NZ Inter Island HVDC Pole 3 Project Completion

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ABSTRACT

This paper provides an update to Transpower's Inter Island HVDC Pole 3 Project commissioned in December 2013. This project was undertaken to replace the existing HVDC Pole 1 mercury arc valve converters with a new 700 MW thyristor converter pole called Pole 3 and complete a replacement on the control system for Pole 2.

Along with a further update with the completion of the project following a previous paper presented in June 2011, the paper will highlight some of the challenges and some novel engineering solutions to problems encountered on the project. Recent HVDC primary plant technology improvements that have occurred and are used on Pole 3, are also discussed.

Retention of the valves and the valve base electronics (VBE) of Pole 2, from a different supplier, required an interface between the new supplier's control system and the Pole 2 VBE. Because of the relatively low short-circuit levels at Haywards, supplementary modulation controls and runbacks were implemented in the HVDC control system to ensure stable operation. A unique reactive power control (RPC) system was also implemented to coordinate the operation of the various voltage control elements with the HVDC control. The installation of a STATCOM at Haywards was necessary to mitigate potential temporary over-voltages (TOV) at the highest power transfers.

Additional features delivered are also discussed which provide benefit for the industry. Testing and commissioning of this project posed a significant challenge, with multiple operational stages, interfacing to existing plant and on-site commissioning being carried out in a market environment.

1 INTRODUCTION

The New Zealand HVDC Pole 3 Project [1]-[4] [6]-[7], between Benmore and Haywards, has recently been completed (December 2013) resulting in a capacity increase of the overall HVDC link to 1200 MW. The thyristor converters of Pole 2 are rated at 560 MW (350 kV, 1600 A) nominal capacity and a continuous overload capacity of 700 MW. The Pole 3 system has a nominal continuous power transfer capacity of 700 MW (350 kV, 2000 A), a continuous overload capacity of 770 MW and a 30 minute overload capacity of 1000 MW. In addition to the existing synchronous condensers, a new 60 MVA STATCOM was installed at Haywards to provide reactive power capacity with a fast response time to control TOV and voltage stability. Fig 1 below shows the final plant configuration for the project.

A paper [6] was presented in June 2011 during the construction phase. Since this time the project has been successfully completed and is now operating with its increased bipole capacity of 1200 MW. Key activities completed since the previous update are equipment installation, off-site functional and dynamic performance testing of the system and on-site testing and commissioning.

This paper describes some of the main engineering challenges and describes some of the new facilities provided. Details of the test and commissioning processes are also described, highlighting the scale and complexity of this activity.

