# PRELIMINARY RESULTS OF THE POWER QUALITY SURVEY IN PROGRESS ON THE MV ENEL NETWORK


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## *ABSTRACT*

*This paper makes a preliminary analysis of the data made available by the power quality instruments (PQI) installed in MV bus-bars of 346 HV/MV substations and 89 MV/LV customers' substations of Enel Distribuzione (ENEL) network in the first 8 months of the survey. The following topics are dealt with:*

- *the quality and reliability of data collected by the instruments and elaborated by QUEEN web site [1],*
- *the preliminary results of the survey and indicative values of the power quality parameters on MV networks,*
- *possible correlation between power quality parameters and network characteristics.*


## INTRODUCTION

Power quality represents today a very important issue for distributors, customers and regulators because many appliances may be affected by power quality parameters (voltage variations, voltage dips, harmonics, flicker and unbalance). As the electric network is a unique system whose behaviour is influenced by features of all the involved subjects (from the plant design to the choice of equipments and machineries), the Italian Electrical Energy Regulator (AEEG) promoted a power quality survey on HV and MV networks [1].

This campaign interests all the country and involves both the transmission and the distribution networks, with the purpose to determine not only the statistic annual value of main characteristics of voltage supply, but also how the disturbances propagate. The overall PQI are 600: 400 of them are installed in MV bus-bars of HV/MV substations and 200 in MV/LV customers' substations (along the feeders).

ENEL has been heavily involved in this campaign installing *346)* power quality instruments on MV bus-bars and *89* along MV lines on MV/LV customers' substations.

This valuable quantity of instruments has the scope to give a sufficiently realistic picture of the power quality on MV networks. Anyway, for the time being and as reported below, the data collected are not fully reliable therefore the relevant consideration must be considered only preliminary.

Finally, voltage dips data are referred to the period between 10/04/2006 and 26/11/2006 whereas flicker, harmonics, unbalance analysis is referred to one month, being a time length like that sufficient to characterize these kind of voltage parameters.

## INSTRUMENTS' PLACEMENT

The parameters characterising the MV networks used to choose the positioning of the power quality instruments are the following:

- prevailing MV feeder typology (3 possible values: "overhead" (if ≥ 90%), "cable" (if ≥ 90%) or "mixed");
- number of MV customers (2 possibilities: "high", when MV customers' MV/LV substations are more than 50% of total MV/LV substations (customers +DNO); "low" in the opposite case);
- prevailing typology of cities supplied by the MV network (3 possible values: "high inhabitant density" (more than 50.000 inhabitants), "low inhabitant density" (less than 5.000 inhabitants) or "medium inhabitant density");
- MV neutral typology (2 possibilities: "insulated" or "compensated" (earthed through impedance)).

The choice of the bus-bars where place the PQI was done in order to represent, as much as possible the real weight of all the 36 combinations of the above mentioned parameters on the overall ENEL network. E.g. if the bus-bars supplying "overhead" MV networks with "insulated" neutral, "high" number of MV customers and cities with "medium inhabitant density" are x% of total, x% of instruments were placed on those bus-bars.

## QUALITY AND RELIABILITY OF DATA

It is worthwhile to mention that the PQ survey system is huge (600 instruments) and, naturally, in this first period of measurement encountered some problem in the instruments, transducers or data management.

In particular:

- for MV NI networks the voltage transformers installed in HV/MV substation, supplying the PQI, are subject to temporary saturation in case of phase to ground faults;
- the MV NC networks are not affected by the phenomena above mentioned. Nevertheless they can be operated at NI and QUEEN, up to now, is not able to manage the actual neutral operation.

For these reasons the data relevant to voltage dips measured in HV/MV substations with duration shorter than 80 ms are not reliable. Therefore ENEL decided not to show these figures and to disregard them in this paper.

Moreover, flicker parameters $P_{st}$ and $P_{lt}$ are calculated by PQI taking into account also samples recorded during voltage dips; therefore, the above mentioned flicker parameters might be affected by significant error.

## VOLTAGE DIPS

Voltage dips have been analysed taking care of the following MV network characteristics:

- MV neutral;
- prevailing MV feeder typology (overhead/buried cable);
- short circuit power.

