FINAL

OPERATIONAL ENERGY EFFICIENCY PROGRAM (OEEP)

APPLICATION GUIDE

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APPLICATION GUIDE

B&V PROJECT NO. 172706

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I. Introduction

A. INTRODUCTION AND PURPOSE

The purpose of this document is to aid water utility personnel in the understanding, assessment and improvement of the wire-to-water efficiency of water pumping plants. The document is organized with an introductory section that provides an overview of pumping plant energy efficiency considerations and the remaining sections provide technical information on implementation of energy efficiency monitoring and controls for water pumping plants.

This document is based on findings from Black & Veatch’s assistance to the California Public Utilities Commission on the Operational Energy Efficiency Program (OEEP). The OEEP involved a pilot testing program that included the installation of power monitoring, VFDs and SCADA controls at twenty-one (21) test sites throughout California. A key OEEP objective was to evaluate the effectiveness of operating pumping plants to optimize wire-to-water efficiency, while meeting the given system operating requirements.

This OEEP Application Guide includes some of the findings from the OEEP pilot program, however, it is not intended to provide a comprehensive summary of the findings of the energy or cost effectiveness of the OEEP program. A separate report prepared by E3 Consultants provides a detailed evaluation of the pilot program and analysis of the operation of each facility that was part of the OEEP research and development (R&D) effort.

Although the OEEP approach of operating a pumping plant to optimize wire-to-water efficiency was found not to be applicable to all pumping plants, the data supports the finding that there were facilities where the improvements could provide benefit in terms of energy efficiency, reduction in losses, reduction in peak demands and power factor improvement.

This application guide does not intend to present an evaluation of the overall effectiveness of the OEEP pilot program however certain observations from that R&D effort are highlighted where appropriate and relevant to pumping plant efficiency. The focus of this report is to provide an approach to evaluate energy efficiency and to identify what elements of the OEEP program may be effective and under what circumstances.

This application guide is focused on providing information to utility users for the implementation of the OEEP improvements at pumping plants that have potential for energy efficiency improvements. This document provides an approach and methodology for identifying facilities that would be good candidates for implementation of the OEEP energy efficiency improvements. By following these guidelines efficiency improvements in the range of 10 to 30%, or greater, are possible depending on the current performance characteristics of the pumping plant. It is beyond the scope of this application guide to determine or evaluate the cost effectiveness of those improvements.
1. Abbreviations

The following abbreviations are used in this document.

Table 1 Abbreviations

<table>
<thead>
<tr>
<th>ABBREVIATION</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEP</td>
<td>Best Efficiency Point</td>
</tr>
<tr>
<td>CPUC</td>
<td>California Public Utilities Commission</td>
</tr>
<tr>
<td>E3</td>
<td>E3 Consultants, Inc.</td>
</tr>
<tr>
<td>EM&amp;V</td>
<td>Evaluation, Measurement and Verification</td>
</tr>
<tr>
<td>hp</td>
<td>Horsepower</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatts</td>
</tr>
<tr>
<td>OEEP</td>
<td>Operational Energy Efficiency Program</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>TDH</td>
<td>Total Dynamic Head</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
</tr>
</tbody>
</table>

Note: Variable Frequency Drive (VFD) is the only term used to describe drives in this document; however, other documents associated with the OEEP program have used Variable Speed Drive (VSD) and Adjustable Speed Drives (ASD) to describe the same drive technology.

2. OEEP Background

The CPUC sponsored the OEEP with the objective of finding technologies or techniques that would help reduce the consumption of energy associated with the production and distribution of water in California.

The following was the stated goal of the OEEP program:

“Improve the Wire-to-Water operational efficiency, when the appropriate combination of induction motors, pumps, VFDs, and SCADA systems are operated at their optimal efficiency levels”

The OEEP program outlined an improvement process that included the following steps:

**Phase 1A**

- Step 1 – SCADA, constant speed, baseline
operational efficiency

- Step 2 – SCADA, VFD, optimization algorithm

**Phase 1B (CPUC directed if necessary)**

- Step 1 - SCADA, VFD bypass, Motor and Pump Replacement
- Step 2 - SCADA, VFD, Motor, and Pump Replacement optimization algorithm

 Twenty-one (21) pumps were retrofitted with power monitoring, VFD's and SCADA improvements, including an efficiency optimization algorithm, and were operated to see if this combination of improvements would result in a reduction in energy use, a reduction in energy losses, and have a positive cost effective impact on energy use in California. Black & Veatch was retained by the participating water utilities after the facilities had been installed and operated for some time. Black & Veatch’s role was to review the implementation of the OEEP installations and work with the participating utilities to review the individual facility OEEP implementations, identify any issues, and assist in bringing the individual pumping facilities in-line with the overall program goals. As a part of this work B&V was tasked with developing a standardized optimization algorithm that could be used by the water industry to control pumping plants to optimize the wire-to-water efficiency while at the same time meeting the operational objectives of the water system. This algorithm was installed at two (2) sites and is described and documented in Section 3.

**OEEP Pump Station Types**

In general terms, the OEEP pumping facilities can be considered in two main categories:

- Vertical turbine well pump stations
- Booster pump stations

**Vertical Turbine Well Pump Stations**

Figure 2 shows the typical arrangement of the well pump, OEEP instrumentation including well level sensor, discharge check valve, pressure transmitter, and flow meter. The data from these instruments is used to calculate real time mechanical energy output. Not shown on the diagram is the power meter used to measure the input power. The ratio of the output power to the input power is used to calculate the wire-to-water efficiency.
A variation on this type of facility is one that includes a hydro pneumatic tank that is interconnected to the distribution system downstream of the discharge check valve. The hydro pneumatic tanks are primarily used for surge control but do provide a small amount of storage that can be used to dampen the variations in pressure and flow.

Another variation on this arrangement includes a downstream pressure reducing valve (PRV) between the pump stations discharge and the system header. The original purpose of the PRV valve
was to maintain a predetermined system pressure for constant speed pump applications. In a couple of cases these were left in place even though the pumps were provided with VFD controls.

![Figure 4 Vertical Turbine Well Pump With Pressure Reducing Valve](image)

**Booster Facility**

The typical booster facility includes one (1) to three (3) pumps that operate in parallel and transfer water from either a pressure zone or reservoir to a terminal reservoir or another pressure zone. Figure 5 provides an overview of a typical arrangement.

![Figure 5 Centrifugal Booster Pump](image)
OEEP Findings Overview

As mentioned above, a separate Evaluation, Measurement and Verification (EM&V) report was prepared by E3 Consultants that evaluated the overall findings of the OEEP program. It was concluded in that report the OEEP as implemented will not provide cost-effective efficiency improvements across a wide variety of pump and motor installations. However, there were selected facilities where the OEEP could provide benefits. One of the reasons identified for not having universal application is that the energy efficiency of a pumping plant is dependent on a number of factors including the motor and pump combination, system demand in terms of pressure and flow, system hydraulics and electrical and control system characteristics. As such, efficiency improvements or optimization control strategies need to be implemented on a case-by-case basis using adequate data and sound engineering practices.

Although not universally applicable, the E3 report concluded that even with modest energy savings, installing VFDs, can provide a combination of demand reduction and load shifting that proves cost effective. The report also recommended that a monitoring and evaluation program, with adequate screening and implementation assistance could potentially identify inefficient pumps and help design their replacements in a cost-effective manner.

B. PUMPING PLANT ENERGY EFFICIENCY

1. General Energy Efficiency Considerations

Energy efficiency ($\eta$) is defined as the ratio between the useful energy output of an energy conversion device ($P_{out}$) and the input energy ($P_{in}$). The useful energy output may be expressed in terms of electrical power, mechanical work or heat.

$$\eta = \frac{P_{out}}{P_{in}}$$

This ratio is a dimensionless number that may also be expressed as a percentage and varies between 0 and 1, or 0 to 100%. This is applicable to individual devices as well as to systems that are comprised of several energy conversion devices. For a system of devices, the overall system efficiency is the product of the individual device efficiencies.

$$\eta_T = \eta_1 \cdot \eta_2 \cdot \eta_x$$

Where:
- $\eta_T$ = Total efficiency
- $\eta_1, 2, 3 \ldots$ = individual device efficiencies

For a pumping plant this would typically include a number of devices with their own inherent efficiencies, an understanding of the efficiency considerations for the individual components will aid in understanding what elements have the most significant impact on system efficiency and based on typical efficiency values where to target improvements. A key step in evaluating potential energy efficiency improvements is to estimate what the particular pumping plant’s theoretical
maximum efficiency is and compare that to its actual performance. That difference will provide a 
good indication of the gap between the theoretical and actual performance.

