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Flexible object-oriented modelling for the control of large gas networks

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Abstract: In this work we develop an innovative framework for the dynamic modelling of natural gas transmission networks. Thanks to its flexibility, this tool may be used to support operation of the network while also giving the possibility to explore and test new optimized scenarios, introduce new elements in the grid itself (ranging from new branches to new machines) and test the use of new gas mixtures. We use as benchmark the Italian high pressure gas transportation network, executing simulations of past daily operation scenarios. Results are compared to real measurements so to prove the validity of the adopted approach.

Keywords: Natural gas networks; dynamic modelling; simulation; Modelica.

1. INTRODUCTION AND MOTIVATION

The energy sector is facing a revolution in the upcoming years. As, at the moment, renewable sources cannot fulfill by their own the whole global energy demand, fighting climate changes requires the introduction of new technologies and an efficiency enhancement for the already present production systems. The major role that natural gas will play in this transition period is largely recognized thanks to its relevant lower heating value and reduced pollutants emissions compared to other fossil fuels (see IEA (2019)). The most common way to transport natural gas is through high pressure pipelines, thanks to gas-powered compression stations that move the fuel from the extraction spots to the delivery points along the grids. Increasing the efficiency of the gas transport system is thus consistent with the goal of progressive reduction of climate-altering gas emissions. This can be obtained for example through daily operation optimization of the integrated asset, by progressively substituting the gas fired compressors with electrically-operated ones and possibly by injecting in the grid larger and larger quantities of hydrogen, allowing to decarbonize also the end-users.

In this paper we propose a comprehensive framework for dynamic modelling and simulation of gas networks, characterized by high flexibility, reusability and extensibility, developed by exclusively using open-source tools.

Such a framework allows to automatically generate models of existing networks with different degrees of detail and accuracy and for different applications (e.g. dynamic simulation, optimal control with direct methods), starting from the network operator's databases, thus enabling improvements in the daily operation and control of the system. It also allows to explore future evolutions of the network in different directions: expansion of the network, addition of new types of machinery (e.g. electrically operated compressors), use of new gas mixtures (e.g. natural gas and hydrogen, or possibly hydrogen alone), with a minimal development effort, thanks to the adopted high-level declarative approach.

The goal of this framework is to eventually support all model-related activities of the network operator in a unified fashion, in particular the daily operation of the current system, as well as studies of its evolution in the near and far future.

The framework was developed with open-source languages and tools, namely Python and Modelica (Mattsson et al., 1998). The first one is an high-level object-oriented programming language that was used to create suitably simplified graph-based representations of the system. The second one is a declarative, object-oriented, multi-domain modelling language used to write the models of the components that are assembled together following the indications stored in the graph, so as to create complete dynamic system models. OpenModelica was the environment chosen to run the simulations (Fritzson et al., 2020).

The case study presented in this paper is the Italian natural gas high pressure network, see Fig. 1. This is a very large, complex and strongly integrated network, managed by a single public operator, with a total length of approx. 8000 km, featuring about 1800 pipes and 6000 nodes

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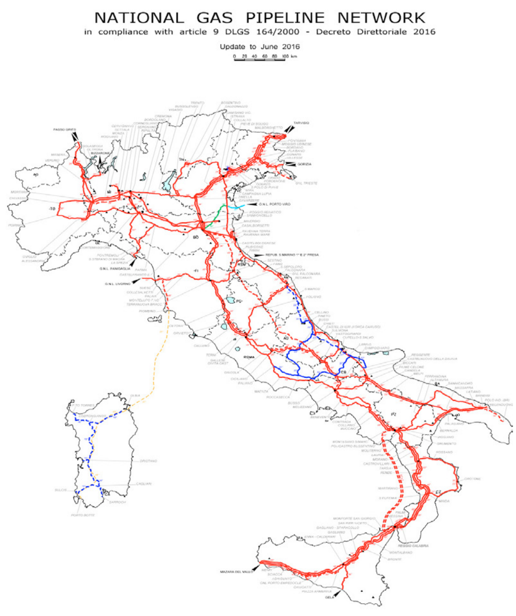