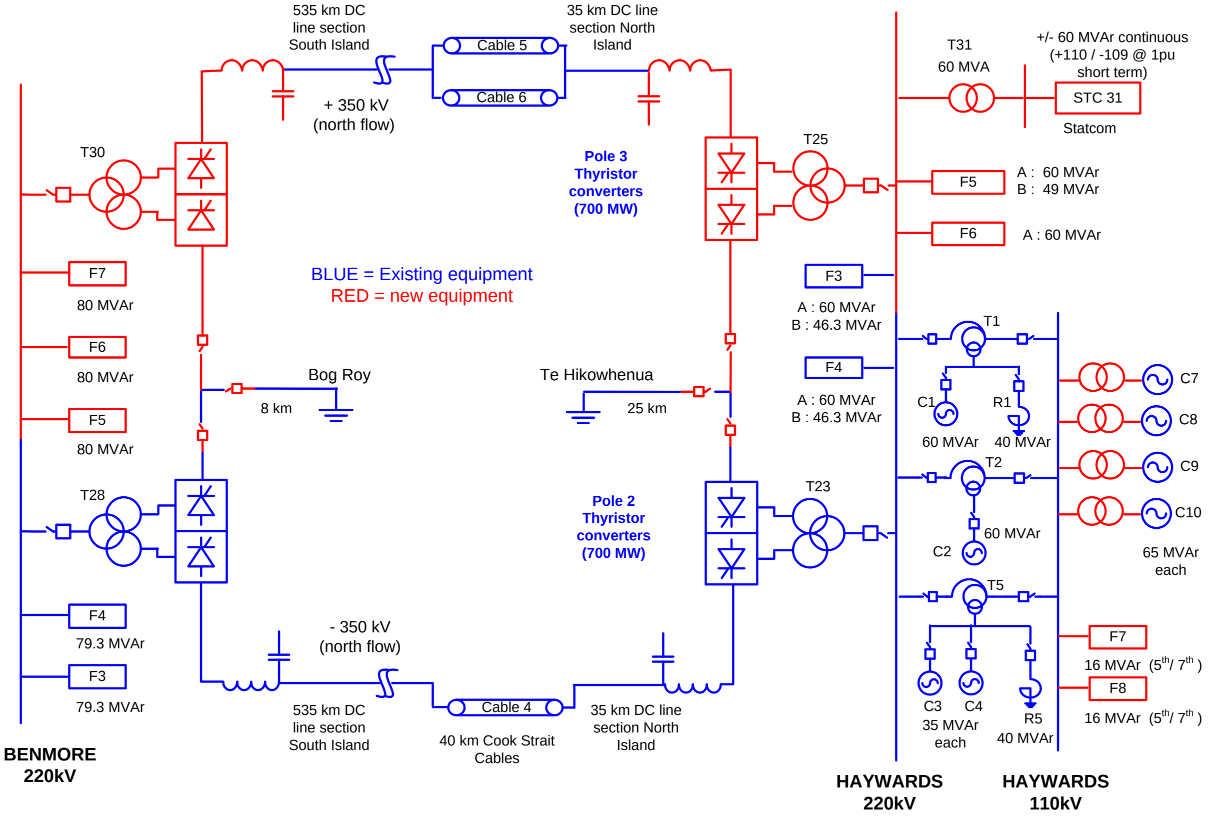

Figure 1: Final state of plant delivered under the project

2 BROWN FIELD CONSTRUCTION AND SEISMIC CHALLENGES

A significant extension of the 220 kV AC switchyards was required to connect the new Pole 3 converters, AC harmonic filters and associated plant items at both Haywards and Benmore, and a STATCOM at Haywards. Both Pole 2 and Pole 3 share a common DC switchyard which meant some of the Pole 3 work could directly impact on the operation of Pole 2.

One of the project objectives was to maintain availability of existing Pole 2 operation during the construction of Pole 3. This was required to ensure the interisland HVDC transmission capacity was not disrupted due to any construction works being carried out.

The brown field sites made construction and installation works alongside live equipment extremely difficult and this was compounded by the limited space available, particularly at Haywards substation. The substation layout was a major challenge due to space constraints and the need to stage construction in a live environment while maintaining commercial operation of Pole 2. Over several stages the congested DC yard in Haywards was upgraded by removing old Pole 1 equipment and installing new Pole 3 components.

Both converter stations are required to have a high level of seismic resilience. A contract requirement was included to ensure that as far as possible the seismic design for the Pole 3 converter used different principles and methods of damping to the Pole 2 converter in order to provide an increased level of diversity between the Poles. The Pole 3 control system was also installed in a separate building to Pole 2 to provide full redundancy and physical diversity. A base isolation of the Pole 3 building was achieved, using a Lead Rubber Bearing (LRB) seismic isolation system, which is capable of horizontal displacement of up to ±600 mm.

All 220 kV and HVDC equipment and selected items of critical plant were qualified by shake-table testing. This required an extensive programme of testing in laboratories in Germany, UK, USA, Italy and Greece. Additionally, all equipment was seismically analysed for compliance with IEEE 693 ‘High’ level and the site specific spectra. The latter was used to assess the need for additional spares holding.

3 PRIMARY PLANT TECHNOLOGY IMPROVEMENTS

Since the Pole 2 upgrade work carried out in the early 1990s, primary plant technology improvements have occurred internationally and a number of them have been used by the Pole 3 Project.

The Pole 3 converter transformers were specified to have a 90 degree C maximum winding copper hot-spot temperature at full load, rather than the higher value allowed by the IEC 60076-2 and used for Transpower’s conventional transformers. This enables cooler transformer operation, a subsequent reduction in winding insulation degradation and, accordingly, a possible designed increase in complete transformer life. The Pole 3 converter transformers were also provided with winding copper hot-spot temperature monitoring instrumentation that was non-standard for the factory which operates by modelling thermal characteristics of the windings derived from factory test results. This allows greater ability to more accurately utilise the transformers’ thermal overload capability. Each converter transformer was also provided with an integral redundant oil/air cooler to allow maintenance of any one of the normally in-service coolers while the transformer remains energised, thus allowing an increase in DC link availability.

