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Operational energy-efficiency improvement of municipal water pumping in California

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ABSTRACT

This paper implements a normalization/regression-based approach to estimate the kWh energy and kW savings from an experimental OEEP (operational energy-efficiency program) for municipal water pumping in California. The voluminous 1-min data collected in the course of the OEEP presents a unique opportunity to analyze how VSD (variable-speed drive) technology aided by a PLC (programmable-logic-controller) may improve municipal water pumping's operational energy efficiency. Our proposed approach enables a comparison of pump operations with and without the OEEP, yielding accurate estimates for kWh energy and kW capacity savings that are useful in evaluation, monitoring, and verification of the program. Our findings lead us to conclude that (a) variability of efficacy by analyzed pump sites suggests targeted implementation of the OEEP; and (b) for a correctly-sized pump operating near its optimal kW-output value, adding a VSD and PLC can actually harm the pumping system's overall energy-efficiency.

1. Introduction

California's water pumping consumes approximately 1600 GWh, about 6% of the state's annual total consumption, suggesting its promising conservation potential [1,2]. Electricity savings can occur via water demand management [3,4]: reducing water consumption cuts water pumping and hence, its electricity use. Alternatively, electricity savings can occur via water supply management that encompasses leak detection and remedy, and replacing energy-inefficient equipment [5,6]. Another path is to improve the operational energy efficiency of water pumping, exemplified by the experimental OEEP (Operational Energy-Efficiency Program)[1] approved by the CPUC (California Public Utilities Commission) in 2010.[2]

The California OEEP has generated a large file of 1-min data on kW-output and kW-input collected during May 2010–August 2011. To fully utilize this voluminous and potentially noisy data file, however, requires an approach that can produce summary results useful in energy policy decision making. Our key findings are as follows. First, our normalization/regression-based approach enables a comparison of pump operations with and without the OEEP, yielding accurate estimates for kWh energy and kW capacity savings. Second, these estimates suggest targeted implementation of the OEEP, consistent with prior recommendations for the state's demand-side-management programs [7]. Finally, for a correctly-sized pump operating near its optimal kW-output level, adding a VSD (variable-speed drive) and PLC (programmable-logic-controller) can actually harm the pumping system's overall efficiency. This supports the recommendation for better pre-screening, technical assistance and post installation verification made by prior studies that have found measured savings lower than those predicted at several water pumping sites in California [8,9].

This paper makes three contributions. First, it analyzes an OEEP for municipal water pumping in California, the first VSD-PLC field experiment of its kind. Its results are immediately useful to energy and water utilities that wish to implement similar programs in their service areas. Second, it enriches the literature on electricity savings related to motor and pump and VSD technologies [e.g., Refs. [10–16]]. Third, it adds to studies published by this journal on the energy performance of VSD and control systems [17,18], and the energy-efficiency of motor systems in Europe [19], India [20] and the world [21]. Since the VSD-PLC technology considered herein

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[1] Note that a list of all acronyms and symbols used in this paper appears in Table 1.

[2] A description of this program is available at: http://www.cpuc.ca.gov/PUC/Water/oeep/

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has many industrial and commercial applications beyond municipal water pumping, we opine that operational energy-efficiency improvement deserves the attention of policymakers and exploration by energy researchers worldwide. Finally, it proposes a method for normalizing the operational requirements of VSD-PLC controlled pumps with fixed-speed drive pumps. Taken together, these contributions make the paper an original study in terms of data collection, real-world relevance, and methodology development.

This paper proceeds as follows. Section 2 describes the California OEEP. Section 3 presents our method for comparing pump operations and energy usage with and without the OEEP. Section 4 compares the OEEP's kWh and kW saving estimates obtained via a simple method and our method for four pumping stations. Finally, Section 5 concludes.

2. California OEEP

2.1. General description

The California OEEP aims to reduce the power consumption of a motor-pump system by replacing a pump run by a fixed-speed drive with a VSD. In addition, the OEEP installs a PLC, efficiency optimization software, and monitoring equipment at the facility to improve operational energy-efficiency.

A fixed-speed drive pump is only capable of running at full capacity; turning on and off to meet system demands. In contrast, the VSD controlled by the PLC continuously adjusts the motor speed to optimize the pump's output within the system constraints of pressure, level, and flow. Because of this difference in operation, a pump outfitted with a VSD and PLC is expected to run at a higher energy-efficiency than a fixed-speed drive pump, in spite of the fact that the addition of the VSD can reduce the system's energy efficiency by approximately 3% [22].

