Practical Considerations and Experiences Protecting 230kV Shunt Air-Core Reactors Banks

Kevin Damron, *Avista Utilities*

Abstract — **Avista recently completed the installation of two 230kV 50-Mvar shunt air-core reactor banks. Shunt reactors are commonly employed in substations as a cost effective way of reducing voltage rise during conditions of low load. When the transmission line is loaded below the surge impedance load (SIL), the line experiences a voltage rise due to the line's natural shunt capacitance (Ferranti Effect) drawing charging current through the series inductance. Shunt reactor are switched into the circuit to compensate for this effect. [1]**

Transient switching studies were conducted to evaluate the required performance of the two (2) 230kV 50-Mvar shunt reactor banks and zero-crossing/point-on-wave (POW) circuit breakers planned for the Noxon Rapids Reactor (NRR) substation.

While researching the protection design and relay settings, the author discovered that there was very limited information for this application. Most papers presented reactor banks that were either connected to the tertiary-winding of an autotransformer or were oil-filled reactor banks.

The paper will present the challenges and considerations a protection engineer needs to consider in this application through the use of actual relay events, ATP simulation results, and IEEE Comtrade data.

I. Background & Introduction

The planned rebuild of Avista's Noxon Rapids 230kV (NRS) Switchyard provided the opportunity to review the past performance and requirements for the switchyard. The 230kV voltage at Noxon had always been difficult to control with voltages exceeding 246kV regularly especially when the Noxon generation was low. In 2008, Bonneville Power Administration (BPA) requested that Avista begin controlling the Noxon bus voltage as high voltages were being impressed onto the BPA system. As a result of BPA's request, Avista began using the Noxon generators to help control the 230kV voltage. Over time changes in the area made it to where Noxon needed to condense more VARs than the existing generator condensing could provide. The alternatives investigated were using the existing and additional generators to condense or installing shunt reactors on the Noxon 230kV bus. Avista determined that operating the Noxon generators at their maximum condensing capability did not address the problem so the shunt reactor solution was pursued.

Avista determined that two (2) 50-Mvar (total capacity of 100-Mvar) would lower the 230kV voltage by as much as 4kV. Transmission Operations also requested that the reactors be installed such that a single contingency event would not remove both reactors from service. Dry-type air-core reactor banks were chosen due to the proximity to the Clark Fork River. Figure 1 shows the NRR installation.

Reference [3] makes an important statement that shunt reactors are important assets and demand a robust protection scheme to safeguard them from abnormal operating conditions. Similar to that discovered by previous authors, in-depth discussions of the guidelines available for reactor protection are very limited. Most references consider dry-type reactors to be limited in voltage rating and applied to the tertiary of a transformer, and the resources focus on oil immersed shunt reactors for high-voltage applications. Hence, the discussion of types of faults and relaying practices for dry type reactors is oriented towards transformer tertiary applications. But, Avista's application did not fit the typical application so detailed analysis was performed to verify the expected operations and transients from the installation of the reactor banks.

Figure 1 – Avista's NRR Reactor Banks (one bank shown)

II. Switching Transients

High voltage shunt reactors switching is a normal system operation that can be performed several times a day.

Because of the shunt reactor technical characteristics and their special purpose, its current is mainly inductive and can be referred to as a small inductive current. It is considerably smaller (10 or 20 times) than nominal currents of today's most commonly used SF6 circuit breakers, and even up to 200 times smaller than the expected short-circuit currents. [2]

Transient switching studies were conducted to evaluate the required performance of the shunt reactor banks and zero-crossing/point-on-wave (POW) circuit breakers planned for the new Noxon Rapids Reactor (NRR) substation. The zero-crossing circuit breakers limit the NRS 230kV transient voltage peaks to 1.04 per unit, versus 1.656 per unit without a zero-crossing breaker. The POW breaker allows for asynchronous closing and opening to minimize transients on the power system.

