Advanced Synchronising System Provides Flexibility for Complex Bus Arrangement

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***Abstract*—The Upper Tumut Switching Station connects Snowy Hydro generators to the TransGrid 330 kV transmission grid via four lines. The substation was originally designed with two bus sections and a reserve bus. Each generation line breaker can be connected to a bus section or bypassed to connect the line to the reserve breaker. TransGrid wanted to operate the system as a three-bus substation, with one bus sectionaliser breaker separating the A1 bus from the A2 bus and one bus coupler breaker connecting the B bus to either A bus. The new arrangement allows each generator line breaker to be connected to one of the A buses or the B bus. Or, when the line breaker is bypassed, the line can be connected directly to one of the A buses or the B bus. This arrangement created the need for a complex synchronising system that would allow each line to be remotely synchronised via any of the three breakers in five switching scenarios. This paper describes the robust and flexible system that was designed to allow this operating flexibility. The automatic synchroniser on each line can automatically reconfigure itself to determine the topology of the station via logic processors and to select the appropriate voltage transformer signals and breaker to close when the operators initiate synchronising.**

I. Introduction

The 330 kV Upper Tumut Switching Station in New South Wales, Australia, was constructed in the mid-1950s. The switchyard topology had two normal buses separated by a bus sectionaliser breaker and one reserve bus that could be connected to either normal bus via a reserve breaker. Any faulty circuit breaker could be bypassed and swapped for the reserve breaker. The arrangement included a large number of disconnects, as shown in Fig. 1.

The switching station's purpose was to connect two hydroelectric power plants to the 330 kV grid. Each power plant has four generating units. Two generating units share a bank of three single-phase, three-winding transformers with a wye-connected high side and two delta-connected low sides, as shown in Fig. 2. The four generator step-up (GSU) transformers (two at each generating station) are each connected to the switching station by their own transmission line. Operating procedures, described later in this paper, require the ability to remotely synchronise a generator using the 330 kV breakers at the switching station.

When the Snowy Mountains Authority, the entity that originally developed the generating plants and switching station, was reorganised into a corporation, ownership of the 330 kV Upper Tumut Switching Station was transferred to TransGrid, while ownership of the two generating stations, Tumut 1 and Tumut 2, was transferred to Snowy Hydro.

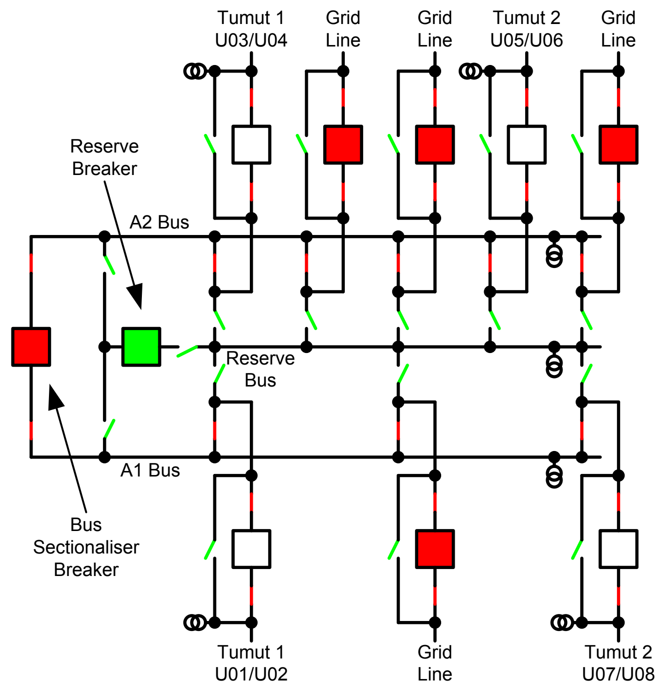

Fig. 1. Upper Tumut Switching Station—Original Arrangement

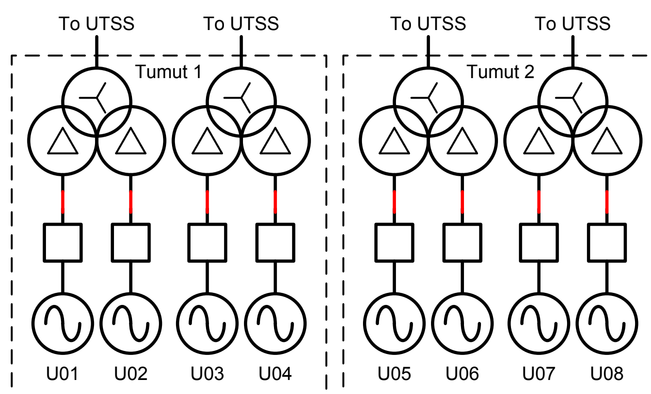

Fig. 2. Tumut 1 and Tumut 2 Generating Stations

TransGrid decided to have full operating flexibility in the switching station. This change in operating philosophy allowed several switchyard topologies not anticipated in the original design. The proposed solution was to use the reserve bus as a normal bus (now called the B bus) and to allow a bypassed circuit breaker to be replaced by the bus coupler or the bus sectionaliser breaker. Fig. 3 shows the new configuration [1].

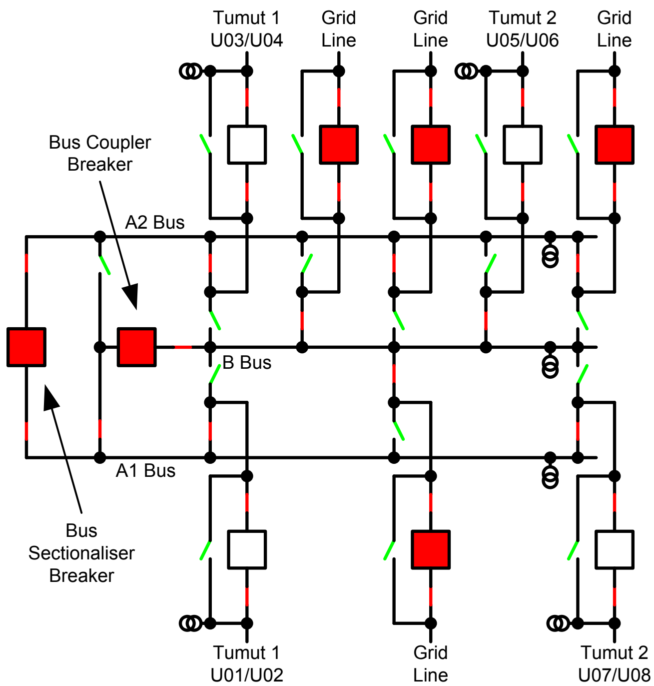

Fig. 3. Upper Tumut Switching Station—New Arrangement

This change prompted the need to upgrade the synchronising system to provide the required operating flexibility to work under the new operating philosophy. This paper (an expansion of [2]) describes the new synchronising system that was developed and implemented to provide this extreme degree of flexibility.

