MODELLING INTERDEPENDENT URBAN NETWORKS IN PLANNING AND OPERATION SCENARIOS

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ABSTRACT
We propose a cross-domain methodology to model and evaluate efficiency indicators of a Medium Voltage/Low Voltage (MV/LV) smart grid and its SCADA, interdependent, at physical layer and ICT layer, with water and gas urban networks. Models account the interdependency among the networks, a) adding, when possible, to the main sources of each network, sources belonging to the other networks; b) looking at the active components of water and gas networks energized by the electrical grid and c) considering ICT, which represents a common means, supporting and interconnecting SCADA devices of all the networks. Models use domain simulators to faithfully represent each physical network, and transversal simulators, to represent together the three interdependent physical networks and their SCADA systems. Models built by domain simulators are used to validate models built by transversal simulators. Efficiency indicators, and particularly, the Quality of Service of each network, are predicted along planning and operation scenarios.

Keywords: smart city, smart grid, gas network, water network, energy efficiency, interdependency models, SCADA

1. INTRODUCTION

Modernized urban networks will constitute the backbone of Smart Cities. They will ideally enable the integration of small distributed generation sources and will increase the customers awareness, providing real time optimization of network flows at the urban level, enabling interdependence and facilitating a multi services approach. They will strengthen the links among the electricity carrier and gas, water and ICT infrastructures. Increased use of SCADA (Supervisory Control And Data Acquisition) ideally improves reliability, security, and efficiency of modernized urban networks through a dynamic optimization of urban network operations and resources. Modernization of urban networks is a big long term challenge, for social, economical and technical reasons and it is far away to be realised. An extensive use of models at adequate level of granularity are needed to support such a modernization process (Johansson, 2010). Models have the aim to investigate the Quality of Services (QoS) delivered by each network to customers and citizens.

This paper proposes an cross-domain methodology to represent and evaluate the QoS of interdependent urban smart grid, gas and water networks and their SCADA (Supervisory Control And Data Acquisition), along the phases of planning and deployment of each modernization solution and along the phase of network operation. Planning and operational models, other than physical networks, have to include SCADA that constitute the nervous system of each network, network interdependencies (at physical, geographical, cyber and ideally at organisational levels) and have the aim of predicting QoS and efficiency degradation due to natural, technological and malicious adverse events (Ciancamerla, 2011).

The methodology, the first models and their results will then extended and instantiated on the modernization of the urban networks of the city of Catania, within the MIUR funded research project SINERGREEN, as a mean to evaluate the efficiency of a Medium Voltage/Low Voltage (MV/LV) smart grid interconnected with to water and gas networks. Such models will ideally provide knowledge and algorithms to feed a near real time decision support system for urban network utilities, l utilities of local generation sources, customers, local authorities and regional Civil Protection.

2. MODELLING APPROACH

To build consistent models, we assume a scenario, which includes the three urban networks, with the following minimum requirements: a) a minimal topology of each physical network, that allow to investigate solutions of local generation, load shedding, detection of natural, technological and malicious contingencies and their mitigation, by means of network reconfiguration performed by its SCADA. The topology consists of two (electricity, water or gas) feeders, each one feeding its subnet. In normal operative conditions the two subnets are separated one each other by two two Normally Open Tie switches. Each subnet delivers the physical flow to different (public, commercial, industrial) types of loads/passive customers network by means of physical trunks, connected one each other by Normally Close flow breakers. Local generation sources (such as photovoltaic, gas co-generator, mini- hydro and bio-methane sources) and storage devices (i.e. electrical batteries, water and gas tanks) are also connected to the network, Tie switches, flow breakers and protection breakers at feeder, are remotely controlled by SCADA. SCADA, by means of its Remote Terminal Units (RTU) which monitor the status of the physical network, implements load shedding, network reconfiguration upon contingencies (Bobbio, 2010); b) a minimal SCADA, which includes RTUs to monitor and operate the network ; c) indicators of network efficiency and QoS.

Starting from the above requirements, the first models of smart grid, water and gas urban networks and their interdependencies are implemented, at the adequate level of granularity and abstraction, also in presence of contingences by means of an advanced simulation environment, as shown in figure 1. The environment is constituted by: i) specific domain simulators and transversal simulators, based on equations domain, able to generate data and status of the physical layer of each urban network, plus ii) event based simulators which may properly represent SCADA functionalities and network operational layer and iii) a contingency generator to inject natural, technological and malicious adverse events in networks and SCADA models.

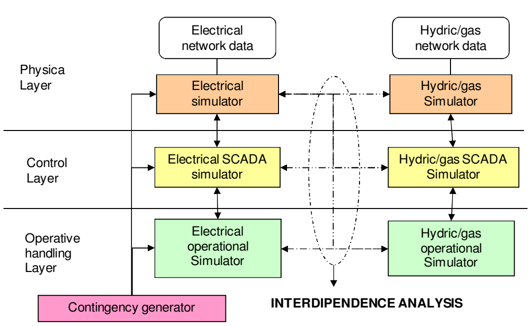

Figure 1: Simulation Environment

Each urban network model is under construction, starting from a basic network and adding devices and functionalities in incremental way, to include local generation sources and reconfiguration strategy. Models intend to predict efficiency and QoS of each network , from the point of view of the network public utility, utilities of local generation sources, local storage and passive customers. Models are built in two steps: i) to represent the physical networkand its SCADA as an isolated network and then ii) to represent its interdependencies with the other two nets. At this stage, we are representing, in an incremental way, into the models: a) local electricity sources, such as mini hydro, shared with water network and gas co-generators shared with gas network; b) active components of water and gas network energized by the electrical grid; c) ICT which support and interconnects SCADA devices of each network; d) local gas sources as bio- methane.

