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A methodology for pumping control based on time variable trigger levels

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Abstract

A methodology for the control of a pumping plant feeding a tank is presented. This methodology is aimed at minimizing the energy costs by maximizing pumping during off-peak electricity tariff periods. It is based on trigger levels which are variable during the day according to a prefixed pattern in order to ensure that the water level in the elevated tank is at its minimum and maximum values at the end of the peak and off-peak tariff periods respectively. The pattern of the trigger levels is defined by solving a multi-objective problem aimed at minimizing the energy costs and the number of pump switches.

The methodology was applied to the real case of a pumping plant feeding an elevated tank for daily balance which, in turn, feeds a small town in northern Italy; one week of hourly observed total consumptions was considered. This methodology was compared with other two methodologies typically used for pump control, i.e. pump scheduling and fixed trigger levels. The results show that the proposed methodology allows for achieving energy costs that are definitively lower than those obtainable by using fixed trigger levels, and comparable with those obtainable by using pump scheduling, being the number of pump switches the same. On the other hand, unlike the pump scheduling, the methodology presented does not require any water demand forecast and scheduling optimization to be repeated daily, thus representing an effective and efficient tool for pumping plant operation.

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Keywords: pump operation; trigger level; scheduling; water distribution network

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Nomenclature

Tc	time window
n_t	number of time periods characterized by different energy tariffs
n_p	number of pipes
$tpeak_{start}$	starting time instant of the peak tariff period
$tpeak_{end}$	ending time instant of the peak tariff period

1. Introduction

Water distribution systems are designed and managed in order to provide the desired amount of water to the users with an adequate pressure head. To this end, in several water supply and distribution systems pumping stations are used to pump water from the intake structure or water treatment plant to tanks or directly into the water network system. The energy cost due to pumping stations is one of the largest components of the total system management costs [1]. Therefore, in order to minimize the network management costs, pumping operation need particular attention. More specifically, when the pumping station pumps water directly into the water network system, the pumped flow directly depends on, and must be equal to, the total amount of water required by the users at each time instant. In this instance, the most effective action that can be performed by the water utility technicians in order to minimize the total system costs consists of an accurate selection of the pumps to be installed in the pumping station, so that they operate mainly at their Best Efficient Point (BEP), in order to limit the consumed power and therefore energy consumptions and costs. On the other hand, when downstream the pumping station a tank there exists featuring a significant volume which can compensate the differences between the pumped flow and the total amount of water required by the users at each time instant, a key to reduce management costs is that of properly controlling the operation of the pumps during time. In particular, since electricity price is time dependent, the pumping control can be developed in order to maximize the pumped volumes in the off-peak electricity tariff periods and to minimize those in the peak electricity tariff periods, taking care of the management constrain on minimum nodal heads in the network and other factors affecting the costs, such as water losses [2] and pumps deterioration caused by frequent switching on and off operations.

Two methodologies for pump control are currently used [2]: (a) scheduling the on/off switches of each pump on a time interval and (b) controlling the on/off switches of each pump according to prefixed values of the water level reached in the tank fed by the pumps themselves. The first one can provide an optimal arrangement between the tank's filling and releasing phases and the off-peak and peak electricity time periods, thus ensuring the tank's storing in the off-peak hours and its emptying in the peak hours; however, its application requires the water demand to be forecasted over the scheduling time window [3] and the use of optimization algorithms in order to periodically (e.g. daily) identify the optimal scheduling. The second methodology does not involve forecasting and optimizing issues because the pumps are switched on/off according to the occurrence of a fixed water level in the tank; on the other hand, this method can produce a time shifting between the tank's filling and releasing phases and the off-peak and peak electricity tariff periods, thus causing an economic benefit reduction.

