RTDS-based HIL testing platform for complex modern electricity transmission systems

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Abstract: This study demonstrates the capability and performance of the developed state-of-the-art hardware-in-the-loop (HIL) testing platform based on the real-time digital simulator (RTDS). The evaluations of (i) the effects of thyristor-controlled series compensation (TCSC) on the feeder protection first main (unit protection) and (ii) the performance of feeder protection second main (distance protection) of multi-ended transmission circuits with adjacent TCSC are carried out. Realistic parameters of transmission lines and TCSC are used for system modelling, and practical physical relays are used for the testing. The potential impacts of TCSC on both unit protection and distance protection are analysed based on the simulation results and relay measurements from the developed RTDS-based HIL testing platform.

1 Introduction

Modern electricity transmission systems are becoming more complex during their continuous network evolution. One particular feature of this network evolution is that there are increasing installations of power electronic (PE) devices in the existing AC network, e.g. HVDC and FACTS devices [1]. These PE devices are either used for (i) integrating renewable energy sources, for instance, onshore/offshore wind farms or (ii) increasing the stability/power transfer capability of part of the electricity transmission network. Taking Great Britain (GB) HV transmission system as an example, two units of thyristor-controlled series compensation (TCSC) has been installed in the National Grid Electricity Transmission Network to increase the boundary power transfer capability between England and Scotland [2]. Another example is a 2.2 GW thyristor-based Western HVDC link to provide additional submarine route to facilitate the power delivery of renewables from Scotland to England [3].

However, the installations of PE devices would lead to a set of new risks relevant to the performance of existing protection and control (P&C) systems. For example, the dynamic behaviour of TCSC may affect the performance of existing pre-defined protective schemes for transmission lines [4]. As a result, the configurations and settings for these protective schemes may need to be modified to maintain the performance of protection system. In some practical cases, it is even more challenging for protection systems to operate as appropriate when HVDC and/or FACTS devices are installed adjacent to complex transmission topologies, e.g. multi-ended transmission lines. For these potential risks mentioned above, if not properly managed, they may cause undesirable consequences, e.g. system instability and even severe blackouts which will bring great damages to the benefits of transmission owners and their stakeholders.

Previously, there was no existing test facility within National Grid, which owns HV electricity transmission assets in England and Wales, to study these risks during project development and post-delivery support. As a result, an innovation project was established in collaboration with the University of Birmingham, aiming to co-develop such a facility to investigate the performance of P&C systems as the transmission network evolves.

This paper is structured as follows:

1. Configuration and the main components of the testing platform based on advanced real-time digital simulator (RTDS) are described in Section 2. Then the modelling of power system components and measurement equipment are described in Section 2.
2. In Section 4, two case studies were carried out to demonstrate the performance and capability of the developed testing platform. The first case study is focused on the evaluation of differential protection of a 400 kV series-compensated overhead line. The second case study is focused on the evaluation of the effect of series compensation on the distance protection of adjacent multi-ended HV overhead lines. Discussions and analysis of the testing results are presented in Section 4 as well. Finally, Section 5 concludes the paper.

2 Setup of the hardware-in-the-loop (HIL) testing platform

Fig. 1 shows the schematic diagram of the HIL testing platform. The arrangement of a unit protection scheme for a double-circuit line is shown. The main components of the platform are

- RTDS
- Hardware I/O interface cards
- Power amplifier
- Physical protection relays.

The power system, the protected primary side equipment, circuit breakers (CBs), current transformers (CTs) and voltage transformers (VTs) are represented in detail via the user-defined models in RTDS. The physical protection relays are used to simulate the practical operation of feeder protection system.

With this setup, the dynamics of both the primary side and secondary side equipment can be simulated with high accuracy compared with those in actual network. Then the testing of various protection schemes under different fault scenarios can be carried out and suggestions can be made to National Grid on the potential risks associated with the protection arrangements/settings.

3 Modelling of power system components and measurement equipment

As the case studies of the paper is focused on analysing the effect of TCSC on the protection of transmission line, the modelling of TCSC and the transmission line are explained first. The models for the measurement equipment of CT and VT are explained next.
3.1 Modelling of TCSC

Fig. 2 shows the single-line diagram of the in-house TCSC model developed in RTDS. The following is a brief explanation of the main components of TCSC and their associated functions.

1. **AC capacitor banks**: The capacitor units are connected in series and in parallel to achieve the desired level of compensation.
2. **Metal oxide varistor (MOV)**: It is connected in parallel with the capacitor banks to limit the level of capacitor overvoltage when there is excessive line current during fault.
3. **Thyristor-controlled reactor (TCR)**: By controlling the timing of firing pulses to the thyristor, the TCR behaves as a controllable reactor, and it is connected in parallel with the fixed capacitor banks to achieve a controllable capacitive compensation.
4. **Disconnector**: It is used for safe isolation of TCSC from the high-voltage line for service or maintenance, or safe reinsertion of the TCSC back into the transmission line.

