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Hardware-in-the-loop Tests on Reverse Power and Over-Frequency Protection for Synchronous Condensers

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SUMMARY

Modern power systems are undergoing the transition from synchronous-generator-based ones towards converter-based ones. This transition tends to reduce the system strength and impair the system voltage and frequency stability. Therefore, synchronous condensers (SCs) are drawing an increasing attention world-widely in recent years, as SCs are able to enhance the system strength, provide dynamic voltage regulation, and contribute inertia to the system. However, less attention has been given to the protection systems for SCs in the literature, especially when a synchronous condenser is equipped at the point of common coupling (PCC) of a HVDC station. Firstly, an SC needs to be protected against over-speed in the rotor under the island scenario of the HVDC station and the SC. Secondly, the protection should not trip the SC undesirably when the SC is supposed to remain connected (within its physical limit) and support the gird operation subject to grid-side disturbances.

This paper investigates the possible undesired trip of an SC by reverser power and over-frequency protection under a certain grid configuration through hardware-in-the-loop (HiL) tests. The tests have identified that, when there are two transmission lines emanating from the substation and the VSC-HVDC station is operating under inverter mode, the trip of the line that exports active power from the substation may lead to an undesired trip of the SC due to the power swing. Losing the support from the SC during such power swing conditions can result in the instability of the grid. Therefore, it is of great importance to have suitable settings for the reverse power and over-frequency protection for the SC. Besides the physical limits of the SC, the following conditions should also be considered for the case study: (1) How much active power the HVDC is importing prior to the line trip; (2) How much active power the other transmission line is importing to the substation prior to the line trip; (3) How fast the HVDC is able to switch to weak grid mode after the line trip; (4) What is the active power reference for the HVDC under weak grid mode; (5) The strength of the grid that the HVDC is connected to after the line trip. The investigation in this paper points out a specific scenario that should draw more attentions for an improved application of synchronous condensers. It provides insights for grid operators and engineers regarding the planning of power dispatches and the settings of generator relays for synchronous condensers.

KEYWORDS

Frequency, hardware-in-the-loop test, HVDC, low-inertia system, power swing, power system protection, reverse power, synchronous condenser, voltage source converter.

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INTRODUCTION

With the aim of being fossil-fuel independent in the energy sector, power systems are undergoing significant changes world-widely in terms of the generation mix. Conventional power systems are operating based on the physical properties of synchronous generators, which have rotational shafts and are strong natural voltage sources. They are able to provide inertia to the system to counter the frequency deviation, increase the system strength and contribute high amount of short circuit current. However, renewable energy sources typically interface with grids through power converters, whose operation is based on the presumption of having a 'strong grid'. They do not have physical inertia coupled with grids and have limited capability in terms of voltage regulation and short circuit power provision. Therefore, synchronous condensers, which are in principle synchronous machines without prime movers [1], are re-gaining popularity in recent years [2-3]. The studies in [4-7] have shown that SCs can help enhance system frequency response, contribute short circuit current, provide voltage and reactive power regulation through dynamic simulations. However, less attention has been given to the protection system of SCs in the existing literature.

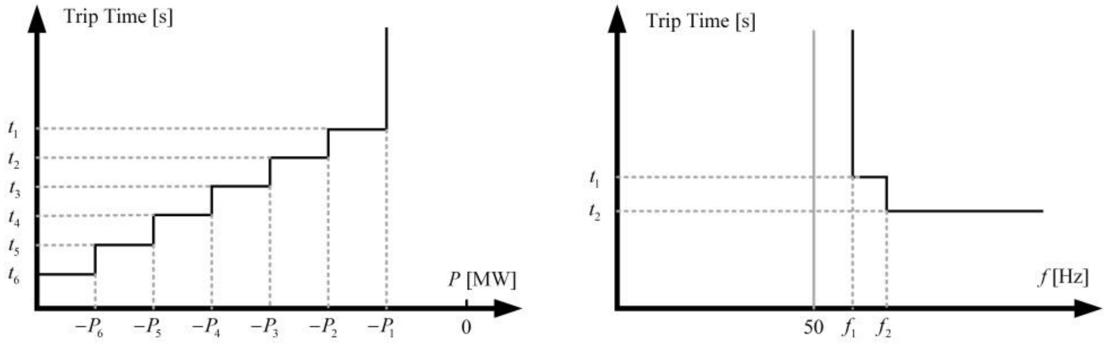
As a piece of synchronous generator, a synchronous condenser needs to be protected against mechanical problems, electrical faults and adverse system interactions. Generally, failures inside generator plants are very well covered, and protection systems can offer high reliability, high dependability, as well as high selectivity. However, generators can also be damaged due to incidents in the grid. For the faults in the grid the picture is more complex. Some failures can even damage generator plants if the protection is insufficient.