The following sections explore these efficiencies in more detail with the goal to understand the 
expected efficiencies of these components, the typical range of expected efficiency values and the 
relative impact that device's efficiency 
has on the overall facility efficiency. 
The following elements of a pumping 
plant will be considered: power monitoring, motor, VFD, pump, 
hydraulic systems, and controls.

2. Power Monitoring

The concept that “you can’t control what you can’t measure” was a driving 
factor behind the first step in the OEEP program which was to install 
instrumentation that could be used to 
monitor, in real time, the wire-to-water 
efficiency of the pumping facility on an 
individual pump/motor basis. Kilowatt input, flow, suction and discharge head 
are needed for the calculation of wire-to-water efficiency.

This step involved installation of the necessary instrumentation to measure the performance of the 
facilities and to provide data needed to support the validation of the test results. A key 
measurement is the power consumption or kW of the pumping plant. Efficiency monitoring over a 
wide range of operating conditions is an important first step in evaluating whether or not there are 
opportunities for improving the efficiency of the pumping plant. For most of the OEEP test sites 
discharge pressure (head) and flow were already installed. Suction pressure (head) and power 
monitoring was added for most sites.

Monitoring efficiency over a long period of time will provide for operational data that varies on a 
daily or seasonal basis. Periodic or annual pump tests may not provide a true picture of how the 
estation efficiency changes over time or operating conditions. Once the baseline is established for 
system operation, then a comparison can be made between what the theoretical maximum 
efficiency should or could be versus how it is actually operating. The E3 report provides data on the 
estimated costs to provide power monitoring and establishing wire-to-water efficiency. Refer to 
Section II of this report for details on determining wire-to-water efficiency.
3. Motor Efficiencies

Over the past 10 to 15 years there have been technological advances as well as regulatory requirements to improve the efficiency of motors. Also there have been a number of water and electric utility initiatives and incentive programs to improve the efficiency of motors in the water industry. This has resulted in a significant increase in the use of premium efficiency motors and it is very common to find three phase induction motors in the 92% to 95.5% efficiency ranges in water pumping applications. Figure 7 shows typical efficiency values versus motor horsepower values.

In general, the data indicates that higher efficiency can be achieved with larger capacity motors over smaller motors; however, significantly under utilizing the rated capacity of the motor can negatively affect the motors overall efficiency.

Figure 8 shows the efficiencies of several induction motors sizes at varying operating loads.

The actual efficiency achieved is dependent on the motor load. From the affinity laws, the load a pump draws from a motor varies based on the cubic ratio of the speed. For example, if a 100hp pump was operating at 65% speed the pump would draw about 27.5 hp. This is because \( (.65)^3 = 0.275 \) where .65 is the speed ratio and .275 is the speed ratio cubed. The OEEP project limited the pump speeds to 83% which in the example above would equate to 57.2 hp. In conclusion, operating a motor at less than 50% of rated load can affect the efficiency of the motor significantly, especially smaller rated motors under 40hp.

There is limited industry data available on the degradation of motor efficiency over time.
Data indicates that degradation of motor efficiency occurs primarily in the event of physical damage to motor components from adverse environmental or electrical supply conditions, bearing failure and motor winding damage. Many of these are prevented through an effective maintenance program. Barring any of these, motor efficiency should remain relatively constant over time. Given the relatively high efficiency under most operating conditions and high durability of motors, the biggest impact motors may have on overall plant efficiency is the initial motor selection.

4. **VFD Efficiencies**

Figure 9 shows typical VFD efficiencies and provides some perspective on how the efficiencies of VFDs improved during the period from 2003 to 2008. Despite this improvement VFD’s are not 100% efficient. Efficiency losses in the 3% range are viewed as typical however data obtained from the OEEP trial period showed that efficiency losses in the range of 0.1 to 3.2 % were observed in practice when the VFD was in the circuit.

This guide is intended to provide insight into whether or not a VFD will provide benefit based on the pump application and system requirements. VFD’s may not be suitable in all situations. The OEEP results show that many pump stations couldn’t outperform the constant speed on-off controls even after VFDs where installed because the maximum pump hydraulic efficiency was not achievable given the system operating conditions and the limitation of maximum speed of the motor driving the pump. In these cases, it was more beneficial to leave the existing constant speed equipment in place and not retrofit the controls with VFD’s.

Figure 9 Variable Frequency Drive Efficiency vs. Load

However, there are certain facilities that would benefit from the application of VFDs. VFDs inherently add losses to the system so any OEEP style algorithm installed would need to be able to improve the operational efficiency more than the losses introduced into the system by the installation of the VFD. There are times when input transformers or input line reactors are needed as a part of the VFD installation. These devices can also introduce additional energy losses into the system.

The OEEP program included the installation of VFDs to vary the speed of the pump to optimize the efficiency at the given operating point; however, the installation in some cases resulted in an overall loss of efficiency.
The OEEP power monitoring and bypass contactors allowed for a comparison of operation on VFD at 60 Hz and across-the-line operation with no VFD. The following table provides one set of data from the OEEP which shows the net reduction in efficiency due to the installation of a VFD.

<table>
<thead>
<tr>
<th>MODE</th>
<th>INPUT KW</th>
<th>OUTPUT KW</th>
<th>LOSS KW</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bypass Contactor – across the line no VFD</td>
<td>170.0</td>
<td>85.9</td>
<td>84.0</td>
<td>50.6%</td>
</tr>
<tr>
<td>VFD manually set at 60 Hz</td>
<td>175.8</td>
<td>85.1</td>
<td>90.8</td>
<td>48.4%</td>
</tr>
<tr>
<td>Net Reduction due to VFD and OEEP electrical equipment</td>
<td></td>
<td></td>
<td></td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Table 2 Typical OEEP Test Site VFD Loss Data

Although VFD performance can degrade over time, the voltage and voltage balance of the incoming utility service can have a significant effect on the performance of VFDs. A large voltage imbalance on the incoming utility service observed at one of the OEEP test sites caused a significant reduction in VFD efficiency. The lesson learned from that site is that it is very important to identify any potential voltage imbalances prior to the installation of VFDs.

In general, modern VFDs have a relatively high efficiency over normal operating ranges that would be found at a pumping plant. A first step in evaluating the efficiency of a pumping plant would be to review whether or not there are variable speed control devices and what the efficiencies of those drives are over their operating range.

5. Pump Efficiencies

The pump efficiency is defined as the ratio of energy delivered by the pump (hydraulic energy) to the energy supplied to the pump shaft by the motor (mechanical energy).

The efficiency of a pump is highly dependent on the characteristics of the particular type of pump as well as the characteristics of the system it is operating within. Figure 10 is an example of a typical pump curve that shows the relationship between flow and total dynamic head. It also includes an overlay of efficiency for the various operating points. The red triangle shows the Best Efficiency Point (BEP). As can be seen from the graph as the pump moves along its pump curve there can be a significant change in the pump efficiency. The steeper the pump curve the greater the variations in efficiency can be for changing operating conditions. The accurate determination of operating points and the selection of the correct pump for those conditions can have a significant impact on pump station efficiency.

The selection of the pump has long-term implications for overall facility energy consumption and costs. The determination of the correct range of operating points requires the accurate evaluation of flow demand over the year (including normal day, peak day and peak hour) and an estimate of the projected demand changes during the lifetime of the pump station.
The following table provides typical maximum efficiencies for various types of pumps operating at their best efficiency point on the pump curve.

