(b).

Fig. 1: (a) M-SSSC (SmartValve), and (b) M-SSSC installation

The 10 VSCs are connected in series arrangement with a parallel bypass circuit, which protects the power electronics, and a bypass filter device, which diverts high frequency transients from entering the M-SSSC. In Section 3.1, the electrical arrangement and M-SSSC components are described in more detail.

Fig. 2-(a) presents the M-SSSC voltage operating range against the line current. The orange boundary of the operating range represents the limits for the injected voltage, which can be varied independently of the line current within the range indicated by the grey area. Fig. 2-(b) shows the effective reactance injection as a function of line current. The orange boundary of the operating range reflects the limits of the effective reactance, and the grey area inside reflects the range available if the output voltage varies within the operating range shown. For instance, the device shown in Fig. 1-(a) has also an overload capability for 2 hours of 120% of the rated current.

The device can be controlled to maintain a fixed reactance since the injected voltage can be controlled as a function of line current. It can also be observed that the effective reactance injection increases as the line current reduces. This M-SSSC model can provide a maximum reactance injection of ±56.6 Ω at the minimum operating current of 100 A_{rms}.



(a) Voltage operating range

(b) Reactance operating range

Fig. 2: M-SSSC device capabilities

At its rated current of 1800 A$_{rms}$, the compensation capabilities from each M-SSSC device drop to ±3.1 Ω. To achieve higher reactance injection levels at a line current close to the continuous rating of the device, an M-SSSC system with more devices connected in series can be considered, taking advantage of the modular and scalable nature of this technology.

An example of the 10 x 1 MVAr M-SSSC injected voltage and line current in time is shown in Fig. 3, resembling an effective capacitance or inductance respectively. A Pulse-Width Modulation (PWM) control strategy is used to establish an adequate VSC firing scheme and determine the set of duty cycles and DC voltage setpoint to minimize the harmonic emission.

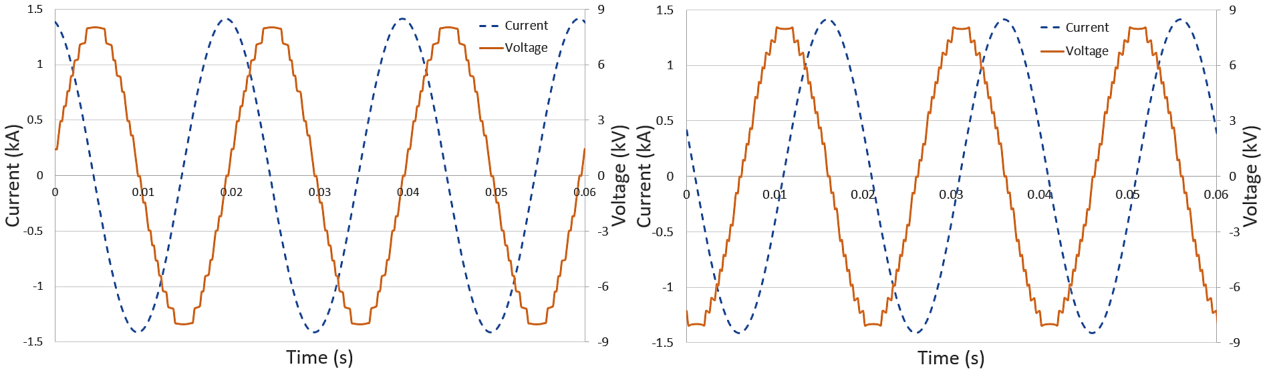


Fig. 3: Voltage injection in quadrature with line current. Left: capacitive injection; Right: inductive injection

3 M-SSSC: EMT MODELING

The model described in this chapter was developed for offline simulations (power system EMT simulation software), as well as real-time applications.

3.1 M-SSSC Primary Components

An M-SSSC acts as a solid-state synchronous voltage source, consisting of a series of VSCs. Fig. 4 depicts an M-SSSC's primary components, consisting of ten VSCs or single-phase H-bridges utilizing a DC capacitor, four Insulated Gate Bipolar Transistor (IGBT) switches and antiparallel diodes. Each VSC injects an AC voltage directly in series with the line.

