ASSESSING ITALIAN MV NETWORK PERFORMANCE: A DETAILED ANALYSIS OF SHORT CIRCUIT POWER LEVELS

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ABSTRACT

The Italian Regulator (Autorità per l'Energia Elettrica e Gas, hereinafter AEEG) promoted an analysis of the structure and the performances of distribution networks, both on HV (132/150 kV) and on MV levels. This paper is focused on the analysis of MV network structures: for the characterization of these networks, a large sample has been investigated by AEEG. About 400 MV primary busbars (i.e., MV busbars directly fed by a HV/MV transformer) out of about 4,000 MV primary busbars of the overall MV Italian system were selected. The data were requested by AEEG to Distributors: a huge sample of about 60,000 records (each of them representing a bus of a MV feeder, with the relevant information in terms of rated voltage, load connected, short circuit power etc) has been collected. These data allowed for the calculation of short-circuit power at all busses of the sample; the values obtained have been compared to minimum short-circuit power levels needed to guarantee a suitable performance of the MV network in case of transients (i.e. fast variations due to motor starting) in the customers' load.

INTRODUCTION

Power quality is attracting the attention of Regulators all over Europe [1]. Many voltage quality parameters (rapid voltage changes, flicker, harmonic voltages, unbalances, etc.) are strictly related to the short circuit power levels (S_{sc} in the following) available in the Point of Common Coupling (PCC). As a consequence, S_{sc} represents a meaningful parameter for ensuring suitable levels of power quality on distribution networks.

Without entering into more specific matters, the reasons why attention has been focused on S_{sc} with reference to power quality, can be found observing that voltage quality is obtained by minimizing (at any time and in any point of the network) the difference between the voltage supplied to customers and the ideal values (constant frequency and voltage, a perfectly sinusoidal waveform, etc.).

In fact, many factors can lead to differences from the ideal power supply conditions, such as:

a) variation of the operating conditions due to the variability of loads;
b) absorption of distorted currents through non-linear loads (harmonics) or through loads which vary rapidly and repeatedly in time (flicker);
c) abnormal operating conditions, due to random events (faults related to weather conditions).

By analyzing the above-mentioned phenomena, it is possible to notice that the quantitative correlation between the S_{sc} levels and the consequences of the phenomena described in c) (faults) is nor immediate nor univocal. However, such phenomena represent an example of a "pathology" affecting the electrical network, that is particular situations limited in time.

Just as complex is the punctual correlation between the S_{sc} levels and the consequences of the phenomena described in b) (distorting loads, i.e. loads characterized by a peculiar absorption). This is also due to the fact that the closeness of two or more distorting loads on the network can lead to global damages related to the S_{sc} value, but also strongly influenced by the interaction of two (or more) disturbing sources and by the impedance to different harmonics determined by all the network components (distribution network and customers).

On the contrary, it is appropriate (and technically feasible, as described in [2]) to correlate the variations in operating conditions due to the "ordinary" load variability (a) to the capacity of the network of facing such variability without an excessive diminution of the voltage value in the PCC. In fact, the variations of loads can be considered as independent events, thus allowing to correlate the requirements of each load to the S_{sc} level of the corresponding PCC, without taking into consideration the interaction between two or more loads.

For the above reasons, the AEEG has focused his attention on short circuit power as a possible synthetic indicator of network performance. The first step of the regulatory body was to acquire the knowledge of the minimum levels of short circuit power on the Italian transmission network. Resolution n. 250/04 has stated the publication of such values, that are available on TERNA (Italian TSO) website. As a consequence, the same values have been published also for the HV distribution networks.

The second step, described in this paper, regards the assessment of short circuit levels for MV networks. In this case, the number of busses of the whole MV network did not allow an exhaustive analysis: a huge sample was examined, and some semplifications were needed.

Minimum short-circuit power levels needed to assure a suitable performance of the network have been determined by AEEG, as described in [2]. To test the structure of the Italian MV networks with respect to these levels, the data of about 60,000 MV busses have been collected.

The paper describes the data collection process, and reports the most important results of the analysis.

Finally, some possibile regulatory addresses are presented.

