

CORRELATION BETWEEN RENEWABLE POWER PLANTS AND VOLTAGE DIPS IN ELECTRICAL DISTRIBUTION SYSTEMS

Morris BRENN¹, Federica FOIADELLI², Michela LONGO³, Dario
ZANINELLI⁴

The significant increase of the Renewable Energy Sources (RESs) has radically transformed the electricity generation system presenting many aspects to be studied and analyzed. This study represents a research of the impact in terms of Power Quality (PQ) of RES into Italian electric grid. In particular, the attention is on different aspects, in particular weakness, topology of the electric grid, photovoltaic systems (PV) and wind farms penetration in function of the geographical position considering all Italian regions.

Keyword: Renewable Energy Sources (RES), Power quality (PQ), Voltage dips, Photovoltaic systems, Wind farm

1. Introduction

Climate change is posing an ever-increasing risk on human and natural systems. The temperature at the Earth's surface is steadily growing, as testified by the fact that the last three decades have been the warmest since 1850 [1].

The increasing trend observable in both phenomena is attributable to the intensification of greenhouse gas concentrations in the atmosphere.

Electricity and heat production accounts for about 25% of total anthropogenic GHG emissions [2]. Therefore, reducing the emissions in this sector is of critical importance to mitigate the impact of global warming. For this reason, many countries in the world have outlined strategies to move to a low-carbon energy future. This is typically achieved through obligations to produce part of the national electricity demand by means of renewable energy sources [3 - 4].

The 2030 climate and energy framework sets three key targets for the year 2030: at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 27% share for renewable energy, and at least 27% improvement in energy efficiency. The framework was adopted by EU leaders in October 2014. It builds on the 2020 climate and energy package [5].

¹ Department of Energy, Politecnico di Milano, Italy

² Department of Energy, Politecnico di Milano, Italy

³ Department of Energy, Politecnico di Milano, Italy, e-mail: michela.longo@polimi.it.

⁴ Department of Energy, Politecnico di Milano, Italy

In Europe, the Directive 2009/28/EC has imposed a reduction of the greenhouse gas emissions by 20% in 2020 compared to 1990, as well as a 20% increase of energy efficiency and a requirement to produce 20% of the electricity consumption from RES. The consequent requirement to be met by each Member State has led to a rapid spread of renewable sources, such as hydro, biomass, wind and solar photovoltaics [6 -8]. Between 2003 and 2013, the share of renewable energy sources in the electricity mix within the EU-28 increased from 12.6% to 23.2%. PV and wind experienced the biggest growth, with an expansion from 0.01% to 2.7% for the former and from 1.4% to 7.5% for the latter [9].

The huge development of wind and PV, in particular, requires an accurate analysis. Indeed, a big penetration of such resources, which are variable and unpredictable, has posed the question of how to securely integrate them in the electric system, where injections and withdrawals of electricity have to be balanced at any instant of time [10 - 11]. When this cannot be done without hitting constraints on transmission capacity or on provision of ancillary services, wind and/or solar resources need to be curtailed. Renewable Energy Sources (RES) curtailment wastes free and clean energy, thus leading to an economic loss and to an increase in GHG and polluting emissions [12 - 14].

The great development undergone by renewable energy sources such as wind and solar in the last decades has significantly affected the operation of the electric power system [15 - 17]. Wind and solar are, indeed, non-predictable and non-programmable energy sources, since they rely on natural resources that are intrinsically intermittent and affected by local weather conditions. Due to these characteristics, when wind and solar are present with high penetration levels, technical and operational issues may arise that limit their full exploitation. In such cases, their power is curtailed and their production lost, thus leading to an economic damage for the producer [18].

Indeed, the power produced from RES plants comes for free, since no fuel is needed and the operational costs (except for the variable operation and maintenance costs) are null. However, plant operation – and, consequently, electricity sale – is needed by the plant owner to recover its initial investment. Therefore, when wind or solar energy is curtailed, the levelized cost to produce an energy unit increases [19 - 21].

This study represents a research of the impact in terms of PQ (Power Quality) of RES into Italian electric grid. In particular, the attention is on different aspects, in particular weakness, topology of the electric grid, photovoltaic systems and wind farms penetration in function of the geographical position.

The paper presents a description of the European and Italian policies for RES (Section II) and the Analysis of the Italian Grid performances (Section III). Paragraph IV presents the statistical analysis and discussion of results are reported in Paragraph V.

2. European and Italian policies for RES

As part of the European Union, Italy has embarked on a sustainability roadmap involving the energy sector, aimed at tackling global warming and ensuring security of supply – two objectives that go concurrently in the direction of a greener energy mix. According to the Directive 2009/28/EC of the European Parliament [22], commonly referred to as the 20-20-20 targets, the following objectives have to be fulfilled in the year 2020 by the EU as a whole:

- A 20% reduction in the GHG emissions with respect to the 1990 level;
- A 20% reduction in primary energy consumption compared to BAU, by means of increased energy efficiency;
- A 20% share of renewables in the energy mix, with the additional constraint of a 10% share of biofuels in the transportation sector.

The latter target is directly connected to the development of RES in the European Union. It is achieved by imposing specific national objectives to each Member State, which, in turn, are in charge of drawing up national plans to fulfill such requirement. This encompasses the three main sectors of energy consumption: heating (RES-H), transportation (RES-T) and electricity (RES-E) – with only the latter being of interest in the discussion about renewables' curtailment [23].

