A SHIFT IN POWER – OPERATIONAL IMPROVEMENTS FROM BIOGAS ENGINE UPGRADE

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ABSTRACT

The Christchurch Wastewater Treatment Plant (CWTP) has traditionally used gas and diesel fuelled engines to generate heat and power from biogas produced in sludge digesters. Until 2013 three engines provided this function – two 400kW Allen dual-fuel engines and one 1,550kW Waukesha gas engine. The two 400 kW Allen engines were at the end of their economic life.

The goals of the replacement project were to achieve integration between the powerhouse and the process, thereby relieving operational constraints, and to improve the site's disaster resilience with respect to power generation. Underlying both of these goals was the desire to reduce the operator workload required to effectively manage the plant by simplifying operation.

Successful completion of this project has resulted in improved automation, relieving the operator of the need to actively manage the engine power output, better utilisation of site resources, and a power generation system that can accommodate loss of mains power or fuel gas and maintain CWTP operations in emergencies.

KEYWORDS

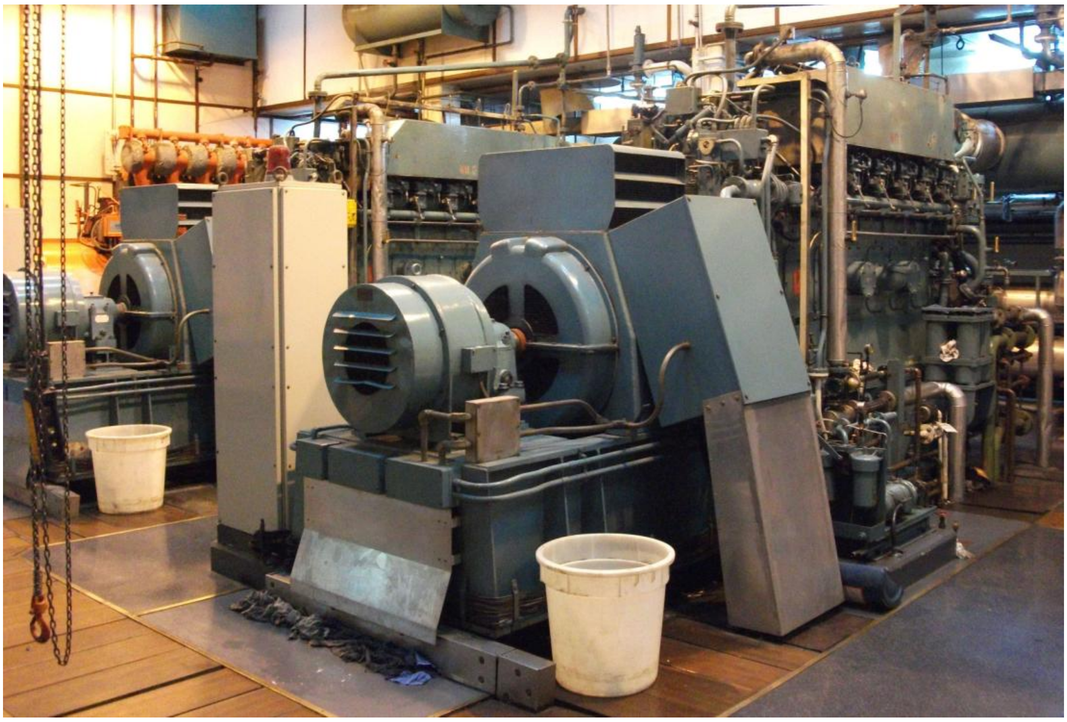
Biogas, Power Generation, Process Integration, 11kV, Synchronising, Automation

1 INTRODUCTION

In 2009 Christchurch City Council (CCC) first started to consider how the ongoing energy requirements of the Christchurch Wastewater Treatment Plant (CWTP) could be met, taking into consideration the planned future biogas export to the Christchurch Civic Centre in the CBD and the need to replace the existing two Allen Engines in the CWTP powerhouse. CWTP traditionally used a spark ignition gas engine and dual-fuel engines (gas plus pilot diesel ignition) to generate heat and power from biogas produced in sludge digesters. This power is used to supplement mains power within the site, with any surplus exported to the grid. Until 2013, three engines provided this function – two 400kW Allen dual-fuel engines and one 1,550kW Waukesha gas engine. All the engines are located within a building referred to as the powerhouse.

The two 400 kW Allen engines were installed in 1978 and were at the end of their economic life. As part of their replacement CCC took the opportunity to look for ways to improve the overall integration of the powerhouse with the process, make the site more resilient to power outages and simplify power generation operation. This paper outlines how this was achieved in the biogas upgrade project completed by CH2M Beca Ltd at CWTP.

