Synchronism-Check Application Over a Wide-Area Network

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Abstract

Recent technological developments have enabled solutions to power system protection and control issues that have previously been either too difficult or too expensive to implement. Synchronising generators to the power system requires analogue and digital information from both the generator and the network. Transmitting information via copper cabling requires the power station and the point of connection to the power system to be in close proximity, but how do you achieve this when the sites are 1 kilometre or more apart?

This paper describes the first stage of a synchronism-check upgrade to the Whakamaru Power Station and its connection to the 220 kV transmission network. The paper describes the design installation, commissioning, and operation of the first stage of the scheme. The scheme has been designed to allow any of four 27 MVA hydro generators to be synchronised from any of four 220 kV line voltage transformers. The choice of hardware and the design process have allowed for future enhancements such as the addition of an autosynchroniser. The scheme has been designed to protect against the following:

- Misoperation of the existing autosynchroniser equipment
- Incorrect connection of the synchronising signals to the autosynchroniser
- Manually synchronising machines out of phase

The scheme employs a real-time automation controller using IEC 61131 logic. The main unit is located at the power house and connected via 1 kilometre of single-mode fibre to the remote unit at the ODM. Analogue and digital information is transmitted between the ODM and the power house using a high-speed, industrial-based communications protocol known as EtherCAT. Synchronised sampling of the local and remote measurement units avoids the need for an external GPS clock, reducing complexity and improving the availability of the system.

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I. Introduction

Whakamaru is a Mercury-owned power station on the Waikato River in New Zealand. The station is presently undergoing a generator rehabilitation project. The existing 27.7 MVA generators will be replaced with 35 MVA units over the next four years. This paper describes the design and testing of a project to upgrade the existing synchronism-check equipment. This work will be carried out during the individual unit outages scheduled for the rehabilitation project, and commissioning will take place as part of the overall unit commissioning plan.

The solution allows any of four generating units at the Whakamaru Power Station to be synchronised with any of four 220 kV lines at an outdoor switchyard 1 km away. The system is capable of simultaneously synchronising multiple generators to independent VTs, if required.

This paper describes the scope of the project, the choices available, and the selection of the final design. The design process and the final design itself are also described, as are testing and a recommended commissioning procedure. The paper concludes with a summary of the lessons learned from adopting this solution.

The scheme has been acceptance-tested and is ready to install and commission, but due to delays in the generator upgrade project, at the time of this writing the synchronism-check system is not in service.

II. Background

Historically, many schemes for the control of power systems were restricted to one or two devices and limited by their ability to communicate information or process logic. Electromechanical devices relied on hard-wired inputs and outputs or summation CTs to transfer information. The arrival of electronics allowed programmable logic controllers (PLCs) to communicate with and control many of the devices that control industrial processes. Systems for coordinated control of valves, switches, and other devices typically employ a PLC over a distributed bus network.

Many industries have adopted a bus approach to connect multiple devices with high-speed control and communication. Control of the electric power system is achieved by connecting to circuit breakers and switches via a remote terminal unit (RTU) or, more recently, by connecting directly to an electronic device (relay), providing protection to each individual piece of equipment. For many years, distributed protection and control systems have used serial peer-to-peer communications and SCADA. Adoption of Ethernet protection and control protocols has been slow as compared with other industries.

In the high-voltage (HV) electricity industry, many generating stations use PLCs. For the remainder of the HV network, cost and complexity have constrained the development of wider-area control. Distribution and transmission systems rely on copper or fibre-optic cabling and digital I/O to implement simple schemes (e.g., on-load tap change control and circuit breaker failure or interlocking) within substations or local areas. Communications between devices in HV transmission networks employing dedicated communications equipment depend on other technologies, such as power line carrier or the embedding of optical fibre to communicate through the optical ground wire. Today, microprocessor-based relays employ communications protocols to share digital and analogue information over simple media such as radio and fibre-optic cabling.