Additionally, current transformers are used for power harvesting and current sensing. A Phase-Locked Loop (PLL) is used to determine the phase of the line current, while a DC voltage controller controls the DC link voltage and ensures the required AC voltage injection contribution of each VSC is met. An integrated fast-acting bypass diverts fault currents from the VSC through the parallel Silicon Controlled Rectifiers (SCR) and consequently stops the voltage injection during system faults. The fast bypass feature minimizes the risk of interactions with existing distance protection schemes. As shown in Fig. 4, M-SSSC solution is comprised of the following primary components:

Diagram Key:

1. Input Terminal
2. Output Terminal
3. Surge Protection
4. High-Pass Filter
5. Low-Pass Filter
6. Surge Protection
7. Silicon-Controlled Rectifier (SCR)
8. Vacuum-Switch Link (VSL)
9. Enclosure/Faraday Cage
10.1 – 10.10. Voltage-Source Converter (VSC)
11. Converter-Level Bypass

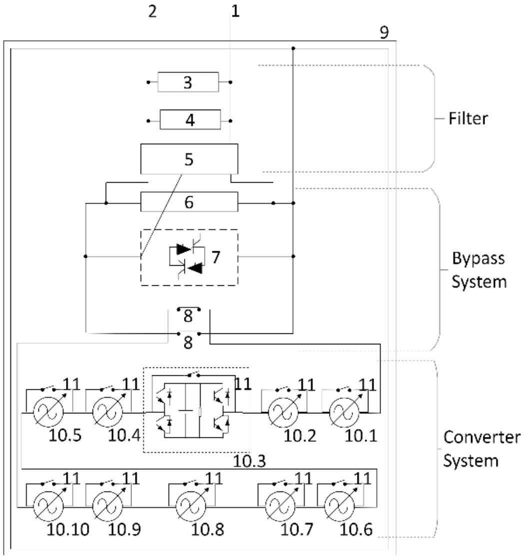


Fig. 4: M-SSSC Electrical Configuration [3]

a. High-Pass and Low-Pass Filter

During system transients such as lightning surges, traveling waves can be induced to the line and eventually into the M-SSSC. To mitigate the effects of high-frequency waves causing large voltage differentials along the M-SSSC, the filter system (number 3 to 5 in Fig. 4) provides a low-impedance path for high-frequency components of line current in the order of MHz.

b. Bypass System

The bypass system provides protection and control to the converters. The principal components of the bypass are the redundant normally closed mechanical VSLs, SCRs and a Surge Protection (number 6 to 8 in Fig. 4). The bypass enables the rapid bypass of the VSCs during fault conditions and enables operators to switch the VSC in series with the line. The bypass can withstand fault currents of up to 63 kA RMS for a duration up to 1 s. During Monitoring Mode, no voltage is injected as the VSLs are closed and the converters are bypassed.

c. Converter System

The VSCs (number 10.1 to 10.10 in Fig. 4) inject the voltage in series with the line. The maximum RMS value calculated from the injected AC voltage of one VSC is approximately 566 Vrms. Considering the rated current 1800 A, it results in 1 MVAr reactive power capacity. That means that the M-SSSC described in Chapter 2 has a 10 MVAr reactive power capacity per phase, or 30 MVAr in the three-phase power system. Optionally the converter system can include individual VSC bypass (number 11 in Fig. 4) to enhance system availability.

3.2 M-SSSC operation modes

The M-SSSC devices modelled in this paper has four modes of operation:

- Monitoring Mode: The M-SSSC system is bypassed. It doesn’t inject any voltage.
- Fixed Voltage Mode: The M-SSSC system is set to output a fixed voltage injection that is either capacitive or inductive an invariant to the line current.
- Fixed Reactance Mode: The M-SSSC system is set to output a fixed reactance that is either capacitive or inductive. In this control method, the injected voltage will vary as the line current changes to keep the effective reactance at the set value.
- Current Control Automatic Mode: The M-SSSC automatically starts or stops injecting based on the line current flow and depending on pre-defined capacitive and inductive operation bands.