II. Generator Synchronising Procedures

The GSU transformers are left de-energised when both generators are shut down. The generators may be started and stopped several times a day, depending upon the load profile at the time.

To avoid transformer inrush, the first generator to be started on a transformer closes its generator 12.5 kV circuit breaker when the generator is still stationary. The generator then runs up to speed and is excited. The first generator is then synchronised in the 330 kV switchyard.

The synchronisation of the second generator occurs in the power station across the generator 12.5 kV circuit breaker. Either generator can be the first generator online on a transformer.

The systems in the Upper Tumut Switching Station must allow synchronising of the generator on the 330 kV side of the transformer.

A. General Synchronising Considerations

Reference [3] goes into great detail on the fundamentals of designing generator synchronising systems. The major points of that paper are highlighted in this subsection to provide context for the new system advancements discussed in this paper.

1) Consequences of Faulty Synchronising

Poor synchronising can have the following consequences:

- Damage to the generator and the prime mover because of mechanical stresses caused by the rapid acceleration or deceleration required to bring the rotating masses into synchronism (exactly matched speed and rotor angle) with the power system.
- Damage to the generator and GSU transformer windings caused by high currents.
- Disturbances to the power system, such as power oscillations and deviations from nominal voltage.
- Generator prevented from staying online and picking up load when protective relay elements interpret the condition as an abnormal operating condition and trip the generator.

2) Synchronising System Components

The synchronising system must perform the following functions:

- Control the governor to match speed.
- Control the exciter to match voltage.
- Close the breaker as close to a zero-degree angle difference as possible.

These functions can be provided manually by the operator, by automated control systems, or by some combination of both. Permissive devices are often included to monitor the process. In this application, because the synchronising breaker is located remote from the generating station, automatic synchronising is required.

3) System Design Considerations

Synchronising systems must be designed to be robust and fault-tolerant. It is important to include redundancy so that no single point of failure makes the generator unavailable. Redundancy typically involves making sure that the manual and automatic synchronising systems are relatively independent of each other so that either can be used to bring the generator online.

B. Original Synchronising System

As previously mentioned, the Upper Tumut Switching Station was originally run as a two-bus station. The reserve bus, now known as the B bus, was only used when a circuit breaker needed to be bypassed. This made synchronising reasonably simple. Under normal situations, the line voltage transformer (VT) (incoming signal) was synchronised to the relevant A bus VT (running signal). When a line was bypassed, the B bus VT was the incoming signal and was synchronised to either the A1 or A2 bus VT, depending upon the orientation of the bus coupler disconnectors.

Although this was the simplest possible configuration for synchronising, it was still reasonably complex. The disconnectors had follower relays to provide all of the required contacts for an automatic system. These follower relays and associated contact logic circuits were problem-prone and could introduce hidden failures that were difficult to troubleshoot. Further, modifying the existing system to allow the desired flexibility would have been extremely difficult and would have dramatically increased the complexity of the system.

C. New Synchronising System Overview

Snowy Hydro was looking for a solution that could use advanced technology to improve flexibility to allow synchronisation under all possible substation topologies while reducing complexity and improving reliability. The design was jointly developed by the authors of this paper based on an advanced automatic synchroniser (A25A) that can internally switch voltage signals in its logic [3].

The design allows remote automatic synchronising under any of the following five scenarios. Generator U01/U02 is used to illustrate.

1. Breaker connected to A1 bus.
2. Breaker connected to B bus.
3. Breaker bypassed to B bus, synchronise to A1 bus via bus coupler breaker.
4. Breaker bypassed to B bus, synchronise to A2 bus via bus coupler breaker.
5. Breaker bypassed to A1 bus, synchronise to A2 bus via bus sectionaliser breaker.

Logic/communications processors monitor the topology of the switching station and determine if a valid synchronising scenario is present. These devices provide information so that the A25A devices can switch between three possible running voltage signals and determine which of three possible breakers to close when synchronising is initiated by the operator. All problem-prone follower relays were eliminated from the design.

III. ADVANCED AUTOMATIC SYNCHRONISING SYSTEM

A. Requirements

There were several requirements for the synchronising system design.

Minimal auxiliary relays were to be used. A typical automatic synchroniser has inputs for one incoming voltage and one running voltage, with one circuit breaker close command output. To use such a device with multiple synchronising configurations requires the use of auxiliary relays and/or synchronising switches to switch the correct voltages to the synchroniser and to switch the close command output to the correct circuit breaker close circuit. Snowy Hydro had previous experience with these types of circuits and decided not to apply this design again.

The automatic synchronising design was to allow the full flexibility of the switchyard without separate operator input. The operation was to be transparent. This required the disconnector positions to select which circuit breaker to use for synchronising.

The equipment was to be very robust. Lightning strikes are a serious problem in the area. There is a high earth resistivity. The circuit is complex, and a low probability of failure was required. Accordingly, all of the synchronising functions were to be performed in protection-grade, rather than control-grade, equipment.

The equipment also needed to be able to provide more functionality in the future, if required.

B. System Details

The system consists of the following devices:

- One advanced automatic synchroniser (device A25A) per generator 330 kV line (four total).
- One logic processor (device 69) per 330 kV bus (three total).
- One bay controller (device 99) per bus breaker (two total).
- One programmable logic controller (device PLC) per generator 330 kV line (four total).
- One synchronism-check relay (device 25) per breaker (six total).

1) Switching Station Topology Monitoring

Fig. 4 shows the communications architecture for the system. Each synchroniser (A25A) and each bay controller (99) monitors disconnector and breaker positions for its bay and shares that information with the logic processors. Each logic processor (69) monitors the disconnectors and breakers for the TransGrid line bays connected to it.

