Enspec Power Ltd
6 Waterside Court
St. Helens Technology Campus
St. Helens
Merseyside
WA9 1UA

T: +44 (0) 1744 610940
E: info@enspecpower.com

ABC Wind Farm – Shunt Reactor TRV Study

Client: NA

Report number: NA

Location: ABC

Prepared by: Kerim Ozer

Date: 24/07/2020

Revision: 0

Position: Electrical Engineer

Email: kerim.ozer@enspecpower.com

Phone: +44 1744 610946

Website: www.enspecpower.com

Authorised: Tim Rastall

Position: Director

Revision Control

Revision	Status	Prepared by	Approved by	Date
R0	First Issue	KO	TR	24/07/2020

Executive Summary

This report was produced by Enspec Power LTD on behalf of Ltd. It details a Temporary Recovery Voltage (TRV) study carried out for ABC Wind Farm in order to assess TRV ratings of the shunt reactor circuit breaker.

The following events have been investigated: De-energisations of the shunt reactor, credible single phase-to-ground and three phase-to-ground faults, simulations of the worst case TRV peak and Rate of Rise Recovery Voltage (RRRV) values of the vacuum circuit breaker (VCB), with a comparison of the results with the switching capability of the VCB according to IEC 62271-100, and finally a discussion of the possible solutions in order to reduce the TRV values to below VCB ratings.

In conclusion, the investigations found that the TRV values for the de-energisation of the shunt reactor and the fault interruption of a three phase-to-ground and single phase-to-ground fault at the reactor terminals were not compliant with the corresponding envelopes described in IEC 62271-100 (T10 / T60).

The probability of a fault between the VCB and shunt reactor terminal is low. Nevertheless, the de-energisation of the shunt reactor would be considered as frequent. Thus, a TRV / Overvoltage suppression / mitigation method should be considered. It is essential not only for the TRV requirement, but also for protecting the reactor against over voltages.

An RC snubber with appropriately sized SAs, or controlled switching with appropriately sized SAs are considered to be the best solutions to suppress the TRV to below the breaker ratings, minimise/eliminate probability of reignition phenomena and reduce the overvoltage stress at the reactor terminals. Note that independent pole operation is required for the solution of controlled switching.

Table of Contents

Figure Lists

Table Lists

1 Introduction

This report details a TRV study carried out for ABC Wind Farm WF, on behalf of Ltd. A TRV study was carried out in order to investigate the TRV ratings of the VCB caused by de-energisations of the shunt reactor and credible faults at the reactor terminals. The results were compared to the CB TRV ratings defined by the IEC 62271-100 standard.

The ABC WF consists of 11 x 3.6 MW and 3 x 3.45 MW Vestas Wind Turbine Generators (WTGs), with the total capacity of 49.95 MW. The WF is divided into two arrays (A&B) and each array is connected to the switchgear room at the control room - Each array is equipped with seven off WTGs via 4 MVA 33/0.65 kV step up transformers. The switchgear room is connected to the SSEN 33 kV switchgear room via 33kV, 15m, 2 x 3 x 1c x 630mm2 Al XLPE cable. The 33 kV, 2.5 MVAR, shunt reactor is connected to the SSEN 33kV switchgear room via 33 kV, 43m, 3 x 1c x 800 mm^2, Al, XLPE cable. The power is then exported to the 33kV SSE substation via ~14km, 33kV, 2 x 3 x 1c x 800 mm^2, Al, XLPE cable.

The following studies have been undertaken using the power systems software package PSCAD™/ EMTDC™:

- A TRV study was carried out to investigate peak TRV and RRRV values of the related VCB based upon the normal de-energisation of the shunt reactor – 20 different opening points were considered over a 20ms time period at 1ms intervals. The results were compared to the two parameter T10 envelope defined by IEC 62271-100.

- A TRV study was carried out to investigate the peak TRV and RRRV of the related VCB based upon the credible single phase-to-earth and three phase-to-earth faults at the reactor terminals. The model was run for the fault clearance time range between 20ms and 60ms at 1ms intervals. The results were compared to the two parameter T10 and T60 envelopes for single phase-to-earth and three phase-to-earth faults, respectively.

- Based upon the IEEE Guidance for the Application of Shunt Reactor Switching (IEEE Std C37.015™ - 2017), each possible over voltage mitigation method maintain TRV ratings of the VCB have been detailed.

2 Study Data

Based upon the SSEN-SHEPD Long Term Development Statements (LTDS) and National Grid Electricity Ten Year Statement (ETYS), the model has been extended up to the 132 kV substation. The model includes a detailed representation of ABC WF and an equivalent model of EFG WFs at the 33 kV Busbar. The total capacity of ~20 MW load at the various 11 kV busbars has been modelled at the 33 kV busbar with a 33/11 kV transformer. A PSCAD snapshot of the site under study including the external grid is shown in Figure 2- 1.

2.1 External Grid Data

[redacted] substation is connected to the nodes [redacted] and [redacted] at the 132 kV [redacted] substation via two off 33/132 kV step up grid transformers. [redacted] 132 kV substation is linked to SSEN [redacted] substation via 2 off 13.08km Overhead Lines (OHL). Also, [redacted] substation is connected to the nodes [redacted] and [redacted] at the 132 kV [redacted] substation via two off 33/132 kV step up grid transformers. The schematics of external grid, fault level, transformer and cable details are given in **Error! Reference source not found.**. Based upon the ETYS and SSEN-SHEPD the following external grid details were used:

- A maximum fault level of 3001.9 MVA at [redacted] substation was modelled – the fault level refers to Winter, 2028/29.
- 2 off parallel OHLs were modelled. A maximum fault level of 3001.9 MVA at [redacted] substation has been used – the fault level refers to Winter, 2028/29.
- The grid transformers of 2x90 MVA and 2x60 MVA at [redacted] substations will be replaced by 120 MVA transformers in 2021 and 2023, respectively, so 120 MVA transformer details were used.

2.2 WFs Details at CAAD 3J

[redacted] WFs were modelled with their full capacity of 30 MW, 43.7MW and 15 MW at unity PF. [redacted] WFs export power via 5647m and 7936m underground cables - the model also includes a Bergeron Model of the cables. Due to the short length of the cable between [redacted] WF and [redacted], it was not included in the model.

