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Optimal Scheduling of Variable Speed Pumps in Mahasawat Water Distribution Pumping Station

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***Abstract*—An optimum energy conservation technique for water treatment plant, both in term of costs and environmental impacts, have been studied and implemented primarily at Mahasawat Water Distribution Pumping Station, Thailand. This article proposes an optimum scheduling of 4-variable speed pumps operating under their actual conditions. We apply affinity laws with simple measures of performance; delivery pressure, power, and speed; to a group of pumps before scheduling them in parallel as 4-3-2 pump configuration. Energy costs are computed in term of specific energy consumptions (SEC's) to compare them for all configurations. This proposed technique is tested and the test results demonstrated that it can reduce energy consumption by more than 12%.**

Keywords—energy conservation; variable speed pumps; water distribution pumping; specific energy consumption;

I. INTRODUCTION

Demands for household and industrial use of water around Bangkok area and its vicinity have been rapidly increased. Many condominiums or high rise buildings have been built along the new electric mass transit railway system. The Metropolitan Waterworks Authority (Thailand) has to build more water supply distribution system for its increasing customers that found to be growing at the rate of 1.6% yearly [1]. The hydraulic pressure and volume of water have to meet the demand of customers at all time.

In water distribution systems, water often needs to be pumped to a higher elevation with adequate pressure. For example, hydraulic pumps transport water from a treatment plant into an elevated storage tank. From an elevated tank, water falls by gravity to reach with adequate pressure nodes in the water network where water is consumed. Hydraulic pumps consume most of the energy required to operate a water distribution system. Therefore, optimizing pump operations may lead to significant reduction in energy expenditures [2]. Thus, in order to make the water supply system more economically reliable, there is a need for the optimization of the system, in term of reducing the operational cost of the system which related directly to the energy cost, treatment and maintenance costs, and still be able to satisfy the demand requirements of the customers.

In the optimization of the system, numerous approaches have been employed such as pumping of less water, lowering the head against which water is delivered and scheduling the operations of the pump to concentrate more pumping activity during less expensive tariff period. Of all the aforementioned approaches, the scheduling operations of the pumps has been proven to be the most reliable and viable means of achieving a reduced operational cost without necessarily making changes to the system infrastructure [3]. Pump scheduling involves the process of selecting the right combination set of pumps within the system to operate at a specified time in order to meet the desired objective. Hence, a pump schedule is the set of all pump combinations chosen for all time intervals which must satisfy particular objective, such as energy and or maintenance cost, for which it was created while fulfilling the physical and system requirements [4].

The study was made at Mahasawat water distribution pumping station (MHDPS) located in Plaibang district Nonthaburi province. MHDPS has 4 pumps (centrifugal variable speed pumps) each unit rated at 1,460 kW, maximum flow rate of 26,000 m^3/h and maximum discharge pressure of 43 meters (4 pumps). MHDPS distribution network layout is shown in Fig. 1. MHDPS serves water supply to customers with a capacity of 500,000 m^3/d. Peak demand of water is in the period of 6-7 a.m. and the period of 7-8 p.m. on week days.

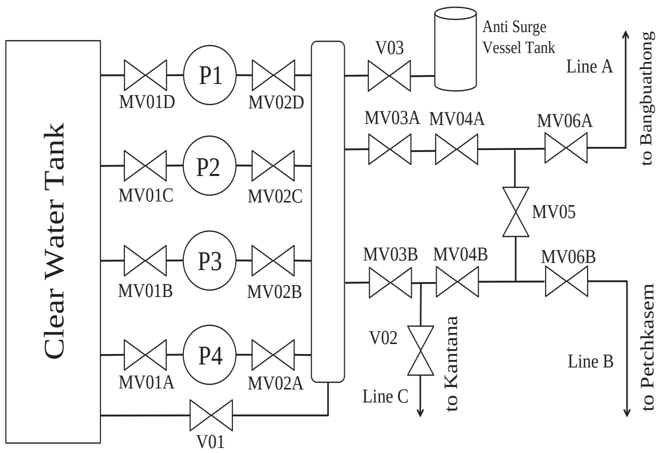


Fig.1 MHDPS distribution network

II. Pump Scheduling

A. Pump Scheduling Problem

Main goal of the pump scheduling problem is to schedule the operation of N pumps over a time period, typically 24 hours, in such a way that system constraints and boundary conditions are satisfied, while the operational cost is minimized. The most important costs associated with the operation of pumps are *electrical* and *maintenance* costs. The electrical cost is composed of the *consumption charge* (THB/kWh), i.e., the cost of electrical energy consumed during a time period, and the *demand charge* (THB/kW), i.e., the cost associated with the maximum amount of power consumed (peak energy). The consumption charge usually varies depending on the time of the day, with peak and off-peak electricity tariffs. Maintenance costs cannot be easily estimated, however, the wear and tear of pumps is mainly caused by frequent switching them on and off. Formally, a *pump switch* is defined as turning on a pump which was previously off. Therefore, minimizing the number of pump switching will result in minimization of maintenance costs.