As stated in the Italian National Renewable Energy Action Plan [24], the RES share in the energy mix mandated to Italy is 17%, starting from a level corresponding to 8% in 2010. According to the forecasted energy demand in 2020, this equals a renewable energy production of 22,617 kToe. The electricity sector is the most affected one, since RES-E are projected to cover 26.39% of the gross electricity consumption by 2020.

The National Energy Strategy [25] published in 2013, however, pushes these objectives further. Indeed, it states the intention for Italy to exceed the targets mandated by the 20-20-20 package and to play a leading role in the perspective of the Energy Roadmap 2050 [26], which sets out the goal of reducing the emissions by at least 80% with respect to the 1990 levels. The SEN envisages a 19-20% share of RES in the energy mix by 2020 (instead of the 17% required by the 2009/28/EC Directive), with RES-E reaching 35-38% of the electricity consumption. This would give renewables a primary role, together with natural gas, in the national electricity generation portfolio.

In order to achieve such ambitious targets, Italy has put in place several support schemes to incentivize renewables' installation and production in the electricity sector [27]. Different incentives' regimes were initially conceived for solar photovoltaics and all the other RES, since the former needed at the beginning a greater support due to the higher entailed costs.

As concerns all RES but solar, a great distinction has to be made between plants built, upgraded, re-activated or renewed before 2013 and those that came

after. Big plants (more than 1 MW) built between April 1st 1999 and December 31st 2012 have been subject to the mechanism of Green Certificates. This consists of forcing conventional producers to provide a certain quota of their generation (calculated at the previous year) with green energy, either by actually producing it or by purchasing Green Certificates from renewable generating facilities, such as wind, geothermal, wave and tidal, hydro, biomass and waste plants. GCs are granted to such plants on the basis of the amount of electricity they produce, so that the sale of the certificates represents an additional source of income besides the electricity sale itself. For plants built or renewed before December 31st 2007, GCs are conceded for 12 years and there is no distinction among the different sources – a mechanism that tended to exclude less mature resources in favor of the already competitive ones. In order to expand the RES portfolio, a differentiation (in the form of a multiplying factor in the calculation of the yearly incentivized energy) was introduced for those plants built or renewed after January 1st 2008. These are also granted the certificates for 15 years. The quota obligation has been modified yearly and has now gone to zero in 2015, as the GC mechanism has been phased out and the system is transitioning to a new support scheme. Small plants (with a capacity lower than 1 MW) built between April 1st 1999 and December 31st 2012 could choose between an all-inclusive fixed Feed-in Tariff (FiT) granted for 15 years, comprising both the remuneration on the energy injected and a subsidy component, and the Green Certificate mechanism. With the new decree D.M. 6/7/2012, RES (excluding solar) plants built or renewed after January 1st 2013 are subject to the following support scheme:

- Small plants (less than 1 MW) receive a fixed all-inclusive FiT, called Tariffa Onnicomprensiva (TO), based on the energy injected in the grid;
- Bigger plants (more than 1 MW) receive an incentive on the energy produced, equal to the difference between the FiT and the hourly zonal price (so that, by selling the electricity, the overall revenue is about equal to the FiT).

Access to the incentives is also differentiated on the basis of the size of the plant. Direct access is allowed to small plants, such as wind below 60 kW, hydro below 50 kW and biomass below 200 kW. Medium-size plants have to enroll in dedicated Registries and each year incentives are given only to the first-registered ones until the maximum supportable-capacity quota has been reached. Bigger plants (exceeding 10 MW for hydro, 20 MW for geothermal and 5 MW for all other RES) have to participate to competitive auctions, where they place bids for their FiTs (and are, therefore, granted lower tariffs).

As concerns photovoltaic plants, they have been relying since 2005 on a feed-in scheme called Conto Energia. Between 2005 and 2012 four Conto Energia schemes have been decreed, all based on a fixed Feed-in Premium, which incentivizes the energy produced (leaving the electricity itself to be sold by the

producer) for a period of 20 years. The D.M. 5/7/2012 issued the fifth Conto Energia, which has changed the rules for plants built or renewed after August 27th 2012. According to this, solar photovoltaics is supported with a mechanism analogous to that established for the other RES in D.M. 6/7/2012, with the difference that the incentives are granted for 20 years (instead of 15) and that a bonus is conceived for the energy that is self-consumed in-situ (which would be otherwise disregarded by the FiT scheme). Similar conditions to the other RES also hold as regards the access to the incentives. Indeed, PV plants have to enroll in Registries, with the exception of the following categories, which are ensured direct access:

- Building-integrated PV plants with rated power up to 50 kW;
- New PV plants with rated power up to 12 kW and upgraded, renovated or repowered ones presenting a rated power increase of maximum 12 kW;
- Innovative building-integrated PV plants until a cumulative cost of 50 M€ has been reached;
- Concentration PV plants until a cumulative cost of 50 M€ has been reached;
- PV plants built by the public administration until a cumulative cost of 50 M€ has been reached;
- PV plants with a rated power ranging 12 to 20 kW applying for a 20% lower FiT.

The fifth Conto Energia has ceased to be applicable on July 6th 2013, when the cumulative cost of 6.7 billion € has been reached. As of now, thus, no further PV plants can access any incentives.

Alternatively, to the incentives authorized by the D.M. 6/7/2012 and 5/7/2012, the producers may opt for indirect incentives, which are services involving the selling of electricity. These are the assisted selling and the on-spot trade mechanism.