The optimal control of pumping stations has been widely studied in the past decades. The pump scheduling issue in particular, has been approached with a large number of different methodologies developed in order to establish the optimal switching on/off sequence of the pump(s), based on different optimization techniques such as linear programming (e.g. [4]), nonlinear programming (e.g. [5]; [6]), dynamic programming (e.g. [7]; [8]) or algorithms based on metaheuristics concepts, such as evolutionary algorithms (e.g. [9]; [10]; [11]; [12]), simulated annealing algorithms (e.g. [13]), and ant colony algorithms (e.g. [1]; [14]). In most of these studies the pump scheduling is coded as a binary string containing, at each time step of the scheduled time window, the on/off (1/0) state of each pump. Thus, if for example one day at hourly time step is considered, 24 binary values are coded for each pump. [1] and [14] developed an alternative technique for the characterization of the pump scheduling based on codification of the time instant when each pump switch occurs, clearly requiring in this latter case the a priori definition of the maximum number of pump switches that can occur in the scheduled time window.

On the other hand, it is worth noting that compared to the intense pump scheduling research activity developed in the past years, a only few studies concerning the approach based on fixed trigger levels have been developed e.g. [15]). This fact can be clearly understood considering that the pump scheduling approach requires the utilization of forecasting and optimization algorithms to determine the optimal solution, unlike the "fixed trigger level" methodology whose application does not need any optimization algorithm or model. With reference to both approaches, it is worth mentioning the methodology proposed by [16], which provides a hybrid approach based on the application of different trigger levels depending on peak and off-peak tariff periods of the day combined with a scheduling technique in order to maximize the pumping operation in the off-peak tariff periods ensuring the maximum water volume storage in the tank at the beginning of the peak tariff periods. Thus, a genetic algorithm is applied to determine the optimal combination of the pumps' control levels and scheduling, taking into account the water consumption forecasts for the next day. Consequently, this methodology, as well as that based on pump scheduling, clearly needs the forecasting of the water consumptions for the next 24 hours and application of an optimization algorithm for the periodical (daily) identification of the optimal solution.

This paper proposes an alternative methodology to the traditional pump scheduling or the "fixed trigger level": like the "fixed trigger level" methodology, this methodology is based on the water level in the tank but it is developed so that the pumps' switching on/off occur when time-dependent threshold levels are reached. These levels change in fact in time, according to a prefixed pattern defined in order to ensure that the largest and the smallest water volumes are stored in the tank at the beginning of the peak and off-peak electricity tariff periods, respectively; these time variable trigger levels avoid the shifting of the tank filling and releasing phases from the peak and off-peak electricity time periods without requiring, in the meantime, the water demand forecast and the application of optimization algorithm to find the optimal time plan.

In the subsequent sections the proposed methodology is presented and is applied to a real case consisting of a pump station feeding an elevated tank which represents the inlet point for a water distribution network supplying a medium town in northern Italy. The results are compared with those obtained through the application of the "fixed trigger level" and the pump scheduling methodologies and, lastly, some conclusive considerations are provided.

2. The proposed methodology

Let us consider a pumping station, featuring n_p fixed speed pumps, which feeds an elevated tank located at the inlet point of a water distribution system. The tank allows for a compensation of the total water demands over an assigned time window Tc, e.g. Tc=24 hours. Over the same time window, let the energy tariff been fixed; in particular, let n_t be the number of time periods making up the time window Tc which are characterized by different energy tariffs. In the following let us assume Tc = 24 hours and n_t=2, that is, within the day two time periods there exist, featuring a peak energy tariff and a off-peak energy tariff. It is worth noting that the proposed approach, presented in the following with specific reference to the case of n_t =2, could be easily extended to cases featuring n_t >2. On the other hand, it is also worth remembering that within a day generally n_t =2 tariff periods there exists, where the lowest tariff period typically includes the night hours, whereas the highest tariff period generally starts in the morning and ends at the late afternoon, as shown in Figure 1.

Still with reference to Figure 1, let $tpeak_{start}$ and $tpeak_{end}$ be the starting and ending time instants of the peak tariff period respectively. Clearly, being n_t =2, $tpeak_{start}$ represents also the ending time instant of the off-peak period, whereas $tpeak_{end}$ coincides with the starting time instant of the off-peak period. The proposed methodology for the control of the switching on/off of the pumps is based, as well as the "fixed trigger level" methodology, on tank levels; indeed, in the proposed methodology the trigger levels are defined as variable during the day according to a prefixed pattern in order to ensure that the level in the elevated tank is at its minimum and maximum at the end of the peak and off-peak tariff periods, respectively. These time variable trigger levels allows for the filling and releasing phases of the tank to coincide with the off-peak and peak electricity tariff periods, respectively.