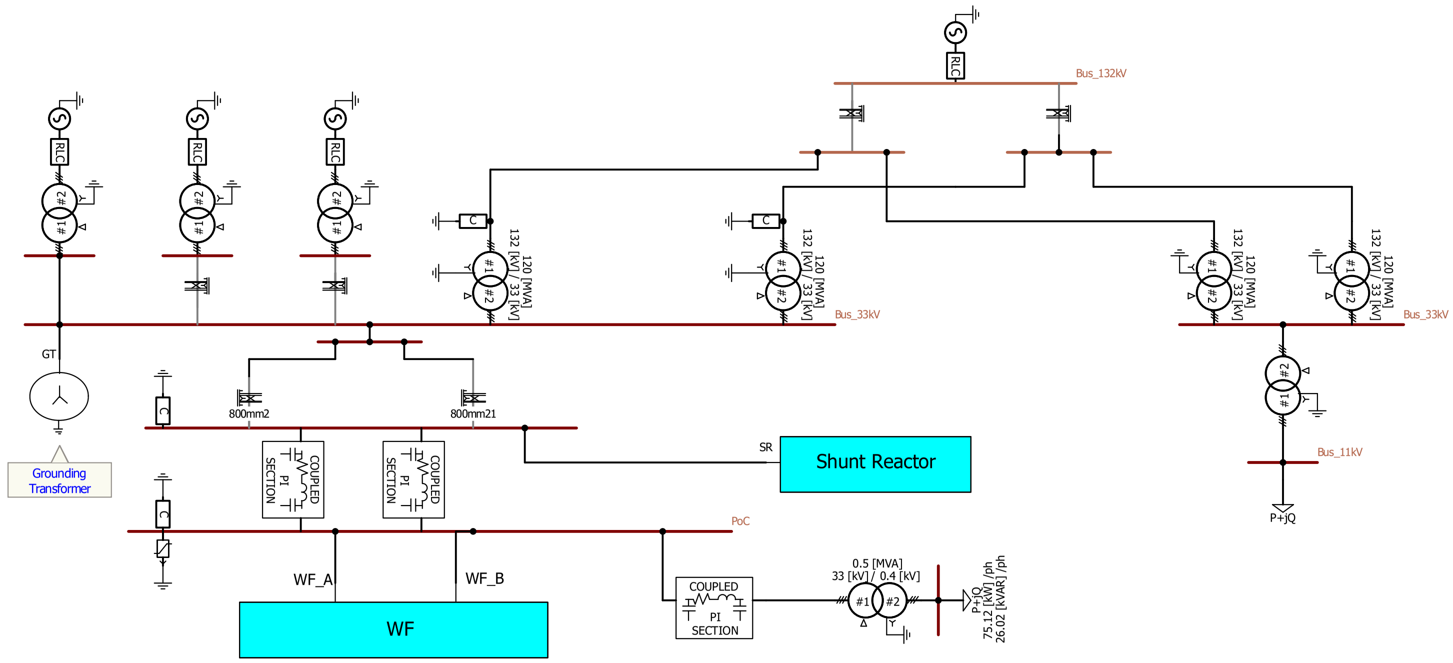

Figure 2- 1 – Snapshot of the Site's PSCAD Model

2.3 ABC WF Data

The [redacted] WF consists of 11 x 3.6 MW and 3 x 3.45 MW Vestas Wind Turbine Generators (WTGs), with the total capacity of 49.95 MW. The WF is divided into two arrays (A&B) and each array is connected to the [redacted] switchgear room at the [redacted] control room – Each array is equipped with seven off WTGs via 4 MVA 33/0.65 kV step up transformers. The [redacted] switchgear room is connected to SSEN 33 kV switchgear room via 33 kV, 15m, 2 x 3 x 1c x 630mm2 Al XLPE cable. 33 kV, 2.5 MVAR, ungrounded star shunt reactor is connected to SSEN 33kV switchgear room via 33 kV, 43m, 3 x 1c x 800 mm2, Al, XLPE cable. The power is then exported to the 33kV SSE [redacted] substation via ~14km, 33kV, 2 x 3 x 1c x 800 mm2, Al, XLPE cable.

The electrical data of wind farm items such as, cable schedules and datasheets, transformers and Wind Turbine Generator (WTG) fault contribution details are given in the appendix.

A snapshot of the Wind Farm model that was used during the TRV study is shown below in Figure 2- 2.