The monitoring equipment records real kW-input of the VSD-motor-pump combination at 1-s intervals, which are averaged to obtain 1-min data. It also records the pump's water flow in gallons per minute and pressure differential, or head, in feet. Flow and head can be converted into kW-output using

$$\mathrm{kW-output} = 1/5310 \times \mathrm{Flow} \times \mathrm{Head}. \quad (1)$$

We use the 1-min kW-input and kW-output data to compute the output/input ratio, to which we refer as WWE (wire-to-water efficiency).

To test if the OEEP improves a motor-pump system's WWE, the system was intended to be run in bypass mode once every eight days, thus ensuring that bypass mode did not repeatedly occur on the same day of the week. In bypass mode, electricity is provided to the motor through a separate parallel electrical circuit, using an across-the-line motor-starter. The VSD is not powered-up and the PLC and its control algorithm are inactive, causing the pump and motor to operate as if the pump has a fixed-speed drive. However, inconsistent implementation did not yield this systematic distribution of bypass days, necessitating our normalization approach detailed in Section 3.

2.2. Pump sites

Sponsored by the state's two largest electric utilities (Pacific Gas and Electric and Southern California Edison) and two water utilities (Alco Water Services and San Jose Water Company), the OEEP was implemented at five pump sites differentiated by pump type and HP (horse power). Owned by San Jose Water Company, the first two sites are:

- Grant Street Station, a vertical turbine type well pump operating at a groundwater production facility. The motor is a 200-HP premium efficiency model operating at 1750 RPM (revolutions per minute) and 480 VAC (volts alternating current), 3-phase. Design conditions are 2000 gpm (gallons per minute) at 300 feet head.
- Bascom Station, a horizontal centrifugal booster pump. The motor is a 75-HP premium efficiency model operating at 1750 RPM and 480 VAC, 3-phase; design conditions are 2000 gpm at 128 feet head.

Owned by Alco Water Company, the next three sites are:

- Alisal Well and County Well with vertical shaft turbine pumps, each driven by a 300-HP hollow shaft motor. The pumps are operated on pressure set points; the pump starts when pressure drops to a certain value. Shut down of the pump occurs when a set point of pressure is reached or a low frequency (Hz) condition exists.
- Hemingway booster pump that pumps from three underground storage tanks (12 feet deep), through a hydro-pneumatic tank, and into the distribution system. It operates on time of day, pressure, and tank level set points.

Our analysis below excludes the Hemingway pump because of the significant voltage imbalance on the main feeders during the OEEP test period. A voltage imbalance can damage the motor and, in this case, caused the VSD to operate at a degraded efficiency and power factor. As a result, the Hemingway pump's kW-input and kW-output data are not meaningful and are excluded from our WWE assessment.

3. Approach

A simple assessment of the program's WWE performance can be performed by computing an average WWE in bypass mode and

Table 1
List of acronyms and symbols used in this paper.

Acronym or symbol	Definition
OEEP	Operational energy-efficiency program
CPUC	California Public Utilities Commission
VSD	Variable-speed drive
PLC	Programmable-logic-controller
WWE	Wire-to-water efficiency
Y_t	WWE at time t
X_t	kW-output at time t
M_t	Binary indicator for VSD-PLC active
β_0	Intercept coefficient (includes binary indicators for month and hour)
β_1	Coefficient for kW-output
β_2	Coefficient for square of kW-output
θ_0	Coefficient for binary indicator for VSD-PLC active
θ_1	Coefficient for kW-output times binary indicator for VSD-PLC active
θ_2	Coefficient for square of kW-output times binary indicator for VSD-PLC active
ε_t	Random error term
D	Number of days of available data for a given pump
$\mathrm{kWh}_{\mathrm{out,avg}}$	Daily average kWh-output for a given pump
$\mathrm{kW}_{\mathrm{out},i}$	kW-output in minute i for a given pump
$\mathrm{kW}_{\mathrm{out},i,n}$	kW-output in minute i for a given pump in operational mode n
$\mathrm{kW}_{\mathrm{out,avg},n}$	Average kW-output level for a given pump in operational mode n
$\mathrm{kW}_{\mathrm{out,norm},n}$	Normalized kW-output level for a given pump in operational mode n
H_n	Normalized number of hours during which a given pump runs in operational mode n