The adoption of technology used in other industries to connect devices by Ethernet has led to the development of newer protocols to transfer high-speed, time-critical information for both control and protection signalling and the application of special protection schemes in the electric utility industry. However, adopting Ethernet communications requires additional engineering, including topology design and management and message timing issues that bring cybersecurity concerns with them.

The solution described in this paper employs a high-speed, industrial Ethernet communications protocol known as EtherCAT®. This protocol eliminates the need for switches and external time synchronisation, and it allows for the high-speed transfer of digital and analogue information. The speed and simplicity of this protocol make it the ideal choice for this application.

III. What Does the System Need?

The first stage of the synchronism-check upgrade was to design, install, and commission a controller to provide a close-permit signal to the autosynchronisation equipment of each of the four generators at the Whakamaru Power Station. The existing unit PLCs provide contact outputs to declare which unit is to be synchronised with which 220 kV line. There are four three-phase VTs at the outdoor switchyard and each generator has its own set of three-phase VTs. In addition, any of the 220 kV line VTs can be selected and switched, via a copper circuit, to a single-phase running bus signal for use at the power station.

The power station and the outdoor switchyard are located 1 km apart. The system communicates the necessary information over the existing fibre-optic network. It is required to provide simultaneous synchronisation of up to four generators with one or more of the 220 kV lines from the outdoor switchyard. The first stage of the project provides a close-permit output for each of the machines to allow its own autosynchroniser to close the unit breaker(s). The controller must operate in fail-safe mode. A failure of any part of the system bypasses the close-permit outputs to allow manual synchronisation of the generators.

IV. How Will the System Communicate?

The overarching requirement of the project is the reliable transmission of line voltage signals to the power station. Many devices, including PLCs, have the logic and processing capability to provide the synchronism-check function needed; however, very few of these devices transfer analogue values reliably and deterministically.

The first option investigated to transmit these values was the use of IEEE C37.118 synchrophasors. This solution requires the use of phasor measurement units at both sites that are connected via Ethernet switches and which employ high-accuracy external time synchronisation. Although a sound solution, the availability of a dedicated Ethernet channel allowed a second solution to be considered: the use of a single real-time automation controller coupled with EtherCAT.

The hardware for this solution comprises two modular chassis with one CPU, power supplies, I/O, and CT/PT modules. The chassis are connected directly via the Ethernet channel. The measurement logic control and timing requirements are all met by the one system. The CPU uses an internal clock to provide the timing for the system. Although a synchrophasor-based solution would have worked, the lower product count, standalone nature, and simplicity favoured the EtherCAT solution.

V. High-Speed Communications

EtherCAT is an industrial Ethernet protocol that employs standard Ethernet frames as defined by IEEE 802.3. The topology is an open-ended ring in which each slave device (whether on the same backplane as the master or in a remote device) is connected to the EtherCAT bus [1]. The payload, or EtherCAT telegram, contains up to 1,486 bytes of process data consisting of individual datagrams. Each slave device subscribes to a particular datagram and reads or writes to it as the message passes through. Unlike traditional Ethernet, the datagram is processed in hardware and is not dependent upon stacks, queues, or CPU burden [2]. Known as "Ethernet on the fly," the transfer of information takes less than 1 µs.

The last device in the chain transmits the updated message back to the master. A typical update time for 1,000 distributed I/O devices is only 30 µs, including the processing delay of each device. The fast throughput allows up to 60 devices to be connected to the master controller while still guaranteeing time-stamping with better than 1 ms accuracy for the digital I/O devices.

Analogue quantities require high precision. Currents and voltages are sampled at a rate of 24 kHz. The sampling rate is synchronised to the top of the second, with the datagrams time-stamped at each CT/PT module.

Time synchronisation of the modules is achieved via the distributed clock mechanism described in IEEE 1588. The reference clock in this system is the automation controller clock. The controller broadcasts a message to the address of the distributed clock receive time port of each CT/PT module. Each module responds with a time-stamped reply for both the forwarding path and the processing path of the ring. After collecting the time stamps from the CT/PT modules, the controller calculates the individual offset times from the known topology information and the time stamps. It then writes the offsets into the system time offset register of each module [3]. Any CT/PT module can then calculate the system time by adding its local time to the offset time. This process is repeated periodically to counter any drift caused by temperature or crystal oscillator variations. Timing accuracies of less than 1 ms between the master and slave devices are easily achievable through the distributed clock mechanism.

