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Software-in-the-Loop Testing of SSSC with Type-1 Controller Connected to SMIB

S. Venkateswarlu[1] *and M. Janaki*[2]
[1]Research Scholar, School of Electrical Engineering, Vellore Institute of Technology, Vellore (Tamil Nadu), India.
[2]Associate Professor, School of Electrical Engineering, Vellore Institute of Technology, Vellore (Tamil Nadu), India.

(Corresponding author: M. Janaki)
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ABSTRACT: This paper presents a Software-In-the-Loop (SIL) simulation of the Single Machine Connected to Infinite bus (SMIB) with Static Synchronous Series Capacitor (SSSC).The linearized model of SMIB with SSSC is developed in MATLAB/Simulink using the differential and algebraic equations of the system. The controller for SSSC is modeled in typhoon HIL 402, a Real-Time (RT) emulator. The Real-Time Interface (RTI) of dSPACE is used to implement the Input/output (I/O) capabilities to the Simulink model. Subsequently, the model of SMIB with SSSC in MATLAB/Simulink is interfaced to typhoon HIL 402 through dSPACE. The performance of the type-1 controller is tested for step change in the mechanical input torque and reactive voltage reference. The results of SIL testing with two digital platforms show excellent transient response under different operating conditions.

Keywords: Static synchronous series capacitor, Typhoon HIL, dSPACE Simulator, real-time simulation, Software-in-the-Loop.

I. INTRODUCTION

The series compensation using capacitors is an economic solution to improve the power transfer capability of a long transmission line. The hybrid series compensation can be done with fixed series capacitor and active FACTS devices such as TCSC and SSSC etc. The TCSC is the first generation FACTS device, whereas the SSSC is the second generation FACTS device. SSSC has several advantages than the TCSC. The SSSC can be used control the active power flow in the line and its degree of the freedom control is one [1, 2]. Several papers exists in the literature on the investigations of power system with SSSC, which are reported in [3, 5]. The linear model of SMIB system using dynamic simulator is presented in [6], which is used to simulate the synchronous power plant in real time.

The off-line simulations used within the early phases of the development process are often referred to as model-in-the-loop simulations (MIL). At the MIL stage, standard tools such as MATLAB/Simulink can be used. The next step is software-in-the-loop (SIL) simulation, where the functional model is replaced by C-code and coding errors can be found independent of the future hardware [7]. Wang *et al.,* presents hardware-in-the-loop (HIL) validation of microgrid using real time simulator. Such an approach is suitable for testing the system-level controller energy management systems and hardware controllers at signal level, as well as hardware devices like power converters at power level [8]. A novel real-time laboratory capable of rapidly validating UPFC controls and placements are presented in [9]. The advantages of the developed real time hardware/software loop (RTHSL) are: large-scale real-time simulation, ability to rapidly to test UPFC control interactions and placements, ability for both manual and automated (DSP-based) control. The Controller Hardware-in-Loop (CHIL) Simulation of a multi-machine system using RTS is presented in [10].

In order to ensure the robust and satisfactory performance of controller as close to clock time of physical system, the Software-In-the-Loop (SIL) testing can make it possible to test software prior to the initialization of the hardware prototyping phase. At the same time significantly accelerates the development cycle.SIL testing enables the design of robust controller in order to get superior performance under various operating conditions [6-17].

The main objective of this paper is to design and test the type-1 controller of the SSSC in typhoon HIL 402. The Real-Time (RT) emulator, Typhoon HIL, is used for verification of SSSC control system in Software-In-the-Loop (SIL) simulation. The performance of SSSC type-1 controller connected in SMIB is verified with SIL simulation through dSPACE. The performance of power system with SSSC under different operating and transient conditions is validated in SIL testing. The results shows excellent transient response to a step change in the mechanical input torque and reactive voltage reference.

The sections of this paper are organized as follows: The Section II reports the system description with SSSC type-1 controller. SIL setup with typhoon HIL 402 and dSPACE is explained in Section III. The results and discussion are presented in Section IV. At last, the conclusions are presented in Section V.

II. SYSTEM DESCRIPOTION

The following subsections present a brief overview about the system diagram, Type-1 controller of SSSC, initial conditions and the operating points at which the analysis is performed.