Assisted selling consists of a way to sell the electricity produced that is alternative to market trading and bilateral contracts. The producers eligible for such service are any plants (also conventional ones) with an apparent power below 10 MVA and all the non-programmable RES (any size). According to this mechanism, producers sell their electricity to the GSE, which is then in charge of operating in the market. The electricity is remunerated at the hourly zonal price, although small plants (up to 1 MW) are ensured minimum prices, updated periodically and differentiated by source. Assisted selling is mainly aimed at supporting small plants (which is the most common case when dealing with renewables) by avoiding the administrative burdens entailed with the participation in the market.

The on-spot trade mechanism allows partially offsetting the expenses for purchasing electricity from the grid thanks to the contribution given by the electricity injected in the grid, although consumption and injection occur at different times. The plants eligible for such service are:

- RES plants with rated power up to 200 kW, if built or renewed after December 31st 2007;
- RES plants with rated power up to 20 kW, if built or renewed before December 31st 2007;
- High-efficiency CHP plants with rated power up to 200 kW.

3. Analysis of the Italian Grid Performances

This section wants to group different information on the Italian grid, in particular the distribution of the voltage dips and the diffusion of the photovoltaic systems and wind farms in all Italian regions from 2009 to 2015 in order to perform a correlation among their values. This survey has been carried out considering the data available from different websites, and specifically the 'QuEEN' site [28] and the TERNA site [29].

Using the first site, it is possible to take some information on the Italian system for power quality monitoring of MV distribution networks. Infact, this site allowed the identification of the number of voltage dips in all Italian regions. While, the second site is the Italian Transmission System Operator (TSO) that manages electricity transmission in Italy guaranteeing its safety, quality and affordability over time. It ensures equal access conditions to all grid users. Moreover, it develops market activities and new business opportunities with the experience and technical skills gained in managing complex systems.

3.1. High Voltage Substations

Italy can be divided in different zones grouping more geographic regions, in specific:

- North Italy: that includes the regions of the North-West (Liguria, Lombardy, Piedmont, Aosta Valley) and the North-East (Emilia-Romagna, Friuli-Venezia Giulia, Trentino-Alto Adige, Veneto);
- Center Italy: that includes the regions of Lazio, Marche, Tuscany and Umbria;
- South Italy, that includes the regions of South Italy (Abruzzo, Basilicata, Calabria, Campania, Molise, Apulia) and those of Insular Italy (Sardinia, Sicily).

The electric distribution grid for the three (North, Center and South) Italian zones are presented in Fig. 1 [29].

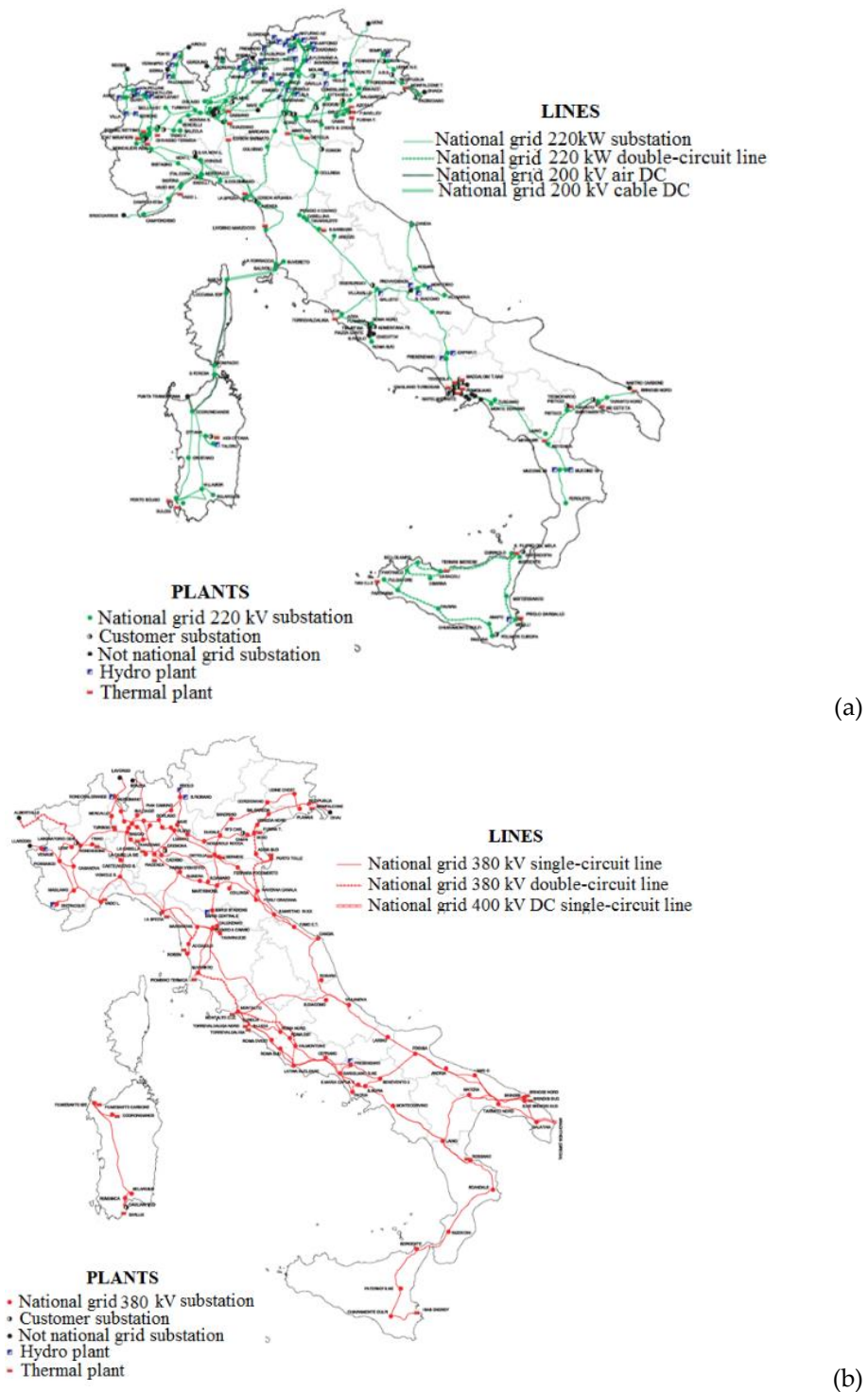


Fig. 1. Italian transmission high voltage (a) 220 kV Grid and (b) 380 kV Grid [29].