More in detail, considering the generic pump i of the pumping station (with i=1:n_p), the trigger level controlling the "switching-on" phase of the pump is assumed to increase during the off-peak tariff period (i.e. during the night hours) reaching its maximum at $tpeak_{start}$ (see green line in Figure 1); vice versa, the trigger level controlling the "switching-off" phase of the pump is assumed to decrease during the peak tariff period (i.e. during the day) reaching its minimum at $tpeak_{end}$ (see red line(s) in Figure 1). In this way the system is forced to ensure large and small volumes of water stored within the tank at the end of the off-peak and peak tariff periods, respectively.

The shape of the functions representing the pattern of the switching on trigger levels during the off-peak tariff period and those representing the pattern of the switching off trigger levels during the peak tariff period (see for example curves a), b) and c) in Figure 1) is defined by a power law relationship (e.g. linear, parabolic, cubic, etc.). Note that during the off-peak tariff period the switching off trigger level is constant and equal to the maximum level in the tank. At the same time, during the peak tariff period, the switching on trigger level is constant and equal to the minimum level in the tank. These functions and the maximum and minimum levels at the time instants $tpeak_{start}$ and $tpeak_{end}$, highlighted with a black arrow in Figure 1, are fixed in such a way to minimize the energy cost, ensuring in the meantime that the number of pump switches is kept under control in order to avoid pump deterioration and failure [7]. To this end, a multi-objective problem is formulated; the decision variables are, for each pump i (with i=1:n_p) a) the exponents of the power law relationships representing the pattern of the switching on/off trigger levels in each of the n_p =2 time periods and b) the values of the maximum and minimum levels at the time instants $tpeak_{start}$ and $tpeak_{end}$. The objectives (to be minimized) are a) the energy cost and b) the number of pump switches over the Tc time window. For the solution of this multi-objective problem application of the NSGA-II [17] algorithm is proposed.

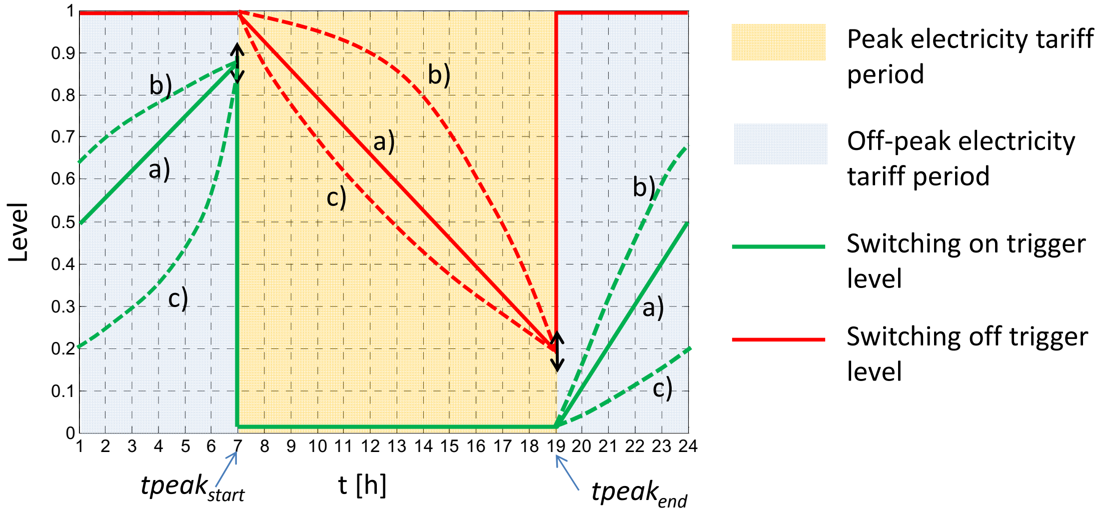

Fig. 1. Example of peak and off-peak tariff period and variable trigger levels.