2.1. Smart electrical grid : planning & operation scenarios

Table 1 shows the main planning & operation scenarios for the smart electrical grid.

The scenarios reflect the following considerations: i) the integration of local sources may present high variability in producing energy. For instance, solar and wind energy, depending on weather conditions, are intermittent; ii) the high variability of renewable energy requires means to reduce the power imbalance due to the mismatch between the available renewable power and the load.

Table 1: MV Smart Grid Scenarios

Subject	Planning scenario	Operation scenario
MV public utility	Power flow inversion at HV/MV station versus HV network	Power flow inversion at HV/MV station versus HV network
	Thermal overload of MV trunks	Outage due to failure or maintenance & FISR
	Voltage variation over ± 10% of nominal value	Voltage variation over ± 10% of nominal value
	Short circuit currents at the active user nodes	
Renawable source producer	Long distance between renewable plant and MV grid connection point (increased connection costs)	Renewable plant disconnection from MV public utility due to failure or maintenance
		Renewable plant disconnection due to voltage variation over ± 10% of nominal value
Passive customer		Voltage variation over ± 10% of nominal value
		Outage due to failure or maintenance

2.2. Gas network: planning & operation scenarios

Currently, gas network is, and it is managed as, a passive network. The most prevalent topology for gas distribution network consists of a simple mono feeder type branched tree with one-way flow from the first gas Pressure Regulating Station PR (UNI CIG 9167, 2009), to the final gas pressure regulating installation PRI (UNI CIG 8827, 2009). In more complex cases (large urban centers with industrial districts) the number of the first gas PRS s is increased, according to load and pressure requirements and to a proper and optimal network balance. The stations are also interconnected one each other to create a mesh, reconfigurable network (UNI CIG 9167, 2009), (UNI CIG 8827, 2009). On particular conditions or on critical faults, an inversion of gas flow may occur in some sections of the network (even the ones used for network reconfiguration), causing pressure reduction and in some extreme cases even the "extinguishing of flame”.

In near future, European technical standards will regulate the injection of biomethane local production into natural gas distribution networks, within safety, reliability, flow and operating pressure network constraints (D.Lgs 28/2001). Such an innovation will transform the current passive gas networks into active networks, with bidirectional gas flows and will change its planning and operation scenarios as in table 2.

Table 2: MP Gas Network Scenarios

Subject	Planning phase	Operation phase
Gas DSO public utility	Designs network in terms of maximum flow Q_{max} and operating pressure is maintained in the outlet system within required limits.	Monitors and controls Q_{max} and P_{min} within the contractual requirements in any point of network.
	Designs network in terms of safety and reliability constrains.	Verify safety and reliability constrains due to local regulations (annual percentage of network inspected for both medium and low pressure network; annual number of measures of the degree of odorized gas; time responses to emergency calls; number and duration of interruption per consumer; gas flow rate within limits to reduce load losses)
	Gas flow inversion (extinguishing the flame)	Monitors imbalance of the network (normal or emergency contingencies)
Producer (active user)	Connection to the network (specifications in terms of flow Q and pressure P)	Disconnection from the network by the utility in the event of faults or maintenance
Passive User		Must not exceed the contracted flow (Q_{max} per consumer)
		Verify compliance with the minimum contractual pressure P_{min}

Even for the gas network there is a strong demand variability between consumption and supply by the Distribution System gas Operator (DSO). The gas demand is variable according to the season (winter/summer), daily temperatures, the production cycle of industrial users, the demands of electricity and thus presents a consumption profile variable. Instead, the contracts for the import/transport/distribution of gas have limited flexibility with fairly linear trend and constant in time. The physical balancing is concerned with the optimal management of gas flows on the network to ensure the safe and reliable operation based on the actual demand for gas. The main effort for the DSO is to ensure a correct balance for the entire period of operation time.

2.3. Water network: planning & operation scenarios

In our urban water distribution network there are no active users and the water flow proceeds normally from the feeders to the consumers. Undesirable situations may occur and fault scenarios and network reconfiguration should be forecasted in order to limit degradation of water flow to customers and even disruptions of network elements and devices (UNI EN 1074-5:2002). The focus here is efficiency and interdependency, then, water contamination is out of the scope. Table 3 shows the main planning and operation scenarios for the urban water network. Certainly, a proper planning of network maintenance drastically reduces the service outage.

Table 3: Water Network Scenarios

Subject	Planning scenarios	Operation scenarios
Public Water Utility	Interruptions of supply from a feeder due to a failure (breakage or malfunction of network elements)	Network reconfiguration (alternate feeder)
	Avoid speed below 0.5 m/s and the water age greater than 10 hours.	Limitations or loss of service
	Overpressure	- Monitoring and remote control - Speed in the pipes below 1.5 m/s - Avoid abrupt operations that can generate harmful pressure waves
Passive User		Limitations of use or lack of service

Flow parameters have to consider physical-chemical-biological requirements for drinking water (i.e. Legislative Decree no. February 2, 2001, n. 31 et seq.), to avoid speed below 0.5 m/s and in any case the water residence times (age) in the pipes greater than to 10 hours. Also overpressure and consequences: water hammer; permissible tolerance range in according to the manufacturer's specification. Speed in the pipes below 1.5 m/s and avoid abrupt operations that can generate harmful pressure waves.