Photograph 1: Allen Engines – now removed



CCC engaged CH2M Beca to study the site operational requirements and constraints and to design and manage the implementation of a range of projects culminating in the replacement of the Allen engines. One key project objective was to change from the use of dual fuel generation to only biogas fuel, so that the cost of continuous diesel use could be eliminated. The economics of various sized engines and number of engines were studied. Power generation is now shared across a new 900kW gas engine, the existing 1,550 kW gas engine, and a new 800kW back-up diesel generator. Space has been left for another engine generator set of 900kW capacity if this is justified in future. The generation system can run either parallel to mains power or in islanded operation.

Photograph 2: New 900kW Waukesha

The goals of the project were to achieve integration between the powerhouse and the process, thereby relieving operational constraints, and to improve the site's disaster resilience with respect to power generation. Underlying these goals, was the desire to reduce the operator workload required to effectively manage the plant by simplifying operation. Achieving the project goals was deceptively complex. The complexity arose from the tight integration of the powerhouse operation with the process plant. The process plant supplies biogas as fuel from the mesophilic and thermophilic digesters and clarified effluent as a heat dump for the engines. The engines supply heat back into the site hot water system and power for process operation. The project achieved a scheme where, despite these linkages, power production was effectively decoupled from the process.

2 PROJECT RESCOPING

2.1 PLANNED REPLACEMENT OF ENGINES

Prior to the Christchurch earthquakes, the inflows to the CWTP were well understood and profiling of the available landfill gas (LFG) and biogas supply and demand had been completed. The planned renewal of the Allen engines was based on an estimated date for replacing LFG supplies to the CBD with biogas of mid-2016, and a similar replacement for the QEII sporting complex by mid-2027. The site was also in the process of constructing two new thermophilic digesters, in addition to the existing four mesophilic digesters, with an increase in gas yield expected once these were online.

An NPV analysis was undertaken to evaluate how best to replace the Allen engines with a scheme that would utilise the available biogas to provide heat to the site and back-up power in the event of a grid outage. The recommendation from the analysis was to install two new 900 kW engines in the same physical location as the existing Allen engines.

The project scope also included a number of other enabling work packages such as; upgrade of the powerhouse ventilation, installation of dedicated blowers for gas supply to the new engines, upgrade of the existing dump heat exchange system, installation of a back-up standby diesel generator, and new power generation management and synchronisation equipment.

Design and tender documentation was prepared for the project and had been issued in 2010 when the first of the Christchurch earthquakes struck.

2.2 EFFECT OF EARTHQUAKES ON PROJECT DRIVERS

The Christchurch earthquakes of 2010 and 2011 significantly changed the nature of the influent streams to the CWTP and the nature of the biogas being produced. The planned biogas uses in the Christchurch CBD and at QEII no longer existed, significant budget was required for earthquake repairs and consequently the NPV calculations that justified the capital expenditure for two new engines were no longer valid. However, the risk associated with the ageing engines remained.

CCC and CH2M Beca revisited the project drivers and a reduced scope option was progressed. This involved the supply of a single 900kW engine with as many elements associated with the second engine removed as practicable, without eliminating the possibility of installing the second engine in the future.

The original project programme was significantly extended due to the earthquakes and the need to rescope and redesign parts of the project. However some works, such as the installation of the standby diesel generator, were able to be progressed during this time. The measure of the financial success of this process was the amount of generation that could have potentially been lost under pre-earthquake projections. To date the choice to defer capital has been justified by the high utilisation of the existing and new engine and the low level of gas flared.

