

# A robust approach based on time variable trigger levels for pump control

Stefano Alvisi and Marco Franchini

## ABSTRACT

An approach for the control of a pumping plant feeding a tank at the inlet of a water distribution system is presented. The approach 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 approach was applied to a couple of real cases with a single tank. The approach was compared with other methodologies typically used for pump control, i.e. fixed trigger levels (FTLs) and pump scheduling (PS). The results show for the two particular cases that the proposed approach achieves energy costs that are lower than those obtainable by using FTLs, and comparable with those obtainable by using PS. This is based on achieving a similar number of pump switches.

**Key words** | pump operation, scheduling, trigger level, water distribution network

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## 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 (Filion 2008). The energy cost due to pumping stations is one of the largest components of the total system management costs (Lopez-Ibanez *et al.* 2011; Jung *et al.* 2016). Therefore, in order to minimize the network management costs, pumping operations need particular attention (Jamieson *et al.* 2007). 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 consumption and costs. On the other hand, when downstream of the pumping station there is a tank of significant volume that can compensate for the differences between the pumped flow and the total amount of water required by the users at each time instant, a key to reducing management costs is to properly control the operation of the pumps over 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 account of the management constraints on minimum nodal heads in the network and other factors affecting the costs, such

as water losses (Giustolisi *et al.* 2013) and pump deterioration caused by frequent switching on and off operations.

Two approaches for pump control are currently used (Giustolisi *et al.* 2013): (a) scheduling the on/off switches of each pump on a time interval basis 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 is storing in the off-peak hours and emptying in the peak hours. However, application of this approach requires the water demand to be forecasted over the scheduling time window (Alvisi *et al.* 2007) and the use of optimization algorithms in order to periodically (e.g. daily) identify the optimal scheduling. The second approach, i.e. controlling the on/off switches of each pump according to prefixed values of the water level reached in the tank, is typically applied either without performing an optimization, by fixing *a priori* the levels that control the switching on/off of the pumps, or by optimizing these levels just once, considering an average pattern of consumption. However, this second approach can produce a time shift between the tank's filling and releasing phases and the off-peak and peak electricity tariff periods, due to the natural variability of the water demand, thus causing an economic benefit reduction. This phenomenon can be understood considering that in a day characterized, for example, by lower water consumption, during the first hours of the day (typically corresponding to the off-peak tariff period), the tank will be filled more quickly. As a consequence, the switching off level will be reached earlier, and the tank will begin to empty before the end of the off-peak tariff period. Thus, the tank will not be full at the beginning of the peak tariff period and the time shift mentioned above will occur.

The optimal control of pumping stations has been widely studied in recent decades. The pump scheduling (PS) 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. Jowitt & Germanopoulos 1992), nonlinear programming (e.g. Chase & Ormsbee 1993; Yu *et al.* 1994), dynamic programming (e.g. Lansey &

Awumah 1994; Nitivattanannon *et al.* 1996), branch and bound methods (Menke *et al.* 2016) or algorithms based on metaheuristics concepts, such as evolutionary algorithms (e.g. Savic *et al.* 1997; Van Zyl *et al.* 2004; Farmani *et al.* 2006; Martinez *et al.* 2007; Salomons *et al.* 2007; Giacomello *et al.* 2013), simulated annealing algorithms (e.g. Goldman & Mays 2000), ant colony algorithms (e.g. Lopez-Ibanez *et al.* 2008; Lopez-Ibanez *et al.* 2011) and operational graph optimization (Price & Ostfeld 2016). In most of these studies, the PS 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 steps is considered, 24 binary values are coded for each pump. Lopez-Ibanez *et al.* (2008, 2011) developed an alternative technique for the characterization of the PS 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 PS research activity developed in recent years, only a few studies concerning the approach based on fixed trigger levels (FTLs) have been developed (e.g. Blinco *et al.* 2016). This fact can be clearly understood considering that the PS approach requires the utilization of forecasting and optimization algorithms to determine the optimal solution daily, unlike the 'FTL' approach. With reference to both approaches, it is worth mentioning that proposed by Kazantzis *et al.* (2002), which provides a hybrid solution based on the application of different trigger levels for the peak tariff period 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 approach, as well as that based on PS, clearly needs the forecasting of the water consumption for the next 24 hours and application of an optimization algorithm for the periodical (daily) identification of the optimal solution. The same authors pointed out that an approach simply based on different trigger levels depending on peak and off-peak tariff periods of the

day, and in particular on a high switching on trigger level constant during all the off-peak tariff periods and a low switching off trigger level constant during all the peak tariff periods, could be effective in terms of energy cost reduction, since it ensures that the volumes pumped during off-peak and peak tariff periods are maximized and minimized respectively. However, when using such an approach, hereinafter referred to as reduced fixed trigger level (RFTL), pump switching on and off may be a limiting factor, as, if the reduced trigger level interval in which the pumps have to operate is too narrow, the number of pump switchings per hour may become excessive (see also Lansey & Awumah 1994).