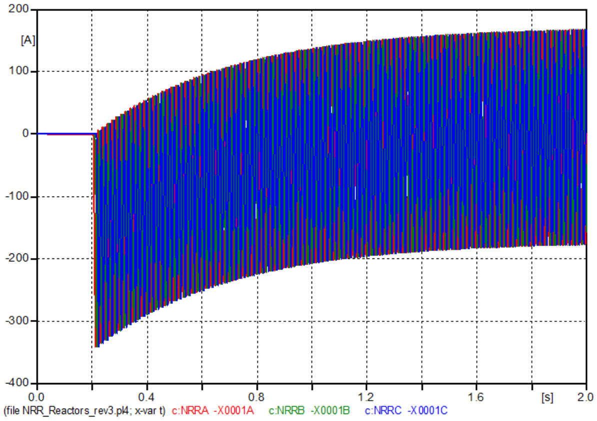
The Alternate Transient Program (ATP via the ATPDraw interface) was used to model the Noxon Rapids region system and perform voltage transient switching simulations. ATP-EMTP (ATP) is used world-wide for switching and lightning surge analysis, insulation coordination, shaft torsional oscillation studies, protective relay modeling, and harmonic and power quality studies. The main objectives were to:

1. Verify voltage reduction performance,
2. Determine the optimum zero-crossing breaker closing & opening point,
3. Identify potential circuit breaker rating violations,
4. Evaluate possible system resonant frequencies.

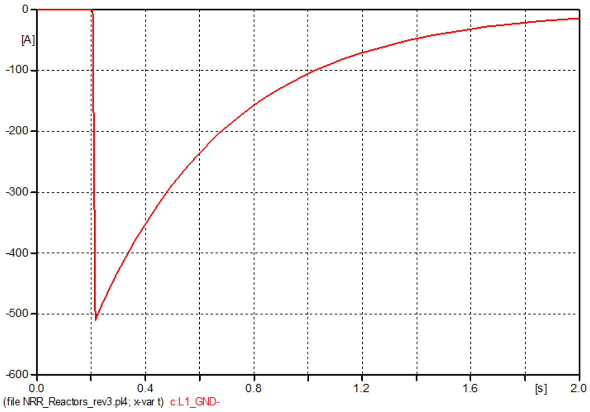
The primary advantages of dry-type air-core reactors, compared to oil immersed types, include lower initial and operating costs, lower weight, lower losses, and the absence of insulating oil and its maintenance. The main limitation for the application of dry-type air-core reactors is that of connection voltage where the reactor size becomes prohibitive for higher transmission system voltages. Since these reactors do not have an iron core, there is no magnetizing inrush current when the reactor is energized. [4]

Reactor bank switching however does impose a significant requirement on circuit breakers, hence it is critical to simulate such cases and develop any required mitigations.

The simulation of the shunt reactor energization was carried out for several closing times. Figure 2 shows the phase and shunt reactor neutral currents for a worst case energization, occurring when a bank is energized near the voltage zero-crossing. The individual poles of the power circuit breaker were closed near the zero-crossing of the individual phase voltages.