3. URBAN NETWORKS MODELS

Models of each urban network and its SCADA system are under construction. The jointly representation of the physical infrastructure and of its SCADA system in a single model is not an easy stuff, if one would represent the physical network at a sufficient level of detail to adequately compute its efficiency and QoS indicators. A relevant aspect is model validation. To address model validation, we are using domain simulators which can faithfully represent the physical infrastructure, combined with the use of transversal simulators, such as Matlab and Simulink, which can more easily represent physical network and its control system in a single model. Moreover, Matlab and Simulink may easily represent network interdependencies at physical, logical and geographic levels. Models built by domain simulators, one for each urban network, are used to validate Matlab and Simulink models.

3.1. MV smart grid

For the purpose of model validation, two models of the same basic MV/LV smart grid have been built. Models implement the above minimum requirements:

- two HV/MV substations with their protection breakers,
- a set of users (U),
- renewable generators (G),
- a set of prosumers (generators/users) (P)
- and a Low Voltage backbone, with its own set of U,G,P.

Electrical parameters of grid elements and their values are actual ones, including the ones of photovoltaic sources. Table 4 and 5 report some of them.

Table 4: Transformers Parameters

Transformers	TR CP1	TR CP2	TR PRIV1	TR PRIV2	TR PRIV3	TR DISTR
Avvolgimento	Yyn	Yyn	Dyn	Dyn	Dyn	Dyn
V1n [kV]	150	150	20	20	20	20
V2n [kV]	20	20	0,4	0,4	0,4	0,4
Sn [kVA]	25 000	25 000	630	800	630	400
Smax [kVA]	32 500	32 500	820	1040	820	520
fn [Hz]	50	50	50	50	50	50
Vcc% [p.u.]	13	13	6	6	6	6
Pcc% [p.u.]	0,42	0,42	0,76	0,75	0,76	0,81
Po [kW]	22,75	22,75	0,68	0,80	0,68	0,52
Io% [p.u.]	0,2	0,2	1,8	1,65	1,8	1,9

Table 5: Generators and Loads Parameters

Generator	DC1	DC2	DC3	DC4
P [kW]	400	500	50	20
Q [kVar]	0	0	0	0

Load	C1	C2	C3	C4
P [kW]	500	500	50	50
Q [kVar]	242	242	24,2	24,2

Figure 2 shows the load flow computation of the model of the basic MV/LV electrical grid, built by means of PSS-Sincal simulator. While, figure 3 shows the model of the same grid built by Simulink.