B. Pump Operation System

MHDPS is allowed to hire just only one operator to control pumps manually by reducing or increasing pump speed and to monitor the pressure trend curve via remote terminal unit (RTU). The control system of MHDPS is shown in Fig 2. The pressure at the control point must be in the middle range between lower and upper bounds as shown in Fig.3.

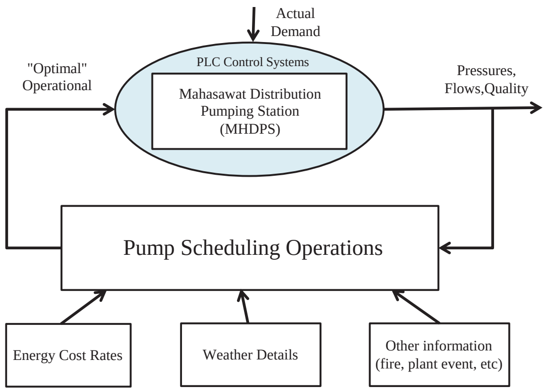


Fig. 2 MHDPS control system

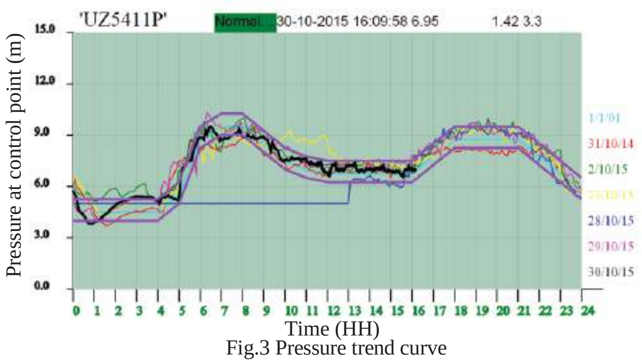


Fig.3 Pressure trend curve

III. Affinity Laws

The affinity laws are derived from a dimensionless analysis of three important parameters that describe pump performance: flow, total head and power [5]. The analysis is based on the reduced impeller being geometrically similar and operated at dynamically similar conditions or equal specific speed. If that is the case, then the affinity laws can be used to predict the performance of the pump at different diameters for the same speed or different speed for the same diameter. Since in practice impellers of different diameters are not geometrically identical, it is necessary to limit the use of this technique to a change of impeller diameter no greater than 10 to 20%. In order to avoid over cutting the impeller, it is recommended that the trimming be done in steps with careful measurement of the results. At each step compare your predicted performance with the measured one and adjust as necessary. The affinity laws were developed using the law of similitudes which provide 3 basic relationships.

- Flow vs. diameter and speed

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2}\frac{D_1^3}{D_2^3} \tag{1}$$

- Total Head vs. diameter and speed

$$\frac{H_1}{H_2} = \frac{n_1^2}{n_2^2}\frac{D_1^2}{D_2^2} \tag{2}$$

- Power vs. diameter and speed

$$\frac{P_1}{P_2} = \frac{n_1^3}{n_2^3}\frac{D_1^5}{D_2^5} \tag{3}$$

Subscripts 1 and 2 denote the value before and after the change. *P* is the power, *n* the speed, *D* the impeller diameter, *H* the total head. If the diameter is fixed the affinity laws become:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad , \quad \frac{H_1}{H_2} = \frac{n_1^2}{n_2^2} \quad , \quad \frac{P_1}{P_2} = \frac{n_1^3}{n_2^3} \tag{4}$$

The process of arriving at the affinity laws assumes that the two operating points that are being compared are at the same efficiency. The relationship between two operating points, say 1 and 2, depends on the shape of the system curve.

IV. Methodology

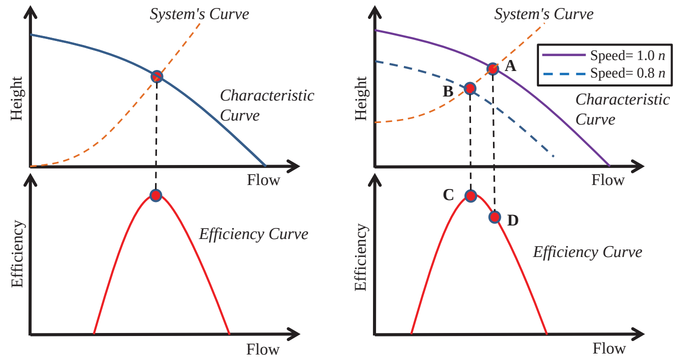
In order to achieve the goal of optimized problem of such a pump scheduling. We have to organize the system in following:

A. Pumping Systems

Every water distribution system has a pumping station responsible for giving the system the required pressure for its correct functioning. The main elements of the pumping stations are the pumps themself being the ones that collect the water from the natural source and propel it to the required height with an adequate flow. There are mainly two different types of pumps, Unique Speed Pumps and Variable Speed Pumps [6].