The following operational modes are considered and designed for the TCSC system:

1. **Thyristor blocked mode**: No firing pulses are issued for both thyristors and the TCR branch behaves like an open circuit. The TCSC is working as a fixed series capacitor.
2. **Capacitor bypass mode**: Continues gating signals are applied to both thyristors. The TCSC is working as the paralleled connection of a fixed capacitor and a fixed reactor. The apparent TCSC impedance is inductive under this operational mode and hence can be used to limit the magnitude of fault current.
3. **Vernier mode**: It is the normal mode of operation for TCSC. The thyristors are in partial conduction under this mode, and the apparent TCSC impedance is controlled by controlling the firing angles.

The reactance control mode of TCSC is proposed to be implemented in RTDS for two case studies in Section 4. Under this control mode, the TCSC is controlled to have a constant capacitive impedance of 8.2 Ω, corresponding to a boost factor of 1.2. (Note: Constant current mode was considered as well for this project. However, it has not been considered in this paper for the purpose of the paper.)

Simulation case studies are carried out to validate the TCSC model. In particular, the controller parameters are tuned so that similar dynamic behaviour of TCSC as that of practical system is achieved to ensure realistic test conditions.

3.2 Modelling of AC transmission line

The travelling wave transmission line models are adopted for the case studies. Realistic transmission line parameters are obtained from [5].

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Fig. 1 Configuration of the RTDS-based HIL testing platform

Fig. 2 Single-line diagram of TCSC model
The effect of saturation and hysteresis are represented in detail as simulation studies are focused on the evaluation of differential protection of series electromagnetic transient characteristics similar to a practical CT. Power system for testing of practical physical protection relays. Compensated lines. Case 2 is focused on the evaluation of the complicated current/voltage measurements as used in the physical protection relays. They may affect the performance of protection relays. The detailed CT models are used and they consider full electromagnetic transient characteristics similar to a practical CT. The effect of saturation and hysteresis are represented in detail as they may affect the performance of protection relays.

Similar to the CT models, the saturation and hysteresis effects are considered for detailed VT models as well.

In doing so, it can simulate the accurate response of the complicated current/voltage measurements as used in the power system for testing of practical physical protection relays.

### 3.3 Modelling of CT and VT

The detailed CT models are used and they consider full electromagnetic transient characteristics similar to a practical CT. The effect of saturation and hysteresis are represented in detail as they may affect the performance of protection relays.

Similar to the CT models, the saturation and hysteresis effects are considered for detailed VT models as well.

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### 4 Simulation studies

The results of two case studies are presented in this section. Case 1 is focused on the evaluation of differential protection of series compensated lines. Case 2 is focused on the evaluation of the effects of series compensated line on the distance protection of adjacent multi-ended lines.

Fig. 3 shows arrangements of CTs and CBs for the protected series compensated line between B1 and B2. The TCSC is installed at B1. Two CTs at both ends of the transmission line are providing current measurements, and fibre optic links between two relays are used for exchanging information. The fault being simulated is a 200 ms phase A to ground fault with 100 Ω fault impedance close to B1 end as shown in Fig. 4. The maximum value of source impedance at both ends is used according to the lowest fault levels at B1 and B2. This fault is considered to be the most severe case for differential protection. If it can be cleared by the differential protection, it can be expected that other earth faults can also be successfully cleared.

Figs. 5 and 6 show the simulation results. In both figures, the first graph shows the three-phase currents at the primary side of CT. The second graph shows the three-phase currents at the secondary side of CT. The third graph shows the RMS value of three-phase differential currents. The fourth graph shows the trip signal from the relay. The last graph shows the RMS value of three-phase differential currents. The trip signal corresponds to the CB status for each phase, where a ‘high’ indicates that the CB is closed and a ‘low’ indicates that the CB is open. From Fig. 5, it can be seen that as fault happens, the B2 end does not experience any significant changes in its measured current. At the same time, as can be seen from Fig. 6, the phase A current at B1 drops. The phase A differential current is increased and this is seen by both relays. Trip signals are sent to the CBs at both ends within 40 ms of fault initiation to clear the fault.

Fig. 7 shows the differential currents at B2 when TCSC is not in service. The phase A differential current is slightly smaller than the case with TCSC in service, and the operation of differential protection is not significantly affected.

Current inversion [6], as the most severe phenomenon related to the series compensation, is analysed. Theoretically, the current inversion could occur at B1, when the net fault impedance from the source to the fault is negative. This will happen when the source impedance is <0.51%, which is the capacitive reactance of TCSC on 100 MVA base, corresponding to a fault level higher than 30 kA at B1. For the worst case scenario, the switchgear rating source impedance behind B1 of 0.23% (63 kA) is considered. Then for a close in fault, the net impedance will be ~0.28%, which corresponds to a fault current of ~51.5 kA. Such a fault current will cause the immediate bypass of the TCSC to prevent capacitor overvoltage and hence damage to MOV. Therefore differential protection is not compromised for this particular application.

