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Water Distribution Networks Optimization: a real case study

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Abstract: This paper presents a project aimed at the optimization of a water distribution network located in Trento (Italy). Several in-depth hydraulic studies have been conducted in order to perform hardware modifications through sectorization procedures. Advanced Process Control methods have been designed in order to optimally and automatically manage the net pressure and the scheduling of the involved pumping stations. Net pressure has been minimized through two-layer Model Predictive Control techniques, while advanced logics have been designed for the pumps scheduling. The developed Advanced Process Control system has been successfully installed on the considered network and the achieved results are here illustrated.

Keywords: Water Distribution Network, Pressure Minimization, Pumping Stations Scheduling, Model Predictive Control, Energy Efficiency.

1. INTRODUCTION

In the last years, water industry is gaining the attention of control/automation engineers and researchers. The presence of different conflicting objectives, e.g. fulfilling customers' water demand versus the minimization of the water losses/leakages, represents an interesting challenge in the Water Distribution Networks (WDNs) management.

A significant problem that often appears in WDNs is represented by water loss: this phenomenon has non-negligible social and economic impacts. For this reason, the detection, prevention and prediction of water losses are topics under the attention of the research community aiming at their avoidance or at least their reduction. A leakage detection and isolation method is proposed by Pérez et al. (2009): exploiting Barcelona network calibrated model, the resulted pressure estimations are compared to the real measurements, detecting the significant discrepancies. An optimal sensor placement methodology has been applied based on the pressure sensitivity matrix to the leakage presence in the network; the obtained optimization problems are solved through a genetic algorithm. An approach for the localization of leaks is proposed by Steffelbauer et al. (2014): pressure sensors alongside a calibrated hydraulic model are used and a differential evolution algorithm solves the leakage localization. The tied relationship between water losses and operational pressure in WDNs has been proven in different research activities (e.g. Ghorbanian et al. (2015), Walski et al. (2006)). Lambert et al. (2013) addressed the modelling of leakage and pressure management. It has been shown that high pressure leads to increased water loss and to pipe damages. A real time pressure control methodology for leakage reduction by pressure control valves is presented by Campisano et al. (2016) and by Nicolini et al. (2009). The potential of Model Predictive Control (MPC)-based approaches in WDNs has been proven in different research works. In particular, Grosso et al. (2017) propose a distributed MPC approach designed to work in a cooperative manner for controlling flow-based networks showing periodic behaviours. Local controllers cooperate in order to enhance the performance of the whole flow network avoiding the use of a coordination layer; this approach has been tested on Barcelona case study. A health-aware MPC that includes an additional goal to extend the components and system reliability has been proposed by Pour et al. (2018): the MPC model uses an extra parameter varying equation that considers the control action as a scheduling variable. A small part of a real water network is used as a case study for illustrating the performance of the proposed approach. Non-linear economic MPC of WDNs is proposed by Wang et al. (2017): an economic MPC strategy is designed with a two-layer control scheme.

This paper describes a project aimed at the optimization of a subnetwork of a WDN located in Trento (Italy). Two distinct phases have characterized the project: the first phase has been focussed on the creation of District Metered Areas (DMAs) within the WDN while the design and installation of an Advanced Process Control (APC) system have been performed in the second phase. The APC system aims at improving the energy efficiency of the subnetwork through an automatic and smart management of the involved pumping stations while minimizing the average pressure of the considered DMA. The paper is organized as follows: Section 2 describes the considered WDN, focusing on the subnetwork that has been optimized. The algorithm for the automatic and smart management of the pumping stations is reported in Section 3, while Section 4 describes the developed MPC scheme that minimizes the DMA pressure. Field results are reported in Section 5 and conclusions are summarized in Section 6.

2. WATER DISTRIBUTION NETWORK DESCRIPTION

The considered WDN refers to Trento, a city located in the north of Italy. It provides water for about 100000 inhabitants. The WDN extends for more than 600 km and it is characterized by freshwater sources, underground aquifers, water tanks and reservoirs; furthermore, the WDN counts thousands of pipes and nodes and hundreds of valves and pumps. Before designing and installing the APC system, hardware modifications on the WDN have been performed, aimed at the creation of District Metered Areas (DMAs) (D'Ercole et al. (2018), Morrison (2004), Morrison et al. (2007)). Fig. 1 reports the previous WDN pressure distribution, simulated through InfoWorks WS software (HR Wallingford). Areas characterized by a pressure lower than 2.5 bar (yellow, light-red and red) can be noted, together with areas with a pressure greater than 4 bar (blue, dark blue and purple). The conducted simulations have certified that the WDN was characterized by an excessive pressure in most of its valley floor extension, essential to serve utilities located at higher altitudes. This called for a sectorization study ending up, at the time of the present project, in the creation of some districts. Among the many benefits achievable through the sectorization, the most interesting effects are the contribution offered to the mitigation of the water losses and the reduction of the maintenance costs.