3. Case study

The proposed approach was applied to the real case study of the pumping station feeding an elevated tank located at the inlet point of the water distribution system of a town in northern Italy. The pumping station features n_p=3 fixed speed pumps. Observed data concerning the discharges released by the tank, thus corresponding to total water distribution system inlet, at 1 hour time step for one week were available. Energy tariffs for the nt=2 time periods, peak and off-peak periods, in which the Tc = 24 hours time window is subdivided, are equal to 0.5 €/kWh and 0.1 €/kWh respectively. In particular, the peak period starts at $tpeak_{start}$ = 7 a.m. e ends at $tpeak_{end}$ = 7 p.m.; during the remaining hours of the day the off-peak tariff are applied.

Operatively, within the optimizing phase, it was assumed that all the n_p=3 pumps are characterized by similar functions representing the pattern of the switching on/off trigger levels; that is, for each time period, just one exponent value characterizing the switching on trigger level pattern (and the one characterizing the switching off) for all the n_p =3 pumps was searched for (i.e. 2 decision variables); on the other hand, different, among the n_p =3 pumps, maximum and minimum levels at the time instants $tpeak_{start}$ and $tpeak_{end}$ were searched for (i.e. 6 decision variables, for a total of 2+6=8 decision variables). In particular, the parameters characterizing the variable trigger levels and the maximum and minimum levels were optimized considering an average day of hourly water consumption of the entire system served by the tank, i.e. the average hourly pattern of the discharge released by the tank. Subsequently, given the optimized patterns of the variable trigger levels, the proposed approach was applied in face of the observed time series of hourly discharges actually released by the tank for one week.

The results were compared with those provided by the fixed trigger level and by the pump scheduling methodologies. For the application of the fixed trigger level methodology, the switching on/off levels of each pump, which are constant over the Tc = 24 hours time window, were fixed through an optimization process aimed at minimizing the energy cost over Tc = 24 hours time window considering the average day of hourly water consumption of the entire system served by the tank, as done for the proposed variable level trigger method; similarly, the fixed trigger level approach was subsequently applied for the control of the pumps in face of the observed time series of hourly discharges actually released by the tank during a week.

The pump scheduling approach, given its very nature, was instead applied considering directly the observed time series of hourly discharges actually released by the tank for the one week, by searching for, through an optimization process repeated at the beginning of each day, the hourly on-off sequence for each pump for the 24 hours ahead. Within the optimization process, it was assumed that the total water consumption of the system (i.e. discharge released by the tank) for the 24 hours ahead were perfectly known; that is, it was assumed that the water consumptions were forecasted without any error. Clearly, within a real operation framework, the total water consumptions to be used within the optimization process for the definition of the pump scheduling should be those actually forecasted, and even though the forecasting errors for the next 24 hours can be very small (see, for example, [18]), this would lead to an efficacy of the pump scheduling approach that is at most equal, but actually slightly lower, than the one obtainable by using perfect forecasts.

4. Analysis of the results

The Pareto front obtained by the application of the NSGA-II algorithm for the multi-objective optimization of the parameters characterizing the variable trigger levels is shown in Figure 2. For some solutions, the variable trigger levels of one of the three pumps making up the pumping station are also shown. It is worth remembering that the shape of the functions charactering the variable trigger levels in the different time period in this numerical application is assumed to be the same for all the three pumps. In particular, by comparing solutions a) and b) of Figure 2 it can be observed that as the switching on level at the end of the off-peak tariff period (i.e. at $tpeak_{start}$) increases and the switching off level at the end of the peak tariff period (i.e. at $tpeak_{end}$) decreases, the system is forced to store larger and smaller volume of water within the tank at the end of the off-peak and peak tariff period respectively, with a direct consequence in terms of energy cost reduction. On the other hand, this leads to an increase in terms of number of pump switches.