DATA COLLECTION

The data sample chosen for this analysis by AEEG consists of about 60000 MV busses, belonging to the MV lines fed by about 400 MV primary busbars (i.e. busbars directly fed by a HV/MV transformer). As the overall MV Italian system consists of about 4000 MV primary busbars, the data collected are relevant to the 10% of the total Italian MV networks.

The primary busbars selected are the same equipped with the recently installed monitoring system (QUEEN, depicted in [3]). This will allow for some comparisons between the parameters selected for determining short-circuit power levels and the real behaviour of the network, i. e. rapid voltage changes (RVC) occurring in presence of fast load variations. RVCs are evaluated in terms of the maximum variation during the transient (ΔU_{max} according to the standard EN 61000-3-3).

The data were supplied from many distributing companies. ENEL Distribuzione is the most important distributing company in Italy: the records relevant to this company are about 50,000 on a total number of 60,000 records. The remaining data are relevant to other distributing companies, each of them serving more than 100,000 LV customers.

The data were collected by AEEG from Distributors, on the basis of a suitable protocol of acquisition.

Considering that every MV line can be considered as a radial structure, it is possible to define a procedure of acquisition based on the link between a bus and the relevant upstream bus, up to the primary busbars.

Therefore, the information relevant to every bus of interest of the MV network consisted in the data of Table I.

TABLE I

code of the bus (“*bus to*”);
name of the “*bus to*”;
type of the bus (“MV customer ”, “Mixed customer-transformer (MV/MV or MV/LV)”, “MV/LV Transformer”, “Primary MV busbar”, “MV/MV Transformer”)
code of the regulatory district of the bus [regulatory districts contain information used for continuity incentive regulation: three different classes of districts are given: low load density (L), medium (M) and high (H)]
nominal voltage (kV)
eventual declared voltage (only customer busses, kV)
contractual power (kW), or rated power (kVA) in case of transformers;
minimum short-circuit power declared ($S_{cc,dec}$, MVA)
presence of power quality monitor in the bus (Y/N);
code of the MV primary busbar feeding the bus;
code of the MV line to wich the bus is connected;
code of the first bus (“*bus from*”) upstream the examined bus (this bus is univocally determined given the radial structure of MV lines)
name of the “*bus from*”
type of connection between “*bus from*” and “*bus to*” (aerial cable, overhead line, underground cable, transformer);
for “transformer” type connections: short circuit voltage, losses, rated power
for “line” type connections: lenght (km), resistance (Ohm), reactance (Ohm).

With this information every bus is univocally described with respect to all other busses of the network.

DATA VALIDATION: NETWORK RECONSTRUCTION AND S_{SC} CALCULATION

The above described data were made available by each distributor in the form of an Excel table for each of the 400 primary MV busbars requested. All the records were gathered in an Access database, and some validation checks were performed, with the aim of minimizing possible errors in data.

Network topology reconstruction

In order to check the data collected, it was necessary to set-up a procedure for determining the (unique) path that connects every bus belonging to the types:

- “MV customer ”;
- “MV/LV Transformer”, and
- “Mixed customer-trasformer (MV/MV or MV/LV)”

with the relevant primary busbars.

Hereinafter, for the sake of simplicity, these three bus types will be referred to as “final busses”.

On the base of the acquired information (links between each “bus to” and the relevant “bus from”) it is possible to reconstruct the connection between a bus and the bus immediately upstream on the same MV line.

This step is repeated until the primary busbars are reached: in this way, it is possibile to determine the topology of the part of MV network fed by each HV/MV transformer.

Calculation of S_{SC}

The same topology reconstruction procedure provides the data for calculating the values of S_{sc} at every final bus. In particular (see fig. 1) at each step *i* of the reconstruction procedure a contribution Z_i to the total impedance exixsting between the final bus studied (A) and the primary busbars (PB) is found. At the end of the procedure, all contributions are summed and the total impedance (final bus-primary busbars) is found (ΣZ_i). In the same fig. 1, Z_{HV} represents the totale impedance of the HV network and of the HV/MV transformer; such value is reconstructed on the base of the short circuit power declared by the Distributors at the primary busbars ($S_{sc,dec}$).