Taking the cue from Alvisi & Franchini (2016), in this paper an alternative approach for pump control is investigated: like the FTL and RFTL approaches, this is based on the water level in the tank, but is developed so that the pumps' switching on/off occurs 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 (VTLs) avoid the shifting of the tank filling and releasing phases from the peak and off-peak electricity time periods, and, differently to the RFTL approach, do not lead to a very high number of pump switchings on and off. In the meantime, this approach does not require the water demand forecast and the application of optimization algorithm to find the optimal time plan.

Summing up, the approaches considered and compared in this study are: (1) the PS, which is based on the solution of an optimization problem performed at the beginning of each day in order to define which pumps are 'on' or 'off' in each hour, (2) the FTL, in which the pumps are switched on/off according to the occurrence of a fixed water level in the tank, (3) the RFTL, in which, similarly to the FTL, the pumps are switched on/off according to the occurrence of a fixed water level in the tank, but the switching on trigger level is high and constant during all the off-peak tariff periods and the switching off trigger level is low and constant during all the peak tariff periods, and (4) the method here proposed and named 'variable trigger level' (VTL), in which the trigger levels change 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.

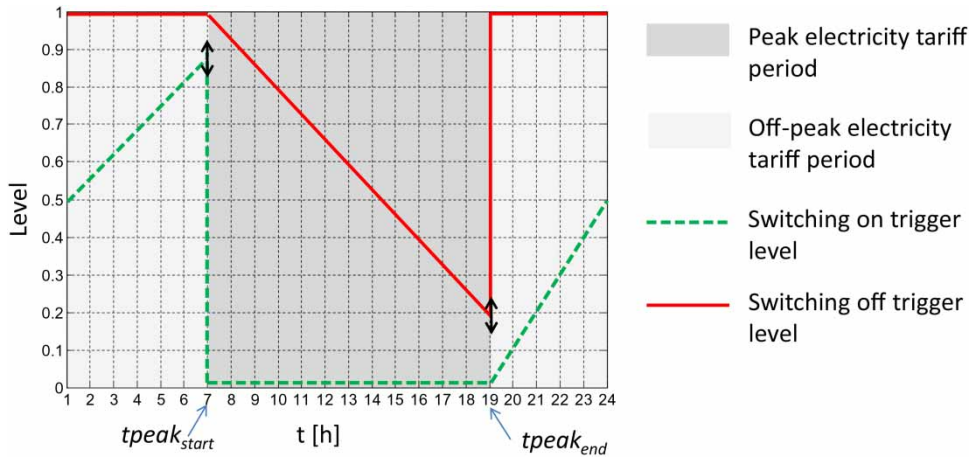
In the subsequent sections the proposed approach is presented and then applied to real case studies. The results are compared with those obtained through the application of other approaches and, lastly, some conclusive considerations are provided.

## THE VTL APPROACH

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 or a district. More precisely, in this study attention is focused only on a single pumping station and the subsequent tank, disregarding the water distribution system downstream of the tank. Leakages are considered together with actual water consumption in the total discharge released by the tank. Indeed, leakages could vary according to the level within the tank (Pacchin *et al.* 2017), and this effect could be limited either by placing a pressure reducing valve at the outlet point of the tank or by modifying the pump control in order to reduce the level during the night, but this aspect is not addressed here.

The tank allows for a compensation of the total water consumption over an assigned time window  $T_c$ , e.g.  $T_c = 24$  hours. Over the same time window, let the energy tariff be fixed. In particular, let  $n_t$  be the number of time periods making up the time window  $T_c$  which are characterized by different energy tariffs. In the following, let us assume  $T_c = 24$  hours and  $n_t = 2$ , that is, within the day, two time periods exist, featuring a peak energy tariff and an 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  $n_t = 2$ , i.e. two tariff periods exist, where the lowest tariff period typically includes the night hours, and 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  $t_{peak_{start}}$  and  $t_{peak_{end}}$  be the starting and ending time instants of the peak tariff



**Figure 1** | Layout of the VTLs during peak and off-peak tariff periods. The black arrows highlight the switching on and switching off levels at the time instants  $t_{peak\_start}$  and  $t_{peak\_end}$ . Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/hydro.2017.141>.