The network configuration for the distance protection of three-ended lines with an adjacent series compensated line is shown in Fig. 8. It illustrates the arrangements of CTs, VTs and CBs of the three-ended transmission lines. The parameters of the three-ended lines are shown in Table 1. There is one distance relay located at each end measuring the local current and voltage. The series compensated line is connected between Bus A and Bus D. The TCSC is installed at Bus A to provide capacitive compensation. The TCSC model is the same as that described in Section 3. The largest source impedances for Bus B, Bus C and Bus D are calculated using the minimum fault level data. The settings of distance relays at Bus A, Bus B and Bus C are calculated as appropriate under NG’s guidance for three-ended lines without considering the effect from TCSC.

### 4.1 Effect of fault location

Fig. 9 shows the relay 2 (D2 as shown in Fig. 8) measurements (phase A impedance) of three-phase faults with fault resistance of 0.1 Ω. From the figure, it can be observed that under both fault locations, the measured impedance is within Zone 2. It can also be seen that when the fault is further away from the relay (at 15% down the line) the impedance measurements becomes closer to Zone 1. This means that the electrical distance measured by the relay is decreased rather than increased. This is because under fault conditions, the transmission line tends to be over-compensated as a result of the increased fault current flowing through series capacitor.
In this specific case, as relay 2 is electrically closer to Bus A than relay 3 (D3 in Fig. 8), its measured impedance is closer to Zone 1. For relay 3 at Bus C, it does not pick up when the fault is located at 0%, due to its longer electrical distance from Bus A and the throttling effect from Bus B. However, its Zone 2 picks up the fault when the fault is located at 15% of the line, for both 0.1 and 5 Ω fault resistances. Simulation results for relay 3 measurements of three-phase fault with fault resistances of 0.1 and 5 Ω are shown in Fig. 10. From Fig. 10, it can be seen that the measured impedance falls into Zone 2 due to the effect of series compensation. The same effect from different fault resistances can be observed. It can also be expected that if the fault is located further down the line, or the fault resistance is further increased, relay 3 in Zone 2 will not pick up.

4.2 Effect of boost factor

As seen from Fig. 9, the measured impedance of relay 2 is around the boundary of Zone 1 due to the effect of series compensation. It can be expected that if the boost factor is further increased, its Zone 1 can pick up the fault and trip its CB. To demonstrate this effect, Fig. 11 shows the relay measurements of a three-phase fault located 15% away from the line with an increased boost factor of 1.4. Fault resistances of 0.1 and 5 Ω are simulated. It can be seen

![Fig. 7 Differential currents at B2 without TCSC](image)

![Fig. 8 Configuration of series compensated line adjacent to three-ended lines](image)

![Fig. 9 Three-phase 0.1 Ω fault located on transmission line between Bus A and Bus D (relay 2 measurement)](image)

(a) Bus A, (b) 15% away from Bus A

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Table 1 Parameters for the three-ended transmission lines

|         | Length, km | B1, % | X1(%)/X0(%) | R1(%)/R0(%) |
|---------|------------|-------|-------------|-------------|
| B-Tee   | 9.6        | 6.46  | 0.17/0.47   | 0.0085/0.0742 |
| A-Tee   | 34.42      | 20.61 | 0.66/1.80   | 0.0536/0.2952 |
| C-Tee   | 32         | 19.17 | 0.61/1.67   | 0.0498/0.2742 |

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from Fig. 11 that the measured impedance of relay 2 drops into Zone 1, causing the trip of the associated CBs.

5 Conclusions

To demonstrate the capability of the developed RTDS-based HIL testing platform, two case studies are presented to analyse the effects of TCSC on (i) the differential protection of transmission line and (ii) the distance protection of three-ended lines. It has been found that the current inversion phenomenon does not compromise the differential protection for this particular application. For the effects of TCSC on the distance protection of adjacent three-ended lines, it has been found that if the degree of compensation is high, Zone 1 of one or more of the three-ended distance protections...

Fig. 10 Three-phase fault located 15% away from Bus A with a TCSC boost factor of 1.2 (relay 3 measurement)
(a) Fault resistance of 0.1 Ω, (b) Fault resistance of 5 Ω

Fig. 11 Three-phase fault located 15% away from Bus A with a TCSC boost factor of 1.4 (relay 2 measurement)
(a) Fault resistance of 0.1 Ω, (b) Fault resistance of 5 Ω
could pick up the fault when the fault is located beyond the point of series compensation. Such capabilities are useful for National Grid for effective risk assessment for both current and future protection schemes.

In the next stage of the project, the testing capability of the developed platform will be modified and/or further expanded. In doing so, it will enable the testing of physical protection devices for future other types of HVDC and FACTS applications.

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