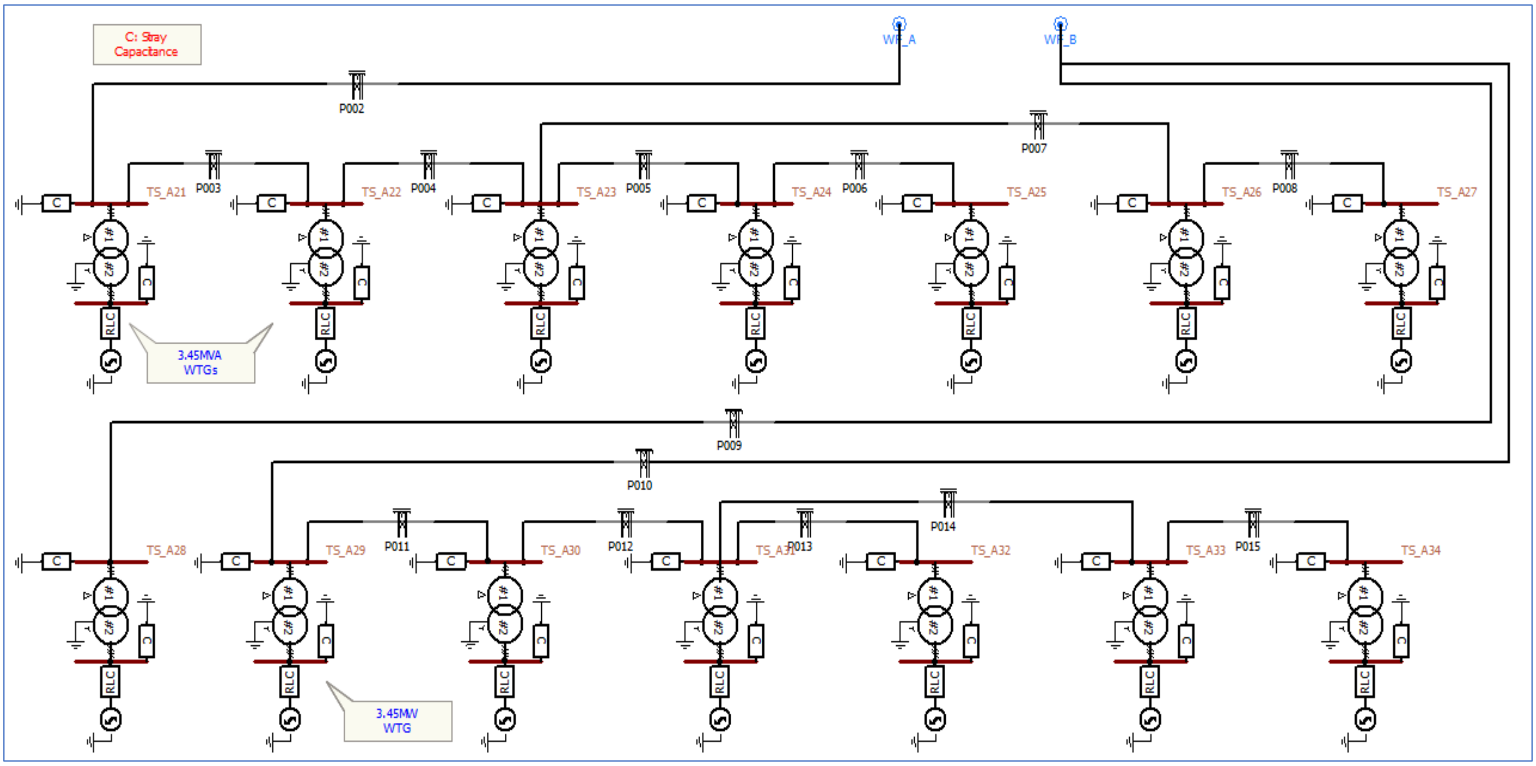

Figure 2- 2 – Snapshot of ABC WF PSCAD Model

2.4 WTG Data

As instructed by the turbine manufacturer, the following fault contribution details of the Vestas 3.45 MW and 3.60 MW WTGs, when a three-phase solid fault was applied at 33kV WTG transformer terminals, were used in this study. Thevenin equivalent circuit parameters of the WTGs were calculated using the WTG transformer impedance details. The fault contribution details are tabulated in Table 2- 1.

Fault currents	3.45 MW WTG @60.36A	3.60 MW WTG @62.98A
I peak (pu)	2.053	2.079
Ik (pu)_RMS	1.1	1.1

Table 2- 1 - WTG Fault Contribution (33 kV)

The study was carried out with all WTG units in the wind farm operating at their maximum MVA levels with unity power factor.

2.4.1 WTG Transformer Data

Siemens 4MVA WTG transformer details are tabulated in Table 2- 2.

S(kVA)	Nominal Voltage (kV/kV)	Uz (%)	Winding Connection	Load Losses(kW)
4000	33/0.65	9.02	Dyn5	29.3

Table 2- 2 - Siemens WTG Transformer Detail

2.4.2 WF Cable Schedule

Apart from the 40m cables between WTG switchgears and WTG towers, all WF Cables were modelled. Also, WF power exporting cables located between the 33 kV SSE Carradale 1 were included in the model - the 2 off parallel ~14km, 33 kV, 2 x 3 x 1c x 800 mm^2, Al, XLPE cables (Nexans). The cable schedules and datasheets are given in the appendix.

2.4.3 Shunt Reactor Data

A 33 kV, 2.5 MVAR, ungrounded WYE shunt reactor is connected to the SSEN 33kV switchgear room via 33 kV, 43m, 3 x 1c x 800 mm², Al, XLPE cable. In order to consider the damping of the shunt reactor, winding and core losses were model in detail. The reactor details are tabulated in Table 2- 3.

V_N [kV]	S_N [MVAR]	Inductance [H]	Coil Losses [kW]	Core Losses [kW]	Coil Resistance (r) [ohm]	Core Resistance (R) [ohm]
33	2.50	1.38656	4500	11000	0.78408	99000

Table 2- 3 - Shunt Reactor Detail

A PSCAD snapshot of the shunt reactor under study is shown in Figure 2- 3.

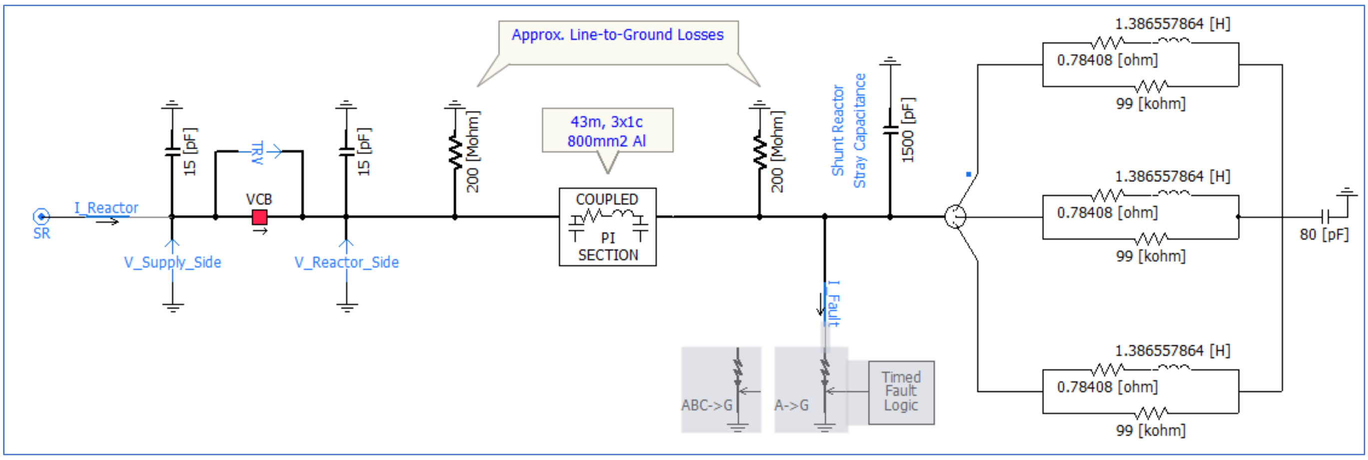

Figure 2- 3 - Snapshot of Shunt Reactor PSCAD Model

2.5 Stray Capacitance Values of the Equipment

Based upon the IEEE C37.011-2011 standard, typical capacitance values were used to represent equivalent stray capacitance values of the equipment – Transformers, shunt reactors, voltage transformers, circuit breakers and disconnectors. Typical stay capacitance values used in the study are tabulated in Table 2- 4. The stray capacitances at the grid side of the shunt reactor do not significantly impact on the TRV results because cable capacitances are dominant. However, the stray capacitances were included in the model.