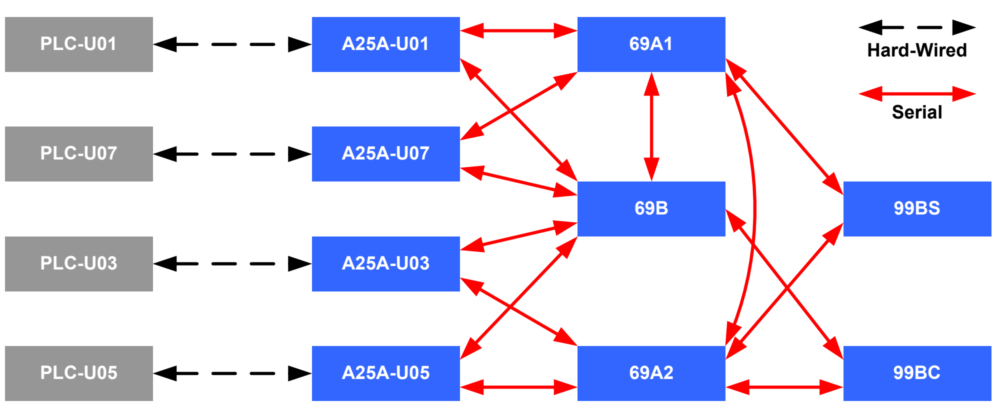

Fig. 4. Communications Diagram

Because the status of each disconnector and breaker is only measured once and shared between all devices that need to know, the need for auxiliary relays for contact multiplication was eliminated. Each disconnector status is measured by monitoring both the 29A and 29B contacts, and any incongruency is alarmed.

A relay-to-relay logic communications protocol over serial links was chosen for its simplicity and compatibility with the selected logic processors. IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messaging could have been used, but there was no need for the additional payload of status bits beyond the eight bits provided by the serial protocol. Each synchroniser and bay controller has two serial ports that can be programmed to use the peer-to-peer protocol, which allows each to communicate with both logic processors associated with its bay.

The only device that could have benefited from the GOOSE multicast capability was the bus coupler bay controller (99BC), which needed to communicate its disconnector and breaker statuses to all three logic processors. The authors decided that this did not justify the additional complexity and expense of an Ethernet solution. Instead, 99BC information is passed to 69A1 via both the 69B and 69A2 controllers, with failover from one link to the other if one of the controllers is out of service.

2) Advanced Automatic Synchroniser (A25A)

The connections for the A25A are summarised in Fig. 5. The device has six isolated VT inputs. In most applications, all six voltage inputs can be used for a single-phase synchronising application. Also, in most synchronising applications the current transformer (CT) inputs are not wired. However, in this application, three of the VT inputs were grouped for three-phase sensing and the CT inputs were added to provide metering, oscillography, and synchrophasor monitoring.

When enabled by the operator, the A25A performs the following processes:

- Determines if the switching station is in a proper topology to allow synchronising.
- Selects which breaker to close.
- Selects which VT input to monitor for running (bus) voltage.
- Determines if the conditions are appropriate for synchronising (i.e., bus and generator voltage and frequency are good).
- Sends frequency and voltage raise and lower pulses to the PLC to bring monitored parameters into synchronism acceptance limits.
- Initiates close of the required breaker at the slip-compensated advanced angle.
- Monitors the breaker for close fail or close lockout alarm conditions.

Records sequence of events recordings and oscillography for each synchronisation.

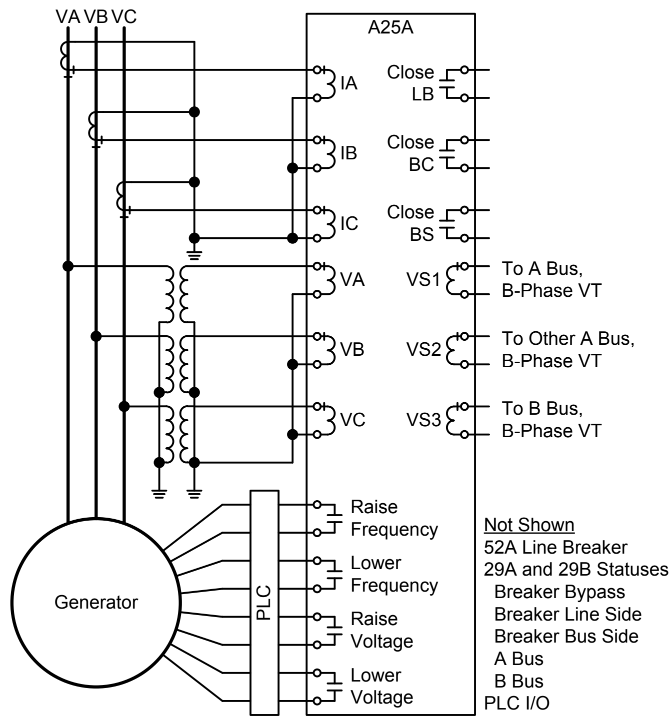

Fig. 5. A25A Connections

3) Logic Processors (69)

Each logic processor monitors which circuits are connected to its bus and provides information to the A25A so that it knows if there is a valid scenario when the operator selects it for a synchronising operation. The information from the logic processors is only required for scenarios in which the line breaker is bypassed to a bus and it is necessary to synchronise the generator using either of the two bus breakers. This is a rare scenario. So, the system is not very dependent on the complexities of the right-hand side of Fig. 4.

When a generator line breaker is bypassed and connected directly to either its A bus or B bus, the system requires that no other circuit be connected to that bus. This allows the generator being started to energise that bus so that the A25A can control the voltage and frequency on the ad hoc reserve bus and close the ad hoc reserve breaker.

Fig. 6 shows the bus breaker synchronising panel with the manual synchronising controls for the bus coupler and the bus sectionaliser breaker.

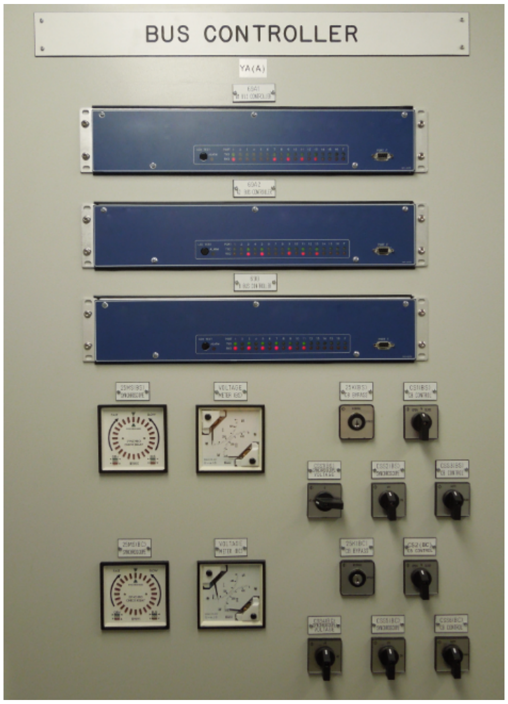

Fig. 6. Example Bus-Synchronising Panel

4) *Bus Breaker Bay Controllers (99)*

Each bus breaker bay controller monitors the disconnectors and breaker status for its bay. It also tells the synchronising system if its bus breaker is in automatic mode such that it can be controlled by the synchronising system.

5) *Programmable Logic Controllers*

Each PLC provides an interface to the operator control room for starting and stopping the synchronisation process. It also directs the frequency and voltage raise and lower pulses to the governor and voltage regulator on the appropriate generator. Recall that either generator can be selected for "first on" synchronising.

