Thyristor-Controlled Reactor Protection VAR Compensator

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Presented at the
50th Annual Western Protective Relay Conference
Spokane, Washington
October 10–12, 2023

Thyristor-Controlled Reactor Protection in Static VAR Compensator

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***Abstract*—Static VAR compensators (SVCs) provide rapid, dynamic reactive power support with the ability to compensate individual phases of the connected power system. SVCs are generally constructed using thyristor-controlled reactors (TCRs), thyristor-switched capacitors (TSCs), mechanically switched capacitors (MSCs), and harmonic filter banks (HFBs). One of the common types of faults in SVCs are turn-to-turn faults in TCRs. Reactor winding insulation degrades over time, leading to turn-to-turn faults. Turn-to-turn faults are generally difficult to detect and are very damaging. It is essential to detect these turn-to-turn faults early because prolonged operation under these conditions cause excess damage and is also a safety hazard. The resulting longer maintenance outage affects SVC availability and power system performance.**

Turn-to-turn fault detection in air core reactors is difficult in any situation. In addition, commonly applied protection schemes for turn-to-turn faults in TCR air core reactors are challenged by being connected in delta as well as by unsymmetrical compensation. This paper provides insight into unique aspects of TCR protection in SVCs, examines conventional protection for reactor turn-to-turn faults, and describes their limitations and challenges in TCR applications. The paper then proposes a novel logic for detecting turn-to-turn faults in a TCR.

I. Introduction

Static VAR compensators (SVCs) are shunt-connected systems that use power electronic components to provide fast, dynamic reactive power support for transmission and distribution systems. They are capable of providing individual phase compensation. SVCs are typically built from a combination of variable reactors and variable capacitors, allowing them to provide both capacitive and inductive compensation [1][2]. The variable reactance is usually achieved using delta-connected thyristor-controlled reactors (TCR), where the thyristors provide the ability to rapidly vary the inductive current drawn by the compensator, with response times in the order of a cycle. TCRs are built with thyristors connected in series with an air core reactor.

One of the faults experienced in SVCs are turn-to-turn faults in the reactor windings of the TCR [3]. Reactor winding insulation degrades over time, leading to turn-to-turn faults that are generally difficult to detect and very damaging. Prolonged operation under the faulted condition can cause excess damage to the reactor, pose a safety hazard, and result in a longer maintenance outage. TCR outages reduce the dynamic compensation ability of the SVC and degrade power system performance. Turn-to-turn faults are especially difficult to detect in air core reactors. Applying protection schemes commonly used for turn-to-turn faults in air core reactors are challenged by the delta connection and unsymmetrical operation of the TCR.

This paper provides insight into unique aspects of TCR operation in SVCs, discusses different types of TCR faults, and suggests suitable protection schemes. We examine different types of conventional turn-to-turn fault protection schemes and describe the challenges and limitations of those approaches when applied in TCR applications. We then propose a novel logic for detecting turn-to-turn faults in the TCR.

II. SVC and TCR Operation

SVCs use control systems to provide dynamic support for the power system in the event of a disturbance. One of the most common control systems injects capacitive or inductive current based on the measured bus voltage. The control system responds only to system disturbances and restraint during normal operating conditions.

SVCs are generally constructed using TCRs to provide rapidly variable inductive reactive compensation. The SVC capacitive compensation is implemented using a combination of mechanically switched capacitors (MSCs) and thyristor switched capacitors (TSCs). TSCs provide faster responses compared to fixed or switchable shunt capacitor banks. SVCs also require shunt harmonic filter banks (HFBs) to filter the harmonics produced by the TCR, with a combination of single-tuned filters for specific low-order harmonics plus a high-pass filter. Fig. 1 shows a diagram of an SVC with a single TCR, a TSC, an MSC, and HFBs on a medium-voltage bus on the delta side of the wye-grounded delta SVC stepdown transformer.

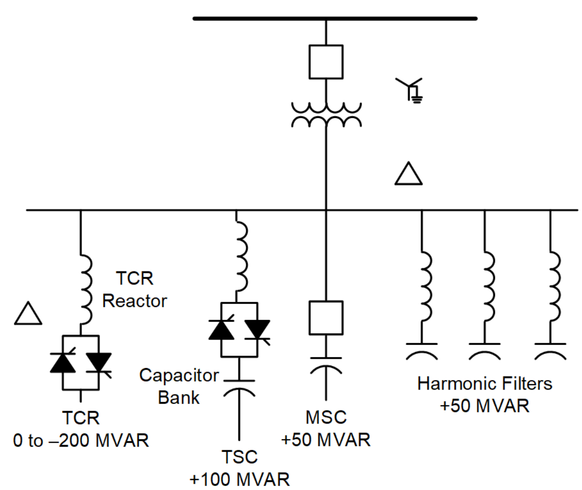


Fig. 1 SVC with a single TCR, TSC, MSC, and HFBs

The reactors typically have very high X/R ratios. The filters are designed such that they appear capacitive at the fundamental power system frequency, contributing fixed capacitive compensation. An SVC with a single TCR will most likely have filters tuned for the fifth and seventh harmonics plus a high-pass filter tuned at about 600 Hz. If the TCR is likely to supply unbalanced current, the installation will need a third-harmonic filter as well.

Conventional capacitor and reactor banks provide steady-state reactive compensation. SVCs normally operate in a zero net injection state under steady-state conditions to maintain the ability to provide full dynamic reactive power capability in the event of a disturbance. Under normal operating conditions, the switched capacitors are usually offline. However, the harmonic filters will still inject capacitive current, therefore, the TCR will inject inductive current to cancel the reactive current. If a disturbance requiring capacitive compensation occurs, the TCR will decrease its current, and if necessary, the TSCs will be switched in.

Fig. 2 shows a single-phase TCR. The TCR current is controlled by timing the turn-on of the thyristors relative to the peak of the voltage across the inductor. If the delay angle is set to zero, current flows in the inductor for a full half-cycle. If the firing angle is set to α (radians), the current is zero until angle α. Current then flows in the inductor until the conduction angle σ = π – 2α, as shown in Fig. 3.

