Model of a Real Medium Voltage Distribution Network for Analysis of Distributed Generation Penetration in a SmartGrid Scenario

Adinolfi, F.; Baccino, F.; Marinelli, Mattia; Massucco, S.; Silvestro, F.

Published in:
Proceedings of 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)

Publication date:
2012

Citation (APA):
Adinolfi, F., Baccino, F., Marinelli, M., Massucco, S., & Silvestro, F. (2012). Model of a Real Medium Voltage Distribution Network for Analysis of Distributed Generation Penetration in a SmartGrid Scenario. In *Proceedings of 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)* IEEE.

Model of a Real Medium Voltage Distribution Network for Analysis of Distributed Generation Penetration in a SmartGrid Scenario

F. Adinolfi, F. Baccino, M. Marinelli, S. Massucco and F. Silvestro, *Members, IEEE*

Abstract— **The paper aims at simulating the behaviour of a real medium voltage electric network in order to analyse the effects of distributed generation penetration, in particular from solar source. Firstly the network model has been designed by the simulation tool DIgSILENT, using data obtained from the Distribution System Operator (DSO) to highlight, through subsequent checks, the likeliness between results from simulated scenarios and available measurements. Then static simulations were performed, with different scenarios of PV generation, in order to check the possibility to manage this generation. The behaviour of the network in compliance with the current national standards has been verified. Finally some dynamic simulations were performed in order to analyse transients due to typical operations of distribution systems.**

Index Terms—**Smartgrid, ancillary services, PV integration, national standards, MV distribution network.**

I. INTRODUCTION

SMART grids are electrical networks that use distributed intelligence and other technologies to collect information about the behaviours of prosumers and customers in general to improve the efficiency, reliability, economics, and sustainability of the energy. The implementation of this kind of networks requires that the Energy Regulators welcome European Union initiatives to accelerate the development of technologies for Smart Grid. At European level the Council of European Energy Regulators (CEER), due to 20-20-20 target, is deploying some demonstration projects, making available its knowledge for efficient solutions in terms of the balance between costs and benefits of technological innovation [1], [2].

In Italy the Authority for Electrical Energy and Gas (AEEG) participates in the CEER's works and has started several years ago a path for identifications of optimal conditions to move forward to a Smart Grid scenario. The first step was a study, started in 2009, about the impact of Distributed Generation (DG) on Medium Voltage (MV) network.

This study [3], using appropriate load flow, allowed the evaluation of hosting capacity of MV distribution network in respect of the main nodal constraints (rapid/low variations of voltage, thermal limitations of current).

The results showed that, in order to fully exploit the hosting capacity, some problems must be solved. In particular the main problems concerned more the lines loading that the nodes voltages, because the protection system does not guarantee a safe operation during any reversals of the power flow. One possible consequence is the operation of certain part of the network in "islanding" conditions (only supplied by DG) with consequent negative effects on service quality, operator safety and plant operation [4], [5].

The second step was to select the pilot projects admitted to an incentive treatment, subject to the satisfaction of certain conditions such as:

- Represent a real MV network
- Concern a part of active network (reversal power flow during at least 1% of the year)
- Have a system to monitor/control voltage
- Use a non-proprietary communication protocol
- Comply with the current national standards.

The present work focuses on the modeling of a real distribution network located in the Mediterranean Area. The network is characterized in detail at the medium voltage level while the low voltage networks connected to the public substations are lumped with an equivalent load function on the customers' number. The procedure adopted is derived from the one described in [6].

The study provides a first characterization of the users' consumption profiles, being known the feeder active and reactive power flows. Subsequently a penetration analysis of the photovoltaic (PV) systems connected at the public substations and the issues related to the lines loading and voltage profiles is performed, with the aim of evaluating the losses in function of the PV penetration. After the static studies some dynamic scenarios are studied with the purpose of evaluating the voltage capability control during voltage dips and the behavior during the faults.

The conclusions and future developments are reported along with the bibliography at the end of the paper.