In this study, it has been assumed that the robustness or the weakness of the transmission grid is proportional to the number of high voltage (HV) substations. The development of the Italian transmission grid is represented in Fig. 2.

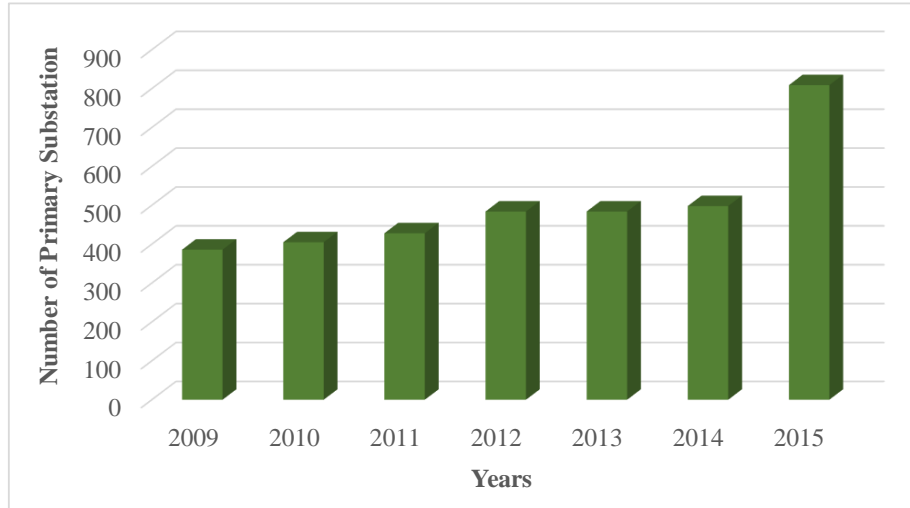


Fig. 2. Number of primary substations installed in Italy.

3.2. Voltage Dips

A voltage sag is defined by IEEE Standard 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality, as a decrease in RMS voltage at the power frequency for durations from 0.5 cycles to 1 minute, reported as the remaining voltage. The measurement of a voltage dip is stated as a percentage of the nominal voltage; it is a measurement of the remaining voltage and is stated as a dip to a percentage value.

Voltage dips can occur on utility systems, both at distribution voltages and transmission voltages, and inside industrial plants. A cause of this the problem in utility system can be the operation of recloses and circuit breaker. The depth of the voltage dip at the consumer's site will vary depending on the supply line voltage and the distance from the fault.

The number of voltage dips has been recorded from the Italian power quality monitoring system considering the 400 most important HV/MV substations and referring to the years from 2009 to 2015. This survey has been conducted for all Italian regions. Subsequently, these data are grouped evaluating the sum of voltage dips for different years. The analysis method and the classification of the voltage dip in terms of deepness and duration are reported in [18]. Fig. 3 shows the voltage dips number in Italy recorded different years.

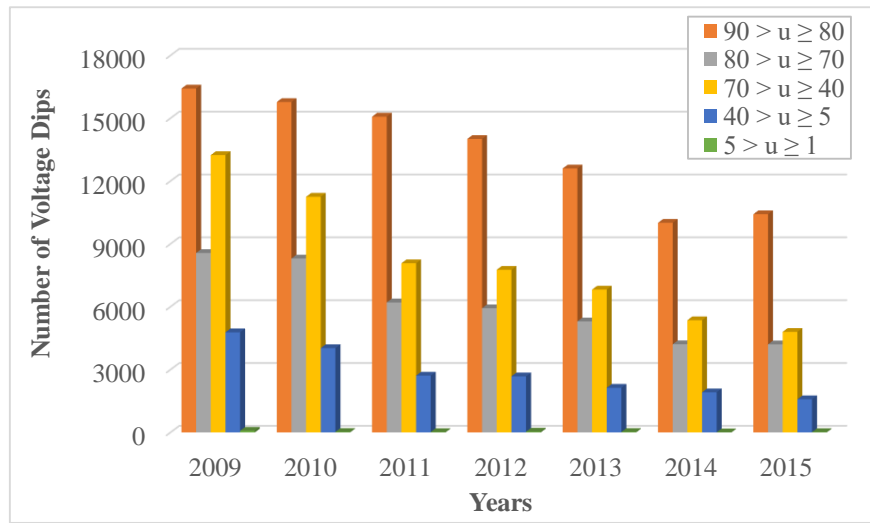


Fig. 3. Distribution voltage dips in Italy recorded in different years.