The present paper refers to a subnetwork that includes one DMA (Fig. 2: *DMA1*) and three pumping stations (Fig. 2: *PS1*, *PS2*, *PS3*). *DMA1* represents the bottom of the valley of Trento. The tank that is filled by *PS1* supplies water to *DMA1* and the regulation of the pressure of the pipes between the tank and *DMA1* is performed by a PRV (Pressure Reducing Valve). Furthermore, a subpart of the water contained in the tank filled by *PS1* supplies the tank where *PS2* and *PS3* get water. *PS2* supplies a single tank while *PS3* supplies two tanks located at different altitudes; the *PS3* water path is regulated by an on/off valve (see Fig. 2).

Plant measurements (e.g. water level within each tank, pressures at critical nodes, flow rates…) are available through remote terminal units that are interrogated with sampling periods that are characterized by a lower bound. For example, all measurements related to the PRV and to the bottom of the valley of Trento (pressures at critical nodes) are refreshed with a period greater than or equal to 15 minutes. In order to optimally and automatically manage the PRV pressure

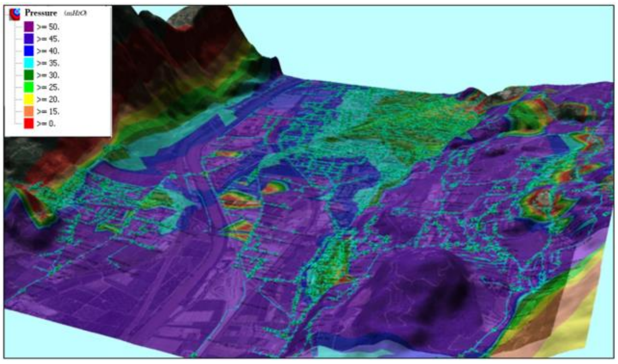

Fig. 1. WDN pressure distribution (1 bar ≈10.19 mH_2O): the high pressure at the bottom valley called for the creation of DMAs.

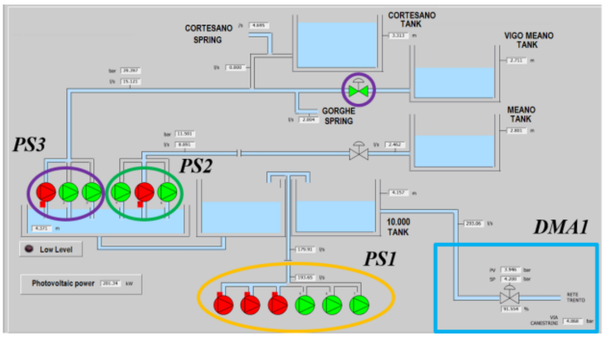

Fig. 2. Scheme of the considered WD subnetwork.

set-point and the on/off of the pumps and valves, an APC system has been designed. Being a multivariable process, its control is a nontrivial task for a human operator. In fact, it is required to ensure a correct behaviour of the pressure at critical nodes and within the pipes, to maintain the tanks level at the desired values exploiting also natural energy sources (e.g. photovoltaic power), and to smartly switch the pumps of each pumping station.

3. PUMPING STATIONS SCHEDULING ALGORITHM

As stated in the previous Section, three pumping stations (see Fig.2: *PS1*, *PS2*, *PS3*) characterize the case study of the present paper. A scheduling algorithm for each pumping station has been designed. The scheduling algorithm has been customized for each pumping station and the common concepts and ideas are reported in the following. All the set physical specifications have been obtained through InfoWorks WS software simulations. Subsection 3.1 details the customization of the algorithm for *PS1*.

Table 1 reports the main features of the pumping stations; the third column represents the minimum and maximum number of switched on pumps to be guaranteed by the APC system in order to avoid, for example, high pressure on the pipes; the fifth column reports the sampling time related to the algorithm of each pumping station. The sampling time has been defined based on the assigned control specifications and taking into account the time that each pump/valve requires for its switch on/off. Table 2 reports the main features of the tanks supplied by the pumping stations: here *PS1*-Tk1 and *PS2*-Tk1 denote the tanks supplied by *PS1* and *PS2*, while *PS3*-Tk1 and *PS3*-Tk2 denote the tanks supplied by *PS3*. The APC system must guarantee that the level of each tank violates, as little as possible, the imposed safety constraints. Furthermore, the maximum value of the lifting pressure (related to the pipes that link each pumping station with the related tank/tanks) has been indicated in Table 2: the APC system must manage the switched on pumps of each pump station in order to respect the upper constraint related to the lifting pressure. In addition to the level safety constraints, a set of more conservative constraints have been defined, named *tube* constraints. Their use for *PS1* will be clarified in subsection 3.1.

