PROTECTION OF 220 kV 50 MVAr SHUNT REACTOR AT TRANSPOWER'S WAIRAU RD SUBSTATION

Paper Authors:

David Harper, AECOM NZ Ltd

Winodh Jayewardene, AECOM Australia Pty Ltd

Rebecca Shaw, AECOM NZ Ltd

Stuart Sim, Transpower NZ Ltd

Paper Presenter:

Rebecca Shaw, AECOM NZ Ltd

EEA Conference & Exhibition 2014, 18 - 20 June, Auckland

Abstract

The North Auckland and Northland (NAaN) upgrade project has been undertaken by Transpower to reinforce their 220 kV network from Auckland to North Auckland with the installation of new cable circuits from Pakuranga to Albany through various substations. A 220 kV, 50 MVAr shunt reactor directly connected into a 2500 A, 9 km cable circuit was installed at Wairau Road Substation to counteract shunt capacitance and associated voltage rise associated with the cable circuits.

This paper describes the unique challenges associated with applying traditional transformer biased differential schemes with circuit breaker fail to directly connected shunt reactors.

Attention is paid to the effects of Point on Wave circuit breaker control on inrush current characteristics, resonance effects following line de-energisation and the ability of biased differential schemes to provide security during various switching and contingency events. Disturbance records following commissioning are analysed in order to assess the impact on the selected settings and confirm security of the scheme.

Background

The North Auckland and Northland (NAaN) upgrade project has been undertaken by Transpower to reinforce the 220 kV network from Auckland to North Auckland with the installation of new cable circuits from Pakuranga to Albany through various substations.

A 220 kV, 50 MVAr shunt reactor directly connected into a 2500 A, 9 km cable circuit was installed at Wairau Road Substation to counteract shunt capacitance and associated voltage rise associated with the cable circuits.

This shunt reactor is the first of its type and size in Transpower's network, and it was installed during a time critical project with tight commissioning deadlines. Therefore it was imperative that a protection scheme be developed that utilised Transpower's existing standard protection relays, to make the most of the design effort that had already gone into their selection, such as SCADA and monitoring configurations, and testing against relay performance requirements.

There are significant differences between a transformer and shunt reactor with regards to detection of faults and stability during inrush or power system disturbances. This posed some interesting challenges to overcome when adapting the transformer protection scheme to the reactor protection.

Shunt Reactor Requirements

Shunt Reactors are typically used in transmission networks to absorb capacitive power and prevent over-voltages in the system during lightly loaded conditions. They are often switched in and out of service depending on the loading in the system. Shunt reactors can be connected to busbars, or directly into a transmission line.[1]

Shunt reactors at Transmission voltages are normally oil-immersed types, with iron cores and an air gap. The air gap prevents the iron core from becoming saturated, giving the reactor a reasonably linear behaviour during energising events. At Transmission voltages, the typical

---

[1] *Protection, Monitoring and Control of Shunt Reactors*, CIGRE WG B5.37, final draft August 2012

construction is a five-leg core type or shell type, to ensure that the three phases are magnetically independent.[2]

At Transpower’s Wairau Road Substation, the shunt reactor is directly connected into the Hobson St Circuit 1 between the 220 kV cable and the 220 kV, selectable Gas Insulated Switchgear (GIS) bus.

The shunt reactor is a 5-limb, oil-immersed type with an iron core and air gap. It has the following ratings:

Reactor rating at 220kV	50 MVAr (50Hz rating)
Reactor rating at 245kV	62 MVAr (50Hz rating)
Reactor Vector Group	YN

The Single Line Diagram shown in Figure 1 shows the shunt reactor connection. In this paper, reference is made to the ‘line side’ of the reactor and the ‘neutral side’. The ‘line side’ refers to the side connected to the GIS while the ‘neutral side’ refers to the side of the reactor where the neutral point is formed.

There is a 4-core CT on the line side of the reactor, contained within the GIS bus duct. There are also 2 CTs on the neutral side of the reactor, one 2-core, 3-phase CT, and one 2-core neutral CT (NCT) after the neutral point of the reactor.

The Line Protection has Reactor CT connections so that it can exclude the reactor currents from the line currents to ensure correct operation for line (cable) faults.

The reactor protection cross-trips the local (Wairau Rd) and remote end (Hobson St) circuit breakers for all fault types via the line protection relays at Wairau Rd substation.

