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Optimal control approaches of pumping stations to achieve energy efficiency and load shifting

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ABSTRACT

Load shifting (LS) is a main task of demand side management (DSM). It has been treated as a kind of operation efficiency improvement in the POET (performance, operation, equipment and technology) framework and has been formulated as an optimal control problem. In literature, the number of pump switches and the accumulative operation time of individual pumps are barely considered in the operation optimization of pump stations. In this paper, we integrate the two issues into the general optimal control (GOC) problem of pumping stations to form an optimal control problem with consideration of pump switches (OCPS) and an optimal control problem with consideration of accumulative operating time (OCOT), respectively. Particle swarm optimization (PSO) algorithm is employed to solve the newly formulated problems. An intake pump station is taken as a case study. GOC, OCPS, OCOT and a hybrid of OCPS and OCOT (OCPS + OCOT) are applied to the station for simulation study. The results show that the optimal control approaches have the ability to achieve both energy efficiency and LS. Nearly 30% energy cost savings can be obtained by the optimal control approaches. The savings are mostly generated by shifting the operation status of the pumps according to time, specifically, time-of-use (TOU) tariff. Compared with GOC, the newly proposed approaches are more feasible for field applications.

1. Introduction

Load shifting (LS) is an issue of demand side management (DSM) where electricity demand is shifted from peak time to off-peak time or standard time. Time-of-use (TOU) tariff is one of the key strategies of LS and is a possible mechanism for DSM [1,2]. LS benefits energy suppliers and energy consumers at the same time. Particularly, LS reduces the requirement for installed capacity and increase the utilization of generating plants and would therefore increase the efficiency of generation investment for energy suppliers. On the other hand, consumers can save energy cost by shifting the controllable load away from the peak time. LS has further been reflected as a kind of energy efficiency improvement according to the POET (performance, operation, equipment and technology) framework in [3], more precisely, operation efficiency. According to POET, operation efficiency of an energy system is improved through the coordination of two or more internal subsystems, or through the coordination of the system components and time, or through the coordination of the system and human operators. Specifically, LS is generally achieved through the coordination of operation status of the energy-consuming devices and time.

In practice, LS may be obtained manually or automatically. However, manual coordination cannot deal with most industrial processes because of their complexity and various constraints. Consequently, optimization methodology has been employed for LS in industries. In [4–7], the on/off status of belt conveyors and pumps are optimally controlled to improve operation efficiency. The formulation of the optimization problems take TOU tariff into account, hence, the optimal control instruction is capable of shifting the load away from peak time to achieve LS. In [8], a physically based model for load management is proposed and used for optimization. The above approaches are intrinsically open loop control. Usually, a closed-loop control strategy is expected to handle the uncertainties and the disturbances. The model predictive control (MPC) strategies have further been proposed in [9–12] for LS of pumping stations. A feedback mechanism is also proposed for energy efficiency control in [13]. The optimal control models in [7,10–12] use energy cost as the objective functions for minimization. Their purpose is to improve the operation efficiency of pumping stations, where LS is in fact a control means to achieve efficiency improvement. Pumps are consuming a considerable part of the power supply. A field characterization project revealed that pumps are responsible for about 21% and 16% of the electricity consumed in the industrial and in the services sectors in the European

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Union (EU) [14]. Hence, pumps have been viewed as the main targets for energy saving. Many large pumps are installed within pumping stations. Pumping stations are facilities including pumps and equipment for pumping fluids from one place to another. In our case study, the intake pumping station is used to lift water from the river to a water treatment plant. The design issues [15], such as the pump capacity, the pressure differences and the operating demands, installation issues [16] and operation issues [17] of the pumping stations can be the answers for energy saving. On the other hand, for an existing pumping system, optimization is a widely accepted methodology for efficiency improvement, like in [7,10–13,18–20]. For energy audit purpose, a current measurement-based approach is proposed to monitor pump operation and energy efficiency [21]. Then, the energy saving suggestions may come from the audit results.

As above mentioned, LS has been formulated as an open loop optimization problem or a closed-loop optimization problem. Various optimization techniques have been employed in load shifting for different processes, such as the linear programming (LP) in [5,6] for belt conveyors, the dynamic programming (DP) in [22]. Further, some modern optimization methods, such as genetic algorithm [23], simulated annealing [24], particle swarm optimization [11,20], ant colony optimization [25] and fuzzy optimization [26], have been adopted for the optimal scheduling of pump operation.