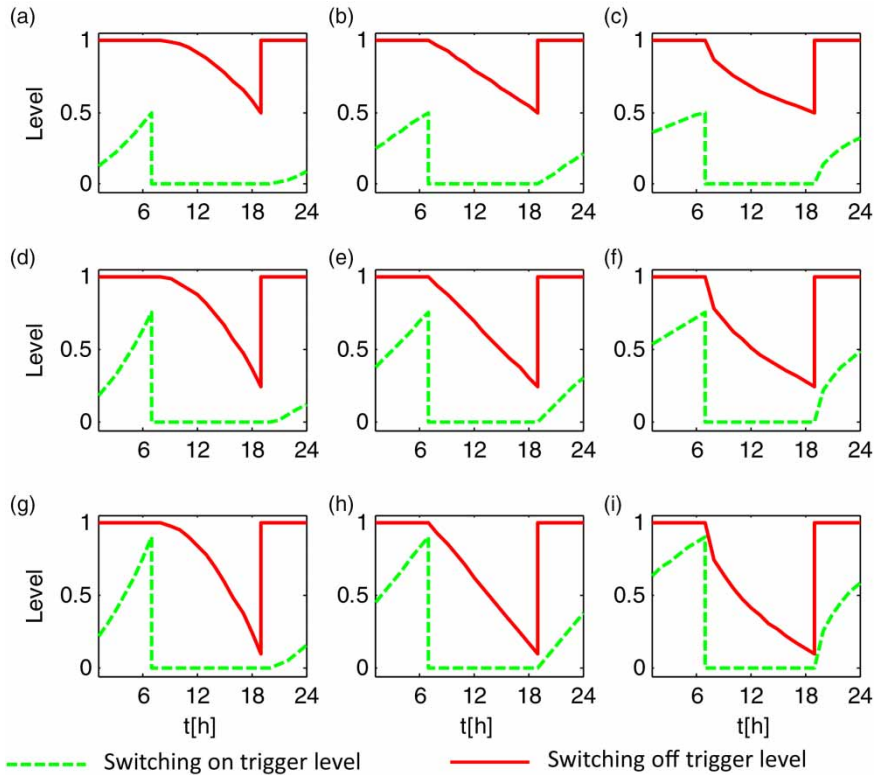
period respectively. Clearly, since  $n_t = 2$ ,  $t_{peak\_start}$  represents also the ending time instant of the off-peak period started in the previous day, whereas  $t_{peak\_end}$  coincides with the starting time instant of the off-peak period, which will end in the subsequent day. The proposed approach for the control of the switching on/off of the pumps is based, as in the FTL approach, on tank levels. In the proposed approach, 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 VTLs allow for the filling and releasing phases of the tank to coincide with the off-peak and peak electricity tariff periods, respectively.

In more 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  $t_{peak\_start}$  (see green dashed 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  $t_{peak\_end}$  (see red continuous line in Figure 1). In this way, the system is forced to ensure large and small volumes of water are stored within the tank at the end of the off-peak and peak tariff periods, respectively.

In particular, in Figure 1 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 are assumed to be linear. Furthermore, 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.

Indeed, still maintaining the switching off trigger level constant and equal to the maximum level in the tank during the off-peak tariff period and the switching on trigger level constant and equal to the minimum level in the tank during the peak tariff period, 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 could be defined by any power law relationship (e.g. linear, parabolic, cubic, etc.). In Figure 2, several different examples of VTLs are shown. In particular, the switching on trigger levels during the off-peak tariff period and the switching off trigger levels during the peak tariff period shown in the first column of Figure 2 (i.e. Figure 2(a), 2(d) and 2(g)) are produced by a power law relationship with an exponent equal to 2. The trigger levels shown in the second column of Figure 2 (i.e. Figure 2(b), 2(e) and 2(h)) are produced by a linear relationship (i.e. exponent equal to 1). Finally, the trigger levels shown in the third column of Figure 2 (i.e. Figure 2(c), 2(f) and 2(i)) are produced by a power law relationship with an exponent equal to 0.5. The trigger levels shown in Figure 2 differ also for the values of the maximum and minimum levels at the time



**Figure 2** | Example of different VTLs obtained considering different power law relationships and maximum and minimum levels at the time instants  $t_{peak\_start}$  and  $t_{peak\_end}$ .