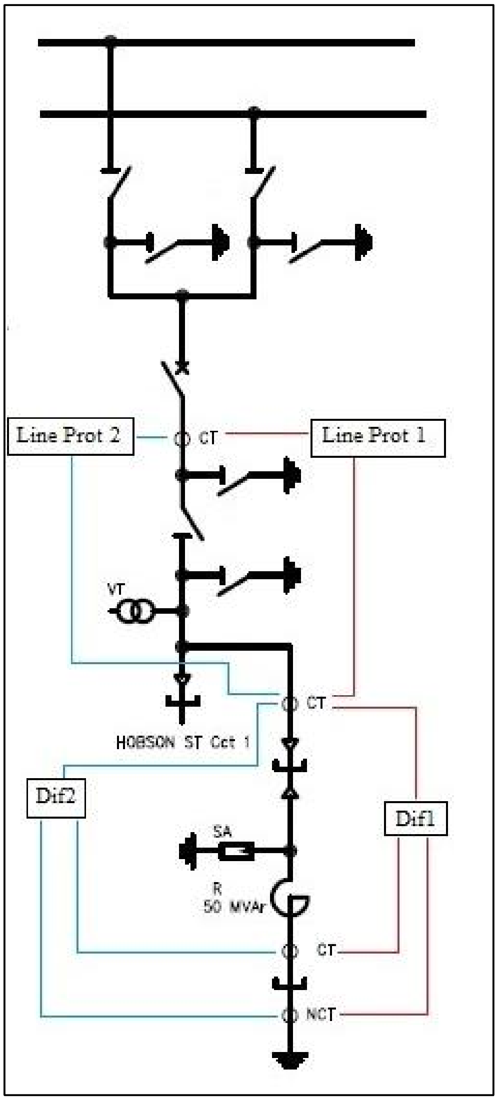


Figure 1 - Reactor Connections

Shunt Reactor Protection Scheme

The Wairau Road Shunt Reactor protection consists of duplicated, biased differential main protection and overcurrent and earth fault backup protection. The protection scheme is based on Transpower’s standard protection scheme for an interconnecting transformer, with modifications to suit the specific Shunt Reactor protection requirements.

---

[2] *Protection, Monitoring and Control of Shunt Reactors*, CIGRE WG B5.37, final draft August 2012

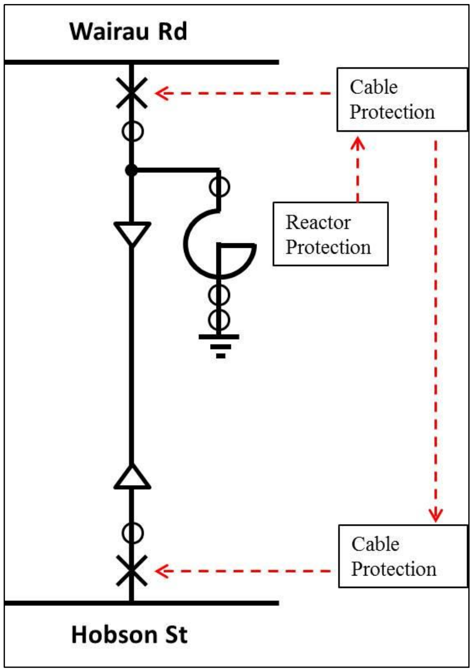


Figure 2 - Reactor and Cable Trips

The reactor protection relays trip via inputs on the line protection relays as shown in Figure 2. Supervision of these trip circuits from the reactor Dif relays to the line protection inputs is provided, as they are vital in enabling reactor faults to be cleared.

CBFail protection is provided in the reactor protection relays, and back trips both the local and remote end busses for failure of either of the CBs via the Cable Protection.

Reactor Fault Detection

The main types of faults for the reactor are as per Figure 3[3].

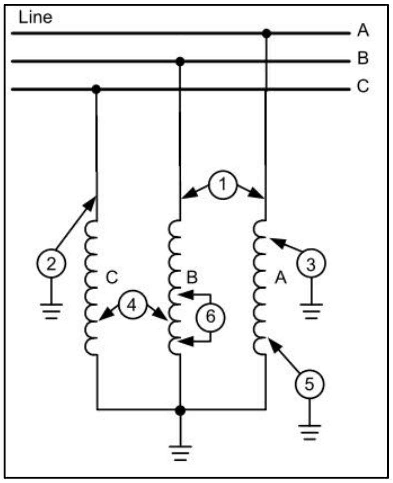


Figure 3 - Types of faults on shunt reactor

A summary of the different fault types and expected current, along with the protection elements set is shown in Table 1.