In order to increase the pumps lifetime and to minimize the pumps maintenance costs, time constraints have been defined. First, each pumping station must respect the following constraint: a new pump switch on can be performed only if a

Table 1. Pumping stations main features.

Pumping Station	No of Pumps	Min-Max Switched On Pumps	No of Valves	APC Sampling Time (min)
PS1	6	1-4	0	2
PS2	3	0-2	0	2
PS3	3	0-1	1	2

Table 2. Tanks main features.

Tank	Safety Constraints (m)	*Tube* Constraints (m)	Pressure Constraints (bar)
PS1-Tk1	2.5-5	adaptive	not required
PS2-Tk1	2.5-3.1	2.7-2.8	0-25
PS3-Tk1	2.9-3.3	3-3.1	0-60
PS3-Tk2	1.5-3.25	2.7-2.7	

Table 3. Pumps time constraints (min).

Pumping Station	Downtime Lower Constraint	Uptime Lower Constraint	Uptime Upper Constraint
PS1	720	120	10080
PS2	10	10	1440
PS3	10	10	1440

Table 4. Pumps "move suppression" time constraints (min).

Pumping Station	*PS1*	*PS2*	*PS3*
***Tube* Sw. On/Off**	30/90	45/ not required	not required

minimum time since last switch on has been elapsed. For example, this lower constraint has been set to 5 minutes for *PS1*. Furthermore, the constraints reported in Table 3 must be observed by the scheduling algorithm. Considering *PS1*, it is preferable that a pump is switched on only if at least 12 hours (720 minutes) have elapsed since its last switch off. Furthermore, if a pump has been switched on, it is preferable that at least two hours (120 minutes) have elapsed before switching off. Finally, it is preferable that a pump remains in switched on status (continuously) no more than seven days (10080 minutes). Finally, in order to limit the controller moves, a set of "move suppression" factors (from a MPC theory point of view) has been defined for each pumping station (see Table 4), related to its level *tube* constraints (based on the tanks geometry and on the mean in/out flow rates). Considering *PS1*, the next pump switch on action can be performed only if 30 minutes have passed since last pump switch on action. A similar scheme applies to the switch off procedures: for *PS1*, 90 minutes are required (see Table 4).

Taking into account the parameters reported in Tables 1-4 and the previous description, the generic pumping stations algorithm, at each control instant, is based on the following steps:

- Acquire plant measurements related to the pumping station (e.g. levels, pressures, pumps status, valves status, in/out tank flow rates) through the SCADA (Supervisory Control And Data Acquisition) system.
- Perform bad detection procedures on the acquired plant signals, in order to detect validity limits violation, freezing/rate of change conditions; if bad detection procedures give positive results, no moves are performed by the algorithm at the current control instant and the next steps are skipped.
- Update the uptime (time since last switch on) and the total uptime (total switch on time since algorithm start up) of each pump with an on status.
- Update the downtime (time since last switch off) and the total downtime (total switch off time since algorithm start up) of each pump with an off status.
- Increase the counter (F) of failed switch on attempts for each pump, for example due to communication problems or to an undetected anomaly.
- Compute, for each pump, a switch on/off priority (Sw_{ON}, Sw_{OFF}), based on the following formulas:

$$Sw_{ON} = Sw_{ON_0} + R - fix(\frac{F}{S}) \tag{1}$$

$$Sw_{OFF} = Sw_{OFF_0} - R \tag{2}$$

$$R = fix(\frac{M - T}{U}) \tag{3}$$

where Sw_{ON_0} and Sw_{OFF_0} represent the default on/off priorities of each pump (default value equal to 1, see subsection 3.1 for the customization related to *PS1*), F is the counter previously defined and S is a scaling factor. M represents the maximum value among the pumps total uptime at current control instant, T represents the current total uptime of the considered pump, U is the uptime upper constraint reported in Table 3. The fix operator rounds its argument to the nearest integer smaller than or equal to it.