All the Pole 3 converter transformer bushings and the valve hall DC wall bushings use solid resin impregnated paper (RIP) insulation with composite material sheds, rather than the conventional oil impregnated paper insulated bushings with porcelain sheds. There are twelve DC side bushings from three converter transformers which protrude into each valve hall, see Figure 2. There are also two additional DC wall bushings per valve hall. The use of RIP in these bushings considerably reduces the potential fire load in each hall. Historically in other countries, there have been catastrophic valve hall fires caused by cracked or broken bushings allowing oil under pressure into the hall and to vigorously burn. Such valve hall fires are a high insurance risk and for Pole 3 it has been mitigated by the use of RIP bushings. The RIP bushings also provide better seismic performance.

Figure 2: Converter transformer bushings

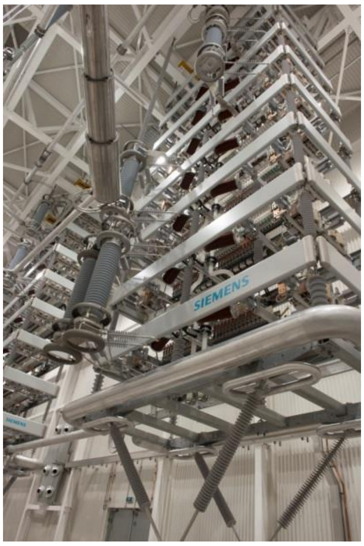

Figure 3: Roof suspended Quadrivalve

The most significant technological change regarding the thyristor valves since Pole 2, has been the change from four inch diameter electrically triggered thyristors to the use of five inch diameter laser light triggered thyristors. The new thyristors have a higher peak reverse voltage, increasing from 5.5 kV to 8.0 kV. Hence there has been a reduction in the number of thyristors per valve, from 66 for pole 2 to 52 for Pole 3. This has resulted in a reduction from 20 t. to 17 t. in the suspended weight from the roof for each Quadrivalve (see Fig 3). In spite of the reduced weight, Pole 3 valves have a higher maximum continuous current of 2857 A for each pole compared to 2000 A for Pole 2.

The outdoor plant used for measuring 350 kV DC current and voltage has also benefitted from step changes in technology. Analogue DC current and voltage signals are measured and converted to optical digital signals via on-board electronics mounted at measuring potential. The digital signal is sent to ground level and the control system via direct optical fibre connections. Separate fibres containing higher power laser light are used to provide energy to power the A/D converter electronics.

4 CO-ORDINATION OF NEW AND EXISTING PRIMARY PLANT

Pole 3 has a higher nominal and overload rating than Pole 2, and is now connected to the same 220 kV AC busbars as Pole 2 (unlike Pole 1). This new configuration requires consideration of a number of technical issues that could arise for the existing Pole 2 equipment. The main issues relate to the loading of the common DC neutral equipment, the surge arrester loading, and the AC filter loading (with both poles now injecting harmonic currents at 220 kV).

The DC current rating of Pole 3, particularly the continuous overload of 770 MW, 2200 A and the 30 minute overload of 1000 MW, 2857 A, is considerably higher than the existing plant rating. The DC yard needed rearranging and several components on the DC neutral bus required replacement with higher rated components. This included the disconnecting switches of the electrode lines, the high-speed neutral bus switch (HSNBS) of Pole 2, the neutral surge capacitors and the DC neutral surge arresters. Installing four new DC switches and associated commutation circuit as well as consideration of the individual protection zones/functions added to the complexity in the congested DC yard, particularly at Haywards.