The most challenging reactor fault type to detect is the turn-to-turn fault. Documentation outlined in the references section indicates that the reactor Buchholz and pressure relief devices will provide the best protection. However the neutral CT connected overcurrent elements will also provide some protection for these faults.

Overcurrent and earth fault protection elements are set in the Wairau Road end cable protection relay to provide backup for reactor faults. At the Hobson St end, the cable protection zone 2 distance elements see into the Reactor HV zone, so are able to provide backup for fault infeed from the remote end.

---

[3] *Practical EHV Reactor Protection*, Faridul Katha Basha and Michael Thompson, Schweitzer Engineering Laboratories, Inc.

Table 1 Shunt reactor types of faults, expected current and protection coverage

No.	Fault Type	Line side current	Neutral current	Main Protection	Backup Protection
1	Phase fault (non-winding)	System fault level	-	Dif1 Dif2	OC(DefT)1 OC(DefT)2
2	Earth fault (non-winding)	System fault level	-	Dif(EF)1 Dif(EF)2	EF(DefT)1 EF(DefT)2
3	Earth fault (winding)	Moderate	Moderate	Dif(EF)1 Dif(EF)2	EF(IT)1 EF(IT)2
4	Phase fault (winding)	Moderate/Low	-	Dif1 Dif2	OC(IT)1 OC(IT)2
5	Earth fault (winding)	Similar to reactor rated current	High	Dif(EF)1 Dif(EF)2	EF(DefT)3 EF(DefT)4
6	Turn-to-turn	Similar to reactor rated current	Moderate	Buch(Main)1 Buch(Main)2	EF(DefT)3 EF(DefT)4

Protection Challenges

Resonance effects following line de-energisation

De-energisation of the cable (either during switching or following a fault) will result in slowly decaying current and voltage oscillations (current is directly proportional to voltage) as energy is exchanged between the cable shunt capacitance and reactor shunt reactance via small system resistances. The frequency of oscillation is related to the level of shunt reactive compensation.

The frequency of oscillation can be estimated as follows:

$$\omega = \frac{1}{\sqrt{LC}}$$

Where:

ω = $2\pi f$ – Angular frequency (rad/s)
L = 3.08H per phase inductance of reactor (968Ω)
C = 2.73μF per phase shunt capacitance of cable

Re-arranging for f,

$$f = \frac{1}{2\pi\sqrt{3.08\text{H} \times 2.73\mu\text{F}}}\text{Hz}$$

$$f = 54.9\text{Hz}$$

Since the oscillation frequency was likely to be very close to fundamental frequency, there was uncertainty around whether the protection relays would be able to successfully filter out these oscillating currents.

These oscillations were not expected to cause problems for the overcurrent elements because they were set above reactor maximum load current and the oscillations were expected to decay over time (ie were damped).

There was a possibility that the sensitive earth fault elements such as EF(IT)1/2 and EF(DefT)3/4 may operate depending on the severity of any unbalance in the voltage (hence currents) and the duration of the unbalance during resonance. An extended time delay was applied to the affected elements to allow the currents to decay.

The oscillations could also affect the CBFail protection, so a special 2-stage CBFail scheme was implemented, with Stage 1 being fast and desensitised, and Stage 2 being slow and sensitive. This is discussed in detail in the next section.

Circuit Breaker Failure (CBFail)

The shunt reactor is directly connected to the cable, which presented two main challenges when setting the CBFail protection, firstly ensuring that CBFail will operate correctly (hold up when a CB fails to open at either end of the cable and drop off when both CBs have correctly opened), and secondly to ensure that the CBFail protection is sensitive enough.

Generally a CBFail scheme would back-trip the bus at the location of the failed CB. However, for certain low level reactor faults, such as faults near the neutral end of the reactor, the combination of the reactor and cable capacitance in series, which are very closely matched, can cause difficulties for the cable CBFail relays to detect fault current still flowing, since the reactive and capacitive currents essentially cancel each other out. This is shown in Figure 4 and Figure 5 below.

