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Real-Time Testing of STATCOM and SVC Controllers

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SUMMARY

Hardware-in-the-loop is utilized to individually simulate a static var compensator (SVC) controller and static synchronous compensator (STATCOM) controller with a real-time digital simulator (RTDS) simulation software and processor. Operational and dynamic performances of each controller are tested and meet the criteria from vendor reports. A simplified equivalent system model of Dominion Energy's power system is used to investigate the interaction between these two devices. Recovery-time analysis is performed by applying several faults at a variety of locations in the reduced system to test the devices' combined performance. The recovery times at all buses in the equivalent system are reduced when both devices are present and operational; no negative interactions are found between the SVC and STATCOM when in close proximity.

KEYWORDS

STATCOM, SVC, RTDS, Power electronics, HIL, FACTS.

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I. PROJECT INTRODUCTION

As coal generators and power plants are becoming obsolete and are being retired, renewable energy sources, such as wind turbines and solar panels, are being installed to provide a cleaner form of generation. However, this variation, in turn, changes the available power on the grid constantly and calls for a form of voltage regulation. To address this problem, flexible alternating current transmission system (FACTS) devices are being installed across the grid. These devices utilize power electronics to quickly respond to changes in the grid and regulate voltage on transmission lines in addition to providing stability control. Two such devices which will be discussed in this paper are the static var compensator (SVC) and static synchronous compensator (STATCOM). These shunt devices control reactive power injected at a bus to regulate voltage and increase system stability. However, as vendors do not provide detailed dynamic models, the devices are black boxes for power system dynamic analysis. Additionally, the interaction of multiple FACTS devices in close proximity must be investigated as there are possible consequences which come with having these devices near one another. Such consequences can include harmonics and system stability; however, the study of [1-3] uses simulation models for FACTS devices which may not be 100% accurate.

The Real-Time Digital Simulator (RTDS) is a powerful tool that can perform hardware-in-loop (HIL) simulations. It is possible for utilities to test the FACTS controllers and validate the static and dynamic behaviours of the power electronics devices. This paper describes how the hardware of the SVC and STATCOM controllers are being tested individually for functionality studies and together for interaction studies using RTDS software and hardware. The tested controllers are the same as those operated onsite. Two types of tests are performed: functional performance tests and dynamic performance tests. For the former, the grid is modelled as a simple three phase voltage source with impedance. For the latter, a reduced equivalent model of an urban section of the grid is used where the devices are connected at different, but neighbouring, buses.

This paper is organized as follows: section II introduces the RTDS software and hardware as well as the setup of HIL simulation. Section III discusses the SVC controller being tested and the test results. Section IV is about the STATCOM topology and RTDS test results. Section V is the interaction study of the SVC and the STATCOM. Section VI is the conclusion.

II. RTDS INTRODUCTION

RTDS is a multiprocessor system that is optimized to perform power system simulations in real-time with a time step as small as 1.4 µs, which is small enough to capture the dynamics of power electronics devices. In addition, RTDS has numerous dedicated, high-speed digital and analogue I/O interfaces. Figure 1 is the general I/O between the RTDS software (RSCAD) and the controllers of the SVC and STATCOM for HIL simulation. RSCAD downloads the model to the RTDS hardware; the voltage and current measurements are passed to the controllers via digital to analogue cards. The controllers, in turn, passes the converter states and breaker statuses to the circuit model through analogue to digital cards and front-panel interface cards, respectively, which are used by the model to set the statuses of various components.

