Advanced RTDS-based studies of the impact of STATCOM on feeder distance protection

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Abstract: The studies of the performance of feeder distance protection with multiple installations of the static synchronous compensator (STATCOM) are presented. Detailed representation of delta-connected multi-level modular converter (MMC) STATCOM is modelled and its impact on feeder distance protection is analytically studied. A real-time digital simulation (RTDS) based hardware-in-the-loop testing platform is established using practical distance relays, multiple detailed MMC STATCOM models and realistic transmission data. Different types of internal/external faults at varying locations are simulated to investigate the STATCOM’s impact on feeder distance protection.

1 Introduction

The emerging static synchronous compensator (STATCOM) technology is commonly regarded as an effective solution for fast-response voltage/reactive power support during normal and faulty conditions [1, 2]. In recent years, there has been an increase of STATCOM applications in the high-voltage (HV) transmission systems around the world [3].

However, implementation of STATCOM technology in the HV transmission systems may introduce certain risks to the existing protection and control systems [4, 5]. For example, if one or more STATCOMs are put into service for fast voltage/reactive power control, it may cause unexpected transient changes of impedance [6]. As the performance of feeder distance protection is heavily dependent on the impedance measurement, these unexpected changes of impedance may trigger mal-operation of feeder distance protection. As a result, such risk should be carefully investigated when introducing the STATCOM into HV transmission system.

In [6], comparative investigation of the performance of various distance protection schemes is presented for transmission lines compensated by shunt connected flexible AC transmission system (FACTS) devices. In [7], the impacts of VSC-based multilevel FACTS controllers on distance relays are evaluated. An adaptive distance protection scheme in the presence of STATCOM is presented in [8]. An adaptive distance protection scheme is proposed in [9] to improve the performance of the conventional distance protection scheme for compensated lines with high resistance faults. In [10], a methodology of calculation of fundamental frequency-based per phase digital impedance pilot relaying scheme for STATCOM compensated transmission lines is presented using two-end synchronised measurement.

To investigate the potential impact of STATCOM on the performance of feeder distance protection, a trial network with multi-STATCOM installation is presented, which is modelled in detail using the real-time digital simulation (RTDS). Then the studies of interactions between STATCOMs and physical distance protection relay in the RTDS-based hardware-in-the-loop (HIL) testing platform as shown in Fig. 1 are introduced.

In order to make the simulation/testing results reflect practical network behaviour, the methodology for the investigation is carried out with the following technical considerations:

(i) The use of realistic transmission line parameters [11];
(ii) The use of practical distance protection relays;
(iii) Detailed representation of multiple STATCOMs with appropriate control modes;
(iv) Different types of internal/external faults occurred at various distances on the double-circuit lines.

2 Modelling of STATCOM

In this section, the modelling of the detailed delta-connected multi-level modular converter (MMC) based STATCOM and its control system is presented.

2.1 Configuration of STATCOM

The three-phase circuit configuration of the STATCOM is shown in Fig. 2. As shown in Fig. 2, the detailed model of delta-connected STATCOM consists of three MMC-based legs. There are 26 full-bridge submodules and two identical series phase reactors in each leg. All the full-bridge submodules are identical, and all the switches and diodes have the same ratings.

The purposes of using delta connection of STATCOM are as follows:

• by use of delta topology, the zero sequence fundamental current is circulated through the arm converters to keep active power of each phase zero, when it is connected to unbalanced circuit;
• the rated current of switching devices is lower compared to star-connection.

2.2 Control system of STATCOM

Fig. 3 shows the single-line diagram of the STATCOM and its control system. dq decoupling control is used. DC voltage across the capacitors of submodules on each arm is controlled. AC side voltage at common coupling point or the reactive power exchange between the STATCOM and external AC network are given by

\[ P = \frac{V_{c,abc}V_{r,abc}}{X_c}\sin \delta \]  
\[ Q = \frac{V_{c,abc}V_{r,abc}}{X_c} \]  

where \( V_{c,abc} \) and \( V_{r,abc} \) are the magnitudes of converter output voltage of STATCOM and external AC network voltage at common coupling point, respectively; \( X_c \) is the equivalent impedance between STATCOM and external AC network; \( \delta \) is the angle difference between the converter output voltage of
When $Q$ is positive, the STATCOM supplies reactive power to the external AC network. When $Q$ is negative, the STATCOM absorbs reactive power from the external AC network.