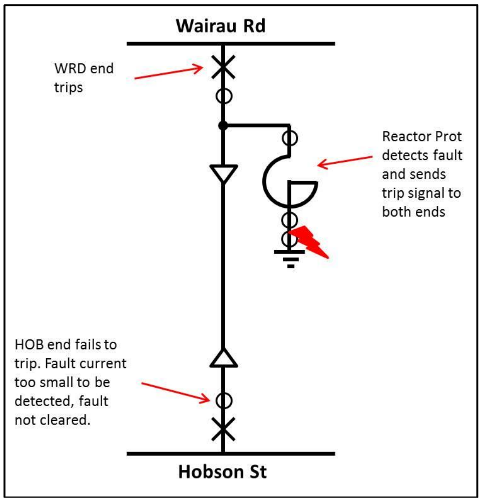


Figure 4 - CBFail operation, HOB end fails

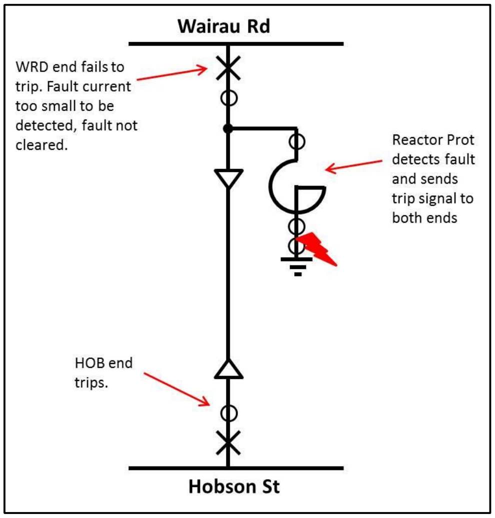


Figure 5 - CBFail operation, WRD end fails

Therefore the reactor CBFail scheme tripping has been implemented so that it back-trips both Hobson and Wairau Rd busses for a reactor CBFail condition to ensure that the fault is cleared properly from both ends of the cable.

Reactor CBFail (including timing) is carried out by the reactor protection relays as this allowed a more sensitive CBFail OC pickup than the cable protection due to the mismatch mismatch in currents between the cable rating and reactor rating (2500 A vs 130 A). Hence there is a risk that the oscillating current following cable de-energisation could be detected by the CBFail current detectors and back-trip both Hobson and Wairau Road busbars.

In order to prevent the CBFail operating during resonance conditions a two stage CBFail scheme is implemented as follows:

- Stage 1 – Fast and desensitised (Prot 1 and Prot 2 relays)
- Stage 2 – Slow and sensitive (Prot 1 relay only)

The pickup and time delays are selected to coordinate with the current levels and decay rates estimated from system modelling.

The Stage 1 (fast) element is selected for both relays in order to provide fast backup clearance of high magnitude fault currents, which pose the greatest hazard to plant and system security. This is at the sacrifice of providing sufficient backup clearance of low level faults but is justified by the following reasoning:

- Duplicating fast backup clearance of faults was considered paramount from a system stability perspective
- If the Prot 1 relay is taken out of service, then there is no fast backup clearance for large magnitude faults
- Implementing slow CBFail settings would not allow grading with backup protection (backup overcurrent elements in the local line protection or zone 2 distance elements on the remote line protections) due to the relatively long time delay implemented.

Reactor inrush characteristics and ability of biased differential schemes to provide security during various switching and contingency events

A reactor's gapped iron core results in little to no remanent flux. Consequently the 2nd harmonic inrush current magnitude can be much less than for a transformer.

The component of 2nd harmonic current (as a percentage of the fundamental current) is largely dependent on the voltage point at which the reactor is energised. There could be little (<5% of fundamental current) to zero 2nd harmonic content in the current in some cases. Point on Wave (POW) closing of the reactor is not employed at Wairau Rd or Hobson. This resulted in less predictable values of the inrush current, and made it difficult to set the protection inrush restraint characteristics based on the 2nd harmonic levels.

However, the reactor high X/R does result in a long lasting DC component upon energisation. This can be in the range of 1-2 seconds, compared to a few hundred milliseconds for a transformer.

The lack of 2nd harmonic current requires an alternate method of restraining or blocking the differential element during inrush. Typically this is via detection of this DC current. Some relays have an adaptive restraint algorithm for the differential element while others block the differential element on detection of a DC offset (based on wave shape recognition).

For this protection scheme, the ability of the numerical relays to reject the DC components of the waveform for differential and overcurrent protection elements allowed sensitive settings to be applied in most cases, and longer time delays than standard are used in cases where the potential for maloperation due to inrush was high.