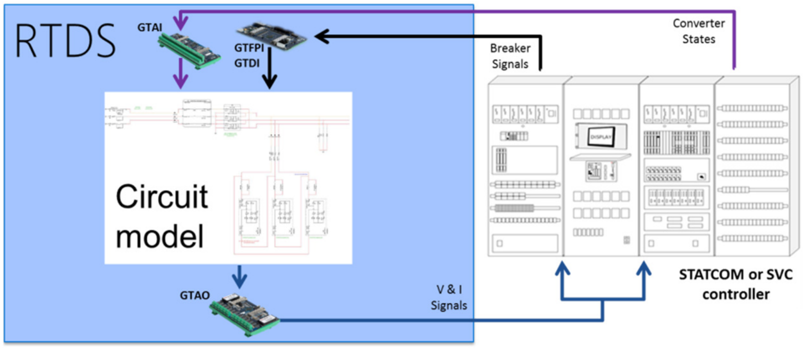
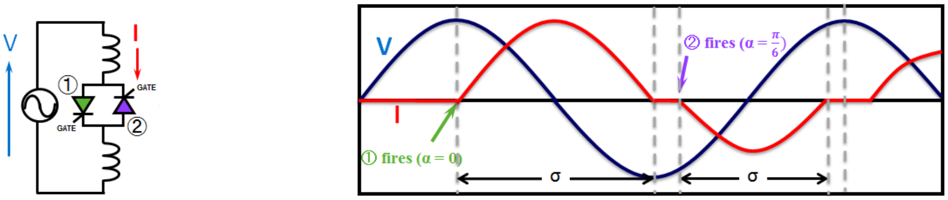


Fig. 1: RTDS I/O for testing controllers via HIL.

III. SVC

The SVC is a shunt FACTS device which utilizes power electronics, specifically thyristors, to regulate transmission voltage through the injection and absorption of reactive power. The two main components of Dominion Energy's SVC are the thyristor-controlled reactor (TCR) (-200 Mvar ~ 0 Mvar) and thyristor-switched capacitor (TSC) (0 or +200 Mvar). A simple TCR, as shown in Figure 2a, is composed of a reactor, a bidirectional thyristor valve, and a surge current-limiting reactor. The thyristor valve, and, subsequently, the current through the valve, is controlled by a firing angle delay, α. α is defined as the delay in which a gate pulse is provided to a thyristor to conduct current with respect to the peak of the voltage waveform during a half-cycle. By increasing or decreasing α, the current through the reactor can be decreased or increased, respectively. When the TCR is in full conducting mode, the SVC operates in full inductive mode; in other words, it is absorbing the maximum amount of reactive power. On the other hand, when the TCR is in full blocking mode, the SVC is not absorbing any reactive power. As a result, σ can be defined as the conduction angle, where $\sigma = \pi - 2\alpha$. The resulting waveform through the reactor when the firing angle delay is changed is shown in Figure 2b. At the current's zero-crossing, the thyristors will automatically block the current unless another gate signal is provided.



(a) (b)

Fig. 2: A simple TCR (a); voltage and resulting current waveforms as a result of firing angle delay (b).

A TSC works in a similar fashion, except that the angle delay for turn on is always set to α = 0. This is due to the fact that the capacitor must be switched in at specific times in an AC cycle to reduce transients [4]. Although the TSC does not produce any harmonics, the TCR does. For the TCR, balanced firing removes even harmonics, and its delta configuration removes triplen harmonics. For this reason, the TCR and 5th and 7th harmonic filter (+50 Mvar) must always operate in conjunction while the 3rd harmonic filter (+72 Mvar) is only switched in in cases of unbalanced operation.

The SVC's control strategy has three levels. At the top level, the SVC has two modes of operation: reactive power Q control (QC) and voltage control (VC). In QC, the SVC is controlled to produce a constant Q which is dependent on the SVC's high-side voltage, some constant, and reactive power reference value set by the user, as shown in Figure 3 by the red curve during steady state and blue curve in transient. In VC, the SVC's Q output is a function of the SVC's high-side voltage, some constant, and the voltage reference set by the user, as shown in Figure 3 by the blue curves. This level then passes a susceptance value to the next level: the susceptance control. At this level, the SVC's controls determine the necessary α to produce the required current, with the given applied voltage, to achieve the required Q. This α is then passed to the valve control, the third tier of the SVC's control strategy.

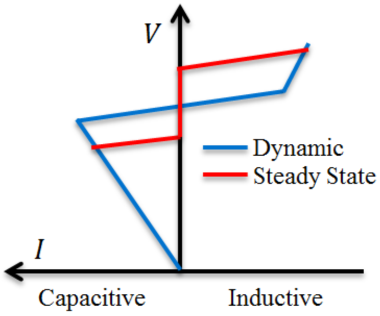


Fig. 3: V-I characteristic of the SVC

With these controls, it is now possible test the functionality of the SVC controller using HIL. Test procedures included start up and shut down sequences, protection sequences, voltage-current characteristics, and fault analysis. Figure 4 depicts the SVCs response to a change in bus voltage when in susceptance control mode. The user selects a reactive power reference of +50 Mvar. At t = 6 s, the voltage is ramped down from 1.02 to 1.00 per unit (pu) over 30 seconds. The SVC responds 12.8 ms after the ramping begins by increasing its reactive power injection in order to boost the voltage as it sees it is decreasing. Once the voltage ramping is complete, the SVC's reactive power output begins to return to the reference value of +50 Mvar.

