Investigation of an Energy Efficient Pump Speed Control Algorithm For Controlling Sump Level

Josh Dubey and Keith Goossen
Department of Electrical and Computer Engineering
University of Delaware
Newark, DE, USA
{dubej@udel.edu, goossen@udel.edu}

***Abstract*— This paper explores a new nonlinear control algorithm for variable speed centrifugal pumps at water/wastewater pump stations that leads to specific energy savings over the conventional linear one. The algorithm is useful for facilities where pump speed is a linear function of liquid level in order to transport fluid and smooth inflow peaks. A non-linearity in the form of a quadratic term is added to the conventional linear one in order to produce efficiency gains, with a single parameter, curvature, varied to optimize energy savings. Results obtained by implementing the new algorithm on a pilot-scale pump station show significant energy savings for fixed pump flow, with a parabolic correlation of specific energy savings versus curvature of the nonlinear quadratic determined. In addition, the cost of implementing this algorithm is minimal to none, so the work presented has major industrial potential.**

Keywords*— *Variable Speed Drive, Centrifugal Pump, Nonlinear Level Control, Specific Energy, Energy Efficiency

I. INTRODUCTION

Growing awareness of issues such as sustainable energy use and energy efficiency have prompted interest in energy saving research in various industrial applications, including pumping systems. Particularly, *Goldstein and Smith* [1] reported that nearly 4% of United States electricity is consumed by wastewater treatment plants and almost 80% of the electricity in the wastewater treatment process is used by pumps. Based on the large proportion of energy used for pumping, and the vast number of wastewater plants across the country, just a small reduction in energy use can lead to large savings. Here, we report a new control algorithm for sump pumping systems, for example in wastewater treatment plants that results in up to 4 % savings compared to the currently used control algorithms.

In general, savings in pump energy can be achieved in two main ways. One is by designing more efficient pumps. Another, discussed and presented here, is improving pump performance with effective control strategies. The latter often times involves employing speed control of centrifugal pumps with frequency regulated by Variable Speed Drives (VFD). By regulating pump speed according to process parameters such as tank level, pump power can be reduced significantly compared to constant-speed control. However, the precise speed control algorithm can result in additional savings. Roughly, there are two algorithmic approaches. One is to attempt to maintain speed at the best-efficiency point of the pump. *Bakman, Geverkov and Vodovozov* [2] discussed a method for single and multi-pump predictive control to maintain operation in the best-efficiency region. *Tang and Zhang* [3] considered a model predictive control approach to improve operational efficiency incorporating variables such as TOU tariff and water demand. Zhang, Zhen and *Kusiak* [4] developed a scheduling model to generate energy optimal operational schedules for wastewater pump systems. As discussed in [2-4], most of the pump control research has focused on predictive control strategies, with emphasis on scheduling variable speed centrifugal pump runs based on modelling of future inlet flow rates. While these methods have potential to bring about efficiency gains and better operation, they are often costly and require large investments in existing pump control systems. Therefore, a simpler more cost-effective control strategy that results in energy savings is highly desirable.

Wastewater treatment plants as well as other applications usually have an input sump for collecting inlet flows. Since the inlet flows are highly variable, it is essential to have an effective control strategy that will adjust outflow. For sump stations that employ centrifugal outflow pumps on variable speed drives, two types of control strategies exist. Constant sump level control, a form of closed loop Proportional-Integral (PI) control where pump frequency is adjusted to maintain the tank level at a desired set point, is one method. Variable level control, a soft control strategy where pump frequency is a linear proportional function of sump level, is the second method, and has the advantage of smoothing large inflow peaks compared to constant level control. In the latter strategy, pump speed increases as inlet flow increases and level rises, with no actual level set point and error variable, until a new equilibrium level is achieved. All reported algorithms for speed-level control show pump speed increasing linearly with level. In this paper, a nonlinear, quadratic term is added to the speed versus level function and is explored experimentally to show lower energy use compared to the linear-only function. Particularly, using a quadratic negative-curvature function, a 4 % reduction in energy is found for a particular curvature. While the exact curvature for a particular sump pumping system that minimizes energy may depend upon the particular pumping system, we demonstrate here that adding the quadratic into the algorithm can result in significant energy savings, and potentially reduce overall United States electricity consumption on the order of a tenth of a percent.