6) *Synchronism-Check Relays (25)*

Each breaker also includes a synchronism-check relay that must indicate that the generator angle and voltage are appropriate for a close during manual synchronising. This relay is wired to the appropriate VT signals on each side of its breaker. The switching of the VT signals is independent from that of the A25A.

7) *Typical Synchronising Panel*

The line synchroniser panel for U05/U06 is shown in Fig. 7. The manual synchronising controls and indications are shown below the A25A.

Fig. 7. Example Line-Synchronising Panel

IV. Continuous Monitoring and Operator Indications

All critical signals required for the system to operate are continuously monitored to eliminate any possible hidden failures. Summary alarm indication is provided to the operator via the PLC interface. A more detailed alarm indication is displayed on the front panels of the A25A devices to ease troubleshooting and allow fast restoration of the system. Fig. 8 shows status information screens available from the rotating LCD.

```
ROTATING DISPLAY
SWITCH STATUS ALARMS
29A BUS A ISOLATOR=1/0
29B BUS B ISOLATOR=1/0
29C CB BUS  ISOLTR=1/0
29D CB LINE ISOLTR=1/0
29E CB BYPASS  SW =1/0
      LINE BREAKER=1/0
BUS CONTROLLER
SWITCH STATUS ALARMS
  BUS A CONTROLLER=1/0
  BUS B CONTROLLER=1/0
Press ↵ for menu
```

```
ROTATING DISPLAY
A CONTROL COMMFAIL=1/0
B CONTROL COMMFAIL=1/0
TOPOLOGY PERMISSIVES
SYNC TO A VIA 52=1/0
SYNC TO B VIA 52=1/0
LINE BYPASSED TO B
    SYNC TO A 5012=1/0
SYNC TO OTR A 5012=1/0
SYNC TO A1/A2 5012=1/0
LINE BYPASSED TO A
SYNC TO OTR A 5102=1/0
Press ↵ for menu
```

Fig. 8. LCD Status Indications

Fig. 9 shows local operator controls and indications available on the front panels of the A25A devices and the synchronising parameters that are continuously updated during the synchronising process. This extensive user interface makes monitoring and troubleshooting the synchronising system easy during commissioning and operation.

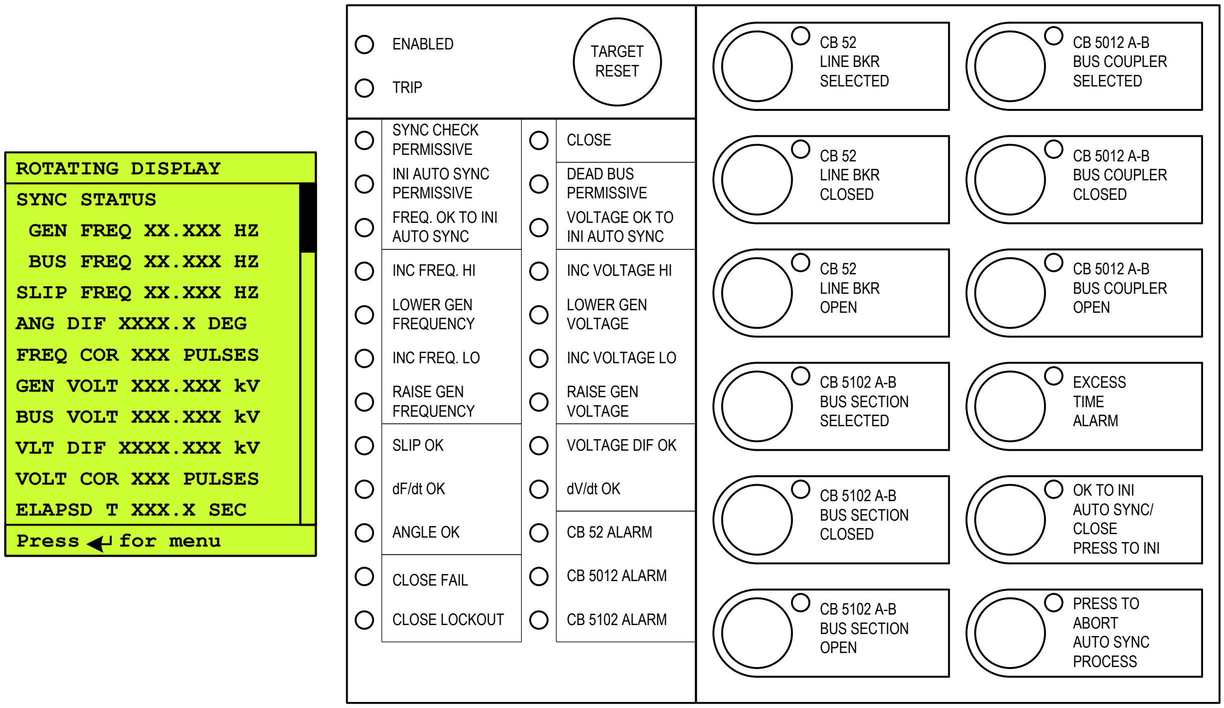

Fig. 9. Front-Panel Controls and Status Indications

V. Example Applications

To illustrate the elegant simplicity of the system, two of the five possible synchronising scenarios are described in this section. All five scenarios are described in Section II, Subsection C.

A. Scenario 1 – U01/U02 Breaker Connected to A1 Bus

The system topology for this scenario is shown in Fig. 10. The topology permissive logic determines the following:

- Breaker isolation disconnects are closed.
- Breaker bypass disconnect is open.
- A1 bus disconnect is closed.
- B bus disconnect is open.
- No disconnect incongruency alarms are asserted.
- Line breaker is open.

If all of these conditions are true, the operator is allowed to select the generator for synchronising. The A25A-U01/U02 then selects its VB input for incoming voltage and its VS1 input (see Fig. 5) for running voltage. It checks that the signals are in the appropriate frequency and magnitude bands and provides a "permissive to initiate" indication back to the operator. Once the automatic synchronising process is initiated by the operator, the A25A sends frequency- and voltage-matching pulses to the PLC, which steers the signals to the appropriate generator. Then, once the synchronism acceptance criteria are satisfied, the A25A closes the breaker via its Close LB output contact (see Fig. 5).

If the synchroniser is not able to bring the slip and voltage difference into the synchronism acceptance bands in the user-settable "time allowed to synchronise," an excess-time alarm asserts. If the synchroniser attempts to close the breaker and it fails to close within the user-settable "close fail time" and "close fail angle" criteria, a close fail alarm is asserted. If the breaker closes, but opens again within the user-settable "close lockout time" window, a close lockout alarm is asserted.

