Research Journal of Applied Sciences, Engineering and Technology 7(11): 2232-2241, 2014
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: June 07, 2013 Accepted: June 25, 2013 Published: March 20, 2014

# A Power Quality Study on the Italian Electric Grid: Statistical Analysis of the Voltage Dips and Compensation Strategies

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**Abstract:** This study presents a power quality study on the Italian Electric Grid. The most probable voltage sags, in terms of number and duration, have been identified thank to a statistical analysis, based on a yearly survey (2012). In particular, four zones have been considering (North, Central, Central-South and South) in order to represent the whole Italian situation. This data have been used to define a suitable system that can compensate many power quality problems. The study proposes a Dynamic Voltage Restorer (DVR) as compensation device where a sensible load is connected. A model realized in SIMULINK environment of the network is presented and many simulations are performed in order to indicate the right compensation strategy.

**Keywords:** Dynamic voltage restorer DVR, power quality, SIMULINK, statistical analysis, voltage dips

## INTRODUCTION

The electric distribution grids are in continuous evolution and especially it is necessary to let them available a growing number users of passive and active guaranteeing an adequate safety level. However, studies regarding the main network problems show that the electric distribution grids are interested by considerable disturb that affect their stability and energy delivered for the users (Ssu-Han *et al*., 2011).

Power quality is the interaction of electrical power with electrical equipment. If electrical equipment functions correctly and reliably without being damaged or stressed and in this case the electrical power is of good quality. Otherwise, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, the power quality is poor (Bollen, 2003). When sensible loads are connected to the grid, particular care has to be assigned to these power quality aspects and it is necessary to evaluate the right compensation system (Alwan *et al*., 2013; Obinabo and Anyasi, 2011).

This study presents a statistical analysis of the power interruptions in the Italian electric grid based on experimental data collected during a whole year, in particular they were studied the voltage dips. The focus has been on the disturbs characterized by the short duration and restrained undelivered energies that are highly suffered by the electric users in terms of service continuity. In order to provide the right solution to voltage sag problems, it is necessary to determine the frequency, depth and duration of each voltage sag. These can vary widely even in apparently similar industrial facilities. The collection of this data is essential if the optimal solution has to be identified. Thanks to the results of this analysis, it is possible to propose a compensation strategy when sensible loads are connected.

The proposal consists in the installation of a dynamic compensation system, fast and strong enough to sustain the users supply without considerable distortions due to the supply switch, upstream the most sensitive points.

The Dynamic Voltage Restorer (DVR) is a power electronic device that provides a three-phase controllable voltage source, whose voltage vector (magnitude and angle) adds to the source voltage during each sag event, to restore the load voltage to pre-sag conditions (Leela and Dash, 2010; Gharedaghi *et al*., 2011).

DVR is a fast, flexible and efficient solution to the voltage dip problem. A critical aspect can be the static storage source, because dedicated batteries are generally expensive and bulky, especially for high power. For this reason, it is necessary to estimate the power and energy quantities needed by the loads. This study is focused on the short period disturbances. In the study, knowing the voltage dips characteristic, obtained from the statistical analysis, a negative event is simulated and the compensation and the storage capability is evaluated.

## POWER QUALITY ASPECTS

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

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the power frequency for durations from 0.5 cycles to 1 min, 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 (Ian, 2007; Lidong and Math, 2000). A cause of this the problem in utility system can be the operation of recloses and circuit breaker. The depth of the voltage sag at the consumer's site will vary depending on the supply line voltage and the distance from the fault. Typically, a higher supply voltage will have a larger sag affected zone. Other causes can be the equipment failure, bad weather, pollution, animals, vehicle problems and construction activity. Voltage dips can be caused within an industrial facility or a group of facilities either by the starting of large electric motors individually or in groups. The large current inrush initial can cause voltage dips in the local or adjacent areas even if the utility line voltage remains at a constant nominal value.

In Fig. 1 are shown the possible causes of voltage dips based on their amplitude and duration.

Both single-phase and multi-phase voltage dips can cause unplanned production stoppages but single-phase is equal to 120V control devices and electronic sensors can be very vulnerable to voltage sags. Modern electronic equipment requires more precise voltage regulation than traditional devices such as induction motors. Electronic process controls, sensors, computer controls, PLC's and variable speed drives, even conventional electrical relays are all susceptible to voltage sags (D'Urso *et al*., 2011). In many cases, one