Considering the benefits of SCs, a synchronous condenser is likely to be installed that the PCC of a HVDC station [8]. If the HVDC station is operating under inverter mode and there is only one transmission line emanating from the substation, the trip of this last line will result in an island operation of the SC and the HVDC. This scenario is critical because the imported active power by the HVDC will be absorbed by the SC after the line trip, leading to the speed-up of the rotor. As a result, reverser power and over-frequency protection have to be included in the generator relay that protects the SC. On the other hand, an SC should remain connected to the grid during power swing conditions to support the grid operation, and should not be tripped by the reverse power and over-frequency protection under stable scenarios that are not considered to be island operation. This paper investigates the possible undesired trip of a synchronous condenser under a specific grid configuration through HiL tests. The grid model including an SC and a VSC-HVDC system is simulated in Real Time Digital Simulator (RTDS), while the automatic voltage regulator (AVR) and the generator relay for the SC are using hardware.

REVERSE POWER AND OVER- FREQUENCY PROTECTION

For synchronous generators in conventional power systems, reverse power protection is used to monitor the motor operation of generators and thus detects driving failures. It prevents endangering the turbine by opening the circuit breaker of the system and protects a turbo-generator set [9]. The protection calculates the active power flowing into the generator through the measured three-phase voltage and current at the machine terminal. The generated average value of the active power over a fixed number of cycles is compared with a settable threshold. The protection picks up when the threshold is exceeded. If the reverse power stays above the threshold over a certain amount of time (a settable time delay), the protection generates a trip signal. Otherwise, the pick-up will drop out after a settable time delay if the reverse power drops below a pre-defined value. In this paper, reverse power protection is used for the synchronous condenser to prevent over-speed in the rotor. It can be configured by different stages as shown in Fig. 1(a). Each stage has its own threshold and operating delay. For example, if the reverse power stays below $-P_1$, the protection generates a trip signal after t_1; if the reverse power stays below $-P_4$, the protection generates a trip signal after t_4;

Over-frequency protection is used to monitor the frequency band and output failure indications. It detects over-frequencies in electric power systems or machines and disconnects generating units when the power frequency is critical, providing additional turbine protection if the speed limiter fails [9]. The protection measures the frequency of the three-phase voltage at the machine terminal. The measured frequency is compared with a settable threshold and the protection generates a trip signal with the same logic as that of reverse power protection. In this paper, over-frequency protection is also configured by different stages as shown in Fig. 1(b). For example, if the frequency stays above f_1, the protection generates the trip signal after t_1.



(a) reverse power protection

(b) over frequency protection

Fig. 1: Configurations of reverse power and over-frequency protection for SCs

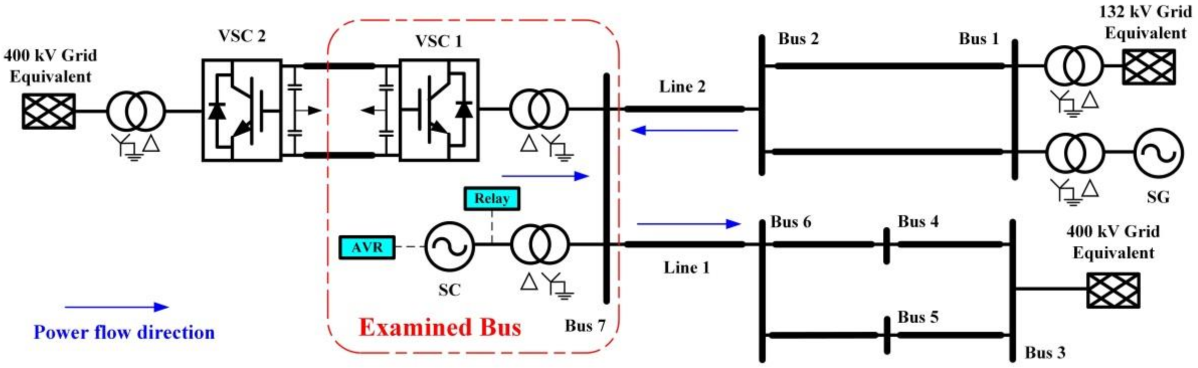


Fig. 2: Single-line diagram of the test system.