For insulation co-ordination, the surge arrester arrangement, the V-I characteristics and the protective levels of the new surge arresters were selected such that the rating of the existing plant will not be exceeded. The philosophy adopted here is for the new arresters to take most of the duty when both poles are in service and rely on Pole 2’s existing arresters when it is in monopole operation. The existing “A” or “E” arresters [3] provide adequate protection of Pole 2 plant with Pole 3 not in service, so these existing arresters have not been removed and remain installed. However, to ensure that all AC plant is adequately protected against low-frequency, switching surge and lightning impulse over-voltages during bipolar or standalone operation of Pole 3, new “A” arresters with considerably lower protective levels (SIPL, LIPL) have been installed.

During the Pole 2 outage for installation of the new controls, Transpower also took the opportunity to replace the old valve arresters on Pole 2 with new technology arresters. These new arresters will allow the removal of some existing limits on Pole 2 operation and allow for possible use of higher overloads on Pole 2 in the future.

For the Pole 3 Project, the AC filter requirements have changed considerably from the design requirements of the Pole 1/Pole 2 configuration. Previously each pole was provided with two AC filters and while there would be some transfer of harmonic currents from one pole to the filters of the other pole, the design intention was to provide filtering for each pole separately. With all filters connected to 220 kV, the burden of filtering the injected currents is now fully paralleled for the two poles and all connected filters. Also, the potential for resonances within the filters themselves has to be avoided for all possible combinations of filters in service.

In addition, the design criteria including the system impedance envelopes used, the calculation methods used, the treatment of background harmonics, and the required tolerances for off-nominal AC system frequency (now +/-2 Hz) were all changed since the installation of the Pole 2 AC Filters. The new AC filters installed at the 220 kV AC buses at Haywards and Benmore address these issues and meet the stringent harmonic performance requirements of NZECP36 [5].

The design of the new AC filter scheme considers the symmetry requirements between the existing and new AC filter sub-banks (for adequate sharing of harmonics), as well as other design aspects such as the Mvar sub-bank size limits and the layout/footprint constraints of both converter stations. The design also required that filter component ratings were adequate to ensure there would be no transfer capability reduction for the HVDC for a single outage (i.e. N-1 of a sub-bank at Haywards and N-1 of a bank at Benmore), and that at least 1200 MW transfer was possible with a full bank outage at Haywards.

At Haywards the existing Pole 2 AC filters do not provide sufficient filtering of the 11th and 13th harmonics to simply allow their impedance parameters to be copied. New triple-tuned AC filters TT 11/13/24 with a significantly lower impedance at the characteristic 11th and 13th harmonics have been installed. These new filters will draw more (but not all) of the 11th and 13th harmonic currents than the Pole 2 filters. The existing filters will therefore still share the harmonic load when they are connected in parallel. The new filters are preferred in the Reactive Power Control scheme to ensure harmonic compliance levels are met for all operating conditions. The decommissioned Pole 1 filters at Haywards had 5th and 7th harmonic branches to allow for 6 pulse operation of the Pole 1 Mercury Arc valves. This had the considerable side benefit of providing filtering of the high levels of background harmonics at these frequencies. New 110 kV 5th and 7th harmonic filters have therefore been installed which are no longer related to HVDC operation but are required to filter these background harmonics to keep the Haywards site compliant with the NZECP 36 limits.

At Benmore, the existing Pole 2 AC filters parameters could be copied more directly. However instead of parallel branches for 11th/13th/24th and higher frequencies, the new filters are triple-tuned AC filters TT 11/13/24 including damping resistors to provide a high-pass characteristic. The impedance variation with frequency has been designed to closely match that of the parallel design of the existing filters. At Benmore the design analysis showed that the impedance of some AC filter combinations could lead to resonances and amplification of the pre-existing low order harmonics which might result in harmonic voltage distortions above compliance limits. Therefore, a single-tuned low order filter, tuned between 3rd and 4th harmonics to provide filtering of 3rd, 4th and 5th harmonic has been installed. Harmonic recordings since installation have demonstrated the benefit of this filter and that it was required to meet overall distortion limits.

Besides the steady state stresses, all new filter components are adequately rated for the duty resulting from transient events, such as unbalanced faults, DC load rejection, parallel filter switching, transformer energization and/or AC system frequency excursions which will result in high short-time stresses. Furthermore, design calculations prove that the design of the new AC filters does not result in any over-loading of the existing filters.

