More Transmission STATCOMs

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ABSTRACT

Three new high voltage power electronic dynamic reactive STATCOM power plants have recently been constructed and connected to the Transpower transmission system. They have all been provided by the same supplier/contractor and utilise high voltage multilevel Insulated Gate Bipolar Transistor technology.

One plant was installed at the Haywards converter station site as part of the Pole 3 HVDC upgrade project and is required to complement the operation of the new Pole 3 and refurbished Pole 2 converter plant. The other two plants were installed at the Penrose and Marsden substation sites and are required for dynamic reactive power support.

This paper provides an overview of the high voltage multilevel Insulated Gate Bipolar Transistor technology provided. This is followed by an outline description of the STATCOM plant and components installed. Also discussed are aspects of factory manufacturing, testing, site construction and commissioning.

1. INTRODUCTION

Since Transpower's successful introduction of its first multilevel isolated gate bi-polar transistor (IGBT) Synchronous Compensator (STATCOM) at Kikiwa substation in 2011, three more of a similar type have been successfully installed and commissioned in the North Island transmission system. All three were commissioned in 2013 and supplied by the same manufacturer.

The STATCOMs primary purpose at Haywards converter station is to provide fast dynamic control of transient 220 kV over-voltages generated by HVDC contingencies. It does this by providing dynamic leading or lagging reactive power with a response time of 40 ms. The second purpose is to provide fast response dynamic reactive power to maintain system voltage and hence maximum power flow in the DC link. The control of this STATCOM is tightly integrated with the new HVDC Link Pole 2 and Pole 3 controls.

The requirement of the STATCOMs installed at Penrose and Marsden substations is to provide fast response dynamic reactive power to support system voltage during contingent events and to maintain peak power flow limits in the surrounding transmission system. This maximises the thermal capability of existing transmission lines.

This paper introduces the multi-level IGBT STATCOM technology provided at the three sites, with an overview of the working principles involved. This is followed by a discussion regarding factory manufacturing and testing, site construction and commissioning issues, and connection methods to the transmission system. Figure 1 shows locations for the recent STATCOM sites in the North Island.

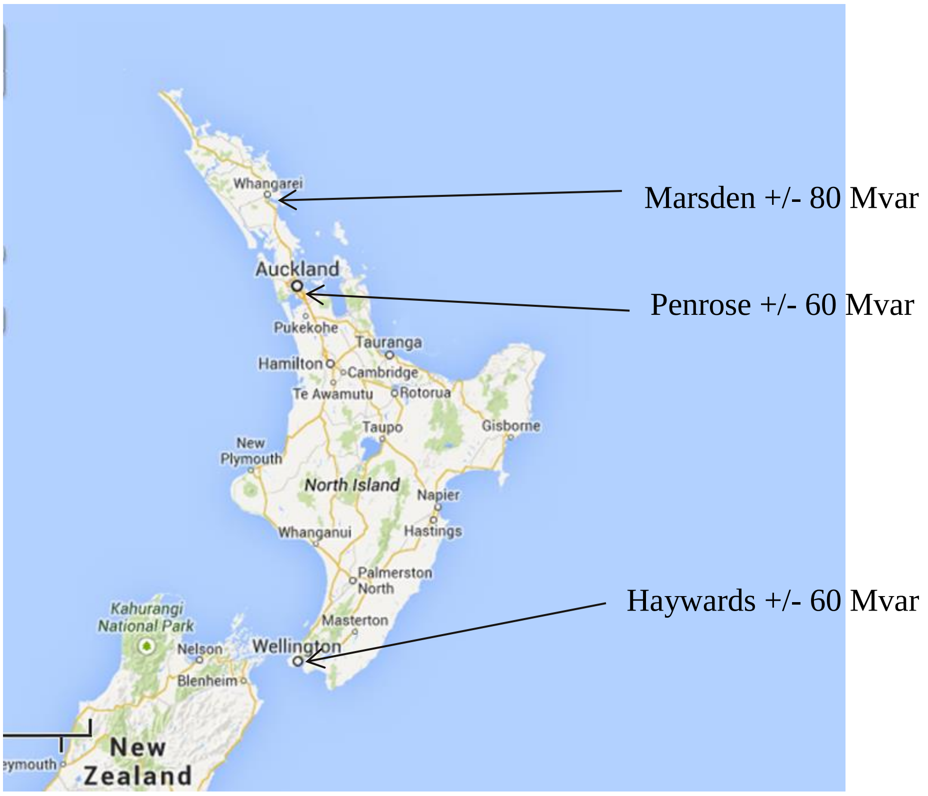

Figure 1: North Island STATCOM locations

2. DEFINITIONS

FACTS: **F**lexible **A**lternating **C**urrent **T**ransmission **S**ystem. (An AC Transmission system incorporating power electronic and static controllers to enhance controllability and increase power transfer capability).