SCENARIO DESCRIPTION

Figure 2 shows the single-line diagram of the test system, whose configuration can possibly exist in reality. If VSC1 is operating under inverter mode and Line 2 has been disconnected, Line 1 becomes the last line emanating from the substation. A further trip of Line 1 will form an island operation of VSC1 and SC and the active power imported from VSC1 will be absorbed by SC. Therefore, reverse power and over-frequency protection can be used to prevent SC from over-speed in the rotor.

On the other hand, if the system is operating with the indicated configuration and the power flow condition in Fig. 2 (both Line 1 and Line 2 are in service), the trip of Line 1 can result in power swing conditions, which will push active power to flow into the SC. Therefore, there is a potential risk that SC is tripped undesirably by the reverser power and over-frequency protection, while SC is supposed to remain connected to the grid (within its physical limit) and helps stabilize the grid operation.

HARDWARE-IN-THE-LOOP PLATFORM

This paper investigates the potential undesired trip of synchronous condenser using HiL test as shown in Fig. 3. The power system model shown in Fig. 2 as well as the corresponding control system for the HVDC is simulated in RTDS, while the generator relay and AVR for the SC are using hardware. The three-phase voltage and current signals from the low-voltage side of the SC terminal, the voltage and frequency measured at Bus 7 are sent out from RTDS through the Analog Output Card. Since the output card has a maximum output of ±10 V, an amplifier is used to increase the level of the three-phase voltage and current signals. Based on the received signals, the AVR platform generates an AVR set-point to control the excitation of the SC. It also generates the ‘on grid signal’ to connect the SC to the grid after a synchronization check. The trip signal generated by the relay, as well as the ‘on grid signal’, is sent back to RTDS through the Digital Input Card.

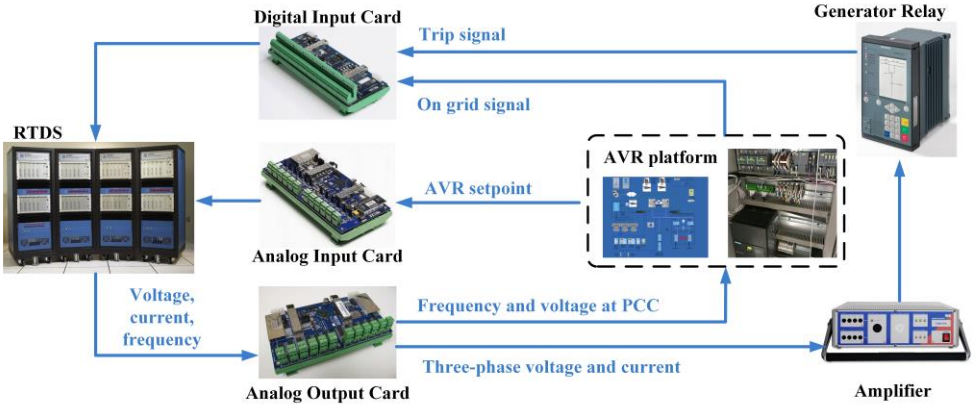


Fig. 3: Hardware-in-the-loop test platform.

TEST RESULTS

This section examines the performance of the system in Fig. 2 subject to a trip of Line 1 under the different scenarios listed in Table I. The ratings of VSC1, SG and SC are 600 MVA, 300 MVA and 270 MVAr respectively. The control system of VSC1 is implemented based on [10]. Prior to the line trip, VSC1 delivers a certain amount of active power at unity power factor, and SC is excited to exchange around 0 MVAr with the grid. The 132 kV grid equivalent is modelled as an voltage source behind an grid impedance, and it exchanges around 0 MW active power with the rest of the grid.

After the line trip, VSC1 switches to weak grid mode by reducing its active power reference with a time delay. The reverse power and over-frequency protection for SC is configured with 6 and 2 stages respectively according to the schematic diagrams in Fig. 1. Since the main focus of this paper is the reverser power and over-frequency protection, other protection functions for SC and HVDC are not considered in this study.

Table I: List of test scenarios.