Fig. 1. Italian natural gas high pressure network

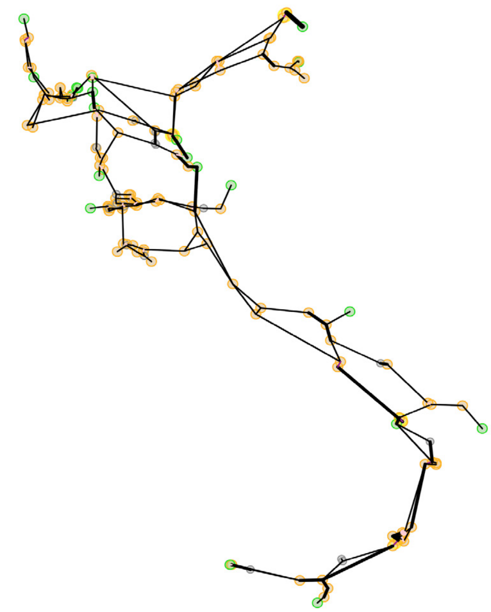

Fig. 2. Simplified graph of the grid

and comprising 15 compression stations, each employing multiple machines in parallel.

Up to the authors' knowledge, previous published work focusing on dynamic modelling of natural gas networks (e.g. Taherinejad et al. (2017), Pambour et al. (2016), Herrán-González et al. (2009)) used as benchmarks sample grids which are not comparable in terms of geographical extension and complexity to the network which is the subject of the present study. The largest case has half the length and far less nodes in which three or more pipes converge compared to the Italian grid.

The main contributions of the work presented in this paper are the use of abstract graph representations, to automatically reduce the complexity of the network to one suited some specific modelling objectives, and the use of object-oriented modelling languages and tools to translate such graph representations into executable simulation code, or possibly into the input for activities other than simulations, such as linearization and frequency-domain dynamic analysis or optimal control with direct numerical methods, which will be the subject of other publications.

Section 2 of this paper explains how graph representations and manipulations are used to derive a simplified description of the network, and how this is then translated into an object-oriented dynamic model of the system, including local controllers, using the Modelica language. In Section 3, the validation of the tool against real operating data from the Italian network is presented. Section 4 concludes the paper with final remarks and an outline of future work.

2. METHODOLOGY

The data we are basing the analysis on provide information about the structure of the grid, incoming flows from producers and outgoing flows to consumers (or storage systems), the measurements of quantities like pressures and mass flow rates, and setpoints for local controllers in compression stations and regulating valves. It also crucially includes the status of on/off valves that determine a certain overall flow scenario of the system. The network is represented through edges and nodes: the former comprise all the physical components, including their datasheets, as well as operating information. Nodes serve as junctions between components and they store information about measured pressure and the amount of gas entering or leaving the grid through exogenous flows. All measured quantities have a sampling time of four minutes.

Generating the graph Given the high complexity of the studied network, pressure drops introduced by on/off valves are neglected, limiting the analysis to pipes, pressure control valves and compression stations. Once a configuration is given to on/off valves, it will be considered fixed through the whole simulation. Furthermore, series-connected pipes are merged to reduce the effective number of elements in the grid, provided that they have the same diameter and roughness.

Starting from a complete representation of the grid as a graph object obtained with the Python library NetworkX (see Hagberg et al. (2008)), all the on/off valves are progressively removed: first the closed ones are substituted with open circuits, by removing the connection between the inlet and the outlet node, while the open valves are replaced with short circuits. During this last phase it is important to keep every information present in both the boundary nodes, particularly the extraction or injection of natural gas. Being the graph structured as a dictionary, to speed up the process and to reduce the number of times the list of valves to remove is evaluated, the algorithm proceeds to eliminate all the valves near non-valve elements, it updates the list and restart with the process until every valve is removed. Then, pipes in series are merged, storing the information about consumption of the removed nodes for later use in the pipe model. If any node that remains in the simplified version of the graph lacks a pressure information, it is obtained looking at the geographically nearest data available in the original grid.