<table>
<thead>
<tr>
<th>PUMP TYPE</th>
<th>MAXIMUM EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Suction/Split Case</td>
<td>84%</td>
</tr>
<tr>
<td>Vertical Turbine (Bowl Assembly)</td>
<td>84%</td>
</tr>
<tr>
<td>Large End Suction Pumps</td>
<td>84%</td>
</tr>
<tr>
<td>Axial Flow Pumps</td>
<td>82.2%</td>
</tr>
<tr>
<td>End Suction ANSI/API Pumps</td>
<td>81%</td>
</tr>
<tr>
<td>Multi Stage Boiler Feed Pumps</td>
<td>80%</td>
</tr>
<tr>
<td>End Suction Stock Pumps</td>
<td>75.2%</td>
</tr>
<tr>
<td>End Suction Sewage Pumps</td>
<td>72%</td>
</tr>
<tr>
<td>End Suction Slurry Pumps</td>
<td>66%</td>
</tr>
</tbody>
</table>

Table 3 Typical Pump Efficiencies
Table developed from HI 20.3-2010, courtesy of Hydraulic Institute, Parsippany, NJ [www.Pumps.org](http://www.Pumps.org)

Data from the Department of Energy (DOE) indicates that it can be common for a pump to degrade in efficiency as much as 10% to 25% before any corrective action is taken to replace or repair the pump. As such, the degradation of pump efficiency can have a significant contribution to reducing the overall wire-to-water efficiency of a pumping plant.

6. Overall Pumping Plant Wire-to-Water Efficiency

For a pumping plant the term wire-to-water efficiency is used to describe the overall or combined efficiency of the pumping plant. To calculate the overall system efficiency, the efficiency of each device must be taken into account to determine the overall efficiency for the pumping plant. Figure
Figure 11 Energy Loss Components

The wire-to-water efficiency for the pump station is calculated as follows:

\[ \eta_T = \frac{P_W}{P_e} \]

The overall efficiency is a composite of the efficiency of the pumping plant components. The product of the efficiency values for each of the components is the overall efficiency.

\[ \eta_T = \eta_{VFD} \cdot \eta_{motor} \cdot \eta_{pump} \cdot \eta_{dynamic} \]

Where:
- \( \eta_T \) = Total efficiency
- \( \eta_{VFD} \) = VFD efficiency
- \( \eta_{motor} \) = Motor efficiency
- \( \eta_{dynamic} \) = System misc. & dynamic efficiency
- \( P_W \) = Work produced by the pump station in horsepower
- \( P_e \) = Electrical power consumed by the pump and motor in horsepower

The original efficiency of a particular device can be estimated using vendor product data. The combined efficiency depends on a number of factors including:
Original equipment efficiency ratings

Pump sizing and selection for the application and where it is operated on its curve

Motor loading and operating speed

System hydraulic characteristics

System operating constraints

Equipment aging or wear

To calculate the wire-to-water efficiency, the following variables must be known: discharge pressure, discharge flow, power used by each pump, suction pressure or wet well level, elevation of the discharge pressure transmitter and elevation of the suction pressure transmitter or wet well level transmitter.

A general observation from the OEEP project indicated that there were a number of cases where the efficiency calculation did not adequately consider the location of the pressure transmitters or well level transmitters which led to inaccuracies in the efficiency measurement. These were corrected where possible. The application of instrumentation monitoring of wire-to-water efficiency is covered in Section II of this guide.

Southern California Edison reports that 28,000 pump tests had wire-to-water efficiencies in the range of 44 to 63%\(^3\). Data from the OEEP pilot study indicates that on average pump station wire-to-water efficiencies in the range of 70 to 72% is a reasonable target to achieve in practice for water well or booster pumping plants.

C. OEEP PUMPING PLANT EVALUATION METHODOLOGY

Although the OEEP approach of operating a pumping plant to optimize wire-to-water efficiency was found not to be applicable to all pumping plants, the data supports the finding that there are facilities where the improvements could provide benefit in terms of energy efficiency, reduction in overall losses, reduction in peak motor loads and power factor improvement. This section provides a recommended approach for evaluating pumping plant performance and efficiency and provides a general screening process for OEEP improvements worth considering.

The original OEEP program included several steps as described in the previous section on OEEP background. As a result of the findings in the report and in reviewing the performance improvements, it is recommended that an initial evaluation be performed prior to the installation of any elements of the OEEP. The recommended evaluation methodology is summarized in the flow chart shown in Figure 13 and 14, and includes the following main steps:
Step 1 – Pump Station Data Collection
Step 2 – Operational Data Review
Step 3 – Instrumentation Improvements and Data Collection
Step 4 – Preliminary Performance Evaluation
Step 5 – Pump Performance Evaluation
Step 6 – VFD and OEEP Algorithm Installation

The methodology is intended to serve as an approach for identifying what OEEP improvements would be appropriate for a given facility. As such, it may be appropriate to complete only a few steps of the methodology. The following sections provide more detail on the recommended steps.
Step 1 – Pump Station Data Collection:
- Eq. Arrangement
- Manuf. Pump Curve
- Motor Data
- System Curve

Is wire to water data available?

Y

Step 2 - Operational Data:
- Prior efficiency tests
- Wire to water analysis

N

Step 3 – Instrumentation
Install Power monitoring & WTW calculations

Y

Step 4 – Preliminary Data Quality/Efficiency Analysis

Is the WTW efficiency Within +/- 0 - 10% of Theoretical Max

Y

Collect Representative Data

N

Station Highly Efficient
Continue to monitor long Term trends

To Figure 14

Figure 13 Recommended OEEP Evaluation Methodology Flowchart
Step 5 - Perform Pump Assessment to determine if the correct pump is installed for the application in terms of TDH, Flow, η.

Is the current pump appropriately sized for the application?

Operational Flexibility/changes to better match pump?

Perform Cost Benefit analysis of pump replacement

Does the cost benefit support the replacement?

Step 6 - Evaluate if OEEP Algorithm & VFD would provide benefit

Change operational settings including pressure and/or flow

Do system operating points fall near or on both sides of the BEP?

Consider OEEP Algorithm & VFD installation

Continue to monitor long term trends & reevaluate performance data

Pump replacement candidate

Figure 14 Recommended OEEP Evaluation Methodology Flowchart
1. **Step 1 – Pump Station Data Collection**
Collect data on the pumping station equipment including:

- Physical installation and equipment arrangement
- Original manufacturer’s pump curve (TDH Vs flow and Efficiency Vs flow)
- Motor nameplate data including efficiency and horsepower
- System static and dynamic curve information
- Instrument locations

The equipment data should be reviewed to establish the original individual component efficiencies. The original manufacturer’s pump curve is an important part of the evaluation because it will help to establish what the original “theoretical maximum efficiency” of the pumping station was when originally constructed.

2. **Step 2 – Operational Data Review**
Review existing operational data and determine if sufficient data has been collected for the following:

- Prior efficiency test data
- Discharge flow rate
- Total Dynamic (Duty) Head, which may include suction and discharge pressure or well depth measurement and reservoir levels.
- kW power consumption
- If variable speed drives are installed, frequency or speed of the motor
- Full range of operating conditions covering typical daily and annual variations (range of demands and range of operating pressures)

A key determination at this step is whether or not adequate instrumentation is in place to calculate wire-to-water efficiency. This step should include a review of the operational constraints for the pumping plant, as well as, a review of whether or not there is flexibility in adjusting the discharge flow rate or operating pressure.

3. **Step 3 – Instrumentation Improvements and Data Collection**
If adequate instrumentation is not in place then this step would include installation of additional instrumentation or data collection equipment. Reference Section II for technical information on instrumentation applications. Once adequate instrumentation is in place it is recommended that long term data is collected for evaluation. The intent is to collect representative data that includes typical daily and annual variations.
4. **Step 4 – Preliminary Data Quality / Efficiency Analysis**

The objective of this step is to perform an initial assessment of the quality of the data being collected and identify how the currently installed pump is operating. It should be determined how closely the pump is operating to the original manufacturer’s pump curve and how closely the pump is operating to its Best Efficiency Point (BEP) given the current operating conditions.

The difference between the “theoretical maximum efficiency” and current operating performance provides an estimate of the potential for efficiency improvement. Any significant gaps between the theoretical and actual performance may require further investigation to identify what element of the pump station is causing the gap. This step will aid in determining if there has been any degradation in the pump characteristics or other components. Degradation in performance could be an indication the monitoring equipment is improperly installed and calibrated. A mismatch between the original pump curve and the current operating points may also be caused by faulty monitoring equipment.