II. THEORY

A. Background on Pumping

Over the last 10-15 years, there has been a large increase in the number of municipalities adapting variable frequency drives (VFDs) to their pump stations. Advantages of variable speed operation include the potential of decreased energy use, more flexibility and the ability to soft start pump motors to extend lifetime. While not all pump stations are necessarily fit for variable speed operation, particularly those who are solely lift stations with high static head, many accrue considerable benefit from installing adopting these drives. Energy savings for centrifugal pumps on variable drives are a direct result of the pump affinity laws. Equations (1) and (2) shows the relationships between pump speed N_1 and N_2, discharge flow Q_1 and Q_2, and pump power consumption P_1 and P_2.

$$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right) \quad (1)$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad (2)$$

Based on the affinity laws, just a small reduction in pump speed can result in a much larger reduction in pump power consumption. However, for municipalities determining whether to incorporate variable speed operation, simply looking at power consumption does not show the complete picture regarding energy savings and potential payback. The most useful variable, and one that will be referred to in this paper, is specific energy SE written as:

$$SE = \frac{E}{V} \quad (3)$$

where E is the unit energy and V is the unit volume. Specific energy takes into account the amount of discharge flow for a unit of energy consumed, and therefore serves as the preferred statistic for comparing energy savings for different control algorithms on a given pumping system. Figure 1 from Xylem Corporation [5] shows an example of three different system curves operated by a single pump. Since the static and dynamic head components are different for each system, the specific energy curves shown in Figure 2 are dramatically different.

In retrospect, S3 brings the most benefit to incorporating variable speed operation, since the system curve roughly follows the path of the isoefficiency lines. This particular aspect of the system is important in developing pump control algorithms that bring about efficiency gains. Often times, there is an optimum speed that minimizes specific energy, and operating as close as physically possible to the point should be the focus of a particular algorithm.

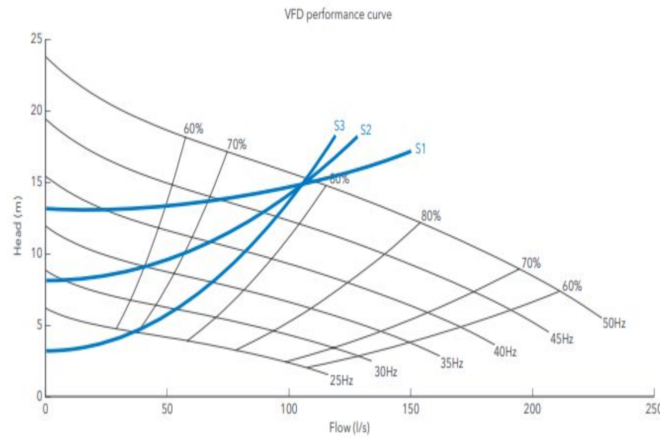

Fig. 1. An arbitrary pump system with three system curves, S1, S2 and S3. Isoeffieincy lines are plotted as well. Adapted from 'Variable speed wastewater pumping", 2013, *White Paper*, 7.

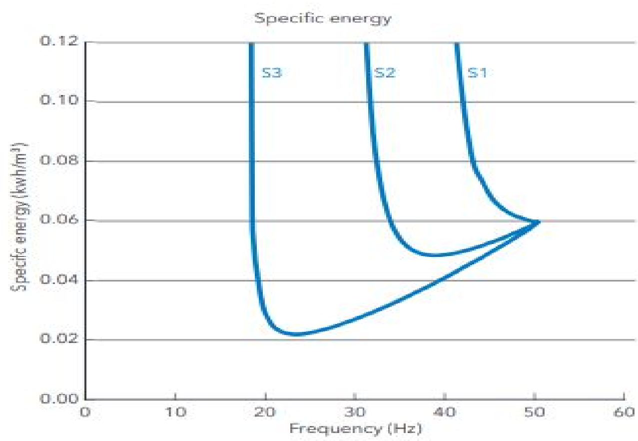

Fig. 2. Specific energy as a function of frequency for the system curves from Figure 1. Adapted from 'Variable speed wastewater pumping", 2013, *White Paper*, 7.

B. Variable Level Control

For pump stations employing the technique known as variable level control, pump speed is a function of sump level where the speed increases proportionally with level. The pump speed will fluctuate with tank level until a temporary equilibrium point is reached where the inlet flow matches the outlet flow from the sump. Thus far, only algorithms where speed varies linearly with level have been in use, however exploring adding a nonlinearity can potentially result in specific energy reductions for pump systems. Especially for systems like S3 in Figure 2, it is possible that developing an algorithm that results in a higher average sump level, and lower average pump speed for a given operational period can bring about efficiency gains.