5 WORKING WITH A WEAK AC SYSTEM

The HVDC link connects two relatively small independent AC island systems. The voltage and frequency can fluctuate more widely in the two islands than in a large interconnected grid. This requires the DC link to have special design and operational considerations so the Grid Asset Owner can maintain its regulatory obligations on New Zealand’s power system. Because of the relatively low short-circuit levels at Haywards converter station as well as the increased rating of the HVDC Inter-Island link, additional over-voltage control measures, supplementary modulation controls and various power runbacks were implemented in the

HVDC control system to ensure stable and compliant operation. The implementation of the stability control (special protection) schemes enables high pre-contingency transfer levels and hence increases availability of HVDC link capacity.

5.1 Voltage and Stability Management

In order to maintain stability of the North Island AC system, a Fault Recovery Modulation (FRM) controller for transient AC voltage support at Haywards has been implemented. The modulation of the DC current effectively damps voltage swings at the Haywards AC buses during the DC power recovery following AC fault clearing, this significantly helps the Synchronous Condensers at Haywards to retain synchronous operation and thus prevents potential instability or voltage collapse.

At high power transfers north on the HVDC link there are some AC system faults on the North Island that are very difficult for the AC system to recover from. These include AC faults that result in busbar clearances at Haywards or Bunnythorpe. Fast power limit functions based on the bus zone protection signals are integrated into the HVDC controls to instruct the HVDC not to attempt recovery to the full power level for such events, this ensures stability of the AC power systems is maintained.

At high power transfers south on the HVDC link, the reactive power margin at Haywards can be eroded very rapidly for a wide range of system disturbances. To ensure the AC voltage remains healthy and stable operation of the HVDC can continue, various power runback functions are implemented based on the Synchronous Condenser loading and the AC voltage level. A reduction in the HVDC transfer reduces the reactive power demand of the HVDC link and therefore assists the voltage recovery.

At high power transfers in either direction, the weak AC system also creates AC over-voltage problems when the DC power is interrupted either transiently for AC faults, DC line faults etc or permanently in the unlikely event of a bipole trip.

To manage this, the HVDC control system applies power limits to reduce the HVDC maximum power capability when AC equipment is out of service. So if multiple AC lines are undergoing maintenance then the maximum HVDC transfer will be limited. This function also existed in the older ABB control system but the new control system has enhanced the functionality primarily by recognising that the reduction in HVDC capability (for North flow) does not need to be so large if the demand is high at Haywards. This increases availability of HVDC link capacity during outages.

In addition to applying power limits based on outages, the new controls have fast acting AC filter switching controls and control of a STATCOM to ensure that over-voltages are controlled after an event. Under normal circumstances the DC power will recover quickly and these schemes will not operate; however, in the event that the over-voltage is prolonged, the control system will switch out AC filters sequentially to reduce the AC voltage. In the event of a bipole trip, the controls will simultaneously switch multiple filters out of service; it can do this for a bipole trip as under this condition the filters will clearly no longer be required for harmonic reasons.

5.2 Frequency Management

The HVDC link has historically been operated with a Frequency Stabilization Control (FSC) and a Spinning Reserve Sharing (SRS) control function [8]. These control actions modulate the DC power transfer when the AC system frequency changes on one or both islands. These control actions aim to reduce the extent of a frequency excursion (FSC) and to transfer spinning reserve to the other island if there is a prolonged frequency dip (SRS).

This functionality has been retained in the new control system and in addition an alternative Frequency Keeping Controller (FKC) has been developed. The FKC would act to keep the two ac systems operating at the same frequency, this function was unavailable with the previous control system. This function is added to allow for possible changes in the electricity market operation, enabling the HVDC link to perform a frequency keeping role across the two islands. The FKC control also includes a non-linear gain function which provides a number of potential benefits – including the ability for the control to know when to stop acting; e.g. when one island is below (or above) a certain frequency.

If the AC system of the Wellington area becomes separated from the rest of the North Island power system (ie islanded), a Constant Frequency Controller (CFC) will control the AC frequency of the Wellington island ensuring stable operation under such contingency conditions. In addition to the frequency control, a fast DC power reduction may be initiated to limit the frequency rise to 52 Hz in the Wellington area after islanding (Wellington Over-frequency Brake (WFB)). These functions were transferred from the previous control system.