The architecture of the control loop of the STATCOM is shown in Fig. 4. The STATCOM can operate in either AC voltage regulation mode or reactive power control mode.

The performance of the AC voltage regulation mode after a change of reference at 0.2 s is shown in Fig. 5. The performance of the reactive power control mode after a change of reference at 0.2 s is shown in Fig. 6.

### 3 STATCOM’s impact on apparent impedance

The mathematical analysis of STATCOM’s impact on the apparent impedance measured by feeder distance protection relay is presented in this section.

#### 3.1 Analysis of internal fault

Fig. 7 shows the simplified single line diagram of a faulted network for the analysis of internal fault. Two AC systems (represented by ideal voltage source with internal impedance) are connected via double-circuit transmission lines TL1 and TL2. A STATCOM is connected near B1 (the distance between STATCOM and B1 can be neglected) to provide voltage support. Two distance relays (Distance relay 1 and Distance relay 2) are located at both ends of one single-circuit of TL1. These distance relays collect voltage and current measurements from voltage transformer (VT) and current transformer (CT) and send trip signals to circuit breakers (CB1 and CB2). An internal single-phase-to-ground (SLG) fault or three-phase fault on TL1 is simulated.

The apparent impedance of STATCOM-compensated transmission line measured by distance relays is derived for SLG faults and three-phase faults.

For SLG faults, the voltages seen by VTs at both ends of TL1 can be expressed as:

$$V_{Lx} = p Z_{Lx} (I_{Sx} + I_{f x}) + I_{f x} R_f$$

$$V_{Rx} = (1 - p) Z_{Lx} I_{rx} + I_{f x} R_f$$

where $x = 1, 2$ or 0 as a suffix denotes the sequence components; $V_{Lx}$ and $V_{Rx}$ are sequence voltages seen by VTs at both ends of TL1; $p$ represents the fault location from B1 to B2 in per unit of the total line length; $I_{Sx}$ is the sequence current of STATCOM; $I_{Sx}$ and $I_{rx}$ are the sequence currents seen by CTs at both ends of TL1; $I_{f x}$ is the sequence current through fault resistance; $R_f$ represents the fault resistance; $Z_{Lx}$ represents the sequence components of the line impedance of TL1.

By adding all three sequence components of left-hand side of (1) and (2), the voltages seen by VTs can be expressed after simplification as:

$$V_{L} = p Z_{L} (I_{S} + k I_{s0}) + p Z_{L} (I_{STAT} + k I_{STAT0}) + I_{f} R_f$$

$$V_{R} = (1 - p) Z_{L} I_{r} + I_{f} R_f$$

where $Z_{L}$ represents the sequence components of the line impedance of TL1.
affected by compensation of STATCOM.

By using phase voltage measurements at both ends of transmission lines ($V_L$ and $V_R$) and phase current compensated by zero sequence current ($I_L$ and $I_R$), the apparent impedance seen by the distance relays are given as

$$Z_{relay} = \frac{V_L}{I_L} = pZ_{L1} + \frac{pZ_L(I_{STAT} + kI_{STAT})}{I_L} + \frac{I_f}{T_c} + R_f$$  \hspace{1cm} (7)$$

$$Z_{relay} = \frac{V_R}{I_R} = (1 - p)Z_{L1} + \frac{I_f}{T_c} + R_f$$  \hspace{1cm} (8)$$

where $I_L = I_s + kI_{STAT}$, $I_R = I_r + kI_{STAT}$ as a consideration of current compensated by zero sequence current.

As proposed in [6], by use of delta connection at one side of the coupling transformer for STATCOM, the zero-sequence current injection can be eliminated. Hence, the zero-sequence current of STATCOM is eliminated ($I_{STAT} = 0$). Then (5) can be further simplified as

$$Z_{relay} = pZ_{L1} + \frac{pZ_LI_{STAT}}{I_s} + \frac{I_f}{T_c} + R_f$$  \hspace{1cm} (9)$$

For three-phase faults ($Z_{L0} = Z_{L1}$), the phase current seen by distance relay is

$$I_L = I_s$$  \hspace{1cm} (10)$$

$$I_R = I_r$$  \hspace{1cm} (11)$$

Similarly, the apparent impedance seen by the distance relays are given as

$$Z_{relay} = \frac{V_{LII}}{I_{LII}} = pZ_{L2} + \frac{pZ_LI_{STAT}}{I_s} + \frac{I_f}{T_c} + R_f$$  \hspace{1cm} (12)$$

$$Z_{relay} = \frac{V_{RII}}{I_{RII}} = (1 - p)Z_{L2} + \frac{I_f}{T_c} + R_f$$  \hspace{1cm} (13)$$

where $V_{LII}$ and $V_{RII}$ are line voltage measurements at the ends of transmission lines; $I_{LII}$ and $I_{RII}$ are line current measurements at the ends of transmission lines.