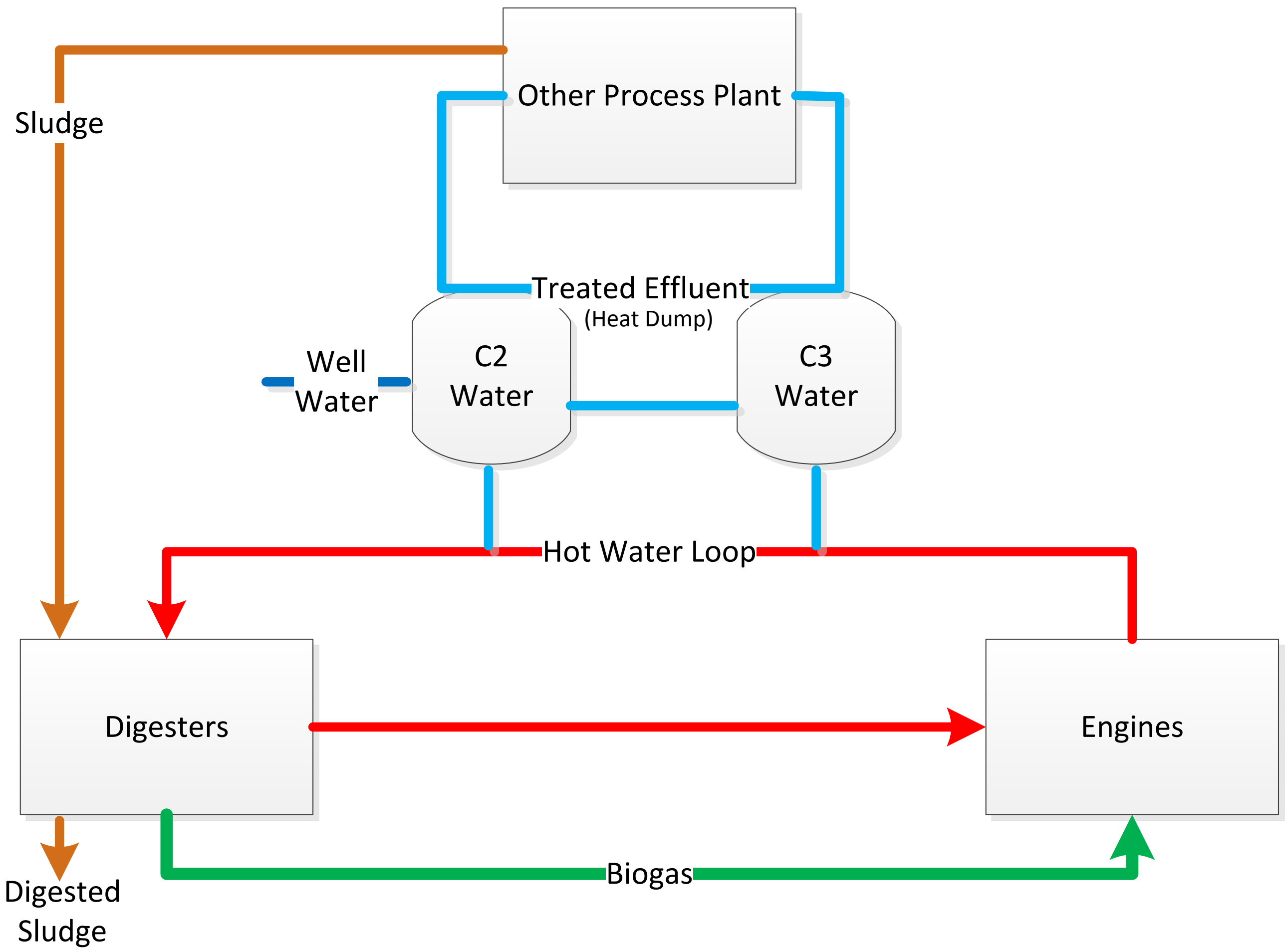
3 PROCESS

There are numerous interconnections between the CWTP process and power generation at the site. Biogas is produced from anaerobic digestion, the digesters in turn require heat to bring the sludge in the digesters to the required operational temperature (35°C for mesophilic and 55°C for thermophilic) and to make up for heat losses from both tanks and pipework. The site hot water loop transfers heat between the digesters and the site engines by collecting reject heat from the engine jacket water cooling loop and exhaust gases. Water in the site hot water loop is bore water and primary-treated wastewater (having passed through the screens, grit removal and primary treatment stages) from the process. The latter loop is used for heat dumping at the air compressors and engines.

The new engine rejects heat via a recovery plate heat exchanger into an extension of the plant hot water loop. Once the engine is at optimal temperature all the heat is rejected into the hot water loop. The amount of return heat to the engine can be adjusted to increase or decrease the engine temperature and as a consequence the heat available for transfer to the plant. Full heat dump is achieved when no heat is required in the plant hot water loop, but gas is available and generation is required.

Biogas from the digesters is used to fuel the engines which produce heat and electricity to run the site. A simplified overview of the connections is shown in Figure 1.

Figure 1: Process and Powerhouse Connections



The C2 water (bore water) holding tank is positioned immediately outside the powerhouse. Process water that has been used for cooling of the compressors is returned to the C2 water tank to be reused. C3 water is the name given to treated effluent taken from the discharges of the clarifiers.

As part of the upgrade, project control of the dump heat system was improved to allow continuous heat dump to maintain a constant jacket water inlet temperature. This was done by installing a new C3 water tank outside the powerhouse and using connections to both C2 and C3 water to provide cooling through a plate heat exchanger at the engines. A new function was also incorporated to provide a dump heat facility for the existing engine when the new engine is switched off. This function pulls heat from the heat loop and discharges it to the new C2 and C3 water cooling system. So while the engines use renewable and reusable process water as part of their operation, the two different sources give the system added resilience and flexibility.