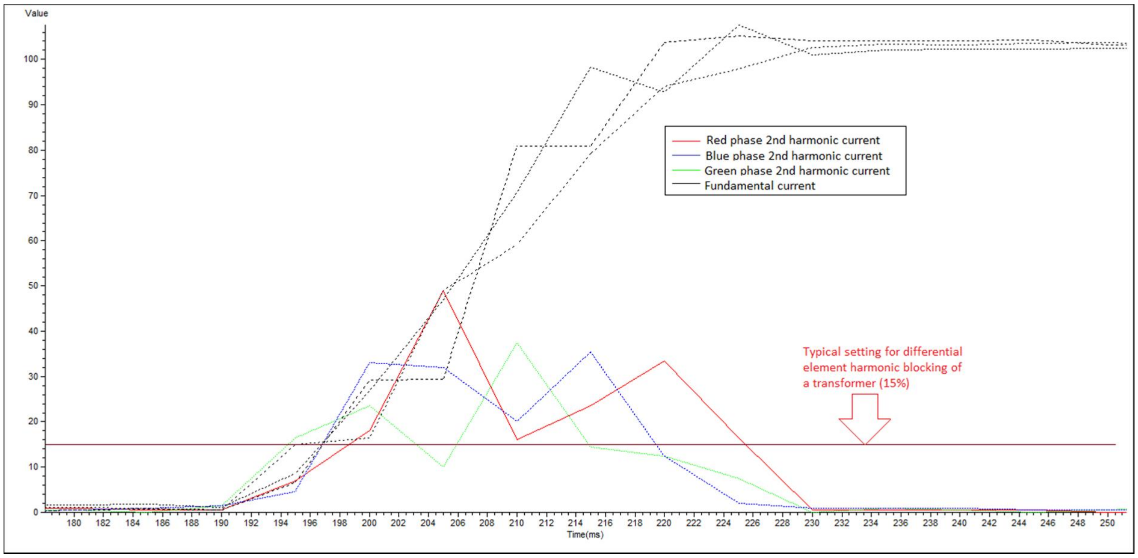
Commissioning Results

The two main focus areas for the commissioning were:

1. Ensuring stability of the differential elements during energisation
2. Ensuring that resonance currents do not result in nuisance trips or operation of the Circuit Breaker Fail elements following de-energistation

Commissioning of the reactor protection went relatively smoothly and there was much interest in comparing the simulated resonant currents with those measured during commissioning.

On first energisation, as expected the 2nd harmonic currents were quite low with a short duration. A typical setting for transformer differential relays is to block or restrain the element when the level of 2nd harmonic exceeds 15% of the fundamental. When the reactor was first energized, it was found that the 2nd harmonic current was above this 15% threshold for a period of approximately 32ms or around 1.6 cycles only as per Figure 6.



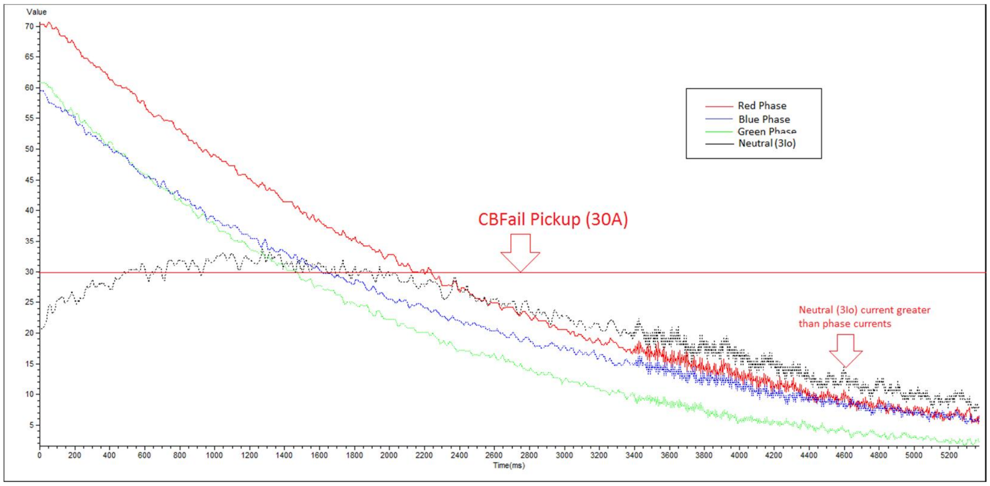
Typical setting for differential element harmonic blocking of a transformer (15%)

Figure 6 – Reactor inrush currents (as a percentage of fundamental current) on energisation for all three phases

Following de-energisation of the reactor, the measured resonant frequency was found to be around 56Hz with decaying phase current components having a time constant of approximately 1.2 seconds.