Equipment	Capacitance(pF)
Shunt reactor	1500
WTG transformer	2000
Grid transformer	5000
WTG	10000
Voltage transformer	200
Current transformer	150
Circuit breaker	30
Disconnector	50
Surge arrester	80
Bushing Capacitance	80

Table 2- 4 - Typical Stray Capacitance Values

2.6 Circuit Breaker Detail

The ORMAZABAL CPG.0-V SF6 insulated Vacuum Circuit Breaker is to be used as the shunt reactor switch. The details are given in Table 2- 5.

Rated voltage (U_R)	36
Rated busbar current (A)	1250
Rated short time withstand current I_{SC} (kA)	25
Rated peak withstand current Ip (kA)	63
Frequency (Hz)	50
Class	S1 – Cable system

Table 2- 5 – VCB Details

Small inductive currents are usually interrupted in vacuum breakers before current zero. This phenomenon is known as current chopping. Chopping current (I_{ch}) was assumed to be 5 A in this study.

3 Methodology

Circuit breakers have no difficulty interrupting shunt reactor currents. The energy trapped in the load side inductance and capacitance at the instant of chopping will oscillate between the inductance and the parallel capacitance, causing high frequency/magnitude overvoltages to occur. If the overvoltage exceeds the breaker withstand limit, a restrike, reignition or multiple reignition can occur.

The following methodologies have been used to assess the VCB TRV capability and the overvoltages at the reactor terminal and supply side of the VCB.

- An Ideal VCB model with I_{ch} of 5 A was used.
- The external grid has been modelled up to 132kV [redacted] substation. Maximum FL equivalent was used at [redacted] substation.
- A distributed parameter model of Bergeron was used to represent OHLs and cables – the Bergeron model enables an accurate analysis.
- A grounding transformer with a 12.5ohm neutral earthing resistor was used to ensure the single phase-to-ground fault current of approx. 1.52 kA RMS.
- In order to simulate the max. fault current at the reactor terminal, the planned replacement 120MVA grid transformer detail was used.
- A total load of 20 MW load was modelled at [redacted] substation.
- All WFs at [redacted] including the [redacted] WF were modelled based upon their rated power exports with approx. unity PF.
- All WFs at [redacted] including the [redacted] WF were modelled based upon their rated power exports with approx. unity PF.
- A 500kVA auxiliary transformer located at [redacted] WF was modelled with 250kVA of load at 0.98PF. All WFs at [redacted] including the [redacted] WF were modelled based upon their rated power exports with approx. unity PF.
- The shunt reactor was modelled including winding/coil and core losses, represented by series (r) and parallel (R) resistors.
- The fault contribution by [redacted] WFs were tuned to ensure max. fault level of 905.9MVA at [redacted] - the fault level refers to Winter, 2028/29. Also, the fault current contribution of [redacted] WF was included.
- The TRV study was carried out the based upon the rated operating voltage of 33kV at the reactor connection point.

- The TRV results were compared with the T10 envelope for the case of de-energisations of the shunt reactor and single phase-to-ground fault clearance, and T60 envelope was used for three phase-to-ground fault clearance.
- Due to the low possibility of occurrence, three phase-to-ungrounded faults were not investigated in this report.
- Fault resistance was assumed to be a considerably small value of 1 milli-ohm.
- Due to the lack of SAs information for the [redacted] 33 kV SWITCHGEAR ROOM ([redacted] CONTROL BUILDING), typical I-V curve of 29 kV MCOV, 10 kA, UltraSIL, Distribution Class SAs were assumed.

4 TRV Studies

According to the standard IEC 62271 - 100, the TRV peak value/RRRV rating of the VCB has to be within the envelopes T10 and T60 for de-energisations of the shunt reactor & clearance of single phase-to-ground and three phase-to-ground faults respectively.

4.1 Model Validation

A model validation was carried out to ensure the maximum three phase-to-ground and single phase-to-ground fault levels at [redacted] substation [redacted] were fully representative of that under study. The validated result can be seen in Figure 4 - 1 and Figure 4 - 2 . The models were confirmed and tuned to a more than adequate level of representation.

The three phase-to ground and single phase-to-ground fault current waveforms at the shunt reactor are shown in Figure 4 - 3 and Figure 4 - 4.