- Compute the number of pumps to be switched on/off, based on their ranking (see Table 5: a smaller ranking number represents a greater priority), on pumps uptime upper constraints (see Table 3) and respecting the imposed minimum time since last switch on. Note that the specifications reported in Table 5 require either a switch on or a switch off action. In some cases, in addition to the possible action required by the specifications reported in Table 5, it could be needed that a pump is switched off because its uptime violates the imposed uptime upper constraint; in this case, it will be replaced by another pump.
- Select which pumps to be switched on/off, taking into account the parameters of Table 3. The algorithm

Table 5. Specifications ranking.

Specification	Ranking
Min-Max Switched On Pumps	1
Pressure Constraints	2
Safety Constraints	3
Saturation of the photovoltaic power (if present)	4
Tube Constraints	5

searches in descending switch on/off priority order. For the definition of the pumps to be switched off, the algorithm first evaluates the uptime upper constraints and then the uptime lower constraints.

3.1. PS1 scheduling customization

As can be noted in Table 1, *PS1* is characterized by six pumps (pumps #1-#3, #5-#7). These pumps get water directly from underground aquifers and the power required by each pump is 75 kW. *PS1* is equipped with a photovoltaic field. The presence of a photovoltaic field represents an important feature from the point of view of energy efficiency but it creates a conflict with the common management of a pumping station. In fact, if a photovoltaic field is not present, the only economic aspect to be taken into account is represented by the energy price in the different hours of a day: generally, it is preferable to fill the tanks during the night. In order to include this feature, *tube* constraints are adapted based on weekly and seasonally settings. Due to the presence of the photovoltaic field, the algorithm tries to guarantee that the overall energy provided by the field is always saturated (see Table 5). Pumps 2 and 7 are characterized by automatic discharge. Pumps equipped with automatic discharge at start perform for a certain time the running with the discharge valve open and the valve toward the network closed. In this way, any impurities in the source are not directly fed into the network but discharged. For this reason, it is preferable to have a greater number of switch on/off action on these pumps, in order to limit the side effects of a pump status switch. In order to guarantee this important aspect, Sw_{ON_0} and Sw_{OFF_0} parameters (see (1), (2)) related to pumps 2 and 7 have been set greater with respect to the other pumps.

4. PRESSURE MPC STRATEGY

As reported in Section 2, the regulation of the pressure of the pipes between the *PS1* tank and *DMA1* is performed by a PRV (Pressure Reducing Valve). The PRV pressure set-point represents the manipulated variable (MV, *u*) of the proposed MPC strategy. The main controlled variables (CVs, *y*) are pressures at critical nodes of *DMA1*. The disturbance variables (DVs, *d*) are the flow rates forwards and backwards *DMA1* with respect to other DMAs.

Step test procedures have been executed on the process in order to capture the most significant dynamics on the pressure at critical nodes of the *DMA1* district. First-order plus deadtime (FOPDT) models have been obtained; Table 6 reports the gain signs of the obtained models. Note the different signs in Table 6: DV4 represents a water lift toward another *DMA* that decreases the pressure at critical nodes.

Table 6. u-y and d-y transfer function gain signs.

Process Variable	**MV1** [*bar*]	**DV1** [$l \cdot s^{-1}$]	**DV2** [$l \cdot s^{-1}$]	**DV3** [$l \cdot s^{-1}$]	**DV4** [$l \cdot s^{-1}$]	**DV5** [$l \cdot s^{-1}$]
CV1 [*bar*]	+	+	+	+	-	
CV2 [*bar*]	+	+	+	+	-	
CV3 [*bar*]	+				-	+
CV4 [*bar*]	+	+		+	-	
CV5 [*bar*]	+					
CV6 [*bar*]	+	+	+	+	-	

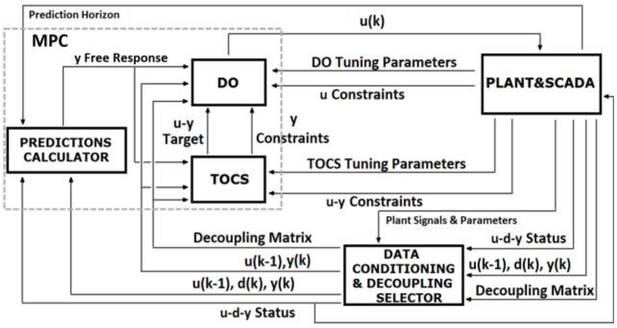

Fig. 3. Pressure MPC architecture.