This evaluation focuses on the pump efficiency of the considered facilities. As previously discussed, this efficiency is only one fraction of the overall facility wire-to-water efficiency. The pump efficiency is the ratio of the energy delivered by the pump to the energy received on the pump shaft from the motor. The pump efficiency is not measured on site but is indicated on pump performance curves as a function of flow. Pump performance curves are provided by the manufacturer at the time of pump purchase or pump test; however, they typically degrade with time due to wear and tear of the impeller and bearings. Therefore the actual pump performance, including efficiency, may deviate from the original performances indicated on the manufacturer’s curves. As part of this evaluation it is therefore critical to identify if pumps are still operating near the original manufacturer’s curves.

The analysis is primarily a graphic analysis where test points are plotted on a graph showing Total Dynamic Head (TDH) versus flow rate. These points are then compared to two performance curves provided by the pump manufacturer, they are: pump efficiency versus flow and the pump TDH versus flow.

**Validate Pump Curve and Measured Data**

Recorded data, flow and TDH, are plotted on a graph along with the original flow and efficiency curves from the manufacturer. Figure 11 is representative of the data that might be plotted for a constant speed application. The alignment of data points along the plot of the original manufacturer’s curve indicates that the pump is operating close to its original pump curve.

If the site has a VFD installed then pump speed varies with the use of VFD and data must be "adjusted" through affinity laws to make the comparison meaningful. Two approaches are recommended to "adjust" the data (see Figure 15 and Figure 16):

- Adjust the recorded points to full speed operation and plot along the original full speed curve provided by the manufacturer (Figure 15).
- Extend manufacturer’s curves to include operation and efficiency at reduced speed and plot along the recorded points. (Figure 16).
**Figure 15** Recorded Data at Full Speed or Adjusted to Full Speed

**Figure 16** Pump Curves with Recorded Data and Efficiency Gradients

BEP Gradient
If the recorded points align well with the manufacturer’s curve as in Figure 15 the analysis of pump efficiency will be relatively accurate. Recorded points plotting slightly below the manufacturer’s curve would be an indication of normal pump performance degrading over years of operation. For these, the BEP is assumed to be close to the location indicated on the manufacturer’s curve, but slightly reduced in value.

Points plotting far from the curve (25% below or more) or above the curve would indicate errors or other problems and as a consequence, the analysis of the opportunities for improvement may not be possible. The potential causes of a recorded point plotting far from the curve include:

- Flow or pressure measurement errors (meters installed incorrectly or not calibrated)
- The calculation of the TDH includes an error (i.e. ignoring suction pipe head loss)
- Damaged pump
- The pump impeller has been trimmed
- The pump curve provided is not the correct curve for the pump

In such cases resolving these issues is recommended prior to collecting more data and performing an evaluation of the pump performance.

If the preliminary analysis indicates that the current pump station is operating within 10% of its peak efficiency point then it is recommended that long term data collection continue.

5. **Step 5 – Pump Performance Evaluation**

This step includes completion of a preliminary hydraulic analysis to determine whether the correct pump has been installed for the application. Typical questionable applications include facilities with a discharge valve continuously throttling the pump output indicating the pump is oversized on pressure or facilities with pumps oversized on flow which may have been selected for peak demand conditions or future demands which never occurred.

In addition to evaluating the pump application, this step also includes the more refined evaluation of equipment flexibility meeting the optimal operating conditions. For a constant speed pump an adjustment in the discharge pressure settings could move the pump operation to a point on the pump curve that is closer to or at the BEP. For a VFD installation an adjustment in operating schedule may allow the pumps to produce the required volumes while moving the operating flow closer to the BEP.

In order for a VFD with wire-to-water efficiency control to be effective the system operating requirements must have some flexibility since the speed of the pump will be varied to optimize efficiency. The speed changes have a direct impact on the pump output pressure and flow.

If system operating constraints are such that the system must be operated over a very narrow pressure control band or over a very narrow flow band then the OEEP efficiency algorithm will not be applicable. Such constrains can be illustrated by VFD installations discharging directly into a distribution system without storage. In this case the pump output must match the instantaneous demand and cannot be changed. Another example is a facility timed to operate in periods of lower energy cost or “off-peak” periods. In this case, averaging the flow over 24 hours to operate closer to the BEP may not offset the penalty of operating during periods of higher energy cost or “on-peak” periods.
It may be that due to system demand changes a VFD with a pressure control set point would provide the best improvement in energy efficiency.

**Hydraulic Analysis**

The basis of the evaluation is to compare the location of the recorded points relative to the BEP. When all recorded points plot to the left of the BEP, generally the speed of the pump would be increased to improve the efficiency.

In many cases the OEEP algorithm operated pumps at or close to full speed. These results were because the pump sizes were larger than needed for the operating points collected. This means that the pumps were operating significantly left of the BEP on the pump curve and the pumps could not achieve the BEP unless they were operated faster than full speed. The over sizing of these pumps may have been intentional for large fire flows, future demands or other reasons; however, it is possible the pumps were not matched to the distribution system for optimal efficiency. If a pump is oversized the OEEP program will seek the maximum speed because it will trend toward the BEP and if the BEP is not achievable the pump will simply run at full speed. Full speed with a VFD is less efficient than full speed with a bypass contactor or reduced voltage soft starter because they are essentially 100% efficient where a VFD might be 97% efficient. In conclusion, the OEEP algorithm will not aid pumps that are significantly larger than operating conditions of the system and attempting to implement the OEEP program will only make the system less efficient.

See Figure 17 and 18 examples.

![Figure 17 Pump Curves with Operating Points to the Left of the BEP](image)
More detailed analysis of the pumping system and establishing system curves would provide an effective way to evaluate each facility; however, such information may not be readily available. Typical characteristics and associated recommendations were identified for the following cases:

- All recorded points plot to the left or below the BEP (similar to Figure 17): In this case the pump would appear to be oversized for the system requirements. A pump may be considered “oversized” if sized for larger flows or higher TDH than values recorded. In Figure 17 the pump is oversized for flows but not for TDH. This is a typical configuration where replacing the pump by a smaller unit may be recommended. However, it should be carefully checked that the existing unit is truly oversized, since the capacity may be required for the occasional fire flows or peak demand days, not recorded during the test period. A cost-benefit analysis should also be performed for pump replacement candidates.

- All points plot in a narrow pressure band above and to the left of the BEP (similar to Figure 18): In this case the pump may appear oversized; however, the narrow band indicates a well regulated system pressure. If acceptable, rather than replacing the pump, changing the system operation may be a more cost effective alternative. Reducing the pressure setting in the system fed by the pump would shift the pump operating points closer to the BEP.

- Insufficient gain from OEEP (similar to Figure 16 or Figure 18): This is a case where the OEEP operation does not increase the pump efficiency by more than about 3%. Power losses through the VFD would not be compensated by the gain of pump efficiency; thus eliminating the benefit of the OEEP.
All points plot to the left of the BEP but within 5-10% of the BEP. Replacing the pump may not be economical since the pump efficiency is acceptable. However, all the points are located to the left of the BEP. In this case the OEEP will force the VFD to maximum speed. This could be achieved as well by a constant speed drive, but with reduced power losses. Therefore the VFD and OEEP may reduce the overall facility efficiency.

6. Step 6 – Evaluate If OEEP Algorithm and VFD Would Provide Benefit

This step includes the evaluation of whether a VFD operating under an efficiency control algorithm could provide efficiency improvements. The improvement would need to be at a level that could offset the inherent losses introduced by the VFD and associated electrical equipment. Install a VFD and optimization algorithm if the improvement criteria can be achieved.

Although the focus of the OEEP program was to improve the efficiency of individual pump motor combinations it is important to note that the actual operating efficiency is highly dependent on the system operating characteristics that includes set pressures in the distribution zone, well levels, terminal reservoir levels, system hydraulic characteristics as well as interactions with other facilities.

The original OEEP concept of simply adjusting the speed of a VFD to optimize its efficiency had some inherent challenges that were introduced by the pump characteristics and the system operating conditions. There were numerous examples where the control strategy operated the pump at close to 60 Hz to find the optimum efficiency. It was identified that many facilities often operated under conditions for which the installed pumping unit was oversized. Although designing slightly oversized facilities is a general practice to include safety factors and accommodate future growth, it results in the OEEP pushing the VFD operation to 60 Hz. The OEEP may have improved efficiency in such facilities; however, in that case even better efficiencies would be obtained through constant speed operation.