Biogas from the digesters is collected in the low pressure gas holding tank located outside the northern wall of the powerhouse. Gas for the existing engine is supplied from the low pressure gas holding tank via the Wittig compressor located outside the northern wall of the powerhouse building. The new engine receives gas from the low pressure gas holding tank via a new gas compressor. A key part of the process and powerhouse integration is maintaining a level in the gas holding tank that does not vent gas or result in engine shutdowns due to low level.

4 OPERATIONS

The CWTP is run from a control room located at the plant by shift engineers who are responsible for both operation and maintenance of all equipment on site. The shift engineers are fully conversant with the use of SCADA control and monitoring systems. Each item of plant control needs to consider the need to minimise operator inputs and monitoring, while providing sufficient information and alarms to allow speedy troubleshooting should the need arise. As the shift engineers are required to attend to breakdowns as well as inspect the process during their shift, there may be long periods of time when the shift engineer is away from the central control room. The control system must therefore be relatively self-sufficient and not result in spurious alarms or shutdowns. However the quality and composition of the biogas can change as a result of external factors, so the controls should not attempt to automate decisions that shift engineers make based on understanding of the overall process.

The aim for this project was to operationally integrate the existing engine with the new engine(s) under a single power management control system (e.g. load sharing, synchronisation, islanded operation etc) and therefore minimise issues with interfaces between new and old and process and power generation. In the event of a loss of mains power from the grid and loss of power from the engines, the diesel generator starts automatically to maintain process operations. Furthermore, the operation of the gas engines had to be continuous and stable on any volume of biogas produced from the mesophilic and thermophilic digesters. The heat recovery and dump system for the new gas engine unit was made fully automated, so as to provide an effective automated response to changes in the heat demand on the CWTP site heat loop without the need to shut down the gas engines.