instants  $t_{peak\_start}$  and  $t_{peak\_end}$  (these levels are also highlighted with a black arrow in Figure 1). In particular, in Figure 2(a)–2(c) (first row) both the switching on trigger level at  $t_{peak\_start}$  and the switching off trigger level at  $t_{peak\_end}$  are fixed at 50% of the tank height. In Figure 2(d)–2(f) (second row) the switching on trigger level at  $t_{peak\_start}$  is fixed at 75% of the tank height and the switching off trigger level at  $t_{peak\_end}$  is fixed at 25% of the tank height. Finally, in Figure 2(g)–2(i) (third row) the switching on trigger level at  $t_{peak\_start}$  and the switching off trigger level at  $t_{peak\_end}$  are fixed at 90% and 10% of the tank height respectively. Note that varying the maximum and minimum values at the time instants  $t_{peak\_start}$  and  $t_{peak\_end}$  has an impact on volume stored within the tank at the end of the off-peak and peak period respectively. Similarly, different power law relationships can force the water level within the tank to be increased or decreased more quickly during the off-peak and peak periods. For example, the trigger levels shown in Figure 2(i) should lead to (a) larger and lower volumes stored within the tank at the end of the off-peak

and peak period, respectively and (b) quicker filling and emptying of the tank during the off-peak and peak period respectively, than the trigger levels shown in Figure 2(a). Clearly, this also has an impact on the energy cost and on the number of pump switches, as numerically shown in the subsequent section. Operatively, 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, and the maximum and minimum levels at the time instants  $t_{peak\_start}$  and  $t_{peak\_end}$ , could be fixed in such a way as 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 (Lansley & Awumah 1994). 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  $n_t = 2$  time periods and (b) the values of the maximum and minimum levels at the



time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$ . The objectives (to be minimized) are (a) the energy cost and (b) the number of pump switches over the  $T_c$  time window. For the solution of this multi-objective problem use of the NSGA-II (Deb *et al.* 2002) algorithm is made.

## CASE STUDIES

The VTL approach was applied to two real case studies. The first one is represented by a pump feeding a small elevated tank located at the inlet point of a district. The tank has a cylindrical shape with a volume of  $200 \text{ m}^3$ . The daily average demand of the district is around  $10 \text{ L/s}$  and the hourly pattern of total water consumption of the district for a generic working day is available. Energy tariffs for the  $n_t = 2$  time periods, peak and off-peak periods, in which the  $T_c = 24$  hours time window is subdivided, are equal to  $0.5 \text{ €/kWh}$  and  $0.1 \text{ €/kWh}$ , respectively. In particular, the peak period starts at  $t_{peak_{start}} = 7$  a.m. and ends at  $t_{peak_{end}} = 7$  p.m. During the remaining hours of the day the off-peak tariff is applied. This simple case study was used to highlight the effects of using the different power law functions representing the pattern of the switching on/off trigger levels and the maximum and minimum levels at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  shown in Figure 2, and compare them with the FTL and RFTL approaches shown in Figure 3 (Kazantzis *et al.* 2002).

The second case study considers a 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. The tank has a truncated cone shape with a volume of  $1,000 \text{ m}^3$ . Observed

data concerning the discharges released by the tank, thus corresponding to the total water distribution system inlet, at 1 hour time steps are available. Energy tariffs for the  $n_t = 2$  time periods, peak and off-peak periods, in which the  $T_c = 24$  hours time window is subdivided, are equal to  $0.5 \text{ €/kWh}$  and  $0.1 \text{ €/kWh}$  respectively. In particular, the peak period starts at  $t_{peak_{start}} = 7$  a.m. and ends at  $t_{peak_{end}} = 7$  p.m. During the remaining hours of the day the off-peak tariff is applied.