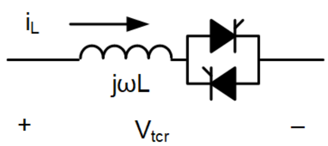


Fig. 2 Single-phase TCR

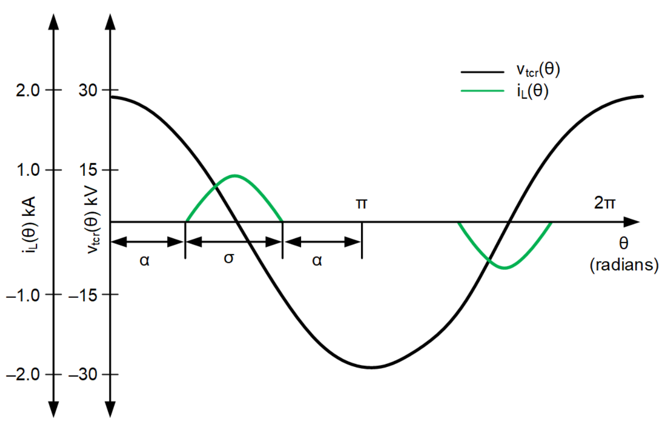


Fig. 3 Voltage across TCR and TCR current for a firing angle of α over one power frequency cycle

The RMS magnitude of fundamental component of the current (I_L) can be expressed in terms of voltage across TCR (V_{tcr}), reactor inductance (L) and firing angle α (in radians), as shown in (1).

$$I_L(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right) \tag{1}$$

The TCR behaves as a harmonic current source, with the amplitudes of the individual harmonics varying nonlinearly with the firing angle. The largest harmonic for most firing angles is the third harmonic. Other low-order odd harmonics are also significant, as shown in Fig. 4 [2].

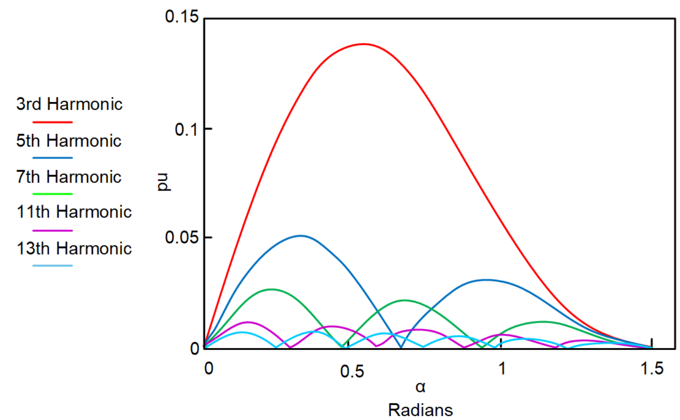


Fig. 4 TCR harmonics magnitudes pu of fundamental versus firing angle in radians

TCRs are connected in delta to allow the third-harmonic currents to circulate within the delta. Under balanced operation, no third-harmonic current leaves the delta. If the individual phases have uneven firing angles, some third-harmonic current will be injected to the power system. Installations designed for unbalanced operation may have third-harmonic filters. Unbalanced operation also results in fundamental frequency negative-sequence currents. Section III discusses the challenges harmonics and unbalanced operation pose for TCR protection.

Because of the critical nature of the SVC, TCRs can be operated with filter banks in case of a fault in a TSC or MSC, and vice versa. This is called SVC degraded mode of operation. Some installations will supplement the TCRs with mechanically switched reactors (MSR) or thyristor-switched reactors (TSRs). A TSR is built the same as a TCR but is always switched with firing angle α = 0. In TSR, the reactor is usually inserted for an integer number of cycles. As a result, the TSR does not produce harmonics. TSRs can still have unbalanced currents. The TSR reactor has similar protection requirements to the TCR.

III. TCR Faults and Protection

This section discusses different types of faults that could occur in TCR and provide guidance on how to detect these faults. Fig. 5 shows a typical TCR connection diagram with different types of faults, which can be classified as follows [3]:

- Phase faults (F1, F2, F3, F4)
- Ground faults (F5)
- Reactor overheating
- Thyristor valve short circuit (F6)
- Turn-to-turn faults (F7)

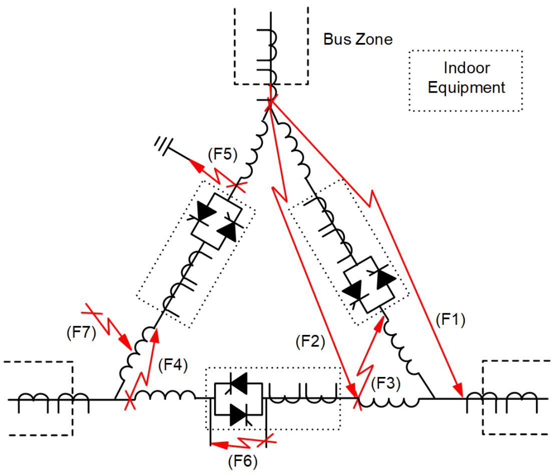


Fig. 5 Different types of faults in TCR

The SVC bus protection zone should include the coverage for the faults on the conductor from the SVC bus to the TCR and overlap with the TCR protection zone. The TCR branch CTs are usually located inside the thyristor valve/control room to avoid interference from the reactor stray flux.

A. Phase Faults

The probability of phase faults in a TCR is generally high [4] because of the following reasons.

- Proximity of conductors arranged for connection to indoor thyristor valves (often vertical)
- Proximity of conductors at SVC bus
- Phase-over-phase bus configuration

The primary protection for phase faults in TCR branches can be provided with 87 differential protection whose zone is comprised of one line CT and two TCR phase CTs, as shown in Fig. 6. Three such zones are required to cover the entire delta-connected TCR.

From a protection point of view, phase faults can be divided into two categories: Category 1, those that can be detected by the differential protection, like a short circuit between phase conductors (F1 and F2 in Fig. 6); and Category 2, those that are challenging for the differential protection (F3 and F4 in Fig. 6).

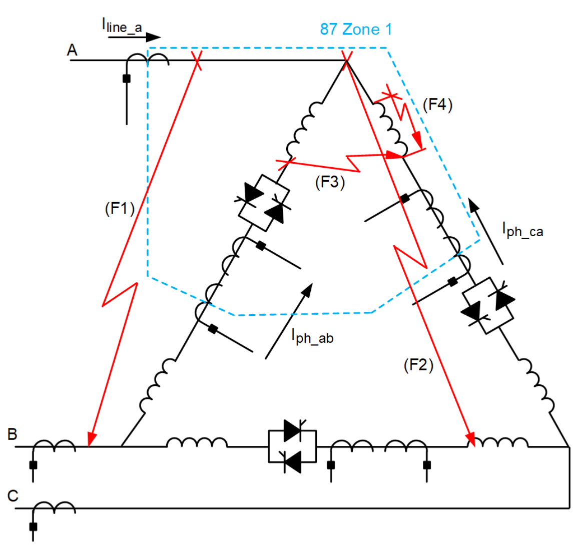


Fig. 6 TCR with differential zone and different phase faults

1) Category 1: Low-Impedance Differential

Category 1 faults result in a differential current (i.e., fault return path is outside the differential zone), making differential protection a viable option. The differential element can be either low-impedance or high-impedance [5]. High-impedance differential is not commonly used because of the need for dedicated CTs.