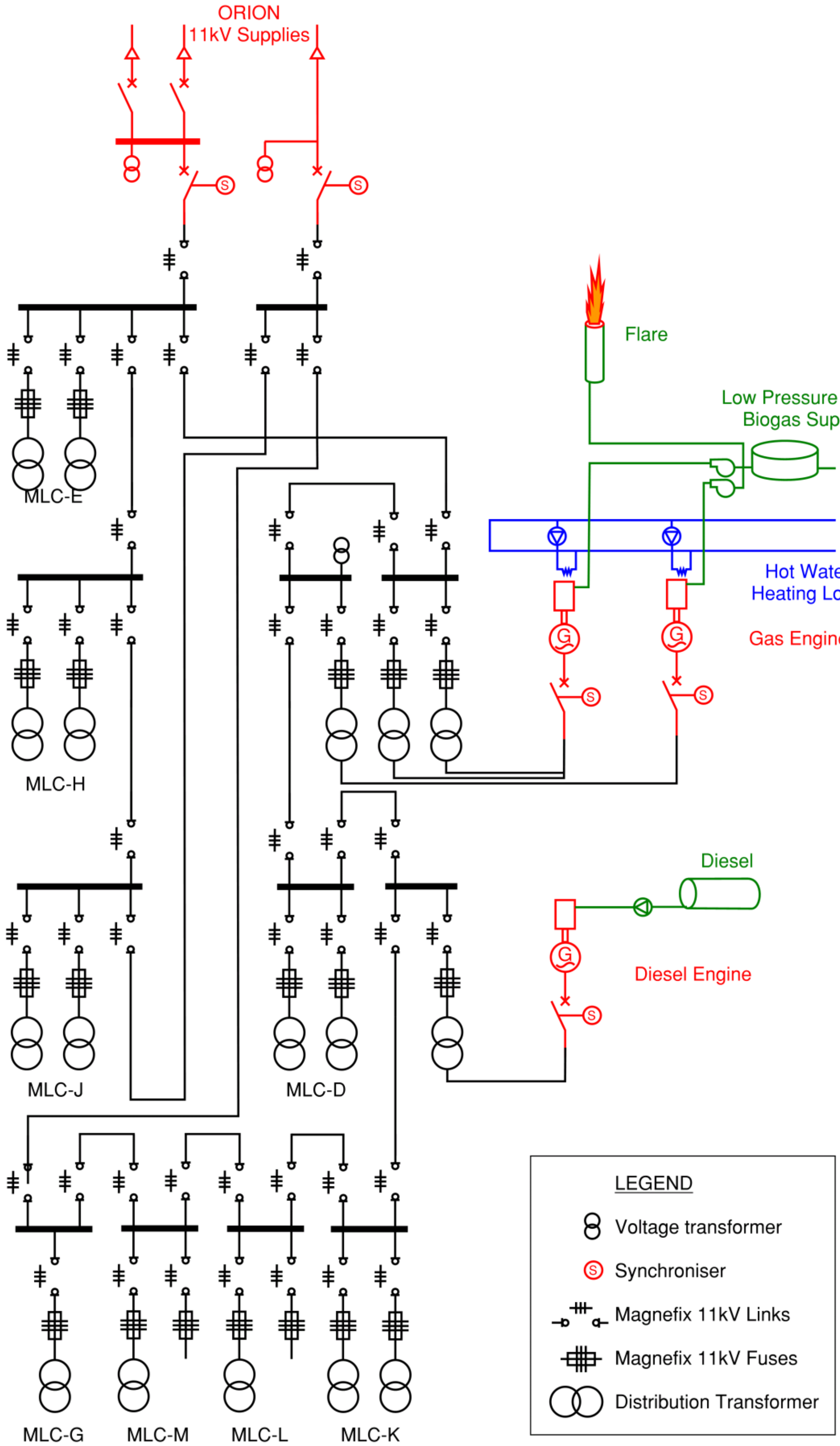
5 ELECTRICAL

5.1 SYSTEM DESCRIPTION

CWTP has been generating power from biogas into their 11kV network for over 30 years. The 11kV network had been arranged with a single point supply from Orion. The 11kV on site was arranged as separate spur lines. The main engine, a 1,550kW Waukesha, had been directly connected with switched VT circuits to permit a complex arrangement of synchronising.

Over the past 8 years, culminating in the replacement of the existing Allen engines, the network configuration has been simplified and more resilience has been incorporated. The 11kV spurs were linked to form a ring main, a second feeder from Orion was added and the synchronising altered so that all generators can synchronise to the mains. The result is illustrated in Figure 2.

Figure 2: CWTP Site Electrical Single Line Diagram



5.2 POWER SYSTEM CONTROL

The two main modes of operation for the CWTP 11kV system are either in parallel with the Orion network or islanded. When islanded the site generation must provide stable frequency and voltage. There are several possible ways to achieve this. The simplest is to rely on the inherent frequency and voltage droop responses typically used in the generation industry. This requires an additional overseeing Generation Management facility. Standard generator controller load sharing facilities do not manage this process well. While they do provide a built-in load sharing mechanism there are two common assumptions that are not valid in this application. Firstly the gas engines are tied to the process by the biogas use and for the heat rejected into the site hot water heat loop. Secondly, at CWTP, the diesel engine is not tied to the process at all, so when this is able to run, it can be configured to provide a more positive frequency response.

A droop-based load sharing system has another important advantage in that it depends only on the power flow between generators and load to work. This means that any future engine replacement will not require a compatible engine controller to load share effectively in islanded operation.

5.3 UNIT CONTROLS

The generator control architecture has been chosen to maintain independence from a particular manufacturer or era of controller and to achieve good generation management. Figure 3 shows Generation Management in PLC36, which sends a power and power factor set point to each engine. Each engine can be set to a joint control mode or a fixed control mode, which allows the operator to define the degree to which an engine contributes to process control.

The Engine Controller can be any of a range of standard engine controllers.

