Simulation Methodology with Control Approach for Water Distribution Networks

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Abstract—This work presents and tests a simulation methodology for water distribution networks, developed as a simulation platform for dynamic pressure control purposes. The three model integration presented by Diaz y Quijano in 2012 is extended here as a general methodology including the Extended Period Simulation Global Gradient Algorithm proposed by Todini in 2000, the dynamic Pressure Reducing Valves model presented by Ulaniki in 1999 and the Stochastic Demand Model presented by Garcia in 1999. All these models are properly described and included in a general algorithm that solves all node pressure signals and pipe flow signals in a water distribution network under a dynamic scenario. This methodology is qualitatively tested in a simplified two variable tank network presented by Todini in 2000, showing satisfactory results.

Keywords—Distribution, EPS.GGA, Modeling, Network, Simulation, Water.

I. INTRODUCTION

WATER volume losses in Water Distribution Networks (WDN) represent a serious problem for provider companies. In some cases they could be near to 65% [1], [2]. The main cause of these losses is leakage in pipes, which is a pressure dependent variable. A strategy to reduce leakage in the WDN is to regulate pressure over the entire network using a control system [3]. This system has to maintain a certain pressure level for each node in the network under all the operation conditions (variable demand, disturbances, etc).

There are different approaches for the control problem in WDN. Most of them includes optimal control techniques such as: [4] who use the WATERNET solver, [5] who solve the system using Linear Theory Method (LTM) based on loop equations, [1] who assume steady state conditions, [6] that bases is formulation on LTM, [7] who use non-linear programming and LTM and [8] who support the solution of its model in EPANET. Other approaches consider hierarchical control [9], [10], robust control [11] that considers hydraulic models with non linear coupling, adaptive control [12] which includes modeling by identification, population dynamics based control [13], [14] and real-time control for wastewater systems [15].

Despite all these approaches contribute to the WDN control problem, many of them assume static conditions in their solvers (without dynamics) and present different tests with a maximum resolution of 1 hour. In order to develop a pressure control technique that considers the dynamics of the network in high resolution (in terms of seconds) it is necessary first to proposed a preliminary stage where the WDN can be modeled and properly simulated (focus of this paper). Taking into account these items, it is important to have a simulation system capable of:

1) Dynamically\(^1\) modelling the changes in the network.
2) Considering valves as time-varying actuators (not as static devices)\(^2\).
3) Managing a great quantity of variables.

There are various software that provide a simulation platform for WDN like EPANET [16], [17], WaterGems [18] and MIKE [19]. All of them are based in the Global Gradient Algorithm (GGA) [20] to solve the hydraulic model. Despite this is a powerful algorithm, it decouples the steady-state analysis from the mass balance analysis at fixed times. This feature limits the application of the algorithm to networks with non variable storage devices (otherwise the system can reach a unsteady solution [20]). On the other hand, the valves included in many of these software are considered as static parameters, not as devices with variable setting (typically, valves are the actuators of pressure control systems, and have to be considered as variable devices).

In order to reduce the water volume losses in a WDN using pressure control systems, none of the simulation software presented above seems appropriate. In a water distribution network, the presence of variable storage devices induces considerable dynamical changes that the controller has to take into account to accomplish the control goal. Also, it is required the time-varying manipulation of valves parameters.

As the controller has to be designed and evaluated first in simulation, it is necessary the implementation of a specific control oriented WDN simulation methodology that includes variable tanks. In this paper, such simulation methodology is presented based on the integration of three different models: The Extended Period Simulation Global Gradient Algorithm (EPS-GGA) [20], the pressure reducing valve model developed by [3] and the stochastic network user demand model proposed by [21]. The integration of these three models and its extension to a general methodology are based on [22] where a specific two loops network with no variable storage devices was modeled with control purposes.

The remainder of this paper is organized as follows. Section II; Water Distribution Model, section III; Dynamic WDN Simulation Algorithm, section IV; Results and Discussion:

\(^1\)Here dynamical makes reference to changes caused by variations in demand and water storage. It is not consider instantaneous changes as the water-hammer phenomena.

\(^2\)For pressure control purposes the valves in the system are consider actuators.
Simulation Methodology Test, section V; Conclusion and section VI; Future Work.

II. METHODS: WATER DISTRIBUTION MODEL

The main purpose of a WDN is to deliver drinkable water from one or several main reservoirs to the final users who can be spread over different rural and urban area. Usually the reservoirs are located in high places and distribute water by gravity to the users located in lower areas. The water is distributed using a pipe network where each node is considered as a demand point that aggregates the user’s demand near to it.