Once the algorithm produces the new graph (shown in figure 2), the corresponding Modelica dynamic model is obtained by instantiating the appropriate physical models corresponding to the surviving edges in the graph, parameterized with the available information, and then connecting them in the same fashion. The physical models of all components are stored in the *GasNetworks* library, which was developed specifically for this work. The final grid model in the studied case accounts for 211 edges and 158 nodes.

Natural gas model As the operative pressure range is $45 \div 75\,bar$, real gas effects must be considered by using an equation of state in which the compressibility factor Z is considered, which normally depends on temperature (T), pressure (p) and composition. Many authors use an important simplification hypothesis, see Liu et al. (2020), Osiadacz and Chaczykowski (2001): temperature is considered constant along the grid as pipelines are most of the time underground and fixed to 15^oC. This reduces the equation of state to

$$pv = Z(p, \mathbf{x})R^*(\mathbf{x})\bar{T}, \tag{1}$$

where R^* is the individual gas constant of the natural gas and v the specific volume. Italy mainly gets natural gas from Russia and Africa, that extract gas with significantly different compositions. Explicit modelling of the transport of individual chemical species is possible, but would increase the computational load substantially. For the purposes of this work, for a given flow configuration, it was possible to approximate Z (as computed by Lemmon et al. (2018)) as two linear functions of pressure, one for the northern part of the grid and one for the southern one.

Pipe model Assuming that natural gas behaves as a compressible, Newtonian, single phase fluid flowing inside infinitely rigid cylindrical pipes and considering the flow completely turbulent, one-dimensional and isothermal, the equations that describe the dynamic phenomena in the grid are the reported mass balance (2), momentum balance (3) and energy balance (4)

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \int_{\Omega_f} \frac{\partial \rho}{\partial t}\,\mathrm{d}\Omega + \int_{\Omega_f} \nabla\cdot(\rho\mathbf{u})\,\mathrm{d}\Omega = 0 \tag{2}$$

$$\begin{aligned}\frac{\mathrm{d}\,(m\mathbf{u})}{\mathrm{d}t} &= \int_{\Omega_f} \frac{\partial \rho\mathbf{u}}{\partial t}\,\mathrm{d}\Omega + \int_{\Omega_f} \nabla\cdot(\rho\mathbf{u}\mathbf{u})\,\mathrm{d}\Omega = \\ &= \int_{\Omega_f} \mathbf{f}\,\mathrm{d}\Omega + \int_{S_f} \boldsymbol{\tau}\,\mathrm{d}S - \int_{\Omega_f} \nabla p\,\mathrm{d}\Omega\end{aligned} \tag{3}$$

$$T(x,t) = \bar{T} = 15^oC \tag{4}$$

where m is the mass, ρ the fluid density, $\boldsymbol{u}$ the velocity vector, Ω_f is the control volume, S_f the control surface, $\mathbf{f}$ the volume forces and $\boldsymbol{\tau}$ the shear stresses.

Considering that normal operation gas speed is on average less than $10\,m/s$, the kinetic term in the momentum balance is negligible as suggested by Liu et al. (2020) and Guandalini et al. (2017). The linearized model can be interpreted, as done by Taherinejad et al. (2017), as an electrical equivalent so that a capacitance, inductance and resistance may be identified when interpreting mass flow rate variations as currents and pressure variations as voltages. The results of Peres et al. (1998) for the electrical case lead to the following transfer function that links the variation of the inlet mass flow rate (imposed by the compression station that can be seen as a current generator when it regulates the mass flow rate) to the variation of the outlet pressure for a RIC pipe:

$$\frac{\Delta p_{out}}{\Delta w_{in}} = \frac{\sqrt{\frac{r+si}{sc}}}{\sinh(\sqrt{(r+si)sc}\cdot L)} \tag{5}$$

where r, c and i are the specific resistance, capacitance and inductance per unit length, respectively, and L is the length of the considered pipe. To reduce the computational effort, it is possible to neglect the inertial effects, i.e., the left-hand side of Eq. (3), reducing the RIC model to an RC one. This is valid when the condition presented in equation (6) is satisfied in equation (5).

$$\sqrt{r + j\omega i} \approx \sqrt{r} \rightarrow \omega \ll \frac{1}{\tau_{ri}} \tag{6}$$

where $\tau_{ri} = i/r$. Typical values for τ_{ri} in the considered case study are below one minute, which is a very fast time constant considering the overall system dynamics, that has time scales of hours, and even the sampling interval of four minutes.

The balance equations resulting from the simplifications are (7) and (8)

$$AL\frac{\mathrm{d}\rho}{\mathrm{d}t} = w_{in} - w_{out} - w_{cons} \tag{7}$$

$$p_{out} - p_{in} = c_f\bar{\rho}\,\omega\frac{u^2}{2}\frac{L}{A} - \bar{\rho}g(z_{out} - z_{in}) \tag{8}$$

where A is the cross section of the pipe, w are mass flows, z the height of inlet and outlet of the pipe, c_f is the Fanning friction factor, ω the wet perimeter and w_{cons} is the summation of all the consumptions/injections resulting from the simplification algorithm presented in subsection 2.0.1. Dividing the volume representing the pipe into smaller ones allows to be more accurate while assigning the geographical position of the exogenous fluxes and to obtain better pressure profiles describing the ongoing dynamics. This leads to a model built with several RC units in series; in particular, we chose the CRC representation splitting the capacitance into two halves connected to the boundaries of the resistance placed in the middle.

To determine the appropriate number of finite volumes, a simple system comprising a pipe between two compression stations prescribing the mass flow rate was analyzed. The analytical solution of the linearized partial differential equation describing this system (Polyanin (2001)) is:

$$w(x,t) = \frac{2an\pi}{L^2}\sum_{n=1}^{\infty}\sin\left(\frac{n\pi\xi}{L}\right)\left(1 - \exp\left(-\frac{an^2\pi^2 t}{L^2}\right)\right) \tag{9}$$

where time constants can be identified in the exponential time-dependent term: they are function of the parameter n that describes the spatial modes of the system. Considering the longest pipe in the simplified Italian network model, the minimum number of volumes so that their time constant is way lower than the sampling time for the inputs of the model (four minutes) turned out to be four.

Compression station model Each compression station features several radial compressors working in parallel (some of which may be of the same type), a bypass valve, and a network of on/off valves to connect the compressors to pipelines with a certain direction of flow, according to the given flow configuration. Each compressor is driven by a gas turbine, using the flowing gas as fuel. Once the graph simplification algorithm has run, the station can be described by the object diagram of Fig. 3. Physical connections are a-causal, i.e. they describe the flow rate of fluid at a certain pressure (light blue connections) and the exchange of mechanical power at a certain rotational speed (orange connections) without determining *a priori* which are the inputs and outputs of each component model; the Modelica tool figures out automatically how to solve the equations of the connected system.

The compressors are described by maps supplied by the network operator, relating the volumetric flow, the rotational speed, the isentropic head, and the isentropic efficiency, and are represented by suitable polynomials. The gas turbines are also described by polynomials, relating the fuel flow, the mechanical power output and the rotational speed, which is an input provided by the control system. The object-oriented models of the compressor model and of the gas turbine model are written independently, and are then bound to operate at the same speed by the mechanical connection in the object diagram.