5.3 Special Control Features

An HVDC converter has a minimum DC current requirement to avoid intermittent DC current operation. For Pole 2 this is 30 MW and for Pole 3 it is 35 MW. With a normal control system this imposes a minimum power below which the bipole cannot operate. Historically the bipole would need to be switched off for 5 minutes when a power direction change was required.

One distinctive feature of the upgraded HVDC link is the new round power control mode. This control mode allows for the bipole power to be automatically reduced through zero MW and into operation in the other direction without any interruption. It achieves this by stopping one pole and going into monopole operation at an operator specified power level, and then starting the stopped pole in the opposite direction as the overall DC power transfer level reduces (see Figure 4).

At low power transfer levels, the HVDC system is then operated with one pole in north flow and the other pole in south flow. This mode of operation allows the total bipolar HVDC power transfer to be zero with neither pole operating below its minimum current. As the power level is increased the system would automatically return first to monopole operation and then to bipole operation in that direction.

The round power control mode has been designed to work with the frequency modulations enabled and this would allow the HVDC link to remain connected and providing all its required frequency control and stabilisation functions even if no HVDC transfer was required. This functionality can also enable or assist with possible changes to the electricity market operation in the future.

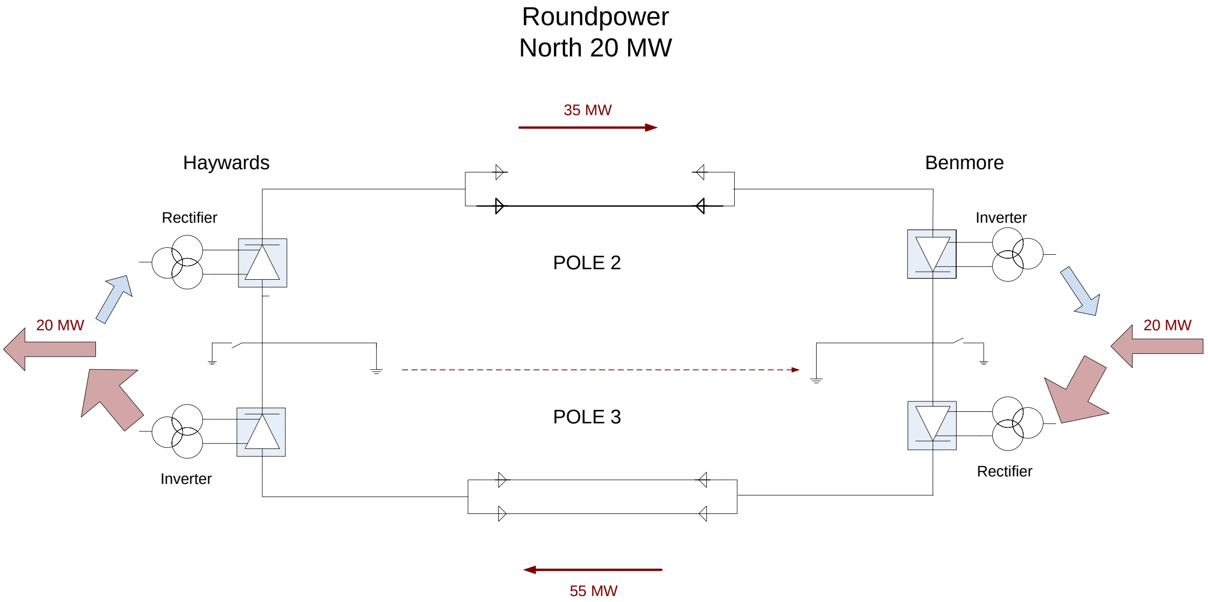

Figure 4: Representation of round power in operation (losses ignored for clarity)

6 CONTROL AND PROTECTION IMPLEMENTATION

6.1 Co-ordination of New and Existing Control Systems

Prior to the commissioning of the new Pole 3 controls, the old and new bipole controls were operating simultaneously with Pole 3 acting as the master. The old bipole control was scheduled to be decommissioned with the Pole 2 control system replacement (i.e. following commissioning of Pole 3). This necessitated a temporary interface during the interim period to communicate between the existing Pole 2 control systems and the new Pole 3 control systems.