In many cases due to varying reservoir or well levels, the system operating conditions vary over time, so efficiency measurements at one operating point may not provide a representation of the full range or even the average efficiency that might be achieved over the long term. In order to provide a comprehensive evaluation of the efficiency of the pumping plant it is important to look at the system hydraulic characteristics.

It was noted in the CAW Monterey facilities that one transmission header or pipeline was fed by 10 pumping plants that operate in response to reservoir levels as well as system demands. To further complicate the analysis there are several points along the pipeline where water is drawn by customers. The result is that depending on the operating conditions and amount of water being drawn from the system along the pipeline there is the potential to have more than one system curve.

In general, the VFD and control algorithm appear to provide benefit when the operating conditions of the pump station result in the pump operation on both sides of the BEP. In those cases the pump speed was adjusted over the control range to seek the optimum efficiency for the current operating conditions.
D. Conclusions and Recommendations

When pumping plants are designed, pumps are selected for peak demand requirements that may include fire flows and system operating condition extremes including well levels, pressures, etc. As a result, if normal design practices are followed, it would be expected to find under typical operating conditions most pumps to be moderately oversized. Pumps that are oversized in general operate to the left of the BEP and as a result the faster they are operated (up to 60 Hz) the better the efficiency. A constant speed system (without VFD) would perform more efficiently under these circumstances.

For systems that operate on either side of the BEP during normal system operation the OEEP efficiency algorithm may provide an improvement but only if the gain in efficiency can compensate for the additional losses due to the VFD operation. Total energy savings can be difficult to estimate without long term operational data.

Many times pumps are selected on the conservative basis of high flows and high TDH. As a result, if the demand flows are less than anticipated the operating points land to the left of the BEP and the OEEP algorithm will not provide a benefit; however, if the TDH is less than anticipated the operating point may go to the right of the BEP and there the OEEP may be quite useful. This is the case in systems where well levels are higher than anticipated and where the distribution pressure in the grid is lower than anticipated.

In general, it would be expected that in many cases pumps would be oversized and since the OEEP algorithm would tend to find the optimum operating point at higher or full speed operation; we would expect there to be a limited number facilities that would benefit from the current OEEP strategy of controlling the speed of the pump to optimize efficiency. For facilities that have the characteristics where the OEEP would be beneficial this could result in significant energy savings.

It should be noted that variable speed control is an effective means to match pump speed and output to changing system demands and operating requirements however this may not translate to the highest instantaneous wire-to-water efficiency.

Design Development and Testing

During the review of the OEEP facilities several cases of instrument and control system calibration problems were noted that affected the calculation of efficiency and facility performance. It is recommended that any efficiency or control system improvements be thoroughly planned and designed and that control equipment and instrumentation be thoroughly tested as a part of the commissioning and start-up phase of the project.
II. OEEP Common Control Strategy Functions

This section of the document is written to be referenced by personnel that will be configuring Programmable Logic Controllers (PLC) and/or Human Machine Interface (HMI) software. It is intended to provide enough detail about the OEEP controls to ensure smooth control of each system and provide consistency between different sites implemented by different programming personnel. The content in this document is technical in nature. Information on instrument calibration and calculation of the wire-to-water efficiency can be used even if the full OEEP control algorithm is not implemented.

The following functions will be monitored or calculated in the PLC continuously while the PLC program is in operation. Calculated values and measured values used in calculations below shall be floating point values that are represented in engineering units; for example, a flow value will be represented by a floating point register that represent gallons per minute (GPM). Logic diagrams for most of the described functions are included in Appendix A. Sample PLC programs were developed for the strategies described but due to the length of the document the files will be provided on CD.

A. TOTAL DYNAMIC HEAD CALCULATIONS - TYPICAL BOOSTER PUMP

The total dynamic head shall be calculated by subtracting the discharge pressure from the suction pressure per the following equation.

\[ H_{TDH} = H_{DB} - H_{SB} \]

Where:
- \( H_{TDH} \) = Total Dynamic Head (ft)
- \( H_{DB} \) = Discharge Head (ft) Booster Pump
- \( H_{SB} \) = Suction Head (ft) Booster Pump

Calibration is critical to properly measuring and calculating the Total Dynamic Head TDH and both the discharge head and suction head must be calibrated to provide a reading from a common elevation. Typically a common elevation is pump datum for a booster pump; however, in some cases if both the suction and discharge pressure instruments are mounted at the same elevation then their values can be read directly. If the conduit diameters at the suction and discharge points of measure differ, the TDH calculation must be adjusted by the velocity head difference:

\[ H_{TDH} = H_{DB} - H_{SB} + \frac{(V_{DB})^2}{2g} - \frac{(V_{SB})^2}{2g} \]

Where:
- \( V_{DB} \) = flow velocity at point of measure in discharge conduit (ft/sec)
- \( V_{SB} \) = flow velocity at point of measure in suction conduit (ft/sec)
- \( g \) = gravitational acceleration (32.2 ft/sec²)
**Note:** The following calculations provide an approximate TDH calculation, since both the headloss in the suction pipe from the tank to the pump and the discharge pipe velocity head are ignored. Although these two errors can cancel each other out, they cannot be ignored for long suction pipes and high discharge velocities. A hydraulic engineer will need to examine each case to determine if the calculation is a good approximation for the TDH. If it is not a good approximation the value can be used to determine relative changes in efficiency; however, the accuracy may be affected. Alternately, the suction and discharge headlosses can be calculated or approximated and included in the TDH calculation for improved accuracy.

1. **Booster Pump TDH Calculation Example**

The following shows an example of how to calculate the TDH for a typical booster pump where the suction pressure is estimated from a level in a reservoir or tank.

![TDH Calculation for Typical Booster Pump](image)

When calculating the TDH for the system above the suction pressure and the discharge pressure must be calibrated such that they are measured from a common elevation; typically the pump datum or the center line of the pump is used as a common reference point. To determine the suction head relative to the system datum for the example system above see the following calibration calculation.

\[
H_{SB} = L_T - L_{PSDO}
\]

\[
H_{SB} = 25' - 3' = 22'
\]

Where:
- \(H_{SB}\) = Suction Head (ft) for Booster Pump
- \(L_T\) = Tank Level (ft) from bottom of tank - Varies with tank level
- \(L_{PSDO}\) = Level (ft) Suction Pump Datum Offset - Fixed Value at 3 feet

Note that the pump datum is 3 feet above the bottom elevation of the tank; therefore, the suction pressure relative to the pump datum is lower than the tank level by a constant 3 feet.
To determine the discharge head for the system relative to the pump datum; the discharge pressure must first be converted from PSI to feet then adjusted relative to the pump datum. The following equation can be used to determine the discharge head.

\[ H_{DB} = 2.309 \times P_D + L_{PDDO} \]

\[ H_{DB} = 2.309 \times 80 \text{ PSI} + 5' = 189.7' \]

Where:
- \( H_{DB} \) = Discharge Head (ft) Booster Pump
- \( P_D \) = Discharge Pressure (PSI) - Varies with system dynamics
- 2.309 = Conversion Factor to convert PSI to feet of water
- \( L_{PDDO} \) = Level (ft) Pump Discharge Datum Offset - Fixed Value at 5 feet

Note that the pressure transmitter is mounted 5 feet above the pump datum; therefore, the pump pressure relative to the datum is a constant 5 feet higher.

From the discharge and suction pressures relative to a common elevation, the pump datum in this case, the total dynamic head is typically derived for this example as follows.

\[ H_{TDH} = H_{DB} - H_{SB} \]

\[ H_{TDH} = 189.7' - 22' = 167.7' \]

Where:
- \( H_{TDH} \) = Total Dynamic Head (ft)
- \( H_{DB} \) = Discharge Head (ft) see equations above for this example
- \( H_{SB} \) = Suction Head (ft) see equation above for this example

B. TOTAL DYNAMIC HEAD CALCULATIONS - TYPICAL WELL PUMP

The total dynamic head shall be calculated by subtracting the discharge pressure (head) from the suction pressure (head) per the following equation.

\[ H_{TDH} = H_{DW} - H_{SW} \]

Where:
- \( H_{TDH} \) = Total Dynamic Head (ft)
- \( H_{DW} \) = Discharge Head (ft) Well Pump
- \( H_{SW} \) = Suction Head (ft) Well Pump

Calibration is critical to properly measuring and calculating the Total Dynamic Head TDH and both the discharge head and suction head must be calibrated to provide a reading from a common elevation. Typically a common elevation is the center line of the pipe above grade for well pumps.