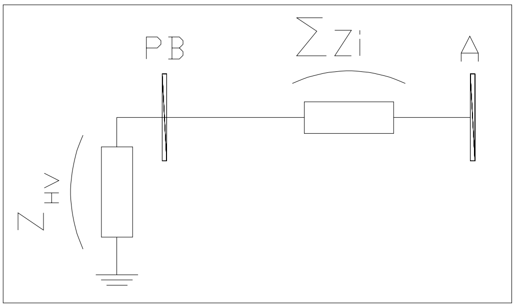

Fig 1: equivalent circuit for calculating S_{sc} at every final bus.

The values of $S_{sc,dec}$ given by distributors have been validated with the values obtained on the base of the topology reconstructed from the database and of the values (resistance, reactance) given for every connection.

MINIMUM SHORT CIRCUIT POWER LEVELS

The values of $S_{sc,dec}$ at every bus of the sample have been compared with the S_{sc} levels defined on the base of a procedure described in the following, and reported in details in [2].

For a MV distribution system it is possible to characterize two macro-categories of busses which directly feed a load:

1. MV customers;
2. MV/LV transformers owned by the Distributor.

To characterize both bus classes in terms of power available at the bus, for the first class of busses (which groups also "Mixed customer-transformer" busses), the contractual power is chosen (S_{cust}, corresponding to the contractual power of the customer expressed in MVA), while in case of MV/LV transformers, the rated power of the transformer is chosen (S_{trans}).

On the base of an empirical rule it has been assumed that the load at every bus (both classes 1 and 2) can show a fast variation of the consumed power ΔS_{cust}; this variation is related to S_{cust} (S_{trans}) by a coefficient $K_{t,cust}$ ($K_{t,trans}$) given by the following formulas (see [2] for further details):

$$K_{t,cust} = 2 \Big/ \sqrt{S_{cust}} \,. \tag{1}$$

$$K_{t,trans} = 1{,}3 \Big/ \sqrt{S_{trans}} \,. \tag{2}$$

Equations (1), (2) and the following (5)..(8) are empirically based and are consistent in terms of dimensions only considering that apparent power is divided by 1 MVA.

While (1) applies to MV customers, (2) is valid to determine the maximum fast variation to be expected in the load fed by a MV/LV transformer (owned by the distributor) with a rated power of S_{trans} MVA.

For example, the value of $K_{t,cust}$ for a MV customer with a contractual power of 1 MW is equal to 2: it means that the maximum fast variation of the load expected in that bus is 2 MVA. In other words, it is assumed that the load of this customer is made up of several induction motors, none of them exceeding a rated power of 400 kW. In case of motor starting, it is reasonable to assume that each motor will absorb a current equal to 5 times its rated value, leading to a load variation ΔS_{cust} equal to 2 MVA, with a suitable power factor (of course, it is assumed that the contemporary starting of different motors is not permitted). In this condition, it can be calculated that the RVC within the customer plant (given the standard parameters of transformers) reaches about 12-15%: a voltage drop on the distribution network exceeding 5% could lead to a non acceptable value of the voltage at the motor terminals (<80%).

The following simplified relationships between the load variation at a given bus, the short-circuit power at the same bus and the RVC change occurring are then defined:

$$\frac{\Delta U_{net}}{U_n} = \Delta u_{net} = \frac{\Delta S_{cust}}{S_{sc,net}} = \frac{K_{t,cust} S_{cust}}{S_{sc,net}} \tag{3}$$

$$\frac{\Delta U_{net}}{U_n} = \Delta u_{net} = \frac{\Delta S_{trans}}{S_{sc,net}} = \frac{K_{t,trans} S_{trans}}{S_{sc,net}} \tag{4}$$

In (3) and (4), valid respectively for MV customers and MV/LV transformers, Δu_{net} is the RVC (expressed in per unit) occurring in the PCC in case the load varies according to the relevant coefficient K_t.