STATCOM: **S**tatic **S**ynchronous **C**ompensator. (A voltage source of dynamic reactive power. This is also a FACTS device).

VSC: **V**oltage **S**ource **C**onverter.

IGBT: **I**solated **G**ate **B**i-Polar **T**ransistor.

RFI: **R**adio **F**requency **I**nterference.

3. TECHNOLOGY OVERVIEW

The multilevel STATCOM technology used is based on the electronic synthesis of a voltage wave shape, amplitude and phase shift and is therefore considered a voltage source converter. Because of this, it can generate dynamic leading or lagging reactive power with a fast response time of 40ms. It utilises multiple standard power switching modules. Each module contains four power IGBTs and diodes connected in an 'H' configuration with an associated DC storage capacitor.

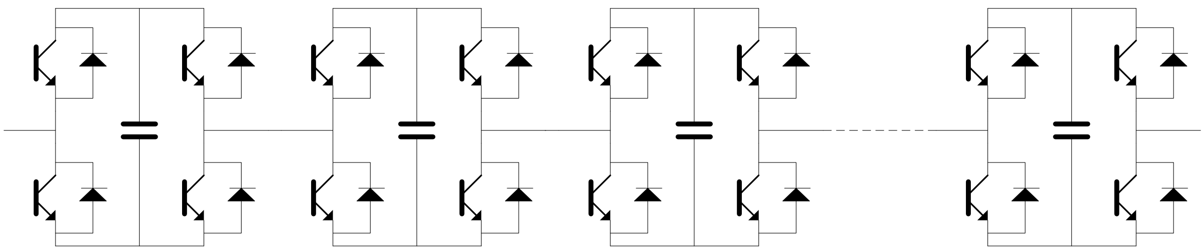

Figure 2: String of 'H' configuration switching modules

A string of multiple modules are series connected, see Figure 2, to provide a synthesised voltage wave shape at the string terminals. Each module can contribute to the total output voltage by providing three different voltage levels, which are: plus Vdc, minus Vdc and zero. The dc voltage is that stored in each module's capacitor. The specific voltage level a module contributes at any point in time is determined by the switching of the individual IGBTs in each module. Hence to achieve a 21 level output voltage wave shape, as shown in Figure 3, ten modules are required. Per cycle there will then be ten positive voltage levels, ten negative voltage levels and one zero voltage level; producing 21 levels.

An increasing number of switching levels results in fewer steps in the resultant waveform produced, hence less waveform distortion. For this reason external harmonic filters are not always required when using this technology with higher switching levels.