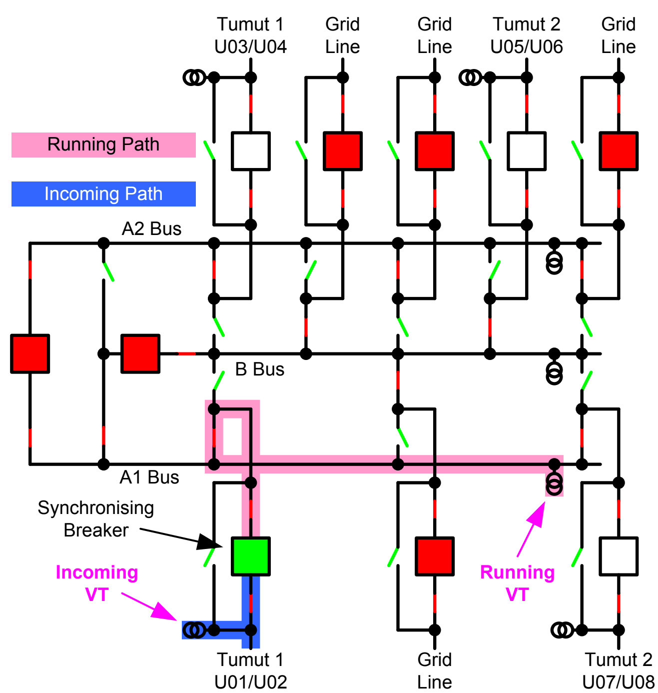

Fig. 10. Scenario 1 Topology for U01/U02 Line

B. Scenario 3 – U01/U02 Breaker Bypassed to B Bus, Synchronise to A1 Bus Via Bus Coupler Breaker

The system topology for this scenario is shown in Fig. 11. The topology permissive logic determines the following:

- Breaker isolation disconnects are open.
- Breaker bypass disconnect is closed.
- A1 bus disconnect is open.
- B bus disconnect is closed.
- No other circuit is connected to B bus (from 69B).
- Bus coupler breaker is connected to A1 bus (from 69B).
- Bus coupler breaker is open and in automatic mode (from 69B).
- No disconnect incongruency alarms are asserted.
- No critical communications link is failed.

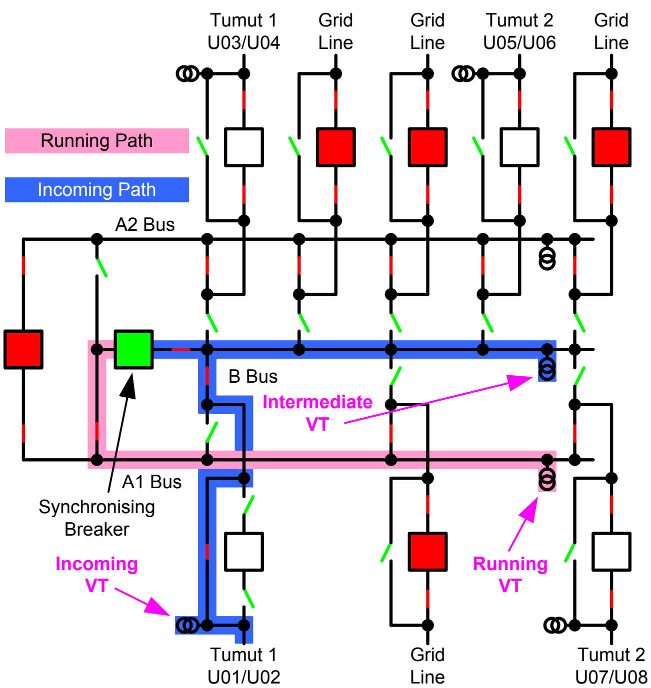

Fig. 11. Scenario 3 Topology for U01/U02 Line

If all of these conditions are true, the operator is allowed to select the generator for synchronising. The A25A-U01/U02 then selects its VB input for incoming voltage and its VS1 input for running voltage (see Fig. 5). It checks that the signals are in the appropriate frequency and magnitude bands and provides a "permissive to initiate" indication back to the operator. The A25A also checks the intermediate VT input, VS3 (see Fig. 5), located on the incoming side of the bus coupler breaker (see Fig. 11) and ensures that this voltage is healthy and not slipping relative to the incoming VT signal.

Once the automatic synchronising process is initiated by the operator, the A25A sends frequency- and voltage-matching pulses to the PLC, which steers the signals to the appropriate generator. Then, once the synchronism acceptance criteria are satisfied, it closes the bus coupler breaker via its Close BC output contact (see Fig. 5).

Close success monitoring is the same as in the previous scenario.

VI. Testing

Testing this system created its own issues. Ideally, the disconnectors would be opened and closed as required to check all of the functions. However, this is a brownfield site. The switchyard is in service. To perform all of this switching with regard to operational requirements would take many months. Therefore, Snowy Hydro built their own switchyard simulator (see Fig. 12) for the purposes of validating the design and all of the programming [4].

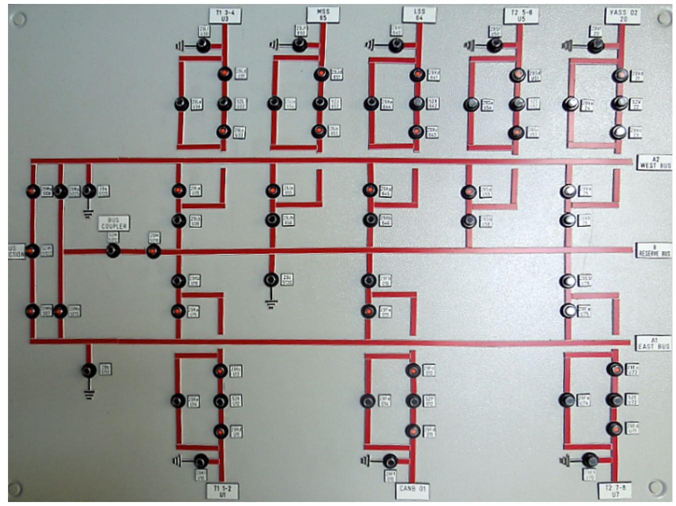

Fig. 12. Upper Tumut Switchyard Simulator

This simulator allowed all of the switchyard operations to be simulated without affecting plant operation. The inputs from the field to the relays were tested at times when the primary plant could be operated. Initial testing was performed in a workshop area prior to installation. The final testing of the whole system was performed on site.

The test switchyard allowed all of the switchyard configurations to be simulated. With protection testing, the "no-go tests" are just as important as the "go tests." The switchyard simulator allowed all of the configurations to be tested in a small amount of time. However, it did take a long time to connect it all. Fig. 13 shows the test switchyard connected to the system.