According to Lansey and Awumah [27], a pump switch is defined as turning on a pump that was not operating in the previous period. In [28,29], the number of pump switches is taken as an alternate way to evaluate the pumps' maintenance cost and has been formulated as an objective function of the multi-objective optimization strategies. In [30], a discrete multiple threshold hysteresis control is proposed with the goal to minimize the number of switch cycles of pumps. Meanwhile, most of the literature about optimal control of pumps, barely take the pump switches into account. Consequently, the solution to these optimization problems may switch the pumps frequently. The frequent pump switches bring extra operation fees and affect the lifetime of the pumps. Moreover, most pump stations are equipped with more than one pumps, which generally operate in parallel. In practice, the accumulative operating time of the pumps is expected to be approximately equal such that the maintenance of the pumps can be done synchronously. It is a way to save manpower, consequently, cost. However, the current control systems of the pumps, even the ones with optimization functionality, have not taken this issue into account. It may result in large gaps among the accumulative operating time of the pumps in a station.

The main purpose of this paper is to introduce optimal control to pump stations to achieve operation efficiency and LS. We start with an energy model of the constant speed pumps. Then, a general optimal control (GOC) problem of an intake pump station will be formulated. The GOC approach takes the TOU tariff into account and considers other relevant constraints to achieve the minimization of energy cost. This economic indicator of performance efficiency in [3] is employed to drive the operation of the pump station in its optimal efficiency. And then, the pump switches and the accumulative operating time of the pumps are to be integrated into the GOC problem, respectively. Thus, an optimal control with consideration of the pump switches (OCPS) and an optimal control with consideration of the accumulative operating time (OCOT) will be finally formulated. The GOC is formulated as a binary integer programming (BIP) problem. However, OCPS and OCOT are more complex because two extra nonlinear parts, reflecting the pump switches and the accumulative operating time, are added to the objective function. We employ particle swarm optimization (PSO) technique to solve these optimization problems. An intake pump station of a seaside water treatment plant will be taken as a case study for simulation research. The currently used level-based control (LBC) approach, general optimal control approach and its variations will be applied to this intake pump station, respectively. The simulation results will be presented.

The layout of the paper is as follows: In Section 2, the energy model of constant speed pumps is analyzed. In Section 3, the control approaches for LS of pump stations are formulated. In Section 4, BIP and PSO are employed to solve the optimal control problems. A case study is shown in Section 5, followed by the conclusion section.

2. Energy model

An intake pump station of a seaside water treatment plant, as shown in Fig. 1, is taken as the subject for the following investigation. The intake pump station fetches water from the river to the water treatment process. The water level of the river, denoted by W_L, varies along with the time of a day and the seasons due to the ocean tides. According to the specification, this pumping station is equipped with three constant speed pumps. Under the conventional operational mode, only two pumps works and the third one is on standby.

For a constant speed pump, its electric power is related to its net head, discharge and the efficiency of the pump and the drive motor. It can be expressed as [31]

$$P_e = C_e \frac{H_r Q_r}{\eta_p \eta_m}, \tag{1}$$

where P_e is the electric power, kW, H_r is the net head of the pump, m, Q_r is the discharge of the pump, m^3/h, and η_p and η_m are the efficiency of the pump and the drive motor respectively. In (1), C_e is a coefficient, $C_e = \frac{g\rho}{3600}$, where g is the acceleration of gravity and ρ is the density of water, kg/m^3. The operation point of a pump with fixed speed is determined by its pump head curve, $Q - H$, and the system head curve. The pump head can be expressed as

$$H = H_0 - sQ^2, \tag{2}$$

where H_0 is the theoretical maximum head of the pump and s is a friction related coefficient. On the other hand, the system head is expressed as

$$H = H_T - W_L + s_r Q^2, \tag{3}$$

where H_T is a constant, as shown in Fig. 1, W_L is the water level of the river, and s_r is a friction related coefficient. The actual operation point, $[Q_r, H_r]$, is the section of (2) and (3). Further, the efficiency of a pump is related to its actual operation point; and it can be expressed as [32]

$$\eta_p = aQ_r^2 + bQ_r + c, \tag{4}$$

where a, b and c are constant coefficients. Eventually, the power of a constant speed pump, subject to the variation of the intake water level, W_L, can be obtained using .(1)–(4)

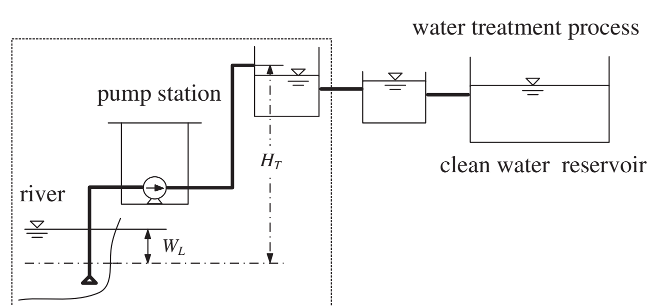

Fig. 1. Process flow diagram of a water treatment plant.