Once a limit for RVC Δu_{lim} is defined, the level of S_{sc} needed at any bus is given by:

$$S_{sc,net} = 2 \cdot \frac{\sqrt{S_{cust}}}{\Delta u_{\lim}} \tag{5}$$

$$S_{sc,net} = 1{,}3 \cdot \frac{\sqrt{S_{trans}}}{\Delta u_{\lim}} \tag{6}$$

According to the above considerations, the value of Δu_{lim} was chosen equal to 5% (0,05 p.u.), coming to the following equations:

$$S_{sc,net,5} = 40 \cdot \sqrt{S_{cust}} \tag{7}$$

$$S_{sc,net,5} = 26 \cdot \sqrt{S_{trans}} \tag{8}$$

As a consequence, every record in the database (relevant to a bus which directly feeds a load) was completed with an additional cell containing the value of $S_{sc,net,5}$. (i.e., the level of S_{sc} needed at any bus to limit the RVC at a value <5%).

Given the value of $S_{cc,dec}$ at every customer bus, it is possible to define an indicator ΔPMA (difference in Power Made Available) that:

- in case $S_{sc,dec} < S_{sc,net,5}$, measures the amount of power made available at the bus exceeding the rule depicted by (7);
- in case $S_{sc,dec} > S_{sc,net,5}$, measures the amount of further power that can be made available at the bus according to the rule depicted by (7).

For customer busses, ΔPMA is given by:

$$\Delta PMA_{cust} = \left(\frac{S_{sc,dec}}{2} \cdot \Delta u_{\lim} \right)^2 - S_{cust} = S_{cust,dec} - S_{cust} \tag{9}$$

where $S_{cust,dec}$ is the amount of power that can be made available at the bus while assuring the network performance above described.

The same indicator can be defined for busses feeding MV/LV transformers, according to (4):

$$\Delta PMA_{trans} = \left(\frac{S_{sc,dec}}{1{,}3} \cdot \Delta u_{\lim} \right)^2 - S_{trans} = S_{trans,dec} - S_{trans} \tag{10}$$

Figure 2 shows graphically the meaning of ΔPMA_{cust} in the case of negative values, that is the most important from a regulatory point of view: in fact, it represents cases in which the power made available at the bus could lead to an insufficient performance of the network.

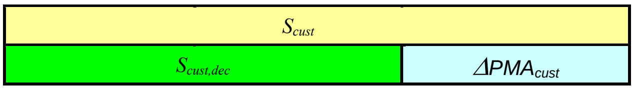

Fig. 2: comparison between S_{cust} and $S_{cust,dec}$ in case of $\Delta PMA_{cust} < 0$

RESULTS

The above described procedure for determining $S_{sc,net}$ has been applied using two different values for Δu_{lim}, namely 5% and 3%. The comparison between values declared by Distributors ($S_{sc,dec}$) and the values calculated with the above depicted criterion ($S_{sc,net,5}$, $S_{sc,net,3}$) led to some interesting results.

In the following, only the results relevant to MV customers are presented: MV/LV transformers have shown minor problems to this regard. As for MV customers, on a total number of 7112 busses examined, 133 were found not complying with the above criterion applied using Δu_{lim}= 5% (about 1,87 %). Using Δu_{lim}= 3%, customer busses non complying were 503 (about 7,07 %).

Figure 3 reports the number of customer busses non complying with the criterion given (i.e., with $S_{sc,dec} < S_{sc,net}$) divided according to five classes of contractual power.

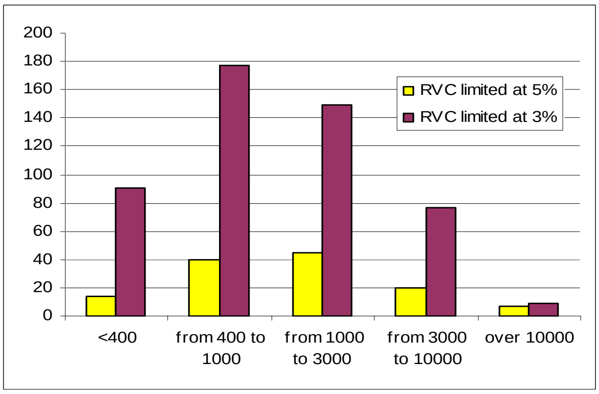

Fig. 3: number of customer busses with $S_{sc,dec} < S_{sc,net}$ per class of contractual power.