The low-impedance percentage differential element compares the operating current, which is the magnitude of vector sum of all the CT currents within the differential zone, against a restrained quantity which usually is the sum of magnitudes of all the CT currents within the differential zone. The element operates when the operating current is above a certain percentage of the restrained quantity. The operating and restraining currents for the TCR differential Zone 1 are as shown in (2) and (3).

$$I_{OP} = \left| I_{line\_a} + I_{ph\_ab} + I_{ph\_ca} \right| \tag{2}$$

$$I_{RT} = \left| I_{line\_a} \right| + \left| I_{ph\_ab} \right| + \left| I_{ph\_ca} \right| \tag{3}$$

This can be repeated for Zone 2 and Zone 3 by using their respective differential zone currents. The operating characteristic of the percentage differential element is shown in Fig. 7. The slope shown in Fig. 7 is typically configurable by a setting, and accounts for the CT and relay errors.

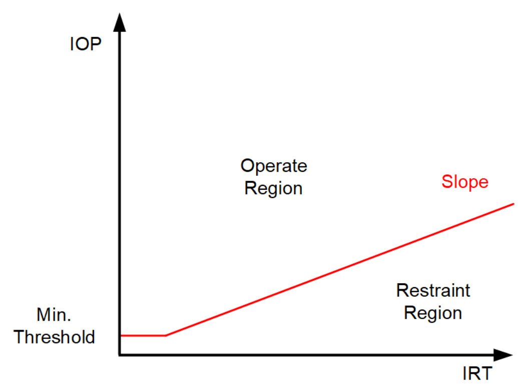


Fig. 7 Percentage differential characteristic

We developed an SVC model and the associated power system in Real Time Digital Simulator (RTDS) to simulate faults and evaluate the performance of the low-impedance differential protection. Section IV and the Appendix provide details of the simulated system. The TCR is operated with firing angle $\alpha \approx 0.4712$ radians when simulating the faults described in this section. Fig. 8 and Fig. 9 show the voltage and current profile and differential element response for faults F1 and F2 (Category 1 faults), respectively, in the TCR. The differential element successfully detected these faults.

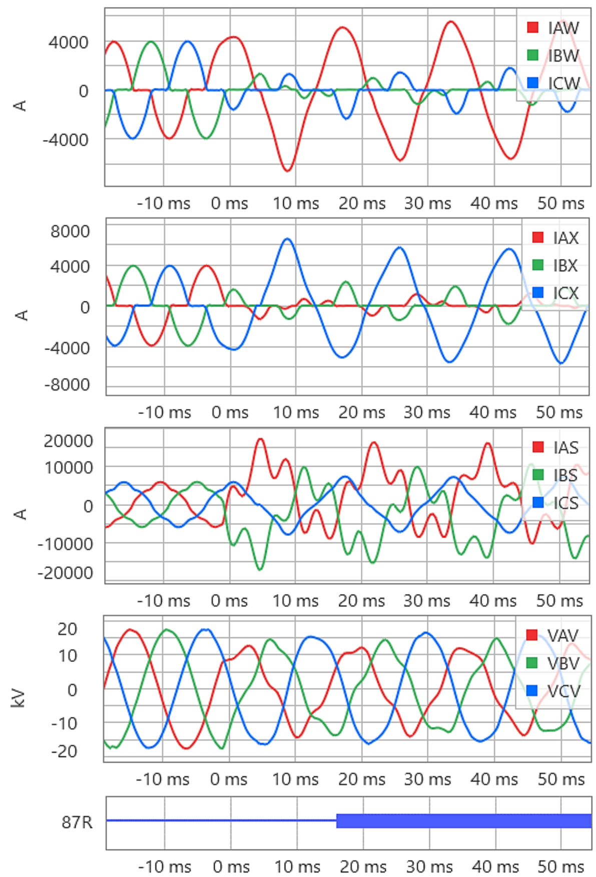


Fig. 8 Currents, voltages, and differential element response for TCR fault F1

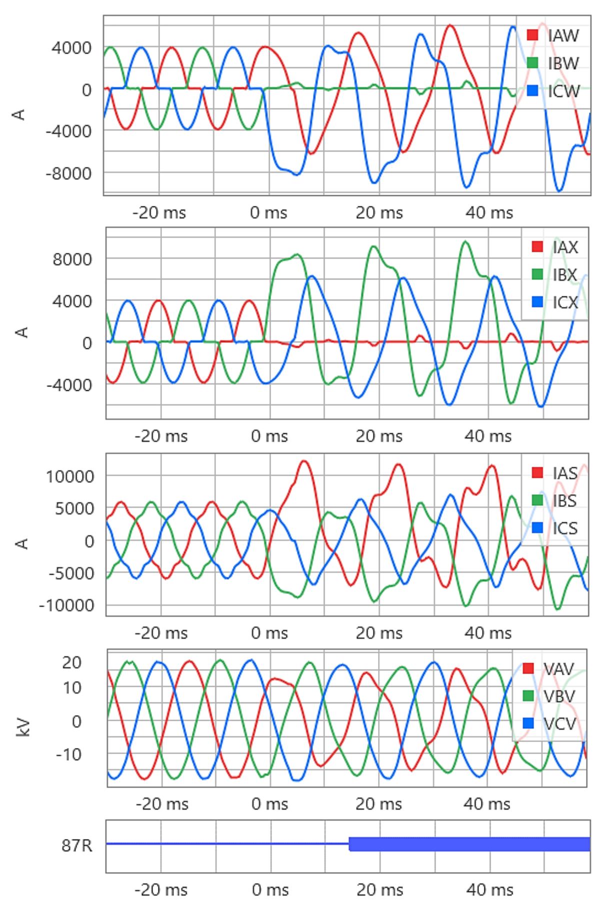


Fig. 9 Currents, voltages, and differential element response for TCR fault F2

where:

IAS/IBS/ICS are the TCR line currents

IAW/IBW/ICW, IAX/IBX/ICX are TCR branch (phase) currents

VAV/VBV/VCV are the line voltages

Terminal S, W, and X currents are included in the differential zone

During TCR energization in full conduction mode, high dc offset transient could drive the CT into saturation, resulting in differential current. Therefore, the differential element should be blocked using an energization indication, like the breaker status, for initial few cycles of TCR energization. This approach will delay the differential element when energizing the TCR with a phase fault.

As discussed in Section II, operation of the SVC could result in harmonics, therefore we recommend not using harmonic restraint or harmonic blocking algorithms when protecting TCRs [4].

2) *Category 2: Overcurrent*

For Category 2 faults (F3 and F4 in Fig. 6), the fault return path is within the differential zone, which does not result in differential currents. When TCR is operated in a symmetrical mode, these faults can be detected by the negative-sequence directional overcurrent element. Fig. 10 shows the directional negative-sequence overcurrent element logic.

