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Severn Trent Water Melbourne real time pump and turbine network optimisation

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1   Synopsis

The Melbourne Area Network has always suffered from large variations in energy use and numerous historic investigations had not uncovered the reasons or best operating policies. The complex algorithms developed as part of the work enable Severn Trent Water (STW) to accurately schedule operation over a set horizon, meeting the demand with very appreciable energy cost reductions - a process simply too difficult for operational staff to do by experience alone. The structured and unbiased methodology means that the annual cost of energy has reduced from £4.5M by 9%. The wealth of data has also identified a further £200,000 of savings available through targeted investment.

2   Introduction

The UK Water Industry is coming under increasing pressure to improve the efficiency of its operations.

The start of the sixth Asset Management Period (AMP6) in 2015 has lead to a longer term view on how costs should be saved. Whereas previous savings have been targeted through short term capital expenditure, AMP6 has concentrated on the minimisation of total expenditure, reflecting the need for capital investment to reduce overall operating costs in the long run.

Severn Trent Water has embarked on a significant programme of operational efficiency savings and capital expenditure efficiency savings through targeted investment.

A key part of Severn Trent Waters infrastructure is the Melbourne Area network near Derby. This system supplies the Smisby, Ragdale and Hallgate service reservoirs and consists of the following elements:

- 1 water treatment works;
- 7 pumping systems;
- 2 reservoirs;
- 1 turbine and break tank;
- Abstraction from a river.

The Melbourne network is subject to 6 different electricity tariffs per day and periodic Triad events resulting in an energy cost of operating the network in the order of £4,500,000.

Forming a significant part of its operations, Severn Trent Water has sought to minimise this cost through efficient use of its existing assets and capital investment for longer term reductions.

As shown in Figure 1, the Melbourne network draws from the River Dove using two pumping stations which deliver water to Melbourne Water Treatment Works through two routes via the Foremark and Staunton Harold reservoirs. This network distribution provides a multitude of pumping combinations that can be used to meet a required demand.

Riventa and Deritend, working in partnership with Severn Trent Water, have applied their patented pump performance monitoring systems across the Melbourne network pumping stations to assess individual pump and station efficiencies and derive live network models. Utilising this data, it has been possible to implement an automated Decision Support System (DSS) to provide recommendations as to which pumps to operate, what speeds, and when, to achieve the lowest overall operating cost whilst taking account of variable tariffs, storage, demand and asset performance.

The specific goals of the project were:

- Provision of a systematic method of identifying the lowest cost operation;
- Communication of real-time operational recommendations through a Decision Support System (DSS) to operational staff.
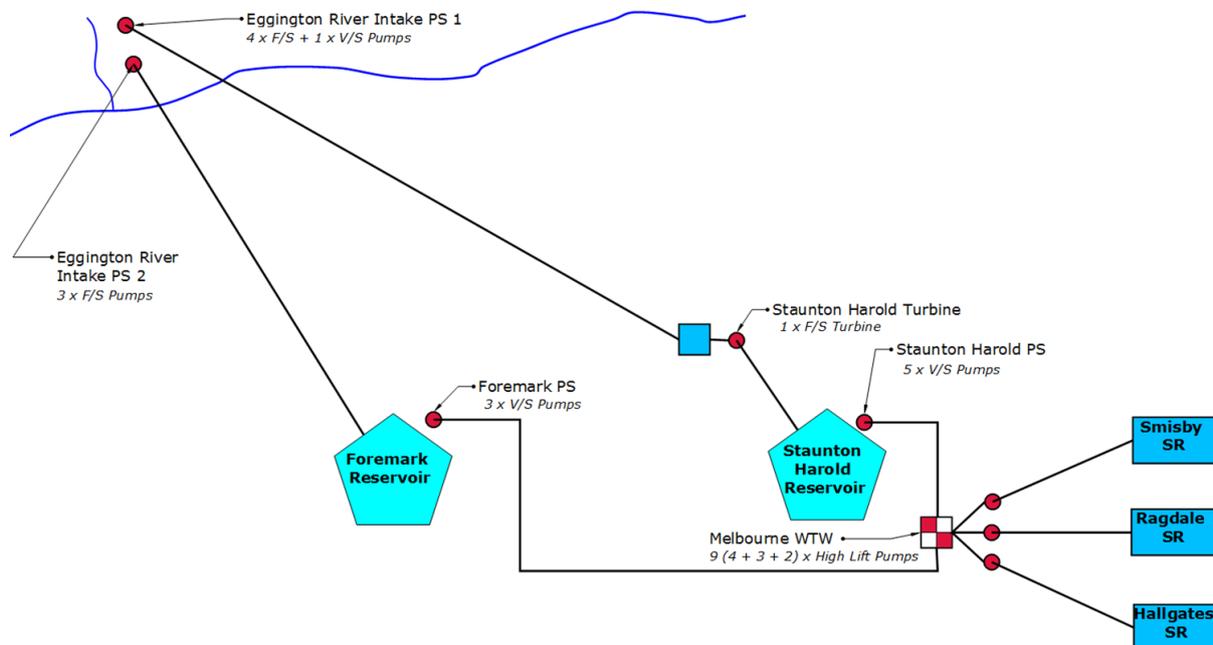