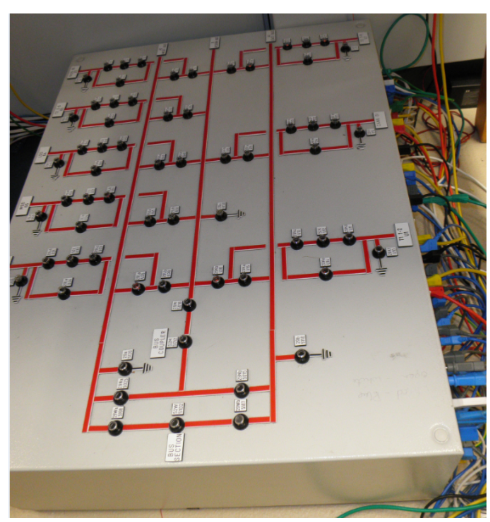

Fig. 13. Upper Tumut Switching Station Simulator for Testing

The relay panels were installed in a small room. The typical layout for a line synchroniser also has facilities for manual synchronising and test socket blocks for testing purposes. This equipment is shown in Fig. 6 and Fig. 7.

A. Injection Tests

A range of injection tests were performed to confirm correct operation of the synchroniser and its control facilities. These tests were performed with different switchyard configurations to simulate operation under various operating topologies.

For all of the tests, a synchroscope was connected in parallel with the incoming and running voltages. Synchronising is a visual process—a user needs to see the operation to ensure the correct results. Table I lists the tests performed on the automatic synchroniser.

TABLE I
AUTOMATIC SYNCHRONISER TESTS

Raise volts	Sync check, positive go
Lower speed	Sync check, positive no-go
Raise speed	Sync check, negative go
Lower volts pulse	Sync check, negative no-go
Raise volts pulse	Dead bus, operate line volts low
Lower speed pulse	Dead bus, operate line volts high
Raise speed pulse	Dead bus, no-operate bus volts high
CB lead time @ 49.95 Hz	Dead bus, no-operate line volts high
CB lead time @ 49.90 Hz	Select B bus, but inject A bus volts
CB lead time @ 49.867 Hz	Sync check positive, no operate
CB lead time @ 50.05 Hz	Select B bus, and inject B bus volts
CB lead time @ 50.10 Hz	CB lead time, B bus
CB lead time @ 50.133 Hz	Sync check, positive operate

A series of functional tests was also performed to prove operation and nonoperation depending upon the switchyard configuration. Table II lists the plant numbers for the circuit breakers and disconnectors.

TABLE II
CIRCUIT BREAKER AND DISCONNECTOR NUMBERS

Plant Number	Plant Description
52	Line circuit breaker
5012	Bus coupler circuit breaker
5102	Bus section circuit breaker
29A	A bus line disconnector and selector
29B	B bus line disconnector and selector
29C	Line-to-bus disconnector
29D	Line side disconnector
29E	Line circuit breaker bypass disconnector
5107	A1 bus section disconnector
5108	A2 bus section disconnector
5015	A1 bus coupler disconnector
5025	A2 bus coupler disconnector
5016	B bus coupler disconnector

Table III lists the tests performed to confirm the operation and nonoperation of the line circuit breaker, depending upon the disconnector positions.

TABLE III
LINE CIRCUIT BREAKER TESTS

State	Topology
52 selected to A bus	29A closed, 29B open, 29C closed, 29D closed, 29E open
52 selected to B bus	29A open, 29B closed, 29C closed, 29D closed, 29E open
52 not selected, A and B buses both closed	29A closed, 29B closed, 29C closed, 29D closed, 29E open
52 not selected to bus	29A open, 29B open, 29C closed, 29D closed, 29E open
52 not fully bypassed	29A open, 29B open, 29C closed, 29D closed, 29E closed
52 not selected, line open	29A open, 29B open, 29C closed, 29D open, 29E open
52 not selected, bus open	29A open, 29B open, 29C open, 29D closed, 29E open

The selection of the bus coupler breaker depends upon the disconnector positions. Table IV lists the tests performed to confirm the selection and nonselection of the bus coupler breaker.

TABLE IV
BUS COUPLER 5012 BREAKER TESTS

State	Topology
5012 selected to A1 bus	29A open, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 closed, 5025 open, all other B bus disconnectors open
5012 selected to A2 bus	29A open, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 selected to A1 and A2 buses	29A open, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 closed, 5025 closed, all other B bus disconnectors open
5012 not selected, 52 not bypassed	29A open, 29B closed, 29C open, 29D open, 29E open, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 not selected, 52 not isolated at the line	29A open, 29B closed, 29C open, 29D closed, 29E closed, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 not selected, 52 not isolated at the bus	29A open, 29B closed, 29C closed, 29D open, 29E closed, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 not selected, 52 not selected to B bus	29A open, 29B open, 29C open, 29D open, 29E closed, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 not selected, A and B buses both closed	29A closed, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 open, 5025 closed, all other B bus disconnectors open
5012 not selected, no A bus selected	29A open, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 open, 5025 open, all other B bus disconnectors open
5012 not selected, another B bus selected	29A open, 29B closed, 29C open, 29D open, 29E closed, 5016 closed, 5015 open, 5025 closed, each of the other B bus disconnectors closed in turn, seven other B bus disconnectors closed in turn

The selection of the bus section circuit breaker also depends upon the disconnector positions. Table V lists the tests performed to confirm the selection and nonselection of the bus section circuit breaker.

TABLE V
BUS SECTION CIRCUIT BREAKER 5102 TESTS

Heading 1	Heading 2
5102 selected to A bus	29A closed, 29B open, 29C open, 29D open, 29E closed, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, 52 not bypassed	29A closed, 29B open, 29C open, 29D open, 29E open, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, 52 not isolated at the line	29A closed, 29B open, 29C open, 29D closed, 29E closed, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, 52 not isolated at the bus	29A closed, 29B open, 29C closed, 29D open, 29E closed, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, 52 not selected to A bus	29A open, 29B closed, 29C open, 29D open, 29E closed, 5015 closed, 5016 closed, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, A and B buses both closed	29A closed, 29B closed, 29C open, 29D open, 29E closed, 5107 closed, 5108 closed, all other A bus disconnectors open
5102 not selected, another A bus selected	29A closed, 29B open, 29C open, 29D open, 29E closed, 5107 closed, 5108 closed, each of the other A bus disconnectors closed in turn

B. Commissioning Tests

1) Phase Out

Snowy Hydro's synchronising circuit commissioning philosophy requires a primary phase-out test to be performed. The system voltage is applied to both the incoming and running VTs. With a common high-voltage connection, the VT secondaries should both be in phase.