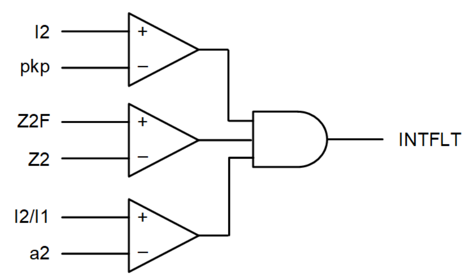


Fig. 10 Negative-sequence overcurrent element with directional supervision

where:

I2 is negative-sequence line current magnitude

I1 is positive-sequence line current magnitude

Z2F is forward directional threshold

Z2 is negative-sequence impedance calculated from the line currents looking into the TCR

a2 is positive-sequence restraint factor setting

Fig. 11 and Fig. 12 show the voltage and current profile and element response for faults F3 and F4 in the TCR. The negative-sequence overcurrent element successfully detected these faults.

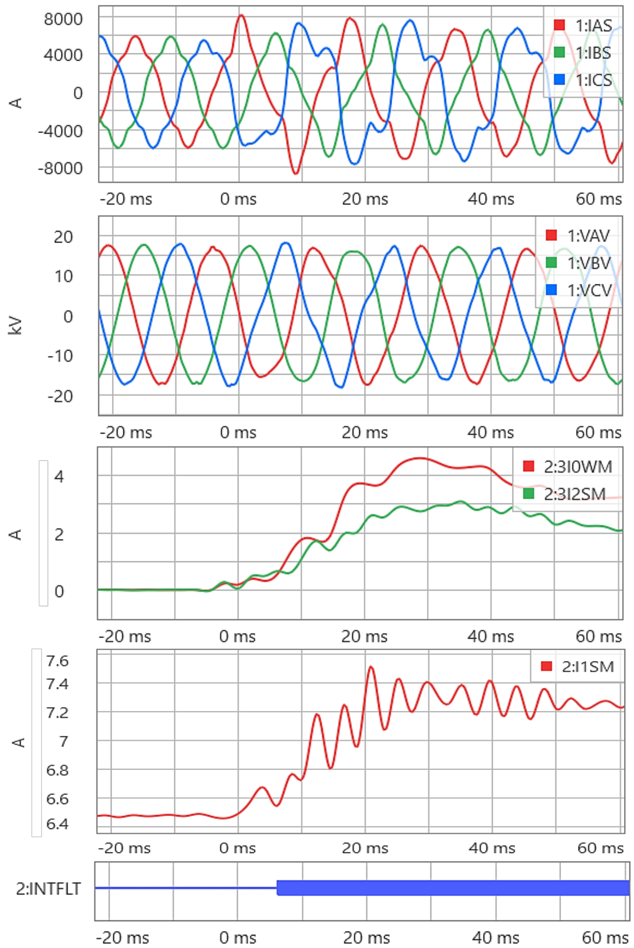


Fig. 11 Currents, voltages, and negative-sequence overcurrent element response for TCR fault F3

3I0WM is the zero-sequence current magnitude calculated from TCR branch currents and 3I2SM is the negative-sequence current flowing into the TCR, both in secondary amperes.

The sensitivity of the overcurrent elements decreases as the firing angle α increases. For example, the current change seen will be very low when $\alpha \approx \pi/2$ radians (refer to (1) in Section II).

As discussed in Section II, triplen harmonics circulate in the TCR delta during normal symmetrical operation. Fundamental zero-sequence currents circulating the delta can also be used to detect these faults.

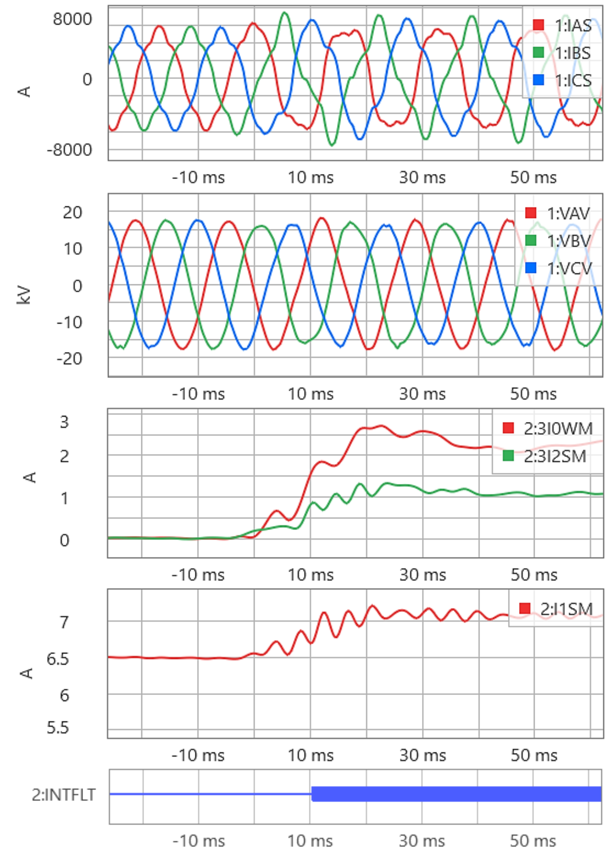


Fig. 12 Currents, voltages, and negative-sequence overcurrent element response for TCR fault F4

B. Ground Faults

Air core reactors are arranged with high ground clearances that reduce the probability of ground faults but does not completely eliminate their possibility [5]. The components on the MV side of the SVC transformer by themselves are ungrounded. Often a grounding (zig-zag) transformer is used to provide the ground reference to accurately detect the ground fault using the residual (zero-sequence) overcurrent element. A sensitively configured residual overcurrent element operating on line currents can detect ground faults within the TCR. Subsequently, residual overcurrent elements on all the components in the SVC MV bus help selectively identify the associated faulted component so the faulted component can be isolated and the SVC can be operated in a degraded mode.

Fig. 13 shows the currents and voltages for a ground fault in the TCR BC phase (F5 in Fig 5 on BC phase) with a grounding transformer on the SVC MV bus. The ground overcurrent element with TCR line currents as inputs was able to detect the ground fault in the TCR.