1) Unique Speed Pumps

Unique Speed Pumps (USP) is the most typical type of pumps. These pumps work with a single characteristic curve. The operation point is where the characteristic curve meets the system's curve; is this point meets the maximum efficiency point, then the pump is working on its optimal operation point, this situation is represented on Fig. 4(a).



(a) USP (b) VSP

Fig.4 Optimal operation point

Theoretically, an optimal functioning situation is not complicated, yet it is not usually fulfilled due to the dependence on the system's curve. When this happens the only solution is to change the pump in order for the characteristic curve meet the requirement for an optimal pumping situation. There is another possible situation, installing variable speed pumps.

2) Variable Speed Pumps

Variable Speed Pumps (VSP) is pumps that, as its name indicates, can vary their nominal velocity. Varying a pump's nominal velocity permits to modify its characteristic curve, making easier to reach the optimal operation point. As shown in Fig. 4(b), the system and characteristic curve's intersection point on the original speed situation does not meet the maximum efficiency point, so by changing its nominal speed it becomes possible to meet this point and so make the pump work in an optimal way. Achieving an optimal pumping situation has great advantages in terms of energy cost due that the pumps power value decreases.

B. Dicision variables

In order to optimize the patterns is necessary to identify which is the moment where the pump should be turn on or off, or on what moment its speed should be modified and what should be these speeds. Make decisions about the pumps, either turn on or modify their speed, may depend on many variables and that is why it is necessary to identify the best way to make this decision. Three different criteria where identified: demand patterns, energy tariff patterns and suction head patterns.

1) Demand Patterns and Energy Tariff Patterns

The first two situations refer to time patterns that can be identified for every network. Demand pattern represents the

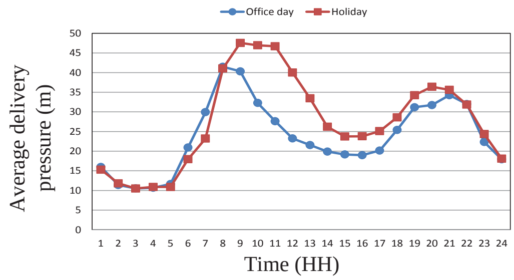


Fig.5 Pressure demand patterns (September 2015)

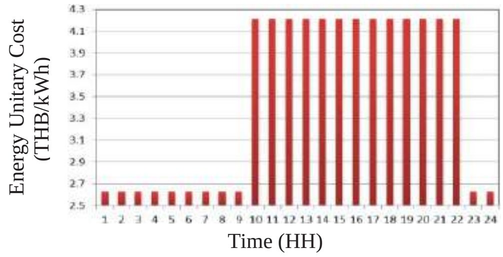


Fig.6 Tariff pattern (MEA-TOU Tariff [7], September 2015)

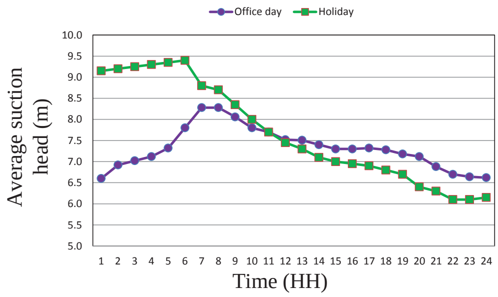


Fig.7 Suction head patterns (September 2015)

consumption behavior depending on the time of the day as shown on Fig. 5. This pattern may permit to select at what time of the day pumping should be higher; for example in the presented case, water consumption is highest at 8:00 am, hence pumping should be the highest at this point. The second option, energy tariff patterns, has the same representation as the first one, as shown on Fig. 6. These pattern may permit to optimize the time at which pumping should be the higher focused on the time interval at which the tariff if the least. For example in given case pumping should be done between 22:00 and 9:00 hours as the tariff here are the lowest.

2) Suction Head Patterns

Since the networks patterns cannot be used as decision variables due to their fixed values, a new solution was explored. Suction heads are the pressure of internal networks as shown in Fig. 7, this means that as the demand becomes higher, and its value decreases and vice versa, hence they could represent the behavior of the networks regardless if its behavior changes over the time.