During distribution, water looses energy mainly because friction within the internals walls of the pipes and also looses mass caused by leakage. The energy loss can be interpreted as a pressure loss which is proportional to the flow in the pipe. Hence, the higher the nodal demands are, the higher flow and pressure losses in the pipes are.

The WDN considered here includes reservoirs (fixed storage devices), tanks (variable storage devices), pipes and pressure reducing valves 3 (PRV). The simple nodes are considered as demand nodes that follow certain pattern according to the location and the activity developed for the population in the area.

The following subsections, the WDN model is described, followed by the valve type and model, and the nodal demand model. Finally all these models are integrated into a complete WDN model.

A. Water Distribution Network Model

In order to model the dynamical behavior of the WDN, two main equations are used: energy balance and mass balance [20]. The energy balance equation defines the energy losses inside a pipe as pressure losses. The mass balance equation models the volume of water storage at each node depending on the inflow and outflow. Each equation is presented as follows:

1) Energy Balance Equation: The balance of energy in a WDN is associated to the pressure difference between two connected nodes. This connection is made by an ij pipe, where the flow inside is directed from node j to node i. The transported water looses energy mainly because friction within the internals walls of the pipe. The higher the flow the higher the pressure loss. According to [20] this pressure loss inside the pipe can be expressed as the pressure difference between ij nodes, as follows:

\[ \frac{\partial H_{ij}}{\partial x} = \Delta H_{ij} = H_i - H_j = -K_{ij}(Q_{ij})^{n_p-1}Q_{ij} \]  

where \( \Delta H_{ij} \) corresponds to the pressure difference between nodes i and j, \( Q_{ij} \) identifies the flow of the ij pipe, \( K_{ij} \) is the resistant coefficient of the ij pipe, and \( n_p \) is the flow exponent. The parameters \( K_{ij} \) and \( n_p \) depend on the equation presented here.

2) Mass Balance Equation: The second differential equation used to model the WDN correspond to the mass balance [20]. This equation express the rate of storage water volume in a tank during a period, as the difference between inflow and outflow. It is defined as follows.

\[ \frac{\partial V_i}{\partial t} = \sum_{k} Q_{ik} + q_i \]  

In this equation i represents the node were the tank is connected and k refers all others nodes connected to the tank node i. \( V_i \) corresponds to the volume of water storage in the tank, \( Q_{ik} \) represents the flow\(^4\) in the pipe that connect nodes i and k. The parameter \( ni \) is the number of nodes connected to the tank node i. Finally \( q_i \) corresponds to the flow demand in the node tank. Here, demand is a flow that leaves the node, then it is considered negative.

According to [20] the change in volume of Equation (2) can be expressed as a function of the transversal area of the tank and the change in high (denoted as \( \Omega_i(H_i) \)). Then Eq. 2 can be rewritten as follows:

\[ \Omega_i(H_i) \frac{\partial H_i}{\partial t} = \sum_{k} Q_{ik} + q_i \]  

This last equation is particularly useful modeling a consumption node\(^5\) or cylindrical tanks. For the first case it is only necessary to assume \( \Omega_i = 0 \). In the second case the \( \Omega_i \) function is constant equal to the transversal area \( A_T \).

B. Valve Model

A complete WDN model includes different kind of components such as valves, pumps, etc. The simulation methodology presented here is intended to be used in a pressure control

\(^3\)This type of valve looses certain quantity of pressure according to a pilot screw reference. This characteristic is useful for the pressure control purposes wanted here.

\(^4\)Flow that leaves the node is considered negative while flow that arrives to the node is considered positive.

\(^5\)Consumption node is a node without tank.
scheme where the pressure excess is reduced using Pressure Reducing Valves (PRV). For that reason, this model considers PRV as the only type of valve in the system.

The PRV dynamic proposed here is based on the behavioral model presented in [3]. The basic function of a PRV (Figure 2(a)) is to regulate output pressure $h_{out}$ despite changes at the input pressure $h_{in}$, modifying the valve opening $x_m$ according to a pilot screw reference. The pressure regulation responds to an exponential behavior and it is expressed here as follows,

$$\frac{\partial x_m}{\partial t} = \begin{cases} \alpha_{open}(x_m^{set} - x_m) & \frac{\partial x_m}{\partial t} \geq 0 \\ \alpha_{close}(x_m^{set} - x_m) & \frac{\partial x_m}{\partial t} < 0 \end{cases}$$

(4)

where $x_m^{set}$ represents the desired opening associated to the desired output pressure $h_{out}^{set}$ and $x_m$ is the real opening associated to the real output pressure $h_{out}$. Here, the valve opening stop changing when the desired value and real value are the same. The valve responds at different speeds depending on the action (open or close) which are respectively associated to the servo-valve speed parameters $\alpha_{open}$ and $\alpha_{close}$.