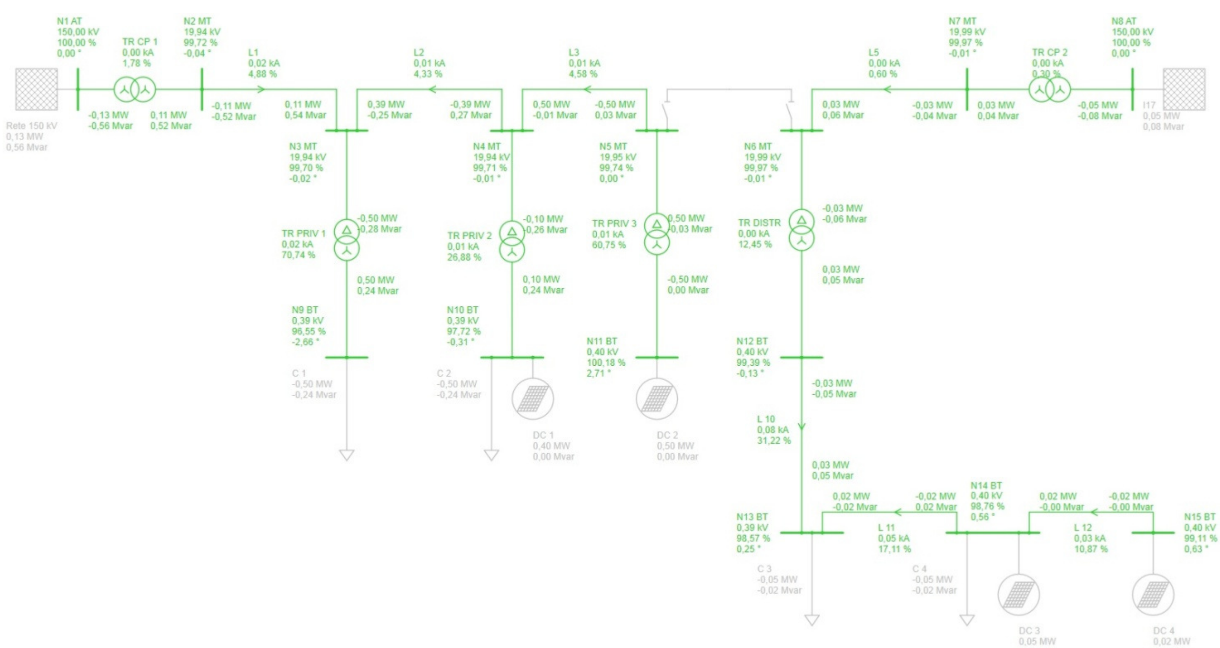

Figure 2: Basic MV/LV Grid Model by PSS-Sincal

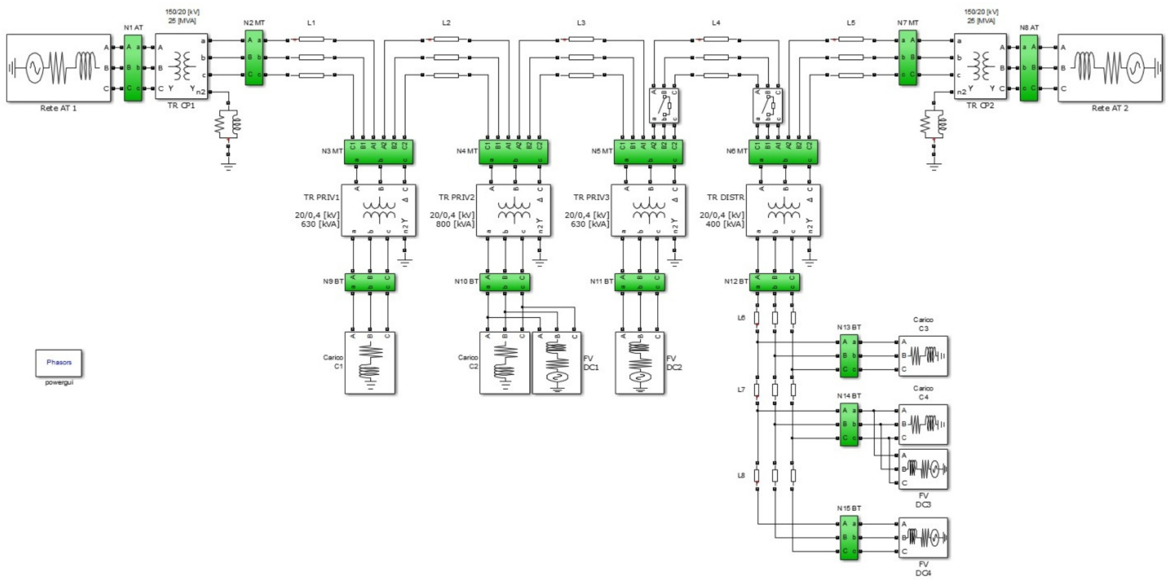

Figure 2: Basic MV/LV Grid Model By Simulink

Table 6 reports the comparative results of load flow computation between PSS-Sincal and Simulink, in terms of voltages on different nodes of the electrical grid and computation errors. Such errors between the two models are very limited, less or equal to 0,25%. Then we consider both basic models and results validated one each other.

Table 6: Comparing Simulink and PSS-Sincal Models

Voltage [kV]	*Simulink*	*PSS SINCAL*	*Error %*
N1 AT	150,000	150,000	0,00
N2 MT	19,946	19,944	0,01
N3 MT	19,941	19,939	0,01
N4 MT	19,944	19,942	0,01
N5 MT	19,949	19,948	0,01
N6 MT	19,995	19,993	0,01
N7 MT	19,996	19,994	0,01
N8 AT	150,000	150,000	0,00
N9 BT	0,386	0,386	0,00
N10 BT	0,391	0,391	0,00
N11 BT	0,401	0,401	0,00
N12 BT	0,398	0,398	0,00
N13 BT	0,395	0,394	0,25
N14 BT	0,396	0,395	0,25
N15 BT	0,397	0,396	0,25

On the validated model of the basic grid, we have introduced physical interdependencies with gas and water networks in terms of mini hydro devices, shared with water network, and gas co-generation devices, shared with gas network, which act as local generation sources.

The main parameters of Mini hydro and gas co-generator used in the models are reported in tables 7,8 and 9. Particularly, a Mini hydro of 0,77 MW installed on the MV subgrid, a Mini hydro of 0,09 MW, installed on the LV subgrid, a co-generator of 20 kW installed on the LV subgrid and a co-generator of 400 kW installed on the MV subgrid.

Table 7: Mini Hydro Parameters of LV Subgrid

Turbine	1 x Francis
Height (H_n)	70 [m]
Flow (Q)	0,100 - 0,150 [m^3/s]
Installed Power	90 [kW]
Yield (η)	80 %

Table 8: Mini Hydro Parameters of MV Subgrid

Turbine	3 x Francis
Height (H_n)	210 [m]
Flow (Q)	0,52 [m^3/s]
Installed Power	2x315 + 1x135 [kW]
Yield (η)	70 %

Table 9: Gas Co-Generator Parameters

Electrical power [kW]	*Thermal power [kW]*	*Electrical yield [%]*	*Thermal yield [%]*
20	39	32,23	62,90
401	549	38,08	52,14

On such models we are investigating indicators of efficiency and quality of electricity, in the planning and operation scenarios of table 1. For example, the model which implements the planning scenario "power flow inversion at HV/MV station versus HV network" may support decisions about location and size of the local sources, to avoid power flow inversion. Here, we shortly describe the model which implements the operation scenario "Fault Isolation and System Restoration (FISR) process", which may help in optimizing the reconfiguration of the grid on its permanent failure. The FISR model includes the electrical grid and its SCADA system. A three phase permanent failure is supposed to occur on the electrical trunk n. 2 of the MV grid (Figure 3). The consequent short circuit current causes the opening of protection breakers of the HV/MV substation on the left of the picture, the complete de energisation of its subgrid and the triggering of FISR process execution over SCADA system . The FISR process consists of the re-energizing step by step the segments of the electrical grid from the feeder downstream.