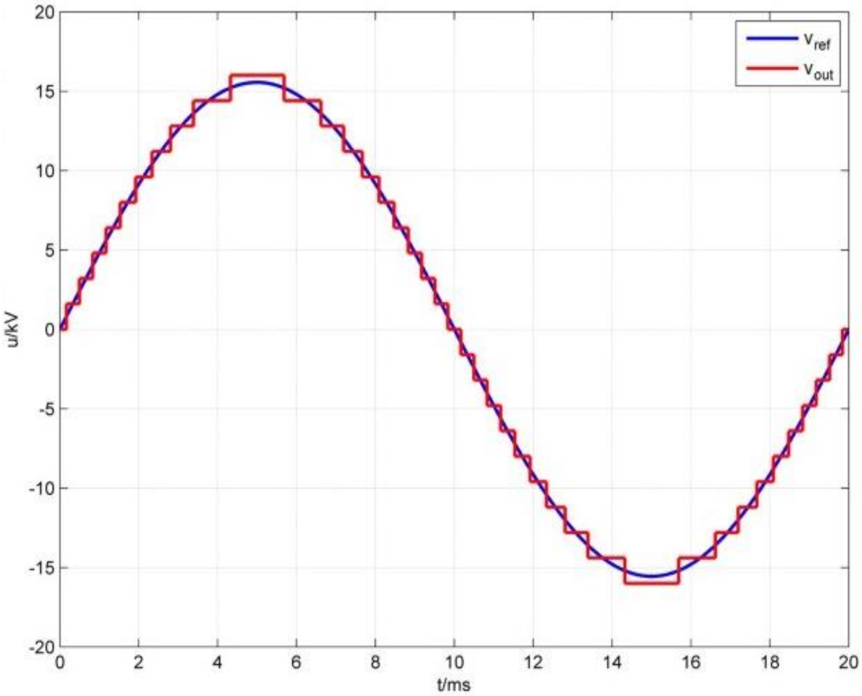

Figure 3: Synthesised 21 level voltage wave-shape

Each string of modules also has spare redundant modules electrically connected and these are electrically by-passed during normal operation. Should one of the in-service modules fail, it is automatically by-passed and one of the spare modules brought into service.

Three strings of series connected modules, associated connection reactors and by-passable capacitor charging resistors, are connected in Delta to provide a three phase converter supply (see Figure 4). By increasing the number of modules, the converter voltage and hence reactive power capacity can be increased.

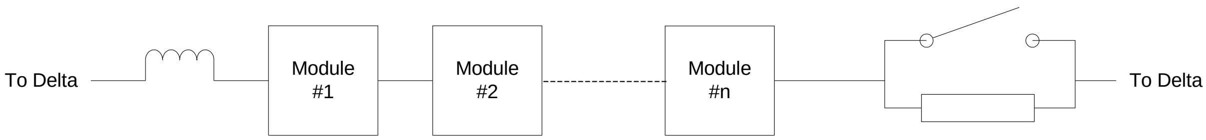

Figure 4: Converter single line diagram

Each module capacitor is initially charged from the power system via the diodes, with the starting resistor in circuit and the IGBTs blocked.

4. COMMON CONVERTER COMPONENTS

4.1. **Power Module**

A typical converter module is shown in Figure 5. Indicated on the right as AC 1 and AC 2 are the module electrical terminals. Also shown are the IGBT and Diodes sandwiched between water cooled heatsinks, together with the IGBT gate driver switching interface boards. Shown on the left is the dry type resin-impregnated DC capacitor which is typically charged to 1,600 volts. This module design is common to all sites.