Actually the process of changing the MV neutral from "insulated" (NI) to "compensated" (NC) is still going on ENEL MV networks. Referring to a certain time period, some MV bus-bars are operated partially or alternatively with NC or NI.

Therefore, for the following voltage dips analyses, a bus-bar has been classified NC or NI only if it has been operated with that MV neutral condition for more than 85% of time.

Correlations between voltage dips and lightning strokes detected by the CESI system SIRF have been carried out as well.

The voltage dips coming from HV network have been also evaluated.

### Voltage dips coming from HV network

The voltage dips coming from HV network have been identified by means of the starting distance relays installed in the HV lined supplying the HV/MV substation.

The analysis enhanced the following aspects:

- the voltage dips coming from HV network have a typical duration between 50 and 100 ms (see Figure 1), the major part of them lasts less than 150 ms. This is due to intervention of distance relays on their first zone;
- there are some voltage dips lasting about 350 ms due to distance relays trips on their second zone;
- there is a significant number of voltage dips shorter than 50 ms. which should need a deep analysis in order to understand their causes (e.g. different propagation on the network of voltage dips due to "electrically far" faults);
- the number of voltage dips coming from HV network (per PQI) is substantially the same for MV networks operated with NI or NC

Table 1 shows all the voltage dips coming from HV network and recorded by PQI installed in the MV bus-bars of HV/MV substations. Those with residual voltage lower than 80% are about 72% of the total amount.

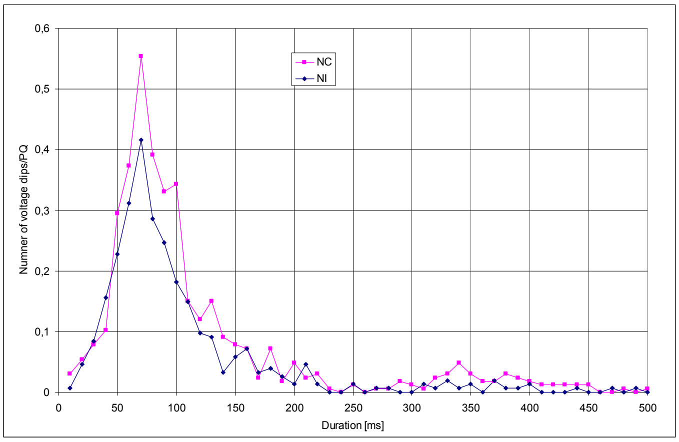


*Figure 1 - Number of voltage dips (per PQI) coming from HV network as a function of their duration*

| Residual voltage [%] | Duration [ms] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10-80 | 80-140 | 140-200 | 200-280 | 280-360 | 360-500 | 500-1000 | >1000 | Total |
| 10-0 | 2 | 9 | 2 | 2 | 2 | 2 | 0 | 0 | 19 |
| 20-10 | 3 | 8 | 9 | 3 | 4 | 0 | 3 | 0 | 30 |
| 30-20 | 11 | 23 | 8 | 2 | 3 | 8 | 4 | 0 | 59 |
| 40-30 | 16 | 25 | 5 | 2 | 3 | 1 | 5 | 0 | 57 |
| 50-40 | 26 | 63 | 11 | 4 | 5 | 6 | 4 | 1 | 120 |
| 60-50 | 22 | 42 | 9 | 2 | 2 | 9 | 4 | 0 | 90 |
| 65-60 | 27 | 27 | 5 | 2 | 0 | 1 | 1 | 1 | 64 |
| 70-65 | 36 | 46 | 11 | 2 | 5 | 2 | 2 | 1 | 105 |
| 75-70 | 46 | 66 | 7 | 3 | 7 | 3 | 4 | 0 | 136 |
| 80-75 | 57 | 63 | 11 | 1 | 4 | 5 | 5 | 0 | 146 |
| 85-80 | 108 | 48 | 12 | 5 | 3 | 4 | 5 | 0 | 185 |
| 90-85 | 110 | 21 | 6 | 2 | 4 | 0 | 1 | 2 | 146 |
| Totale | 464 | 441 | 96 | 30 | 42 | 41 | 38 | 5 | 1157 |
| Total/PQI | 2.7 | 2.5 | 0.6 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 | 6.7 |
| Total/PQI < 70% | 0.4 | 0.7 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 1.6 |
| Total/PQI < 80% | 0.7 | 1.1 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 2.4 |