Based on the obtained linear models, a two-layer MPC strategy has been formulated (Zanoli et al. (2017)). Fig. 3 represents the architecture of the proposed control scheme. As described in Section 2, plant measurements related to the PRV and to the bottom valley of Trento are refreshed with a period greater than or equal to 15 minutes. For this reason, the MPC algorithm sampling time has been set to 15 minutes. These measurements are acquired through the controller SCADA system and they are provided to the Data Conditioning & Decoupling Selector block (see Fig. 3). This block performs different operations, e.g. it verifies bad conditions (i.e. validity limits, freezing, rate of change) in order to decide which process variables have to be considered for the control problem at each control instant (Fig. 3, *u-d-y Status*).

The core of the algorithm is represented by the MPC block that is composed by three modules: Predictions Calculator, DO (Dynamic Optimizer), TOCS (Targets Optimizing and Constraints Softening). Predictions Calculator module computes the *y Free Response*. i.e. the CVs prediction over a prediction horizon H_p assuming no future moves on the MV. H_p has been set to 5 steps (75 minutes) based on the obtained models. TOCS module performs a steady-state optimization, searching pressure minimization directions: it provides to the DO module a steady-state configuration represented by targets and constraints (Fig. 3, *u-y Target* and *y Constraints*). DO module performs a dynamic optimization, computing the MVs value *u(k)* to be supplied to the plant at each control instant.

TOCS module is located at the upper layer of the proposed MPC scheme. It performs the first constrained optimization, based on a Quadratic Programing (QP) problem. The cost function is:

$$V_{TOCS}(k) = \\ = {c_u}^T \cdot \Delta\hat{u}_{TOCS}(k) + \|\Delta\hat{u}_{TOCS}(k)\|^2_{\mathcal{R}_{TOCS}} + \left\|\varepsilon_{y\_TOCS}(k)\right\|^2_{\rho_{y\_TOCS}} \tag{4}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_TOCS} \le \Delta\hat{u}_{TOCS}(k) \le ub_{du\_TOCS} \\ &\text{ii. } lb_{u\_TOCS} \le \hat{u}_{TOCS}(k) \le ub_{u\_TOCS} \\ &\text{iii. } lb_{y\_TOCS} - \gamma_{lby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \le \hat{y}_{TOCS}(k) \le \\ &\qquad \le ub_{y\_TOCS} + \gamma_{uby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \\ &\text{iv. } \varepsilon_{y\_TOCS}(k) \ge 0 \end{aligned} \tag{5}$$

DO module is located at the lower layer of the proposed MPC scheme. Its optimization problem is a QP problem, based on the following cost function:

$$V_{DO}(k) = \\ = \sum_{j=1}^{m_y} \sum_{i=H_{w_j}}^{H_p} \left(Q_{(j,j)}(i) \cdot \left(\hat{y}_j(k+i|k) - r_j(k+i|k) \right)^2 \right) \\ + \sum_{i=1}^{H_p} \| \hat{u}(k+i-1|k) - u_r(k+i-1|k) \|^2_{S(i)} \\ + \sum_{i=1}^{H_u} \| \Delta\hat{u}(k+i-1|k) \|^2_{\mathcal{R}(i)} + \| \varepsilon_{DO}(k) \|^2_{\rho_{DO}} \tag{6}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_DO}(i) \le \Delta\hat{u}(k+i-1|k) \le ub_{du\_DO}(i), i = 1, \dots, H_u \\ &\text{ii. } lb_{u\_DO}(i) \le \hat{u}(k+i-1|k) \le ub_{u\_DO}(i), i = 1, \dots, H_u \\ &\text{iii. } lb_{y\_DO_j}(i) - \gamma_{lby\_DO_j}(i) \cdot \varepsilon_{DO}(k) \le \hat{y}_j(k+i|k) \le ub_{y\_DO_j}(i) + \\ &\quad + \gamma_{uby\_DO_j}(i) \cdot \varepsilon_{DO}(k), \quad j = 1, \dots, m_y, \quad i = H_{w_j}, \dots, H_p \\ &\text{iv. } \varepsilon_{DO}(k) \ge 0 \end{aligned} \tag{7}$$