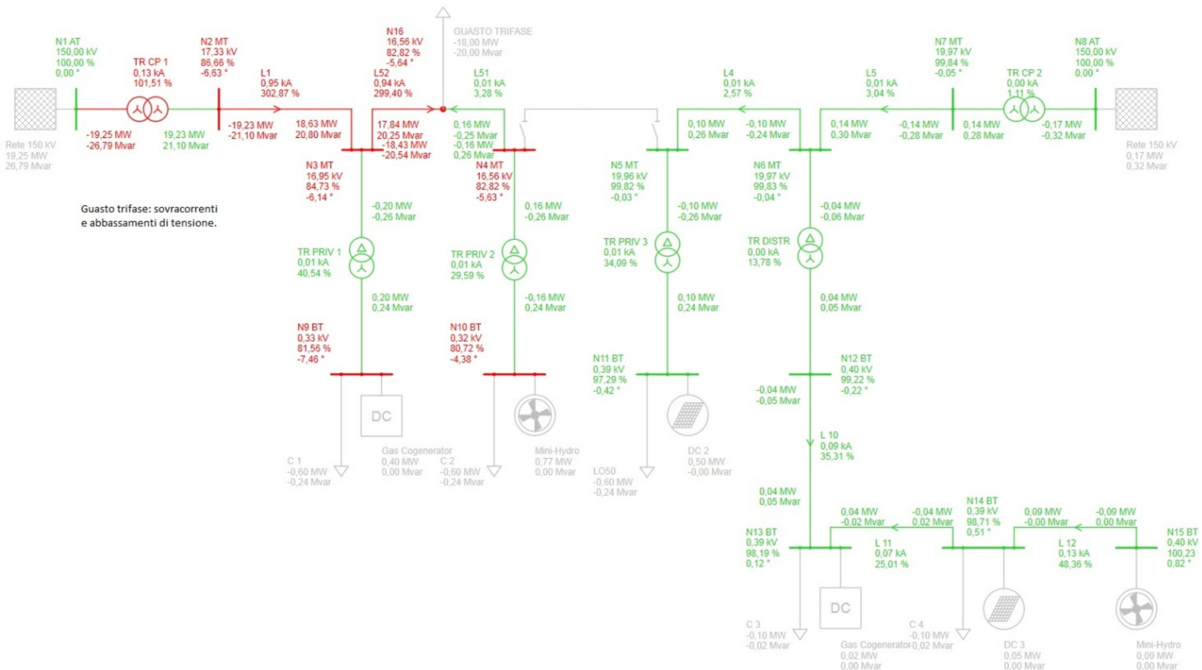

Figure 3: A Failure on the Electrical Trunk N. 2 opens the Protection Breakers and triggers FISR over SCADA System

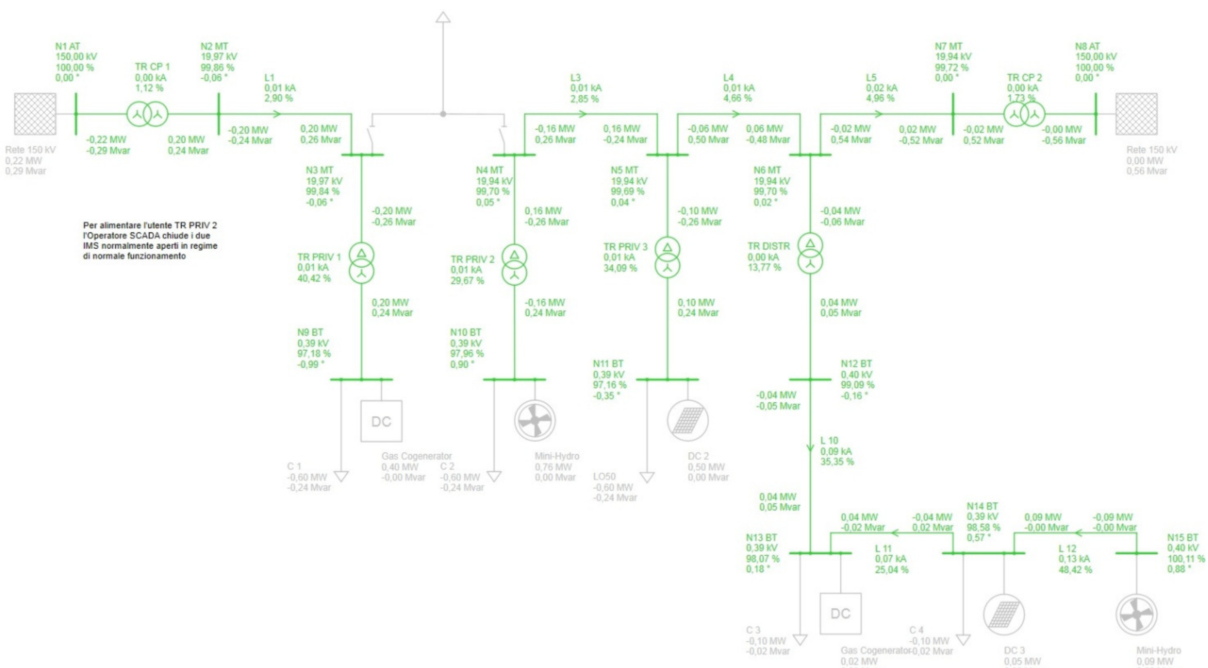

Figure 4 - Grid Reconfiguration on Complete Execution of FISR over SCADA System

Once it comes to the segment containing the faulty line, the feeder breaker trips again, thus signalling the faulty segment has been detected. Once the fault is localized, the faulty segment is isolated, the faulty line is repaired and the normal configuration of the grid is restored by toggling line switches in their normal state.