*Table 1– Average voltage dips coming from HV network*

### Voltage dips detected on MV bus-bar and coming from MV network

Table 1 shows all the voltage dips, originated at MV level, and detected by PQI installed in bus-bars supplying MV networks operated with "compensated" neutral. The values relevant to PQI installed in bus-bars supplying MV networks operated with "insulated" neutral are shown in table 2.

| Residual voltage [%] | Duration [ms] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 80-140 | 14-200 | 200-280 | 280-360 | 360-500 | 500-1000 | > 1000 | Total |
| 10-0 | 82 | 15 | 10 | 5 | 4 | 2 | 4 | 122 |
| 20-10 | 149 | 29 | 14 | 9 | 3 | 8 | 1 | 213 |
| 30-20 | 322 | 93 | 22 | 13 | 4 | 10 | 1 | 465 |
| 40-30 | 419 | 122 | 84 | 18 | 13 | 8 | 0 | 664 |
| 50-40 | 644 | 182 | 43 | 41 | 17 | 9 | 16 | 952 |
| 60-50 | 660 | 138 | 46 | 49 | 19 | 12 | 5 | 929 |
| 65-60 | 381 | 74 | 18 | 72 | 5 | 5 | 5 | 560 |
| 70-65 | 480 | 74 | 19 | 69 | 15 | 9 | 10 | 676 |
| 75-70 | 467 | 111 | 23 | 130 | 22 | 15 | 14 | 782 |
| 80-75 | 483 | 85 | 36 | 169 | 17 | 25 | 27 | 842 |
| 85-80 | 518 | 83 | 32 | 276 | 27 | 30 | 44 | 1010 |
| 90-85 | 381 | 57 | 76 | 208 | 26 | 45 | 38 | 831 |
| Totale | 4986 | 1063 | 423 | 1059 | 172 | 178 | 165 | 8046 |
| Total/PQI | 30,0 | 6,4 | 2,5 | 6,4 | 1,0 | 1,1 | 1,0 | 48,5 |
| Total/PQI < 70% | 18,9 | 4,4 | 1,5 | 1,7 | 0,5 | 0,4 | 0,3 | 27,6 |
| Total/PQI < 80% | 24,6 | 5,6 | 1,9 | 3,5 | 0,7 | 0,6 | 0,5 | 37,4 |

*Table 2 – Average voltage dips, originated at MV level, detected by PQI installed in bus-bars supplying MV networks operated with NC*

| Residual voltage [%] | Duration [ms] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 80-140 | 14-200 | 200-280 | 280-360 | 360-500 | 500-1000 | > 1000 | Total |
| 10-0 | 108 | 30 | 12 | 4 | 3 | 3 | 3 | 163 |
| 20-10 | 164 | 54 | 20 | 8 | 9 | 10 | 2 | 267 |
| 30-20 | 291 | 91 | 78 | 14 | 12 | 12 | 3 | 501 |
| 40-30 | 1029 | 279 | 176 | 74 | 16 | 14 | 2 | 1590 |
| 50-40 | 1363 | 394 | 217 | 100 | 97 | 41 | 10 | 2222 |
| 60-50 | 1016 | 268 | 114 | 82 | 54 | 43 | 3 | 1580 |
| 65-60 | 374 | 83 | 25 | 16 | 7 | 4 | 4 | 513 |
| 70-65 | 403 | 47 | 18 | 22 | 12 | 10 | 5 | 517 |
| 75-70 | 378 | 41 | 17 | 55 | 13 | 5 | 3 | 512 |
| 80-75 | 393 | 59 | 34 | 116 | 16 | 20 | 3 | 641 |
| 85-80 | 459 | 61 | 29 | 129 | 16 | 43 | 19 | 756 |
| 90-85 | 386 | 102 | 72 | 117 | 57 | 63 | 85 | 882 |
| Totale | 6364 | 1509 | 812 | 737 | 312 | 268 | 142 | 10144 |
| Totale/PQI | 37,7 | 8,9 | 4,8 | 4,4 | 1,8 | 1,6 | 0,8 | 60,0 |
| Totale/PQI < 70% | 28,1 | 7,4 | 3,9 | 1,9 | 1,2 | 0,8 | 0,2 | 43,5 |
| Totale/PQI < 80% | 32,7 | 8,0 | 4,2 | 2,9 | 1,4 | 1,0 | 0,2 | 50,3 |