In (4) and (6), $\mathcal{R}_{TOCS}$ and $\mathcal{R}$ weight the magnitude of the MV moves $\Delta\hat{u}_{TOCS}(k)$ and $\Delta\hat{u}(k+i-1|k)$. DO MV moves are computed over a control horizon H_u (in this work H_u=H_p). Pressure minimization direction are guaranteed through c_u positive weight in (4). Hard constraints on MV moves and values are imposed in (5) and (7) through lb_{du_TOCS}, ub_{du_TOCS}, lb_{u_TOCS}, ub_{u_TOCS}, lb_{du_DO}, ub_{du_DO}, lb_{u_DO}, ub_{u_DO} terms. CVs constraints in (5.iii) and (7.iii) have been considered as soft constraints, through the introduction of ε_{y_TOCS} and ε_{DO} slack variables vectors. Each of the m_y CVs has been equipped with a set of slack variables that act only on its constraints; the importance of CVs constraints has been tuned through γ_{lby_TOCS}, γ_{uby_TOCS}, γ_{lby_DO}, γ_{uby_DO} in (5.iii) and (7.iii) and through ρ_{y_TOCS} and ρ_{DO} in (4) and (6). CV4 and CV6 (see Table 6) have been defined as the most important CVs, because they represents the most critical pressure nodes in the considered DMA. In (6), r and u_r represent the targets that are provided to DO module by TOCS module. In the present work, only MV tracking errors have been penalized in cost function (6).

5. RESULTS

The project described in the present paper started in 2017. The sectorization work was completed in December 2018 and the overall APC system has been installed on the real plant in March 2019. The APC system has obtained the Industry 4.0 compliance certification. Up to now, the service factor of the APC system is greater than 95%; a pilot process analysis performed in March 2020 certified a reduction of about 1.4% on the yearly average pressure of the considered DMA. Official energy efficiency results are under evaluation.

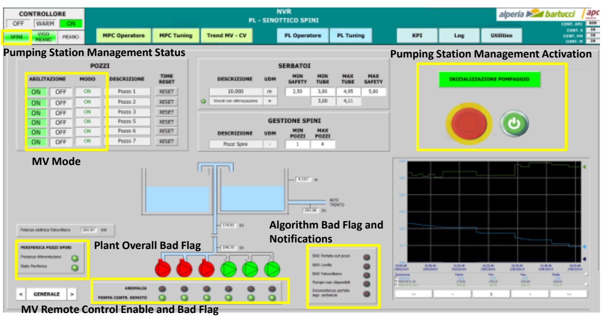

Fig. 4. *PS1* GUI (main page).

Fig. 4 shows a subpart of the Graphical User Interface (GUI) of the *PS1* algorithm. Note the option to disable each pump from the APC control. Furthermore, in order to guarantee a smart monitoring, all anomalies and bad conditions are notified to plant operators.

5.1. PS1 examples

Fig. 5 represents a *PS1* condition under the developed APC system. In the right part of the figure, it can be noted that the level (blue line) is respecting the imposed safety constraints (red dashed lines) but is violating the imposed *tube* upper constraint (green dashed line). The number of pumps with an on status (light green line) is three and the photovoltaic power (dark green line, normalized by a factor of 75) is greater than 150 kW. Remember that, as described in subsection 3.1, each pump of *PS1* requires a nominal power of 75 kW. The described situation shows a conflict between the *tube* constraints and the saturation of the photovoltaic power (see Table 5): the *tube* upper constraint requires a pump switch off, while the photovoltaic power, in order to remain saturated, requires no control actions. The APC system does not perform any control action due to the greater priority of the photovoltaic power with respect to the *tube* constraints.

Fig. 6 represents a *PS1* condition under the developed APC system. In the right part of the figure, it can be noted that the level (blue line) is respecting the imposed safety constraints (red dashed lines) but is violating the imposed *tube* upper constraint (green dashed line). There are three pumps with an on status (light green line) and the photovoltaic power (dark green line, normalized by a factor of 75) is lower than 150 kW. In this situation, the APC system decides to switch off a pump in order to satisfy the *tube* upper constraint: in fact, switching

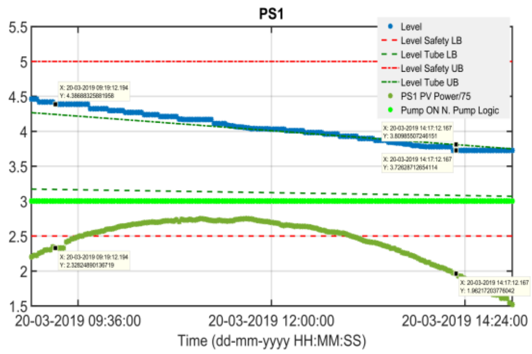

Fig. 5. *PS1* example: saturating the photovoltaic power.