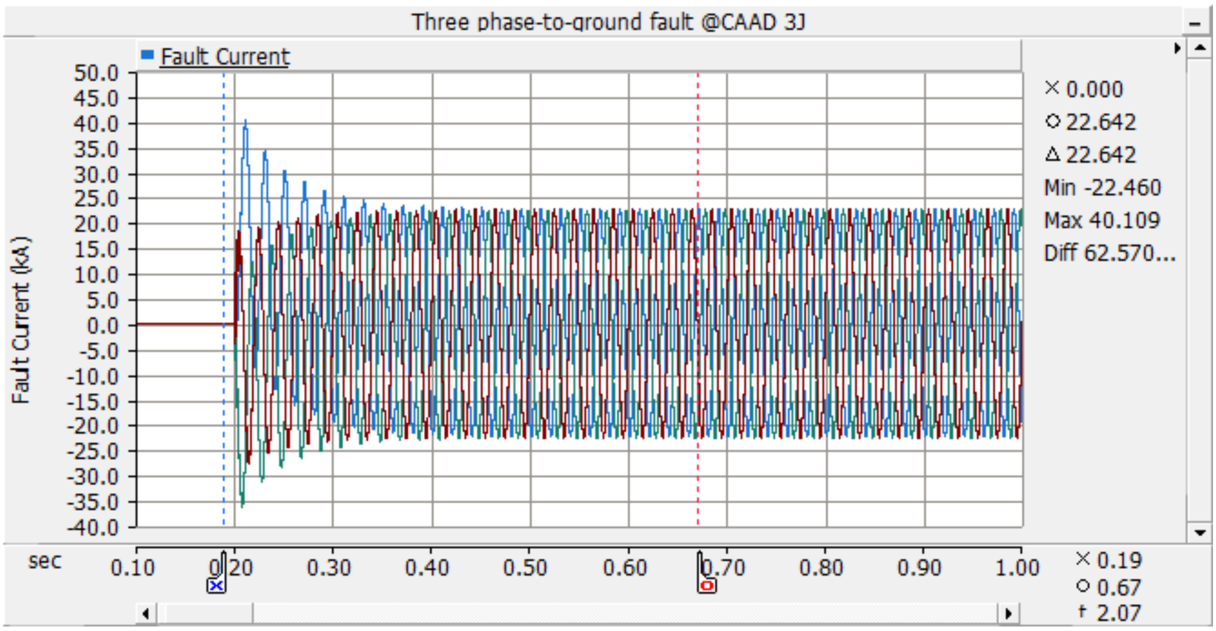

Figure 4 - 1 - Validated Three Phase-to-Ground Fault Current at 1

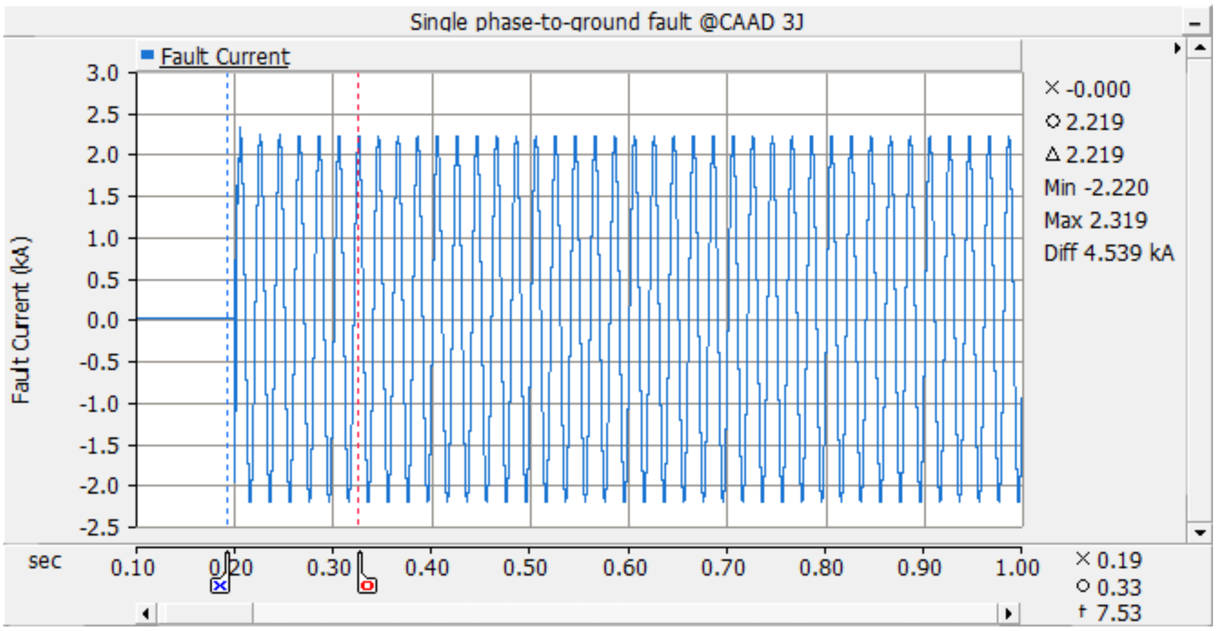

Figure 4 - 2 - Validated Three Single-to-Ground Fault Current at 2

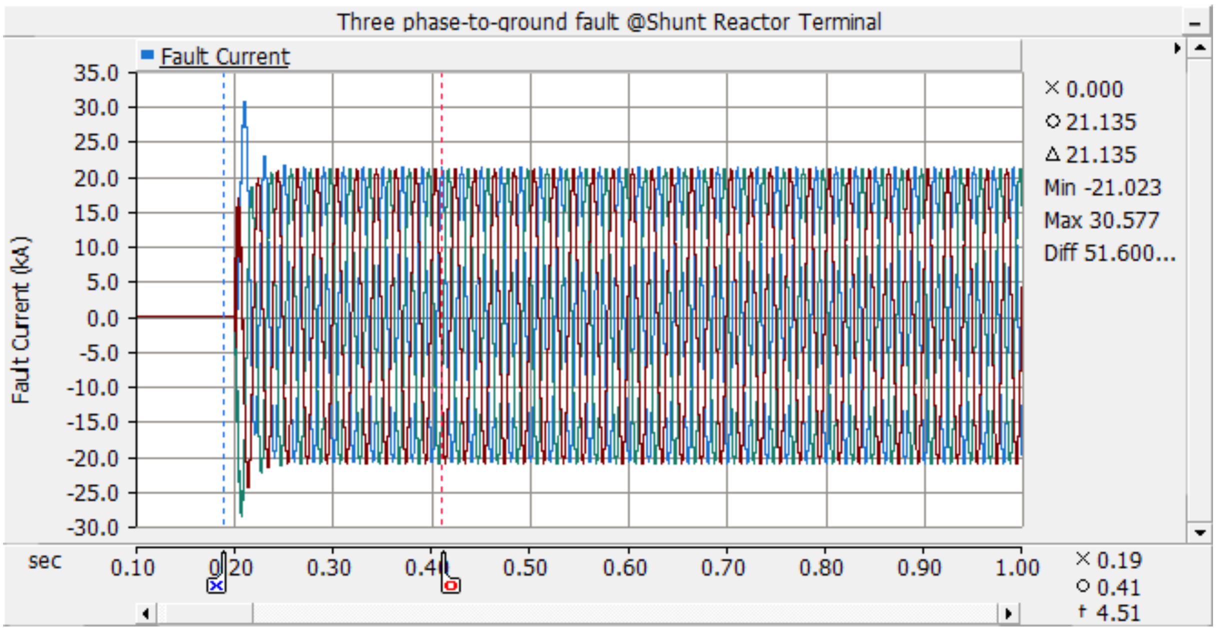

Figure 4 - 3 - Three Phase-to-Ground Fault Current at Shunt Reactor Terminals

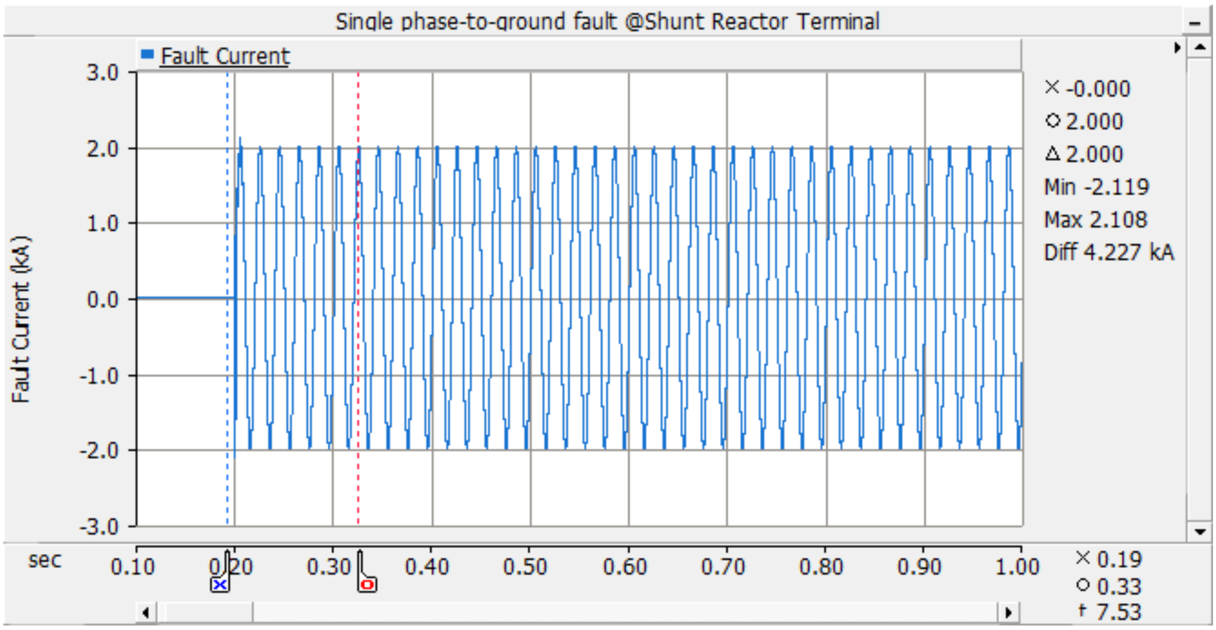

Figure 4 - 4 - Single-to-Ground Fault Current at Shunt Reactor Terminal

4.2 TRV Study Results

The study results are given in this section individually for the various studied cases. The detailed results are tabulated and provided in the appendix.

4.2.1 De-energisation of the Shunt Reactor

