POWER FLOWS IN THE ITALIAN DISTRIBUTION ELECTRIC SYSTEM WITH DISPERSED GENERATION

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ABSTRACT

Nowadays, and in the next future, the increase of the Dispersed Generation (DG) will alter significantly the operation of distribution networks. The attention is focused here on the HV/MV interface, where an inversion of power flow on the HV/MV transformer feeding the MV network, can take place as a consequence of the DG increase.
This particular condition has not been considered so far in the design of the electric protection devices of the HV/MV substations and can lead to critical situations.
For the purposes of this paper, the time percentage when the MV network injects power into the HV (transmission or subtransmission) network is assumed as a possible indicator of the "active" behavior of MV networks.
The proposed research focuses on the analysis of the degree of DG penetration capable to lead to such an inverse power flow: the aim is to point out how much DG can be connected to the MV electric distribution networks assuming to accept a predefined threshold, in terms of yearly hours, of Inverse Power Flow (IPF).

INTRODUCTION

Worldwide the introduction of Dispersed Generation (DG) in the distribution networks is assuming a significant importance. DG allows the improvement of the energy production process efficiency, along with the exploitation of the renewable resources. The technology evolution made available very interesting solutions for the exploitation of the renewable energy (solar energy, biogas, biomass, etc.), or for a more efficient energy conversion (microturbines, high-efficiency cogeneration plants, etc), with "domestic" rated powers. This evolution made it possible to spread a series of small dispersed generators, capable of fully exploiting the resource locally available.
The integration of DG in the electric distribution network requires a revision of this infrastructure and of its protection and control devices, so far designed and developed assuming that power flows in one direction (from the transmission/subtransmission network to the distribution network) to reach final customers connected to the low voltage (LV) network. In fact the presence of DG on the distribution network may cause an Inverse Power Flow (IPF), i.e. a flow from a medium voltage (MV) network to the high voltage (HV) network.
The work here presented is aimed to evaluate the presence of an IPF in the distribution networks w.r.t. the amount of DG connected to the network. The analysis exploited a detailed data set of the Italian MV network, available thanks to a previous research performed in collaboration with the Italian Regulator. A sample of about the 6% of the whole of the Italian MV networks [1], corresponding to 256 specific distribution networks, hereinafter referred to as Network Data Set (NDS), has been used for this study.
In order to estimate the network load in different time periods, an algorithm based on the cumulated load curves has been developed. Starting from public data about the hourly consumption curves of the overall national load and of the LV customers, the hourly consumption chronological curves for the MV and LV loads at national level are computed. From these curves, the correspondent hourly consumption cumulated curves are built. As a next step, each hourly cumulated curve is aggregated in 60 steps, each one representative of 146 operating hours. The two aggregated load curves thus obtained are used to estimate the cumulated consumption curve of each of the 256 distribution networks. Suitable assumptions, consistent with the Italian DNOs (Distribution Network Operators) practice, are made in order to determine the loads factor of usage and the loads coincidence factor.
The developed procedure yields to 60 load scenarios for each specific network: the maximum DG power injectable in each network of the NDS is computed assuming the occurrence of an IPF for a predefined percentage of yearly hours. For example, 5, 10, 15% thresholds are tested.
The results obtained will be useful for a better definition (for example, for regulatory purposes) of the acceptable amount of DG that can be installed in each distribution network before incurring in the IPF and, therefore, in the costs related to the necessary updating of the HV/MV substations, in terms of electric protection devices and of operation logics.

THE NETWORKS DATA SET OF THE ITALIAN DISTRIBUTION GRID

The model adopted for this paper is derived from a large data set of the Italian MV network, consisting of about 60,000 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 4,000 MV primary busbars, the data set covers the 10% of the Italian MV networks [1]. The largest part of the data set (about 85%) was contributed by ENEL Distribuzione, the most important distribution company in Italy. The remaining part comes from other Italian

distributing companies, each of them serving more than 100,000 LV customers. The primary busbars included in the data set are the same equipped with the QUEEN monitoring system, promoted by the Italian Regulator [2]. This will allow some comparisons between the simulation and the real behavior of the network.
Since the Italian MV networks have a radial structure, for the aim of this study the data set was structured as a set of separate networks each of them including the HV/MV transformer, the MV busbar, and the feeders. An example of MV network is represented in Figure 1.

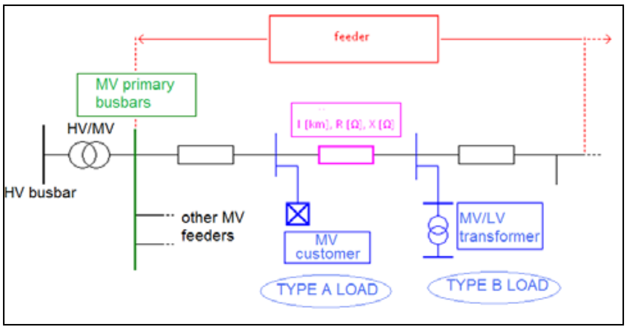


Figure 1: example of one of the 256 MV networks of the sample, with an explicit representation of one feeder

In turn, each feeder includes the loads (MV customers and MV/LV substations) connected to it. For each local network the electrical information of its components and branches are available, as well as its topological structure (see Fig. 1).
For the aim of this paper, a set of 256 MV networks, was included in the NDS; this set covers about the 6% of the Italian MV networks.