Figure 5 shows the SVC's response to a line-to-ground fault applied close to the bus while in voltage-control mode. In this mode, a user sets a voltage reference point and the SVC will inject and remove reactive power to maintain its bus voltage near the reference point. At t = 0.05s, the fault is applied for four cycles and the voltage on the high-side bus is seen to drop. In response, the SVC injects reactive power in an attempt to boost the voltage back to 1 pu. When the fault is cleared at t = 0.1167 s, the SVC temporarily injects even more reactive power to quickly regulate the voltage back to 1 pu in order to reduce the recovery time of the system. The recovery time in Figure 5 is 7.2 ms.

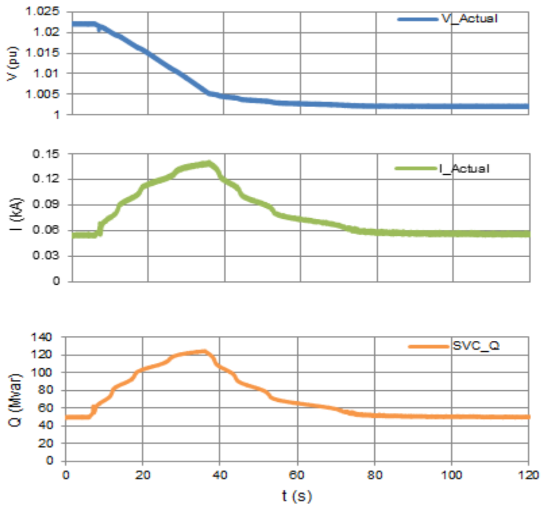


Fig. 4: SVC response under susceptance control.

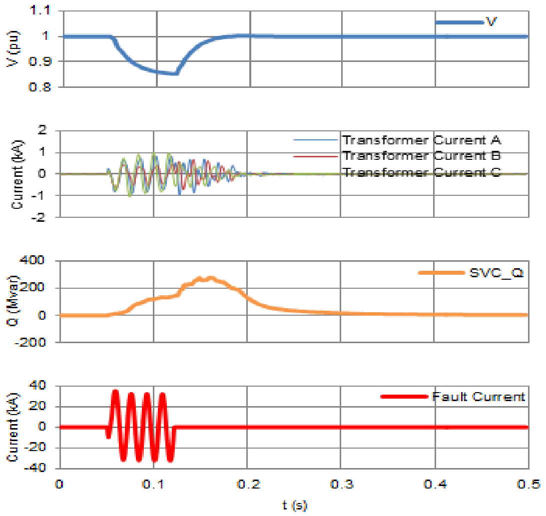


Fig. 5: SVC response under voltage control.

IV. STATCOM

STATCOM is short for static synchronous compensator, a regulating device that can act as either a source or sink of reactive power. Figure 6 shows the topology of the STATCOM being tested. The STATCOM is mainly composed of a DC/AC converter, an inductor as a filter, and a step up transformer. Compared to the light-triggered thyristors in the SVC that can only be turned on by control, the DC/AC converter switches in the STATCOM are insulated-gate bipolar transistors (IGBT) which can be turned on and off regardless of the current through the devices. In this way, the STATCOM converter is triggered by pulse width modulation (PWM) technology, which induces fewer harmonics compared to the SVC. Additionally, the multi-level converter topology of the STATCOM converter further reduces harmonics and filter size. The STATCOM's Q capacity is ± 125 Mvar, and the current limit is ± 1.5 kA in transient and ± 1.2 kA in steady state.

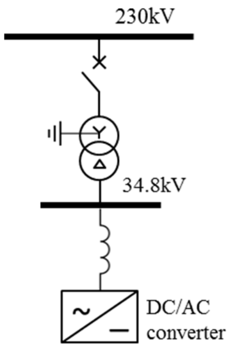


Fig. 6: Topology of the STATCOM.