Compared to an algorithm where pump speed is a linear functional relationship of sump level, a curved, concave up relationship one may result in a reduction in specific energy due to operation at a higher average sump level and lower average pump speed. Figure 3 shows how a potential concave up control function compares to a linear one where pump speed is a function of level.

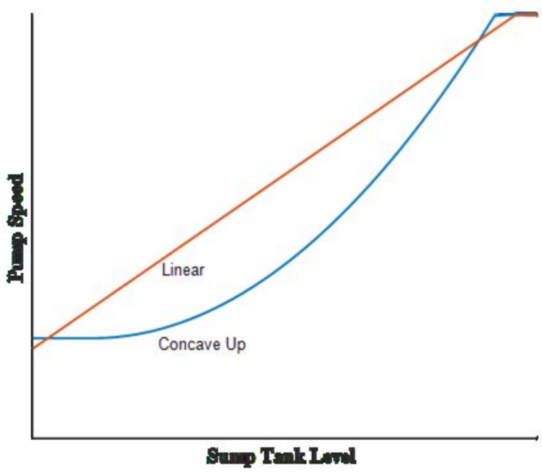

Fig. 3. Pump speed as a function of sump level for linear and concave up control relationships.

Experimentally, the curvature of the quadratic term can be altered to find an optimum one. If the curvature reaches a certain value, it is possible the pump speed will actually increase to an excessively high value for a prolonged period due to the lower initial reaction to increasing sump level from an inlet flow spike. The exact optimum curvature can be determined for a particular pump system by experimentation. It should also be noted that if such a control method were to result in savings, the exact algorithm could be programmed directly into an existing variable level control program with minimal implementation cost due to its simplicity.

III. Experimental Setup

Testing of the proposed control algorithm was done experimentally on a pilot scale pump station. Data was collected and analyzed to determine if there were specific energy reductions. The exact methods used for developing the nonlinear control algorithms are highlighted in this section.

A. Description of Pilot Scale Design

A pilot scale pump station is designed for experimenting with different algorithms. A Xylem 0.75HP centrifugal pump is used to draw room temperature water from a 58 centimeter (20 inch) sump tank that resides 0.61 meters (2 feet) below the elevation of the pump. The pump frequency is controlled by a 1HP TECO-Westinghouse Variable Speed Drive (VFD), which receives both run/stop and frequency command via a 0-10V analog signal from an Allen Bradley Micrologix Programmable Logic Controller (PLC). Water is pumped over a total distance of 10 feet from the sump to a 189 liter (50 gallon) tank that is located 9.5 feet above ground level, which comprises the static head in the system.

Fittings in the pipe system include a full-bore manual ball valve, a swing check valve, a globe valve on the discharge side used for introducing frictional resistance into the system, as well as several 90-degree elbows. An integral flow meter is also located on the discharge side, which records the total flow produced by the pump for a given experimental cycle.

A simulated pump/system curve was created using AFT Fathom, a steady-state fluid mechanics software used for modelling incompressible flow. The curve is developed with the pump manufacture’s data and interpolation at variable speeds, with the system curve created for a sump tank level of 58 centimeters (20 inches). Based on the efficiency curves, it is found that all operating points from 30-60 Hz lie within ± 10% of the Best Efficiency Point (BEP) at a given speed. This figure is shown below:

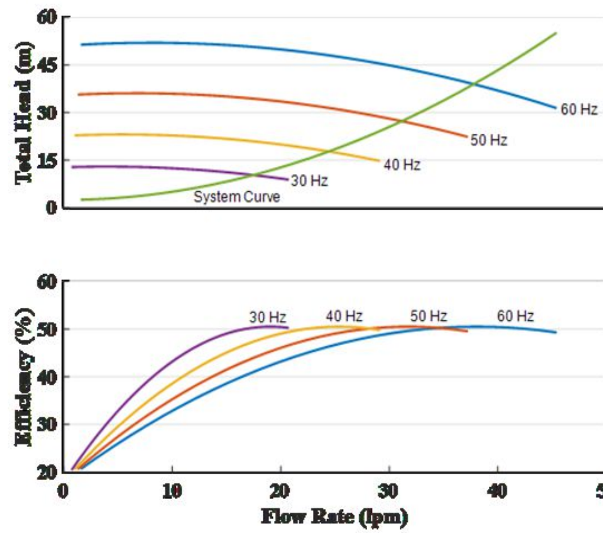

Fig. 4. (a) Simulated variable speed pump curves for the experiment, with the system curve developed for Level=50.8 cm (20 in.) and (b) Pump efficiencies at variable speeds