Considering instead solutions b) and c) (the latter plotted in Figure 2 with a different colour since it does not belong to the Pareto front), it can be observed that, being the maximum and minimum level at the time instants $tpeak_{start}$ and $tpeak_{end}$ the same, application of a proper exponent value of power law function charactering the pattern of the variable trigger level (see solution b), allows for a significant reduction of the number of pump switches with respect, for example, to a linear variation of the trigger level (see solution c), being the total energy cost equal. Solution b) indicated in Figure 2 represents a good compromise between energy costs and number of pump switches. This solution was thus taken as reference and the corresponding variable trigger level used for the control of the pumps in face of the observed time series of hourly discharges actually released by the tank for one week.

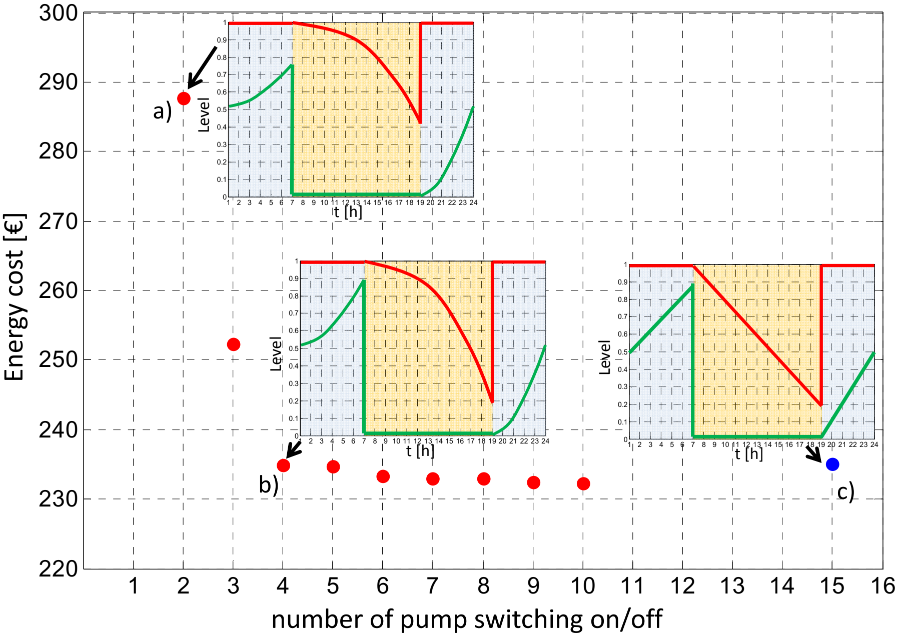

Fig. 2. Pareto front of the variable trigger level solutions.

Figure 3 shows the pattern of the water level within the tank obtained by using the proposed methodology for the entire week considered; this pattern is furthermore compared with those obtained by using the fixed trigger level and the pump scheduling methodologies. The corresponding energy costs are provided in Table 1. As can be observed, the variable trigger level control methodology leads to energy costs that are equivalent to those provided by the pump scheduling control methodology, and definitively lower than those provided by the fixed trigger level control methodology. This can be clearly explained considering that the variable trigger level and the pump scheduling methodologies, differently by the fixed trigger level, ensure that large and small water volumes are stored within the tank at the end of the off-peak and peak tariff period, respectively (see Figure 3a and c). Instead, it can be clearly observed that by using the fixed trigger level control methodology, a sort of shifting for the tank filling and releasing phases from the off-peak and peak tariff periods occurs, and in particular a quite large amount of water tends to be stored within the tank at the end of peak electricity tariff period of some days (see for example the second day), thus leading to larger energy cost than the other two control methodologies. On the other hand, it is also worth remembering that, as regards the pump scheduling, the corresponding total energy cost is given by considering on and off pump sequences for each day of the week obtained by repeating an optimization process at the beginning of each day and by assuming, in this application, that perfect forecasts for the next 24 hours are available.

Summing up, the results obtained highlight the efficacy of the proposed methodology, which allows for a significant reduction of the energy costs with respect to the fixed trigger level methodology, and comparable with the energy cost of the pump scheduling, without, in the meantime, requiring any water consumption forecast and application of optimization approaches to be repeated periodically (i.e. daily) in order to define the optimal scheduling for the next day.