The VCB was opened at 20 different points over a 20ms time period with 1ms intervals. The results were compared to the two parameters T10 envelopes defined by IEC 62271-100. The maximum peak TRV was simulated to be 99.050 kV on phase B at 0.22sec. The maximum phase to ground voltage at the reactor terminal was found to be 72.056 kV. The results can be seen in Figure 4 - 5. The plots consist of 5 graphs – each is clearly labelled.

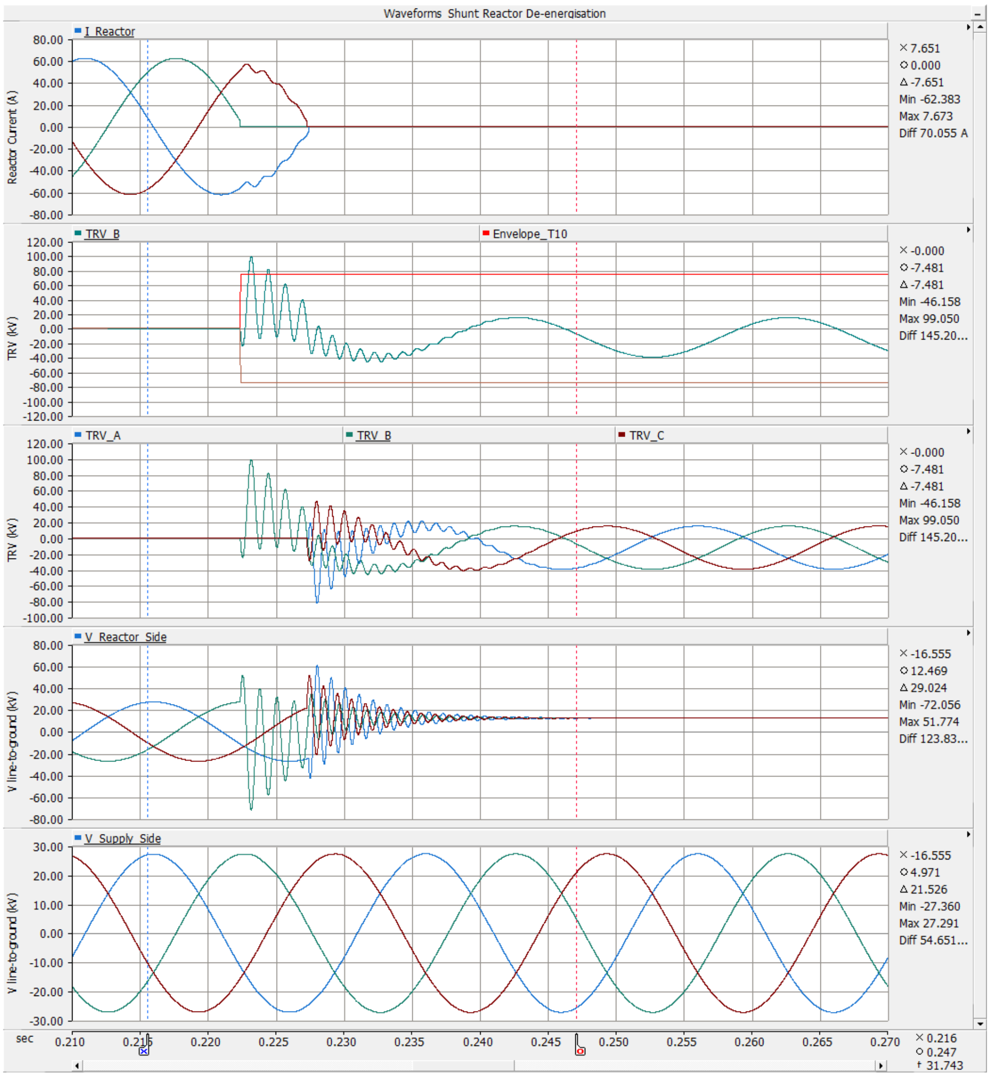

Figure 4 - 5 - Waveforms, Shunt Reactor De-energization

4.2.2 Single Phase-to-Ground Fault Interruption

The single phase-to-ground fault was simulated at 0.20sec. The model was run for the fault clearance time range between 20ms and 60ms at 1ms time intervals. The fault current is ~1.5kA RMS - 6.0% of the CB rating of 25kA; and thus, the results were compared to the two parameter T10 envelopes defined by IEC 62271-100.