F.Adinolfi, F. Baccino, M. Marinelli, S. Massucco, F. Silvestro are with the *DITEN-Department of Naval, Electrical, Electronic and Telecommunication Engineering*, University of Genova, Italy. E-mail: {francesco.adinolfi; francesco.baccino; mattia.marinelli; stefano.massucco; federico.silvestro} @unige.it

II. NETWORK CHARACTERIZATION

A. *Network main features*

The grid studied is a medium voltage network (15 kV) situated in the Mediterranean Area consisting of ten feeders connected to one HV/MV substation (132kV/15kV) for a total length of 116 km. In the primary substation there are two incomes from the HV network through incoming-outgoing connection, two transformers (40MVA, 130±10•1.5% kV /15kV) and two MV busbars connected by a normally closed parallel tie, so all MV feeders are powered by a single transformer at a time.

The single line diagram in Fig. 1 represents the primary HV/MV substation. There are 186 public MV/LV substations fed by the network and the medium voltage customers are 17. It is also present one photovoltaic plant (PV) connected to MV and several PV plants connected to LV network. In each secondary substation the low voltage network is represented by a LV equivalent load included in the substation model.

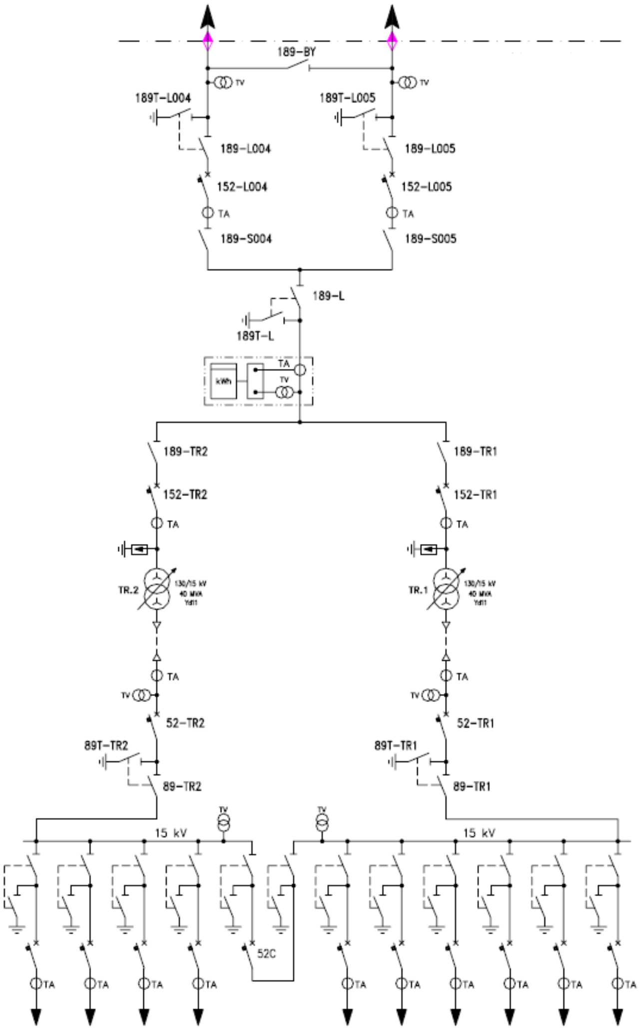

Fig. 1. HV/MV substation of considered network

Fig. 2 shows the MV network's absorption of the active/reactive power and the HV/MV substation voltage profile; both profiles are one week long.

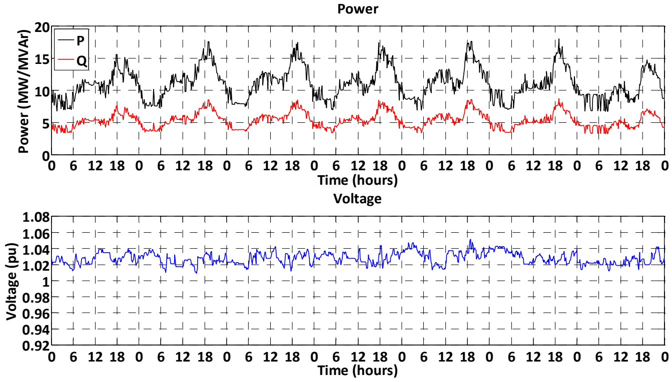

Fig. 2. Network active/reactive power absorption and voltage profile

B. *Feeder characterization*

The model, set-up in DIgSILENT PowerFactory [7] (a software tool for power system analysis), contains the primary substation and five of the ten feeders, with the corresponding secondary substations and active/passive users connected to medium and low voltage.