Besides the described modes, a Current-Control Override feature can be enabled. It overrides the selected mode if the current exceeds a pre-configured and user-selected threshold. In this case, the M-SSSC system will automatically inject inductively using a droop control until current drops below the threshold minus a preconfigured offset and then the system will return to its previous operating mode.

3.3 M-SSSC protection system

The bypass is designed to protect the power electronics of the VSCs in the event of system faults. In the event of a fault, the SCRs and VSLs will carry the entire fault current.

The bypass is activated by the following means:

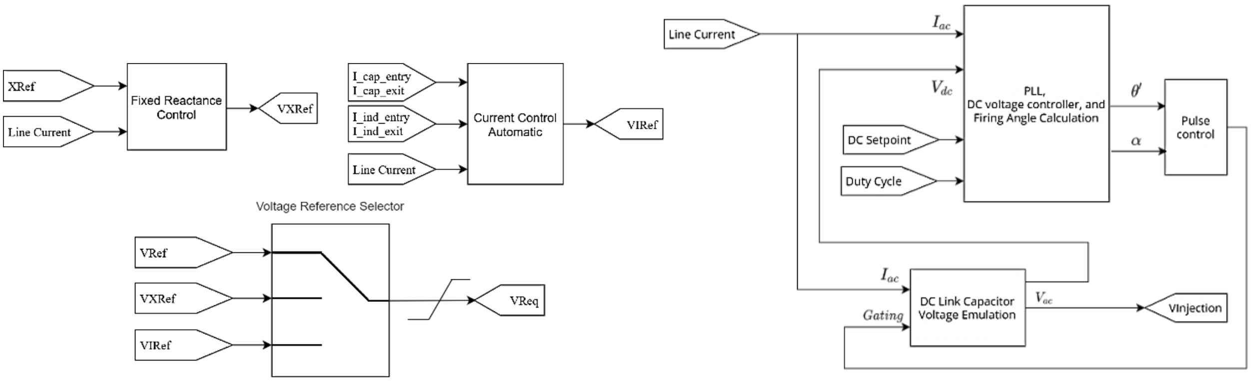
1. Overcurrent (OC) Protection: If any phase current is greater than a pre-programmed level indicative of a fault, the fast-acting bypass will be triggered.
2. Power Electronic Converter Protection: The line fault may cause certain internal operational limits of the converters to be exceeded. This will also trigger the bypass in 1 ms or less after fault detection.
3. When the current exceeds the Overload threshold and does not reach the Overcurrent Protection threshold the M-SSSC will bypass after 2 s. After the current has dropped below the Overload threshold the M-SSSC can begin injecting again.

Note that the M-SSSC device is a single-phase device and minor disturbances on a single phase do not affect all three phases (e.g. a brief PLL unlock). Nevertheless, to minimize an unbalanced behavior during large disturbances (e.g. asymmetrical faults) a "pseudo three-phase" feature is implemented for the overall deployment. The feature enables the communication between devices on all phases to ensure *all* devices will ultimately bypass when protection is triggered on one or two phases only. This feature is called Inter-Phase Balancing (IPB). Any form of undesired balance in voltage injection that can lead to unsymmetric current flows can be avoided by the IPB feature.

One factor that generates uncertainty among utilities and system operators is the impact M-SSSC may have in the coordination of the electrical protections in the transmission lines, since the M-SSSC can modify the line's effective reactance, which raises concerns about potential impacts on the behavior of the distance protections of the transmission lines during faults. To avoid this, the M-SSSC is equipped with a feature that allows transiently interrupting the series injection when a current transient whose is lower than Overcurrent Protection Threshold occurs. This feature is called Low Overcurrent Ride-Through (LOR). If the peak transient current is below the OC protection threshold, and above a LOR threshold, the M-SSSC will halt its injection via the SCRs in less than 1 ms, so the line distance protection will not "see" the M-SSSC on the line during the transient.