The main flow $q_m$ depends on the pressure difference between input and output, and is expressed as follows,

$$q_m = C_v(x_m)\sqrt{h_{in} - h_{out}}$$

(5)

The bigger the difference between $h_{in}$ and $h_{out}$, the bigger the flow. Note that $h_{in}$ must be greater than $h_{out}$ in order to obtain real values (the PRV is a passive device that only losses energy). Finally, the term $C_v(\cdot)$ is called the capacity function of the valve and it depends on the real opening $x_m$ only. This function varies from valve to valve and depends on physical characteristics of each device.

1) Valve Opening Consideration: For simulation simplicity a main assumption is made in the valve model. The opening valve $x_m$ is expressed here as a percentage of its maximum displacement $X_m$, then the PRV opening is manipulated through the variable $\gamma$ as follows,

$$x_m = \gamma X_m \quad \forall \gamma : 0 \leq \gamma \leq 1$$

(6)

It is important to remember that this simulation methodology is intended to be use in a pressure control scheme, then Equation (6) allows the controller to use one single scale for all openings valves in the network despite their different sizes. Therefore, the complete valve model can be rewritten as,

$$\frac{\partial \gamma}{\partial t} = \begin{cases} \alpha_{open}(\gamma^{set} - \gamma) & \frac{\partial \gamma}{\partial t} \geq 0 \\ \alpha_{close}(\gamma^{set} - \gamma) & \frac{\partial \gamma}{\partial t} < 0 \end{cases}$$

(7)

$$q_m = C_v(\gamma X_m)\sqrt{h_{in} - h_{out}}$$

(8)

C. Users Demand Model

The users demand is modeled node by node, where all users located in the same area are aggregated as one and associated to a specific node. Depending on the location and the activity of the users it is possible to model certain behavior pattern for each demand node. Typically, this pattern is constructed in periods of 24 hours.

The simulation methodology proposed here considers the users demand $q_i$ as a known flow that leaves the $i$ node (see Equation (3)). Here the value of variable $q_i$ responds to a stochastic model proposed in [21]. It is important to note that, despite the selection made here, others demand models can be included as well.

The stochastic approach incorporated in this methodology considers consumption as an aggregate signal of many demand events. Each event obeys to certain probabilistic distribution and it is characterized by 3 parameters: occurrence time $\tau_i$, duration time $T_i$ and intensity $I_i$ (see Figure 2(b)). This demand model can be expressed for a $j$ node in terms of volume as follows,

$$V_j = \sum_{i=1}^{C_j} T_i(\tau_i)I_i(\tau_i)$$

(9)

where $C_j$ corresponds to the number of demand events for the $j$ node. The variable $T_i$ and $I_i$ depend on the occurrence time $\tau_i$ and responds to exponential distribution and a Weibull distribution respectively. The occurrence time $\tau_i$ corresponds to a non-homogeneous poisson process with a rate of occurrence $\lambda_j(t)$ defined as follows,
\[ \lambda_j(t) = C_j g(t) + \varepsilon(t) \]  
where \( g(t) \) is the unit time pattern during an entire day\(^6\), and \( \varepsilon(t) \) is a random term with zero average and standard deviation \( \sigma_r \). According to [21] the function \( g(t) \) must satisfy,

\[ \int_0^{24} g(t) dt = 1 \]  

(11)

D. Integrated WDN Model

The integration of models introduced in section II-A, II-B and II-C is presented here. Basically, the complete model includes one mass equation for each node, one modified energy equation for each pipe, and one PRV dynamic equation for each valve. Also, there is one demand equation for each node according to the associated demand pattern.

1) Modified Energy Equation: As the PRV is a passive device that losses energy, it has to be included in the energy equation. According to this, PRV flow Equation (8) can be rewritten as follows,

\[ h_{in} - h_{out} = \frac{qm{|\gamma_m|}}{[C_v(\gamma_m X_m)]^2} \]  

(12)

This formulation is conveniently presented as a pressure difference between the input and output and can be associated to the pressure losses by the PRV. Then, it can be included in the \( ij \) pipe energy Equation (1) as follows,

\[ \frac{\partial H_{ij}}{\partial x} = \Delta H_{ij} = H_i - H_j = - K_{ij} |Q_{ij}|^{np-1} Q_{ij} - \left( \frac{|Q_{ij}|Q_{ij}}{[C_v(\gamma_m) X_m]^{ij}} \right) \]  

(13)

where pressure difference between \( ij \) nodes corresponds to the sum of the pressure losses caused by friction inside the pipe and the controlled pressure losses caused by the PRV. As the friction coefficient \( K_{ij} \) is calculated using the Darcy-Weisbach equation, then \( np \) parameter is 2.