Each machine model has an integer input M_p (orange arrow in the diagram) indicating the number of similar machines operating in parallel, which is easily modelled by multiplying the flow rates and powers by M_p. In case $M_p = 0$ the compressor flow rate and the gas turbine power are set to zero. The parallel operation of machines of different type is instead modelled by the explicit parallel connection of the machine models, as shown in Fig. 3.

The station model is completed by a functional description of the control logic, see Fig. 4. The controller receives the M_p values for each type of machines and three setpoints for the station total flow rate, inlet, and outlet pressure, and computes a master speed signal. Three corresponding PI controllers are implemented with three lead-lag filters, a minimum selector logic and a single integral action block, such that the controller requiring the lower rotational speed wins. The gain of the controller is scheduled on the values of M_p. The master speed signal output is then dispatched to the active machines, so they all operate at the maximum possible distance from their surge limit. When all $M_p = 0$, the bypass valve is operated with a check-valve logic, allowing free flow through the station when the upstream pressure is larger than the downstream one, while preventing back-flows.

Note that introducing electrically operated compressors in such a model is straightforward: one just needs to replace the gas turbine model with a suitable electrical motor model, connecting it exactly in the same way to the compressor mechanical connector.

Control valve model Control valves are used in the network to protect downstream lines. They work following either one or two setpoints: prescribed outlet pressure and maximum flow rate or only outlet pressure. In the first case, a minimum selector logic similar to Fig. 4 is used, while a standard PI controller is used in the second case.

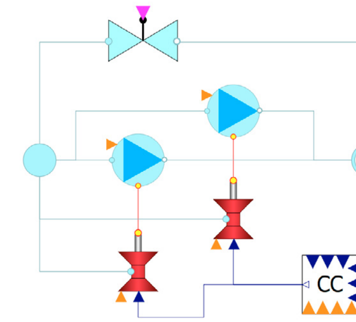

Fig. 3. Object diagram of the compression station model

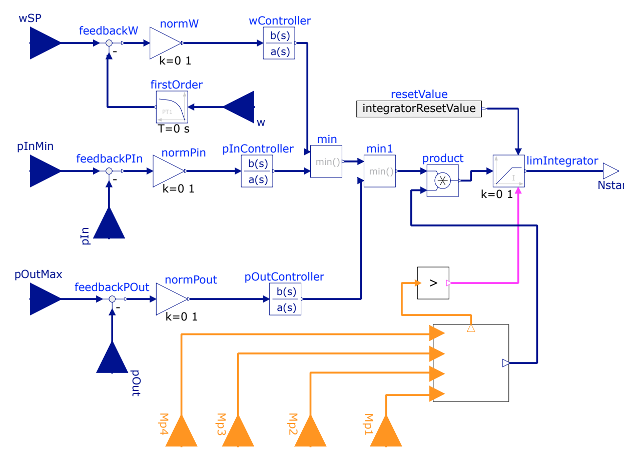

Fig. 4. Block diagram of the compression station controller

In order to minimize the model development effort, an idealized linear valve model was used, which allows reproducing the closed-loop behaviour with satisfactory accuracy, while simplifying the task of tuning the controllers and minimizing the need of detailed process data.

3. VALIDATION RESULTS

The modelling framework was successfully validated on two portions of the network; two different operative scenarios were tested.

3.1 Long-term scenario

The first validation test is conducted on the southern portion of the grid, see Fig. 5, with an extent of about 600×500 km, using recorded data from the system SCADA over a time span of 6 hours.