3.4 M-SSSC control system

The setpoint calculation depending on the selected control mode is depicted in Fig. 5-(a). If the Fixed Reactance mode is selected, the Voltage setpoint *VXRef* is calculated as the product of the measured RMS line current and the reactance setpoint *XRef*. If the Current Control Automatic Mode is selected, depending on the measured RMS current and the entry and exit thresholds for capacitive or inductive injection, a required voltage injection *VIRef* will be calculated by using a droop control. On the other hand, if the Fixed Voltage Mode is selected, that value is considered directly in the Voltage Reference Selector. In that block, the voltage setpoint is calculated and limited depending on the M-SSSC constructive limits. The *VReq* is then obtained.



(a) (b)

Fig. 5: (a) Setpoint calculation based on selected control mode. (b) M-SSSC VSC EMT model diagram

Once the AC setpoint voltage is determined, the M-SSSC control system will determine the VSC pulses to generate and inject the required series voltage. The VSC control system diagram is depicted in Fig. 5-(b). As

stated in section 3.1, to achieve the voltage injection, current transformers are used for power harvesting and current sensing, and a Phase-Locked Loop (PLL) controller monitors the phase of the line current.
Furthermore, the DC link capacitor voltage controller calculates the necessary phase shift to charge or discharge the DC link in order to maintain or change the DC link's voltage level. In theory, during steady state an ideal M-SSSC is not exchanging active power with the network over the duration of an electrical cycle, provided that the injected voltage is in quadrature with the line current. In order to change the setpoint or during transients the phase of the injected voltage must be shifted to be slightly off the ideal quadrature shift with the line current to change or maintain the DC link's voltage level. Any phase deviation of the injected voltage in quadrature to the line current leads to an exchange of energy, charging or discharging the DC link. The DC link controller in combination with the PLL guarantee the dynamic performance of the M-SSSC. In the DC link voltage controller, the expected voltage waveform, based on the DC voltage setpoint, is compared with the measured DC link voltage of the VSC. Based on the DC link voltage deviation, the phase shift is calculated and used by the pulse control in combination with the duty cycle to determine the Pulse-Width Modulation (PWM) for the respective VSC, driving the gates of the H-bridge.
Additionally, the control system supports transient handling through temporal contraction of duty cycles. The set of DC link voltage setpoints and duty cycles are optimized to map the stacked voltage impulses to the ideal sinusoidal waveform to minimize harmonic emissions and increase injection accuracy. Since the line current in combination with the DC capacitance describe the change in DC link voltage, the frequency and number of VSC determine the width of each of the stacked voltage impulses, then an interleaving algorithm in combination with a command distribution algorithm is deployed to determine the optimized PWM settings for the deployment based on power system conditions and M-SSSC configuration.

4 EMT SIMULATIONS

In this chapter, the simulations results shown are generated by the model explained previously. The results of these simulations are presented in a real-time digital simulator platform through the model-in-the-loop methodology. The overcurrent threshold setting was configured to 3800 A_{peak}.

4.1 Setpoint change

Fig. 6 shows the response of the M-SSSC with an injection capabilty of 5660 V_{rms} when the setpoint is changed from 50% (2830 V_{rms}) to 100 % (5660 V_{rms}) inductive injection. A ramp of change of DC link voltage can be configured in the model by the user in order to meet the required response of the injected voltage. The converter duty cycles and DC voltage setpoint change to reach the new setpoint established by the setpoint calculator depicted in Fig. 5.