By carefully looking at (7) and (10), the STATCOM’s impact on apparent impedance measured by neighbouring distance relay (Distance relay 1) in case of internal fault can be summarised as

(i) The first term ($pZ_{L1}$) of (7) and (10) represents the actual proportional line impedance to the fault location. This term is not affected by compensation of STATCOM.

(ii) The second term of (7) and (10) indicates that the STATCOM’s impact on apparent impedance measured by neighbouring distance relay in case of internal fault leads to larger apparent impedance. The under-reach effect is introduced as the impact of STATCOM. Since during internal fault, the STATCOM is injecting reactive power and current to support bus voltage, the apparent impedance is greater than no STATCOM compensated transmission lines. For steady state, while STATCOM is absorbing reactive power and current from bus bar, the second term could be negative. This negative value indicates smaller apparent impedance measured by distance relays which results in overreach effect. This error in apparent impedance measurement caused by STATCOM is proportional to the fault location from B1 to B2 and the current ratio of STATCOM and relay.

(iii) The third term of (7) and (10) also indicates greater apparent impedance measured by neighbouring distance relay as STATCOM’s impact, since $I_f = I_s + I_{STAT} + I_r$. A larger amount of current injection of STATCOM would lead to a larger apparent impedance error and cause more significant under-reach effect.

Similarly, by carefully looking into (6) and (11), the STATCOM’s impact on apparent impedance measured by remote distance relay (Distance relay 2) in case of internal fault can be summarised as:

(i) The first term (($1 - p)Z_{L1}$) of (6) and (11) represents the actual proportional line impedance to the fault location. This term is not affected by compensation of STATCOM.

(ii) On the contrary to the neighbouring relay (Distance relay 1), the remote relay is only affected by the amount of current injection of STATCOM which is the second term of (6) and (11). This issue can be explained by the fact that the STATCOM is located beyond the fault location seen from the remote relay. The second term of (6) and (11) indicates greater apparent impedance measured by remote distance relay as STATCOM’s impact. A greater amount of current injection of STATCOM would lead to a greater apparent impedance error and cause more significant under-reach effect.

3.2 Analysis of external fault

Fig. 8 shows the simplified single line diagram of a faulted network for the analysis of external fault. Identical network topology described in Section 3.1 is used except that the fault location is placed at one single circuit of TL2. The apparent impedance of STATCOM-compensated transmission line measured by Distance relay 1 is derived for SLG fault and three-phase fault. The apparent impedance of Distance relay 2 is not considered in this subsection since the fault location is located out of the protection zones.

The voltage seen by VT at B1 can be expressed as

$$V_{Ls} = Z_{Ls}(I_{STAT} + I_s) + pZ_{L1}I_s + I_fR_s$$  \hspace{1cm} (14)$$

where $x = 1, 2$ or 0 as a suffix denotes the sequence components; $V_{Ls}$ is sequence voltages seen by VT at B1; $p$ represents the fault location from B2 to B3 in per unit of the total line length; $I_{STAT}$ is the sequence current of STATCOM; $I_s$ and $I_x$ are the sequence currents seen by C Ts at B1 and sequence phase current through faulted single circuit of TL2 from B2 to B3; $I_f$ is the sequence current through fault resistance; $R_s$ represents the fault resistance; $Z_{Ls}$ and $Z_{Lx}$ represent the sequence components of the line impedance of TL1 and TL2. By adding all three sequence components of left-hand side of (12), the voltages seen by VTs can be expressed after simplification as

$$V_L = Z_{Ls}(I_{STAT} + kI_s) + Z_{L1}(I_{STAT} + kI_{STAT}) + pZ_{L1}(I_f + kI_s) + I_fR_f$$  \hspace{1cm} (15)$$

where $k = ((Z_{L0} - Z_{L1})/Z_{L0})$ and $k' = ((Z_{L0} - Z_{L1})/Z_{L1})$ are the zero sequence current compensation factors of TL1 and TL2. The line positive and negative sequence impedances are assumed equal ($Z_{L0} = Z_{L1} = Z_{Ls}$).