Figure 1 Melbourne Network layout

3 Technology overview

Two key technologies were amalgamated to provide a network optimisation methodology that was integrated into a unified DSS. These consisted of thermodynamic pump performance measurement for individual pump and station efficiency analysis, and live hydraulic modelling to assess network routes and their hydraulic profiles.

3.1 Thermodynamic pump performance measurement

Pump station optimisation can be achieved through informed scheduling and speed selection of pumps to achieve a required demand at the highest possible efficiency. In order to achieve this, it is critical to establish both individual pump and system curves which require measurement of head, power, efficiency and flow rate.

The conventional method for performance measurement computes the output power of

the pump through measurements of differential pressure across, and volumetric flow rate through, the pump. The input power to the pump is usually obtained by measurement of gross electrical power and an assumption of motor efficiency. This method is often costly to implement on site due to the requirement for a flow meter to be installed on each pump which is not always possible due to physical space constraints which also limit the accuracy of application.

As introduced in our 2014 Pump Centre paper, the thermodynamic technique for pump performance measurement utilities an enthalpy – entropy mapping method to determine pump efficiency without the need for direct measurement of flow rate.

The premise is rooted in fundamental thermodynamics in that if you measure any two thermodynamic state variable's (TSV) (which include temperature and pressure) then you can calculate any other TSV (which include enthalpy and entropy).

The conventional definition of hydraulic efficiency is shown in Equation 1.

$$\eta_H = \frac{OUT}{IN} = \frac{Water\ Power}{Shaft\ Power} = \frac{\rho\ g\ H\ Q}{P_e\ \eta_m}$$

Equation 1

Where η_H = Hydraulic efficiency, ρ = Density of fluid (kg m^{-3}), g = gravity (ms^{-2}), H = Differential Head (m), Q = Flow rate (l/s), P_e = Electrical Power Input (kW), η_m = Efficiency of motor.

Considering this in terms of a systems losses leads to Equation 2.

$$\eta_H = \frac{OUT}{IN} = \frac{OUT}{OUT + LOSSES} = \frac{1}{1 + \frac{LOSSES}{OUT}}$$

Equation 2

Substituting the definition of thermodynamic losses (Equation 3) and definition of output power to the fluid (Equation 4) into Equation 2 leads to the definition of hydraulic efficiency shown in Equation 5.

$$LOSSES = \rho\ C_p\ \Delta T\ Q$$

Equation 3

Where C_p = Specific Heat Capacity of the fluid (kJ/kg°K), T = Temperature differential across the pump (°K)

$$OUT = \rho\ g\ H\ Q$$

Equation 4

$$\eta_H = \frac{1}{1 + \frac{\rho\ C_p\ \Delta T\ Q}{\rho\ g\ H\ Q}} = \frac{1}{1 + \frac{C_p\ \Delta T}{g\ H}}$$

Equation 5

Equation 5 demonstrates that the efficiency of a pump can be calculated by measurements of pressure and temperature only without the need for flow rate measurement.

Using this definition, the flow rate can now be calculated through rearrangement of Equation 1 as shown in Equation 6.

$$Q = \frac{P_e \times \eta_m \times \eta_H}{\rho \times g \times H}$$

Equation 6

The key benefits of using this method of pump performance measurement are:

- Comparatively low cost for site use purchase;
- Simple installation requirements and as such is low cost to install;
- Not dependent on straight lengths of pipe to effect an accurate measurement;
- Well suited to on site application, generally for heads >15m;
- Has head limitations to obtain the best accuracy.

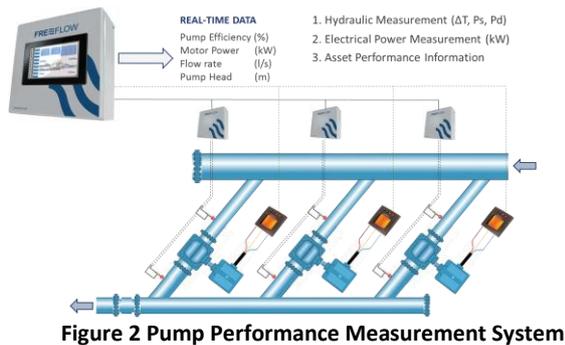A typical installation schematic of a thermodynamic system is shown in Figure 2.