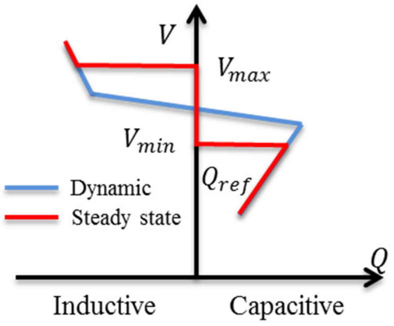


Fig.7: V-Q characteristic of the STATCOM.

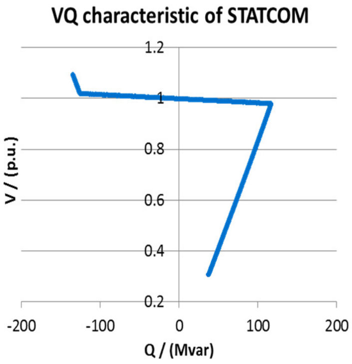


Fig. 8: V-Q curve in the functional test.

The control strategy of the STATCOM is also composed of three levels. The top level is the reactive power control which has two modes: Fixed Q mode (FQM) and Voltage Control mode (VCM). In FQM, the STATCOM is controlled to produce a constant Q, within the STATCOM's capacity. In VCM, the Q output is in terms of the STATCOM terminal voltage V, as shown in Figure 7 by the blue curve. If the steady state Q control is on in VCM, the V-Q characteristic is the blue curve in transient and the red curve in steady state, as shown in Figure 7. The top level then passes a current reference value to the second level of the current controller; the second level, in turn, passes a switch duty ratio and trigger time to lowest level of switch control which is used to control the IGBTs.

Using the HIL function of the RTDS mentioned in section II, tests can be performed on the real STATCOM controllers. These tests are categorized into two types: functional performance tests (FPT) for static behaviour and dynamic performance tests (DPT) for dynamic behaviour. Functional performance tests include, but are not limited, to

(1) Start up and down sequences
(2) V-Q characteristics
(3) Performance of the reactive power controller
(4) Performance of the stability controller
(5) Frequency variations
(6) Angle-step disturbance
(7) Output limitations
(8) Q control mode transfer
(9) Redundancy switchover

Figure 8 is the test result of the V-Q characteristic. The grid voltage is ramped down from 1.1 pu to 0.3 pu. If the voltage is above 1.02 pu or lower than 0.98 pu, the STATCOM produces maximum inductive or capacitive current; otherwise, the Q is a droop function of the V. Figure 9 is the test result of the Q control mode. At t = 4s, Q = 0 Mvar, as set in FQM mode. Then, the control mode is changed from FQM to VCM between t = 5s and t = 10s. After the transition, the controller perturbs the current reference by 200 A at the t = 12s and adjusts the gain of voltage controller.

Dynamic performance tests include load switching, faults, and external transformer energization. Figure 10 is the test result of a line-to-line fault close to the STATCOM. The fault is applied at *t1*. At *t2*, the STATCOM is blocked because of the L-L under-voltage. At *t3*, the fault is cleared and the STATCOM is unblocked and starts to boost up the voltage. The STATCOM aids in reducing the voltage recovery time.

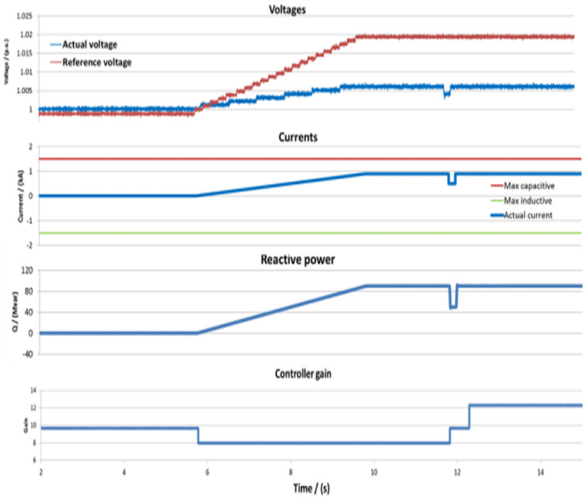


Fig. 9: Test results of Q mode transfer.