By using phase voltage measurements ($V_l$) at B1 and phase current compensated by zero sequence current ($I_L$), the apparent impedance seen by the distance relay is given as
\[ Z_{\text{relay}} = \frac{V_L}{I_L} = Z_{L1} + Z_{L2} + Z_{\text{STAT}} \frac{I_{L} + kI_{m}}{I_L} + \frac{I_{L}I_{R}}{I_L} \]

where \( I_L = I_k + kI_m \) as a consideration of current compensated by zero sequence current.

For three-phase faults \((Z_{L0} = Z_{L1} = Z_{L2} = I_k = I_l)\), similarly the apparent impedance seen by the distance relay is given as

\[ Z_{\text{relay}}^{(L)} = \frac{V_{L0}}{I_{L0}} = Z_{L1} + \frac{Z_{L2}I_{L} + I_{L}I_{R}}{I_L} \]

where \( V_{L0} \) is line voltage measurement at B1 and \( I_{L0} \) is the line current measurements at B1.

By carefully looking into (14) and (15), the STATCOM’s impact on apparent impedance measured by neighbouring distance relay (Distance relay 1) in case of external fault can be summarised as

(i) The first and third terms \((Z_{L0} + pZ_{L0}((I_L + kI_m)/I_L))\) and \((Z_{L1} + pZ_{L2}(I_L/I_L))\) of (14) and (15) represent the actual line impedance of TL1 and proportional line impedance of TL2 to the fault location. The fourth term \((I_{L0}/I_L)\) represents the contribution of fault resistance. On the contrary to internal faults, this term is not affected by compensation of STATCOM, which can be explained by the fact that the STATCOM is not connected to the faulted TL2. These terms (the first, third and fourth) are not affected by compensation of STATCOM.

(ii) The second terms of (14) and (15) indicate that the STATCOM’s impact on apparent impedance measured by neighbouring distance relay in case of external fault leads to greater apparent impedance measurement of connected TL1. The under-reach effect is introduced as the impact of STATCOM. Since during external fault, the STATCOM is injecting reactive power and current to support bus voltage, the apparent impedance is greater than no STATCOM compensation. For steady state, while STATCOM is absorbing reactive power and current from bus bar, the second term could be negative. This negative value indicates lesser apparent impedance of connected TL1, which results in overreach effect as the impact of compensation of STATCOM. On the contrary to internal faults, this error in apparent impedance measurement caused by STATCOM is only proportional to the current ratio of STATCOM and relay, irrelevant to fault location.

### Dynamic simulation study

Dynamic simulation based on RTDS HIL testing platform using practical protective relays is carried out in this section to investigate STATCOM’s impact.

#### Table 1 Test system data

| Power system element | Parameters |
|----------------------|------------|
| TL1                  | length = 25.4 km; \( Z_1 = 0.32\angle84.8^\circ \Omega/km; Z_0 = 0.85\angle80.7^\circ \Omega/km \) |
| TL2                  | length = 26.7 km; \( Z_1 = 0.31\angle85.4^\circ \Omega/km; Z_0 = 0.84\angle80.3^\circ \Omega/km \) |
| Equivalent sources   | 400 kV; 50 Hz; \( Z_1 = 8.37\angle86.5^\circ \Omega/km; Z_0 = 8.37\angle86.5^\circ \Omega/km \) |
| STATCOM              | ±100 MVA |

#### Table 2 Relay readings during internal fault

| Case | Fault | Fault Impedance | Fault type | Fault | Distance relay 1 | Distance relay 2 |
|------|-------|-----------------|------------|-------|-----------------|-----------------|
|      |       |                 |            |       | No STATCOM      | STATCOM         | No STATCOM      | STATCOM         |
| 1    | 15%   | 0.1Ω            | RYB-G      | 600 ms| 114.4%          | 118.3%          | 118.3%          | 118.3%          |
| 2    | 50%   | 1Ω              | RYB-G      | 140 ms| 150.1%          | 154.2%          | 154.2%          | 154.2%          |
| 3    | 85%   | 10Ω             | RYB-G      | 600 ms| ×                | ×               | ×               | ×               |
| 4    | 15%   | 0.1Ω            | RY-G       | 600 ms| 115.6%          | 117.4%          | 118.5%          | 118.5%          |
| 5    | 50%   | 1Ω              | RY-G       | 140 ms| 150.9%          | 153.1%          | 152.3%          | 152.7%          |
| 6    | 85%   | 10Ω             | RY-G       | 600 ms| ×                | ×               | ×               | ×               |
| 7    | 15%   | 0.1Ω            | R-G        | 600 ms| 116.1%          | 117.8%          | 118.3%          | 118.7%          |
| 8    | 50%   | 1Ω              | R-G        | 140 ms| 150.6%          | 152.5%          | 152.3%          | 152.4%          |
| 9    | 85%   | 10Ω             | R-G        | 600 ms| ×                | ×               | ×               | ×               |