(a) Phase Currents

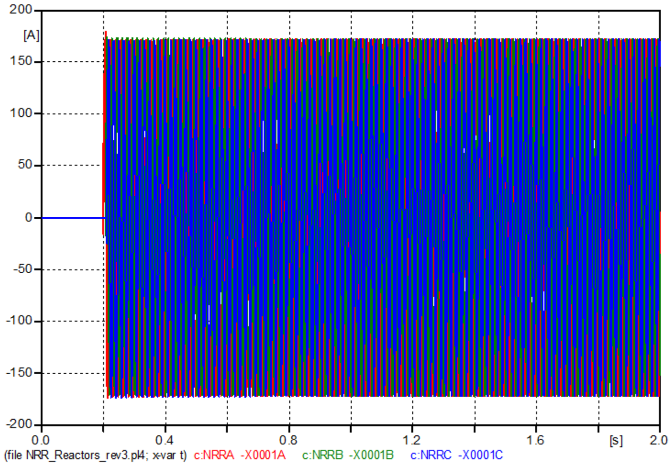


(b) Neutral Current

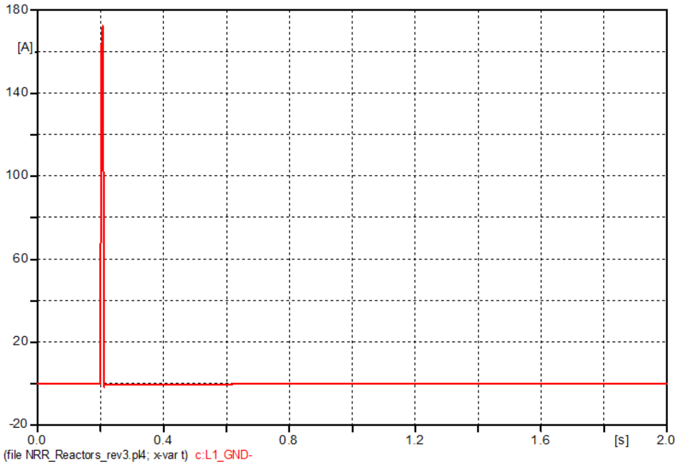
Figure 2 - Worst Case Energization Currents

Figure 2b shows the DC-offset in the neutral and the long-time decay of the DC current. The DC current could lead to current transformer (CT) saturation and subsequent misoperation of the protection scheme.

Conversely Figure 3 shows the phase and shunt reactor neutral currents for a best case energization, occurring when a bank is energized near the voltage peak.



(a) Phase Currents



(b) Neutral Current

Figure 3 - Best Case Energization Currents

Note that while both scenarios I_{MAX} is well within the zero-crossing circuit breaker rating (170kA rated short-circuit making current), there is a significant difference in both the phase and neutral current.. Initially it was believed that the 171A spike shown in Figure 3 was the result of numerical oscillation in the ATP-EMTP program. However, we will show later in this paper that the current spike does exist. Closing the zero-crossing breaker at the phase maximum voltages also causes switching overvoltages. Dielectric stress of reactor insulation caused by the very steep overvoltages originates from the breaker contact gap prestrike immediately before closing

III. PROTECTION DESIGN

The applications discussed in [4] are for two basic shunt reactor configurations with the discussion of dry-type reactors being connected as ungrounded wye to the impedance-grounded tertiary of a power transformer. Avista's NRS did not have a power transformer and with advances in dry-type air-core shunt reactors the application to a 230kV bus is now possible. One of the first challenges encountered was the performance concerns of the current transformers (CT) during switching transients that can cause the CTs to saturate due to the high X/R of the shunt reactors as Figure 2b shows above. The criterion in [3] was followed to select the CT ratings for the reactor protection. Table 1 shows that to obtain a 10% target sensitivity, only the 50T and 240T CT ratios are adequate.

Table I - Saturation Evalution for Low-Ratio CTs

CT Ratio	Minimum Sensitivity in % of Reactor Rating	
	5A Relay, 0.25 A	1A Relay, 0.05A
50T	**10%**	2%
60T	12%	2%
80T	16%	3%
100T	20%	4%
120T	24%	5%
160T	32%	6%
220T	44%	9%
240T	48%	**10%**
300T	60%	12%
320T	64%	13%
400T	80%	16%

Tables II and III show the results of the evaluation of CT saturation on switching.

Table II - Saturation Evalution for Low-Ratio CTs

Current Rating	Accuracy Class	Full Turns	Tapped Turns	Tapped CT Ratio	Vs
50:5	C100	10T	10T	50:5	188
100:5	C100	20T	20T	100:5	94
300:5	C200	60T	60T	300:5	16
400:5	C200	80T	80T	400:5	12

Table III - Saturation Evalution for High-Ratio CTs

Current Rating	Accuracy Class	Full Turns	Tapped Turns	Tapped CT Ratio	Vs
1200:5	C800	240T	60T	300:5	15.41
1200:5	C800	240T	80T	400:5	8.67
1200:5	C800	240T	100T	500:5	5.55
1200:5	**C800**	**240T**	**240T**	**1200:5**	**0.96**
2000:5	C800	400T	80T	400:5	14.45
2000:5	C800	400T	100T	500:5	9.25
2000:5	C800	400T	160T	800:5	3.61
2000:5	**C800**	**400T**	**240T**	**1200:5**	**1.61**
3000:5	C800	600T	100T	500:5	13.87
3000:5	C800	600T	160T	800:5	5.42
3000:5	C800	600T	200T	1000:5	3.47
3000:5	**C800**	**600T**	**240T**	**1200:5**	**2.41**