The maximum peak TRV was simulated to be 107.57kV on phase C at 0.242sec. The maximum phase to ground voltage at the reactor terminals was found to be 81.24kV. The results can be seen in Figure 4 - 6. The plots consist of 5 graphs – each is clearly labelled.

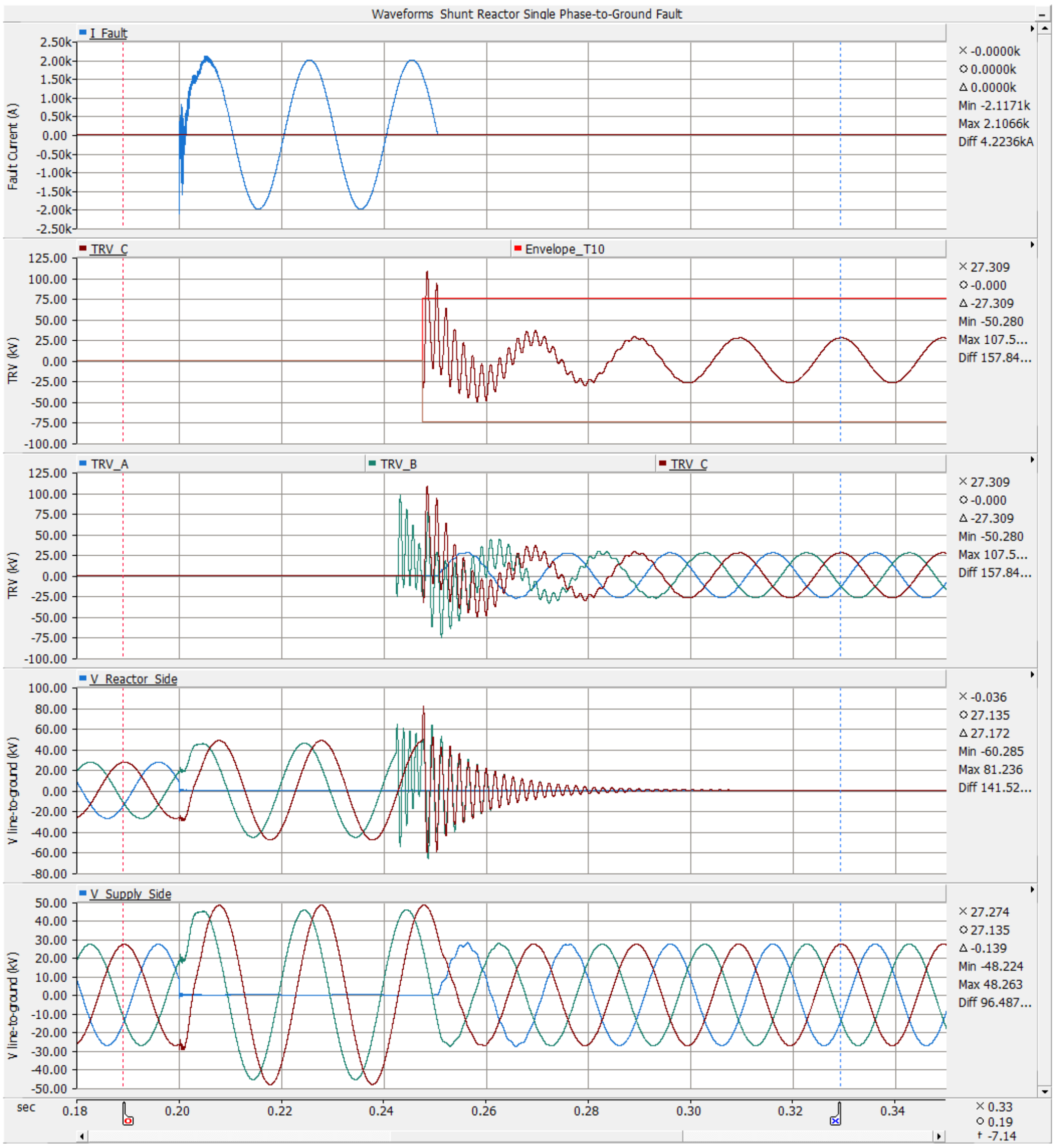

Figure 4 - 6 - Waveforms, Single Phase-to-Ground Fault Clearance

4.2.3 Three Phase-to-Ground Fault Interruption

The single phase-to-ground fault was created at 0.20sec. The model was run for the fault clearance time range between 20ms and 60ms at 1ms time intervals. The fault current is ~14.95kA RMS - 59.8% of the CB rating of 25kA; and thus, the results were compared the two parameter T60 envelopes defined by IEC 62271-100.

The maximum peak TRV was simulated to be 68.156kV on phase C at 0.231sec. The maximum phase to ground voltage at the supply side of the VCB was found to be 68.156kV. The results can be seen in Figure 4 - 7. The plots consist of 5 graphs – each is clearly labelled.