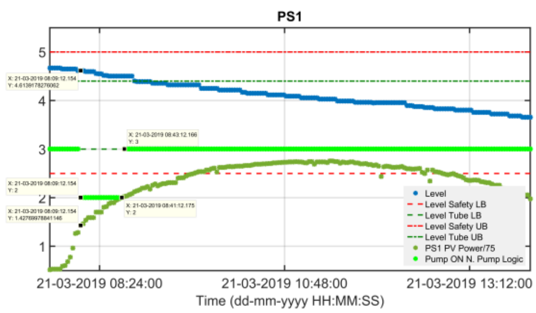

Fig. 6. *PS1* example: controlling the tube constraints and saturating the photovoltaic power (level and photovoltaic power).

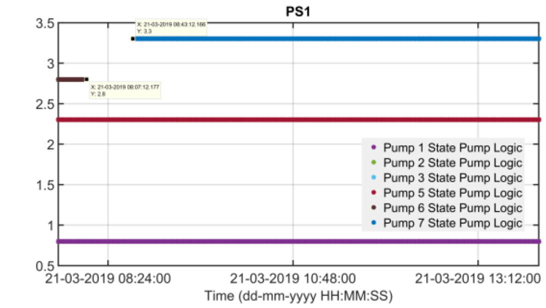

Fig. 7. *PS1* example: controlling the tube constraints and saturating the photovoltaic power (pump status).

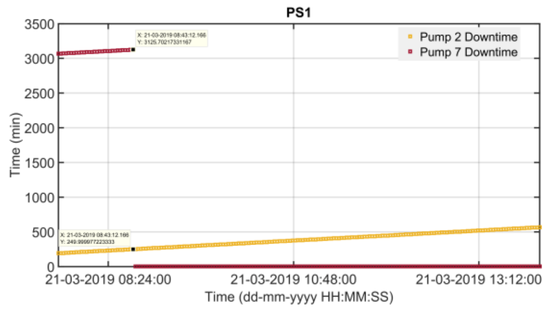

Fig. 8. *PS1* example: controlling the tube constraints and saturating the photovoltaic power (pump downtime).

off a pump, there will be still two pumps with on status and the photovoltaic power will remain saturated. The APC system decides to switch off the pump 6 based on the computed switch off priority (Fig. 7). Afterwards, the photovoltaic power increases up to 150 kW and a pump switch on action is required: the APC system evaluates the switch on priority of the pumps with an off status (pumps 2, 3, 6, and 7). Pumps 2 and 7 have the major switch off priority, but pump 7 is in an off status for a longer time (Fig. 8): pump 7 is switched on (Fig. 7).

5.2. PS3 example

Fig. 9-11 represent a *PS3* condition under the developed APC system. In the described condition, the APC system manages the level of the tank *PS3*-Tk1 positioned at lower altitude (the valve settings are fixed). The *tube* constraints (green dashed lines) are violated; in order to restore the level (blue line) within the desired range, the APC system performs the required actions. For example, on March 27th at time 16:42 the tank level violates the defined *tube* lower constraint while no pumps are in an on status: the switch on priority of the three pumps is the same and for this reason, the APC system

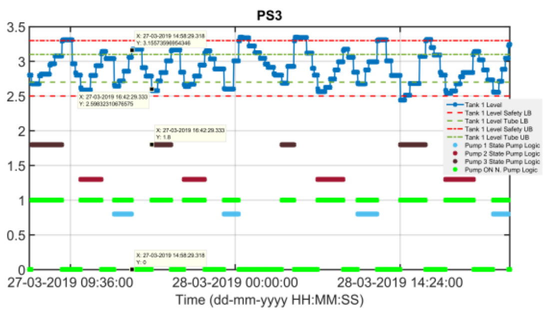

Fig. 9. *PS3* example (tank at lower altitude).

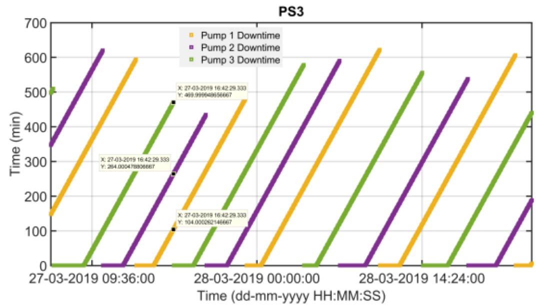

Fig. 10. *PS3* example (pump downtime).