4.1 Establishment of RTDS-based HIL testing platform

A RTDS-base HIL testing platform for protective relay studies proposed in [12] is established as shown in Fig. 1. Digital signals are generated from RTDS, and converted into analogue signals via Giga-Transceiver Analog Output (GTAO) card. The output analogue signals are amplified by signal amplifier for practical distance protective relays. The trip signals are sent back from the protective relays to RTDS via the front panel to control the operations of circuit breakers. Identical network topology described in Section 3.1 is used for internal and external fault test. The test system data is shown in Table 1.

The following considerations are taken into account for the setting of the two-ended distance protections:

(i) Zone 1 is set to 75% of the complete circuit positive sequence impedance. The tripping delay is set to 0 ms.

(ii) Zone 2 is set to reach 150% of the complete circuit positive sequence impedance. The tripping delay is set to 500 ms.

Internal fault occurred at one single circuit of TL1 from B1 to B2 under such fault conditions:

- fault durations are 140 ms (7 cycles) or 600 ms (30 cycles); fault locations are 15, 50 and 85% of the whole line length; fault resistances are 0.1, 1 and 10Ω; SLG, double-phase and three-phase faults are considered.

External fault occurred at one single circuit of TL2 from B2 to B3 under such fault conditions:

- 600 ms fault occurred at 5 and 50% of the whole length; fault resistance is 0.01Ω; SLG, double-phase and three-phase faults are considered.

Table 2 shows the simulation results of internal fault and Table 3 shows the simulation results of external fault. The tripped zone is noted as ‘I’, ‘II’ or ‘X’ for zone 1, zone 2 or no relay operation is seen, respectively. Fault type is noted as ‘RYB-G’, ‘RY-G’ or ‘R-G’ for three-phase, double-line-to-ground or SLG faults, respectively. Fig. 9 shows digital signals from RSCAD for a typical internal fault case 3 of Table 2.

Fig. 10 shows apparent impedance trajectory of an under-reach case during internal fault. Fig. 11 shows apparent impedance trajectory of an under-reach case during external fault.

Seen from the simulation results above, the STATCOM’s impact on feeder distance protection can be summarised as...
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Apparent impedance trajectory during internal fault

Apparent impedance trajectory during external fault

### 5 Conclusion

Detailed representation of delta-connected MMC STATCOM has been modelled and its impact on feeder distance protection has been analytically studied. A RTDS-based HIL testing platform has been established using realistic transmission data and practical distance relays and multiple detailed STATCOM. From different types of internal/external fault test simulation occurred at various distance, the STATCOM’s impact on feeder distance protection has been investigated. The under-reach effect of neighbouring distance relay resulting from compensation of STATCOM during internal fault has shown a positive correlation to fault location and fault resistance. The under-reach effect of remote distance relay has shown positive correlation to fault location and fault resistance. The under-reach effect of remote distance relay has shown positive correlation to fault location and fault resistance. The under-reach effect of remote distance relay has shown positive correlation to fault location and fault resistance.

(i) For internal fault, the under-reach effect of neighbouring distance relay resulting from compensation of STATCOM is positively correlated to fault location and fault resistance. The under-reach effect of remote distance relay is only positively correlated to fault distance. For both distance relays, the under-reach effect during three-phase fault is more significant than SLG fault.

(ii) For external fault, the under-reach effect of distance relay resulting from compensation of STATCOM is only positively correlated to current ratio between STATCOM and relay, uncorrelated to fault location or fault impedance. The under-reach effect during three-phase fault is more significant than that during internal fault.

In general, the under-reach effect of distance relay during external fault is less significant than that during internal fault.

### 6 Acknowledgments

This work was sponsored by EPSRC Grant EP/M002845/1, EP/L017725/1 and EP/N032888/1.