Figure 4 shows the grid at the end of FISR process. The duration of FISR process depends on the SCADA functioning and may increase under ICT contingencies and cyber attacks. The time the FISR process takes influences directly the electrical grid QoS. One of QoS used by electricity utilities is *Tn*:

$$Tn = \sum(KVA*Duration)/Installed\ KVA$$

Tn is indeed an equivalent time of complete loss of electricity for all the customers while executing FISR. More the FISR process takes, greater the *Tn* is.The model simulates FISR procedure and its consequences on the grid. The FISR detects the segment to which faulty line belongs, isolates the segment and restore original configuration after line reparation. To do this remotely, dozens of commands are sent by SCADA to RTUs who open and close switches.

Besides the aggregated QoS indicators used by electrical companies, models also calculate more detailed indicators such as time of energy loss for each customer, loss of power on trunks and transformers and the percentage of distributed generation respect to the total load.

3.2. Gas network

The model of the gas network has also two feeders: two interconnected first gas PRS that feed portions of a branching network to supply different types of users and/or PRI:

- Industrial Consumers (IC) (directly connected to medium pressure network) or thermal power plants;
- Home consumers, connected to final gas pressure regulating groups PRI_f in which the upstream pressure of 5 bar is reduced to the value of 23 mbar (each PRI may feed even hundreds ofconsumers);
- Small industrial PRI_i (upstream pressure is reduced to a range between 50 and 200 mbar). In the model a CHP 401/549 kW with consumption of 105.3 Nm^3/h at 200 mbar has been included;
- Specific consumers with specific values of pressure – flow PRI_u. An example could be represented by a cogeneration unit (in the model a CHP 20/39 kW with consumption of 6.2 Nm^3/h at 50 mbar);
- BIOMETHANE1 that identifies the “active user” type by entering biomethane into the natural gas distribution network.

In the physical model is also entered a branch of the interconnection to be used for network reconfiguration following particular eventualities/faults. To implement the model was used NEPLAN, a powerful software with up-to-date calculation algorithms including Newton-Raphson and Hardy-Cross methods. A load flow simulation was performed on the model developed and the result is shown in fig.5. The characteristic data of each section (diameter, thickness, length, coefficient of roughness, friction coefficient lambda linked to relative roughness and Reynolds number) are known for DSO pipelines.

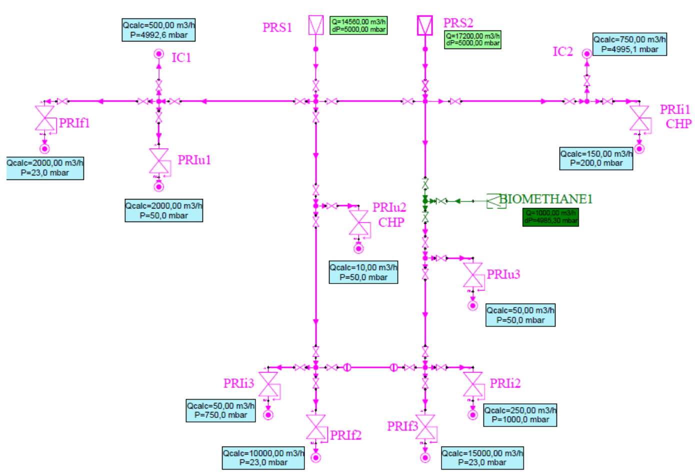

Figure 5: Load Flow of the Gas Network in Normal Conditions by Neplan

In normal operating conditions, the network is balanced, and network main parameters such as pressure, flow, pressure drop and gas speed inside of pipes for each point/node/component of the network are measurable or calculable. Assuming a failure in one of the components of the network, it is possible to isolate the failure and perform a reconfiguration of the network by means of remote controlled valves in order to ensure continuity of operation. Obviously, the failure isolation and reconfiguration procedure may change depending on failure location. For example, if the failure affects the first gas PRS is possible to act on the upstream and downstream valves to isolate it and the supply continuity is ensured by reconfiguration based on the meshing of the stations. If the failure affects a middle section that would isolate an entire trunk (1. Failure) in fig. 6, it is possible to operate the valves upstream and downstream of the affected section and act on valves (normally closed) to make a network reconfiguration (2. Reconfiguration) by means of SCADA system.