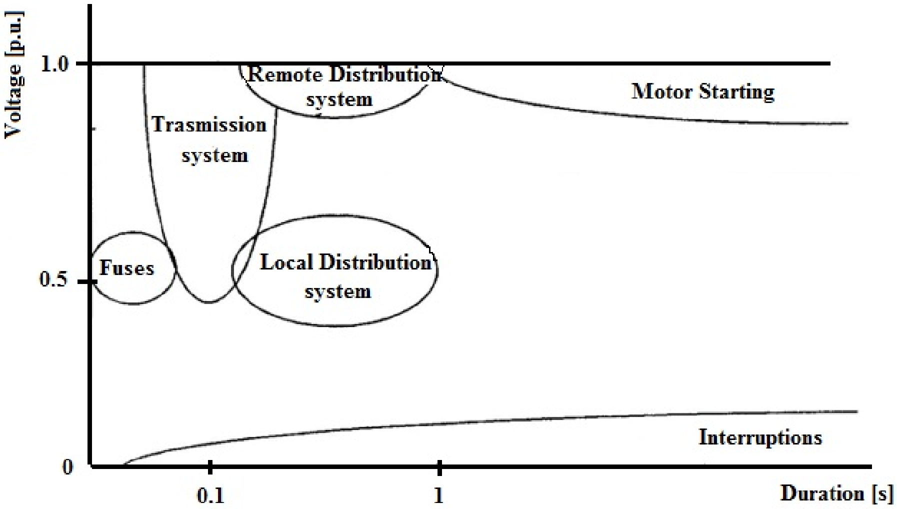


Fig. 1: Possible causes of voltage dips based on their amplitude and duration

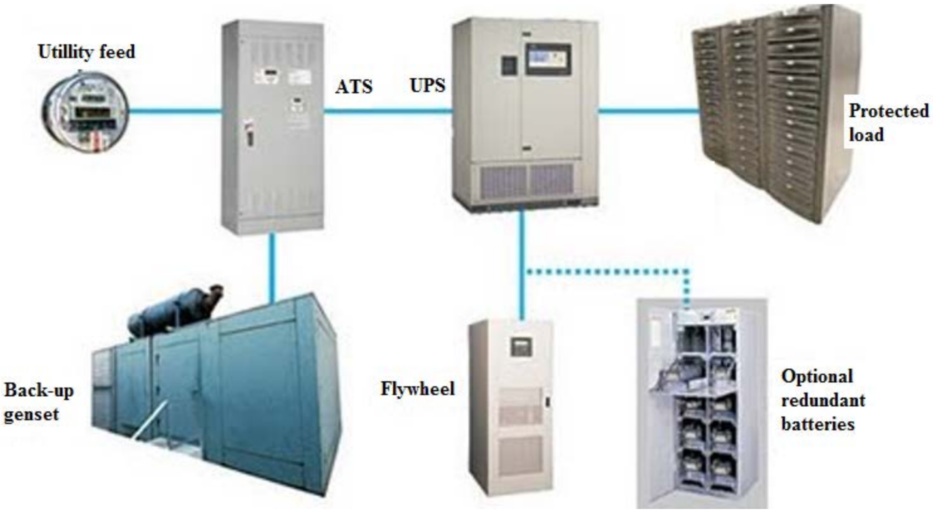


Fig. 2: UPS connected to a sensible load through an ATS

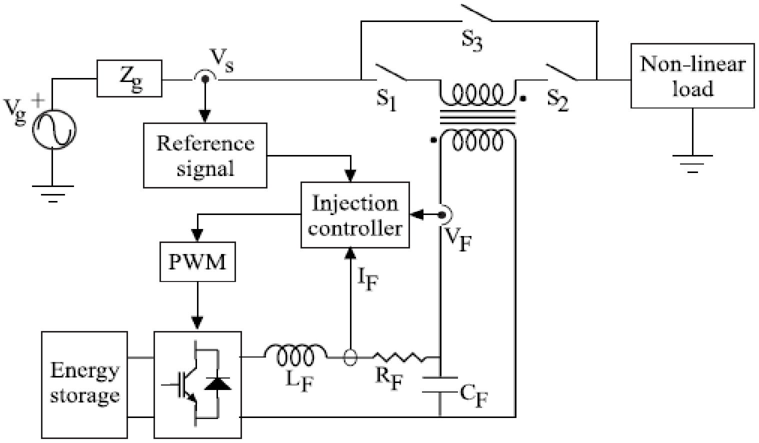


Fig. 3: DVR scheme

or more of these devices may trip if there is a voltage sag to less than 90% of nominal voltage, even if the duration is only for one or two cycles i.e., less than 100 msec.

There are different solutions to limit the voltage dips and interruptions. For the supply network, it is possible to arise the short-circuit power and to decrease the overhead lines length. For the user network, it is possible introduce an adequate protection philosophy and to reduce the voltage drops due to heavy loads starting through dedicated supply. Moreover it can be necessary to introduce a compensation device to guarantee a better quality of the supply and to reduce the network malfunctioning. The traditional UPS (Uninterruptible Power Supply) presents some problems that can be overcome by innovative solutions (Fig. 2).

The study proposes a dynamic voltage restorer as compensation device where a sensible load is connected.