There are two important physical considerations about the PRV model presented here. First, not all pipes in the network has installed a PRV and second a typically PRV does not work with reverse flow. Both cases are detailed next:

For the first case a \( P_{on}^{ij} \) parameter is included, where

\[ P_{on}^{ij} = \begin{cases} 
1, & \text{ij pipe with PRV.} \\
0, & \text{ij pipe without PRV.} 
\end{cases} \]  

(14)

For the second case, if \( h_{in} - h_{out} < 0 \) (reverse flow condition), the valve could operate in two forms depending on the valve type: it can block itself or bypass the water. The blocking case implies a disconnection of the \( ij \) pipe and a change of the network topology. The bypassing case just implies that the PRV has no effect on reverse flow. As a first approach, this work considers the bypassing case only\(^7\) using a \( B_{ij} \) parameter as follows.

\[ B_{ij} = \begin{cases} 
1, & Q_{ij} \geq 0 \\
0, & Q_{ij} < 0 
\end{cases} \]  

(15)

It is important to note that the condition \( Q_{ij} \geq 0 \) implies that the PRV is installed in the same direction as the pipe (from node \( j \) to node \( i \)). Finally, including the \( np \) value and the physical considerations Equation (13) can be rewritten as follows,

\[ \frac{\partial H_{ij}}{\partial x} = \Delta H_{ij} = H_i - H_j = - \left( K_{ij} + \frac{P_{on}^{ij} B_{ij}}{[C_v(\gamma_m) X_m]^{ij}} \right) |Q_{ij}|Q_{ij} \]  

(16)

Note that the PRV losses term in Equation(16) depends on the valve opening \( \gamma_{ij} \) which responds to an exponential behavior given by Equation(7).

2) Complete WDN Model: Summarizing, the complete model of Water Distribution System introduced in this work is given by:

\[ \Delta H_{ij} = - \left( K_{ij} + \frac{P_{on}^{ij} B_{ij}}{[C_v(\gamma_m) X_m]^{ij}} \right) |Q_{ij}|Q_{ij} \]  

(17)

\[ B_{ij} = \begin{cases} 
1, & Q_{ij} \geq 0 \\
0, & Q_{ij} < 0 
\end{cases} \]  

(18)

\[ P_{on}^{ij} = \begin{cases} 
1, & i \text{ pipe with PRV.} \\
0, & i \text{ pipe without PRV.} 
\end{cases} \]  

(19)

\[ \frac{\partial \Omega_i}{\partial t} = \frac{\partial H_i}{\partial t} = \sum_{k} Q_{ik} + q_i \]  

(20)

\[ \Omega_i(H_i) = A_T^i \]  

(21)

\[ q_i = \text{Demand profile} \]  

(22)

\[ \frac{\partial \gamma_{ij}}{\partial t} = \begin{cases} 
\alpha_{op}^{ij}(\gamma_{ij}^{set} - \gamma_{ij}) & \frac{\partial \gamma_{ij}}{\partial t} \geq 0 \\
\alpha_{close}^{ij}(\gamma_{ij}^{set} - \gamma_{ij}) & \frac{\partial \gamma_{ij}}{\partial t} < 0 
\end{cases} \]  

(23)

Equation (17) represent a differential equation expressed as the pressure difference between two \( ij \) nodes. It represent the energy losses caused by internal friction inside the \( ij \) pipe and the controlled pressure losses caused by the installed \( ij \) PRV. There is one equation for each \( ij \) pipe. Equation (18) and (19) denote the configuration parameters for the \( ij \) pipes with a PRV installed. \( B_{ij} \) considers the reverse flow case, \( P_{on}^{ij} \) activates the PRV term in Equation (17). On the other hand, Equation (20) represents the mass balance for each \( i \) node expressed in terms of its pressure \( H_i \). It also includes the demand flow \( q_i \) as a negative flow that leaves the node. Equation (22) models the flow demand for each \( i \) node. Finally, Equation (23) is a differential equation that models the exponential behavior of the PRV opening \( \gamma_{ij} \), which modifies the pressure losses in Equation (17). There is one equation for each PRV.