A. system diagram

In this work, we considered the modified IEEE FBM with the inclusion of SSSC. The system diagram represented in Fig. 1 comprises single-mass turbine-generator and long transmission line incorporated with SSSC. From [1], the knowledge and information of the electromechanical system's model are referred.

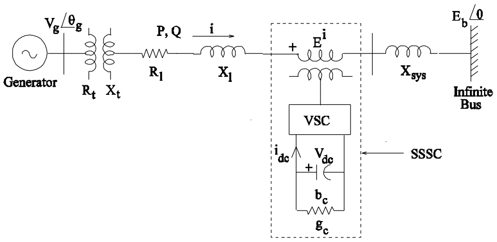

Fig. 1. Modified IEEE FBM with inclusion of SSSC.

B. Type-1 controller of SSSC

The schematic representation of the type-1 controller for SSSC is shown in Fig. 2 [3]. The magnitude and phase angle (δ) of the converteroutput voltage are varied with type-1 controller.By varying dead angle (β_{se}) the modulation index can bevaried, and hence the magnitude of the converter output voltage is controlled. The dc-link voltage V_{dc} is maintained by controlling the phase angle γ. From the dc voltage controller, the real voltage reference $E_{P(se)(ref)}$ is obtained, whereas the reactive voltage reference $E_{R(se)(ref)}$is kept constant.

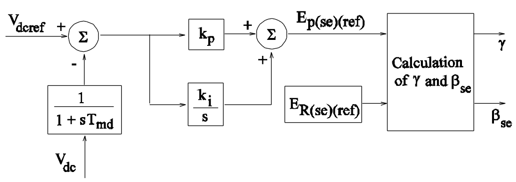

Fig. 2. Type-1 controller of SSSC [2, 11].

In Fig. 2, the phase angle γ and dead angle β_{se} are calculated from the reference values of $E_{P(se)(ref)}$ and $E_{R(se)(ref)}$and are given as

$$\gamma = tan^{-1}\left[\frac{E_{R(se)(ref)}}{E_{P(se)(ref)}}\right] \quad (1)$$

$$\beta_{se} = cos^{-1}\left[\frac{\sqrt{E^2_{P(se)(ref)} + E^2_{R(se)(ref)}}}{p\rho V_{dc}}\right] \quad (2)$$

C. Operating points and assumptions

The initial operating points and assumptions which are used in the analysis are given below.

(1) The power output of the generator is set to be 0.9 p.u.

(2) The mechanical power input of the generator is assumed to be constant.

(3) SSSC compensation, X_{sssc} = -0.2 p.u.

III. SOFTWARE-IN-THE-LOOP SETUP

The Digital Real-Time Simulation (DRTS) is mainly classified into two types, namely:1) Fully Digital RTS, and 2) Hardware-In-Loop RTS. Examples of fully DRTS are: model-in-the-loop (MIL) and Software-in-the-loop (SIL),or processor-in-the-loop (PIL)) [12, 13]. A completely DRTS requires the whole framework (counting control, security, and other accomplices)to be displayed inside the test system and does not include outer interfacing I/O's. The HIL simulation is a method that is utilized in the improvement and test of complex RT systems.

The SIL simulation includes two RT simulators interconnected by hardware. In one of the RT simulator, MATLAB/Simulink model of the system is run. And, in another RT simulator, the controller is modeled. The block diagram of SIL simulation is shown in Fig. 3.

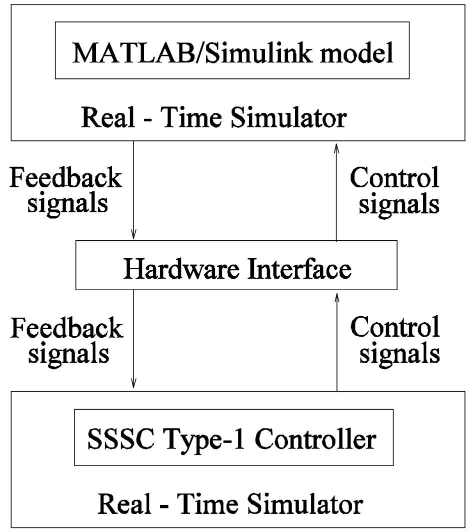

Fig. 3. Block diagram of SIL simulation.

In the following subsections, we present the two digital platforms and their interconnection for SIL testing.