Note: The following calculations ignore the dynamic losses in the vertical section of suction pipe in the well. It is not practical to measure these losses; therefore, in some cases the TDH calculations will have a significantly larger magnitude. The calculations also ignore the velocity head in the
discharge piping. A hydraulic engineer will need to examine each well case to determine if the calculation is a good approximation for the TDH. If it is not a good approximation the value can be used to determine relative changes in efficiency; however, the accuracy may be affected. Alternately, the suction and discharge headlosses can be calculated or approximated and included in the TDH calculation for improved accuracy.

1. **Well Pump TDH Calculation Example**

The following shows an example of how to calculate the TDH for a typical well pump where the suction pressure is estimated from a level in a well.

When calculating the TDH for the system above the suction pressure and the discharge pressure must be calibrated so that they measured from a common elevation; in this case the center line of the pipe will be used as the common elevation point. The following calibration equation can be used to determine the suction head relative to the center line of the pipe the system above see.

\[ H_{SW} = -L_{ID} + L_{WD} \]

\[ H_{SW} = -200' + 125' = -75' \]
Where:

- $H_{SW}$ = Suction Head (ft) Well Pump
- $L_{IN}$ = Instrument Depth (ft) relative to pipe center line
- $L_{WD}$ = Well Depth (ft) water level relative to level instrument

Note that it is important to know how deep the level instrument is mounted relative to the common measurement point. Also note that the suction head is a negative value; this is expected because the level of the water is negative relative to the center line of the pipe.

The discharge pressure transmitter is mounted at the center line of the pipe; therefore, to determine the discharge head the discharge pressure can be read directly and then converted to feet. The following equation can be used to determine the discharge head.

$$H_{DW} = 2.309 \times P_D$$

$$H_{DW} = 2.309 \times 80^{PSI} = 184.7'$$

Where

- $H_{DW}$ = Discharge Head (ft) Well Pump
- $P_D$ = Discharge Pressure (PSI) - Varies with system dynamics
- 2.309 = Conversion Factor to convert PSI to feet of water

Note: if the discharge pressure transmitter is mounted above or below the center line of the pipe the equation will need to correct for the offset. When using pressure gauges for manual read, the pressure is established at the elevation of the reading, not at the point of connection to the conduit.

From the discharge and suction pressures relative to a common elevation, the discharge pressure transmitter in this case, the total dynamic head can be derived for this example as follows.

$$H_{TDH} = H_{DW} - H_{SW}$$

$$H_{TDH} = 184.7' - (-75') = 259.7$$

Where:

- $H_{TDH}$ = Total Dynamic Head (ft)
- $H_{DW}$ = Discharge Head (ft) see equations above for this example
- $H_{SW}$ = Suction Head (ft) see equation above for this example

C. FLOW TOTALIZER (INTEGRATOR)

The program shall monitor the flow as a floating point value and integrate it over time. The integrated or totalized value will operate like an odometer and as flow is detected the value will continue to increase. The totalizer value shall be stored in thousand-gallons as a floating point value.

The programmer shall setup a timer that triggers the following equation to add a value to the totalizer every (3) three seconds when the pump is on. When the pump is off the flow totalizer will not increment even if some minor flow is detected.
Where:

- $T_{flow} = \text{Totalized Flow Value (thousand-gallons) floating point value}$
- $F_{GPM} = \text{Discharge Flow (gpm) floating point value}$
- $1000 = \text{converts gallons to thousand-gallons}$
- $0.05 = \text{represents 3 seconds converted to minutes. Flow rate multiplied by time equals volume.}$

The programmer may choose to make the timer adjustable; however, if the timer is adjustable the constant 0.05 must be calculated based on the timer value and converted to minutes for the equation to totalize flow correctly.

### D. HYDRAULIC POWER OUTPUT CALCULATION

The output power of a pump shall be calculated from the TDH and flow leaving the pump. The following is an equation for the hydraulic power achieved by the pump.

$$P_{kW} = \frac{F_{GPM} \times H_{TDH}}{3958} \times 0.746$$

Where:

- $P_{kW} = \text{Hydraulic Output Power (kilowatts)}$
- $F_{GPM} = \text{Discharge Flow (gpm)}$
- $H_{TDH} = \text{Total Dynamic Head (ft)}$
- $3958 = \text{Conversion Factor for calculating horsepower}$
- $0.746 = \text{Conversion Factor for horsepower to kilowatts}$

**Note:** Flow and TDH values shall be floating point values represented in engineering units.

#### 1. Output Power Totalizer (Integrator)

The program shall monitor the hydraulic output power calculation as a floating point integer. The programmer shall use the same (9) nine second timer described above to trigger the following equation to add a value to an output energy totalizer when the pump is on. When the pump is off the input energy totalizer will not increment even if some power is detected.

$$T_{out} = T_{out} + (P_{kW} \times 0.0025)$$

Where:

- $T_{out} = \text{Totalized Output Energy Value (kWh) floating point value}$
- $P_{kW} = \text{Hydraulic Power (kW) floating point value}$
- $0.0025 = \text{represents 9 seconds converted to hours. Power multiplied by time equals energy.}$

The programmer may choose to make the timer adjustable; however, if the timer is adjustable the constant 0.0025 must be calculated base on the timer value and converted to hours for the equation to totalized power correctly.
E. ELECTRICAL POWER INPUT & MEASUREMENT PARAMETERS

The power measurement parameters shall be read by the PLC from a power meter mounted on the line side of the VFD. The PLC shall be capable of reading power parameters while running with the VFD or other electrical bypass equipment such as a contactor or reduced voltage soft starter. All parameters transmitted to the PLC from the power monitor shall be read directly as floating point registers or shall be accurately converted to floating point registers with a minimum of 4 significant digits. All power parameters used in PLC calculations shall be values represented in engineering units.

The totalized power may be read directly from the power monitor into the PLC or the following function described below maybe used for calculating the totalized power.

1. **Input Power Totalizer (Integrator)**

The PLC shall monitor the real power from the power monitor as a floating point value with engineering units of kilowatts kW. The programmer shall setup a timer to that triggers the following equation to add a value to an input energy totalizer every (9) nine seconds when the pump is on. When the pump is off, the input energy totalizer will not increment even if some power is detected.

\[ T_{in} = T_{in} + (P_{kW} \times 0.0025) \]

Where:
- \( T_{in} = \) Totalized Input Energy Value (kWh) floating point value
- \( P_{kW} = \) Power (kW) floating point value
- \( 0.0025 = \) represents 9 seconds converted to hours. Power multiplied by time equals energy.

The programmer may choose to make the timer adjustable; however, if the timer is adjustable the constant 0.0025 must be calculated base on the timer value and converted to hours for the equation to totalized power correctly.

F. CONTROL EFFICIENCY CALCULATION

The control efficiency calculation will take a snap shot of the input and output energy totalizers and store them for calculating total energy over an adjustable time period. The timer shall be adjustable within the PLC code only and it is anticipated timer values will be set to approximately 2 to 3 minutes initially. Efficiency shall be calculated per the following equation

\[ E_{ctrl} = \frac{T_{out} - T'_{outCE}}{T_{in} - T'_{inCE}} \]

Where,
- \( T_{out} = \) Totalized Output Energy Value (kWh)
- \( T'_{outCE} = \) Control Efficiency Stored Snap Shot of Totalized Output Energy Value (kWh)
- \( T_{in} = \) Totalized Input Energy Value (kWh)
- \( T'_{inCE} = \) Control Efficiency Stored Snap Shot of Totalized Input Energy Value (kWh)
- \( E_{ctrl} = \) Control Efficiency Calculation
The intent behind calculating control efficiency is to ensure that efficiency has representative data over a long enough period to make good control decisions.