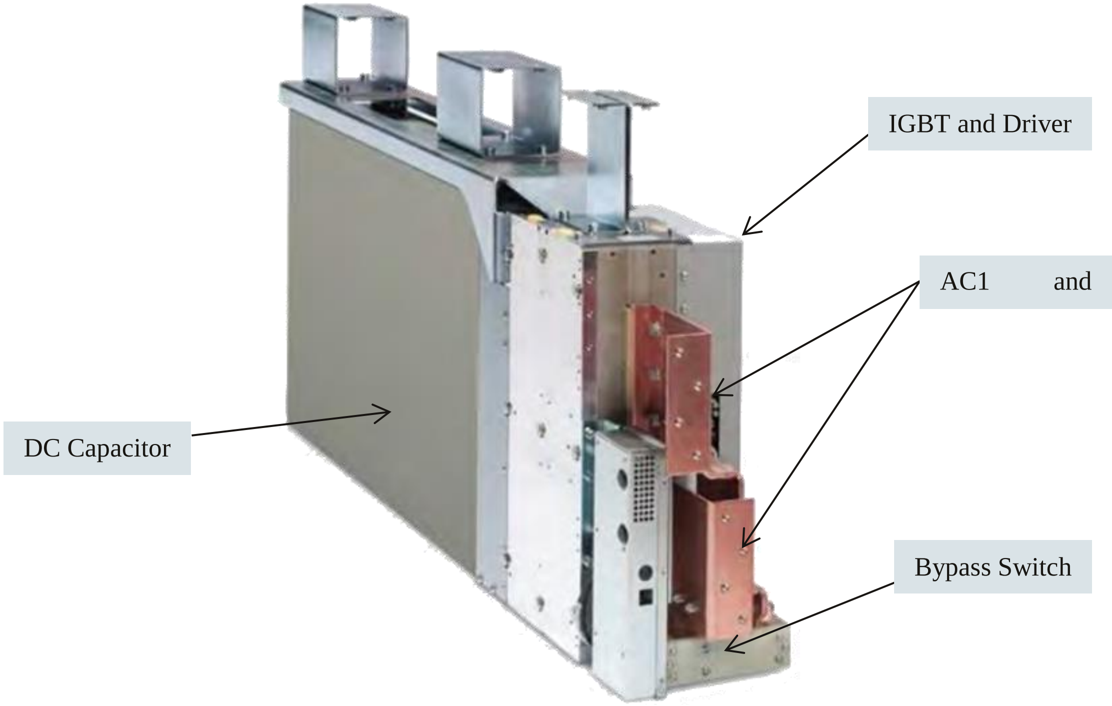

Figure 5: Power module

4.2. **Converter Stack**

Figure 6 and Figure 7 show the two portions of the stack at Haywards. Note the series connected modules and the three strings of modules positioned above each other, one for each phase. Also note the module stand earthquake restraint insulated tie rod cross bracing. Cooling water header pipes can be seen positioned above the modules. Two series connected converter stacks are housed in a purpose designed building at Haywards because the converter size and voltage rating exceeded the available space with standard sized shipping containers. For Marsden and Penrose complete converters were assembled inside standard sized shipping containers in the factory in Germany and shipped “Built-up” to site.

The Penrose and Marsden three phase converters are each rated at 11 kV and 40 Mvar. They operate with 14 modules per phase in service, plus two redundant modules per phase and with 29 switching levels. Each converter has 48 modules installed with 42 in service.

The Haywards three phase converter is rated at 25.5 kV and 60 Mvar. It operates with 33 modules per phase in service, plus three redundant modules per phase and with 67 switching levels. The converter has 108 modules installed with 99 in service.

Figure 6: Left half converter stack at Haywards

Figure 7: Right half converter stack at Haywards

4.3. **Cooling System**

Figure 8 shows the cooling skid assembly for the Haywards STATCOM. The skid contains duty and standby cooling water motor/pumps, instrumentation, valves and piping. At Haywards, this plant is housed in the valve room of the purpose site-built building. At Penrose and at Marsden this plant was incorporated inside standard sized shipping containers, and transported to site ‘built-up’. Critical instrumentation measures water flow, water temperature and water conductivity, with excessive temperature and water conductivity being trip functions.

Figure 8: Cooling Skid

Figure 9: Outdoor coolers

All the Transpower STATCOMs use a similar closed circuit cooling system, where De-ionised Glycol/water cools the power modules and is circulated to outside water/air heat exchangers via pumps. The outside coolers are double-pass-tubing type with fans for forced draft cooling. Figure 9 shows typical outdoor coolers.

4.4. **Outdoor Structure**

All the STATCOMS incorporate separately fenced, outdoor, air insulated, low level structure areas. They contain the medium voltage bus bars, instrument transformers, connection reactors, power cable terminations and auxiliary power transformers. Access to these areas is interlocked with bus-bar earth switches so that access is prohibited if the bus is live. An unusual feature is the space saving vertical positioning of the medium voltage bus bars, which can be seen in Figure 10, together with the connection reactors.

The Marsden and Penrose MV structure areas also include small harmonic and RFI filters. Additional filters are not provided for the Haywards converter because it operates with a higher switching level and produces less troublesome harmonics and reliance is made of other 220 kV connected filters at the site.

Figure 10: Haywards MV structure

4.5. **Control**

The control and protection systems comprise three main components, these are the PlusControl, Plant Control and Closed Loop Control.

The Plant Control system consists of the following functions. This is implemented on the supplier's industrial control platform.

- Interlocking of STATCOM
- Door Interlocking
- ON/OFF Sequences

- Communications
- Sequence of Event Recording (SER)
- Time Synchronisation and Distribution

Interlocking focuses both on safety of the plant and safety of personnel around the equipment. This is especially important with the hazard of the stored energy in the DC capacitors associated with the sub-modules. The charging and discharging of these are managed through the on and off sequences with control of a bypass resistor switch to manage the charging of these capacitors along with the earth switches for the discharge process.

Various communications are implemented across the STATCOM with the general control using Fast Ethernet primarily with fibre optic medium to avoid EMI issues.

For status and event analysis, the Sequence of Event Recording (SER) provides alarms, warnings and status messages which are GPS-time synchronised to allow comparison across various systems. The Plant Control manages generation of the SER messages from the Plus Control, Protection and Closed loop control systems. A Transient Fault Recorder (TFR) is also available for detailed analysis of control signals and analogue waveforms.