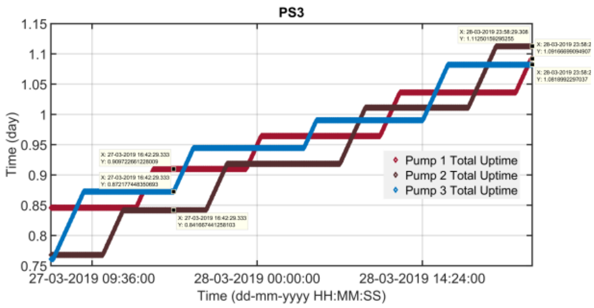

Fig. 11. *PS3* example (pump total uptime).

evaluates the downtime of each pump (Fig. 10), selecting pump 3 (Fig. 9, dark red line). Fig. 11 shows that pumps utilization is balanced over a daily period.

5.3. DMA1 pressure MPC examples

Fig. 12-14 represent a two days *DMA1* condition under the developed MPC scheme. The most critical process variables (CV4 and CV6, Fig. 12-13) have been shown, together with the MV (PRV pressure set-point, Fig. 14). As can be noted, the

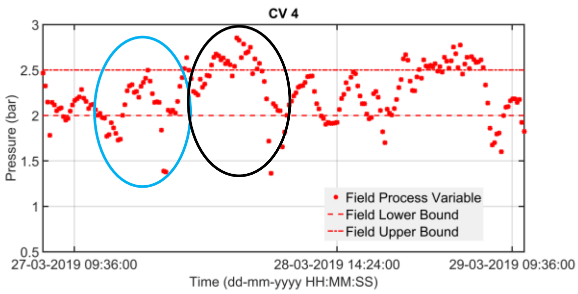

Fig. 12. *DMA1* pressure MPC (CV4).

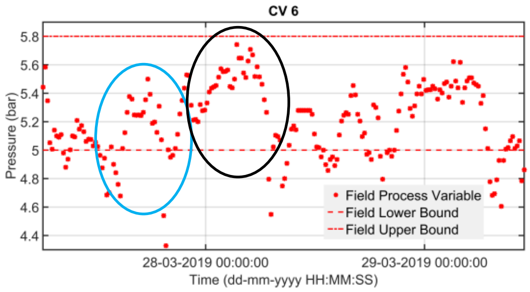

Fig. 13. *DMA1* pressure MPC (CV6).

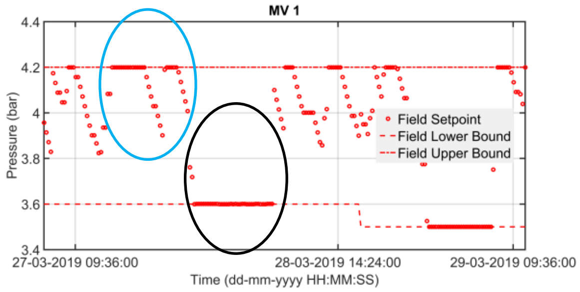

Fig. 14. *DMA1* pressure MPC (MV1).

controller performs different actions on daytime periods and on night periods, based on the behaviour of the CVs. On daytime periods (see cyan circles in Fig. 12-14) the controller moves the PRV pressure set-point (Fig. 14) in order to keep the CVs within the assigned constraints (Fig. 12-13, red dashed lines) and often the MV saturates its upper constraint (Fig. 14, red dashed line). On night, periods (see black circles in Fig. 12-14), due to the increase of the pressures at critical nodes, the controller decreases the MV value.

6. CONCLUSIONS

In the present paper, a project aimed to the optimization of a subnetwork of a Water Distribution Network located in Trento (north of Italy) has been described. The project has been composed by two main parts: hardware modifications and Advanced Process Control design. Hardware modifications, represented by sectorization and by the creation of District Metered Areas, were necessary in order to obtain the physical conditions for the net average pressure lowering.

Among the created districts, the bottom valley of Trento has been chosen as starting point for the optimization procedure. The Pressure Reducing Valve (pressure) set-point is modulated by a Model Predictive Control scheme that exploits the pressure measured at critical nodes. On the other hand, three pumping stations of the subnetwork have been optimized through the creation of a smart and fully automatic scheduling algorithm: the algorithm defines the pumps to be switched on/off based on level constraints and taking into account both energy price and free energy sources (photovoltaic field). The selection of the pumps to be switched on/off takes into account pumps uptime and downtime in order to maximize the pumps lifetime.

The overall Advanced Process Control system, composed by the Model Predictive Control module and the scheduling algorithm, has been successfully installed on the real plant in March 2019. Industry 4.0 compliance certification and a service factor greater than 95% have been obtained. Energy efficiency results are under evaluation: a pilot process analysis performed in March 2020 certified an about 1.4% reduction on the yearly average pressure of the considered DMA.

Future work will be oriented to the improvement of the process modellization and to the extension of the controller to other districts.

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