A. MATLAB/Simulink model in dSPACE RTI

The dSPACE started its journey in the year of 1988 in Paderborn, Germany and it is a HIL based RTS [8, 14]. The pictorial representation of real time interface between MATLAB and dSPACE is shown in Fig. 4.

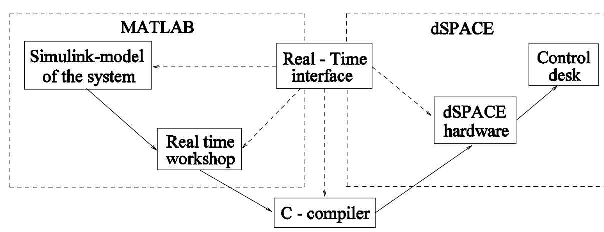

Fig. 4. MATLAB-dSPACE interface [14, 15].

In MATLAB-Simulink, we model the power system as shown in Fig. 4. The model is developed in MATLAB-Simulink using the differential and algebraic equations of the system. The Simulink model is then compiled to C in dSPACE with the help of Real - Time Workshop (RTW).It is an extension of MATLAB-Simulink where the packages are generated in-built and the code is compiled in order to create real time software applications on various systems.

In this work, the dSPACE is used with a MicroLabBox R & D controller board. The picture of MicroLabBox is shown in Fig. 5. The MicroLab Box is an across the board improvement framework for the research center that joins conservative size and low framework costs with superior operation and flexibility.

RTI library is the platform where the I/O connections for the real system is been added to the Simulink model. RTI has the control over every variable after the implementation. The real simulation is performed on DSP where the C code is inscribed. At the time of experimentation, the simulation can be meticulously controlled from our personal computer using the control desk program software and graphical using interface for smooth transition at the time of implementation from off line to real time.

Once the model has undergone testing, then it's replaced by the I/O blocks from RTI library. Rapid design iterations are achieved by the implementing the Simulink model on dSPACE hardware. By varying the input signals, we can have a better understanding about the performance of the model when it's subjected to larger disturbances. In order to monitor the signals and alter the parameters a virtual instrument panel is enabled at the control desk.

Fig. 5. MicroLabBox, top panel variant.

B. Typhoon-HIL Simulator

The typhoon HIL Inc. has started its journey in the year of 2008 as a real-time simulator for different fields like, Micro grid, power electronics etc. [17]. The typhoon HIL has its own built-in libraries which makes its more user-friendly. This reduces the complexity of using the third party software. The typhoon HIL simulator comes in three different configurations for hardware setup. Those are namely; HIL 4 series, HIL 6 series and M series. Here, the HIL 4 series is consist two types of setups, namely: HIL 402 and HIL 404. The HIL 402 is the first note book size HIL system in industries. Similarly, the HIL 6 series is also consist five types of setups, namely; 600, 602, 602+, 603 and 604. The configuration details of HIL 402 is shown in Table 1.

Table 1: HIL 402 configuration details.

Name	HIL 402
Processor	4 cores
Channels	16 × Analog inputs (AI)
	16 × Analog outputs (AO)
	32 × Digital inputs (DI)
	32 × Digital outputs (DO)
Resolution	16 bit
Analog IO voltage range	±10 V
Built-in scope	Yes
Compatibility	HIL dSPACE Interface
Software	HIL Control Center

The typhoon HIL includes the schematic editor, HIL SCADA, test suite and power system tool box.

C. Experimental setup of SIL simulation

The picture of experimental setup developed in the laboratory for SIL including MATLAB-dSPACE, MicroLabbox and typhoon HIL simulator is shown in Fig. 6.

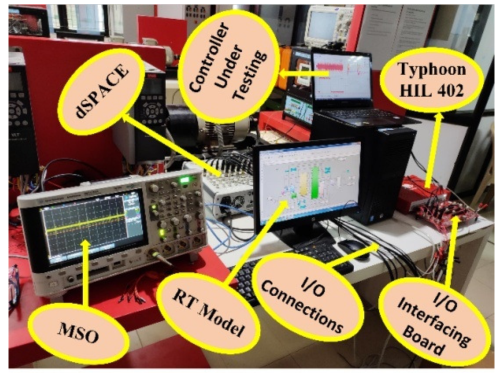

Fig. 6. Experimental setup of SIL simulation.