Fig. 3 shows the layout of feeder number 10, which contains the medium voltage PV plant. This feeder supplies 19 public substations. Nine of these are typical MV/LV substation (rectangular objects) while the remaining are pole transformer (circular objects). The feeder is 10 km long and it is composed by 7.34 km of overhead conductor, 20 meters of ground cable and 2.64 km of overhead cable.

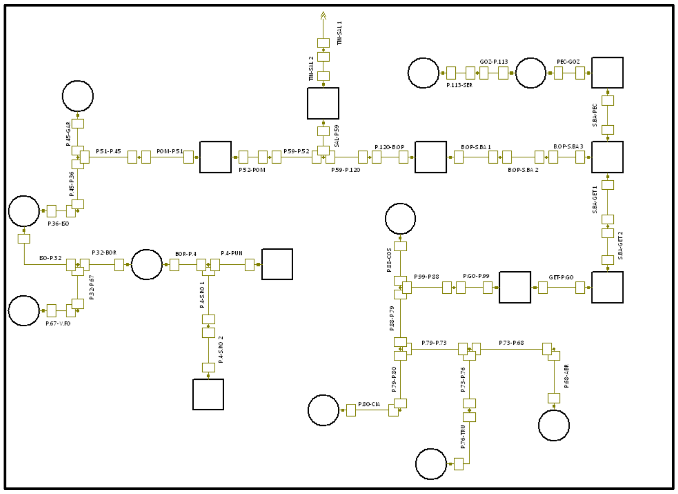

Fig. 3. Scheme of the MV feeder number 10

The feeder number 4 is composed by 4.19 km of underground cables and supplies 9 MV/LV substations and one MV user. The layout is reported in Fig. 4.

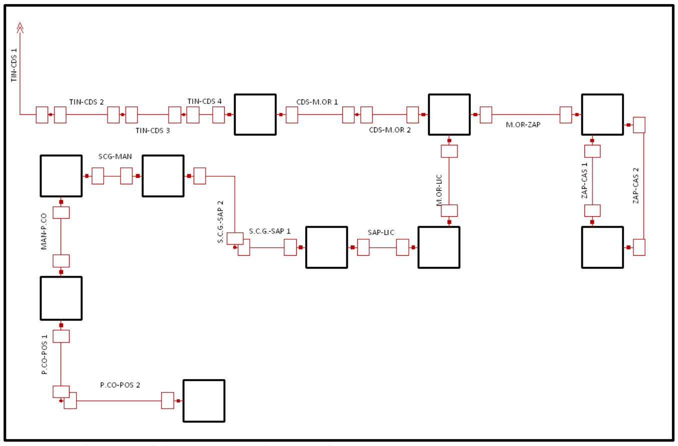

Fig. 4. Scheme of the MV feeder number 4

III. PROSUMERS PROFILE IDENTIFICATION

A. Load estimation hypothesis

In order to perform simulations, each feeder must be characterized through the assignment of a power demand profile. To do that a routine was realized, where the input data are the measures (one week length) of active power and current absorbed by each feeder, the voltage profile in the primary substation and the profiles of active and reactive powers for medium voltage users. The outputs are the low voltage users' profiles of active/reactive powers.

The routine main equations are:

$$\cos\phi = P_{ps} / \left(\sqrt{3} V_{ps} I_{ps}\right) \tag{1}$$

$$Q_{ps} = \sqrt{3} V_{ps} I_{ps} sen\phi \tag{2}$$

$$P_{tot} = P_{ps} + P_{pv} - P_{mv} \tag{3}$$

$$Q_{tot} = Q_{ps} - Q_{mv} \tag{4}$$

Where each subscript below denotes:

- *ps* measures from primary substation.
- *pv* measures from photovoltaic plant.
- *mv* measures from medium-voltage users.
- *tot* total power absorbed by a feeder.