Of particular interest was that although the phase currents were decaying, the neutral (3Io) currents did not reduce substantially. This was attributed to the reduction of the relative phase angles between the decaying phase components which added to produce current in the neutral. Around 2.6 seconds following de-energisation, the 3Io current magnitude was found to be higher than the phase current magnitudes.

Figure 7 shows the point at which the neutral (3Io) current starts to exceed the phase current magnitude.



CBFail Pickup (30A)

Neutral (3Io) current greater than phase currents

Figure 7 – Reactor de-energisation comparison of phase and neutral currents

Analysis of fault traces associated with cable circuits consisting of shunt reactors at both ends of a cable have shown that resonant current can have an additional low order 'beat' frequency. This was not evident on the fault traces for this application with a single reactor however the reader should be aware of this when considering such applications[4].

Considerations for future implementations

In the past, high impedance differential would be the recommended option for protecting a shunt reactor of this type, due to the simplicity in applying and setting a sensitive, stable and fast protection.

However, with modern numerical relays, which have sophisticated signal processing that can reject DC components of the waveform, a biased differential protection scheme becomes a viable alternative. The modern relays also allowed the integration of various other control, monitoring, and protection functions which would have needed to be added to the high impedance scheme.

Ordinary low impedance differential protection is not recommended, unless it is desensitised sufficiently to prevent maloperation.[5]

Significant inrush currents were not observed during the commissioning tests. However, various studies have found that the amount of inrush current can differ depending on the instant of switching.[6] If Transpower find that inrush currents are not properly restrained by the protection in the future, they may consider implementing Point On Wave (POW) switching.

If a similar shunt reactor were to be implemented in the future, consideration might be given to including a dedicated circuit breaker, to overcome the difficulties in setting the CBFail protection. This would need to be balanced against the risk of circuit breakers switching too much capacitive current in certain system conditions.

---

[4] *Disturbance Analysis for Power Systems, Mohamed A. Ibrahim, 2011*

[5] *IEEE Guide for the Protection of Shunt Reactors – C37.109*, IEEE Power Engineering Society, 2006

[6] *Challenges for Design of 275kV Cable Protection & Control Scheme – Adelaide Central Reinforcement,* Brisbane, Australia, SEAPAC 2013

Conclusion

Directly connected, high voltage shunt reactors pose a number of protection challenges, in particular due to the unique characteristics during reactor energising and de-energising. During this period, dc offset with long time-constants and low frequency components of the reactor energisation current can cause problems with the protection.

At Wairau Road, modern numerical relays are used to address these protection challenges and develop a robust shunt reactor protection scheme. Biased differential and overcurrent and earth fault protection is used to protect against the various types of reactor faults. DC blocking and DC adaptive restraint functions are utilised to provide stability in the differential protection during reactor energisation and de-energisation. The overcurrent and earth fault elements rejected the DC component of the waveforms, thus allowing sensitive settings to be applied.

Commissioning results were discussed. On first energisation, as expected the 2nd harmonic currents were quite low with a short duration. Following de-energisation of the reactor, of particular interest was that although the phase currents were decaying, the neutral (3Io) currents did not reduce substantially, and in fact were higher than the phase current magnitudes after a few seconds. This was attributed to the reduction of the relative phase angles between the decaying phase components which added to produce current in the neutral.

References

The following resources were referenced as part of this report.

1. NAaN 220kV PAK to ALB Cable Protection Settings Report, Revision 2, 22 April 2013, Tesla Consultants.
2. Practical EHV Reactor Protection, Faridul Katha Basha and Michael Thompson, Schweitzer Engineering Laboratories, Inc.
3. *Protection, Monitoring and Control of Shunt Reactors*, CIGRE WG B5.37, final draft August 2012
4. *HV shunt reactor secrets for protection engineers*, Zoran Gajić, Birger Hillström, Fahrudin Mekić, 2003
5. *IEEE Guide for the Protection of Shunt Reactors - C37.109,* IEEE Power Engineering Society, 2006
6. *Challenges for Design of 275kV Cable Protection & Control Scheme - Adelaide Central Reinforcement,* Brisbane, Australia, SEAPAC 2013
7. *Disturbance Analysis for Power Systems,* Mohamed A. Ibrahim, 2011
8. *Report of WRD R182 System Tests Dec 1st 2013,* Bernard Palamountain, Transpower, 15th December 2013