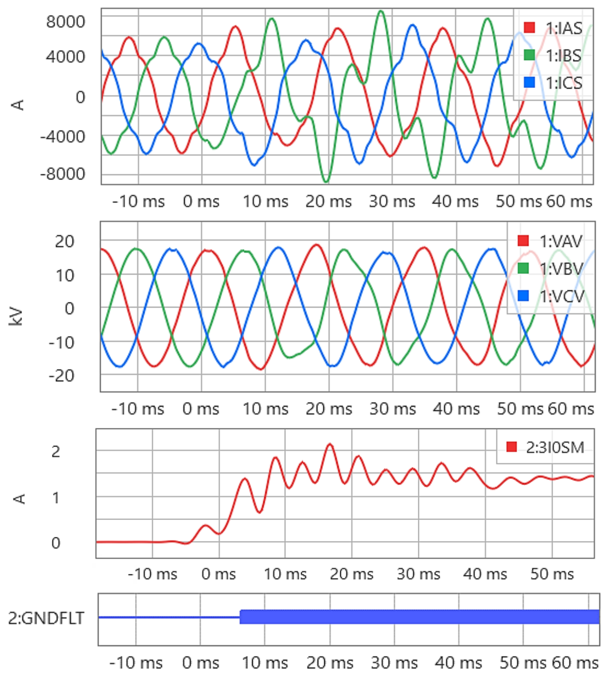


Fig. 13 Currents, voltages, and residual overcurrent element response for TCR fault F5

Ground faults can also be detected by monitoring the zero-sequence voltage either by using an open-delta PT or by calculating zero-sequence voltage from the phase voltages with a wye-grounded PT on the SVC MV bus. The residual overvoltage element can sensitively detect the ground in an SVC MV system but cannot selectively determine the faulted component. Reference [5] provides a solution to identify the faulted component.

C. Reactor Overheating

Thermal protection algorithms can be applied to protect the TCR against overheating caused by harmonics. The probability of overheating from large fundamental currents is rare because of the current limiter algorithm in the TCR control [3], which is primarily intended for the thyristor valve protection. Thermal elements can also be a good backup for the TCR current limiter.

D. Thyristor Valve Short Circuit

The thyristor valves in TCR usually fail in shorted mode. An external short circuit across the thyristor valves can also occur in TCR. To protect the equipment against such scenarios, the TCR control algorithm compares the measured value of TCR current against an internal estimation [3]. The details of this algorithm are outside the scope of this paper.

E. Turn-to-Turn Faults

Turn-to-turn faults are associated with very small changes in phase currents and do not result in differential currents, challenging both phase overcurrent and differential protection. The associated fault current within the shorted turns is very high, which makes the turn-to-turn fault detection failure a huge safety concern. The following is a review of the available existing turn-to-turn fault detection schemes and their application limitations for protecting TCRs.

1) Negative-Sequence Overcurrent Element

A sensitively set negative-sequence overcurrent element with proper directional supervision is applied to detect turn-to-turn faults in conventional wye-connected reactors. The pickup must be set higher than the acceptable reactor unbalance (based on construction), which unfortunately limits the detection of lower order turn-to-turn faults involving a small number of turns. Considering the acceptable unbalance and minimum pickup setting that most modern relays allow, the turn-to-turn fault has to evolve, involving more turns, for this element to detect the turn-to-turn fault. However, this scheme can only be applied to a delta-connected TCR that is designed to operate symmetrically. If the TCR is operating unsymmetrically, negative-sequence currents flow in the TCR, challenging the negative-sequence directional overcurrent element.

2) Zero-Sequence Overcurrent Element

A zero-sequence overcurrent element is also used to detect turn-to-turn faults in conventional shunt reactor applications. In case of TCR, the zero-sequence current circulating within the delta can be calculated from the individual branch currents. The protection based on the fundamental (50/60 Hz) component can still be applied to detect turn-to-turn faults when a TCR is operated symmetrically. Like the negative-sequence overcurrent scheme, this element is also challenged if the TCR is operating unsymmetrically.

3) Voltage Unbalance Element

A voltage unbalance element can be used to detect turn-to-turn faults in conventional, wye-ungrounded air core reactors [6]. The underlying principle is based on the neutral voltage that arises due to unbalance caused by a turn-to-turn fault. This scheme cannot be applied for TCRs, which are configured in a delta connection.

4) Mechanical Relays

Gas accumulator relays and sudden pressure relays are used to sensitively detect turn-to-turn faults in oil-immersed reactors. They cannot be applied to the air core reactors in TCRs.

We propose a novel current waveshape-based turn-to-turn fault detection to address the limitations of the discussed protection elements.

IV. Proposed Turn-to-Turn Fault Detection Using the Current Waveshape

As described in Section II, the dynamic reactive power compensation is provided by varying the firing angle of the thyristors in a TCR. The firing angle change results in a change in the effective impedance of the TCR branch. The turn-to-turn fault also changes the effective impedance of the TCR branch. The current flowing in the TCR branch changes during the following scenarios:

- Change in firing angle of the thyristor
- Turn-to-turn fault in the TCR reactor
- Change in voltage at MV bus

Fig. 14 shows TCR currents concurrently plotted for the three scenarios. For the first scenario, we assume the TCR is operating at a particular voltage and a certain firing angle α, which is the steady-state reference current (in black). The second scenario shows the current for a turn-to-turn fault (T2TFLT) where the effective impedance of the reactor decreases and TCR current magnitude increases, as shown by the dashed red line. The TCR controller then brings the impedance to a pre-fault level by increasing the firing angle, indicated by the blue line.

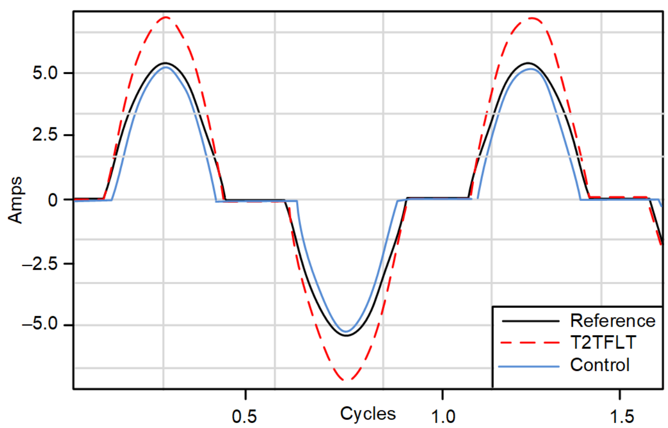


Fig. 14 TCR current waveform for pre and post turn-to-turn fault

The distinct feature to be noted here is the change in TCR current with no associated increase or decrease in dead time (the time the current is zero) during a turn-to-turn fault. The TCR current also changes if the magnitude of the voltage across the TCR changes for a particular firing angle, but not when a turn-to-turn fault occurs. These signatures can be used to selectively detect turn-to-turn faults in the TCR.

Fig. 15 shows the proposed logic based on the unique signature discussed previously. This logic works by detecting the changes in TCR current without any corresponding changes in the MV bus voltage or the TCR thyristor firing angle. For protection purposes, the thyristor firing angle change can be calculated by measuring the dead time (thyristor non-conducting time) in the raw TCR current. Incremental quantities can be used to detect the change in current, voltage, and thyristor dead time.