IV. RESULTS AND DISCUSSION

This section presents the transient response of real power, reactive power, terminal voltage, rotor angle, dc voltage, reactive voltage and real voltage for the step change in input mechanical torque (T_m) and the reactive voltage (V_{Rref}) reference.

A. Step change in input mechanical torque (T_m)

In order to see the transient response, a step change of 40% reduction in mechanical torque is applied and removed at 1 sec and 5 sec respectively. The step change in mechanical input torque T_m is shown in Fig. 7. When a change in input mechanical torque occurs, there will be a corresponding change in active and reactive powers supplied by the generator.

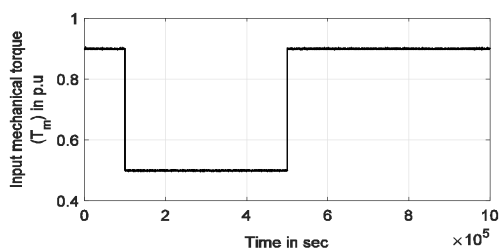

Fig. 7. Step decrease in input mechanical torque T_m.

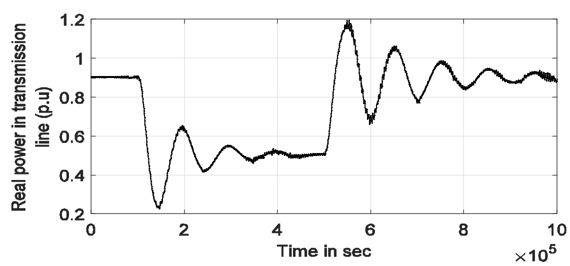

Fig. 8. Response of real power in transmission line for the step change in T_m.

The response of real power and reactive power supplied by the generator are shown in Fig. 8 and 9 respectively. From Fig. 8 and 9, we observe that, the active power and reactive supplied by the generator reduce when the input mechanical torque is reduced.

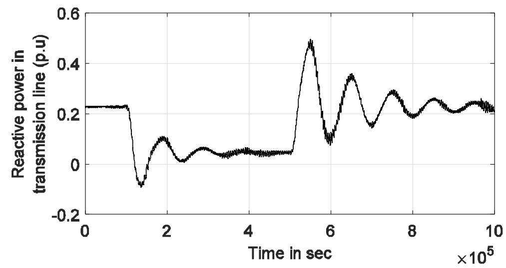

Fig. 9. Response of reactive power in transmission line for the step change in T_m.

From Fig. 9, it is to be observed that, the magnitude of terminal voltage is maintained at the reference value. It is done by the Automatic Voltage Regulator of the generator.

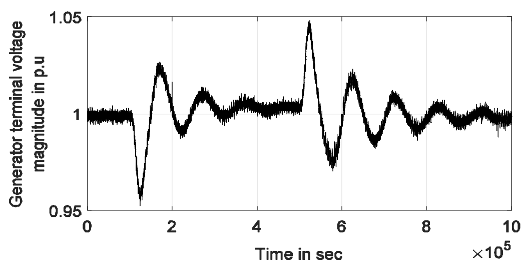

Fig. 10. Response of generator terminal voltage magnitude (V_g) for the step change in T_m.

The response of real power, reactive power, terminal voltage (V_g) and rotor angle (δ) for the step change in T_m are plotted in Figs. 8, 9, 10 and 11, respectively. From Figs. 8, 9, 10 and 11 we observe that, the oscillatory response reduces with increasing the time and reaches steady state value.

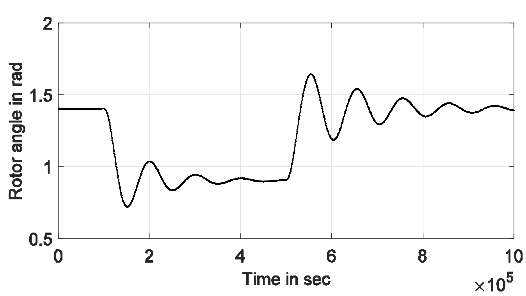

Fig. 11. Response of rotor angle (δ) for the step change in T_m.

The reactive voltage and real voltage for the step change in T_m is plotted in Figs. 12 and 13 respectively.