*Table 3 – Average voltage dips, originated at MV level, detected by PQI installed in bus-bars supplying MV networks operated with NI.*

Table 2 shows that the voltage dips:
- with residual voltage lower than 80% are about 77% of the total amount;
- with duration longer than 80 ms are about 46 per PQI;
- with duration between 80 and 200 ms are around 75% of the total amount.

Examining table 3 it can be observed that voltage dips in NI networks are about 60 per PQI i.e. 130% of those detected in NC networks.

Table 4 shows the comparison between the voltage dips, originated at MV level, detected by PQI installed in bus-bars and those reported in the Unipede reference table [2]. It is worth mention that, being 95th percentile figures, the data gathered from the PQI and relevant to duration longer than 1 s are not statistically valid and have not been shown. Moreover the Unipede figures are relevant to one year while PQI ones to 8 months (even if the missing months are not affected by "heavy" lightning strokes phenomena).

| | | Duration [s] | |
|---|---|---|---|
| Residual voltage [%] | MV neutral | 0.1-0.5 | 0.5-1 |
| 90-70 | NC | 43 | 8 |
| | NI | 28 | 18 |
| | Unipede | 68 | 12 |
| 70-40 | NC | 52 | 3 |
| | NI | 66 | 18 |
| | Unipede | 38 | 5 |
| 40-1 | NC | 32 | 4 |
| | NI | 41 | 5 |
| | Unipede | 20 | 4 |
| Total | NC | 128 | 15 |
| | NI | 134 | 41 |
| | Unipede | 126 | 21 |

*Table 4 -Comparison between voltage dips, originated at MV level, detected by PQI installed in bus-bars and those reported in the Unipede reference table*

The total number of voltage dips is comparable while the distribution of different depths is slight different.

## Voltage dips detected on MV/LV substations

Fig. 2 shows the number of voltage dips per PQI, as a function of their duration, comparing NI and NC networks.

In this case the data relevant to voltage dips with duration shorter than 80 ms are quite reliable (possible periods of NC networks operated with NI are not taken into account) and therefore have been shown.

The following considerations can be carried out:
- there is a strong correspondence between NI and NC networks when considering voltage dips with duration longer than 80 ms;
- the number of voltage dips with duration shorter than 60÷80 ms is about 50% of overall voltage dips detected.

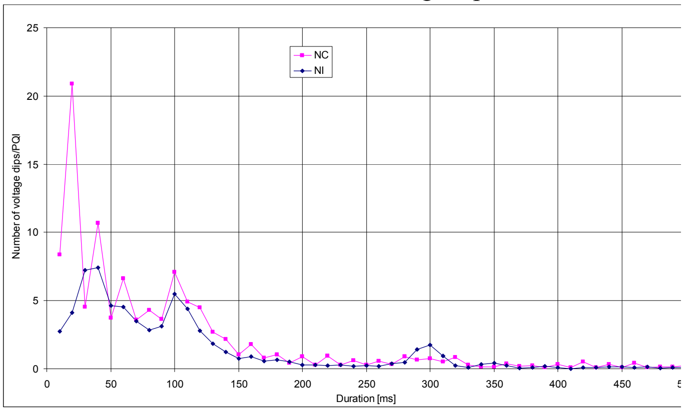


*Figure 2 - Number of voltage dips (per PQI) as a function of their duration*

Table 5 shows all the voltage dips originated at MV level, detected by the PQI installed on networks operated with NC.