III. DYNAMIC WDN SIMULATION ALGORITHM

The WDN model proposed in this work is intended to be simulated using the EPS-GGA algorithm proposed by Todini [20]. This algorithm is an improved version of the GGA.
algorithm used in many water system simulation software like Epanet [16], [17]. The EPS GGA solves the unsteady condition generated by GGA in networks scenarios with variable storage devices (variable tanks) [20]. As those variable tanks induce notorious changes in network dynamic, it is necessary to have an algorithm capable of solving the WDN model under this circumstances. For this reason, the EPS-GGA algorithm is selected here as the simulation hydraulic engine.

It is important to note that the WDN model presented here and the EPS GGA, have some assumption with respect to inertial effects and rapid dynamic changes [20]. Despite this model is useful solving a time varying WDN scenario, it considers a slow-time varying conditions such as relative slow changes in demand and water storage accumulation. Hence, this model is not capable to solve water-hammer phenomena.

**A. EPS-GGA consideration**

In this work, the EPS GGA algorithm is implemented same as proposed in [20]. The only modification corresponds to the $n_T \times n_T$ time varying diagonal matrix $A_{11}^r$ associated to the energy balance equation (17) as follows,

$$A_{11}^r(r,r) = \left(K_r + \frac{P_{on}r B_r}{C_0(\gamma_r X_m)^2}\right) |Q_r|$$

where $n_T$ corresponds to the number of pipes and $r = \{1, \ldots, n_T\}$. In this formulation, each $ij$ pipe is renamed as $r$. It is important to note that, different as [20], this matrix depends on the friction inside the pipe and pressure losses associated to the installed PRV which responds to an exponential behavior.

**B. ALGORITHM DESCRIPTION**

The simulation methodology introduced here is resumed in the algorithm description presented as follows.

**Algorithm 1 Pressure Control Oriented WDN Algorithm**

**Require:** Definition of simulation length $T_s$ and delta time $\Delta T$.

**Require:** Preset file with the physical description of the network and valves $\gamma_{set}$ (if needed).

**Require:** Preset file with the demand profile $q$ for all nodes.

1: $k = 1$
2: $q_k \leftarrow$ Demand values for all nodes at iteration $k$ loaded from file.
3: $[H_k, Q_k] \leftarrow$ Initial values loaded from file.
4: $\gamma_k \leftarrow$ Initial values loaded from file.
5: for $k = 2$ to round($T_s/\Delta T$) do
6: $q_k \leftarrow$ Demand values for all nodes at iteration $k$ loaded from file.
7: $[H_k, Q_k] \leftarrow$ EPS.GGA($q_k, q_{k-1}, Q_{k-1}, H_{k-1}, \gamma_{k-1}$).
8: $\gamma_k \leftarrow$ PRV\_opening($\gamma_{k-1}, \gamma_{k-1}set$, $\gamma_{k-1}set$, $\alpha_{open}$, $\alpha_{close}$).
9: end for

The algorithm requires pre-computed information before it starts calculating network pressure $H$ and flow $Q$. The physical description of the network such as location, tanks, pipes, valves, etc are preset in an external file (see table I). This information is saved in a preset file in order to initialize the algorithm. There is one set of parameters for each node and each pipe. The location parameters $east, north, elv_i$ are for 3D representation purposes only. For fixed reservoirs the parameter $H_{i}^{ij}$ corresponds to the fixed water level.

The demand profile for each node is also pre-computed, according to the demand model presented in section II-C and adjusted for the simulation length $T_s$ and delta time $\Delta T$.

Once all pre-computed information is available, the algorithm loads the initial values of demand $q$ (Equation 22), PRV real opening $\gamma_r$ pressure $H$ and flow $Q$ corresponding to iteration $k = 1$. From iteration $k = 2$ onwards, the algorithm calculates iteratively $H_k$ and $Q_k$ solving the system expressed in Equations (17) to (20) using the modified EPS GGA algorithm described in section III-A. For this calculation it is required all network physics parameters loaded from file and the values of pressure $H_{k-1}$, flow $Q_{k-1}$, demand $q_k$, $q_{k-1}$ and valve opening $\gamma_{k-1}$, described in line 7 of algorithm description.

Next, the real PRV opening $\gamma$ is calculated according to Equation (23), where the exponential dynamic behavior is described. The variable $\gamma_k$ depends on the past value $\gamma_{k-1}$, the desired opening $\gamma_{k-1}set$ and $\gamma_{k-1}set$, the physics parameters of the valve $\alpha_{open/close}$ and the valve capacity function $C(\cdot)$. This last function is assumed as a part of the PRV\_opening function described in line 8.