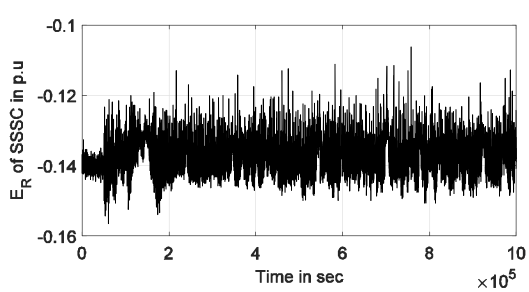

Fig. 12. Response of reactive voltage of SSSC for the step change in T_m.

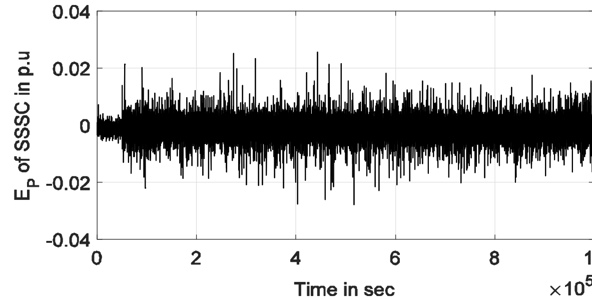

Fig. 13. Response of real voltage of SSSC for the step change in T_m.

The response of the dc voltage (V_{dc}) measured in Mixed Signal Oscilloscope (MSO) is shown in Fig. 14. From Fig. 14, it is evident that, the dc voltage is maintained at the reference value by dc voltage controller. This shows the satisfactory performance of dc voltage controller.

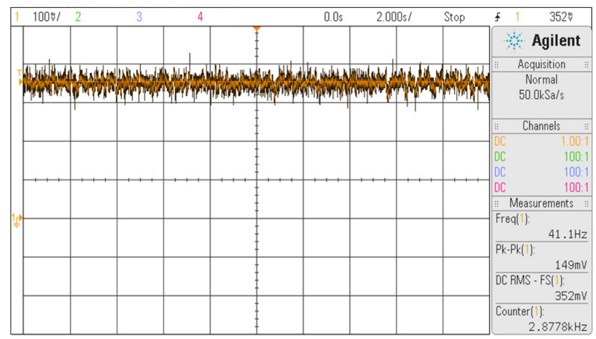

Fig. 14. Response of dc voltage (V_{dc})for the step change in T_m.

From Figs. 12, 13 and 14 we observe that, the value of the reactive voltage, real voltage and dc voltage is oscillating around the constant value as time progresses.

B. Step change in reference value of reactive voltage (V_{Rref})

The step change of 40% reduction in reference value of reactive voltage applied and removed at 1 sec and 5 sec respectively. The response of the real power, reactive power, terminal voltage and rotor angle for the step change in V_{Rref} are plotted in Figs. 15, 16, 17 and 18.

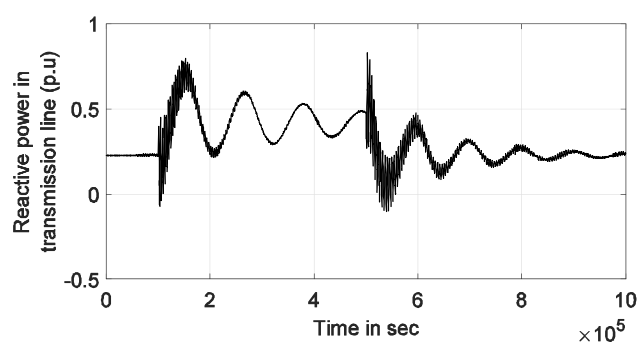

Fig. 15. Response of reactive power in transmission line for the step change in V_{Rref}.

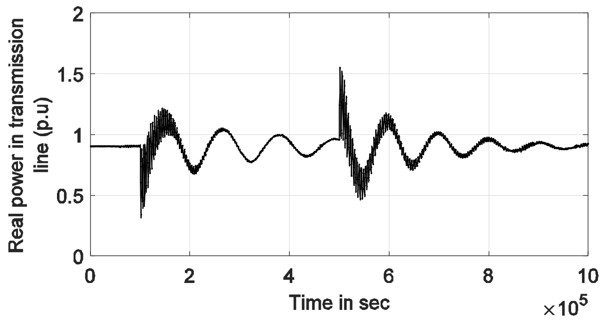

Fig. 16. Response of real power in transmission line for the step change in V_{Rref}.