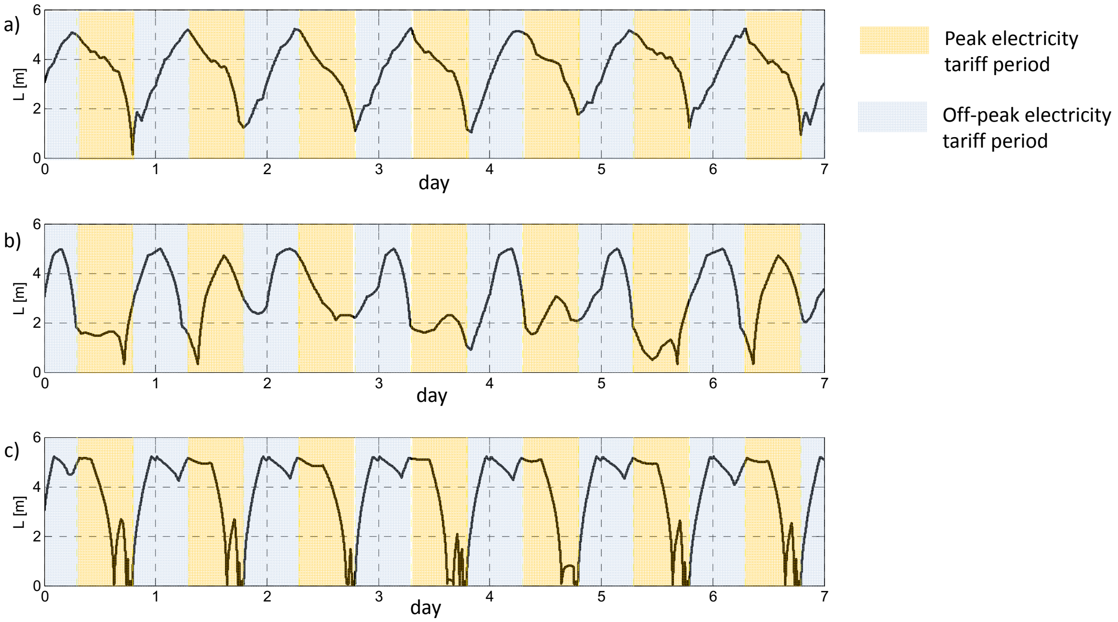

Fig. 3. Tank water levels for one week obtained by a) pump scheduling, b) fixed level trigger and c) variable level trigger.

Table 1. Energy costs obtained for one week by using different pump control approaches.

Pump control approach	Cost [€]
Pump scheduling	1648
Fixed Level trigger	2057
Variable trigger levels	1649

5. Conclusions

A new approach for the control of a pumping station feeding a tank is presented. The proposed methodology is based on water levels reached in the tank, like for the traditional fixed trigger level methodology, but in this case the trigger levels are defined as variable during the day according to a prefixed pattern in order to ensure that the level in the elevated tank is at its minimum and maximum at the end of the peak and off-peak tariff periods respectively. The pattern of the trigger levels is defined by solving a multi-objective problem aimed at minimizing the energy costs and the number of pump switches.

Application of the proposed approach to the case study and comparison with the results provided by more traditional methodologies such as fixed trigger levels and pump scheduling, shows that the proposed approach allows for achieving energy costs that are definitively lower than those obtainable by using fixed trigger levels, and comparable with those obtainable by using pump scheduling. In particular, the lower energy costs achievable with the proposed methodology with respect to the fixed trigger level can be understood considering that the time variable trigger level methodology avoids the shifting of the tank filling and releasing phases with respect to the peak and off-peak electricity time periods, which indeed often occurs when a fixed trigger level methodology is used. Thus, like the pump scheduling methodology, the proposed one ensures that large and small water volume are stored in the tank at the end of the off-peak and peak tariff periods, respectively. On the other hand, unlike the pump scheduling, the proposed approach does not require water demand forecast and scheduling optimization to be repeated daily, thus representing an effective and efficient tool for pumping plant operation.

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