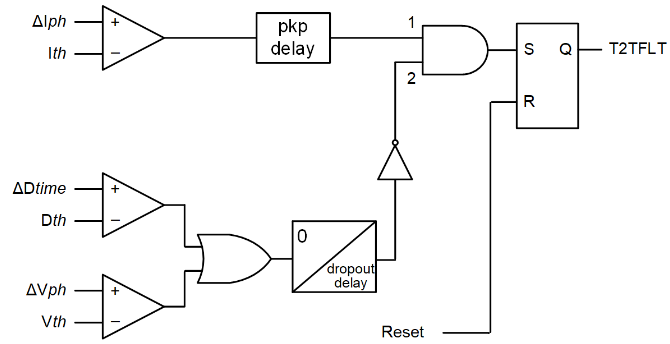


Fig. 15 Turn-to-turn fault protection logic for TCR

where:

Δ represents change in quantity

ΔIph is change in the TCR phase current magnitude

ΔDtime is change in the thyristor dead time

ΔVph is change in the voltage magnitude across the TCR branch

Ith, Dth, and Vth are corresponding minimum thresholds

We implemented the logic in Fig. 15 using voltage and current incremental quantities calculated using a two-cycle window. Magnitude of the incremental quantity is estimated and compared with a corresponding threshold. For better sensitivity, an adaptive threshold is used for Ith and Vth. Fig. 16 shows the logic to derive the adaptive threshold. We used an IIR filter to estimate the standing background noise in the incremental quantity magnitude [7]. The input incremental signal DI is clamped between the minimum and maximum values to restrict the impact of transient/erroneous values on the IIR filter output. The incremental quantity magnitude (ΔIph, ΔVph) is then compared with a factor *K* (we used *K* = 3 in our analysis) times the respective adaptive thresholds.

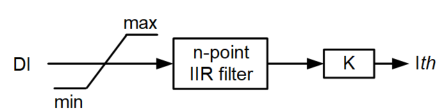


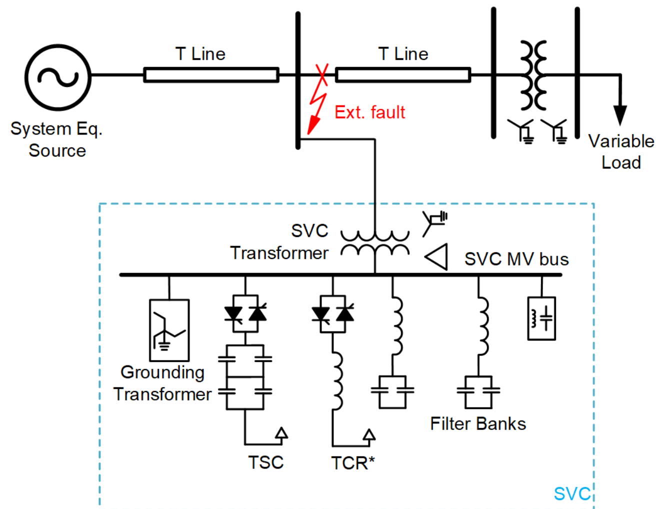
Fig. 16 Adaptive threshold

The thyristor dead time input to the logic is calculated every half cycle and is used for the next half cycle. The incremental dead time change is calculated by subtracting the latest dead time with corresponding value two cycles prior.

The pickup delay should be less than the response time of the SVC controller (a pickup delay of 0.5 cycles and dropout delay of 4 cycles are used for validating the logic). The proposed scheme is phase-segregated and is not affected by the TCR symmetrical or unsymmetrical mode of operation. The sensitivity of this logic is affected when the thyristor firing angle is closer to π/2 radians, i.e., the conduction angle is closer to zero similar to the sequence overcurrent elements discussed in Section III, because of the low current in the TCR. This scheme should also be supervised with energization indication to block it from operating for incremental quantities during initial TCR energization.

This logic is inherently secure for external faults because these faults are associated with voltage and thyristor conduction time changes.

The proposed turn-to-turn fault detection logic is validated using a power system modeled in RTDS. This model includes the SVC along with the control based on [8], as well as the proposed protection scheme. Fig. 17 shows the single-line diagram of the power system model and the SVC, and the Appendix shows parameters associated with the model. The SVC control is designed to operate unsymmetrically, providing individual phase compensation. Fig. 18 shows the delta-connected TCR.



* See Fig. 18.

Fig. 17 Single-line diagram of the simulated system

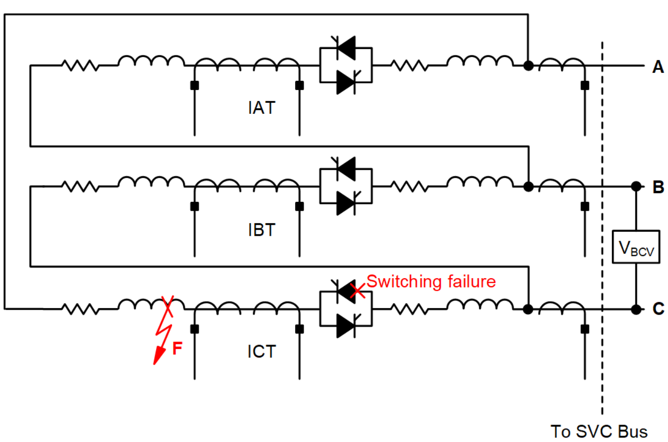


Fig. 18 Delta-connected TCR

The proposed logic monitors the change in phase currents (IAT/IBT/ICT) from the TCR branch CTs location shown in Fig. 18. The logic also monitors the phase voltage across the TCR branches using PTs (V_{BCV} is shown for reference in Fig. 18).

V. Simulation Results Using Proposed Element

The results of the simulation to validate the proposed logic are shown in this section. The cases include:

- Turn-to-turn faults (location shown in Fig. 18)
- External disturbances (location shown in Fig. 17)
- Switching failure (location shown in Fig. 18)

The proposed logic can detect the turn-to-turn faults with high sensitivity compared to the existing protection elements and is unaffected by the external faults, system unbalance, and thyristor gating failures.

A. Case 1: 4 Percent Turn-to-Turn Fault

Fig. 19 shows an RTDS capture for a turn-to-turn fault simulated by shorting 4 percent inductance in the TCR between the A- and C-Phases. The fault is initiated at 0.1 sec. Note that the TCR is operating at firing angle $\alpha \approx 0.471$ radians. VAZ/VBZ/VCZ are phase-to-neutral voltages on the HV side of the SVC transformer in secondary volts. VABV/VBCV/VCAV are phase-to-phase voltages on the MV side of the SVC transformer in secondary volts. IAT/IBT/ICT are the TCR branch currents in secondary amperes. A1, B1, and C1 are the current change detectors for A-, B-, and C-Phase that drive the T2TFLT shown in Fig. 15. On the other hand, A2, B2, and C2 are the corresponding blocks driven by TCR dead time and voltage changes. The turn-to-turn fault resulted in a small change in current without the associated change in dead time or voltage, C1 asserted and C2 remained deasserted, and the logic asserted T2TFLT.