This second case study was used to show the identification of the optimal shape of the law connecting the VTLs and maximum and minimum levels at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  for the specific case considered by solving the multi-objective problem, and for a comparison with the FTL and PS approach. Operatively, for the VTL approach, within the optimizing phase, it was assumed that all of 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 one characterizing the switching off, for all of the  $n_p = 3$  pumps was searched for (i.e. 2 decision continuous real variables). On the other hand, for the  $n_p = 3$  pumps, different maximum and minimum levels at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  were searched for (i.e. 6 decision continuous real variables, for a total of  $2 + 6 = 8$  decision variables). In particular, the parameters characterizing the patterns of the VTLs 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 VTLs, the proposed approach

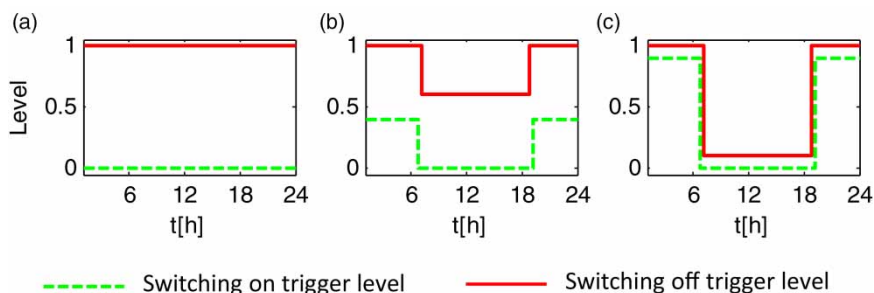


Figure 3 | Layout of (a) FTLs and (b) and (c) a couple of RFTLs.

was applied and verified taking account of the observed time series of hourly discharges actually released by the tank for two weeks, the former pertaining to the winter period and thus characterized by rather low water consumption, the latter pertaining to the summer period and thus characterized by very high water consumption.

For the application of the FTL approach, the switching on/off levels of each pump were assumed constant over the  $T_c = 24$  hours time window, but rather than fixing them at the minimum and maximum tank water level respectively, as done in case study 1, they were fixed through an optimization process aimed at minimizing the energy cost over the  $T_c = 24$  hours time window considering the average day of hourly water consumption of the entire system served by the tank. Indeed, these fixed constant but optimized switching on/off levels should lead to slightly lower energy costs, at least for the average day of hourly water consumption, than the switching on/off levels fixed at the minimum and maximum tank water level respectively (Creaco *et al.* 2016). Similarly to the VTL, the FTL approach was subsequently applied for the control of the pumps, taking account of the observed time series of hourly discharges actually released by the tank during the two weeks considered.

The PS approach, given its very nature, was instead applied considering directly the observed time series of hourly discharges actually released by the tank for the two weeks, 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 that minimized the energy cost. 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 was exactly known. In other words, it was assumed that the water consumption was forecasted without

any error. Clearly, within a real operational framework, the total water consumption to be used within the optimization process for the definition of the PS should be that actually forecasted, and even though the forecasting errors for the next 24 hours can be very small (see, for example, Alvisi & Franchini 2017), this would lead to an efficacy of the PS approach that is at most equal to, but actually lower than the one obtainable by using perfect forecasts.

## ANALYSIS OF THE RESULTS

Considering the application of the VTL approach to the first case study, the daily energy costs and number of pump switching on/off obtained considering each of the nine different VTL configurations shown in Figure 2 are reported in Tables 1 and 2 respectively. By analysing the energy costs it can be observed that, when 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 are the same (i.e. considering each column of Table 1 at a time), variations in the values of the maximum and minimum levels at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  lead to rather different energy costs. In particular, as the maximum level at the time instant  $t_{peak_{start}}$  increases and the minimum level at the time instant  $t_{peak_{end}}$  decreases, the energy cost decreases, with the higher and lower water volume stored within the tank at the end of the off-peak and peak tariff periods, respectively. On the other hand, it can be observed that when the maximum and minimum levels at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  are the same (i.e. considering each row of Table 1 at a time) the shapes of the functions characterizing the trigger levels only slightly affect the energy costs, whereas they

**Table 1** | Case study 1: energy costs [€] for each of the VTL control solutions shown in Figure 2

		Exponent of the power law relationship characterizing the trigger levels					
		2		1		0.5	
Maximum and minimum levels at the time instants $t_{peak_{start}}$ and $t_{peak_{end}}$	50% – 50%	(a)	44.3	(b)	43.2	(c)	42.5
	75% – 25%	(d)	41.0	(e)	40.7	(f)	39.9
	90% – 10%	(g)	38.8	(h)	38.7	(i)	38.0

Note: Each value reported in the table and indicated with a letter from (a) to (i) refers to the corresponding case of Figure 2.