## DYNAMIC VOLTAGE RESTORER FOR THE VOLTAGE DIPS STATIC COMPENSATION

The Dynamic Voltage Restorer (DVR), also referred to as the Series Voltage Booster (SVB) or the Static Series Compensator (SSC), is a device that utilizes solid state (or static) power electronic components and is connected in series to the utility primary distribution circuit (Fig. 3).

The DVR provides three-phase controllable voltage, whose vector (magnitude and angle) adds to the source voltage to restore the load voltage to pre-sag conditions. During voltage sag, the DVR injects a voltage to restore the load supply voltages. The DVR needs a source of energy for the sag compensation (Mahmoud *et al*., 2011). The Voltage Source Inverter (VSI) or simply the inverter converts the DC voltage from the energy storage unit to a controllable three-phase AC voltage. The inverter switches are normally fired using a sinusoidal Pulse Width Modulation (PWM) scheme (Brenna *et al*., 2011, 2012). Since the vast majority of voltage dips seen on utility systems are unbalanced, the VSI will often operate with unbalanced switching functions for the three phases and therefore must treat each phase independently. Moreover, sag on one phase may result in a swell on another phase, so the VSI must be capable of handling both sags and swells simultaneously. Another topology of the DVR is the use of multi-inverter system in cascade. This topology will add the voltage of the single cascaded inverters in series in order to obtain the desired inverter voltage. This method gets rid of the injection transformer used in the basic configuration of the DVR. This arrangement is often called a transformer-less or multilevel or a cascade inverter DVR (Visser *et al*., 2002; Loh *et al*., 2004).

Typically, three compensation strategies are used for sag compensation: pre-sag compensation, in-phase compensation and minimum (optimized) energy injection (Meyer *et al*., 2008). In the pre-sag compensation, the DVR injects the difference (missing) voltage between during-sag and pre-sag voltages to the system and the DVR must compensate for both magnitude and angle. It is the best solution to obtain the same load voltage as the pre-fault voltage and is best suited for loads sensitive to phase angle jumps like angle-triggered thyristors-controlled loads.

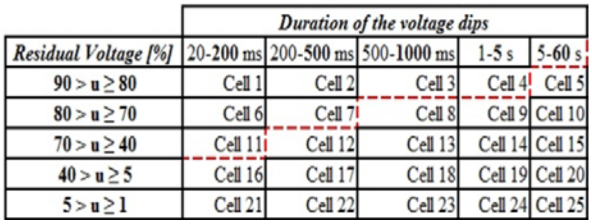
In the in-phase compensation, the injected voltage is in phase with supply voltage. The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied. In this configuration, the DVR is designed to compensate the voltage magnitude only. This method is suitable for loads that can withstand phase angle jumps.

Fig. 4: The specific zone analysed in this analysis

The last strategy is the minimum (optimized) energy injection: the minimum energy injection, which depends on maximizing the active power supplied by the network (keeping the apparent power constant and decreasing the network reactive power) by minimizing the active power supplied by the compensator (increasing the reactive power supplied by the compensator). This technique can be useful in this case to minimize the energy delivered by the vehicles. A voltage sag detection technique detects the occurrence of the sag, the start point and the end, sag depth (magnitude to be restored) and phase shift. Common techniques of voltage sag detection are the peak value method, the Root Mean Square (RMS) method, the Fourier Transform (FT) and the space vector method (Abdelkhalek *et al*., 2009; Tiwari and Gupta, 2010). This study considers a Fast Synchronously Rotating Reference Frame (FSRRF)-based voltage sag detection (Kumsuwan and Sillapawicharn, 2012) that can be applied to any voltage sag or interruption compensation systems to improve the performance of the whole systems.

## STATISTICAL ANALYSIS OF THE INTERRUPTION VOLTAGE

An analysis about the power interruptions during the whole year 2012 in four different Italian zones (Fig. 4) is conducted in order to perform a feasibility study of a system constituted by the components described in the previous Paragraph. In particular, the analysis wants to understand what kind of disturbance can be eliminated by a compensation system and their entity to evaluate the convenience to adopt such a solution.



| | *Duration of the voltage dips* | | | | |
|---|---|---|---|---|---|
| *Residual Voltage [%]* | 20-200 ms | 200-500 ms | 500-1000 ms | 1-5 s | 5-60 s |
| $90 > u \geq 80$ | Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 |
| $80 > u \geq 70$ | Cell 6 | Cell 7 | Cell 8 | Cell 9 | Cell 10 |
| $70 > u \geq 40$ | Cell 11 | Cell 12 | Cell 13 | Cell 14 | Cell 15 |
| $40 > u \geq 5$ | Cell 16 | Cell 17 | Cell 18 | Cell 19 | Cell 20 |
| $5 > u \geq 1$ | Cell 21 | Cell 22 | Cell 23 | Cell 24 | Cell 25 |

Fig. 5: Classification of the voltage dips in according to the norm EN 50160:2010

All the supply interruption, both public and private, for each zone have been recorded (QuEEN Project), classified for position and jurisdiction. In the following the procedure to calculate different indicators is presented.