Inlet flow to the sump comes from the 189 liter (50 gallon) tank, as well as a 95 liter (25 gallon) tank that allows for simulating peak flow rates. Flow rate is modulated with two on-off valves, as well as a proportional analog control valve that also receives a 0-10V analog signal from the PLC. A picture of the pilot scale station is shown below in Figure 5.

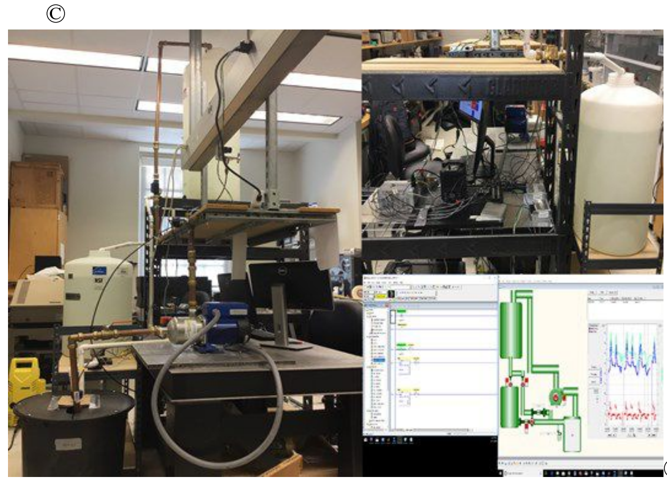

Fig. 5. (a) The pilot scale pump station which the algorithms are tested upon including (b) control electronics and (c) programming software and HMI

The PLC programming software was used to control all process parameters, including pump control algorithms and sump inlet flow rate. Process data was collected via serial communication and sent to a Human Machine Interface (HMI) for viewing and analysis. Pump power consumption was recorded through a plug load logger at an interval of one second and is also collected via data collection software. At the end of every flow cycle, the sump tank level is returned to a predetermined value, and the next cycle commences.

B. Proposed Algorithm

The nonlinear speed versus level control algorithm experimented with is a quadratic function that is concave up and varies in curvature only. Figure 5 shows the algorithm where speed is a function of level with varied curvature (A value) that is tested experimentally.

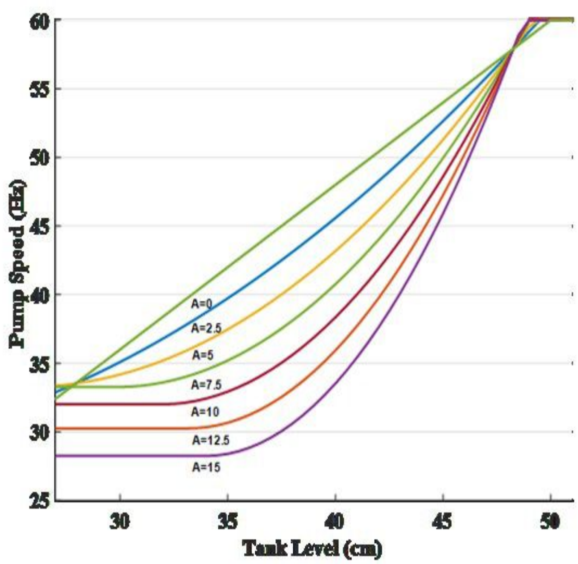

Fig. 5. Experimental concave up speed control curves. "A" is the curvature value. The sump tank level is shown here in centimeters.

The linear functional relationship (A=0) is shown first, with increasing A values listed below consecutively. For this experimental setup, since the sump tank maximum height is 50.8 centimeters (20 inches) and the maximum pump speed is 60Hz, the following linear speed versus level control function is created:

$$LS = 1.2 * L \tag{4}$$

where LS is equal to linear speed and L is the sump tank level in centimeters.