Finally, the iterative process from line 6 to 8 in the algorithm description is repeated round($T_s/\delta T$) times, solving all pressure level $H$ and flows $Q$.

**IV. RESULTS AND DISCUSSION: SIMULATION METHODOLOGY TEST**

In order to test the simulation methodology developed here, three main simulation scenarios are proposed. All of this

<table>
<thead>
<tr>
<th>Node parameters</th>
<th>Pipe parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$ Number of node.</td>
<td>$r$ Number of pipe.</td>
</tr>
<tr>
<td>$east_i$ East location coordinate (m).</td>
<td>$j$ Tail node.</td>
</tr>
<tr>
<td>$north_i$ North location coordinate (m).</td>
<td>$i$ Head node.</td>
</tr>
<tr>
<td>$elv_i$ Node elevation (m).</td>
<td>$d_{ij}$ Pipe diameter (m).</td>
</tr>
<tr>
<td>$tt_i$ Type of node (0-Reservoir, 1-Var Tank, 2-No Tank).</td>
<td>$A_{ pij}$ Pipe transversal area ($m^2$).</td>
</tr>
<tr>
<td>$A_{ij}^t$</td>
<td>$l_{ij}$ Pipe length (m).</td>
</tr>
<tr>
<td>$H_{o i}$ Initial pressure.</td>
<td>$k_{ij}$ Pipe roughness coefficient (m).</td>
</tr>
<tr>
<td>$q_{max i}$ Maximum demand ($m^3/s$).</td>
<td>$k_{mis}$ Minor losses (m).</td>
</tr>
</tbody>
</table>

**TABLE I**

**REQUIRED PARAMETERS TO MODEL THE WDN.**
scenarios are based in the 2 variable tanks network proposed by Todini in [20] where the original EPS-GGA algorithm was presented. As this algorithm is relatively new and is also the core of the simulation engine used here, it is necessary to test it in a reference scenario for performance comparison.

The first scenario replies the results presented in [20] but using a Darcy-Weisbach resistant coefficient $K_{ij}$ as presented in section II-A2. The second scenario is an extension of the first one and is intended to test a PRV inclusion in the same network. Same as second one, third scenario is an extension of the first scenario but including a stochastic demand scheme as presented in section II-C. Finally, the fourth scenario integrates the three presented models.

A. First Scenario: Two Variable Tank Test

This test replies the simulation scenario presented in [20] where two interconnected variable tanks are emptying through a third open node (see Figure 3(a)). The tanks 1 and 2 are set to a initial water level of 30m and 20m respectively. Qualitatively, it is expected an initial flow in pipe 1 from tank 1 to tank 2. After both tanks reach the same level, the flow in pipe 1 will stop and both tanks start to be emptied at the same rate through pipes 2 and 3. In this scenario all node demands are set to zero. The parameters of the test network are presented in Tables II and III. Pressure and flow results are presented in Figures 4(a) and 4(b).

Different as [20], the resistant coefficient $K_{ij}$ is calculated here using the Darcy-Weisbach physic based equation. Despite this change, the flow and pressure results are very similar to the ones presented in [20] and are consistent with the expected qualitatively behavior. In both cases, during the first 15min the tank 3 supplies tank 2 trough pipe 1 (which has a negative flow according to the tail-nail definition). After this, tanks pressure level are equaled where tank 2 reach a maximum of 23m and flow 1 decrease to zero. Next, both tanks are emptied by pipes 2 and 3 at exponential rate during 4 hours approximately.

B. Second Scenario: PRV Test

The second simulation scenario is an extension of the first scenario including a PRV installed in the middle of pipe 2. In this case it is assumed a valve with a servo-speed constant $\alpha_{open/close} = 1 \times 10^{-3}$ and a maximum opening $X_m$ of 70\% of the pipe diameter\(^8\). Capacity function of the PRV is based in the one presented in [3] and assumed as $C_v(\gamma) = 0.45\gamma X_m$.

\(^8\)A completely opened PRV does not have a pressure loss equal to zero. There is a bias losses and here are represented as a percentage of maximum open, which is less than the pipe diameter.
Pressure, flow and PRV results are respectively presented in Figures 5(a), 5(b) and 5(c).