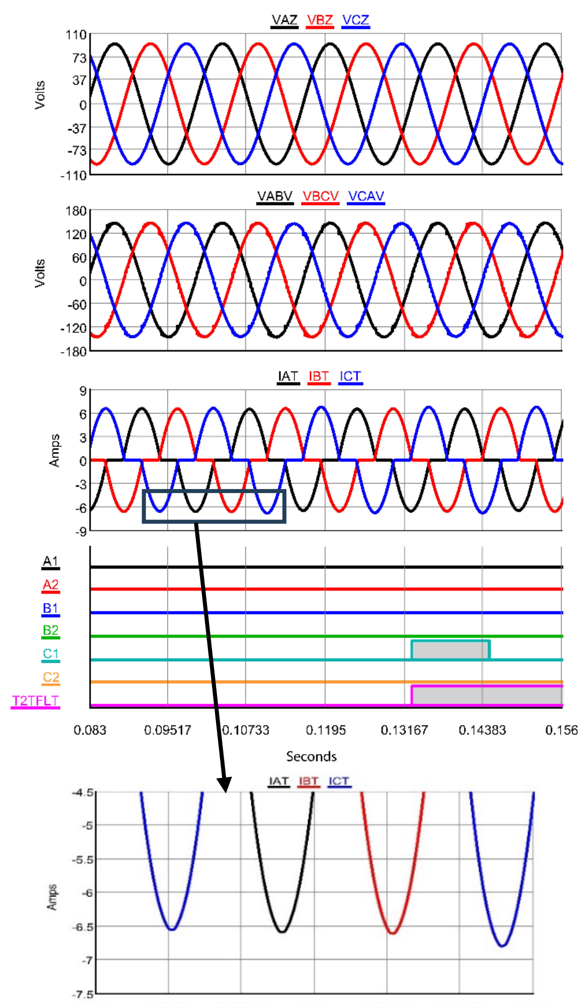


Fig. 19 Voltages, currents, and proposed logic response for 4 percent turn-to-turn fault in TCR AC-Phase reactor

B. Case 2: 25 Percent Turn-to-Turn Fault

Fig. 20 shows the SVC voltage, TCR currents, and proposed logic response for a turn-to-turn fault simulated by shorting 25 percent inductance between the A- and C-Phase of the TCR. Current change (C1) is detected early, and because the effective change in impedance was high, a delayed voltage and dead time change (C2) can also be seen. This is due to the controller action increasing the dead time to get the compensation to a prefault level. C1 initially asserted without C2 asserting, and the logic asserted T2TFLT.

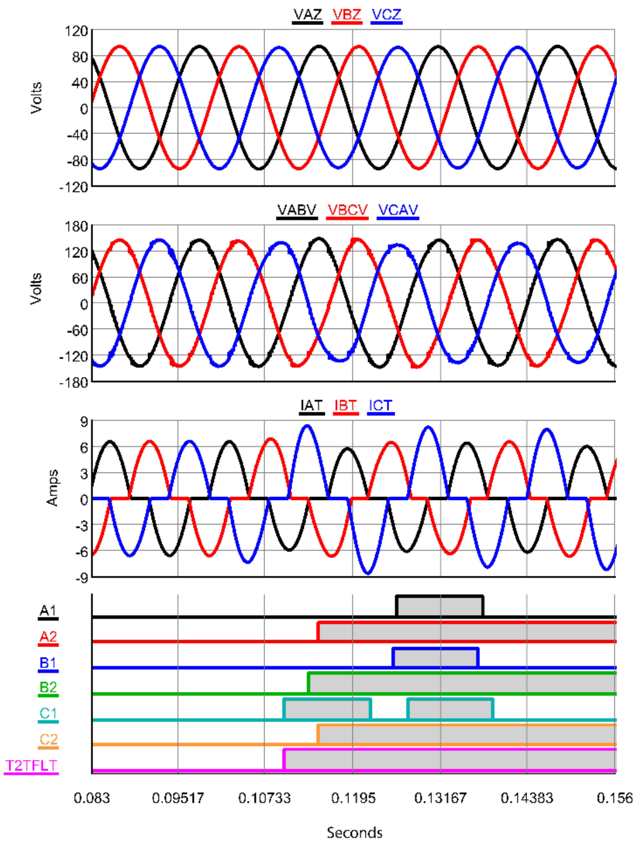


Fig. 20 Voltages, currents, and proposed logic response for 25 percent turn-to-turn fault in TCR AC-Phase reactor

C. Case 3: External CG Fault on the HV Side of the SVC

Fig. 21 shows the SVC voltages, TCR currents, and proposed logic response for a simulated external CG fault on the high voltage side of the SVC transformer at 0.1s. The fault resulted in a significant change in voltage and the SVC started to compensate for the external disturbance. The change in voltage and dead time (C2) was detected before the current change (C1), blocking the T2TFLT assertion.

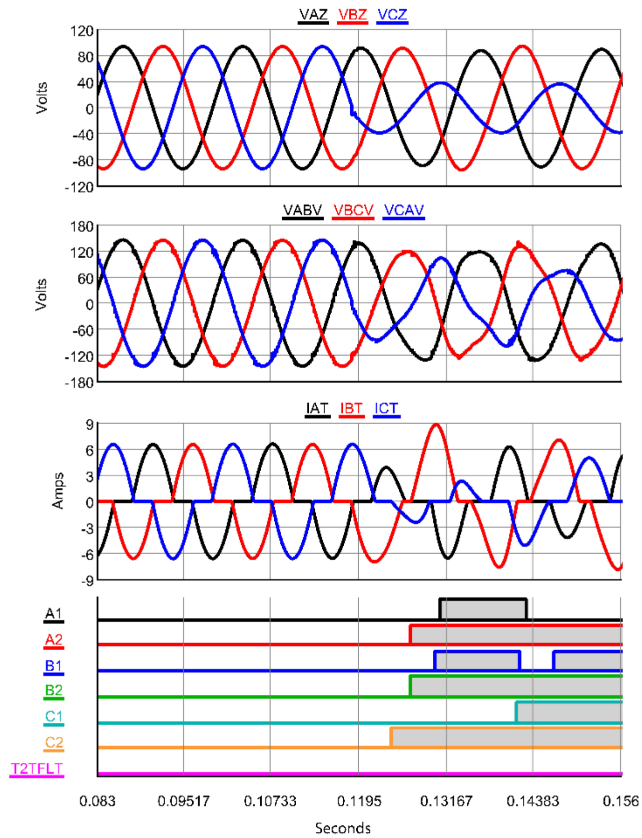


Fig. 21 Voltages, currents, and proposed logic response for CG fault on the HV side of the SVC transformer

D. Case 4: Single-Pole Open

Fig. 22 shows the SVC voltages, TCR currents, and proposed logic response for a single-pole open simulated on the B-Phase at the remote load at 0.1s. The increase in voltage on the HV side of the SVC transformer as a result of external disturbance can be clearly seen. The SVC then started to compensate for the external disturbance. The logic sensed the change in voltage and dead time (C2) that occurred before the current change (C1), providing evidence of an external disturbance, and thereby blocked the T2TFLT assertion.