The values relevant to PQI installed on networks operated with NI are shown in table 6.

| | Duration [ms] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Residual voltage [%] | 10-60 | 60-200 | 200-280 | 280-360 | 360-500 | 500-1000 | > 1000 | Total |
| 10-0 % | 9 | 11 | 8 | 1 | 3 | 1 | 0 | 33 |
| 20-10 % | 0 | 45 | 3 | 4 | 2 | 7 | 0 | 61 |
| 30-20 % | 3 | 66 | 5 | 3 | 6 | 2 | 0 | 85 |
| 40-30 % | 7 | 74 | 10 | 4 | 4 | 3 | 0 | 102 |
| 50-40 % | 6 | 104 | 14 | 7 | 3 | 2 | 0 | 136 |
| 60-50 % | 10 | 127 | 18 | 6 | 8 | 2 | 0 | 171 |
| 65-60 % | 13 | 95 | 23 | 1 | 3 | 0 | 0 | 135 |
| 70-65 % | 19 | 117 | 38 | 2 | 6 | 1 | 2 | 185 |
| 75-70 % | 29 | 111 | 53 | 2 | 6 | 1 | 0 | 202 |
| 80-75 % | 57 | 126 | 83 | 2 | 25 | 4 | 0 | 297 |
| 85-80 % | 110 | 158 | 142 | 6 | 37 | 8 | 9 | 470 |
| 89-85 % | 254 | 133 | 219 | 29 | 30 | 9 | 149 | 823 |
| 90-89 % | 1567 | 312 | 656 | 93 | 122 | 149 | 293 | 3192 |
| Total | 2084 | 1479 | 1272 | 160 | 255 | 189 | 453 | 5892 |
| Total/PQI | 63,2 | 44,8 | 38,5 | 4,8 | 7,7 | 5,7 | 13,7 | 178,5 |
| Total/PQI < 70% | 2,0 | 19,4 | 3,6 | 0,8 | 1,1 | 0,5 | 0,1 | 27,5 |
| Total/PQI < 80% | 4,6 | 26,5 | 7,7 | 1,0 | 2,0 | 0,7 | 0,1 | 42,6 |

*Table 5–Average voltage dips detected by PQI installed on MV/LV substations connected to NC networks*

| | Duration [ms] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Residual voltage [%] | 10-60 | 60-200 | 200-280 | 280-360 | 360-500 | 500-1000 | > 1000 | Total |
| 10-0 % | 16 | 26 | 5 | 3 | 2 | 2 | 0 | 54 |
| 20-10 % | 11 | 55 | 1 | 1 | 4 | 2 | 1 | 75 |
| 30-20 % | 3 | 75 | 4 | 4 | 8 | 3 | 1 | 98 |
| 40-30 % | 72 | 72 | 3 | 2 | 2 | 3 | 2 | 156 |
| 50-40 % | 318 | 124 | 5 | 5 | 3 | 2 | 0 | 457 |
| 60-50 % | 113 | 115 | 5 | 23 | 8 | 4 | 0 | 268 |
| 65-60 % | 37 | 71 | 1 | 29 | 1 | 1 | 2 | 142 |
| 70-65 % | 46 | 86 | 1 | 27 | 1 | 1 | 0 | 162 |
| 75-70 % | 53 | 97 | 8 | 27 | 6 | 6 | 1 | 198 |
| 80-75 % | 83 | 102 | 3 | 26 | 4 | 8 | 5 | 231 |
| 85-80 % | 150 | 142 | 9 | 36 | 3 | 7 | 12 | 359 |
| 89-85 % | 158 | 86 | 26 | 17 | 7 | 4 | 7 | 305 |
| 90-89 % | 74 | 49 | 26 | 10 | 7 | 7 | 8 | 181 |
| Total | 1134 | 1100 | 97 | 210 | 56 | 50 | 39 | 2686 |
| Total/PQI | 32,4 | 31,4 | 2,8 | 6,0 | 1,6 | 1,4 | 1,1 | 76,7 |
| Total/PQI < 70% | 17,6 | 17,8 | 0,7 | 2,7 | 0,8 | 0,5 | 0,2 | 40,3 |
| Total/PQI < 80% | 21,5 | 23,5 | 1,0 | 4,2 | 1,1 | 0,9 | 0,3 | 52,6 |

*Table 6–Average voltage dips detected by PQI installed on MV/LV substations connected to NI networks*

Tables 5 and 6 show a very high number of voltage dips with small depth, mostly on NC networks.

It is worthwhile to mention that 266 voltage dips detected by PQI installed in NC networks have residual voltage greater than 89% and 104 of them have been detected by only two PQI.