Initially, the valve starts open at maximum, which means minimal pressure loss and opening signal $\gamma_{set} = 1$. After the first hour the reference opening signal decreases linearly to a minimal value $\gamma_{set} = 0.001$ and maintains during the rest of simulation. As is expected, the real opening signal $\gamma$ shows the dynamic exponential response of the valve (see Figure 5(c)). The value $\gamma_{set} = 0.001$ corresponds to a maximum pressure loss, which means an almost closed valve. In this case, the flow through the pipe 2 should be minimum near to zero (as is presented in Figure 5(c)). When the real PRV opening $\gamma$ reach its minimum (approximately at 3 hours), tank 2 is practically disconnected from node 1, and the system can only be emptied through pipe 3. At this point, tank 2 supplies tank 3 using the connection pipe 1 (which has now a positive flow according to the tail-nail definition). As is qualitatively expected, both tanks empty their content with the same pressure level, taking more time than first scenario (2 more hours).

C. Third Scenario: Demand Model Test

The third simulation scenario is based on the first scenario but including a flow demand profile in node 3. The demand profile is built using model of section II-C using parameters presented in table IV.

These parameters are based in real data taken from a residential area in Valencia-Spain, presented in [21] and properly scaled to the simulation network used here. The demand profile presents an increasing behavior from 15 mins to 1.3 hours approximately, then during 1 hour decreases until zero. The signal presents 4 notable peaks at 0.7 hour, 0.9 hour, 1.3 hour and 1.7 hour. The maximum demand peak reaches $50L/s$.

During the first 15 min the network has the same behavior as simulation scenario 1. After this, node 3 starts consuming according to the demand signal. As is expected, in order to maintain same level between the connected tanks, tank 2 supplies tank 3 through pipe 1 with a similar rate as demand profile. The flow peaks in pipe 1 occurs at the same time as the peaks in demand signal. As the total demand of the network is higher than scenario 1, the tanks empty their content 4 hour earlier.

D. Fourth Scenario: Integrated Model Test

The last simulation scenario integrates the 3 nodes network, the PRV model and the stochastic demand model. The topology is presented in Figure 3(c) where a PRV and a demand profile are included in pipe 1 and node 3 respectively. In this case it is assumed a faster valve with a servo-speed constant $\alpha_{open/close} = 5 \times 10^{-3}$ and a maximum opening $X_m$ of 70% of the pipe diameter. Capacity function of the PRV is based in the one presented in [3] and assumed as $C_v(\gamma) = 0.45\gamma X_m$. The demand profile has the same form as scenario 3 but with lower intensity ($23L/s$ maximum). The simulation results are presented in Figures 7(a) to 7(d).

During the first 15 mins, there is no demand in node 3 and the PRV remains completely open. Hence the pressure and flow results are practically the same as first scenario. From 15 mins to 45 mins, demand in node 3 increases causing a positive flow in pipe 1 maintaining both tanks at the same level. Therefore, the form of flow signal in pipe 1 is similar to the demand signal in node 3 (both have their peaks at same time). From 45 mins to 1.2 hours, the PRV closes rapidly (a very small opening value $\gamma_{23} = 0.001$). This causes decrease of flow 1 (near to zero) and the disconnection between nodes 2 and 3. Hence, both tanks empty their content at different rates (see Figure 7(a)). Tank 2 supplies only the sink node 1 and empty it content at exponential rate until 3.5 hours approximately. On the other hand, tank 3 supplies sink node 1 and satisfies it own demand, causing a faster emptying, delivering all water at 2.5 hours approximately.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_f$</td>
<td>100</td>
<td>Average number of events.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.4150</td>
<td>Average event length in hours.</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.0136</td>
<td>Parameter of scale intensity in Weibull distribution for the events. (Lt/s)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.3251</td>
<td>Parameter of form intensity in Weibull distribution for the events.</td>
</tr>
<tr>
<td>$\text{Norm}_A$</td>
<td>$1 \times 10^{-4}$</td>
<td>Polynomial factor in demand pattern $g(t)$.</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$-113.2367$</td>
<td>Polynomial parameter of demand pattern $g(t)$. (h$^{-1}$)</td>
</tr>
<tr>
<td>$A_2$</td>
<td>15.5405</td>
<td>Polynomial parameter of demand pattern $g(t)$. (h$^{-2}$)</td>
</tr>
<tr>
<td>$A_3$</td>
<td>$-0.4447$</td>
<td>Polynomial parameter of demand pattern $g(t)$. (h$^{-3}$)</td>
</tr>
<tr>
<td>$C_0$</td>
<td>326.8395</td>
<td>Polynomial parameter of demand pattern $g(t)$.</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>0.6609</td>
<td>Standard deviation in demand pattern.</td>
</tr>
</tbody>
</table>

TABLE IV
PARAMETERS OF THE DEMAND MODEL BASED ON A RESIDENCE AREA IN VALENCIA, SPAIN [21].
V. CONCLUSION

A pressure control oriented simulation methodology for water distribution networks was introduced here based on the integration of three different models [22]: EPS-GGA water network model [20], PRV dynamic model [3] and a stochastic demand model presented in [21]. The complete model presented in Equations (17) to (23) was satisfactorily solved using the modify EPS-GGA algorithm [20] presented in section III-A.