Scenario	SG output	VSC1 output	VSC1 output under weak grid mode	Weak grid mode time delay	132 kV grid short circuit power	SC	SC protection
1	50 MW	600 MW	150 MW	100 ms	528 MVA	No	-
2	50 MW	600 MW	150 MW	100 ms	528 MVA	Yes	Setting 1
3	50 MW	600 MW	150 MW	100 ms	528 MVA	Yes	Setting 2
4	50 MW	600 MW	300 MW	100 ms	528 MVA	Yes	Setting 2
5	50 MW	600 MW	150 MW	200 ms	528 MVA	Yes	Setting 2
6	50 MW	600 MW	150 MW	100 ms	264 MVA	Yes	Setting 2
7	150 MW	600 MW	150 MW	100 ms	528 MVA	Yes	Setting 2
8	150 MW	300 MW	150 MW	100 ms	528 MVA	Yes	Setting 2

Figure 4 presents the test results subject to Line 1 trip at 0 s for the first three scenarios. In scenario 1 where there is no SC, the grid is not able to operate stably after the line trip. In scenario 2 where SC is present and the protection has setting 1, the grid remains stable initially after the line trip. However, due to the sensitive setting of the reverser power protection, the SC is tripped around 0.2 s and the system loses the support from the SC, which indicates that there is a potential risk of undesired trips of SC. This is the case that should be avoided because synchronous condensers are supposed to remain connected to the grid (within their physical limits) and support the gird under grid-side disturbances. In scenario 3 where the settings of the protection are improved, the SC remains connected and provide dynamic voltage support to stabilize the grid operation.

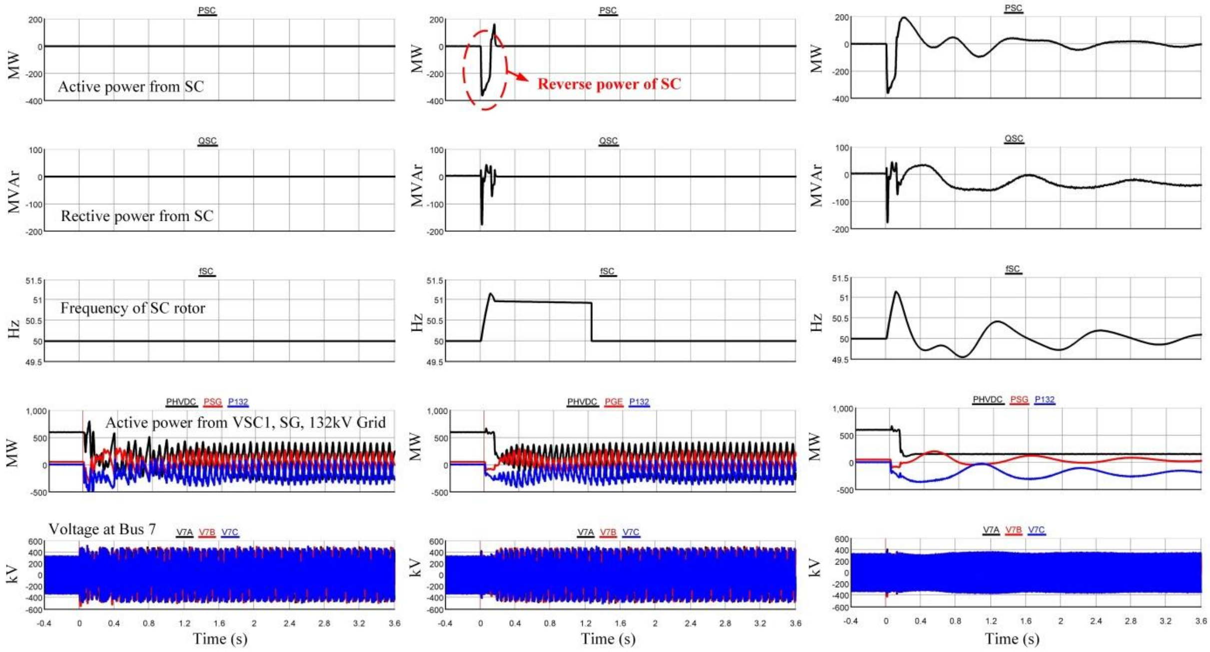


Fig. 4: Test results for scenario 1(left), scenario 2(middle) and scenario 3 (right).