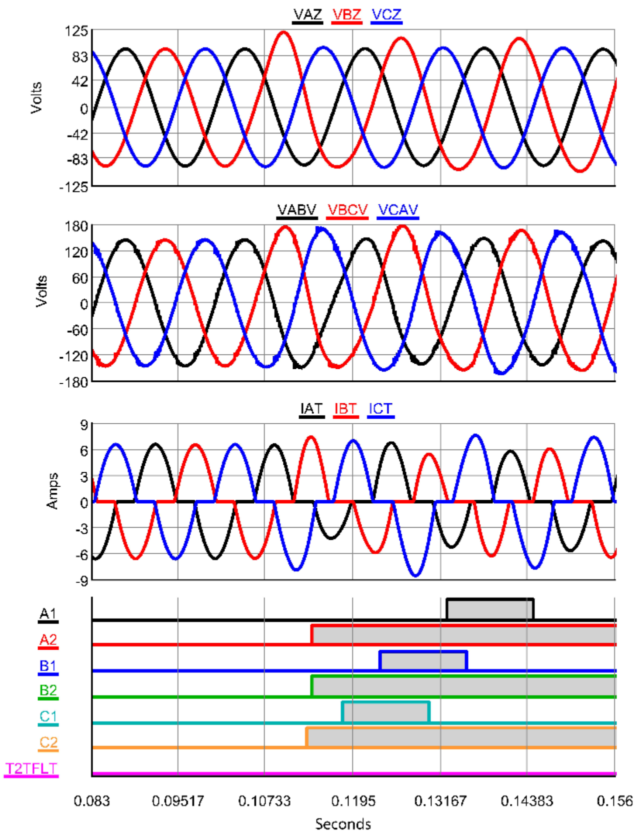


Fig. 22 Voltages, currents, and proposed logic response for remote B-Phase load single-pole open condition

E. Case 5: Thyristor Gating Failure

Fig. 23 shows the SVC voltages, TCR currents, and proposed logic response for a simulated gating failure in the thyristors between the A- and C-Phases. The thyristor switches responsible for positive half cycles failed to turn on. We can see that the dead time changed (C2) due to switching failure, which was detected before the associated current change (C1), thereby blocked the T2TFLT assertion.

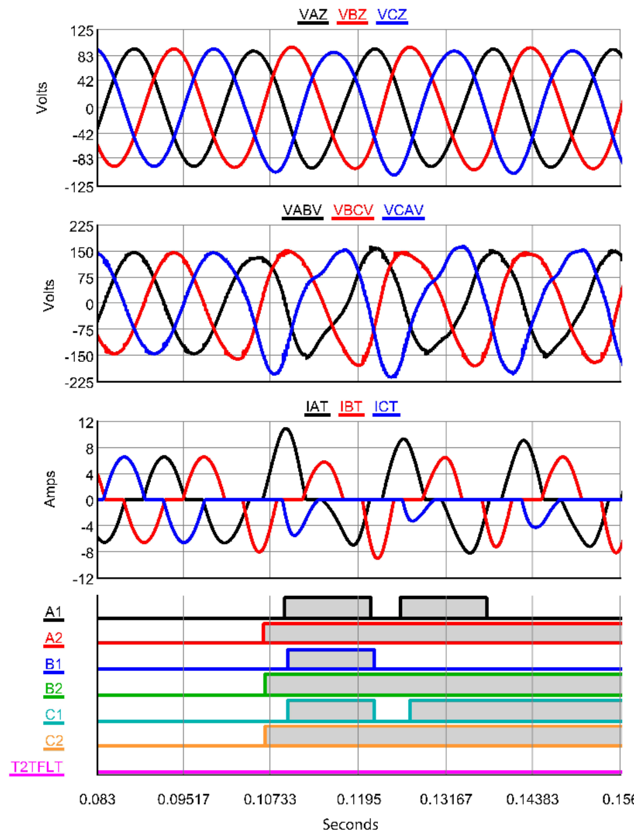


Fig. 23 Voltages, currents, and proposed logic response for thyristor gating failure between A- and C-Phase of the TCR

VI. Conclusion

Rapid reactive power compensation is a possibility because of dynamic control of SVCs. The TCR is a critical component of an SVC, and its availability is affected in case of internal faults. These faults must be detected and isolated promptly so that quick measures can be taken to reduce the SVC down time. Accurate fault identification will help in switching the SVC to operate in a degraded mode.

Differential protection can be used primarily to detect the phase faults in TCR. Overcurrent elements can be used to detect phase faults that do not result in differential currents. Residual overcurrent elements can be used to detect ground faults if there is a grounding transformer on the SVC MV bus. A residual voltage element can also be used to identify ground faults, but it cannot selectively determine the faulted component.

Protection elements used for conventional reactor turn-to-turn fault protection are challenged in TCR applications due to the use of air core reactors and the TCR delta configuration. The TCR modes of operation (symmetrical/unsymmetrical) and thyristor firing angle add further challenges in detection of turn-to-turn faults. The novel TCR current waveshape-based protection scheme proposed and demonstrated in this paper can be used to detect turn-to-turn faults in TCRs. This scheme is secure for external unbalances and switching failures and can be applied independent of the mode of TCR operation.

VII. Appendix

A. System Data

This appendix provides the parameters of the system model designed in RTDS for testing purposes shown in Fig. 17 and Fig. 18. The system nominal frequency is 60 Hz.

Table 1 Model Parameters

Component	Parameters
SVC Transformer	230 kV-Y/24 kV-D, 200 MVA
TSC and HFB	92 MVAR/phase
TCR	0 to –186 MVAR/phase
CTs	Ratio – 600
PT- Z (SVC HV side)	230 kV / 115 V
PT- V (SVC MV side)	24 kV / 115 V
Eq. Source	261 kV / 60 Hz, $Z_{th} = 22\angle 80^{o}$
Transmission Line	140 miles, Z_c = 631.4, R = 70.4
Load Side Transformer	230 kV-Y / 110 kV-Y, 1000 MVA
Load R	420 MW
Load L	0 to 320 MVAR
Load C	180 to 364 MVAR

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IX. Biographies

Shashidhar Reddy Sathu received his Bachelor of Technology degree in Electrical Engineering from Indian Institute of Technology (ISM) Dhanbad, India in 2015. He received his Master of Science degree in Electrical Engineering from the University of Idaho in 2016. He joined Schweitzer Engineering Laboratories in 2016 as an engineering intern and is currently a lead power engineer in the research and development division. He is a member of IEEE.

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20230911 • TP7133-01