V. Results and Discussion

In experiments, first we have to estimate pressure demand patterns or delivery pressures versus pump speeds. Delivery pressures are measured under the same conditions in the actual test. We setup combinations of pump runs in 4-3-2 configuration and use the least square linear curve fitting to build estimated equations to represent delivery pressures as shown in (5), (6) and (7). Equation models are used and have been shown to give a good result in real approximation.

- 4-pump combination:

$$P_{delivery} = 0.00682 \times n_{pump} - 2.40840 \quad (5)$$
$$R^2 = 0.99097$$

- 3-pump combination:

$$P_{delivery} = 0.00549 \times n_{pump} - 1.78999 \quad (6)$$
$$R^2 = 0.99245$$

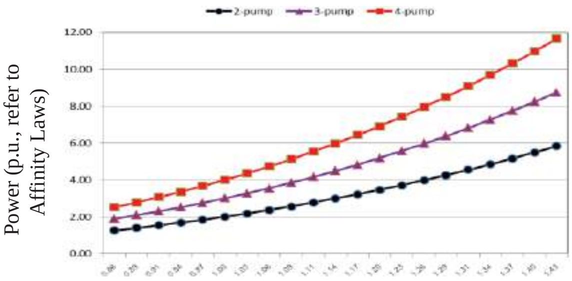
- 2-pump combination:

$$P_{delivery} = 0.00336 \times n_{pump} - 0.77847 \quad (7)$$
$$R^2 = 0.98660$$

Then, we calculated the consumed power of combination pumps by affinity laws and used per unit (p.u.) values for simplicity. For example, base value used are P_{base} = 380 kW and n_{base} = 700 rpm. If we increase speed from 700 rpm to 750 rpm so per unit value is increased from 1.0 p.u. to 1.07 p.u. From (4) we can create a new equation to estimate consumed power as shown in (8).

$$P_{p.u.} = (\textit{The number of running pumps}) \times n_{p.u.}^3 \quad (8)$$

So now we can calculate the consumed power of combination pumps as shown in Fig. 8.



Pump speed (p.u.)

Fig.8 Calculated consumed power

From (5), (6), (7) and (8) bring to the idea for saving energy of scheduling pumps as shown in Table I and testing results shown in Table II.

TABLE I. THE IDEA FOR SAVING ENERGY (CALCULATED)

Combination	4-pump	3-pump	2-pump
Pump speed (rpm)	720	780	980
Delivery pressure (m)	2.5022	2.4983	2.5204
Estimated power (p.u.)	4.35[a]	4.15[a]	5.49[a]

[a]Base values are 380 kW and 700 rpm

TABLE II. TESTING RESULTS

Combination	4-pump	3-pump	2-pump
Pump speed (rpm)	720	780	980
Delivery pressure (bar)	2.5000	2.5100	2.5400
Suction pressure (bar)	0.80	0.79	0.82
Consumption power (kW)	1,685	1,638	2,050
Consumption power (p.u.)	4.43[a]	4.31[a]	5.40[a]

[a]Base values are 380 kW and 700 rpm

TABLE III. THE OPTIMAL SCHEDULING CONDITIONS OF MHDPS

Conditions	Speed (rpm)		
	4-pump	3-pump	2-pump
Reduce 4-pump to 3-pump or Increase 3-pump to 4-pump	840	920	-
Reduce 3-pump to 2-pump or Increase 2-pump to 3-pump	-	620	700

Experiments were made on September 2015 and we received the optimal scheduling conditions as shown in Table III. The verification of the proposed scheduling can be created on the actual operation on October 1st to 16th, 2015 and the result of SEC (kWh/m^3) is shown in Fig. 9.

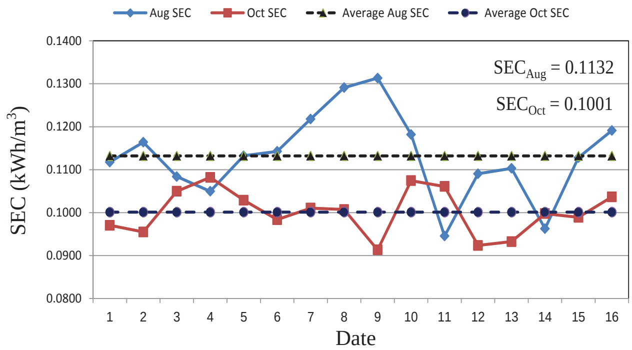


Fig.9 Proposed scheduling (Oct' 15) vs. non-scheduling (Aug' 15)

VI. CONCLUSIONS

The energy conservation in pump scheduling of MHDPS by the proposed method can reduce energy consumption by 12% using SEC (kWh/m^3) in comparison, on August 2015 (before scheduling) and October 2015 (scheduling). The optimal scheduling can be easily done in water distribution pumping station system.

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