To do this, the switchyard A1, A2, and B buses were all energised. The U07/U08 line circuit breaker was closed with the power station circuit breakers open. A series of phase-out tests was performed between all four VTs.

The phase-out test involves comparing the line and bus voltages to ensure that there is no difference in voltage. However, a voltage measurement of zero is not an acceptable result because it could be caused by a range of faults. This causes a false-positive reading that the secondary phase-out measurement was successful. Therefore, voltage measurements are taken to other phases to confirm correct phasing.

2) Generator Control

Speed- and voltage-correction signals are sent to the generator to allow it to match the system conditions. These controls have tuning values that are set in the control systems, and the same correction values are applied to the automatic synchroniser.

There is an art and science to setting automatic synchroniser tuning values. The art side is to modify the initial values until the correct generator response and synchronising time is met.

3) Dead Shot

The automatic synchroniser is allowed to perform a synchronising shot with the circuit breaker close isolated. As with all of the tests, the synchroscope is connected in parallel with the automatic synchroniser. The synchroscope is monitored to ensure that the circuit breaker close is sent at the correct time.

4) Live Shot

The generator is then run up again and a full normal synchronising close is performed. The oscillographic record is then downloaded from the automatic synchroniser to confirm the quality of the synchronising by examining the magnitude of the transients. Fig. 14 shows a record extracted from the automatic synchroniser.

5) Disclaimer

This section does not list all of the tests performed to confirm correct operation prior to the first live synchronising. There are other tests performed to provide a belts-and-braces testing system to ensure that every item has at least two different tests to confirm correct operation.

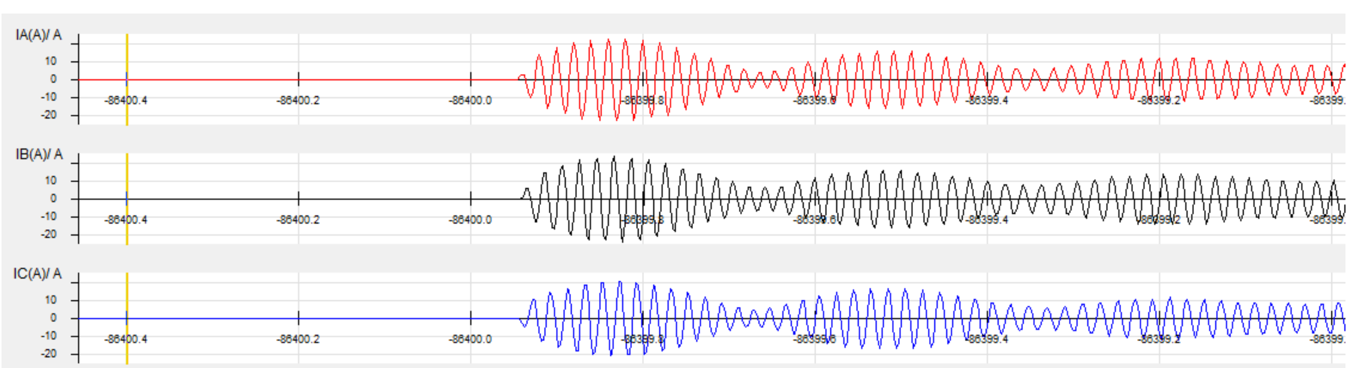

Fig. 14. Current Transients After Synchronising

VII. Optimising Synchronisation

After the installation of the new synchronising system, Snowy Hydro was determined to improve synchronising times. The intent was to increase consistency and reduce the average starting and synchronising times.

A similar synchronising system was installed for three other power stations. At these sites, there is less complexity in the switchyard arrangement, with the power station lines being single- or double-switched.

The improvements changed the speed profile to allow the earliest and best chance of synchronising after the initial speed overshoot. They also increased the chance of first-pass synchronising when the generator speed first passes through the synchronising slip window. These improvements required a significant amount of testing and fine-tuning.

During the optimisation, it was noticed that the bus (running) voltage measurement had an oscillating error that was causing the voltage difference permissive to not assert reliably. This error was traced to the fact that the synchroniser tracks the generator frequency and uses that signal to control the sampling interval. During synchronising, the bus voltage sampling interval is moved from the ideal by the slip rate, which caused the oscillating error that was observed.

To correct this error, a second-order, low-pass digital Butterworth filter was applied to smooth the bus voltage magnitude measurement. The smoothed measurement then had a gain correction factor, based on the measured slip, applied to ensure accurate measurement when there is a large slip frequency between the running (bus) and incoming (line) voltages. This filter removed variation in synchronising times caused by errors in bus voltage measurements with larger slip frequencies. It should be noted that, during initial tuning, the governor response was not yet optimised, which caused a larger range of slip frequencies that made this issue more prominent.

Fig. 15 shows the improved response and consistency after the filter installation on March 20, 2015.

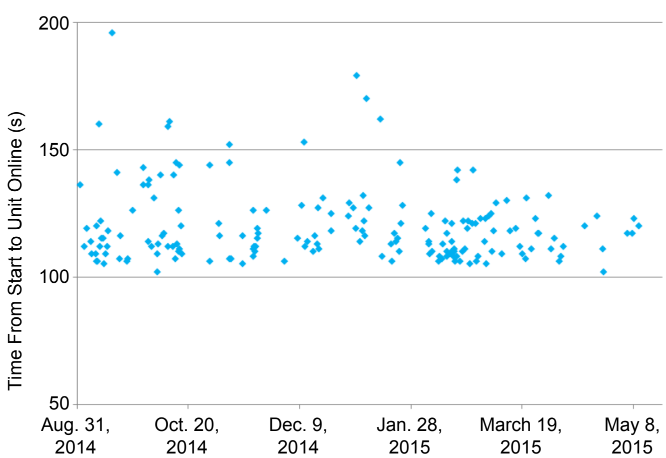

Fig. 15. Improved Response After March 20, 2015

Other changes were performed to further improve the synchronising time and consistency. The generator excitation was turned on earlier, with field flashing time, voltage detection time, and soft start ramp rates reduced. The ramping of the governor was optimised to provide a faster startup time while maintaining the same applied energy over the full run-up sequence. Filtering of the governor when offline was also optimised to provide better speed regulation. This allowed the slip to be maintained at a slip frequency to provide optimal synchronising.

Fig. 16 shows changes that have resulted in decreased synchronising times of between 20 to 50 seconds with increased consistency.