The total power must be divided among the LV users connected to the feeder. Some hypotheses have been made:

1. Each LV load has the same nominal apparent power of the transformer in the substation to which it is connected.
2. Nominal power factor is 0.95 for every LV load.

The results obtained indicate that the model behavior is very close to the measured one as showed in Fig. 5.

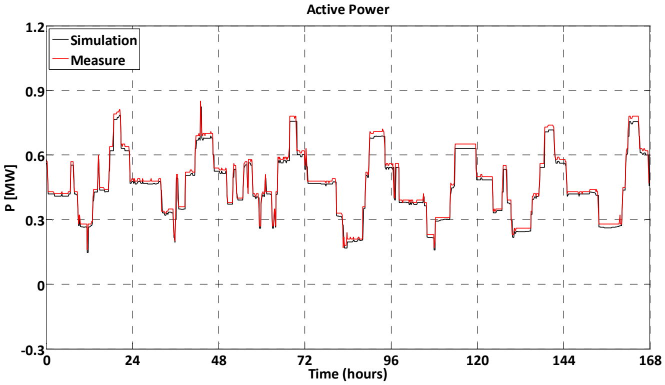

Fig. 5. Feeder MV 10 characterization

B. Photovoltaic production estimation

As foretold, there is a 470 kW photovoltaic plant connected to the MV network. The DSO has made available the produced power, reported in Fig. 6, so that the exact production profile was assigned for the week studied. The peak production was recorded at 11:30 am on Monday, when the plant produced 60% of its nominal power.

The comparison between the energy produced by the plant and the reference value (according to UNI 10349) showed how the week considered has been significantly productive for the plant. This profile has been scaled in order to build a profile significant for the LV photovoltaic plant spread among the network.

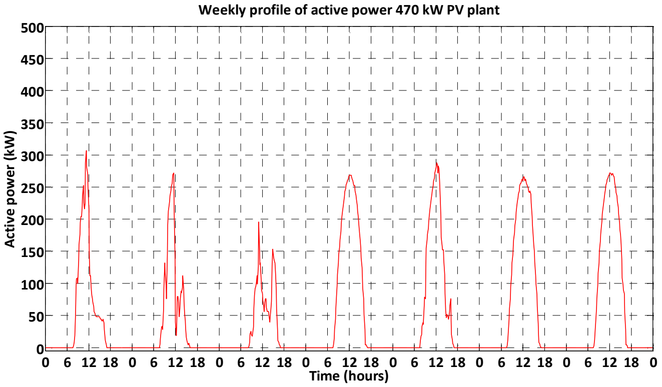

Fig. 6. Active power produced by the 470 kW PV plant during the week studied

C. National regulatory framework

In last four years the Italian Authority produced two different standards concerning the connection of active/passive users to the network.

The Standard CEI 0-16 [8] (edited in July 2008) concerns the connections to the high/medium voltage network and, due to its date of publication, it does not provide specific instructions for connecting active users, owners of static generator, interfaced with the network through converter. However a revised version is expected shortly.

Instead, the more recent Standard CEI 0-21 [9] (December 2011) dedicated to the low voltage connections, has a specific chapter in which several rules are included along with the capability curves that must be respected by the active users. In particular, as showed in Fig. 7, there are two curves (one binding called triangular capability and the other one optional called rectangular capability) about the voltage regulation by means of the reactive power control.

The triangular capability obliges the inverter to change its power factor if the plant is producing active power and voltage out of the predetermined tolerance band. The rectangular capability requires to change the power factor even if the plant is not producing active power instead.