In this scenario, flows are prescribed to be equal to measurements at every entry point (Mazara, Gela, Melendugno, Fiume Treste) and at the node where the grid is cut (Gallese). Three compression stations are running: Enna runs at maximum rotational speed (because of very high flow set point), while Tarsia and Gallese stations are following the inlet pressure set point. The operating points change slowly over time, due to the dynamically evolving imbalance between the incoming gas flows at the entry points, and the distributed consumptions along the

Fig. 5. Southern portion of the network for validation

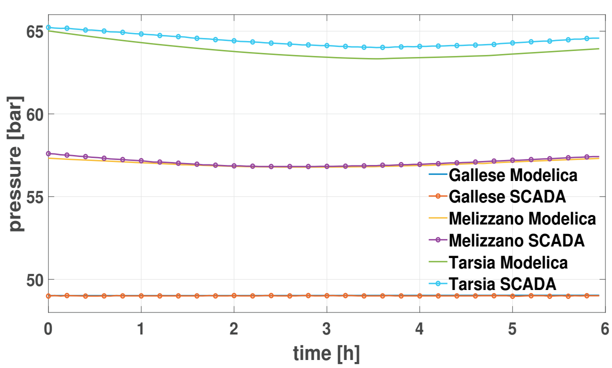

Fig. 6. Pressures along the grid: simulation vs *SCADA*

network. Selected results are reported to show how the simulated results match the data recorded on the SCADA.

Fig. 6 shows pressure trends at nodes further from the Enna station. Both the values and trends of pressures are reproduced accurately, with relative errors below 1.5%, which are probably due to the effects on gas density (and thus friction losses) of the uncertainty on actual gas composition and temperature and to possible uncertainties of the measurement process.

Fig. 7 and 8 report the simulated and measured rotational speed and fuel flow rate of the Gallese station, which operates under inlet pressure control. Although there are some discrepancies between the two, given the uncertainty on the maps that describe the machines' behaviour, the simulation captures the trends in a satisfactory way.

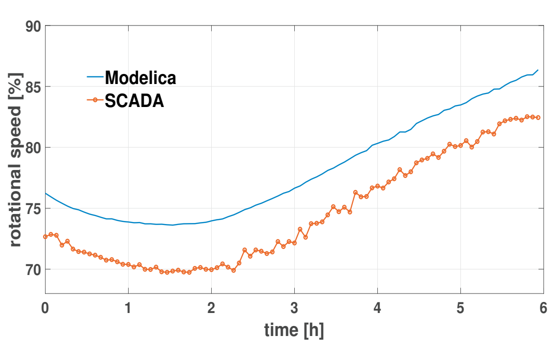

Fig. 7. Rotational speed at Gallese station

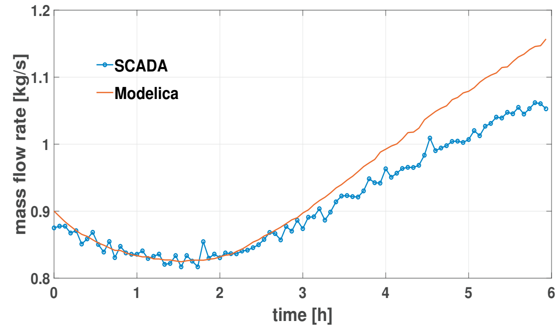

Fig. 8. Fuel consumption of the Gallese station

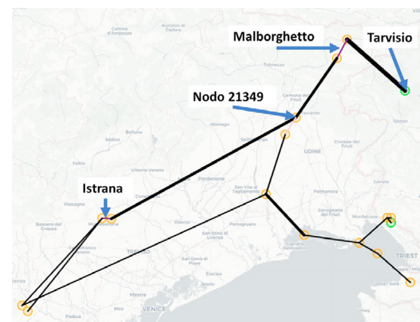

Fig. 9. North-east portion of the network for validation

3.2 Short-term scenario

The goal of the second validation scenario is to confirm that the modelling framework is able to describe faster transients correctly, including complex maneuvers such as turning on a compression station. To this purpose, the section of the grid shown in Fig. 9 was considered. The measured pressures at the boundaries were nearly constant, so the model assumes them as fixed.