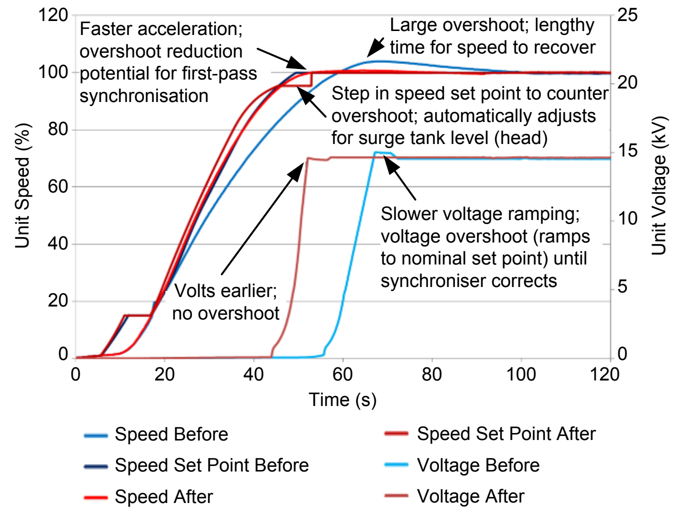

Fig. 16. Synchronising Time Reduction

The effect is better seen when the area around 100 percent speed is examined. Fig. 17 shows the time the generator speed spends within the slip synchronising window at an acceptable rate of change. The amount of time it spends within the acceptable slip window is increased and occurs earlier, allowing an earlier synchronisation.

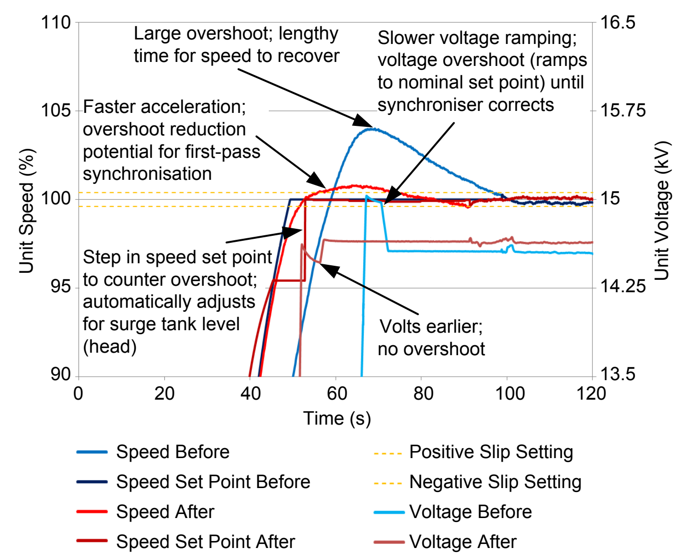

Fig. 17. Generator Speed Within Acceptable Synchronising Window

Once these other changes were applied, the synchronising time was further reduced. The green triangles in Fig. 18 show the improved response.

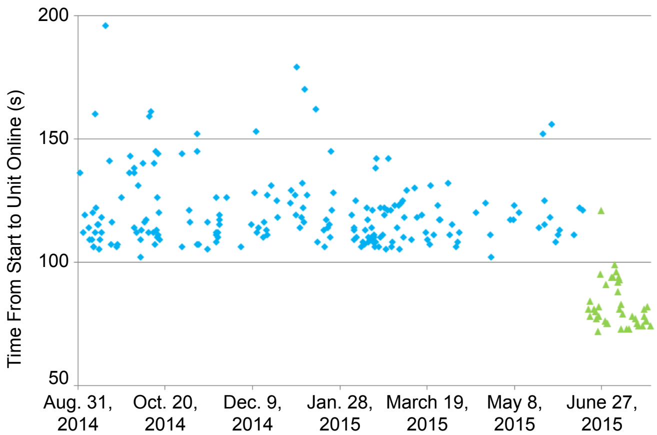

Fig. 18. Synchronising Response With All Modifications

Between March 20 and June 29, 2015, there were other runs used to tune the governor and voltage parameters. These runs are shown by the two dots with extended synchronising times during that period in Fig. 18. Even considering these test runs, the synchronising time between March 20 and June 20 shows significant improvement in time and consistency.

After the additional governor and voltage tuning, the combination of all the modifications has allowed an improved and consistent time from unit start to synchronisation.

VIII. Conclusion

The existing automatic synchronising system at the Upper Tumut Switching Station was complex, problem-prone, and nearing the end of its useful life. Changes in the way the station is operated prompted the need to evaluate alternative systems based on new technology that could provide increased flexibility, reduced complexity, and greater reliability. A system design was developed based on an advanced automatic synchroniser that can internally select synchronising voltages in software. This feature eliminates the need to externally switch VT signals using auxiliary relays and synchronising switch circuitry. The A25A was paired with powerful logic processors that are programmed to monitor the buses and determine the topology of the switching station. A simple, serial peer-to-peer protocol was chosen for communicating statuses between devices that need to share information. The operator only needs to enable the A25A on the generating circuit that is to be synchronised, and the A25A automatically verifies that the scenario is valid and selects which VTs to monitor and which breaker to close.

The A25A can synchronise a generator without any interaction with the logic processors when the line breaker is not bypassed. Thus, the system has high reliability due to the simplicity and low device count for normal operations. Communication with the logic processors is only required during the rare instances when the line breaker is bypassed and the system needs to use one of the two bus breakers to synchronise the generator.

The system design includes robust features to ensure safe synchronisation every time. Nearly everything required for the system to operate is continuously monitored. Extensive alarm reporting and sequence of events recordings ensure that the root cause of any system failure can be found quickly. For these reasons, mean time to repair is minimised.

The extreme flexibility of the system created a challenge for validating the design. A switchyard simulator was built to allow methodical testing of every possible configuration to verify not only that what was expected would happen, but that nothing unexpected would happen.

Once the new system was in place, Snowy Hydro initiated a project to optimise the startup and synchronising system controls to reduce the time required to get a unit online. The testing revealed a measurement error in the bus voltage magnitude measurement when the slip rate was large that caused increased synchronising times. The system was modified by implementing a digital low-pass filter and gain correction function in the programmable logic that eliminated the error and reduced the time to synchronise to the desired level.

IX. References

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X. Biographies

Terry Foxcroft has worked in the power industry for over 36 years. He has worked in the protection, commissioning, testing, and design fields for over 30 years. He has presented papers at many national and international conferences. Terry is also a member of the Australian CIGRE B5 Committee. Terry is responsible for protection design at Snowy Hydro.

Michael Thompson served nearly 15 years at an investor-owned electric and gas utility in the United States. He is presently a Fellow Engineer in the Schweitzer Engineering Laboratories, Inc. (SEL) engineering services division; Chairman of the Substation Protection Subcommittee of the IEEE PES Power System Relaying Committee; and a registered professional engineer. Michael was a contributor to the reference book, *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers, and has a number of patents associated with power system protection and control.

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