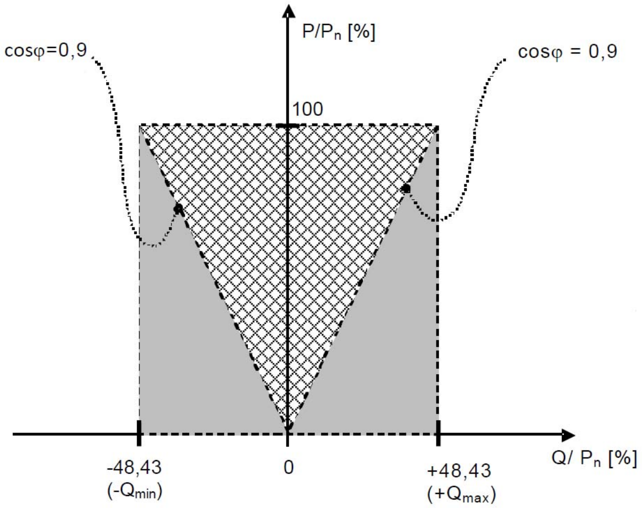

Fig. 7. Required triangular and rectangular capability curve

In the CEI 0-21 it is also present a capability curve (called Low Voltage Fault Ride Through) that shows when the static generator can be disconnected from the network in presence of a voltage drop. The LVFRT curve is shown in Fig. 8.

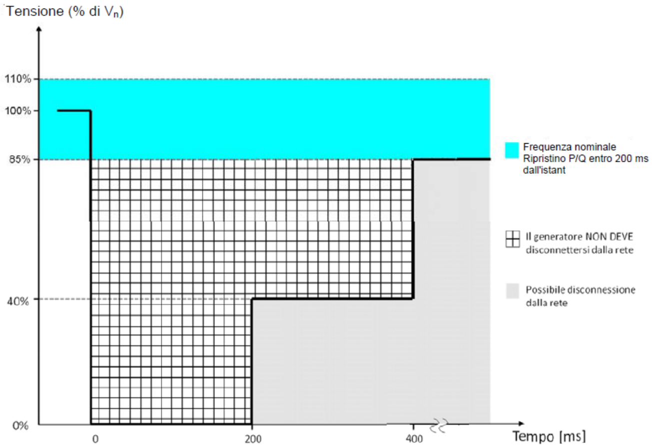

Fig. 8. Capability curve of the static generator (LVFRT)

In Fig. 8 the light blue area represents the normal operation, where the static generators must restore theirs P/Q profile by 200ms after the voltage comes back in the band.

In the dotted line area, generators must not be disconnected from the network, while in the gray area disconnection is allowed.

IV. STATIC STUDIES

A. *PV sensitive analysis*

In each secondary substation present in the model a photovoltaic plant, equivalent for all the possible plants connected to the low voltage, was added. In order to show how DG affects the MV network four scenarios for static studies were defined.

The scenarios are 0-25-50-100% penetration depending on the size of the PV plant compared to the rated apparent power of the transformer in the substation multiplied for a 0.9 factor. The nominal power factor of all the plants is one. For each feeder a static simulation was performed using several load flow calculations during a week (one load flow every ten minutes, 1008 overall for the week) in each scenario. The analysis was focused on reverse power flows, load factor and losses along the lines, voltage profile along the feeder. For example, Fig. 9 shows the feeder MV10 active power flow during the week.

It is important to remember that this feeder is the one with the connected 470 kW PV plant. A reverse flow period occurs already in the 25% scenario for a period equal to about 7% of weekly hours. The penetration of DG helps to reduce the line losses through net metering, which reduces the energy flowing through MV network. This benefit remains until the local production does not exceed the local demand, because otherwise the surplus energy flows to the main substation and losses start to grow again.

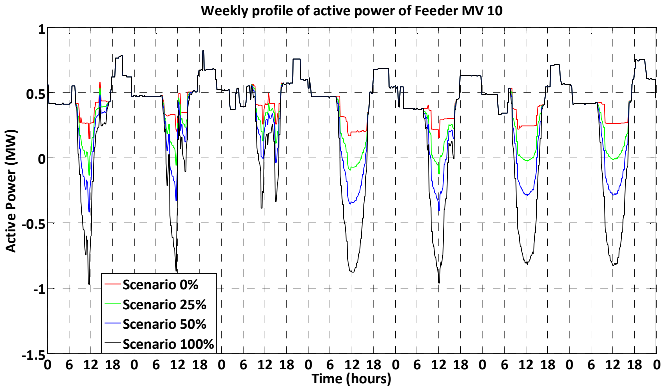

Fig. 9. Active power profile for feeder number 10 in the four different scenarios

In TABLE 1 several results of static simulations on feeder numbers 10 are reported. E_{feeder} is the energy imported from HV network by the feeder. E_{PV} is the energy produced by photovoltaic plants (in Scenario 0% this index is not zero because of the presence of the 470 kW PV plant). E_{loss} is the energy lost among the line. I_{PV} and I_{loss} are indexes that represent how much loads energy is provided by PV plants and the ratio between energy loss and loads energy.