In this scenario, the Malborghetto compression station is initially switched off and bypassed, with about 440 kg/s of gas flowing through the bypass. At time $t = 52\,min$ one compressor is activated, and the compressor flow rate set point is gradually increased. However, the effect of this increase is not visible outside the station until the flow rate set point overtakes the 440 kg/s at time $t = 63\,min$, because until that moment, the compressor flow just reduces the flow through the bypass. After $t = 63\,min$, the bypass closes and the station starts effectively pumping an increased flow rate into the downstream pipelines.

Fig. 10 shows how the model of the compression station (including the controller) is able to handle this non-trivial transient, using the control logic described in Section 2.0.4. The red curve (bypass flow) and the blue curve (station flow) are initially superimposed. The compressor is then turned on and its flow (yellow curve) is gradually increased, taking over the bypass flow, until eventually the station flow is increased.

Fig. 11 reports the comparison between simulated and recorded pressures: the two top curves represent the pressure at the station outlet, which start increasing after $t = 63\,min$; the two middle curves represent pressures at node 21348, which is located 30 km downstream the line, and thus react with a certain delay, while the two bottom

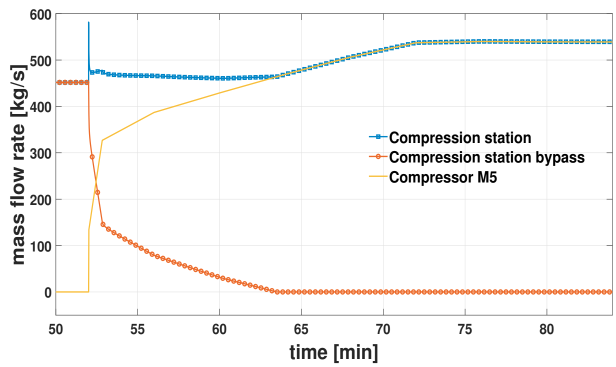

Fig. 10. Mass flow rates in Malborghetto station.

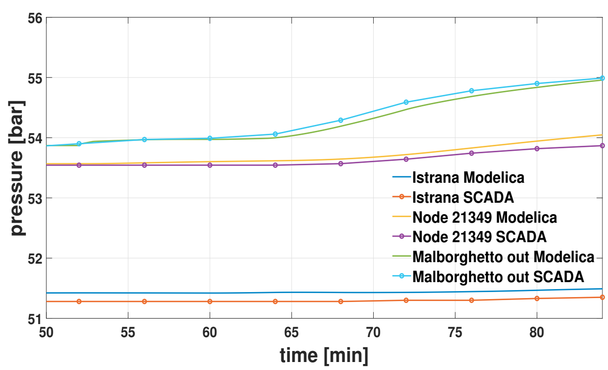

Fig. 11. Pressures in the neighborhood of Malborghetto.

lines represent the pressures at the Istrana station, which are not affected by the transient because the pressure increase has not had yet the time to propagate there within the simulation time span.

4. CONCLUSION

In this paper, a comprehensive dynamic modelling framework for gas networks based on open-source languages and tools has been presented.

The framework is capable to manage complex systems with thousands of components, and to produce suitably simplified equation-based models for simulation purposes, but also to carry out other model-based activities such as direct optimal control. It can then be employed as the foundation for all control, optimization, and planning activities of gas network operators, helping to manage the on-going energy transition.

The tool was validated on the Italian gas network, against measured data obtained from the system SCADA.

The use of the high-level, equation-based, object-oriented Modelica language for the formulation of the physical component model makes the tool flexible and amenable to extensions, such as introducing electrically-operated compressors or natural-gas-hydrogen mixtures, with a limited development effort.

Future work will extend the validation to the entire network; it also may include some of previously reported extensions to the models developed so far, as well as the use of the framework to generate models to solve direct optimal control problems. The tool could then be integrated with the network operator SCADA, to support the personnel responsible for the daily operation of the system. It could also be employed to support the planning of future extensions of the network and of its use.

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