The curves are created by specifying the desired endpoints, and then adding them to the linear control function. The defining characteristic of each quadratic, which is the curvature, is defined as the A value, which is listed as experimental constants in Equation (5):

$$A = [0\ 2.5\ 7.5\ 10\ 12.5\ 15] \tag{5}$$

$$B = \frac{A}{\left(\frac{L1}{2} - \frac{L2}{2}\right)^2} \tag{6}$$

where B is equal to a constant, and L_1 and L_2 are the points where the curve will intersect the x axis, and where the speed curve will intersect the linear speed versus level function.

The equation of the curve C is based on the values of A and B and is shown in Equation (6):

$$C = -A + B * \left(L - \left(\frac{L_1 + L_2}{2}\right)\right)^2 \tag{7}$$

To get the actual speed versus level control curve, C is added to the linear speed LS, to come up with the actual speed curve S, shown in Equation (7).

$$S = 1.2 * L - A + B * \left(L - \left(\frac{L_1 + L_2}{2}\right)\right)^2 \tag{8}$$

The values of L1 and L2 can be chosen based on the physical constraints of any given setup. For the purpose of this experiment, they are chosen as 27.9 cm (11 inches) and 48.3 cm (19 inches) respectively. For A values greater than 5, there exist points where the derivative of the curve is negative and the speed actually decreases with increasing level. These points are rejected, and the last known value with a non-negative derivative is held indefinitely. Since the level endpoint L1 is 27.9 cm, if the level falls below this value, the calculated pump speed will be held indefinitely with no further decrease in speed. No pump speed values less than 27.5Hz are considered in the experiment; in wastewater plants, a minimum speed is generally established to protect against clogging from solid materials in the sump.

The algorithm itself is created and then implemented using PLC ladder logic programming, where the liquid level measurement is the input and the pump speed is the output. The design of the control algorithm consists of specifying the level endpoints, L1 and L2, and choosing an A value that maximizes the system efficiency based on the characteristics of the individual pumping system. Essentially, the value of A can be tuned in order to maximize system efficiency. Since there is no actual level set-point, there is no error input to the algorithm and therefore no additional design parameters are considered.

C. Test Flow Regime

The experiments consist of a test flow regime over a period of 1800 seconds, where the inlet flow to the sump is controlled to meet a dynamic flow set point. This flow regime is repeated for each test cycle. Figure 6 shows flow data collected during one of the cycles to show what the flow regime looks like over an 1800 second period. Noise looking features in the data are a result of oscillatory behavior of the analog control valve.

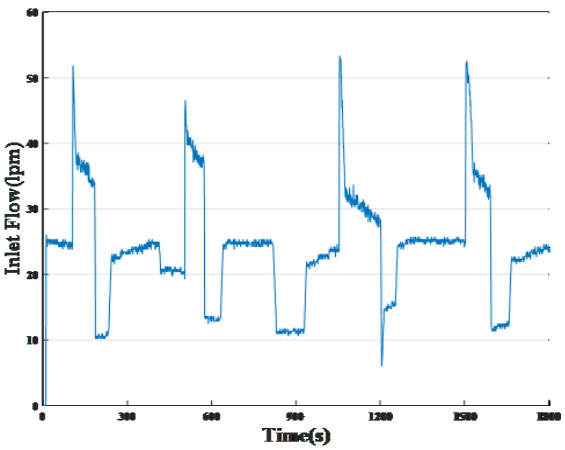

Fig. 7. Sump inlet flow rate (liters/min) as a function of time for one experimental cycle. This exact flow regime is repeated for all cycles.

IV. Results

Each pump run of a single curvature consisted of three cycles, where the tank levels were reset to a predetermined value between cycles. Figure 7 shows the specific energy use of each particular curvature, denoted by "A" value, with A=0 representing the linear only relationship.

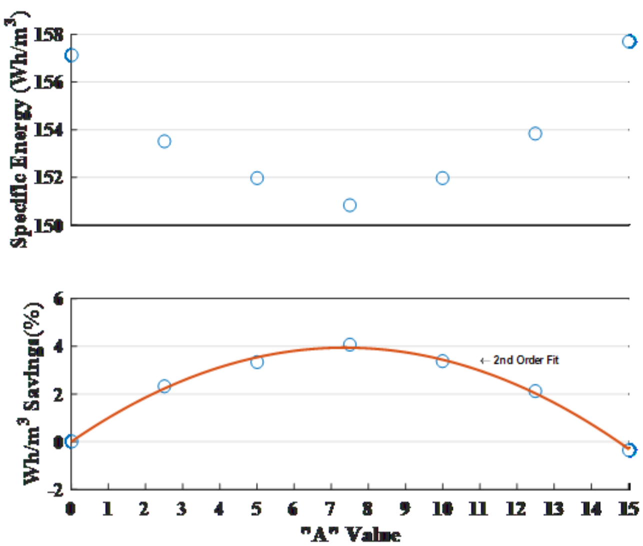

Fig. 8. (a) Specific Energy and (b) Specific Energy Savings plotted for experimental data. The markers are averages of each of the three test cycles for each value of curvature. A second order fit of the savings points is also plotted to show the experimental correlation.