**Table 2** | Case study 1: number of pump switching on/off for each of the VTL control solutions shown in Figure 2

		Exponent of the power law relationship characterizing the trigger levels					
		2	1		0.5		
Maximum and minimum levels at the time instants	50%–50%	(a)	3	(b)	3	(c)	3
$t_{peak\_start}$ and $t_{peak\_end}$	75%–25%	(d)	3	(e)	4	(f)	5
	90%–10%	(g)	5	(h)	5	(i)	7

Note: Each value reported in the table and indicated with a letter from (a) to (i) refers to the corresponding case of Figure 2.

have a more significant impact on the number of pump switching on/off (see Table 2). In particular, moving from functions with an exponent equal to 2 (first column in Table 2) to 1 (second column in Table 2) to 0.5 (third column in Table 2), a general increase in the number of pump switching on/off can be observed.

The results obtained for the control of this simple case study by using the VTLs shown in Figure 2 were also compared with the FTL approach and RFTL approach (Kazantzis *et al.* 2002) shown in Figure 3. In particular, in the FTL approach of Figure 3(a), it was assumed that the pump switches off at the maximum level of the tank and switches on at the minimum level, whereas in the RFTL approach of Figure 3(b) the switching on trigger level during the off-peak tariff period is fixed constant at 40% of the tank height and the switching off trigger level during the peak tariff period is fixed constant at 60% of the tank height. Similarly, in the RFTL approach of Figure 3(c), the switching on trigger level during the off-peak tariff period and the switching off trigger level during the peak tariff period are fixed constant and equal to 90% and 10% of the tank height, respectively. Clearly, with this latter solution the water level within the tank is forced to oscillate in a very narrow band. Nonetheless, this case was considered in order to point out the different behaviour of the VTL and RFTL.

By analysing the corresponding results provided in Table 3, and comparing them with those reported in Tables 1 and 2, it can be observed that the FTL (see first column of Table 3) leads to a very low number of pump switching on/off, but also to very high energy costs, with the filling and emptying of the tank not being in phase with the off-peak and peak tariff period respectively. By using reduced

**Table 3** | Case study 1: energy costs and number of pump switching on/off for the FTL and RFTL control solutions shown in Figure 3

	FTL	RFTL	
	(a)	(b)	(c)
Energy costs [€]	53.7	47.9	37.9
Number of pump switching on/off	2	3	13

Note: Each column indicated with a letter from (a) to (c) refers to the corresponding control solution of Figure 3.

trigger levels, and in particular imposing a high switching on trigger level during the off-peak tariff period and a low switching off trigger level during the peak tariff period, the energy costs reduce, becoming for the case (c) of Figure 3 (see last column of Table 3) equal to 37.9 €/day in line with those of case (i) of the VTL approach (38 €/day, see Figure 2(i) and Table 1 column 3, row 3), but in the meantime the number of pump switching on/off significantly increases, being equal to 13, which is definitively higher than that of case (i) of the VTL approach (equal to 7, see Figure 2(i) and Table 2 column 3, row 3) with the pump being forced to operate in very reduced tank water level intervals, making the application of this control solution in real cases not advisable (Lansley & Awumah 1994; Kazantzis *et al.* 2002).

Considering now the second case study, the Pareto front obtained by the application of the NSGA-II algorithm for the multi-objective optimization of the parameters characterizing the VTLs is shown in Figure 4. For some solutions, the VTLs of one of the three pumps making up the pumping station are also shown. It is worth remembering that the shape of the functions characterizing the VTLs in the different time periods in this numerical application is assumed to be the same for all of the three pumps. In particular, by comparing solutions (a) and (b) of Figure 4 it can be observed that as the switching on level at the end of the off-peak tariff period (i.e. at  $t_{peak\_start}$ ) increases and the switching off level at the end of the peak tariff period (i.e. at  $t_{peak\_end}$ ) decreases, the system is forced to store larger and smaller volumes of water within the tank at the end of the off-peak and peak tariff periods respectively, with a direct consequence in terms of energy cost reduction. On the other hand, this leads to an increase in terms of the number of pump switches.