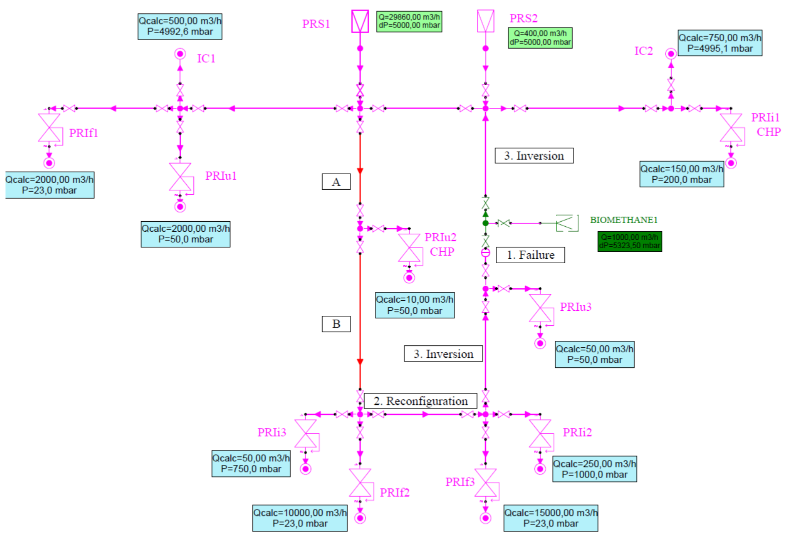

Figure 6: Load Flow of the Reconfigured Gas Network on a Failure.

It is clear that in the portion (3. Inversion) there is a gas flow inversion. At the same time it can be seen that the first gas PRS is subjected to an overload, however, within the limits of design capacity. The different colors of A and B pipes indicate the criticality of the network in such pipes because they do not meet design constraints of pressure and/or speed of the gas inside the pipes.

3.3. Urban Water network

The urban water network model, at this stage, has been developed by using EPANET 2.0 software, provided by the EPA (Environmental Protection Agency). Figure 7 shows such a model, which, in agreement with the general framework described above, satisfies the following minimum requirements:

- Two sources (CP1, CP2), each one capable by itself to feed the whole network when necessary, as it could be in a failure scenario. In normal operating conditions, as shows in figure 7, the left branch is fed by CP1 and the right one is fed by CP2. The pumps P1 and P2 are normally switched off in order that the left branch results disconnected from right one, and the links that connect them to the rest of the network are normally closed. The pump P3 is normally active, and allows the right branch to be fed.
- Public, commercial, and industrial consumers (L1-L5), for a district that serves about 10,000 inhabitants-equivalent, with an expected daily water requirement of 240 l / inhabitant • day.
- Valves V1 and V2: V1 represents a Pressure Breaker Valve (PBV) that simulates a mini hydro plant, V2 a Flow Control Valve (FCV), which limits the flow to the tank, to preserve the speed of the water in the pipes within the specified limits (0.5-1,5 m/s). Each link presents also the possibility to be open or closed.
- Two tanks, PV1 and PV2 that are capable to feed respectively, left branch and the right one for a few hours. To do this, it isn't necessary the use of pumps, because each tank is capable to feed the branch tanks by gravity. Normally, tanks are refilled when the load in the network is low as typically occurs during the night.

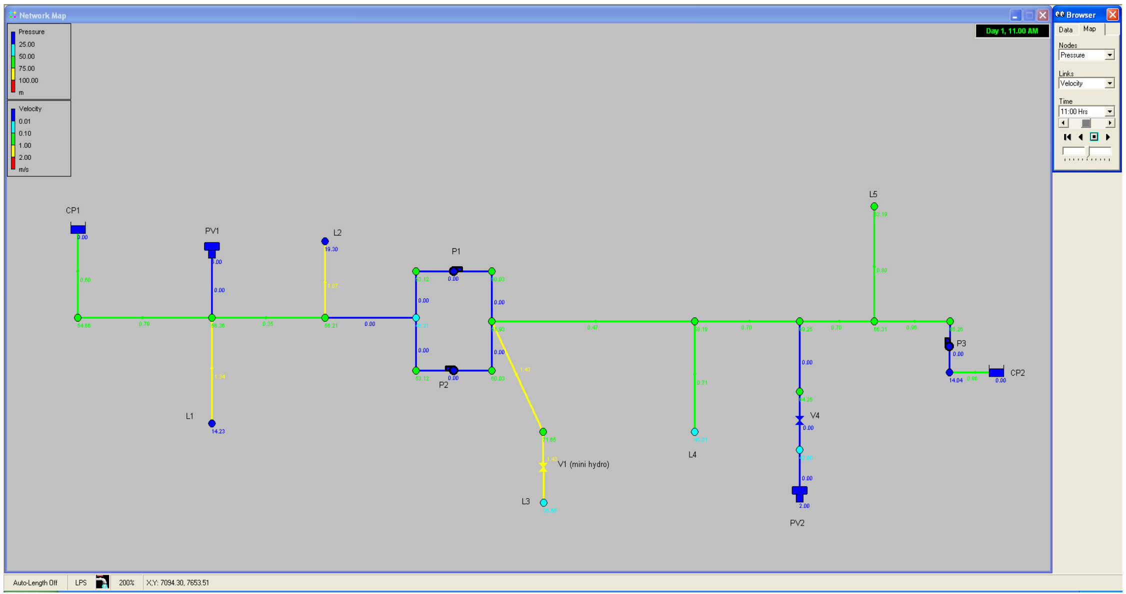

Figure 7: Load Flow of Water Network in Normal Operations by Epanet

A reconfiguration of the network, that may occur on a contingency, in which a single source feeds the whole network is shown in table 3. To reconfigure the network, the following operations have to be performed by means of remote control valves: a) to exclude a source (e.g. CP2); b) to open links upstream and downstream of the pump P1; c) to activate the pump P1.

The reconfigured network is shown in figure 8.