YEARLY LOAD DEFINITION

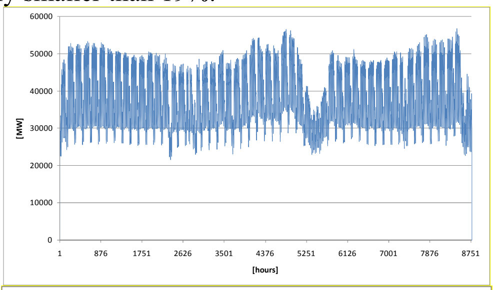
An important pre-requisite for the IPF analysis is the availability of the yearly load profile of each load connected to the network.
As depicted in Figure 1, loads included in NDS belong to two types:

- MV customers, for which the contractual power is given (type A loads);
- MV/LV transformers (secondary transformers, hold by distributors) for which the rated power is given (type B loads).

Theoretically, to give an exhaustive representation of the hourly consumption chronological curves of each network, the introduction of as many hourly load profiles as the number of loads would be necessary.
The correct definition of the consumption profiles for each specific load is a hard task, as they are highly influenced by the geographical location of the load, the season of the year, the type of the load (industrial, commercial, domestic), and so on. To overcome this difficulty, an approximated approach is adopted, based on public available data.

LOAD PROFILES

The Italian TSO (TERNA) is responsible for collecting, elaborating and publishing the national consumption data. For the present study the hourly overall national demand for one year in used [3]. Figure 2 represents the overall national for the year 2007.
It has been supposed that the HV customers consumption profile is similar to the overall demand one. According to this assumption, the overall power flowing in the MV grids (i.e. the sum of the load of LV and MV customers), is computed by scaling down the overall nation demand provided by TERNA of a the same quantity for all the hours of the year, in such a way as the annual reduction accounts for the consumption of the HV customers. For instance, in 2007, the overall national consumption of LV and MV loads was 244 TWh, while the consumption of the HV users was 56 TWh: as a result, the above coefficient is slightly smaller than 19%.



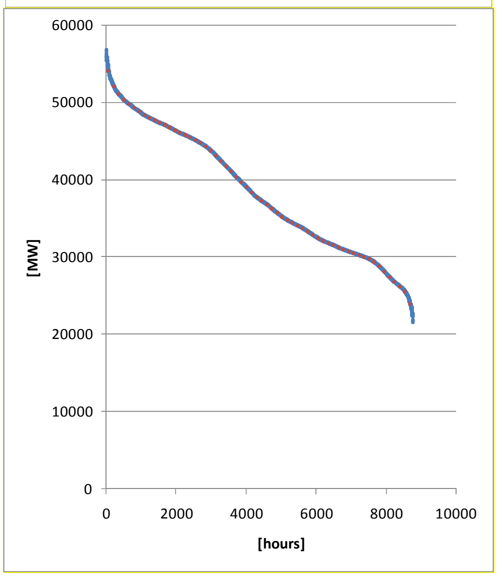


Figure 2: Chronological and Cumulated load curve (load demand [MW] vs. time [hours]) for the Italian electric system in 2007

On July 1st 2007 the Italian electricity market was completely liberalized; in this context the Single Buyer provides the so called universal service [4] mainly to domestic customers and LV small enterprises not yet served by a trader, with an energy tariff is defined by the Regulator [5]. Since most of the LV customers have not chosen a trader yet, in the present work the load served by the Single Buyer is used as a proxy of the load on the LV network. This is an approximation as the Single Buyer serves also minor share of MV industrial customers (up to October 2008 the Single Buyer acted also a supplier of last resort for MV customers without a trader). Nonetheless this is the best estimation of the load on the LV network, given the data publicly available in the Italian framework.

As such, the consumption data served by the Single Buyer in 2007 have been exploited to build the hourly consumption chronological curve of the LV load. The hourly values of this curve are then chronologically subtracted from the hourly consumption curve of the overall national load in the same period[1] thus obtaining the estimated hourly consumption curve of the MV load.

The hourly consumption chronological curves of the MV and LV load are transformed into the correspondent hourly cumulated curves. The 8760 values of each cumulated curve are then aggregated into 60 intervals of 146 hours each. The aggregation is needed to speed up the computation due to the large amount of data of the sample adopted. The load value of each interval is the mean of the 146 hourly load values included in the interval.

Figure 3 represents with a blue/green (solid) line the hourly consumption cumulated profiles of the MV and LV loads and with red points the aggregated profiles (60 values for each hourly curve), showing a good correspondence of the two data sets. The profiles are given in p.u. of the peak load.