The primary functions implemented in Closed Loop Control (CLC) are listed below. These are implemented on the supplier's industrial control platform. The output of the Closed Loop Control is the required converter current (Ireg) which is actioned through to the PlusControl.

- Measurement and HMI interfaces
- Control mode selection for the various control modes delivered including voltage control mode and fixed reactive power control mode
- Stability Controller
- Gain Controller
- Supervision and Protection features such as over/undervoltage protection, converter current supervision and reactive output limitation.

Input signals for the CLC included the HV and LV bus voltages, converter currents, and measurement for the overall STATCOM current. These are then conditioned, sampled and utilised by the remaining control and protection systems within the supplier's industrial control platform.

The primary control mode used under automatic control is voltage control. For this the target of the controller is an operator selected voltage (Vref). This target is then modified to consider a slope characteristic to avoid the STATCOM operating at the limits of the controllable range.

There are also two special functions implemented to maintain stability of the STATCOM controls. The first is hunting detection which is implemented to avoid rapid consecutive changes in the Ireg direction by reducing the gain of the controller until a stable output is observed. This gain is then reset back to nominal value after a fixed time. The second controller is the gain adjustment controller which determines the gain by assessing the system short-circuit level. This is done by periodically applying a small step in the current output and measuring the voltage response.

The output of the STATCOM is monitored continuously to ensure that the output does not exceed the capabilities of the plant. This is especially relevant during system events. The output limiting controller responds to drive the output of the STATCOM back within the envelope of the plant capability by adjusting the current request to the PlusControl. An under and over voltage protection is also implemented to prevent damage to the plant.

The PlusControl system is closely coupled with the valve and is used to send the firing commands to the Power Modules based on the Ireg requested from the CLC. The PlusControl also monitors the performance of the valve. The PlusControl is broken into two components, the first being the current control system (CCS), and the second the module management system (MMS). These systems are built on custom hardware comprising a Microprocessor, Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP). This custom hardware is required to manage the high speed logic signal processing required for control of the valves. Interface to the sub-modules (containing power module and capacitor) is via a fibre optic two-way communications bus from the PlusControl.
Functions within the CCS are as follows:

- Current Order Calculation is used to calculate the active power of the converter
- Output Current Vector Control is used to control the converter currents
- Zero Phase System Balancing is used to balance the capacitor voltages
- Voltage Order Calculation determines the required output voltage of the converter

Functions within the MMS are as follows:

- Capacitor, sub-module and power module monitoring which is used to track the state of the various components for each sub-module
- Pulse generator which generates the switching commands for each of the sub-modules.

Due to the strong reliance on the STATCOM to manage the transient overvoltage performance (TOV) for the HVDC pole and bipole trip events, the STATCOM implemented at Haywards has special integrations back to the HVDC controls. The HVDC reactive power controller (RPC) controls the voltage setpoint in co-ordination with all other plant under the control of the STATCOM. This is done to ensure that the dynamic range of the STATCOM is available to provide response for system events.

4.6. **Protection**

Protection within the controls itself is described in the section above. Along with this a conventional relay-based protection scheme is implemented. This provides transformer protection (where a transformer is present), bus protection and protection of the STATCOM. The STATCOM consists of overcurrent and earth fault protections along with more special protection such as overload and voltage displacement.

4.7. **Human to Machine Interface (HMI)**

A Human Machine Interface (HMI) provides all the required local operator controls, inductions and alarms. A representation of this local HMI is also provided in National

SCADA for remote control. The local HMI indicates the state of equipment, measured values, SER messages and provides a trend displays. An example of the overview screen is shown in Figure 11 below.