3.3. Photovoltaic Power Plants

Renewable energy sources (RES) allow sustainable development for an indefinite period without damaging nature. The most important sources of renewable energy are geothermal, solar, thermal and thermodynamic solar, photovoltaic, wind, biomass and biofuels. Renewable energy replaces conventional fuels in four distinct areas: electricity generation, air and water heating/cooling, motor fuels, and rural (off-grid) energy services. The use of these energy sources contributes to solving the problem of global warming and reducing pollution, in particular CO₂ emissions. In fact, renewable energies do not affect the greenhouse effect and their environmental effects are not harmful. While in the past hydropower systems accounted for 90% of the installed capacity from renewable sources, now they account for only 35%, due to the exponential growth of photovoltaic energy, bioenergy and wind power.

The incentive policies carried out in Italy for several years have led to the development and spread of several photovoltaic installations throughout the nation [30]. In particular, much progress in installed power can be seen starting from 2009, as depicted in Fig. 4.

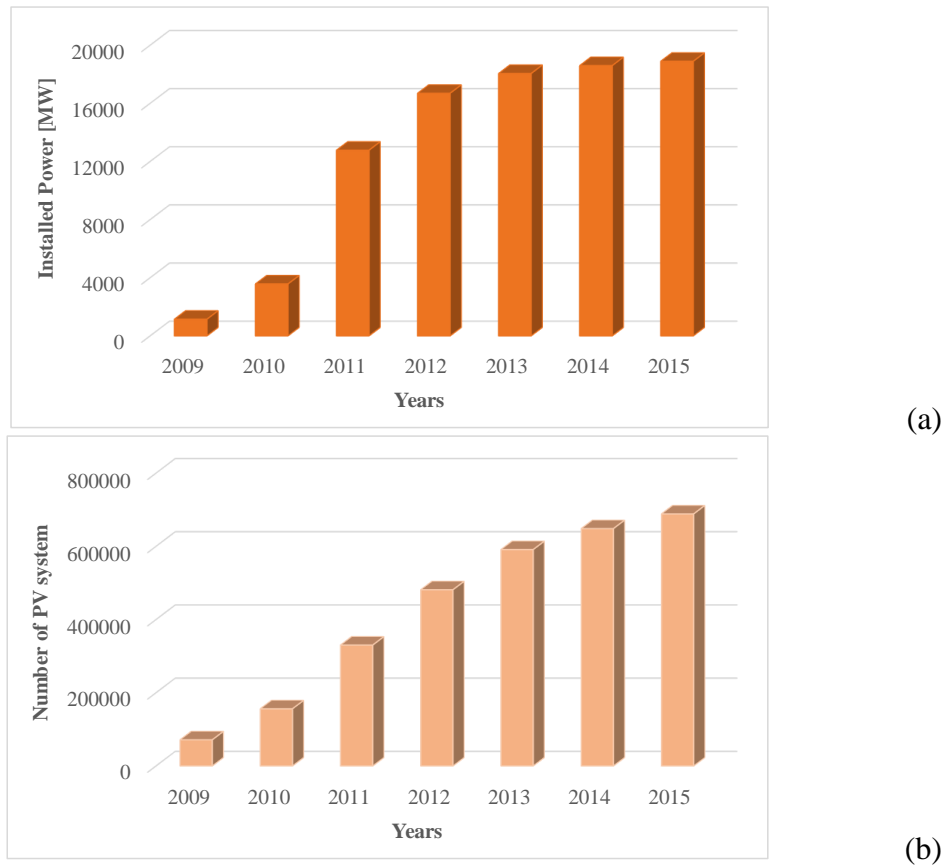


Fig. 4. (a) PV power plant number and (b) total PV installed power in Italy

The development of renewable energy and photovoltaic systems has radically transformed the electricity generation system in Italy. In a few years, it moved from a system that relied on a limited number of large conventional power plants to a system that includes many small and medium sized distributed generators, usually based on renewable energy sources.

However, the distribution of the installed power and the number of photovoltaic systems in Italian regions is not homogeneous. In fact, the North of Italy, especially Lombardy and Veneto, is characterized by many small size power plants. Instead, the South of Italy, due to its highest radiation, is distinguished for high power systems installations.

3.4. Wind Power Generation

The conditions for wind energy production in Italy are not favorable in every region of the country, because of the long and narrow shape of the territory and the presence of high reliefs, such as the Alps, that constitute an obstacle to the

wind [31]. For this reason, the most promising sites are located in the central and southern regions of Italy, particularly along the Apennines and the Adriatic and Tyrrhenian islands. At the end of 2015, Italy has installed more than 1,900 wind turbines. In particular, the 2012 was an important year for wind power in Italy in terms of new installations: more than 1,200 MW was installed in twelve months, as shown in Fig. 5.