VI. The Real-Time Automation Controller Solution

To the authors' knowledge, this application is the first of its kind to use a real-time automation controller to perform a synchronism-check function. A trial project using revenue meters was assembled, and though this preliminary project was not fully tested and was never placed in service on live equipment, it provided a good starting point. Before commencing the development of the solution in earnest, equipment was sourced, and initial testing and evaluation proved that the concept was feasible.

A single automation controller at the powerhouse contains the CPU. Five CT/PT modules collect the voltage signals from each of the generating units and the running bus signal. A digital input module connects to the outputs of each of the four unit PLCs, and a digital output card provides the close permit, synchronism-check active, and alarm signals. The remote slave module at the outdoor switchyard collects the voltage data from the 220 kV line VTs and publishes them as synchrophasor data to the master via the high-speed Ethernet channel connecting the two units.

Users can interface with the automation controller via a web browser or via configuration software. A web browser interface administers users and communications parameters and provides access to alarms, Sequence of Events (SOE) data, and control of the HMI. The software provides a way to programme and communicate with the controller. The software completely defines the project in terms of hardware topology, logic, and control algorithms. Online, the software can be used to monitor all internal tags and logic points, and measure internal cycle times and CPU performance. It can also be used to assist testing by forcing the states of logic and digital points and by writing values to analogue points.

VII. Logic

The processor for the automation controller runs a Linux® operating system using CODESYS as its logic engine. The hardware was connected to secondary test equipment and the controller configuration software was used to view online data to measure behaviour and to help develop and prove the scheme logic.

VIII. Processing Logic

The primary components of the synchronism-check application include the Main_Sync_Check programme and the FB_Sync_Check function block. Main_Sync_Check monitors hardware inputs, controls the output contacts, and calls the functions and function blocks within the automation controller logic.

Twenty digital outputs from the four generation unit PLCs are wired to the digital input card of the automation controller at the power station. The inputs select which line or running bus signal is to be synchronised to each generation unit. It is possible that up to four inputs can be selected at any one time.

Assertion of an input calling for a unit to be synchronised causes Main_Sync_Check to take several actions. The relevant unit synchronism-checks active output closes. It also instantiates the FB_Sync_Check function block and parses the relevant parameters necessary to synchronise the unit with the synchronising voltage. Twenty instances enable numerous synchronising combinations. The voltage select (V_SEL) function comprises several CASE statements that parse the appropriate polarising and synchronising voltages and frequencies to the newly created instance of the FB_Sync_Check function block.

FB_Sync_Check checks that the voltage magnitudes are within 5 percent of nominal and that the slip of the two systems does not exceed 0.1 Hz. If these conditions are met and the normalised voltage angles are within ±20 degrees, a valid synchronism check is declared. Main_Sync_Check closes the unit close-permit and the circuit breaker close-interlock outputs to allow the existing autosynchronisers to finish synchronising the machines.

If the two systems lose synchronism when the voltage or frequency differences exceed the predefined limits, then the program removes the synchronism-check condition and releases the outputs. A communications or hardware alarm is generated for any module or communications failure. All outputs are de-energised and external relaying bypasses the system to allow for manual synchronisation.

IX. Design Considerations

IEC 61131 logic in the automation controller can be programmed in structured text (ST), continuous function chart (CFC), and ladder diagram (LD) forms. Because this was a development project, ST was chosen to make use of cut-and-paste and other hot-key functions to edit the programme as required.

The CT/PT cards sample the input quantity at 24 kHz and are synchronised to the top of the second. Three phase-to-neutral (line) or phase-to-phase (unit) voltages and one single-phase (running bus) voltage are published with the frequency at a rate of 120 Hz. The automation controller offers several types of analogue tags to publish, including fundamental, root-mean-square (rms), and synchrophasor. Synchrophasor tags have a smaller dataset and were chosen in the interest of minimising the EtherCAT bandwidth. Forty-seven percent of the EtherCAT bandwidth is used for this application.