**Statistical indicators:** Over the years at international level have been adopted different methods of presentation of the voltage dip performance of a network (Foiadelli *et al*., 2005). The method utilized is of the type tabular where provides for the classification of voltage dips in duration classes and residual voltage, characterizing the event not only in terms of generic numerousness. In particular, the classification suggested, for statistical purposes, is the new version of the standard EN 501608 (Fig. 5) that proposes to characterize the classes of voltage sags according to the immunity curves. These curves are defined according to the levels indicated for equipment belonging to the classes 2 and 3 in CEI EN 61000-4-11and CEI EN 61000-4-34 (for the definition of class 2 and 3 refer to CEI EN 61000-2-412).

The equipment is considered immune to voltage dips characterized by durations and residual stresses above the curves of immunity (Cells 1, 2, 6, 7 for class 2 and cells 1, 2, 3, 4, 6, 7, 11 for class 3). The identification of immunity areas may lead to the definition of an immunity curve (dotted line). The area of immunity is competence of the equipment manufacturer and of the customer (for the choice of equipment and of plant solutions most appropriate to ensure immunity of processes), while the area defined by the remaining cells is responsibility of the distributor.

One possibility to represent the performance of networks in summary form is given by the evaluation of appropriate indices, whose main advantage compared to previous methods, in addition to the synthesis of one number, is to facilitate comparisons between performance related to monitoring periods different (historical trend analysis) or from individual sites/territorial areas distinct. Given the voltage sags recorded in a year, the indices are evaluated for each voltage dips, according to their definition, to arrive to get the indices of site through direct sum of all indexes of event associated with each measurement site. The indices of system are obtained by summing the indices of the end site of all sites that are part of the system in exam.

It have been discussed in the literature numerous synthetic indicators, also in a perspective of their standardization (Carpinelli *et al*., 2007). Potential indicators for voltage dips are:

- Number of the voltage dips (N)
- Number of voltage dips that fall below the curves of immunity of class 2 (N2a), number of voltage dips that fall below the curves of immunity of class 3 (N3b)

These indicators are calculated by counting the values in the cells of the Table 1 in according to EN 50160:2010. Referring in Fig. 5, add up the values of the holes/voltage dips contained in 25 cells for the indicator N, the values in the all cells except cells 3, 4 and 11 to get the indicator N2a, the values in the all cell expect cell 1, 2, 3, 4, 6, 7 and 11 to obtain the indicator N3b.

**Regional data for the voltage sags during the year 2012:** In the following the results obtained by the statistical analysis performed on the four different Italian zones are presented.

**Lombardy:** The first zone analysed in Italy is been the North, exactly Lombardy. In Table 1 are shown the distribution of the voltage dips for the different duration and different residual voltage (%).

Where the double line identified class 3 and the bold line identified class 2. In this case, it is possible to calculate the three index: *N* is equal to 1833; *Na*2 is equal to 680 and *Na*3 is equal to 221.

**Lazio:** In Table 2 are shown the distribution of the voltage sags for the different duration and different residual voltage (%).

Where the double line identified class 3 and the bold line identified class 2. In this case, it is possible to calculate the three index: *N* is equal to 2507; *Na*2 is equal to 872 and *Na*3 is equal to 372.

Table 1: Classification of the voltage dips in Lombardy (north zone)

| | Duration voltage dips | | | | |
|---|---|---|---|---|---|
| Residual voltage (%) | 20-200 msec | 200-500 msec | 500-1000 msec | 1-5 sec | 5-60 sec |
| 90>u≥80 | 803 | 63 | 11 | 3 | 0 |
| 80>u≥70 | 266 | 21 | 3 | 0 | 0 |
| 70>u≥40 | 452 | 31 | 3 | 0 | 0 |
| 40>u≥5 | 160 | 11 | 3 | 0 | 0 |
| 5>u≥1 | 3 | 0 | 0 | 0 | 0 |

Table 2: Classification of the voltage dips Lazio Italy (central zone)