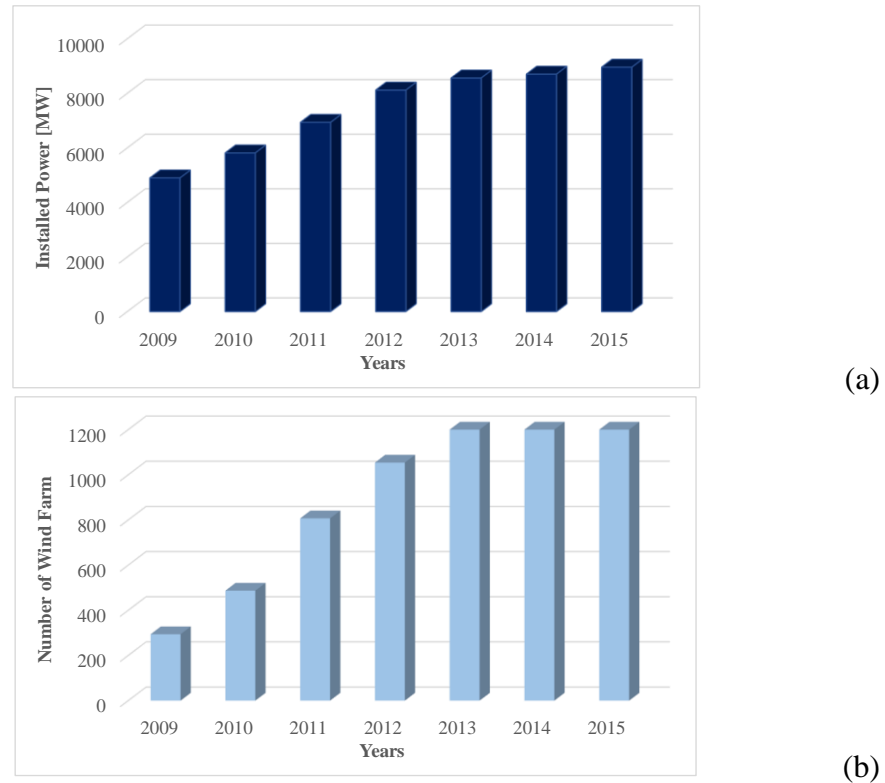


Fig. 5. (a) Wind power plant number and (b) total installed wind power in Italy.

4. Statistical Analysis and Discussion of Results

The share of RES in overall power generation is rapidly increasing in Italy as shown in the previous sections. However, the structure and operation of the existing power grid may need some improvements. For this reason, the trend of the voltage sags in function of the new power generation obtained from RES has been considered, since RES tend to increase the load variability on the electric grid. This is the first step to understand the impact of RES in terms of Power Quality even if the attention for the moment is on voltage sags only.

All the data collected in the survey previously described have been processed in a statistical way, to find possible correlation between PV and wind installation and the number of primary substation with the delivered power quality in terms of voltage dips.

The comparison has been carried out among the 20 Italian regions (*Reg*) that have different characteristics regarding the above items.

In order to facilitate the comparison of the delivered power quality as a function of the grid robustness and the renewable energy installation, a dedicated index has been introduced in Eq. (1):

$$RES_{PSS} = \frac{\left(\frac{Reg_{PV}}{P_{gen}} + \frac{Reg_{wind}}{P_{gen}} \right)}{\frac{Reg_{N_PSS}}{N_{PSS}}} \quad (1)$$

where

- Reg_{PV} [kW]: installed PV power in a specific region of Italy;
- Reg_{WIND} [kW]: installed wind power in a specific region of Italy;
- P_{gen} : total generating power capacity in Italy in 2015 equal to 116995.2 MW;
- Reg_{N_PSS} : number of the primary substations in a specific region;
- N_{PSS} : total number of the primary substations in Italy in 2015 equal to 809;

Therefore, RES_{PSS} index is an adimensional quantity representing the quantity of the regional power generated by RES sources compared to the total national power normalized on the relative number of the local electrical substations (PSS).

In this work, *RES* sources are represented by PV and Wind since they are considered as the most promising alternative generation on the Italian territory.

To comprehend the correlation between the normalized voltage dips and RES (the PV and wind installations), summarized through the RES_{PSS} index, the Pearson index has been used. This index represents the correlation between two variables and it gives also the quality of their relation. It describes the linear correlation (dependence) between two variables, RES_{PSS} and Reg_{dips} . It is widely used in the sciences as a measure of the degree of linear dependence between two variables. The correlation coefficient $\rho_{RES_{PSS}, Reg_{dips}}$ is defined as in Eq. (2):

$$\begin{aligned} \rho_{RES_{PSS}, Reg_{dips}} &= corr(RES_{PSS}, Reg_{dips}) = \frac{cov(RES_{PSS}, Reg_{dips})}{\sigma_{RES_{PSS}} \sigma_{Reg_{dips}}} \\ &= \frac{E \left[(RES_{PSS} - \mu_{xRES_{PSS}}) (Reg_{dips} - \mu_{Reg_{dips}}) \right]}{\sigma_{RES_{PSS}} \sigma_{Reg_{dips}}} \end{aligned} \quad (2)$$

where Reg_{dips} is the normalized number of the voltage dips in a specific region assuming the maximum recorded number equal to 8,000; E is the expected value operator, cov means covariance and $corr$ is used as alternative notation for the correlation coefficient. The possible value obtained can be in the range $(-1, +1)$, where:

- 1 is total positive correlation (direct proportionality),
- 0 means no correlation,
- -1 refers to a negative correlation (inverse proportionality).

After the Pearson correlation coefficient, is important to evaluate the significance of the value obtained. For this reason, it is considered the p -value. This coefficient can assume different values:

- if $p\text{-value} \geq 0.05$ the result is not significant statistical;
- if $p\text{-value} \leq 0.05$:
 - if $0.01 \leq p\text{-value} < 0.05$ significant statistical;
 - if $0.001 \leq p\text{-value} < 0.01$ very significant;
 - if $p\text{-value} < 0.001$ strongly significant.

The data presented and the normalized values and RES_{PSS} index previously described are collected from 2009 to 2015 for each region and reported in Fig. 6. As it is possible to note the characteristics for the various regions are not homogeneous. In fact, each region can be assumed as representative case of the combination of these variables: percentage of PV installation; percentage of wind installation; robustness or weakness of the electric grid; RES_{PSS} index; quality of the power (voltage dips number)

The first step of this analysis is the evaluation of the correlations between RES_{PSS} indexes and the normalized voltage dips Reg_{dips} . The obtained results are reported in Table 1.

Observing these values, it is possible to observe that many regions have $p\text{-value} \geq 0.05$ and for this reason the correlation is not significant statistical.