This temporary interface provided facilities to aid with coordinated bipole dispatch, sharing of modulations/runbacks between the poles and to provide pole-to-pole power transfer. Commissioning test facilities were also provided to enable a special mode to manage the commissioning risk. Lastly, interfacing facilities were provided to simulate signals to the old control system, take over some of the DC neutral protections and integrate the DC measurements.

Associated with the final state of the project, a replacement of the Pole 2 controls was required to interface to the existing valve base electronics (VBE) of the Pole 2 system. This required a VBE interface to be developed to allow the new Supplier’s pole control system to operate the existing VBE from a different supplier. This effectively provided the ability to convert the firing pulses from the new firing control system into a signal that would be recognised by the existing Pole 2 valve. This system also provided a replacement for the valve monitoring system.

6.2 Control System Testing – Factory and On-Site

Development and testing of the control system took place through various stages. Initially, system studies were carried out across a very wide range of scenarios to ensure that the concept design covered the overall performance objectives. From here the detailed design and implementation took place, followed by factory acceptance testing (FAT) and on-site commissioning and testing.

Due to the staged delivery approach of the project, it was essential that each stage was completely tested and proven operationally prior to commencement of the next stage. This essentially resulted in four test phases all independently proven. Off-site factory acceptance testing (FAT) was undertaken with 1600 unique tests resulting in approximately 1900 tests actually run (including 300 repeat tests). On-site, 382 unique tests were required with approximately 460 tests actually run. FAT took 11 months to complete, while the on-site commissioning tests were carried out over a 4 month period for Pole 3 and a 3 month period for the Pole 2 control replacement and STATCOM.

For the off-site FAT testing, three test environments were utilised. The first: the set of controls that were to be delivered and installed at site, the second: Transpower's customer simulator, and the third: simulations in PSCAD™. The customer simulator is a stand-alone simulation environment to be used for future testing and development (see Figure 5). This environment contains a replica set of non-redundant controls, a simulation of the substation equipment and a real time digital simulator (RTDS) for the AC and DC system simulation. Once this simulation environment was delivered to New Zealand in March 2013, it was also used for troubleshooting and testing of issues associated with the on-site testing. Tests were split evenly across these three environments.

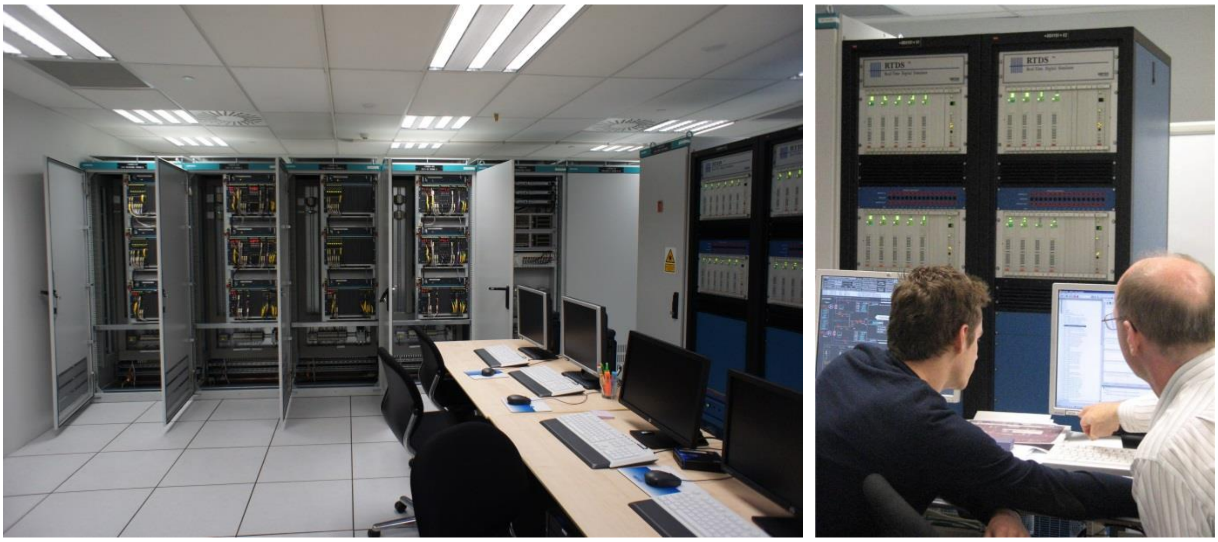

Figure 5: Transpower's GHOST (Grid HVDC Offline Simulator Tool) installed in Wellington