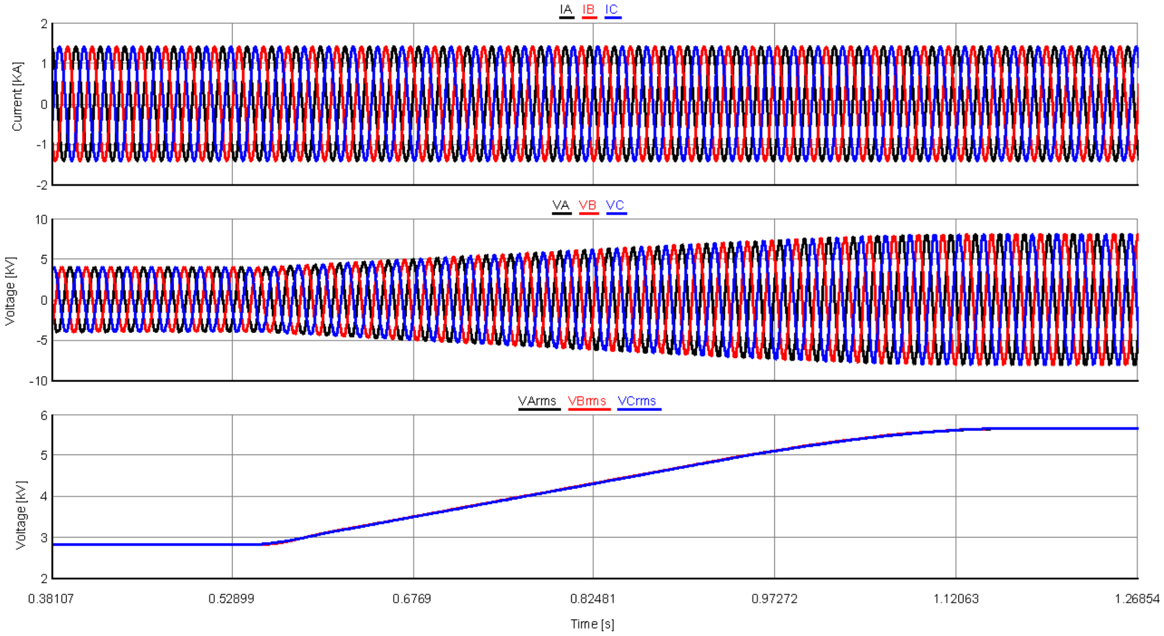


Fig. 6: Setpoint change. Top: Line current, Middle: M-SSSC three-phase voltage injection, Bottom: RMS voltage injection

4.2 Change in line current magnitude

In the case showed in Fig. 7, the M-SSSC is injecting in Fixed Reactance mode, with a 5.6 Ω setpoint. There is a sudden change in the current magnitude from 1000 A_{rms} to 500 A_{rms} caused by a load switching external event. The effective reactance caused by the injected voltage for the respective line current in Fig. 7 shows a step-change after the line current drops. In order to keep the setpoint of 5.6 Ω, the injected voltage ramps down from 5.6 kV to 2.8 kV. After 700 ms approximately, the effective reactance reaches back the setpoint of 5.6 Ω.