Checks of CT saturation for fault conditions must also be performed but are not included in this paper but are covered in [3]. Avista used 3000/5 C800 MR CTs connected 1200/5 based on the results of the analysis shown in Tables I – III. One amp (1A) relays were chosen to meet the sensitivity requirements of Table I. The final concern with applying the 1A nominal relays was the I^2t withstand of the relay. Luckily the manufacturer's protective relays had sufficiently high I^2t ratings.

The protection for major faults was achieved through overcurrent, differential, or negative-sequence relaying schemes. Figure 4 shows the connection of the NRR reactors to the NRS switchyard via a short (0.75 mi) 230kV transmission so the reactor banks are effectively tied to the 230kV NRS bus.

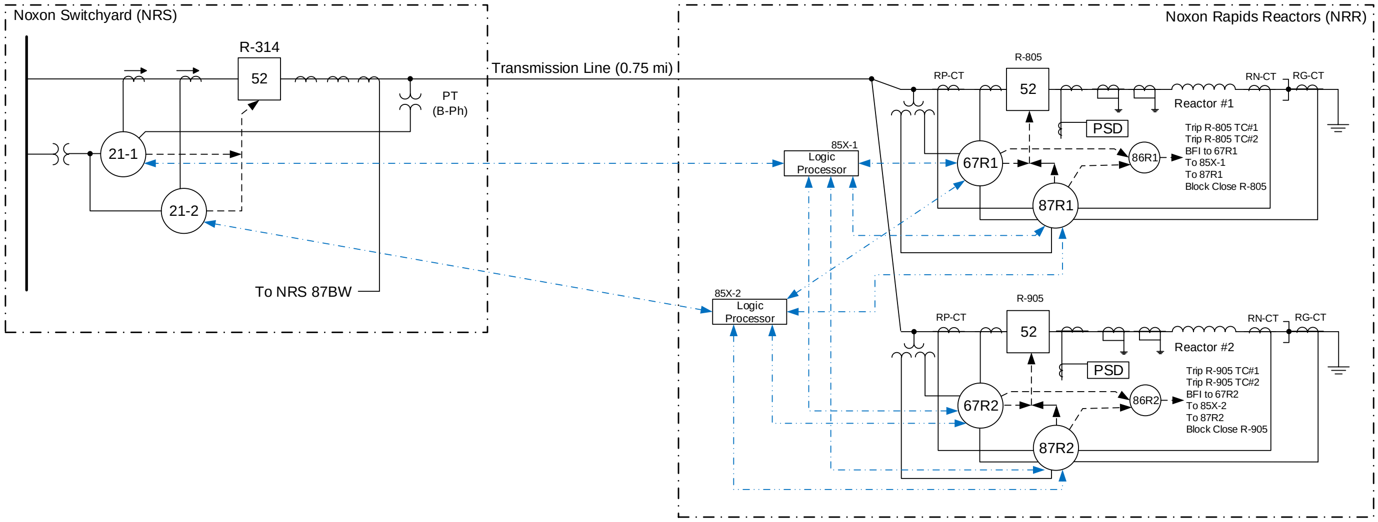


Figure 4 – System Protection Oneline

Much of the guidance from [3] on the settings for the protective elements such as phase differential, phase and ground overcurrent, and restrictive earth fault (REF) were followed. Avista also chose to use a phase balance current (46) relay for an unbalanced condition and this became important for the operation discussed in Section V.

The target sensitivity for detecting turn-to-turn faults is 10-15% of the reactor rating resulting in very sensitive neutral ground overcurrent settings that have to be supervised by inrush suppression logic to prevent tripping during asynchronous breaker closing. The inrush suppression logic allows the directional ground element to be set at four amp (4A) primary. The only undesired operation, due to a setting error, associated with the element was during commissioning of the protection scheme and the scheme has performed as desired since then.