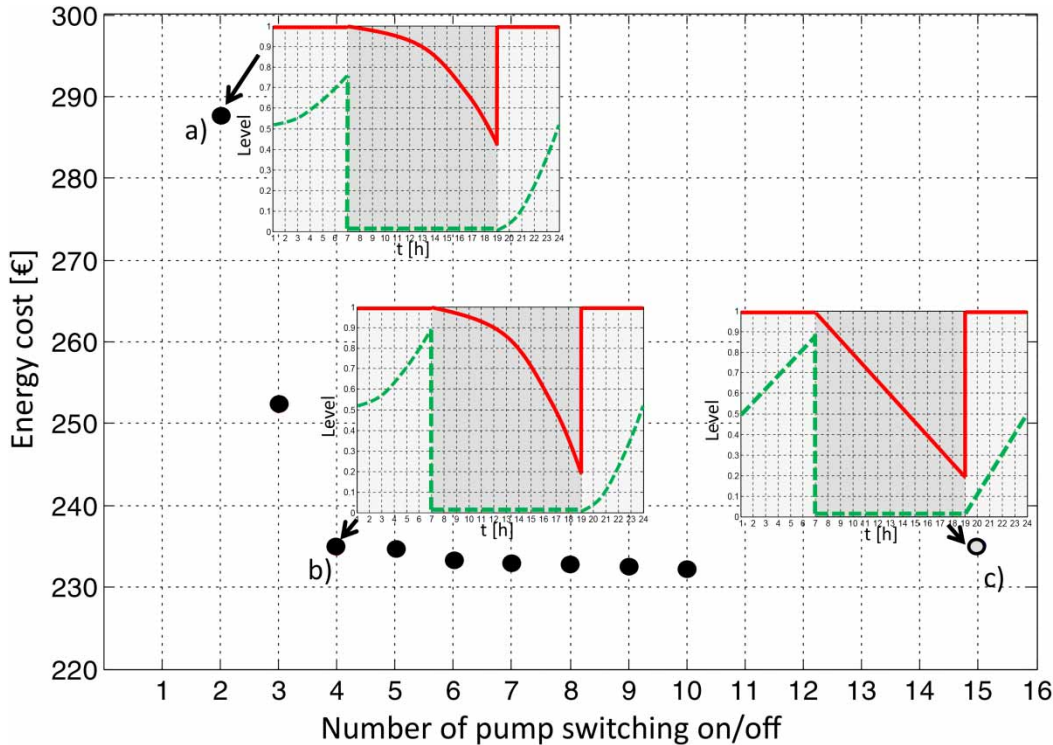


Figure 4 | Case study 2: Pareto front of the VTL solutions.

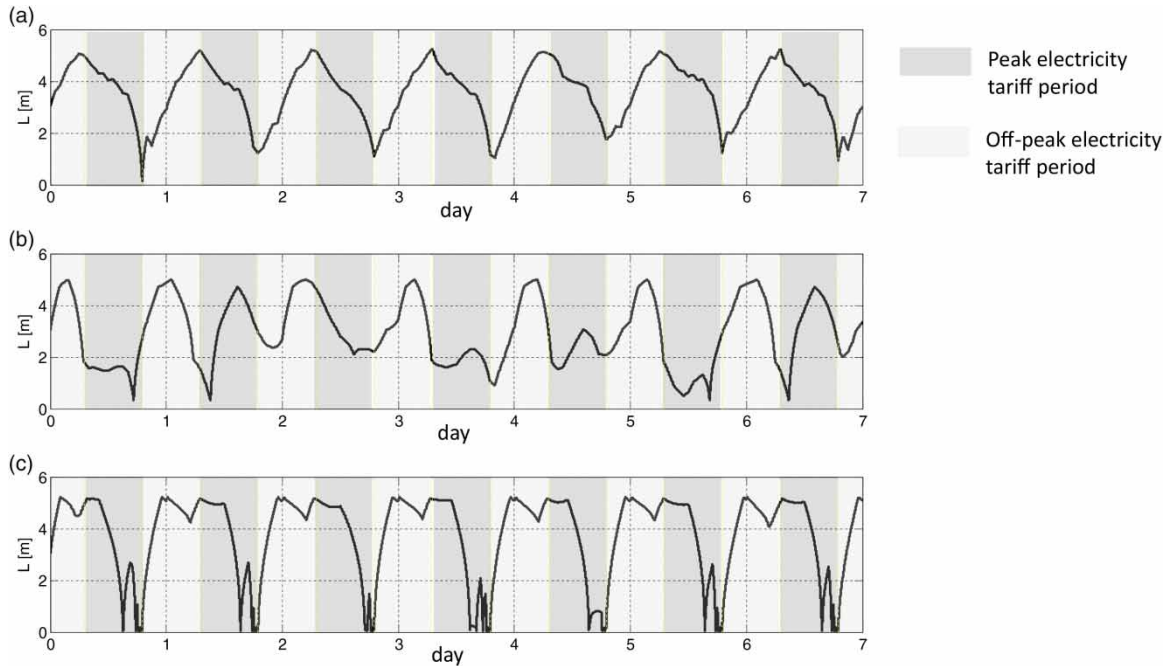
Considering instead solutions (b) and (c) (the latter plotted in Figure 4 with a different symbol since it does not belong to the Pareto front), it can be observed that, when the maximum and minimum level at the time instants  $t_{peak_{start}}$  and  $t_{peak_{end}}$  are the same, application of a proper exponent value of power law function characterizing the pattern of the VTL (see solution (b)), allows for a reduction of the number of pump switches with respect, for example, to a linear variation of the trigger level (see solution (c)), with the total energy cost being more or less the same. Solution (b), indicated in Figure 4, represents a good compromise between energy costs and number of pump switches. This solution was thus taken as reference and the corresponding VTLs used for the control of the pumps taking account of the observed time series of hourly discharges actually released by the tank for the two weeks considered.