Only for the regions, Aosta Valley, Liguria and Campania, $p\text{-value}$ is very significant and the correlation is very negative.

Table 1

Evaluation of the possible correlation between RES_{PSS} and Reg_{dips} considering the Pearson and p -value coefficients.

North Italy		
Regions	$\rho_{RES_{PSS}, Reg_{dips}}$	$p\text{-value}$
Aosta Valley	-0.914	0.004
Emilia Romagna	-0.731	0.062
Friuli Venezia Giulia	-0.126	0.788
Liguria	-0.842	0.017

Lombardy	-0.727	0.064
Piedmont	-0.596	0.158
Trentino Alto Adige	-0.712	0.072
Veneto	-0.749	0.053

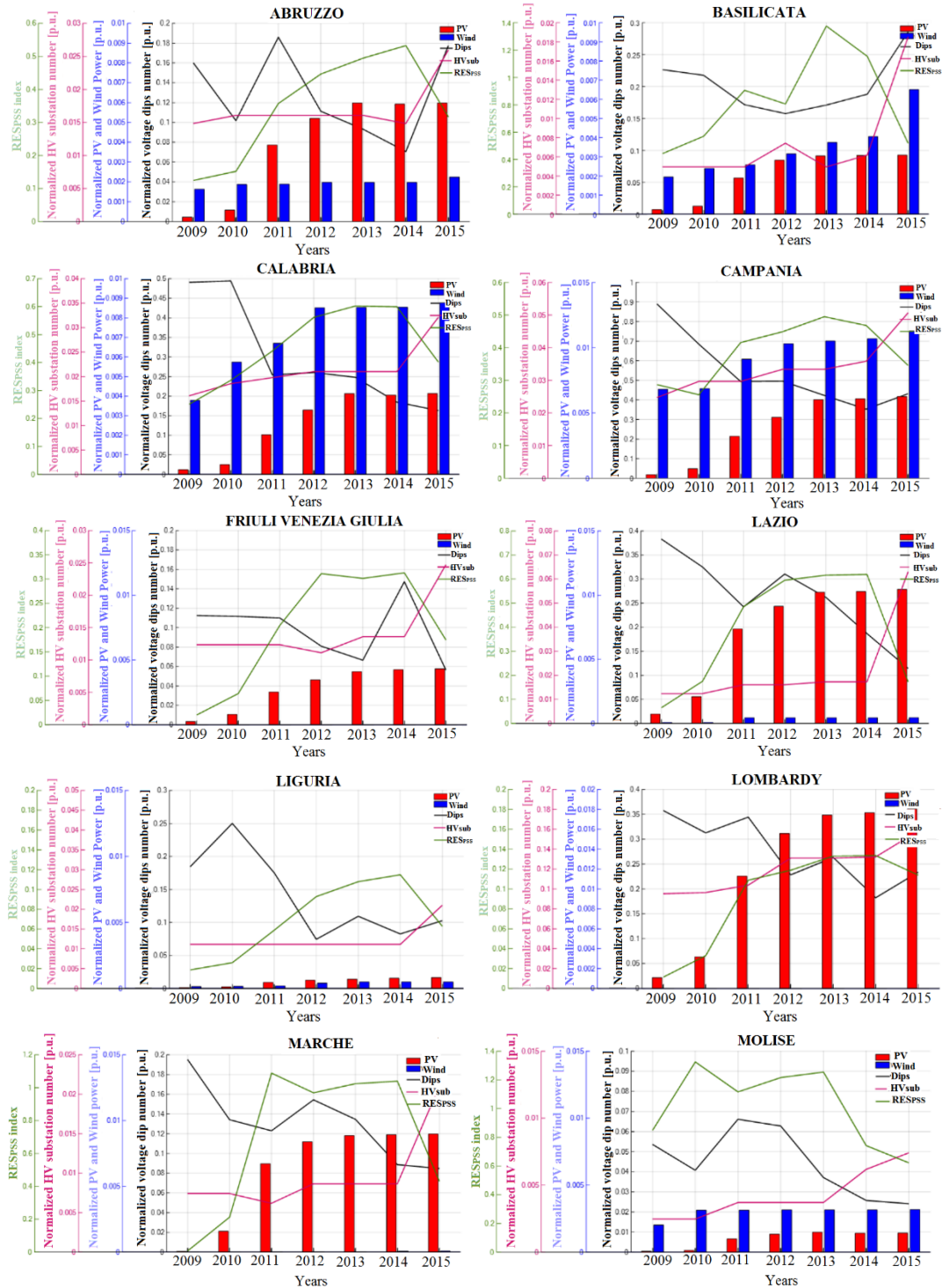
Central Italy		
Regions	$\rho_{RES_{ESS}, Reg_{dips}}$	<i>p</i> -value
Lazio	-0.229	0.621
Marche	-0.396	0.379
Tuscany	-0.230	0.620
Umbria	-0.574	0.178

South Italy		
Regions	$\rho_{RES_{ESS}, Reg_{dips}}$	<i>p</i> -value
Abruzzo	-0.468	0.290
Apulia	-0.295	0.521
Basilicata	-0.672	0.098
Calabria	-0.733	0.061
Campania	-0.785	0.037
Molise	0.517	0.235
Sardinia	-0.372	0.411
Sicily	-0.160	0.731

Fig. 6 shows that starting from 2012 wind power has not significantly grow in most part of the regions and the same happened starting from 2013 for PV generation, due to the conclusion of the national incentive programs. Moreover, it is possible to observe that in 2015 there was a strong reinforcement of the transmission grid in terms of number of substations. This had led to a general decrease of the voltage dips in the distribution network. However, in some regions as Abruzzo or Basilicata characterized by weak transmission grid the benefit of the voltage dips cannot be noted due to an high amount of renewables power plants.