**G. Monitoring Efficiency Calculation**

The monitoring efficiency calculation will work exactly like the control efficiency calculation except the timer will be set to exactly 1 minute and the efficiency will be set to zero when the pump is not running. Efficiency shall be calculated per the following equation:

\[
E_{mon} = \frac{T_{out} - T'_{out ME}}{T_{in} - T'_{in ME}}
\]

Where:

- \( T_{out} \) = Totalized Output Energy Value (kWh)
- \( T'_{out ME} \) = Monitor Efficiency Stored Snap Shot of Totalized Output Energy Value (kWh)
- \( T_{in} \) = Totalized Output Input Value (kWh)
- \( T'_{in ME} \) = Monitor Efficiency Stored Snap Shot of Totalized Input Energy Value (kWh)
- \( E_{mon} \) = Monitor Efficiency Calculation

Note the monitoring efficiency calculation will be used for reporting purposes. The intent is to provide efficiency values based on totals over a one minute intervals.
III.   Single Pump Controls with System Storage

This section describes the control strategy for a single well or booster pump that pumps to system storage which may include a pressurized storage tank or elevated storage tank.

The controls associated with starting and stopping a pump is based on the utility’s operational requirements. It is outside the scope of this project to define the logic that determines when to start and stop the pump; therefore, it is not defined in this the control strategy description below. This activity is left up to the utility to determine. In many cases the OEEP controls were implemented in a separate PLC and the start signal was interfaced to the OEEP PLC; however, a single PLC could be used to implement the program.

The strategy description below defines what mode to use when the pump is started. The mode will be either OEEP or Bypass when called to start. If the pump is started in OEEP mode the strategy below will determine how to control the speed of the pump to achieve optimal efficiency.

The following control strategy descriptions will utilize some or all of the common control strategy functions in Section II described above.

A.   AUTOMATIC MODE CYCLING

The PLC code shall be configured to automatically cycle between OEEP control mode and Bypass control mode. The code will run the pump in OEEP control mode for 7 days; then, on the 8th day, the code will run the pump in bypass mode. On the 9th day, the program will re-enable the OEEP control mode and repeat the cycle.

Note this functionality was incorporated in the OEEP pilot program to allow comparison between the OEEP mode controls and the bypass mode. This functionality may be disabled if this comparison is not needed.

B.   OEEP AUTOMATIC SEQUENCE CONTROLS

The OEEP Automatic Sequence Controls shall utilize a state machine for seeking the most optimal efficiency. A state machine, for the purpose of this control strategy, includes code broken down into smaller functions that are executed one at a time. As an example, if the State Machine is set to 20 then only the code associated with the 20 will be executed; all other states, 10, 30, and 40 will not be executed. As the program progresses through the code the State Machine value will change which will disable one part of the code and execute a different part of the code.

If at any time, the system is not in OEEP Automatic Sequence Control or none of the pumps are running, the State Machine shall be set to zero (0) which will disable code defined in this sub-section.

The following is an abbreviated illustration of the state machine.
1. **Control Mode Initialization (State Machine Initial State = 10)**

The State Machine will be set to 10 when triggered by the following conditions.

1. The pump mode is set to OEEP, and
2. The pump was not running but it was called to start.

In this state (State Machine = 10), the initial Base Speed will be operator adjustable.

After the Base Speed is set the PLC will perform the following functions.

1. The Test Delay Timer will be set to Zero.
2. The Commanded Speed will be set to the Base Speed.

3. Reset the tracking of which speed test was performed last.

4. Verify that the Commanded Speed is within 0.5% of the Base Speed; then evaluate the control efficiency per the Control Efficiency Calculation function described above in Section II.

5. After the Control Efficiency Calculation is complete, the result shall be written to the Base Efficiency.

6. The State Machine will be set to 20.

2. **Base Control (State Machine = 20)**

When the State Machine is set to 20 the program will perform the following actions in the following order.

1. Set the Commanded Speed to the Base Speed.

2. Verify that the Commanded Speed is within 0.5% of the Base Speed; then start the Test Delay Timer.

3. When the Test Delay Timer times out and if the high speed test was performed last the State Machine shall be set to 40. Otherwise the State Machine shall be set to 30.

3. **Test Low Speed (State Machine = 30)**

When the State Machine is set to 30 the program will perform the following actions in the following order.

1. If the Base Speed is at or below an adjustable Low Speed Limit (initially set to 87%) then set the state machine equal to 40.

2. Otherwise, set the Commanded Speed to the Base Speed minus an operator adjustable Speed Increment (initially set to 1%) speed.
   a. If the discharge pressure drops below the operator adjustable Minimum Low Pressure set point then set the state machine value to 40.
   b. If the discharge flow drops below the operator adjustable Minimum Low Flow set point then set the state machine value to 40.

3. Verify that the Commanded Speed is within 0.5% of the Base Speed minus Speed Increment; then evaluate the control efficiency per the Control Efficiency Calculation Function described above.

4. After the Control Efficiency Calculation is complete write the result to Test Low Efficiency. Then compare the Base Efficiency with the Test Low Efficiency.

5. If the Test Low Efficiency is greater than the Base Efficiency by less than 1% efficiency (adjustable in PLC code); then perform the following actions.
   a. Set the Test Delay Timer to 10 minutes (adjustable).
b. Set the Base Speed = Base Speed - Speed Increment.

c. Set the Base Efficiency = Test Low Efficiency.

d. Set the State Machine Value = 20.

e. Reset the tracking for high speed test performed last.

6. If the Test Low Efficiency is greater than the Base Efficiency by more than 1% efficiency (adjustable in PLC code); then perform the following actions.

   a. Set the Test Delay Timer to zero minutes.

   b. Set the Base Speed = Base Speed - Speed Increment.

   c. Set the Base Efficiency = Test Low Efficiency.

   d. Set the State Machine Value = 20.

   e. Reset the tracking for high speed test performed last.

7. If the Test Low Efficiency is less than the Base Efficiency then set the State Machine Value to 40.

4. Test High Speed (State Machine = 40)

When the State Machine is set to 40 the program will perform the following actions in the following order.

1. If the Base Speed is 100% then set the state machine equal to 20.

2. Otherwise, set the Commanded Speed to the Base Speed plus 1% speed.

3. Verify that the Commanded Speed is within 0.5% of the Base Speed plus 1%; then evaluate the control efficiency per the Control Efficiency Calculation Function describe above.

4. After the Control Efficiency Calculation is complete write the result to the Test High Efficiency. Then compare the Base Efficiency with the Test High Efficiency.

5. If the Test High Efficiency is greater than the Base Efficiency by less than 1% efficiency (adjustable in PLC code); then perform the following actions.

   a. Set the Test Delay Timer to 10 minutes (adjustable).

   b. Set the Base Speed = Base Speed + Speed Increment.

   c. Set the Base Efficiency = Test High Efficiency.

   d. Set the State Machine Value = 20.

   e. Set the tracking for high speed test performed last.

6. If the Test High Efficiency is greater than the Base Efficiency by more than 1% (adjustable) efficiency (adjustable in PLC code); then perform the following actions.
a. Set the Test Delay Timer to zero minutes.

b. Set the Base Speed = Base Speed + Speed Increment.

c. Set the Base Efficiency = Test High Efficiency.

 d. Set the State Machine Value = 20.

 e. Set the tracking for high speed test performed last.

7. If the Test High Efficiency is less than the Base Efficiency then perform the following actions.

   a. Set the State Machine Value to 20.

   b. Reset the tracking for high speed test performed last.
IV. Multiple Pump Controls with System Storage

This section describes the control strategy for multiple pumps as a part of a pump station that pumps to system storage which may include a pressurized storage tank or elevated storage tank.

The controls associated with starting and stopping a pump is based on the utility’s operational requirements. It is outside the scope of this project to define the logic that determines when to start and stop the pump; therefore, it is not defined in the control strategy description below. This activity is left up to the utility to determine. In many cases the OEEP controls were implemented in a separate PLC and the start signal was interfaced to the OEEP PLC; however, a single PLC could be used to implement the program.

The strategy description below defines what mode to use when a pump is started. The mode will be either OEEP or Bypass when called to start. If a pump is started in OEEP mode the strategy below will determine how to control the speed of the pump to achieve optimal efficiency.

The following control strategy descriptions will utilize some or all of the common control strategy functions in Section 2 described above.