Figure 2 Pump Performance Measurement System

3.2 Station level optimisation

Using the thermodynamic pump performance measurements, through a combination of real-time analysis, and review of logged data, the following information can be quantified at station level:

- Individual pump curves;
- System curve(s);
- Demand profile (load characteristics).

With this data an automated decision support system (DSS) can been created to compute the most efficient combination of pumps and pump speeds, in real-time, to meet the current operation duty – or any other specified duty, something that is hard to achieve manually due to the sheer number of combinations available.

A station with 10 fixed speed pumps will have 1023 possible combinations to choose from and if they are variable speed pumps the combinations are infinite.

As with dynamic systems like distribution zones or tank level changes, where the system curve is not constant, the head and consequently pump efficiency will constantly change. Use of real-time data allows the DSS to adapt to these changes and compute the efficiency (or specific power) of all possible combinations under all possible circumstances and recommend the combination that provides the lowest possible operating cost for the available plant.

Use of the DSS on previous projects in both European and Asian water industries has shown significant benefits in minimising operating costs at a station level with savings of up to 14% on annual power bills with payback periods as low as 2 months.

Though the use of a DSS in combination with thermodynamic measurement techniques allows for minimisation of station operating costs, when considered as part of a network of other pumping stations and storage, additional factors can influence the overall network operating costs meaning each part cannot be considered in isolation.

3.3 Network modelling

Traditional approaches to network optimisation involve the development of static hydraulic models and optimisation algorithms.

Water distribution systems have a high degree of dynamic parameters which have the tendency to cause inaccuracy in the model simulation result. To overcome this the real time hydraulic models are generated based upon the latest pump, system and demand data acquired from the distributed FREEFLOW systems.

3.4 Combined network optimisation

Combining station level measurement and traditional network modelling techniques, it is possible to generate hydraulic models in real-time to overcome problems of the current state of the art.

Though an optimised station helps to minimise pumping costs, certain stations may be more efficient than others for certain combinations of demand and time. Additionally, dynamic system curves, due to demand variations and network configurations changes add further complexities.

By combining the two techniques, it is possible to create an advanced automated DSS which utilises the real-time pump efficiency data from station level thermodynamic pump performance

measurement and combines it with the network hydraulic data to provide a constantly updated hydraulic model, removing some of the traditional assumptions required in network optimisation. This hydraulic model can then in turn be used to schedule pump operation and speeds, simulate / predicting reservoir and service tank levels and optimising time operation relative to electrical tariffs.

4   Project approach

The creation of a network optimisation system required two distinct pieces of work:

- Provision of real time measurements of pump, station and network performance in terms of efficiency and specific cost;
- Design of a custom Decision Support System (DSS) to enable operators to have real time visualisation of pump efficiency and provide instructions on how to operate the network, meeting demand, at the lowest cost.

4.1   Equipment installation

The first step was to install real time pump and turbine efficiency monitoring equipment on all machines at these stations, a total of 26 pumps.

Each station installation consisted of a Human Machine Interface (HMI) as shown in Figure 3, connected to a series of FREEFLOW Data Acquisition Units (DAU) mounted adjacent to each pump as shown in Figure 4. On each pump, a temperature and pressure transducer were installed in tappings on the suction and discharge position side of each pump as shown in Figure 5 which were connected to the respective DAU. Power meters were also installed on each pumps operating panel as shown in Figure 6 and connected back to the HMI.

Figure 3 Human Machine Interface (HMI) (5 installed)

Figure 4 FREEFLOW Data Acquisition Unit (26 installed)

Figure 5 Hydraulic efficiency pressure and temperature transducers (104 installed)

Figure 6 Electrical power metering (26 installed)

The HMI collates the data from the individual pump DAU's at a station level and provides the following information in real-time:

- Pump Efficiency (%);
- Motor Power (kW);
- Flow Rate (L/S);
- Pump Head (m).

The pumping stations were located within an approximate 10 mile radius of the main Melbourne Water Treatment Works which serves as the hub of operations. Due to the distributed locations of the pumping stations, a satellite broadband system was installed at each location to send data back to the control centre for processing by a custom DSS.

The installation of the pump performance measurement equipment allowed for the determination of individual pump head and efficiency curves and station level system curves to inform the hydraulic model.

4.2 DSS development

Utilising the data flowing back from the network stations, a bespoke DSS was created to assess and provide recommendations on pump scheduling and reservoir valve scheduling (to utilise storage potential) to achieve the lowest network operating cost.

The system works by assessing multiple combinations / scenarios to achieve a given demand.