TABLE I. Experimental SE Values and % Savings

Parameter	A Value						
	0	*2.5*	*5.0*	*7.5*	*10.0*	*12.5*	*15.0*
Specific Energy (Wh/m^3)	157.1 ±0.5	153.5 ±0.4	152.0 ±0.3	150.8 ±0.7	152.0 ±0.3	153.8 ±0.1	157.7 ±0.3
% Savings	-	2.32 ±0.2	3.33 ±0.2	4.08 ±0.4	3.37 ±0.1	2.12 ±0.1	-0.35 ±0.2

The specific energy roughly follows a second order parabolic relationship with a minimum at A=7.5. Using an A value of 15 actually leads to an increase in specific energy compared to linear control, indicating that there is an optimum curvature to the algorithm somewhere between A=0 and 15. In addition, process parameters including average sump level, average pump speed, as well as maximum pump speed are collected and plotted for each A value.

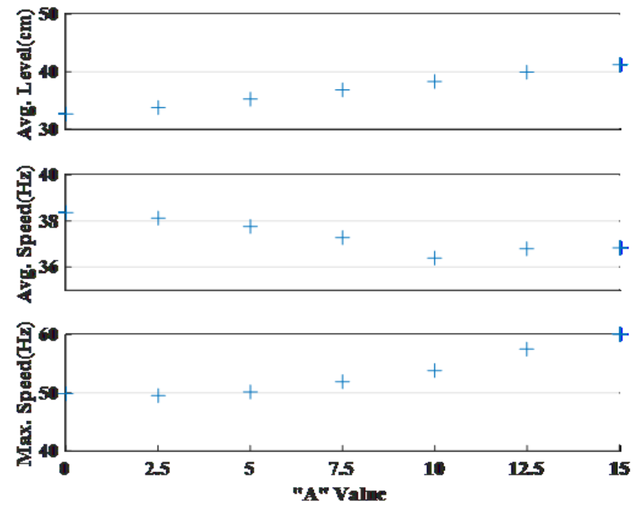

Fig. 9. (a) Average Level, (b) Speed and (c) Maximum Speed collected from data for each curvature value. Each marker represents the average of three test cycles for the corresponding curvature value.

As shown, while average speed is lower for A=15 than A=0, the maximum speed is substantially higher. The amount of time spent operating at speeds in excess of 50 Hz is highlighted in Figure 10(a).

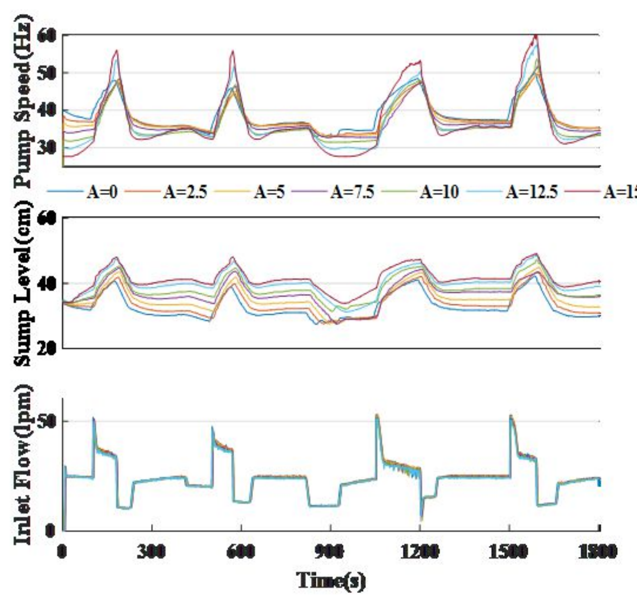

Fig. 10. (a) Pump Speed, (b) Sump Level and (c) Inlet Flow Rate collected over the cycle time of 1800 seconds for each curvature value. Each line represents the average of three test cycles at that particular instance.