Every feeder presents an optimal amount of distributed generation, for the feeder examined equal to 50% of the available transformer power capacity. The losses are equal to 1.71 MWh, this is due to the fact that the production matches the consumption most of the time realizing thus a better net metering, compared to the other Scenarios.

TABLE 1
Results of Static Studies

Feeder MV 10	**Scenario 0%**	**Scenario 25%**	**Scenario 50%**	**Scenario 100%**
Time in reverse power [%]	0	7.14%	16.77%	22.82%
E_{feeder} [MWh]	76.91	68.18	59.49	42.21
E_{PV} [MWh]	8.65	17.33	26.01	43.36
E_{loss} [MWh]	1.78	1.73	1.71	1.79
I_{PV} [%]	10.33%	20.69%	31.04%	51.76%
I_{loss} [%]	2.12%	2.06%	2.05%	2.14%

Another positive effect of DG is showed in Fig. 10 and in Fig. 11 that reports the voltage profiles calculated in the scenarios (0-100%) along the feeder MT 10. The voltage increases especially in the end of the line substations but it never exceeds the threshold value (105% of nominal value), beyond which the standard CEI 0-21 imposes the action of controlling the reactive power in order to lower voltage. Similar results were obtained for the other feeders.

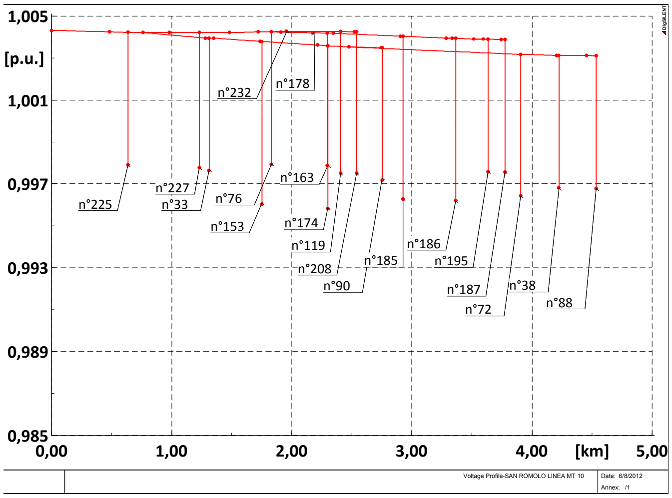

Fig. 10. Voltage profile of feeder MV10 in scenario 0% calculated at maximum production point of PV plants (Monday 11:30 am)

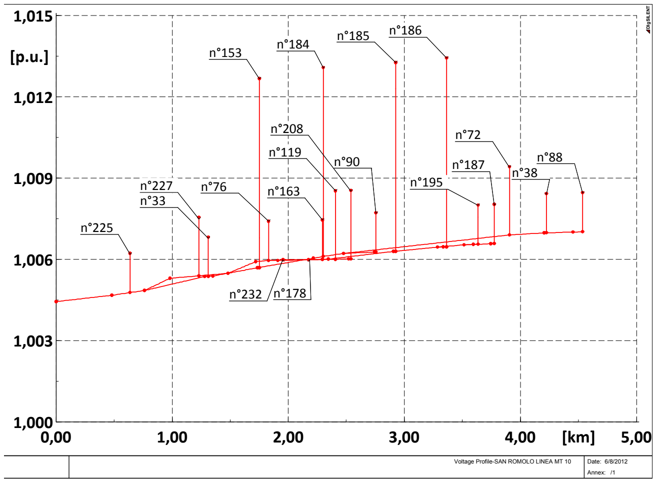

Fig. 11. Voltage profile of feeder MV10 in scenario 100% calculated at maximum production point of PV plants (Monday 11:30 am)

V. DYNAMIC STUDIES

A. Scenarios

The dynamic simulations are focused on transient during voltage dips and short circuit faults, in different network configurations. TABLE 2 summarizes the discussed cases.