In Table 4, the corresponding energy costs together with the average number of daily pump switchings on and off obtained for each of the two weeks are provided. As can be observed, for both the weeks the VTL approach leads

Table 4 | Case study 2: energy costs obtained for two weeks by using different pump control approaches (week 1 – winter period; week 2 – summer period)

Pump control approach	Week 1		Week 2	
	Energy costs [€]	Average no. of pump switching on/off per day	Energy costs [€]	Average no. of pump switching on/off per day
PS	1,648	4	1,945	5
FTL	2,057	3	2,371	4
VTLs	1,649	4	1,945	5

to energy costs that are equivalent to those provided by the PS approach, and definitively lower than those provided by the FTL approach. This can be clearly explained considering that the VTL and the PS methodologies ensure that large and small water volumes are stored within the tank at the end of the off-peak and peak tariff periods, respectively, as can be observed in Figure 5 where, for the sake of example, the patterns of the water level within the tank obtained by using the three approaches for the first week considered, i.e. the one pertaining to the winter period, are shown. Instead, it can be clearly observed that by using



**Figure 5** | Case study 2: tank water levels for week 1 (winter period) obtained by (a) PS, (b) FTL and (c) variable level trigger.

the FTL approach, a sort of shifting for the tank filling and releasing phases from the off-peak and peak tariff periods occurs (see Figure 5(b)), and in particular quite a large amount of water tends to be stored within the tank at the end of the peak electricity tariff period of some days (see for example the second day), thus leading to a larger energy cost than the other two control methodologies. Indeed, it is also worth remembering that, as regards the FTL, the switching on/off levels were fixed through an optimization process aimed at minimizing the energy cost considering the *average day* of hourly water consumption of the system served by the tank, and they were subsequently applied for the control of the pumps taking account of the observed time series of hourly discharges actually released by the tank during the week (as for the VTL). Furthermore, as regards the PS, 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.

Finally, it is worth observing that the average number of pump switching on/off during the day for the VTL is very

low and in line with those of the other two approaches, as confirmed by the values provided in Table 4, even though this switching on/off tends to be concentrated around some hour of the day, at the end of the peak tariff period (Figure 5(c)).

Summing up, the results obtained with reference to the specific case study considered here highlight the efficacy of the proposed approach for the control of a pumping station feeding a tank located at the inlet point of a water distribution system. Indeed, it allows for a significant reduction of the energy costs with respect to the FTL approach, and comparable with the energy cost of the PS, 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.

## CONCLUSIONS

A new approach for the control of a pumping station feeding a tank located at the inlet point of a water distribution system or district is presented. The proposed

approach is based on water levels reached in the tank, like for the traditional FTL approach, 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 case studies, and comparison with the results provided by more traditional methodologies, shows that the proposed approach allows for achieving energy costs that are definitively lower than those obtainable by using FTLs, and comparable with those obtainable by using RFTLs and PS. In particular, the lower energy costs achievable with the proposed approach with respect to the FTL can be understood considering that the time VTL approach 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 an FTL approach is used. Thus, like the RFTLs and the PS approaches, the proposed approach ensures that large and small water volumes are stored in the tank at the end of the off-peak and peak tariff periods, respectively. On the other hand, unlike the RFTLs, the proposed approach does not lead to a large number of pump switchings on and off and unlike the PS, 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.

Finally, it is worth remembering that all these considerations apply for a specific system made up of a pumping station directly feeding a single tank located at the inlet point of the network, disregarding the water distribution system downstream of the tank and the effects of the tank levels on leakages. Further developments will be the application of the proposed approach to more complex systems, including situations (a) with different tanks, also located far from the pumping station, (b) where some parts of the system are directly supplied by the pumps, and (c) where the effects of the pump control on leakages are explicitly taken into account.

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