It is apparent from the speed versus time results that as the A value increases, the absolute maximum recorded speed increases. However, for A values greater than 7.5, the duration of operation at high speeds increases substantially. For A=15, when flow rate reaches one of its four peaks, the speed increases to above 50Hz for a total of 178 seconds on average, substantially more than the 23 seconds for A=7.5. Based on the affinity laws, since pump power increases cubically with speed, the energy use increases drastically during periods of high flow due to the pump operating at really high speeds for an extended duration. At the minimum specific energy value of A=7.5, while the absolute maximum speed (51.9 Hz) was higher than that for A=0 (49.9 Hz), the duration of operation at the maximum speed was comparatively small, and the reduced speed during times of lower inlet flow resulted in significant specific energy savings compared to the linear control. The total operational time at speeds of greater than 45Hz was 248 seconds for A=0, 196 seconds for A=7.5, and 313 seconds for A=15. The same trends can be seen in Figure 11, where active power consumption is monitored over time.

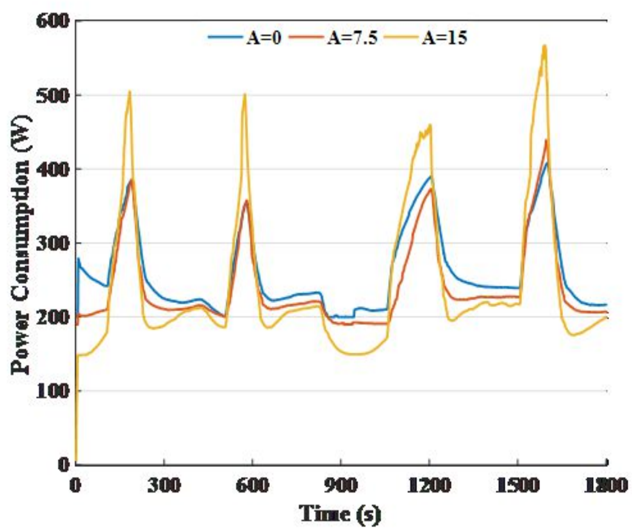

Fig. 11. Active Power plotted for linear and curvature values of 7.5 and 15

While active power consumption for A=15 remains less than that of A=7.5 and A=0 for more than 80% of the cycle duration, the power reaches values in excess of 500 W during the inflow peaks, which actually consumes enough to end up with more energy drawn during the whole cycle compared to the A=0 algorithm. For A=7.5, the peak power actually is only slightly more than that of A=0 and integrated over the whole 1800 seconds and divided by total flow produced, leads to a substantially lower specific energy compared to the A=0, on the order of 4% less.

TABLE II. Experimental Process Parameter Values

Parameter	A Value						
	0	*2.5*	*5.0*	*7.5*	*10.0*	*12.5*	*15.0*
Avg. Tank Level (cm)	32.73± 0.03	33.73 ± 0.09	35.30 ± 0.04	36.81 ± 0.13	38.31 ± 0.05	39.98 ± 0.03	41.24 ±0.05
Avg. In. Flow Rate (lpm)	24.19 ±0.07	24.18 ±0.02	24.05 ±0.03	23.95 ±0.01	23.77 ±0.01	23.65 ±0.05	23.48 ±0.04
Avg. Pump Speed (Hz)	38.36 ±0.06	38.12 ±0.09	37.78 ±0.04	37.26 ±0.07	36.41 ±0.06	36.79 ±0.07	36.83 ±0.09
Max. Pump Speed (Hz)	49.85 ±0.07	49.60 ±0.10	50.20 ±0.05	51.90 ±0.08	53.80 ±0.07	57.57 ±0.08	60.00 ±0.10
Total Pumped Flow (m^3/cycle)	0.8121 ± 0.0006	0.807 ± 0.003	0.801 ± 0.001	0.794 ± 0.001	0.787 ± 0.001	0.778 ± 0.0006	0.7693 ± 0.002

V. CONCLUSION

This paper has examined an energy efficient control algorithm for pump stations tasked with controlled sump level, and has presented experimental results showing specific energy reduction in excess of 4% compared with conventional, linear variable level control. While the exact amount of savings will depend on specific pump station parameters, the experimental data shows that there is savings from varying pump speed nonlinearly with level, and that there is an optimum concave up curve that produces the most reduction in specific energy.

IV. REFERENCES

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