Figure 3: SCADA Power System Control Screen

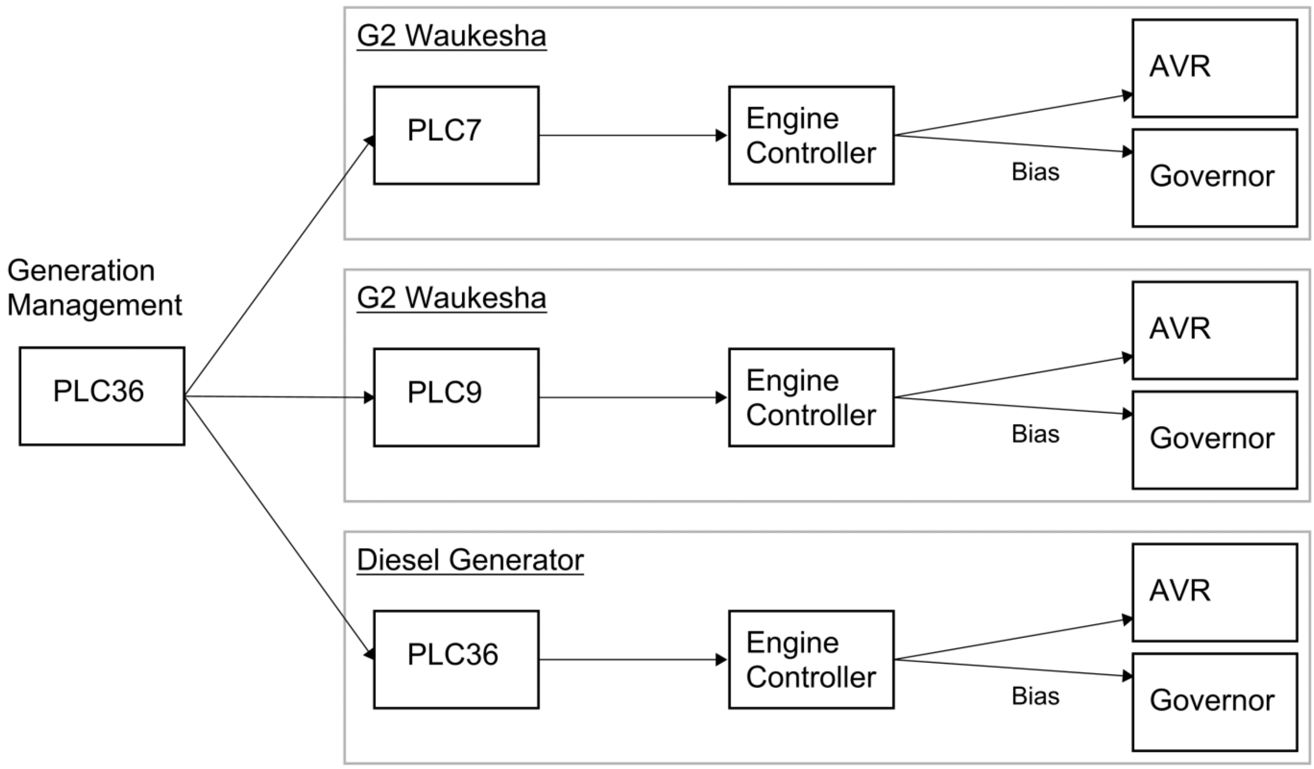


Figure 4 shows the range of controls enabled through the Generation Management function while still maintaining a simple power set point connection between the Generation Management function and the individual unit controllers. The benefit of this strategy is that when an engine is in a power range where it does not perform as well, its set point can be fixed without losing the overall process control functionality.

Figure 4: SCADA Power System Control Screen

	Parallel	Islanded
Unit	Start Stop Joint control - use Scheme setpoints Unit control - kW setpoint - PF setpoint	Start Stop Joint control - Easygen loadshare Unit control - Speed setpoint - Voltage setpoint
Scheme	Site control - site kW target - site kVar target Powerhouse control - powerhouse kW target - powerhouse power factor BioGas control - LP tank level setpoint	Synchronise - CB11 or - CB24 No power setpoints available, load determines power requirements

5.4 ISLANDED OPERATION

During emergency operation, with no connection to the Orion network, control needs to move smoothly from load control to frequency and voltage control. Frequency need not be maintained isochronously. The use of frequency droop allows trading off precise frequency control with the ability to load share. Droop allows generators to share load inherently through the frequency of the system. This removes the need for dedicated communications links between generators and the strict dependency on the type of Engine Controller being used.

The main constraint imposed during islanded operation is that sufficient generation must be available to meet the load demand. If insufficient generation is available for whatever reason, the generators will trip and the site will need to be brought up with the diesel generator running after a black start.

After a black start, the benefit of an 11kV-connected diesel generator is evident. When the diesel generator runs, power is available to the entire site. An operator may freely (within the capability limits of the generator) start any load in any part of the site. This is useful for bringing up the biogas supply, as auxiliary services that are needed to provide gas to the gas engines are distributed across a number of load centres.

The use of an 11kV-connected diesel generator is also valuable for other small loads around the site, such as the UPSs supplying power to the SCADA network switches and PLCs. The operator is provided with visibility of the site parameters over the whole site shortly after the diesel generator restores power.

5.5 SYNCHRONISING

At the end of an outage, either as the result of testing or from a real loss of supply to site, there are two possible means of reinstating normal Orion network supply. The least disruptive approach is to synchronise the site generation with the Orion network. The alternative is to trip local generation, creating a second complete site power outage before closing the Orion network supply onto the site 11kV ring main.

Being able to synchronise without having to shut down the site is particularly advantageous for longer outages. The site operator has both the time and need to bring the plant to full operational status. This process does not need to be repeated because restoring a connection to the Orion supply does not result in an additional power outage.

At the generators, the synchronisers are provided in a typical arrangement. At the 11kV circuit breakers, the synchronisers are atypical. While the normal means of synchronising requires a direct connection to voltages on both sides of the circuit breaker, the governor and circuit breaker close coil, the distances between the 11kV circuit breakers and the generators makes this difficult. Fast and tight control of frequency is not required for the synchronisers to work. It is only necessary that voltage and frequency be brought close enough so that the intermittent occasions when the site and Orion network voltages are in phase, are sufficient to allow the synchroniser to close the 11kV circuit breaker.