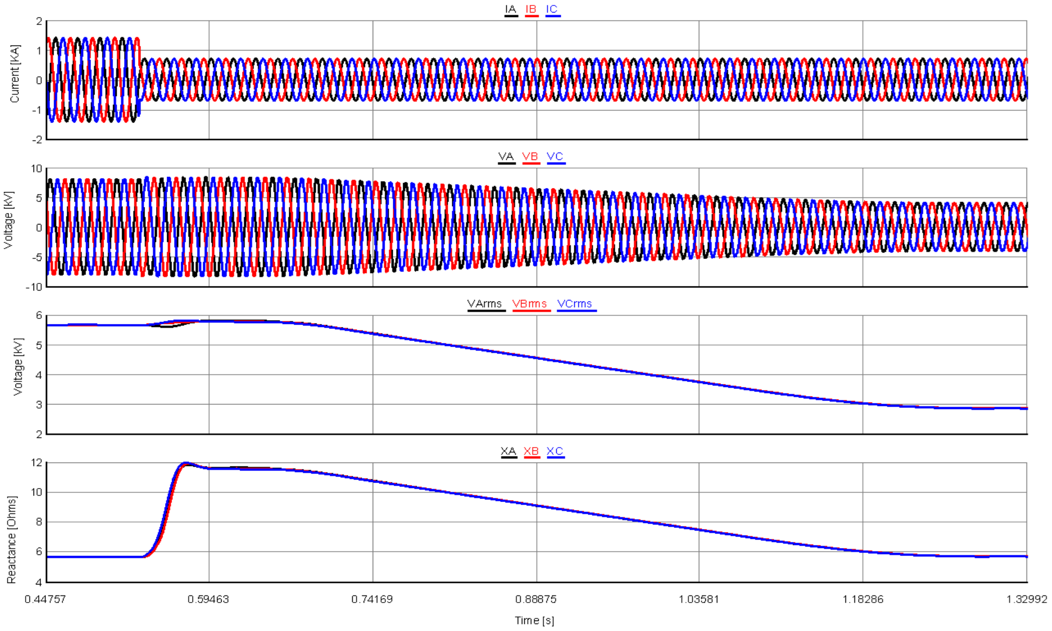


Fig. 7: Current change. Top: Line current, Middle: M-SSSC three-phase voltage injection and RMS voltage injection, Bottom: Equivalent injected reactance

4.3 Line current phase shift

At t=0.5 s, a 10-degrees phase shift was applied in the three-phase line current while the M-SSSC was injecting an inductive reactance with fixed voltage mode, and a setpoint of 100% (5660 V_{rms}), as shown in Fig. 8. The current phase shift causes the voltage injection to shift by 80 degrees which consequently leads to an initial charge of the DC link voltages. The PLL needs to keep track of the line current phase while the duty cycles are contracted for approximately 100 ms to maintain the DC link voltage within its operational voltage range. Due to the duty cycles contraction, the RMS voltage injection is reduced, but it recovers after 200 ms.

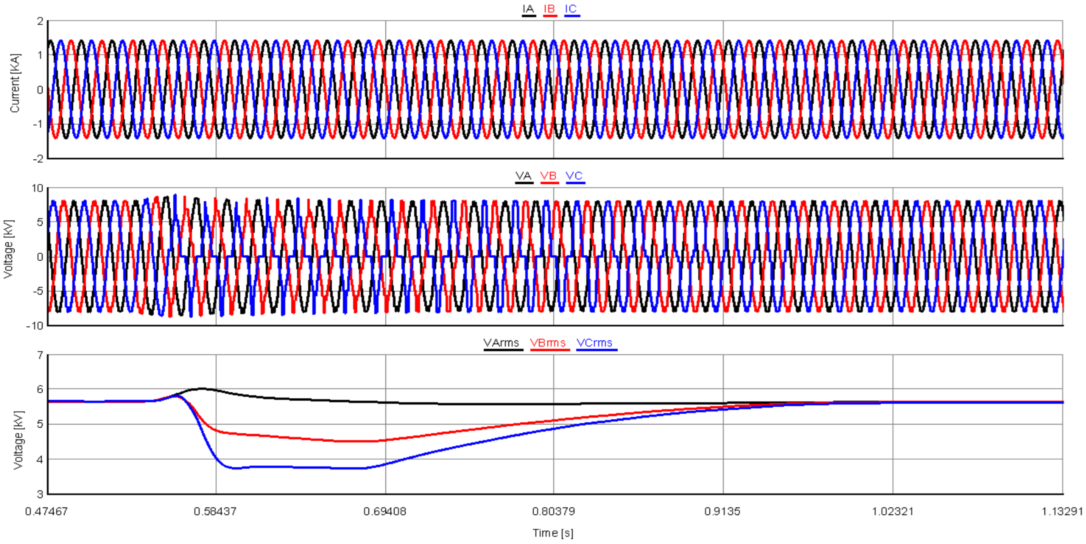


Fig. 8: Phase shift. Top: Line current, Middle: M-SSSC three-phase voltage injection, Bottom: RMS voltage injection