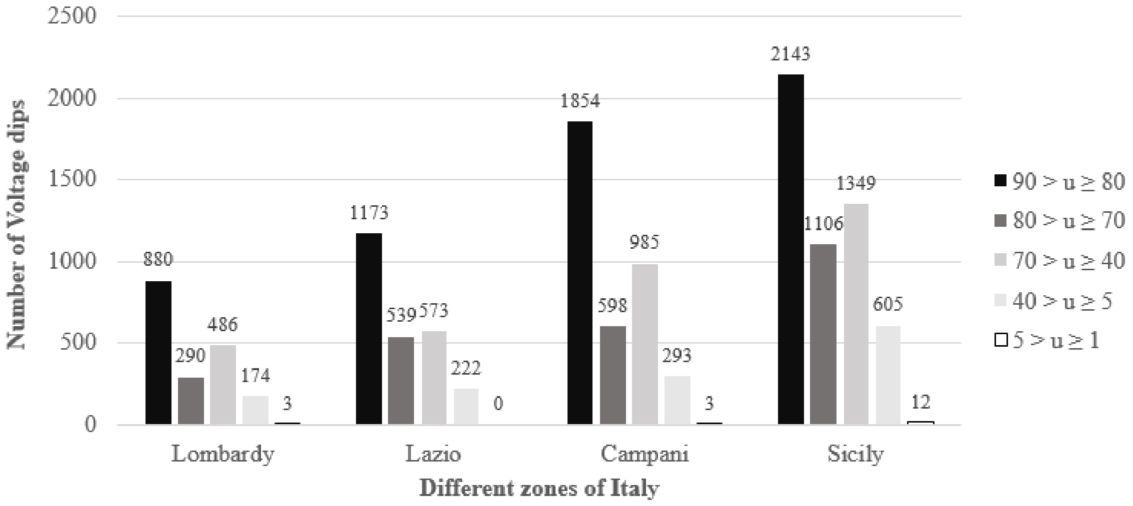
| | Duration voltage dips | | | | |
|---|---|---|---|---|---|
| Residual voltage (%) | 20-200 msec | 200-500 msec | 500-1000 msec | 1-5 sec | 5-60 sec |
| 90>u≥80 | 946 | 166 | 49 | 12 | 0 |
| 80>u≥70 | 444 | 79 | 14 | 2 | 0 |
| 70>u≥40 | 439 | 124 | 8 | 2 | 0 |
| 40>u≥5 | 186 | 32 | 4 | 0 | 0 |
| 5>u≥1 | 0 | 0 | 0 | 0 | 0 |

Table 3: Classification of the voltage dips Campania Italy (central-south zone)

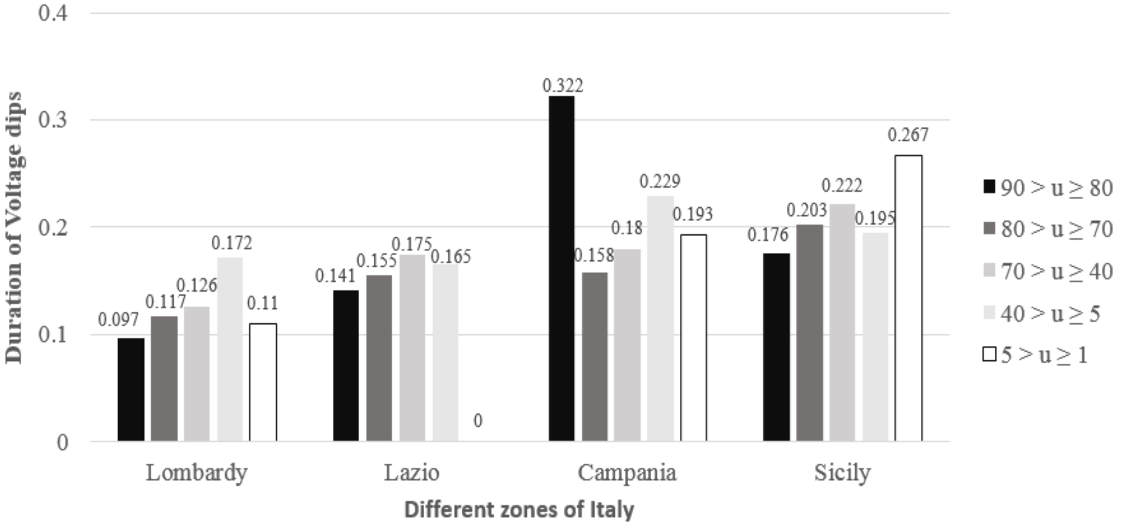
| | Duration voltage dips | | | | |
|---|---|---|---|---|---|
| Residual voltage (%) | 20-200 msec | 200-500 msec | 500-1000 msec | 1-5 sec | 5-60 sec |
| 90>u≥80 | 1595 | 186 | 43 | 14 | 16 |
| 80>u≥70 | 469 | 125 | 4 | 0 | 0 |
| 70>u≥40 | 745 | 213 | 27 | 0 | 0 |
| 40>u≥5 | 176 | 107 | 10 | 0 | 0 |
| 5>u≥1 | 3 | 0 | 0 | 0 | 0 |

Table 4: Classification of the voltage dips south Italy (south zone)

| | Duration voltage dips | | | | |
|---|---|---|---|---|---|
| Residual voltage (%) | 20-200 msec | 200-500 msec | 500-1000 msec | 1-5 sec | 5-60 sec |
| 90>u≥80 | 1551 | 462 | 65 | 65 | 0 |
| 80>u≥70 | 710 | 350 | 33 | 13 | 0 |
| 70>u≥40 | 639 | 679 | 25 | 6 | 0 |
| 40>u≥5 | 383 | 208 | 14 | 0 | 0 |
| 5>u≥1 | 7 | 4 | 0 | 1 | 0 |



(a)



(b)

Fig. 6: Four different areas analysed in particular, (a) total number of voltage dips, (b) duration of voltage dips

**Campania:** In Table 3 are shown the distribution of the voltage sags for the different duration and different residual voltage (%).