This arrangement of synchronisers makes it feasible, in principle, to operate the synchronisers without any connection to the generator governors.

Photograph 3: Opportunistic Synchronising at CB24

5.6 RESILIENCE

5.6.1 EXTERNAL NETWORK FAULTS

In the event of an Orion network fault, it will not be immediately obvious what is wrong or why power has been interrupted. It may take some time before the cause of the fault is known and the corresponding short term response. However there is an immediate requirement to re-establish power to critical systems.

The overall design assists by automatically opening the 11kV circuit breakers in a power loss and starting the diesel generator to provide power to the 11kV network. Having automatically addressed the immediate problem, the site operator will be able to focus on addressing the plant process requirements.

For an external fault, the follow-on actions depend on the type of fault present on the Orion network. The site operator will contact the Orion operator who will have a better indication of the likely outage duration which will allow the site operator to plan. Irrespective of the outage duration, the site power configuration allows the operator to gradually bring up the gas engines, synchronising them to the diesel engine and eventually restore the site to full operational output.

5.6.2 INTERNAL FAULTS

Faults inside the CWTP 11kV network will behave differently to external faults. The initial fault will be similar to an external fault. However once the generator livens the 11kV ring main, the fault will reappear and the generator will trip. The presence of the ring main still provides the possibility of restoring full power to CWTP; however the process of identifying the fault location and switching out the faulted cable is slower.

While the fault remains on the 11kV ring main, emergency 11kV supply to transformers is unavailable. A manual 400V connection has been made from the generator to the essential site switchboard, to provide a means of overcoming this potential issue for the critical site loads.

6 AUTOMATION

6.1 OVERVIEW

The following two images show before and after photos in what was the original control room. In many ways the two systems provide the same underlying control functions; varying biogas flow for power (or frequency) and varying excitation for power factor control. The big difference between these two eras is the ability to integrate the operation of the generators, sharing load with greater flexibility of operational modes, and responding in a co-ordinated manner to process changes.

Photograph 4: Star Trek console for Allen engines (1978)

Photograph 5: New layout, without console

6.2 LOW PRESSURE (LP) BIOGAS TANK LEVEL CONTROL

The LP biogas tank level control is a good illustration of the improved flexibility achieved by the project. The LP tank level is a good measure of the difference between gas production and gas use. Gas production is a slowly varying parameter, so it was possible for operators to set a fixed generator output and to check the levels occasionally.

With the controls upgrade, the opportunity was taken to add a simple PID control loop into the sequence. Locating this control loop in the Generation Management function nicely decouples the standard generator controls from the process control. This permits a more flexible dispatch option to be incorporated more simply than would otherwise be possible. The benefit is the ability to take one generator to a fixed set point while still retaining automatic control of the process.

The technique used is to sum the minimum and maximum control limits for each generator to determine the overall control range. The PID output is then compared to the overall control range to calculate an overall percentage of the control range to be used. This percentage is then applied to each generator's individual control range.

To illustrate:

- If LP Biogas control requires 1,680kW of generation with two gas engines (G2 and G3) running and in joint control then the total powerhouse operational range is:

    - 1,680 / ((900 + 1,550) – (0 + 0) = 68.6%

  Then each generator is set to 68.6% of its available range:

    - For G2 68.6% * (900 – 0) + 0 = 617kW
    - For G3 68.6% * (1,550 – 0) + 0 = 1,063kW

- In the event that the operator needs to move, say, G3 from 1,120kW to 1,200kW then G3 can be taken out of joint control. This causes the available operating range to change, while still needing to meet the same overall target. The new range is:

    - 1,680 / ((900 + 1,200) – (0 + 1,200) = 53.3%

  Then each generator is set to the same 53.3% of the way through its available range:

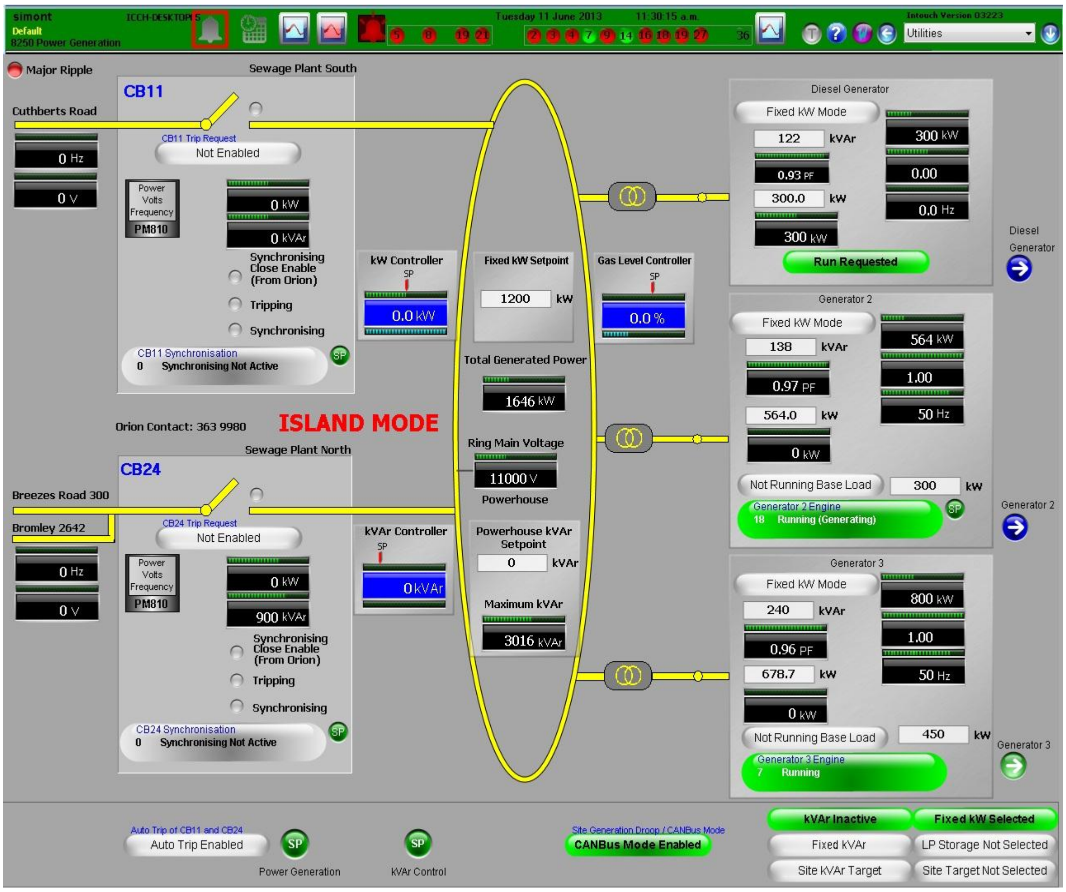
    - For G2 53.3% * (900 – 0) + 0 = 480kW
    - For G3 53.3% * (1,200 – 1,200) + 1,200 = 1,200kW

6.3 COMPLEX CONTROL

Another area where the automation can help is in making it easier to control complex and infrequently used functions. 11kV circuit breaker operation, voltage and frequency control, islanded, parallel and synchronising operations, are all unusual operations at CWTP. As a result it is important to provide a single SCADA screen with the indications and controls needed to help carry out the right control actions when needed.

The screen in Figure 5 was developed to provide the main circuit breaker controls and generator set points needed to operate the scheme both in parallel and islanded operating modes.

Figure 5: SCADA Power System Control Screen



7 CONCLUSIONS

The replacement of two ageing Allen engines at CWTP provided the opportunity for the plant to achieve better integration between site power generation and process operations, and to improve the site's disaster resilience with respect to power generation. However the implementation of the project works to do this was relatively complex.

Complex is defined as consisting of many different and connected parts. In this regard, the electrical and control modifications and the integration of the gas and diesel engines inside a potentially islanded network with multiple process connections at CWTP, can certainly be considered a complex system.

The art in a complex project is to keep some of the fundamental operations simple. This requires arrangement of the controls in a way that naturally supports the process requirements and the actions an operator would expect. Some specific measures taken in this project consistent with this philosophy include:

- Converting the site 11kV supply to a ring main with redundant feeder connections
- Connecting a diesel generator directly to the 11kV network
- Making the diesel generator big enough (800 kW) so that the operator has options when starting essential loads
- Splitting the site Generation Management function apart from the individual unit control

- Splitting off easily separable functions, such as the site synchronisers

- Identifying and grouping the information an operator will need for particular control activities and providing them on a single SCADA page

- Where possible, providing equipment to de-couple constraints, such as the flare (for excess gas) and C3 water (for decoupling from the heat loop)

Individually these are straightforward activities. When combined and implemented coherently over a range of otherwise disconnected projects, this can be a difficult goal to achieve.

The measure of success of this project is evident in the reduced day-to-day monitoring required of the biogas production levels and generation output, the ease with which operators can force a generator out of a generating zone where it may not be performing well, and the re-establishment of routine testing of islanded operation.

Eventually a measure of success will also be the system performance in a power outage. While our preference is certainly for the planned outage for maintenance activities, we can also take comfort from the knowledge that all the practical measures required to minimise the potential impact of a more serious event, have been taken.