4.4 Overcurrent protection

A system disturbance results in an increase of line current in phase A. As shown in Fig. 9, the instantaneous line current exceeds the set Overcurrent threshold of 3800 A Peak which triggers the phase overcurrent protection. After the occurrence of the fault, it takes approximately 0.1 ms for the current to exceed the Overcurrent threshold. After approximately 600 µs, the fault is detected, and the bypass is triggered following the first samples of the overcurrent measurement. Phase B and C continue with their voltage injection until the state of phase A is communicated using the IPB feature. After the healthy phases receive the command to transition to Monitoring mode, they stop injecting immediately to minimize the unbalance on the circuit.

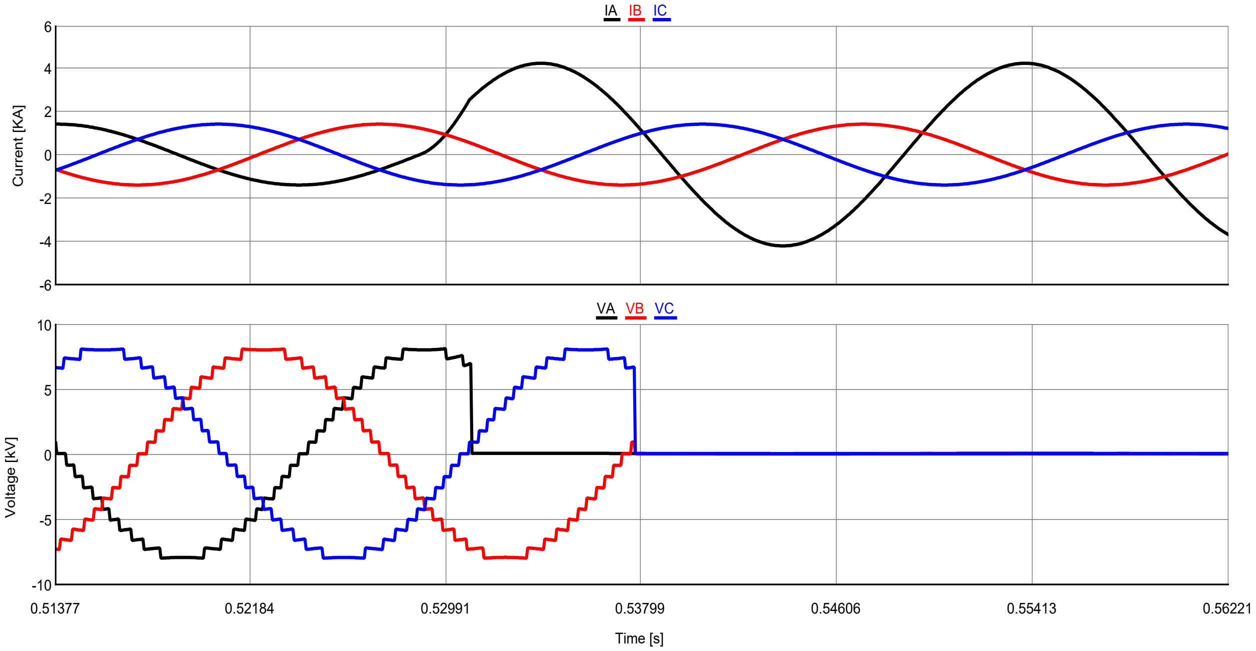


Fig. 9: Overcurrent protection. Top: Line current, Bottom: M-SSSC three-phase voltage injection

5 CONCLUSIONS

The M-SSSC model presented and described in this paper is applicable to offline and real-time simulations. EMT simulations like current phase shift, switching event that causes line current magnitude change, short-circuit and setpoint change are presented to demonstrate the M-SSSC model's dynamic performance. The results of these simulations are presented in a real-time digital simulator through the model-in-the-loop methodology.

This paper provides information on the technical benefits of M-SSSC technology and its ability to dynamically modify the effective reactance of a line to make it electrically shorter or longer and to support system operators to overcome today's and future challenges.

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