Other regions as Calabria and Campania had low benefits even if the actual value of the voltage dips is considerably high.

It is not possible to find a strong correlation between the RES index and voltage dips. That means that the installation of renewable sources does not directly impact the power quality in the network. Indeed, in some cases the presence of these generators can support the network to reduce the number of voltage dips. In some other cases, especially with a weak transmission network renewable sources can lower the quality of the power of the distribution grid.



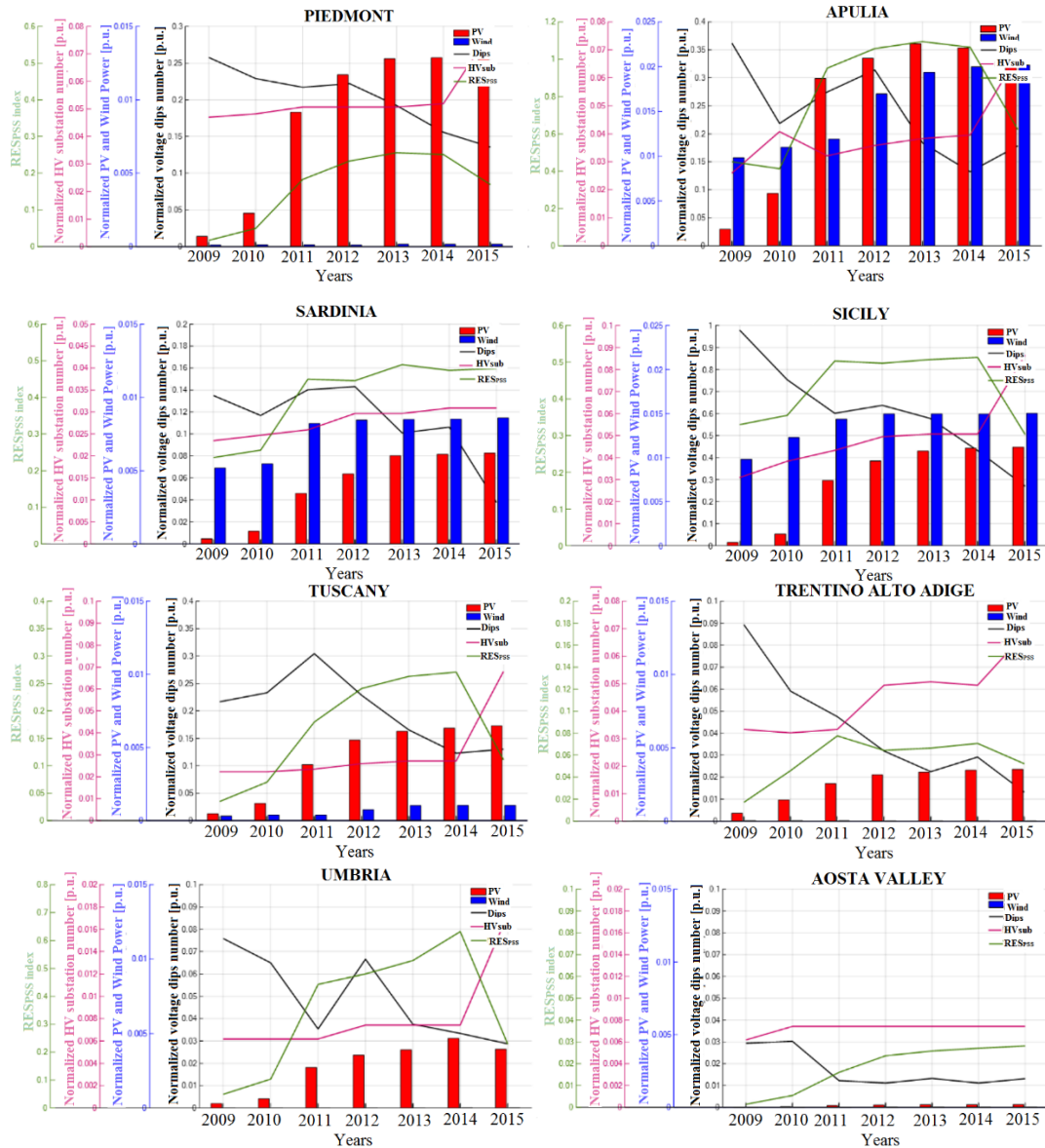


Fig. 6. Details of all Italy's regions indicating Voltage dips, Photovoltaic Systems and Wind Farms

5. Conclusion

This work has shown the possible correlation between the quality of power in distribution grids, considering the number of voltage dips, and the installations of renewable power plants mainly based on wind and photovoltaic generators.

The period analysed in this study, from 2009 to 2015 includes different scenarios in terms of cumulative solar and wind power installed, the robustness of the grid and the number of the substations.

The study has been conducted for the 20 Italian regions characterized by their own RES exploitation. The obtained results show that in genera the connection of the renewable energy sources inside the network does not impact significantly the quality of power delivered to the end users.

However, the network can take advantage with a general reinforcement of the grid, even if strong correlation between the number of substations and RES installations with voltage dips has not been experience.

Therefore, it is possible to conclude that renewable sources interfaced to the grid through electronic converters, as PV systems and wind energy do not affect the quality of power, and they can be connected without any particular adaptation.

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