On-site commissioning was a significant challenge for the project. Testing in a market environment required a trading team to be established to contract the flows required for the testing [7], and difficulties in achieving these flows and interdependencies between tests not accepted resulted in a sizeable planning and coordination effort for the commissioning team. As noted above, the test sequence was split into two stages, the first being commissioning of the new Pole 3 equipment followed by commissioning of the Pole 2 and STATCOM equipment. Between these two stages was a 6 week bipole outage needed to transfer Pole 2 from the old interfaces to the new interfaces which proved to be a challenging exercise.

7 CONTROL FACILITIES FOR FUTURE INDUSTRY BENEFIT

Various additional facilities have been delivered through the project that have either delivered improvement or enable future improvements to be realised. These included thermal models, national markets and improved RPC controls and are discussed further below.

7.1 Thermal Models

Thermal models have been developed and delivered for a majority of the Pole 3 and common bipole assets as part of the project. There are two types of models developed; the first associated with the HVDC assets (DC overhead line, electrode line, DC cable, converter transformer, smoothing reactor, PLC reactor) and the second associated with the AC transmission lines feeding the two converter stations.

The HVDC asset thermal models have been provided to ensure that the full capability of these assets is released and can be managed to a maximum 30 minute overload level post event. All of these thermal models consider the recent historical loading of the plant along with other parameters such as ambient temperature, winding temperature wind speed and solar radiation. The previous controls only provided such models for the DC cable.

Thermal models associated with AC lines serve a slightly different purpose. When AC lines feeding the stations are removed from service there is an associated change in transmission capacity into the station. With the previous design, a conservative approach was taken to ensure that the HVDC transfer would not result in an overload of these AC lines by applying a capacity limit on HVDC transfer. This did not consider whether any lines were actually overloaded. By applying thermal models to the AC overhead lines, any limitation on HVDC transfer capacity is now only initiated if an AC line is actually identified as being overloaded by the thermal models. As with the HVDC thermal models, these models consider the recent historical loading of the plant along with other parameters such as ambient temperature, wind speed and solar radiation.

7.2 National Markets

As discussed in Section 5.3 above, a new bipole transfer mode called round power and a new frequency controller called Frequency Keeping Control (FKC) have been delivered. The combination of these two facilities provides the ability to allow for the physical characteristics of the generating plant on each island to be better managed when providing reserve response in New Zealand. This could see a single frequency market developed. In effect these new facilities enable both islands' frequencies to be managed together, allow reserves to be shared and transferred between the islands across the entire bipole operating range without separation when at low power transfers. The industry benefit from this would be potential reduction in reserve costs to the market. Basic trials have been conducted, and plans are underway to implement an operational trial later in the year.

7.3 Improved RPC Control

The Reactive Power Controllers (RPC) at Haywards and Benmore include a number of changes which improve the functionality and reliability of the system.

At Haywards, several improvements have been put in place to make better use of all eight synchronous condensers, STATCOM and AC filters. One key improvement has been to expand the system configuration cases where the RPC will continue to operate in an automatic mode. This is implemented through the RPC having better awareness of split busses and splits in the Wellington network between the 220 kV and 110 kV network. This will result in less operator interaction required under non-standard system conditions.

For Benmore, changes in the RPC modes have been included. Previously an Mvar exchange mode was provided to maintain Mvar flow through the interconnecting transformers, and this was the default operating mode. With the decommissioning of Pole 1 and the reconfiguration of the Benmore machines onto new unit transformers, the default control method for the new RPC is 220 kV voltage control with voltage droop control of the generators. A new reactive power exchange mode (Q control) has also been provided. This new Q mode monitors the net reactive power of the HVDC converters and AC filters and switches the filters to maintain appropriate reactive power flows. Q mode can be used if the generators at Benmore are unavailable for control by the HVDC control system.

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