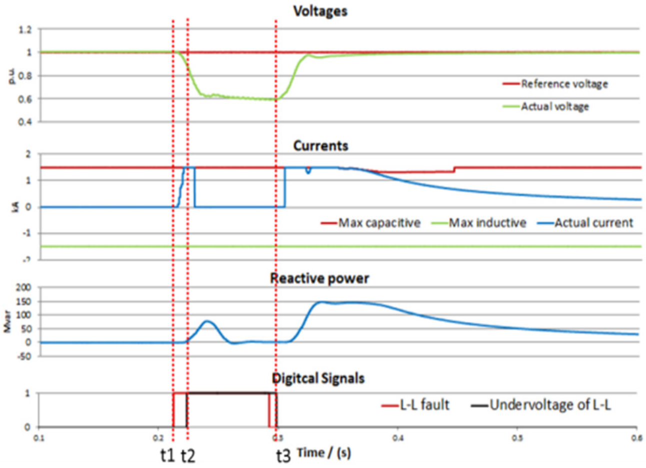


Fig. 10: Test results of line-to-line fault.

V. INTERACTION STUDIES

One of the main goals of this project is to analyse the interaction of the multiple FACTS devices when they are in close proximity. Figure 11 shows the one-line diagram for the interaction study of the SVC and STATCOM. The STATCOM is placed at bus 17 (230 kV) and the SVC is placed at bus 6 (500 kV); the STATCOM and SVC are physically in close proximity. The model in Figure 11 is downloaded to the RTDS and the real SVC and STATCOM controllers are connected to the RTDS using cables and I/O cards.

To test these devices' interactions, a single phase fault is applied at several locations in Figure 11 and the voltage recovery time of the fault bus is recorded for four cases in Figure 12: when there are no FACTS devices in operation (yellow), when only the STATCOM is operating (red), when only the SVC is operating (purple), and when both FACTS devices are operating (green). Figure 12 demonstrates that having both FACTS devices in operation has the smallest voltage recovery time compared to the three other cases. As can be seen, the SVC and STATCOM synergize during steady state and transient operation. Both can achieve their maximum and minimum Q injection and absorption. Additionally, no stability problems are observed during these studies.

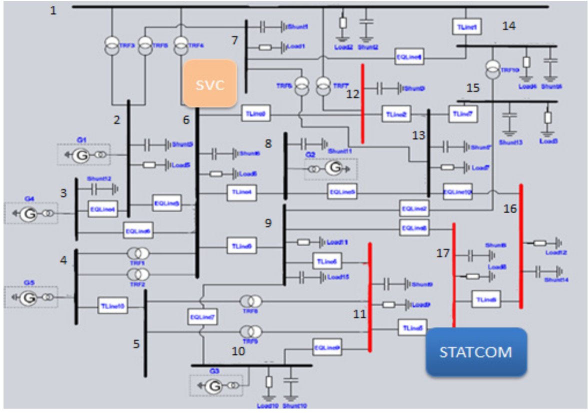


Fig. 11: One-line diagram of reduced system.

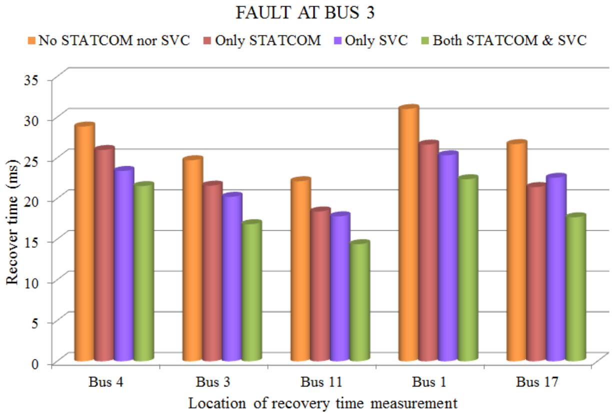


Fig. 12: Voltage recovery time at several buses.

VI. CONCLUSIONS

Individual simulations of the real SVC and STATCOM controllers are completed using the RTDS and its hardware-in-the-loop functionality. Operational and dynamic performances of the SVC and STATCOM are also tested and meet the criteria from vendor reports.

Using an equivalent system model of an urban area in Dominion Energy's grid, the HIL simulations that include both the STATCOM and SVC controllers from different vendors are successfully performed. No negative interactions are found between the SVC and STATCOM when they are in close proximity.

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