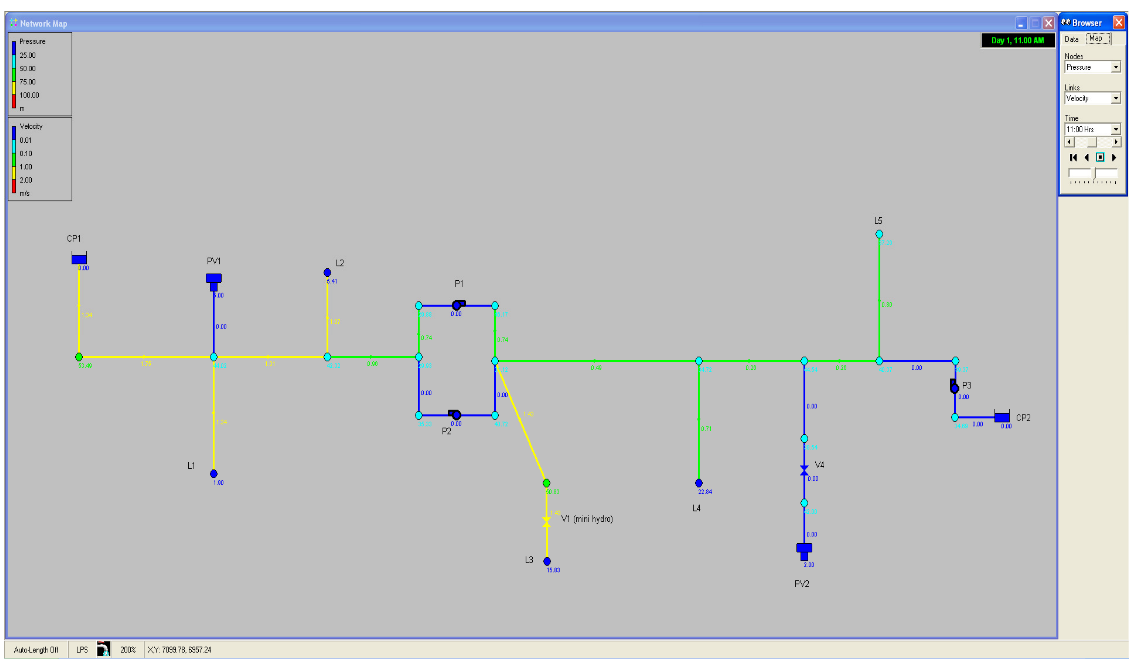

Figure 8: Reconfiguration of Water Network : a Single Source (CP1) feeds the Whole Network

4. INTERDEPENDENCY ELEMENTS

Current models are built to be conceptually interconnected one each other to represent interdependencies among the three urban nets, at physical, logical and geographic layer. Her, we discuss the main elements of interdependency to be represented in our models,

At this stage, we are considering a) distributed electricity sources, such as mini hydro, shared with water network and gas co-generation shared with gas network; b) active components of water and gas network energized by the electrical grid and c)ICT which support and interconnects SCADA devices of each network.

Regarding gas network, the mutual dependencies between the electrical and gas network can be easily identified and represented. Cogeneration units CHP and natural gas thermal power plants or natural gas combined cycle turbine CCGT using natural gas fuel for the combined production of heat and electricity.

A change in the functioning of the above systems has an impact on the electricity grid production. More obsolete gas networks essentially consist of mechanical adjustment with electromechanical type for measurement and data acquisition systems. The dependency from the electrical grid regarded the registration systems of gas network measures, such as volume, pressure, temperature and level of odorized gas. SCADA system was basically a measurement and data acquisition system. The technical evolution and also the increasingly stringent minimum requirements imposed by national authority for electricity and gas have led to current solutions in which each component of the gas network is managed with electromechanical actuators (valves, pressure regulators, ...) and controlled by electromechanical/electrical/electronic transducers (temperature, volume, pressure, odorized, clogging filters, ...). SCADA system of the gas network has become extremely complex and consequently also vulnerable, highly dependent on the electrical and ICT networks.

Regarding water network, the main mutual dependencies with the electrical grid, at physical layer, are the mini hydro plants and the electrical supply of the active components (such as the pumps and remote controlled valves) of water network, and the electrical energisation of SCADA devices. Dependency also arises at logical level by means of ICT technology which support IP based solution for SCADA systems.

5. CONCLUSIONS AND FUTURE WORK

We are developing integrated models of interdependent urban networks to compute their efficiency and quality of services in planning and operation scenarios. Models take into account interdependencies and proper functioning of SCADA when the FISR process is needed to detect, isolate permanent failures on the physical networks and to reconfigure to mitigate the effect of outage on networks stakeholders(public utilities, local generation and passive customers). FISR duration depends also on SCADA command delivery time. Models are under development in incremental fashion. Final models intend to simulate load shedding procedures, which route physical flow by using optimized load scheduling algorithms, which account local storage and cost for customers. In determining routing features, models play a big role. I.e. for the smart grid, they intend to answer how much storage could reduce the power imbalance or how much storage is needed to achieve a required energy reduction. It can be shown that most of the reduction in the power imbalance can be achieved with relatively small storage capacity. Representation of different forms of energy storage are currently under investigation, with their location and their size within the MV network.

The scalability of described models in planning and operation scenarios on the city of Catania, it is a very important step. The role of electricity, gas and water utilities, as stakeholders of SINERGREEN Project, becomes more and more relevant in extending and tuning scenarios and models according to their actual needs.

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