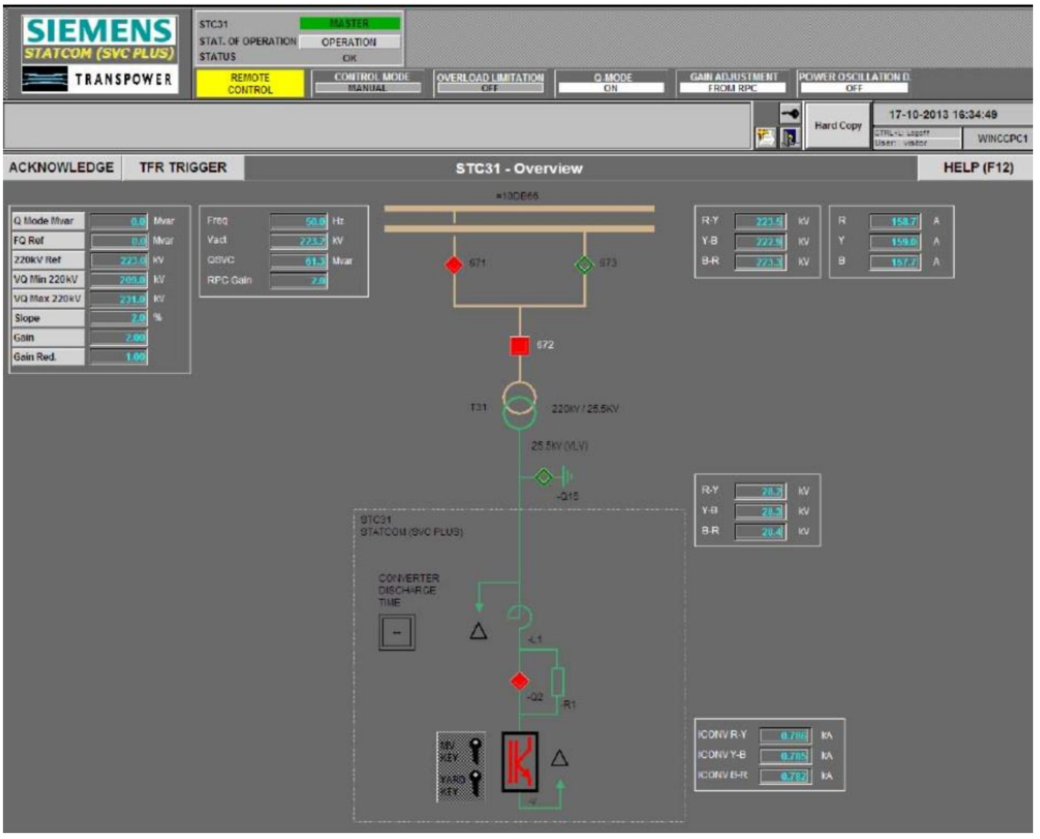

Figure 11: Haywards Overview HMI Screen

5. RATING AND CONNECTION

5.1. Marsden Substation

Two STATCOM converters are installed at Marsden. Each one is rated +/- 40 Mvar, 11 kV and housed in an individual shipping container with one 100% rated outdoor cooler. Two additional containers house the 11 kV switchgear. Each converter is cable connected to individual tertiary windings of existing Marsden 220/110 kV interconnecting transformers. Each tertiary winding and cable connection is rated for 40 MVA continuous. This physical separation of assets and connection method provides continuous n-1 availability for +/- 40 Mvar and n availability for +/- 80 Mvar at 110 or 220 kV. Each STATCOM has a short term rating to provide an output of up to 50 Mvar capacitive and 52 Mvar inductive for 2 seconds.

Figure 12 below shows a single line diagram of the connection of the STATCOMs at Marsden.

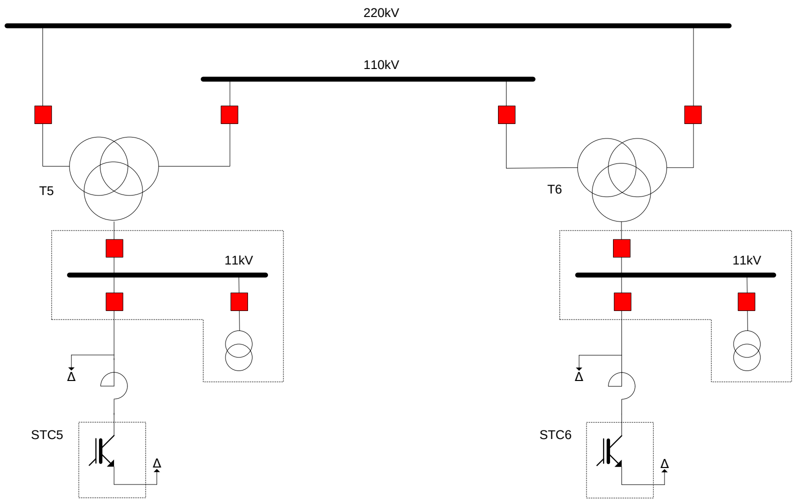

Figure 12: Marsden Single Line Diagram

5.2. **Penrose Substation**

Two STATCOM converters are installed at Penrose. Each one is rated +/- 40 Mvar and 11 kV and housed in individual shipping containers with one 100% outdoor cooler. One additional shipping container houses common 11 kV switchgear. Each converter is cable connected to the switchgear, which in turn is cable connected to a single 11/33 kV transformer and hence connected to the 33 kV Penrose bus. The single transformer and 33 kV cable circuits are continuously rated for 60 Mvar. With both STATCOMs in service, a short term rating is provided with an output of up to 100 Mvar capacitive and 104 Mvar inductive for 2 seconds. Figure 13 below shows a single line diagram of the connection of the STATCOMs at Penrose.