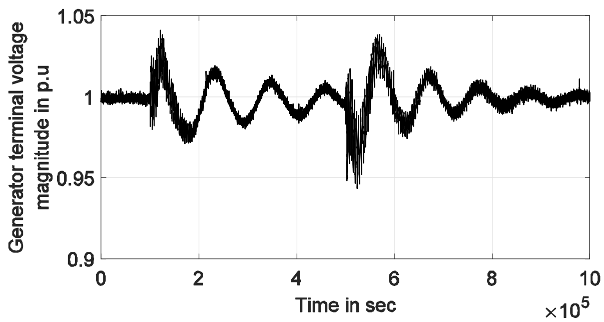

Fig. 17. Response of generator terminal voltage magnitude (V_g) for the step change in V_{Rref}.

From Figs. 15, 16, 17 and 18, we observe that the oscillatory response reduces with increase in the time and the oscillatory response reaches steady state value as progresses.

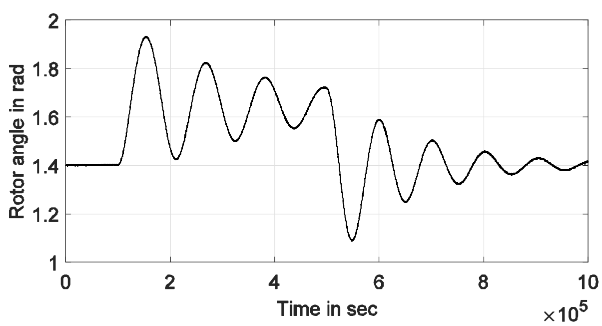

Fig. 18. Response of rotor angle for the step change in V_{Rref}.

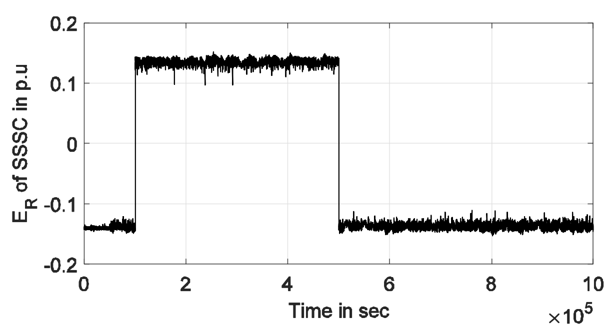

Fig. 19. Response of reactive voltage of SSSC for the step change in V_{Rref}.

The response of reactive and real voltage for the step change in V_{Rref} is plotted in Fig. 19 and 20. From Fig. 19 and 20, we observe that, the value of the reactive voltage and real voltage is oscillating around the steady state value as time progresses.

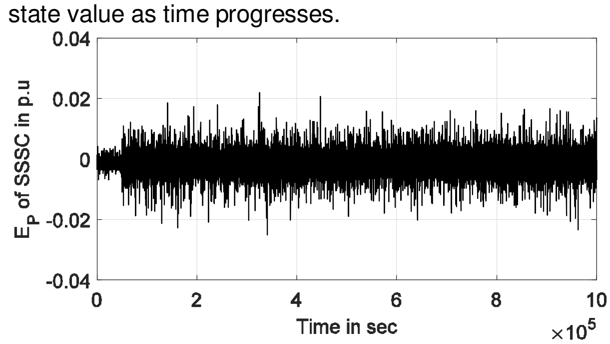

Fig. 20. Response of real voltage of SSSC for the step change in V_{Rref}.

C. Discussion

We presented the Software-in-the-Loop (SIL) simulation of the single machine connected to infinite bus (SMIB) with SSSC. Subsequently, we design and test the type-1 controller of the SSSC in typhoon HIL 402. The performance of the type-1 controller of the SSSC is verified with RT model based on SIL simulation through dSPACE.

From the results, it is clear that the SIL testing with two digital platforms show excellent transient response for the step change in input mechanical torque (T_m) and the reactive voltage (V_{Rref}) reference under different operating conditions.

V. CONCLUSION

In this paper, we design and test the type-1 controller of SSSC in software-in-the-loop simulation. The SIL testing is performed with typhoon HIL and dSPACE. We developed the model in MATLAB-Simulink using the differential and algebraic equations of the SMIB with SSSC. The performance of the type-1controller of SSSC is verified with RT model based on SIL simulation through dSPACE. The results shows excellent transient response to step change in the mechanical input torque and reactive voltage reference.

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