Therefore it has been decided to disregard the voltage dips with depth between 10 and 11%. Taking care of that, the number of voltage dips shorter than 60ms is 19% in NC networks and 41% in NI networks.

It is also to be noted that the values obtained can't be taken as a reference because they are influenced both by the small amount of data available and by temporary operation of NC networks with insulated neutral point. However, the number of voltage dips originated by MV/LV substations (owned by customers or DNO) is anyway not negligible.

The following considerations can be also carried out examining Tables 5 and 6:

- 85% (for NC networks) and 87% (for NI networks) of voltage dips have a duration shorter than 280 ms;
- the voltage dips with residual voltage lower than 80% are about 42 per PQI in NC networks and 52 per PQI in NI networks.

## Correlation between voltage dips and type of MV network

Taking care of what said in clause 2, table 7 shows that the number of voltage dips per PQI in the overhead networks is "only" between 125% (NI) and 150% (NC) with respect to cable ones. The possible causes are the following:

- In the overhead networks the contact between trees and lines, causing a phase to ground fault, likely doesn't evolve to cross country fault, with relevant voltage dip, due to the reduced insulation solicitation during arching faults;
- Faults in the MV/LV substations are, likely, the same for overhead and cable networks and form a basis that tends to reduce the difference.

| | N. dips>80 ms/PQI | | |
|---|---|---|---|
| | NI | NC | Difference NC-NI (%) |
| Overhead - Mixed | 70,6 | 51,2 | -27,5 |
| Cable | 56,7 | 32,7 | -42,3 |

*Table 7–Correlation between voltage dips and feeder topology (Overhead-Cable)*

Finally it is worth to note that the statistical sample of cable networks is not as significant as the overhead-mixed one.

## Correlation between voltage dips and the short circuit power at the MV busabar

Figure 3 shows that doesn't exist a significant correlation between voltage dips and the short circuit power (Scc) at the MV bus-bar.

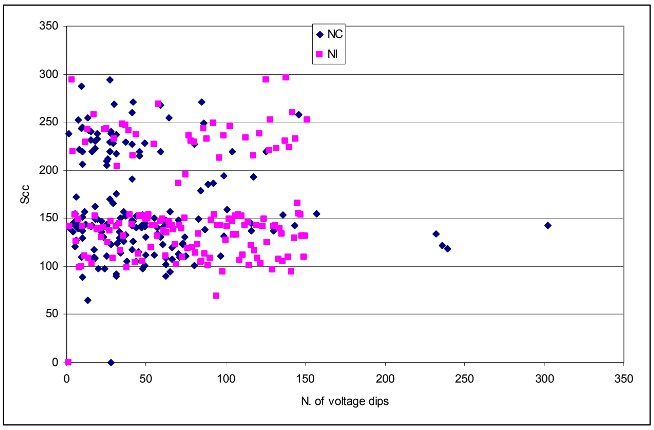


*Figure 3 - Correlation between voltage dips and the short circuit power (Scc) at the MV bus-bar*

## Correlation between voltage dips and lightning strokes

Voltage dips as a function of lightning strokes detected by SIRF are reported in Figure 4, showing a good correlation between the two quantities.

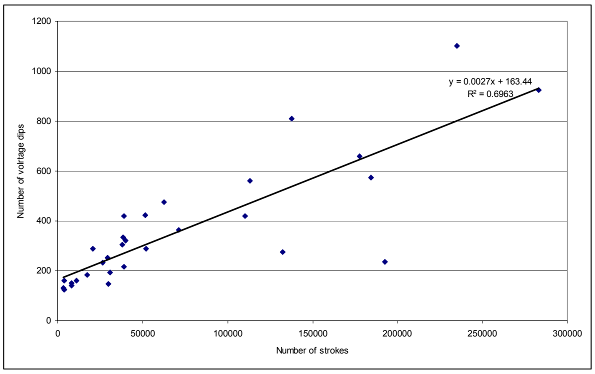


*Figure 4 - Correlation between voltage dips and lightning strokes*

## HARMONICS

The analysis of total harmonic voltage distortion showed that 95% of PQI registered a THDv lower than 3,3%.

Anyway the highest values of THDv, are below the limits foreseen by EN 50160.