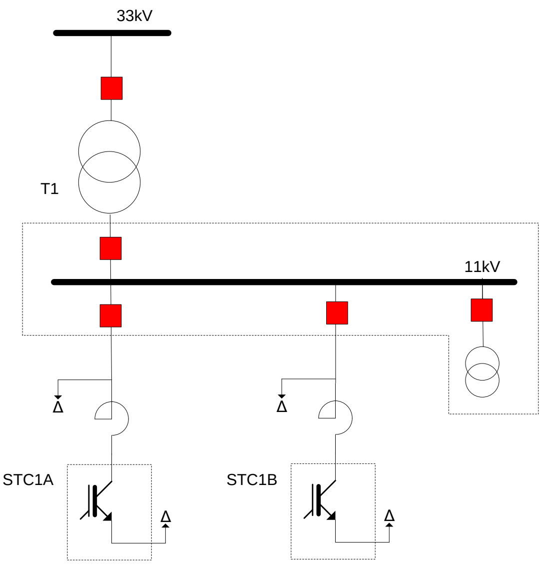

Figure 13: Penrose Single Line Diagram

5.3. **Haywards Converter Station**

One STATCOM converter is installed at Haywards Converter Station. It is rated +/- 60 Mvar and 25.5 kV and has three 50% rated outdoor coolers provided. It is directly cable connected to one 25.5/220 kV, 60 MVA transformer which is selectable to two 220 kV buses via a bay of conventional air insulated outdoor switchgear. A spare 60 MVA transformer is held at site but not connected. The STATCOM has a short term rating with a capacitive output of up to 135 Mvar capacitive and 198 Mvar inductive for two consecutive periods of 2 seconds.

Figure 14 below shows a single line diagram of the connection of the STATCOMs at Haywards.

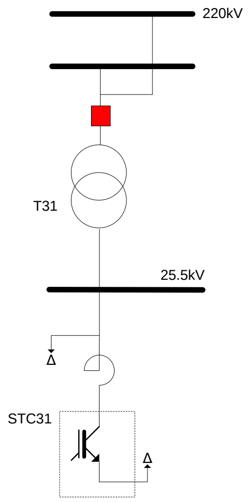

Figure 14: Haywards Single Line Diagram

6. MANUFACTURING, CONSTRUCTION AND COMMISSIONING

For the Marsden and Penrose sites, the supplier/contractor used a construction method not normally used for Transpower projects. This involved assembling, wiring and testing the switching and control plant, and installing it in purpose designed shipping-sized containers at their factory in Germany. The containers were designed to become permanent enclosures for the plant at site. The built-up containers were shipped to site and positioned directly onto foundation piles. This enabled an accelerated construction programme through the simple ability to connect power, control cables and cooling water pipes via the space under the containers. Each Marsden and Penrose converter was provided in a separate container complete with associated cooling plant and control panels. The Marsden 11 kV switchgear was provided in two separate containers and the Penrose 11 kV switchgear was provided in one container. Figure 15 shows a typical 40 Mvar converter container and associated outdoor filtering.

Figure 15: 40 Mvar converter container

Figure 16 below shows the layout at Penrose, with the location of the three containers shown in blue.