A. AUTOMATIC MODE CYCLING

The PLC code shall be configured to automatically cycle between OEEP control mode and Bypass control mode. This mode will be effective for the all pumps associated with the pump station; therefore, if one pump is in OEEP mode they all are. The code will run the pump station in OEEP control mode for 7 days; then, on the 8th day, the code will run the pump station in bypass mode. On the 9th day, the program will re-enable the OEEP control mode and repeat the cycle.

Note this functionality was incorporated in the OEEP pilot program to allow comparison between the OEEP mode controls and the bypass mode. This functionality may be disabled if this comparison is not needed.

B. MODE CONTROLS

The OEEP mode controls shall utilize a state machine for seeking the most optimal efficiency. A state machine for the purpose of this control strategy includes code broken down into smaller functions that are executed one at a time. As an example, if the State Machine is set to 20 then only the code associated with the 20 will be executed; all other states, 10, 30, and 40 will not be executed. As the program progresses through the code the State Machine value will change which will disable one part of the code and execute a different part of the code.

If at any time, the system is not in OEEP mode or none of the pumps are running, the State Machine shall be set to zero (0) which will disable code defined in this sub-section.

The following is an abbreviated illustration of the state machine.
1. **Control Mode Initialization (State Machine Initial State = 10)**

The State Machine will be set to 10 when triggered by the following conditions.

1. The pump station mode is set to OEEP, and
2. None of the pumps are running but one or more pumps are called to start.

In this state (State Machine = 10), the initial Base Speed will be operator adjustable. After the Base Speed is set the PLC will perform the following functions.

1. The Test Delay Timer will be set to Zero.

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**Figure 22** Abbreviated Illustration of the State Machine.
2. The Commanded Speed will be set to the Base Speed.

3. Reset the tracking of which speed test was performed last.

4. Verify that the Commanded Speed is within 0.5% of the Base Speed; then evaluate the control efficiency per the Control Efficiency Calculation function described above in Section II.

5. After the Control Efficiency Calculation is complete, the result shall be written to the Base Efficiency.

6. The State Machine will be set to 20.

2. **Base Control (State Machine = 20)**
When the State Machine is set to 20 the program will perform the following actions in the following order.

1. Set the Commanded Speed to the Base Speed.

2. Verify that the Commanded Speed is within 0.5% of the Base Speed; then start the Test Delay Timer.

3. When the Test Delay Timer times out and if the high speed test was performed last the State Machine shall be set to 40. Otherwise the State Machine shall be set to 30.

3. **Test Low Speed (State Machine = 30)**
When the State Machine is set to 30 the program will perform the following actions in the following order.

1. If the Base Speed is at or below an adjustable Low Speed Limit (initially set to 87%) then set the state machine equal to 40.

2. Otherwise, set the Commanded Speed to the Base Speed minus 1% speed.
   a. If the discharge pressure drops below the operator adjustable Minimum Low Pressure set point then set the state machine value to 40.
   b. If the discharge flow drops below the operator adjustable Minimum Low Flow set point then set the state machine value to 40.

3. Verify that the Commanded Speed is within 0.5% of the Base Speed minus the Speed Increment; then evaluate the control efficiency per the Control Efficiency Calculation Function described above.

4. After the Control efficiency Calculation is complete write the result to Test Low Efficiency. Then compare the Base Efficiency with the Test Low Efficiency.

5. If the Test Low Efficiency is greater than the Base Efficiency by less than 1% efficiency (adjustable in PLC code); then perform the following actions.
   a. Set the Test Delay Timer to 10 minutes (adjustable).
   b. Set the Base Speed = Base Speed - Speed Increment.
c. Set the Base Efficiency = Test Low Efficiency.

d. Set the State Machine Value = 20.

e. Reset the tracking for high speed test performed last.

6. If the Test Low Efficiency is greater than the Base Efficiency by more than 1% (adjustable) efficiency (adjustable in PLC code); then perform the following actions.

   a. Set the Test Delay Timer to zero minutes.

   b. Set the Base Speed = Base Speed - Speed Increment.

   c. Set the Base Efficiency = Test Low Efficiency.

   d. Set the State Machine Value = 20.

   e. Reset the tracking for high speed test performed last.

7. If the Test Low Efficiency is less than the Base Efficiency then set the State Machine Value to 40.

4. **Test High Speed (State Machine = 40)**

When the State Machine is set to 40 the program will perform the following actions in the following order.

1. If the Base Speed is 100% then set the state machine equal to 20.

2. Otherwise, set the Commanded Speed to the Base Speed plus 1% speed.

3. Verify that the Commanded Speed is within 0.5% of the Base Speed plus 1%; then evaluate the control efficiency per the Control Efficiency Calculation Function describe above.

4. After the Control Efficiency Calculation is complete write the result to the Test High Efficiency then compare the Base Efficiency with the Test High Efficiency.

5. If the Test High Efficiency is greater than the Base Efficiency by less than 1% efficiency (adjustable in PLC code); then perform the following actions.

   a. Set the Test Delay Timer to 10 minutes (adjustable).

   b. Set the Base Speed = Base Speed + Speed Increment.

   c. Set the Base Efficiency = Test High Efficiency.

   d. Set the State Machine Value = 20.

   e. Set the tracking for high speed test performed last.

6. If the Test High Efficiency is greater than the Base Efficiency by more than 1% (adjustable) efficiency (adjustable in PLC code); then perform the following actions.

   a. Set the Test Delay Timer to zero minutes.
b. Set the Base Speed = Base Speed + Speed Increment.

c. Set the Base Efficiency = Test High Efficiency.

d. Set the State Machine Value = 20.

e. Set the tracking for high speed test performed last.

7. If the Test High Efficiency is less than the Base Efficiency then perform the following actions.

   a. Set the State Machine Value to 20.

   b. Reset the tracking for high speed test performed last.

C. PUMP STATION SPEED

For pump stations with multiple pumps operating in OEEP mode, the speed of all the pumps will be determined based on the efficiency of the first pump called to start.
V. Pump Station Pressure Control

This section describes the control strategy for pumps and pump stations that pump into a system without system storage. These means that if the pump is not running the pressure in the system would drop below the operational minimums.

Technically this section does not describe OEEP controls; however, a few sites were encountered that did benefit from pressure controls. The original goal of the OEEP controls was to try to operate the equipment at its most efficient point which can vary depending on operating conditions. The OEEP controls would work while delivering water to system storage like an elevated water tank or hydro-pneumatic tank. Since the controls described in this section do not have storage they do not fit the criteria for OEEP controls.

Pressure control varies the speed of the pump or pumps to maintain a specific pressure and it does not attempt to seek the most efficient operating point. However, operating a pump at lower speeds will reduce overall energy consumption regardless if the equipment is operating at its most efficient point or not.

Some pumping systems without storage were encountered in this project and prior to implementing control changes they were installed with constant speed pumps and pressure regulating valves. To maintain a specific pressure on the distribution system the pump would run at full speed and a pressure regulating valve would provide water to the system at the desired pressure. The water between the pump and the pressure regulating valve has a relatively high energy which is wasted as it passes through pressure regulating valve to the system. Pressure controls described in this section will reduce or eliminate energy losses associated with pressure regulating valve provided the pressure regulating valve is bypassed while running in automatic pressure control mode. The pump will be controlling the pressure and valve is no longer needed.

The controls associated with starting and stopping a pump is based on the utility's operational requirements. It is outside the scope of this project to define the logic that determines when to start and stop the pump; therefore, it is not defined in this the control strategy description below. This activity is left up to the utility to determine.

A. Automatic Pressure Control

Pumps will be called to start and stop based on customer defined parameters. All pumps running will run at the same speed. The operator shall enter an operating pressure set point which will be an input to a Proportional-Integral-Derivative (PID) controller located in the PLC. The pressure transmitter will be wired to the PLC and it shall be the process variable input to the PID controller. The output of the PID controller will vary the speed of the pump between operator adjustable maximum and minimum speed set points. The PID constants will be adjusted or tuned when the control system is placed into service.
VI. References


3. Thomas P. Conlon, RLW Analytics, Inc. & Glen Weisbrod, Economic Development Research Group, 1998. SOUTHERN CALIFORNIA EDISON, HYDRAULIC SERVICES PROGRAM MARKET EFFECTS STUDY FINAL REPORT, Study ID # 3507, Los Angeles, CA
APPENDIX B – Sample PLC Program (Provided on CD due to length of printout)