In this case, it is possible to calculate the three index: $N$ is equal to 3733; $Na2$ is equal to 1358 and $Na3$ is equal to 556, where the double line identified class 3 and the bold line identified class 2.

**Sicily:** In Table 4 are shown the distribution of the voltage sags for the different duration and different residual voltage (%).

Where the double line identified class 3; the bold line identified class 2. In this case, it is possible to calculate the three index: $N$ is equal to 5212; $Na2$ is equal to 2142 and $Na3$ is equal to 1373.

In the Fig. 6 are shown the four different areas analysed. In particular the number (Fig. 6a) and the duration (Fig. 6b) of voltage dips are depicted.

All zones observed that the voltage dips mainly fall below the curves of immunity respectively for class equipment 2 connected to the public distribution network compared to those of class 3 that operate in an industrial environment. The number of voltage dips is very different depending on the considered zone. The south zone presents a greater instability than the north and central zones, presenting the measurement number definitely higher.

Once selected the voltage dips that can be dangerous for the sensible loads, it is possible to evaluate the energy and power requested to a static storage thank to the dynamic model proposed in the following.

## STATIC COMPENSATION STRATEGY OF THE NETWORK DISTURBS

The simulation considers an electric network constituted by a generator, one HV transmission linen and two MV radial lines. The goal is the creation of a model able to level the disturbs caused by a voltage sag on a 12.5 kV cable line given an appropriate source of static energy and power (Fig. 7).

The designed circuit simulates a MV network with a sensible load connected. The drop of the network voltage of 60% will be reproduce simulating a fault before the line. The goal will be to know the energy and power requested to a static storage in order to compensate the voltage drop.

Considering the above described network, at the instant T = 500 msec a three-phase to ground fault, able to drop the voltage at the load 2 to 0.7 p.u., happens in the point (40). The fault will be 200 sec long.

The duration of the drop and its module value can be considered as probable. Considering also the hypothesis of the grid protections intervention, the interruption given by the fault is inside the 70% of the micro interruption cases.

In order to compensate all the voltage drops simulated in the model, it is necessary to implement a discrete time control system able to determine the angle and the phase necessary to compensate the disturb,