TABLE 2
Dynamic Studies: considered cases

Event type	**Intensity/Duration**	**Feeder Examined**	**PV Scenarios**
Voltage dip	- 5%	MV4	0% and 100%
	+5% and ± 10%	MV4	0% and 100%
Short Circuit Single phase	Zero impedance 200/300ms	MV4 and MV10	100%
Short Circuit Two-phase	Zero impedance 200/300ms	MV4 and MV10	100%
Short Circuit Three-phase	Zero impedance 200/300ms	MV4 and MV10	100%

B. Voltage Dip

The feeder chosen to evaluate the contribution given by the PV plant in the voltage perturbation counteraction is the number 4. Several situations have been studied, but the most important, here reported, is the 5% voltage dip, that represents the most frequent event for this kind of perturbation. The measures showed that the maximum power absorption by the LV loads has been recorded on Tuesday at 5:00 pm, while the maximum power production by PV plant occurred on Monday at 11:30 am (60% of rated power).

The results are reported in TABLE 3, considering for different Scenarios:

- Monday 11:30 am, 0% PV and 100% PV penetration (Triangular or Rectangular Capability)

- Tuesday 5:00 pm, 0% PV and 100% PV penetration (Triangular or Rectangular Capability)

If the voltage is instantaneously lowered by 5%, the reactive regulation main effect, operated by the PV plants, is to contain this perturbation of two percentage points at the local low voltage buses. While, during sunlight hours (e.g. Monday 11:30), there is no significant difference if choosing the triangular or the rectangular capability. If the voltage dip occurs when PV plants are not producing active power the containment is achieved only if the inverter has been characterized with the rectangular capability that commands the regulation independently to the active power production.

TABLE 3
Voltage Dip Results

5% Voltage dip	**Monday 11:30 am**			**Tuesday 5:00 pm**		
	0% PV	**100% Triangular**	**100% Rectangular**	**0% PV**	**100% Triangular**	**100% Rectangular**
MV bus (start feeder) ΔV [V]	-783.4	-678.9	-678.2	-783.1	-783.1	-672.6
MV bus (start feeder) ΔV [%]	-5.22%	-4.52%	-4.51%	-5.22%	-5.22%	-4.48%
LV bus (end feeder) ΔV [V]	-20.76	-12.37	-12.36	-20.74	-20.74	-12.01
LV bus (end feeder) ΔV [%]	-5.27%	-3.10%	-3.09%	-5.28%	-5.28%	-3.05%

C. *Faults*

Regarding the short circuit analysis, the studies were performed in the feeders MV10 and MV4 in order to observe any potential difference between the rural and the urban feeder behavior.

Without any specific information about which fault is the most relevant and because the aim of the simulation was to evaluate any possible disconnection of the PV plants, the typologies of short circuits chosen were single phase to ground and two/three phases with zero impendence.

The line protection elements were not included in the model and then, in order to validate the results and to perform a realistic simulation, in each study particular attention has been paid to the thermal limit of the smallest conductor section.

The results show an almost total insensibility by the plants which, according to the LVFRT curve, were never disconnected except in the case of zero impedance three-phase faults longer than 200ms.

VI. CONCLUSIONS AND FUTURE DEVELOPMENTS

The procedure for the characterization of the feeders has allowed to provide a valid load profiles of the LV aggregate users, even in absence of detailed information about the actual installed demand.

The analysis of the voltage profiles, in different scenarios of PV penetration, has showed that the voltage never goes out of the bounds prescribed by the National Standard. Thus the regulation of reactive power provided by the inverters is not required yet.

The proposed evaluations, about lines loading factor and weekly energy balance, have highlighted benefits that each feeder can have through lowering energy demand, thanks to its partial satisfaction by active users.

The dynamic studies were intended to evaluate the behaviour of the network with high DG penetration during voltage dips and line faults, thus highlighting the benefits provided by the properly regulated PV plants.