The capability of circuit breakers to interrupt inductive currents is generally not a concern but they may not be able to withstand the high magnitude recovery voltages that can appear across the contacts [5]. The NRS R-314 gas circuit breaker could not adequately withstand such transient voltages so a communication-aided protection was used between NRR and NRS to cover the following scenarios:

- R-314 tripping (via 21-1 or 21-2) → trip both R-805 and R-905
- R-805 protective tripping (via 87R1 or 67R1) → block tripping of R-314 for 4 cycles (50/51 elements)
- R-905 protective tripping (via 87R2 or 67R2) → block tripping of R-314 for 4 cycles (50/51 elements)
- Block R-314 closing if R-805 and/or R-905 is closed
- R-805 breaker failure → trip both R-314 & R-905
- R-905 breaker failure → trip both R-314 & R-805

IV. INITIAL ENERGIZATION

Figure 5 shows the initial asynchronous energization of the R-905 reactor bank with the synchronous breaker controller not being configured correctly. Note that the ground current has the same peak value as Figure 3(b) above and that there is a considerable dc-decay.

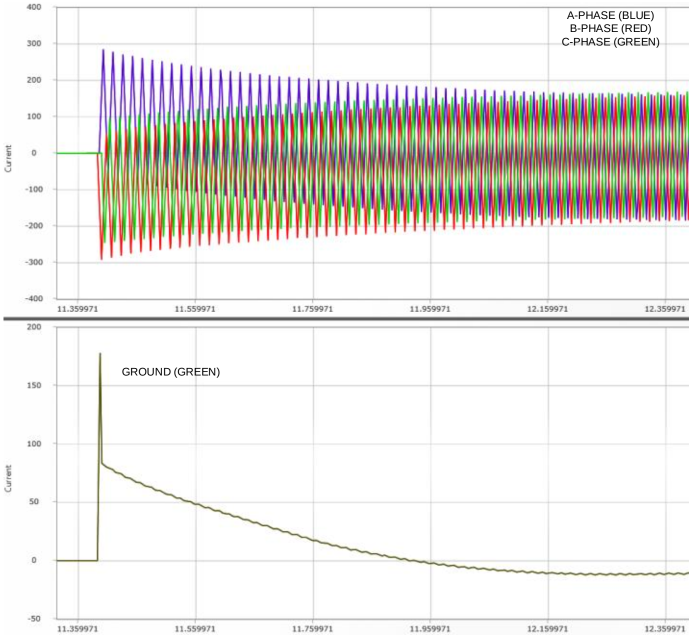


Figure 5 – Initial Asynchronous Energization (Comtrade File)

Figure 6 shows the 3rd energization of the R-905 reactor bank with correct function of the synchronous breaker controller.

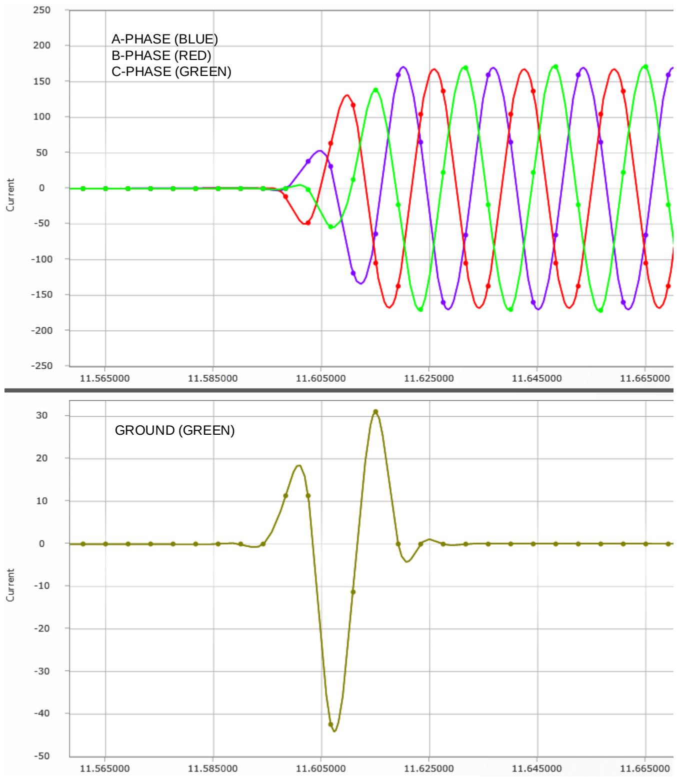


Figure 6 – Initial Asynchronous Energization (Filtered Event)

Note in Figure 6 that the dc-offset is filtered out by the relay's filters. In either case though, the ground current magnitude exceeds the four amp (4A) primary but the relay did not trip due to the inrush suppression logic supervision.