The MV customer exceeding a contractual power of 10 MW (seven cases for Δu_{lim}= 5%, ranging from 10 up to 25 MW) were excluded in the successive analysis.

In fact, according to the connection rules for HV and MV [4] recently published by AEEG, the upper limit for connecting a customer to a MV grid is 10 MW. As a consequence, the presence of customers already connected to MV grids with a contractual power exceeding 10 MW does not influence the possible regulation of minimum S_{sc} levels. Focusing the attention on the remaining busses, table II reports the number of MV customers studied in the sample divided in classes of contractual power, along with the number of customer busses with $\Delta PMA_{cust} < 0$, and with the relevant percentage.

TABLE II

	S_{cust} [kVA]	<= 400	> 400 <= 1000	> 1000 <= 3000	> 3000 <=10000
Δu_{lim}	# Customers	4479	1851	641	129
3%	# Cust. with $\Delta PMA_{cust} < 0$	91	177	149	77
	% incidence	2,03	9,56	23,24	59,68
5%	# Cust. with $\Delta PMA_{cust} < 0$	15	41	48	22
	% incidence	0,33	2,21	7,49	17,05

As shown in the table, the number of busses not complying with the S_{sc} requirements is higher for customers of huge dimensions. In particular, in case Δu_{lim}= 5%, about 8% of customer busses with power ranging from 1000 to 3000 kVA have a value of $S_{sc,dec}$ that does not limit RVC under the given value. The situation is even worse for customer busses with power ranging from 3000 to 10000 kVA (about 17%).

Considering Δu_{lim}= 5%, Table III reports the number of busses not complying with the given criterion divided by regulatory districts' class.

TABLE III

Districts' class	L (rural)	M (suburban)	H (urban)
# MV Customers	1958	4006	1236
# Customers with $\Delta PMA_{cust} < 0$	75	46	5
% incidence	3,83	1,15	0,40

It can be stated that busses not complying with the rules given are essentially in low and medium load density districts: only 5 out of 126 are in high density districts.

Finally, Table IV reports the average contractual power for each class, along with the average power exceeding the given criterion.

TABLE IV

S_{cust} [kVA]	<= 400	> 400 <= 1000	> 1000 <= 3000	> 3000 <= 10000
# Customers	4479	1851	641	129
# Customers with $\Delta PMA_{cust} < 0$	15	41	48	22
Average contractual power	263	694	2062	4352
Average ΔPMA_{cust}	69	259	808	1519
%	26.23	37.32	39.18	34.90

CONCLUSIONS AND FUTURE WORK

The above-described research shows that relatively simple functions allow to evaluate the adequateness of the minimum levels of short circuit power in order to fulfill given parameters of power quality. As such research has been based on theoretical considerations and studies, it is necessary to find evidence about the assumptions adopted, especially regarding the parameters K_t of characterization for the fast load variations by customers.

As the primary busses considered in the sample are all equipped with a monitoring system, it will be possible to measure on-field RVCs occurring in case of fast load variations. Such measurements should allow to correlate the levels (calculated) of short circuit power to the other parameters related to power quality, in particular to the depth oh RVCs on the same busses, in order to evaluate the assumptions by which K_t and the corresponding levels of short circuit power have been determined. As far as now, the values of such parameters must be intended as approximations, to be proven by field research.

While waiting for such evaluations, it is possible to outline some developments of the technical and economic regulations related to short circuit power levels.

An important element of transparency with regards to short circuit power concerns the connection procedures. According to the ongoing elaboration of technical regulations about connection on HV and MV distribution networks by the working group CEI 136 [4], the distributor must provide the MV connection customers with the minimum operating value (calculated) of the short circuit power.

A further level of intervention, concerning technical rules about connections, could be the introduction of different reference levels of short circuit power depending on the contractual power. If the network situation does not allow the accomplishment of reference levels, a measurement campaign should be carried out on the connection site, in order to check if distortions and rapid voltage changes require a further intervention. On the other hand, if the reference values were respected, the customer should limit his emissions with reference to the THD and flicker values established by the technical regulations, or, if not able, should remunerate directly the investments made to increase the short circuit power.

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