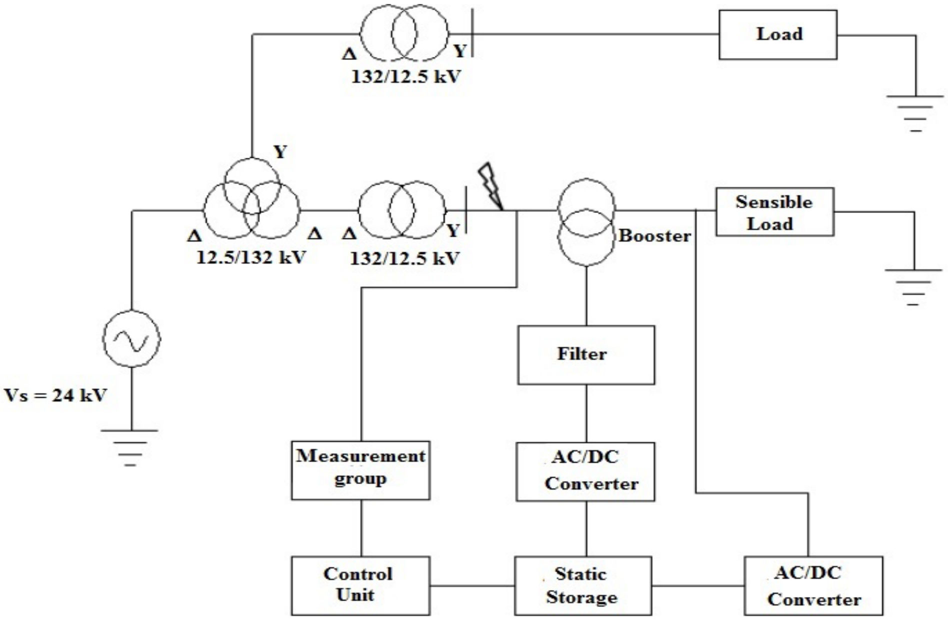


Fig. 7: Scheme of the simulated network

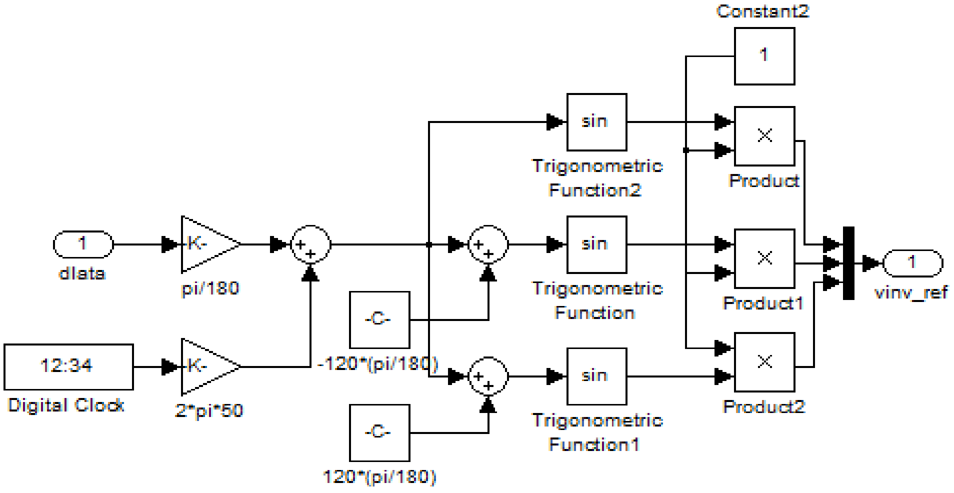


Fig. 8: PWM signal synchronization

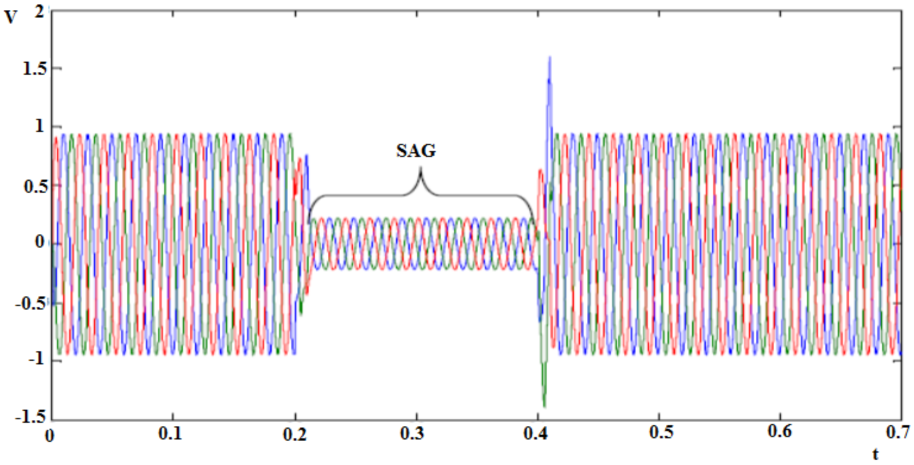


Fig. 9: Load voltage behavior when a fault occurs on the line and there is not a compensation system

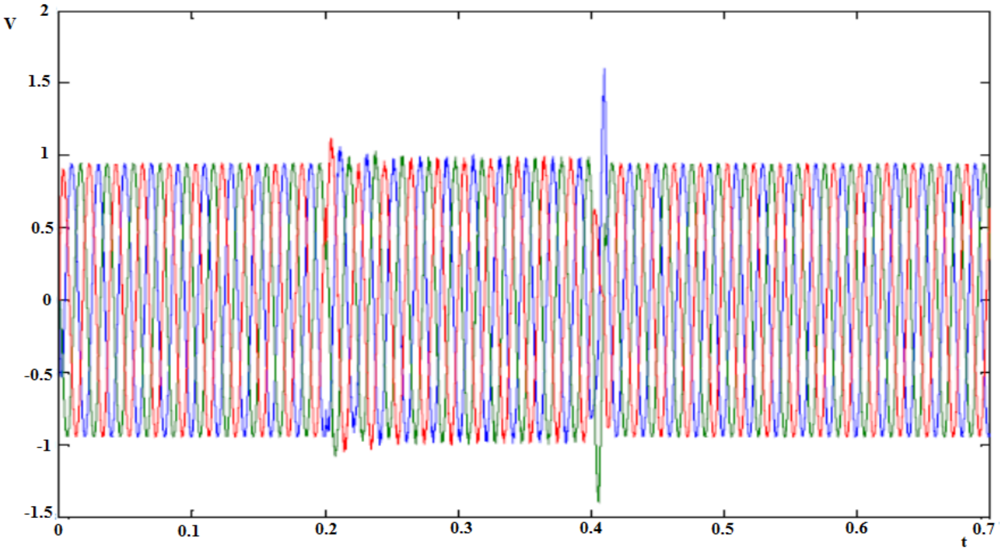


Fig. 10: Load voltage behaviour when a fault occurs on the line and there is a compensation system

cause of the error signal, receiving as input the direct sequence voltage module. The input signal represents the voltage on the load. After the Fortesque transformation, the direct component of this value is compared with the reference voltage value (0.98) by a summative node. After the integrator and the firing angle block transform the input data to generate an angle able to let the error become zero. The output value is the referring values for the PWM that module the frequency pulses of the controlled bridge after the battery (Fig. 8).