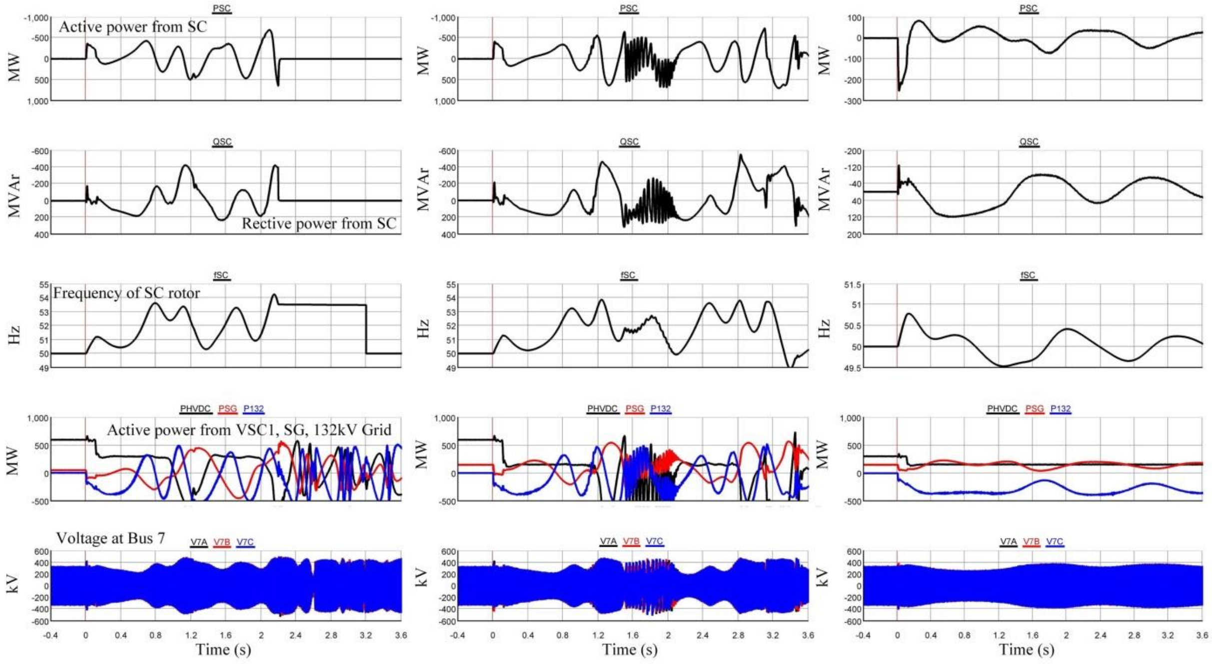


Fig. 5: Test results for scenario 4(left), scenario 7(middle) and scenario 8 (right).

Based on scenario 3, scenarios 4-8 investigates the impacts from the pre-trip power flow conditions, the VSC1 weak grid mode, and the short circuit power level of the 132kV grid equivalent. In scenarios 4-7, SC is all tripped by reverser power or over-frequency protection at different time instant. As an example, Fig. 5 shows the test results for scenario 4 (SC is tripped around 2.1 s) and scenario 7 (SC is tripped around 15 s, which is not shown in the plots). However, these trips are not due to the unsuitable settings of the protection, but because the system after Line 1 trip cannot operate stably even with the presence of the SC. In contrast, in scenario 8 where there is less power flow on Line 1 before the line trip, the grid remains stable and the SC stays connected to the grid as shown in Fig. 5.

For the system in Fig. 2 with the indicated power flow condition, the trip of Line 1 interrupts the power flow on this line suddenly and results in power swing conditions. The power delivered by the HVDC and the SG has to be absorbed by the 132 kV grid equivalent. It may not tolerate such large amount of reverse power flow from Bus 7 to Bus 1 after the line trip, and thus leads to the instability. It can be observed from scenarios 3-8 that this is jointly affected by: (1) How much active power the HVDC is importing prior to the line trip; (2) How much active power the other transmission line is importing to the substation prior to the line trip; (3) How fast the HVDC is able to switch to weak grid mode after the line trip; (4) What is the active power reference for the HVDC under weak grid mode; (5) The strength of the grid that the HVDC is connected to after the line trip.

Therefore, for this specific grid configuration shown in Fig. 2 or similar ones, the grid operator should from the power dispatch perspective identify the worst case in terms of the maximum acceptable reverser power flow. The information of the above identified aspects is of great importance to decide the proper settings of the reverse power and over-frequency protection for an improved application of synchronous condensers.

CONCLUSION

This paper has investigated the possible undesired trip of a synchronous condenser by reverser power and over-frequency protection that is implemented for island conditions through hardware-in-the-loop tests. The test results indicate that synchronous condensers can potentially be tripped by the protection under certain grid configurations that are not considered to be island scenarios, and the settings of the reverse power and over-frequency protection should be carefully selected to avoid undesired trips. The grid conditions prior to the line trip and the actions of converters after the line trip are also playing crucial roles in these scenarios. The examined scenario or similar ones should draw more attentions for the better application of synchronous condensers. It provides insights for grid operators and engineers regarding the planning of power dispatches and the settings of generator relays for synchronous condensers.

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