The complete algorithm formulation of the methodology was presented in section III-B and tested in section IV. As a reference point, the qualitatively results presented in [20] (where the EPS-GGA algorithm was first presented) were reproduced here. A simplified 2 variable tank network was successfully simulated despite both tanks were located relatively near. It is important to note, that this specific condition is not possible to simulate using other simulators like EPANET [17] [20]. Using the same network topology, the PRV and demand model were tested in other new simulation scenarios, showing a satisfactory performance.

The simulation methodology presented here proves to be capable of solving dynamic changes in water network. In light of the good result obtained, the methodology can be included under a pressure control scheme (phase two of this work). Despite the network used here is a very small one, the methodology presented is formulated to solve bigger scenarios including networks with \(i\) nodes, \(r\) pipes and \(m\) PRVs. It just changes the size of the input file and the processing time according to the network size.

The applications of this methodology are not restricted only to pressure control. It could be used to simulate different networks and scenarios for efficient urban planning, management and operation purposes. For example, the dynamic analysis of disconnection in some part of the network, caused by a programmed repair or an emergency situation (like a broken pipe).

As this simulation methodology is based in the relatively new algorithm EPS-GGA [20] and is tested in scenarios that
are not possible to simulate in others simulators [20], [17], it is necessary to compare it performance against real data for accuracy measurement purposes.

VI. FUTURE WORK

The simulation methodology presented here were intended as a first stage of a pressure control problem. Therefore, phase two will be developed including dynamic pressure control techniques in order to reduce volume water losses.

On the other hand, this work presents various ways of additional development. Different models could be added to expand the application scope such as chlorine concentration and water-hammer models. Also, many other devices could be included in the network, such as different types of valves (not only PRV) and pumping systems.

APPENDIX

RESISTANT COEFFICIENT $K_{ij}$

The resistant coefficient $K_{ij}$ is associated to friction inside the $ij$ pipe and calculated here using the Darcy-Weisbach equation as follows,

$$ K_{ij} = \left( \frac{l_{ij}}{d_{ij}} + km_{ij} \right) \frac{1}{2gA_{p_{ij}}^2} $$  \hspace{1cm} (25)

where $l_{ij}$, $d_{ij}$, $A_{p_{ij}}$ and $km_{ij}$ are respectively length, diameter, transversal area and absolute roughness coefficient of the $ij$ pipe. The minor losses $km_{ij}$ are associated with losses in accessories and connections of the respective pipe. The parameter $f_{ij}$ corresponds to the Darcy coefficient and it is calculated depending on the type of flow (laminar or turbulent).

The **laminar case** correspond to a Reynolds number less than 2000 [23] calculated as follows,

$$ Re_{ij} = \frac{V_{l_{ij}}d_{ij}}{\nu} $$  \hspace{1cm} (26)

where $\nu$ is the kinematic viscosity of the water and $V_{l_{ij}}$ is the velocity of the flow $Q_{l_{ij}}$ calculated as $V_{l_{ij}} = \frac{Q_{l_{ij}}}{A_{p_{ij}}}$. For this case, the Darcy coefficient is calculated as follows and depends on the Reynolds number only [23],

$$ f_{ij} = \frac{64}{Re_{ij}} \quad \text{if} \quad Re_{ij} < 2000 $$  \hspace{1cm} (27)

The **turbulent case** correspond to a Reynolds number calculated using equation (26) greater or equal than 2000. In this case the Darcy coefficient depends on the absolute roughness coefficient of the pipe material $ks_{ij}$, the diameter of the pipe $d_{ij}$ and the Reynolds number[23], as follows,

$$ 1 \sqrt{f_{ij}} = -2\log_{10} \left( \frac{ks_{ij}}{3.71d_{ij}} + \frac{2.51}{Re_{ij}\sqrt{f_{ij}}} \right) \quad \text{if} \quad Re_{ij} \geq 2000 $$  \hspace{1cm} (28)

This equation is not explicit for $f_{ij}$, then it needs numerical algorithms to find an approximate value of $f_{ij}$ (knowing first the other variables).

REFERENCES