Two different simulations have been performed. The first configuration presents the switch of the DVR open, while the three phases shunt switches are short-circuited on their Booster transformers. This simulation gives the system behaviour when the voltage compensation system is not inserted.

In the second configuration, the main switch is closed and the Boosters are supplied. In this way it is possible to evaluate the power quality improving given by the use of a DVR.

Figure 9 depicts the load voltage behaviour when a fault occurs on the line and there is not a compensation system.

Figure 10 depicts the load voltage behaviour when a fault occurs on the line and the compensation system intervenes.

The comparison between the results obtained in the two different simulations demonstrates that the presence of a DVR lets to level the voltage before the end of the first cycle.

Neglecting a light module swing of the direct voltage vector but considering the reactive elements of the circuit, it is possible to assure that at the load clamps no swing is appreciated. However, the DVR will compensate not deep sags.

Regarding the control structure, a closed loop solution with load voltage regulation has been adopted.

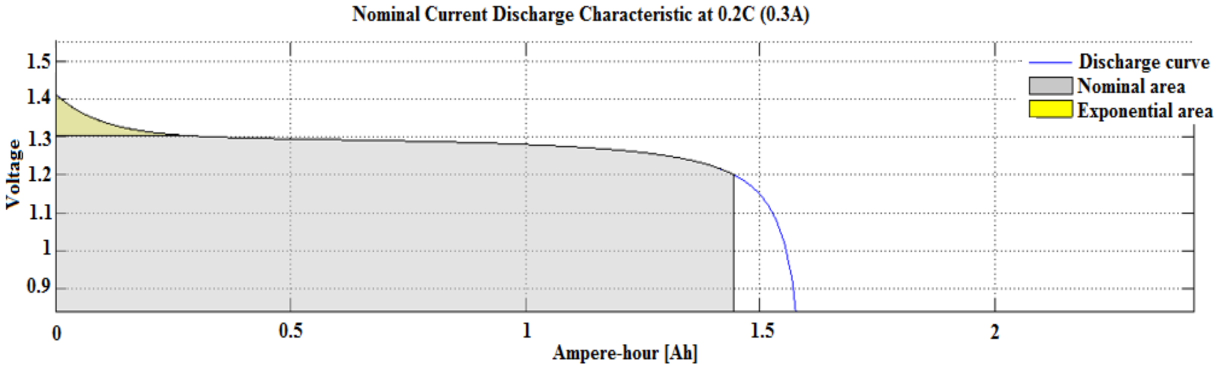


Fig. 11: V-Ah characteristic of an ion-lithium battery

Respect to the open loop strategy, this solution guarantees a better accuracy and to compensate the voltage drop on the equivalent impedance of the disposal following the absorbing of the load supplied after the DVR.

Considering the energy problems of the proposed solution, some considerations follow.

The main batteries normally considered forth are use has a functioning characteristic as the one reported in Fig. 11.

Considering that the power requested by the DVR is equal to 542.5 kW, it is possible to estimate that the batteries are to be grouped in order to furnish an output voltage equal to 250 Vcc. Considering the requested power and the losses in the switch, the current requested by the Booster will be 2200 A.

## CONCLUSION

Power Quality remains one of the most important aspects connected to the Electric Grids. Distorted voltage and current waveforms, RMS voltage variations, frequency shifts, unbalances, electromagnetic disturbances can cause damages as the lack of continuity of the supply or dangerous conditions. The study proposes a compensation strategy able to level the short period disturbances. For this scope, a deep statistical analysis of interruptions during the whole year 2012 in four different Italian zones has been performed. All the supply interruption, both public and private, for each zone have been recorded, classified for position and jurisdiction and the most important indicators have been calculated. Once selected the voltage dips that can be dangerous for the sensible loads, an evaluation of the electric quantities requested to a static storage has been performed thank to a dedicated dynamic model implemented in SIMULINK environment. In order to compensate all the voltage drops simulated in the model, it has been necessary to implement a discrete time control system. As compensation device, the study proposed a dynamic voltage restorer where a sensible load is connected. The many simulations performed showed that the presence of a DVR lets to level the voltage before the end of the first cycle but the DVR will compensate not deep sags. Moreover, considerations on the static storage system are reported. The future development of this research will include the identification and the feasibility study of different static storage source, considering that dedicated batteries are generally expensive and bulky, especially for high power.

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