There is not correlation between THDv and short circuit power (see Figure 5)

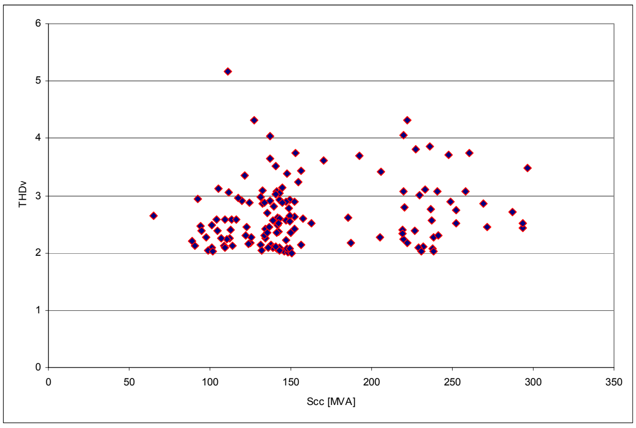


*Figure 5 : Correlation between THDv and short circuit power*

## FLICKER

The flicker analysis has been carried out evaluating the $P_{st}$ and $P_{lt}$ .

The following considerations can be done:
- 86% of PQI registered a Plt lower than 1 (the limit foreseen by EN 50160);
- 47 PQI registered a Plt in the range between 1.01 and 2.69. Nevertheless it is necessary to underline that the flicker's measure may be influenced by voltage dips. In fact the high flicker values are not due to real voltage fluctuations, but to the calculation process that takes into account also samples recorded during voltage dips [3];
- a significant correlation between Pst and Plt and the short circuit power (Scc) at the MV bus-bar doesn't exist.

## VOLTAGE UNBALANCE

The analyses carried out showed that the overall PQI registered a very low value of voltage unbalance (below 0,8%).

Significant correlation between voltage unbalance and the short circuit power (Scc) at the MV bus-bar doesn't exist.

## CONCLUSIONS

The first analysis of the data gathered by PQI installed on the ENEL MV network and made available by QUEEN software has been carried out with the aim to have a preliminary statistical picture of the voltage characteristics at that voltage level.

The main results, taking care of reliability of the data (see clause 2) are reported here after:
- voltage unbalance and total voltage harmonic distortion are well within limits of EN 50160;
- the flicker parameter $P_{lt}$ is greater than 1 (EN50160 limit) in the 14% of PQI. However it's worth noting that $P_{lt}$ evaluation is influenced by samples relevant to voltage dips;
- voltage dips coming from HV network are less than 9% of those coming from MV network and have a duration of 50÷150 ms;
- voltage dips per PQI coming from MV network and lasting more than 80 ms, are 46 and 60 respectively for PQI monitoring NC and NI networks;
- voltage dips coming from MV network and lasting less than 80 ms, detected by PQI installed on the MV/LV substation and therefore not affected by uncertainties experienced for those installed on the MV bus-bars are about 19% in NC networks and 42% in NI ones. This difference is likely due to inconsistency of the sample; nevertheless it shows a significant amount of voltage dips related to intervention of fuses used for protection of MV/LV substations of customers and DNO;
- the number of voltage dips detected in "cable" networks is about 66% of those relevant to "overhead" or "mixed" ones. This is due to natural protection of "cable" networks and to greater length "overhead" or "mixed" ones;
- the total number of voltage dips ($95^{th}$ percentile), with duration between 0.1 to 1 s, detected by PQI installed in bus-bars is comparable with the figure reported in the Unipede reference table while the distribution of different depths is slight different
- there is a good correlation between number of voltage dips and lightning strokes;
- short circuit power is not correlated to voltage dips, voltage harmonic distortion, flicker parameters and voltage unbalance.

## REFERENCES

[1] Villa, Porrino, Chiumeo, Malgarotti "The PQ monitoring of the MV network promoted by the Italian Regulator. Objectives, organization issues, 2006 statistics", CIRED 2007, paper 0042.

[2] Cenelec TR 50422 "Guide to the Application of the European Standard EN 50160", 2004

[3] Valtorta, Cerretti, Sartore, De Berardinis, Cugini, "Power quality analysis of MV networks supplying industrial areas in Italy ", CIRED 2007, paper 0647.