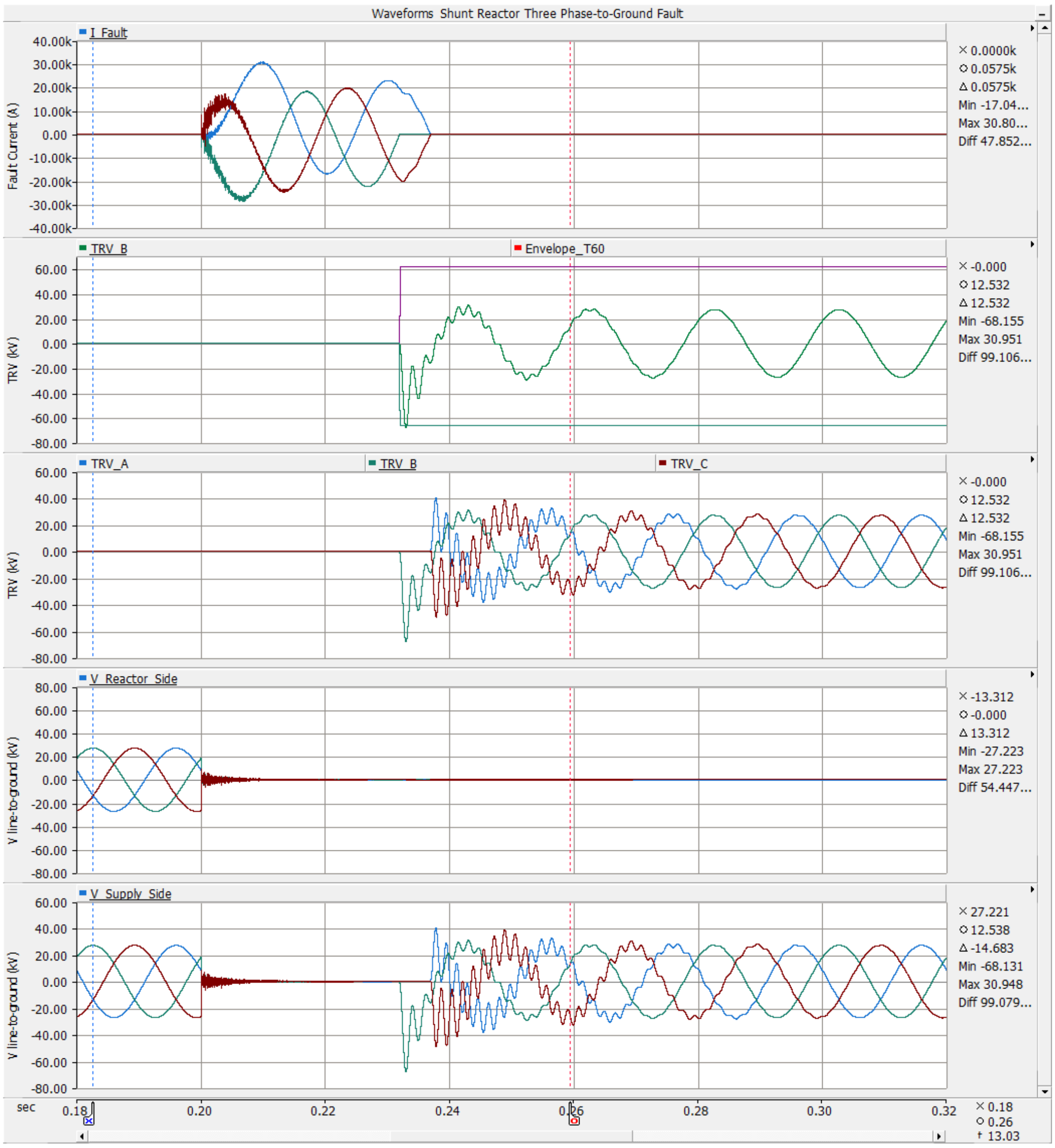

Figure 4 - 7 - Waveforms, Three Phase-to-Ground Fault Clearance

5 Conclusions and Recommendations

The following conclusions can be drawn from the TRV studies undertaken for the shunt reactor used for [redacted] WF:

- For shunt reactor de-energisations, the peak TRV of 99.05 kV is not within the T10 duty value of 75 kV. The phase-to-ground voltage at the reactor was found to be 72.06 kV.

- For single phase-to-ground faults, the peak TRV of 107.57 kV is not within the T10 duty value of 75 kV. The phase-to-ground voltage at the grid side of the VCB was found to be 81.24 kV.

- For three phase-to-ground faults, the peak TRV of 68.15 kV is not within the T60 duty value of 66.10 kV. The phase-to-ground voltage at the grid side of the VCB was found to be 68.13 kV

The results demonstrate that the VCB breaker is not adequately rated for the de-energisations of the shunt reactor and for interruption of the corresponding possible faults.

The over voltages cannot be eliminated. However, the overvoltage can be limited to acceptable values. This limitation is determined by the influence of the shunt reactor surge arrester protection and the auxiliary equipment that can be applied to the circuit breaker to limit the over voltages. In line with IEEE Std C37.015™ - 2017, applicable solutions are tabulated in Table 5 - 1 overleaf.

Number	Overvoltage limitation method	Comment
1	Circuit breaker with higher voltage ratings	Increases dielectric withstand capability. Reduces the probability of reignition. At a minimum, protection with an appropriately sized SA is still recommended.
2	RC snubber with surge arrester (phase-to-ground) at the reactor terminal - SAs are also required on the supply side of the breaker.	Decreases frequency and thereby rate of rise of the load side oscillation; decreases frequency of reignition overvoltage excursion - It does not help to reduce peak TRV caused by three phase-to-ground faults. To also limit three phase-to-ground faults TRV, a combination of an RC snubber with appropriately sized SAs at the supply side of the VCB, or across the VCB may be considered.
3	Surge arresters across the circuit breaker, or phase-to-ground at both sides of the CB.	Limits the peak TRV below its rating. Some re-ignitions may still occur albeit at low voltage level. Using SAs across the CB brings about more complexity.
4	Controlled switching with surge arrester across the circuit breaker, or phase-to-ground at both sides of the CB.	Eliminates re-ignitions, and also limits TRV and over voltages. Suitable only for mechanically consistent circuit breakers with appropriate minimum arcing times. It also requires independent pole operation. Using SAs across the CB brings about more complexity.

Table 5 - 1 - TRV & Overvoltage Mitigation Methods

An RC snubber with appropriately sized SAs, or controlled switching with appropriately sized SAs are the best solutions to reduce TRV to within the breaker ratings, reduce/eliminate re-ignition probability and reduce the overvoltage stress at the reactor terminals. Note that independent pole operation is required for the solution including controlled switching. Using phase-to-ground SAs at the grid side of the breaker is to limit TRV caused by the interruption of the three-phase-to ground fault. If the actual SA's installed at [redacted] 33 kV SWITCHGEAR ROOM ([redacted] CONTROL BUILDING) have a voltage rating below 66.10kV, then supply side VCB SA's would not be required.

The probability of faults between the VCB and shunt reactor terminal is low. Nevertheless, de-energisations of the shunt reactor would be considered as frequent. Thus, a peak voltage mitigation method should be considered. It is essential not only for the TRV requirement, but also for protecting the reactor against over voltages.

6 Appendix

Redacted due to confidentiality.