V. BREAKER POLE CLOSURE FAILURE EVENT

The NRR shunt reactors have been in-service since the beginning of this year and have performed as expected by lowering the NRS bus voltage 2kV per bank when switched in. The only protective operation happened earlier this year when the R-805 B-phase breaker failed to close for a SCADA (201C) close. Figure 7 shows the event oscillography for the B-phase closing failure.

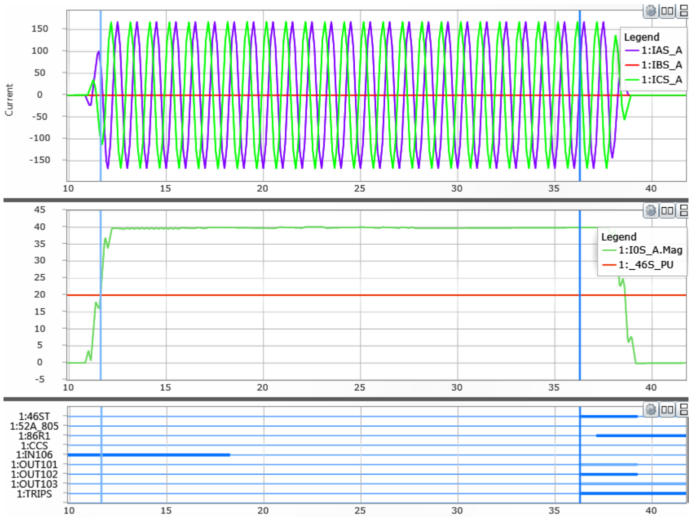


Figure 7 – B-Phase Closure Failure

The phase balance current (46) element of the relay operated for this event tripping the R-805 circuit breaker after a 25-cycle delay. After analysis of this event, Avista chose to reduce the delay to 15-cycles to improve the performance of the protection.

VI. CONCLUSION

Though shunt reactor bank protection is relatively straight forward, there are challenges that need to be addressed by the protection engineer. Detailed current transformer and relay analysis is required to ensure the proper operation of the protection scheme as the reactor bank currents pose challenges. The transients from reactor bank switching must be understood and analyzed to allow the protection engineer to properly set the protective relays.

VII. REFERENCES

[1] S. Sabade, M. Chaganti, H. Bahirat, B. Mork, "Shunt Reactor Switching Transients at High Compensation Levels"

[2] I. Uglesic, M. Krepela, B. Filipovic-Grcic, F. Jackl, "Transients Due to Switching of 400kV Shunt Reactor"

[3] F. Basha, M. Thompson, "Practical EHV Reactor Protection," proceedings of the 40th Annual Western Protective Relaying Conference, Spokane, WA, October 2013.

[4] IEEE Std C37.109™-2006, IEEE Guide for the Protection of Shunt Reactors.

[5] IEEE Std C37.015™-2009, IEEE Guide for the Application of Shunt Reactor Switching.

VIII. BIOGRAPHY

Kevin Damron received his BS in electrical engineering from the University of Kentucky in 2001 and a 'Power Systems Protection and Relaying' certificate from the University of Idaho in 2009. In 2002, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the research and development division. Prior to joining Avista Utilities in 2010, he was employed by Eta Engineering Consultants (EEC), PSC providing engineering and consulting services. Kevin has broad experience in the field of power system operations, maintenance, and protection and has authored/coauthored several papers on protective relaying. Kevin is a registered professional engineer in Washington State, an adjunct professor at Gonzaga University, and is an IEEE member.

20160912