Future collaborations with the DSO are intended to install several remotely monitored meters located at the connection point of the low voltage side of the MV/LV transformers, in order to proper validate the estimation procedure described in the paper.

VII. ACKNOWLEDGEMENTS

The work has been realized within the Project SmartGen supported by MISE the Italian Minister for Economic Development.

VIII. REFERENCES

[1] European Smart Grid Technological Platform, “Vision and Strategy for Europe’s Electricity Network of the Future”, Document EUR 22040, 2006.

[2] European Smart Grid Technological Platform, “Vision Strategic Deployment Document for Europe’s Electricity Network of the Future”, Document EUR 22040, 2010.

[3] Authority of Electrical Energy and Gas, “AEEG Delibera 39/10 – Procedures and selection criteria for the selection of incentivized projects”, Mar. 2010.

[4] A. Neural, V.I Kogan, C.M. Schafer C.M., “Load Leveling Reduces T&D Line Losses”, *Power Delivery, IEEE Transactions on*, vol. 23, no. 4, pp. 2168–2173, Oct. 2008.

[5] A. Borghetti, M. Bosetti, S. Grillo, S. Massucco, C.A. Nucci, M. Paolone, F. Silvestro, “Short Term Scheduling and Control of Active Distribution Systems with High Penetration of Renewable Resources”, IEEE Systems Journal, Special Issue on “Identification and Control of Sustainable Energy Systems”, Vol 4, Issue 3, September 2010, pp. 313-322.

[6] S. Grillo, M. Marinelli, E. Pasca, G. Petretto, F. Silvestro, “Characterization of wind and solar generation and their influence on distribution network performances”, 44th UPEC, pp. 1-6, ISBN: 978-1-4244-6823-2, Glasgow, 1-4 Sep. 2009.

[7] DIgSILENT, Technical Documentation, “DPL Manual”, 2003.

[8] Standard CEI 0-16, “Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company”, July 2008.

[9] Standard CEI 0-21, ”Reference technical rules for the connection of active and passive users to the LV electrical Utilities”, Dec. 2011.

IX. BIOGRAPHIES

Francesco Adinolfi was born in Genova, Italy, in 1988. He received the Master degree in electrical engineering in 2012 with a thesis related to the modeling of a real distribution network and is currently working as a research assistant in the University of Genova. His research interests regard smartgrids and network modeling.

Francesco Baccino was born in Genova, Italy, in 1986. He received the Master degree in electrical engineering in 2010 and is currently pursuing the Ph.D. degree in power systems, both from the University of Genova. His research interests regard smartgrids, focusing on the optimal integration of RES, DG, storage and PEV.

Mattia Marinelli was born in Genova, Italy, in 1983. He received the Master degree in electrical engineering in 2007 and the European Ph.D. in power systems in March 2011 both from the University of Genova. He is currently holding a post-doc contract. His research interests regard wind and solar data analysis, distributed generators (mainly wind turbines) electromechanical and electrochemical storage modeling for integration studies of renewable energy sources in power systems.

Stefano Massucco received the Laurea degree in electrical engineering from the University of Genova, Italy, in 1979. He had been working at the Electrical Engineering Department of Genova University, at CREL - the Electrical Research Center of ENEL (Italian Electricity Board) in Milano, Italy, and at ANSALDO S.p.A. in Genova, Italy. He is currently Fully Professor of Power Systems at the Electrical Engineering Department, University of Genova. His research interests are in power systems, distributed generation and smartgrids modeling, control, and management. Member of CIGRE Working Group 601, of Study Committee C4 for “Review of on-line Dynamic Security Assessment Tools and Techniques”.

Federico Silvestro was born in Genova, Italy, in 1973. Received the degree in electrical engineering from the University of Genoa in 1998 and the PhD degree from the same University in power systems in 2002, with a dissertation on artificial intelligence applications to power systems. He is now Assistant Professor at the Dept. of Naval Architecture and Electrical Engineering, University of Genova, where he is working in power system simulators, security assessment, knowledge based systems applied to power systems and distributed generation.