The Melbourne network elements combine to provide the following combinations:

7 F/S and 19 V/S Pumps

(+ 6 tariffs, 3 storage, Turbine, Variable Demand)

= 1×10^{114} Combinations

Due to the sheer number of combinations available, a simple statistical approach would not be practical, as such, a Multi-Objective Genetic Algorithm with Artificial Neural Network and Caching technique was utilised to simulate 24 hour operation of the network, scheduling pump operation and speeds, simulating / predicting reservoir and service tank levels and optimising time operation relative to electrical tariffs.

The genetic algorithm uses the following approach to select the optimum combination and as shown in Figure 7:

1. Randomly select pump combinations;
2. Run hydraulic model, calculate cost and rank solutions;
3. Pick a selection of the best pump combinations;
4. Combine or 'mate' the best pump combinations;
5. Randomly change some attributes;
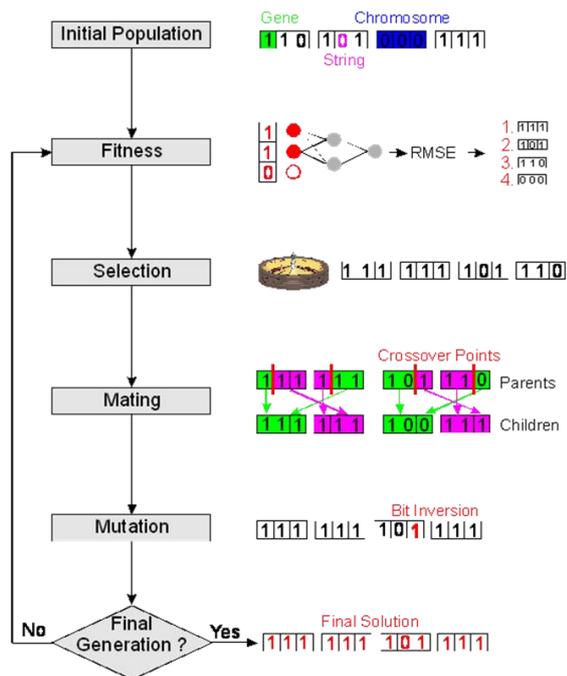6. Loop the outcomes back to step 2 until answer converges.

Figure 7 Genetic algorithm mechanism

The use of the algorithm enables the system to monitor a total of 493 parameters in real time at 5 second intervals with automated file management, analysis and reporting.

5 Project results

The use of distributed pump performance measurement and network optimisation has enabled Severn Trent Water to identify interactions within their network, enabling them to accurately schedule operations to meet the demand with significant energy cost reductions - a process simply too complex for operational staff to do by experience alone.

Savings attributable to the installation of the network optimisation system were categorised on 3 levels:

- Station Level – Those achieved through optimisation of individual stations in isolation through pump scheduling and speed selection.
- Network Level – Those achieved through optimisation of water routing and storage.
- Capital Savings – Savings potential identified through additional capital

expenditure to reduce operating costs in the longer term.

From a benchmark demand of £4.5M / annum, an overall saving of **9%** (£405,000) was realised through operational changes only with no additional CAPEX beyond this project resulting in a **<1 year** payback on the project.

In addition, a further **4.5%** (£203,000) of annual savings were identified through targeted CAPEX of £300,000.

If additional capital expenditure was made and all possible sources of saving were obtained by upgrading the system to '*best practice*', a saving of **19%** could be achieved, equivalent to £855,000 / year.

Taking the problem at its most basic level, the network pumps water from its source to the water treatment works which is it a higher elevation. Conducting a simple hydraulic calculation to calculate the power required to raise water by this height reveals a minimum theoretical energy cost of £1.45M; the current cost is some three times greater highlighting the degree of losses (and so potential) in water distribution systems.

The impressive results have changed the way the network operates and it is intended to role the system out to other networks across the AMP6 period to utilise this new information driven approach as a key feature in targeting resources for OPEX reduction and CAPEX allocation - fulfilling the TOTEX mandate.

6 Technology potential

With AMP6 in full swing it is an imperative of UK water companies to invest with due consideration of capital and operational costs.

This project demonstrates how accurate performance measurement and an information driven approach can be used to

minimise operational energy cost and target investment for maximum long term savings - all with a tangible and transparent decision making process - fulfilling OFWAT's TOTEX mandate.

7   About the author

Director of Consultancy at Riventa Ltd leading technical staff across three service centres in America, Asia, with headquarters in the UK.

Water and waste water pump energy specialists, Riventa, is a world leading organisation manufacturing instrumentation and software with the main pursuit of reducing the cost of energy within the water industry

Tom is responsible for on-site pump efficiency testing, hydraulic engineering consultancy and network modelling. Using a global network of partners, like Deritend, enables delivery of turnkey solutions with proven results for the water industry.