Analogue tags are published between –179.99 degrees and 180 degrees. When calculating the angle difference, attention needs to be given to whether the angles are positive or negative. Simply subtracting the two angles to find the difference is not always valid. Because negative numbers are the issue, they were eliminated by adding 180 degrees to the measured angle and then subtracting one from the other. The synchronism-check angle (SCA) was subtracted from the remainder to normalise the angles to zero degrees. The upper and lower angle limits were set to ±20 degrees.

The SCA is defined as the number of degrees the unit (polarising) voltage lags the system (synchronising) voltage. For the line and running bus, SCAs of 180 and 120 degrees are required, respectively.

The nominal system voltages are 220 kV and 11 kV. For simplicity, the VT ratios were set to 1. All calculations are performed with secondary values (63.5 V line-to-neutral and 110 V line-to-line).

The minimum automation controller processing interval rate is 4 ms. With the amount of logic programmed and the EtherCAT bandwidth available, the cycle rate is set to 30 ms. The CPU burden runs at ~60 percent under operating conditions. The 40 percent buffer is more than adequate for the additional overhead generated by event report retrieval and online interrogation, and it can also accommodate additional functionality in the future.

X. Testing

Much of the testing used the automation controller itself to prove correct operation. Being able to monitor logic online, add watches and break points in the programme(s), force analogue and digital tags, and trigger oscillographic event reports was invaluable during the design and testing stages. A separate relay was also connected in parallel to validate the test procedure, particularly when results were not as expected.

A secondary injection test set provided the voltages and frequencies to simulate installed conditions. Occasionally, step changes to the frequency or voltage angles caused the synchronism-check active outputs to drop out momentarily. Event reports were triggered, and analysis provided confidence that the algorithms in the automation controller were secure.

Testing revealed that synchrophasor tags default to the nominal frequency if tracking is lost. Tracking uses an alpha voltage quantity of Va + Vb/2 + Vc/2 > 20 V. Tracking is maintained until all three phase voltages are lost. A dead bus is declared if the voltages are not within 5 percent of nominal, and the synchronism-check function is disabled. A loss of frequency tracking caused by a loss of voltages is covered by the dead bus; however, qualification of the frequency measurement (i.e., the addition of the FREQOK bit) will be considered before the scheme is commissioned.

Testing the synchronism-check window at different levels of slip yielded different results. As the slip frequency increased, the ±20 degree window shifted. At the upper limit of 0.1 Hz, the operation of the close-permit outputs is delayed by ~6.5 degrees. Investigation revealed that the relationship is linear and is due to the measurement latency of the M class synchrophasor messages. An offset variable has been added to the synchronism-check window to account for this latency. The use of P class synchrophasors guarantees a latency of less than 40 ms. Further testing will be necessary to determine the offset required if the measurement type is changed.

XI. Where to From Here?

It is difficult to see any benefit from changing ST to CFC or LD programming for future projects. ST is simple to debug and develop. The synchronism-check function block could be written in C++ and included as a library for use in the future, although customising the function for future sites could be difficult. One advantage of doing so would be to prevent changes to the function onsite.

There are several options to consider regarding the development of the existing scheme. The RTU functionality could make the controller visible to SCADA. The HMI function could also be enabled to improve local visibility. An autosynchronising function could be added to replace the aging, existing equipment.

XII. Conclusions

One of the key requirements of the design was simplicity. Using EtherCAT protocol and programming the logic using ST supports this requirement. The automation controller is designed for the harsh substation environment, and the low device count (no external time clocks or PMUs) improves the reliability and, hence, the availability of the system.

Testing has revealed that consideration should be given to the use of P class synchrophasor data and supervision of the frequency measurement. However, testing in conjunction with online monitoring has provided confidence that the scheme is robust and ready to be placed into service.

At the time of writing, delays in the generator upgrade project have prevented the installation and commissioning of this scheme.

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