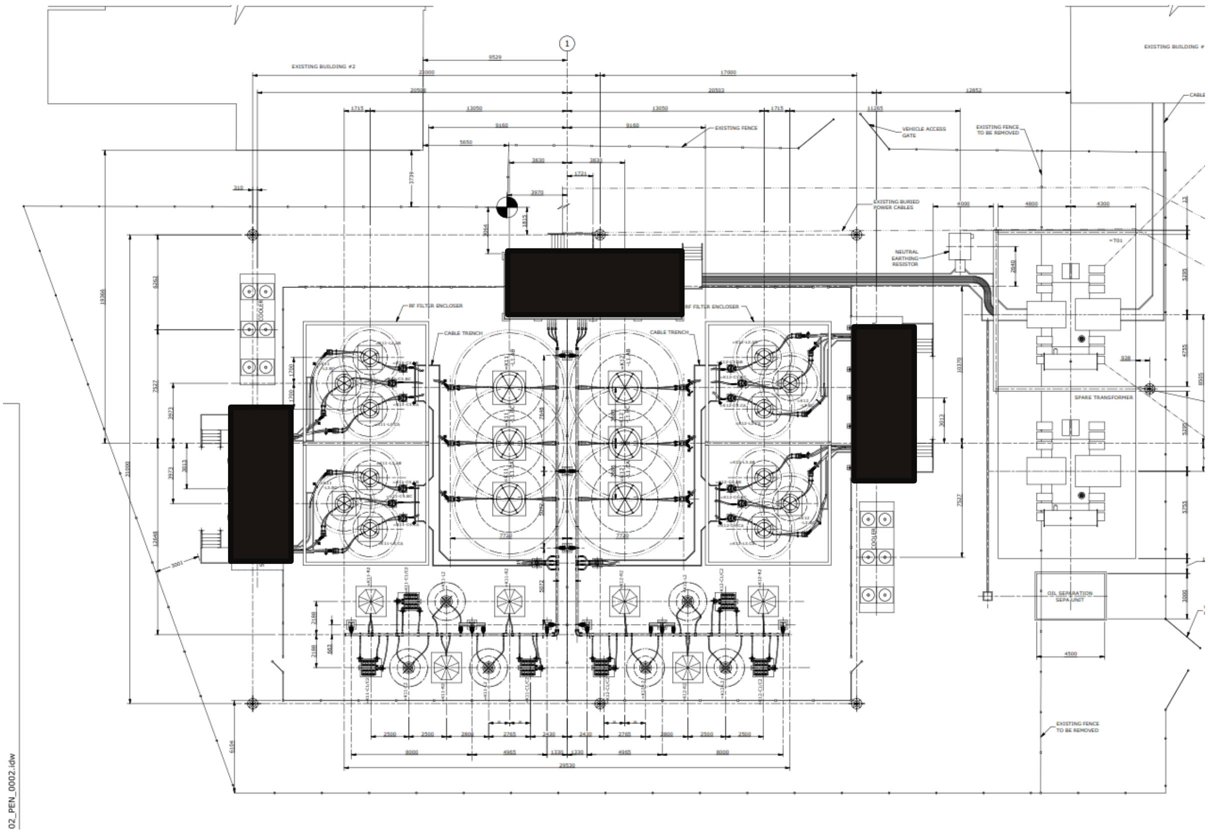

Figure 16: Container layout at Penrose

For the Haywards site the converter could not be assembled inside a standard size shipping container because of the increased number of switching modules involved and the extra internal space requirements for air insulation at the higher rated voltage. Hence a purpose designed building was constructed which incorporated the converter valve, cooling skid, control, protection and human-machine interface panels, batteries and fire suppression gas bottles. To accelerate converter construction timeframes in this environment, the supplier/contractor shipped to site packages of six switching modules in pre-assembled stand sections, which only required simple bolting together inside the converter room.

All primary equipment (capacitors, reactors, transformers and switchgear) underwent factory routine/type testing as required.

For all installations, the control and protection system undertook factory acceptance testing (FAT). The equipment configuration for testing was the full set of control and protection cubicles which would be delivered to site and a real time digital simulator (RTDS) to simulate the response of the power system. Functional and performance tests were carried out in this environment prior to being shipped to New Zealand.

Further functional and performance tests were carried out on-site, following commissioning of the primary equipment. This was undertaken to prove the wider set of results undertaken during FAT and also provided for integrated end-to-end tests across the entire installation. For the Haywards STATCOM this on-site testing was then followed with functional and performance tests while integrated with the HVDC controls.

7. CONCLUSIONS

To contribute to its long term objectives, Transpower installed and commissioned high voltage multilevel type STATCOMS at three of its transmission sites in 2013. Transpower now has multilevel type STATCOMs, of the same type and manufacturer, installed and commissioned at four of its sites.

8. REFERENCES

[1] "Commissioning And Operational Experience With Recent FACTS Projects In The Upper South Island"; I.Hunt, P.Milosevic, P.Cahill & S.MacDonald, EEA Conference, Auckland, June 2011.