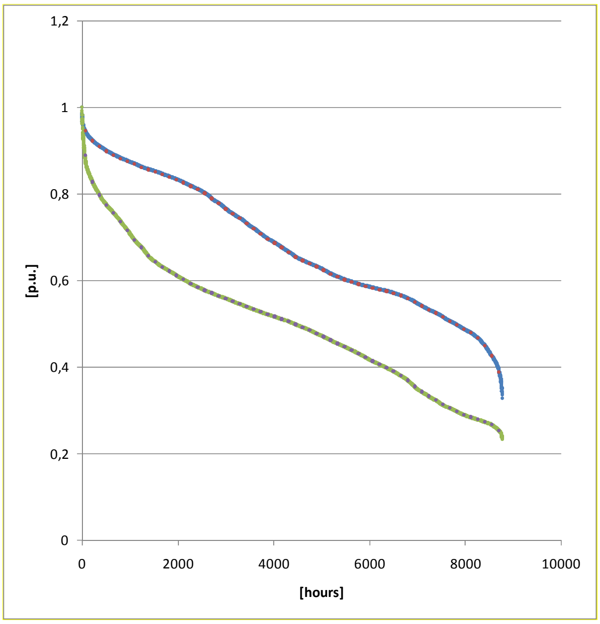


Figure 3: Cumulated MV (blue – higher curve) and LV (green – lower curve) load profiles (in [p.u.] vs. time [hours]) for the Italian electric system in 2007

The aggregated consumption profiles of the MV and LV load are then used to define the load curve of each load bus of the network. In particular the punctual MV value of each load for peak hours is defined according to the load and network main features; the 60 samples are only used to modulate the load curve during the year.

Load value definition – procedure 1

For the definition of the hourly loads, two procedures are developed, both relying on the aggregated curves reported in Figure 3. The procedures are developed according to different hypothesis: the comparison between the results obtained will be used as a validation.. The first procedure is based on the contractual power of each load, i.e. the maximum power the load can consume according to the commercial agreement with the DNO. For each network, the contractual power of its MV loads (type A loads) is summed up to obtain the theoretical peak load condition of the MV loads, i.e. the load condition when all the MV customers contemporary withdraw their contractual power from the network. For MV/LV loads (type B loads) the same procedure is adopted, based on the MV/LV transformer rated power.

Eventually, the theoretical peak load value resulting from the procedure above (summing up the theoretical peak load of the type A and type B loads) is reduced to get the real peak load value of that network. This is done considering that in the Italian DNOs practice the HV/MV transformer is typically operated, in the peak load condition, at about 60% of its rated power (usually in each HV/MV substation two transformers of the same size are installed: the usage coefficient is compliant with the N-1 security criterion, considering a temporary overload acceptable, thanks to forced air cooling). In particular for each network a suitable coefficient (k) is calculated as the ratio between the 60% of the HV/MV transformer nominal power and the theoretical peak load. If $k \geq 1$, the theoretical peak load is assumed to be the real peak load; if $k<1$, 60% of the transformer nominal power is assumed as the effective peak load, thus multiplying by k all the loads in the network.

As depicted in Figure 4, some networks show the k coefficient equal to 1; as this condition is deemed to be unrealistic (this would mean that all the loads are contemporary at their full power), in the present work the k coefficient is capped to 0,8. The networks with k coefficient greater than 0,8 are those not completely developed yet, i.e. the new networks with a HV/MV transformer not yet exploited.

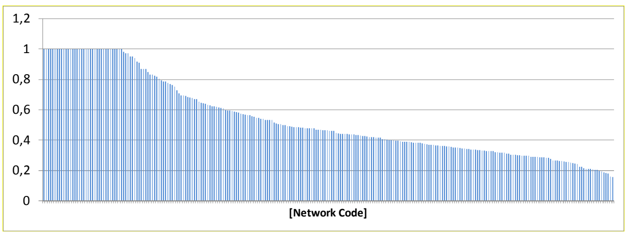


Figure 4: k value for all the network in the NDS (procedure 1)

Once the real peak load is defined, the other 59 load values are generated by scaling down the real peak load according to the cumulated curve coefficients depicted in Figure 3.

To validate the developed procedure, a comparison between the energy consumption of the NDS and the overall energy

[1] Downscaled by the coefficient accounting for the HV consumptions computed above.

consumption in the Italian MV network is performed. The latter for the year 2007 is about 245 TWh [6]; as the networks included in the NDS are the 6.86% of the MV Italian network, keeping the same proportion for the delivered energy, the annual consumption of the NDS would be 16.82 TWh. The sum of the rated power of the HV/MV transformers in the whole Italian power system can be estimated in about 103 GVA [5]; while in the NDS is equal to 6,600 MVA, i.e. the 6.43% of the national value. This analysis validates the approach adopted to define the load profiles: the energy delivered by the NDS turns out to be consistent with the national consumption. To be more precise the NDS delivers just a little more than the national percentage (i.e. the simulated networks are, in terms of average value, a little more loaded).

Load value definition – Procedure 2

The second approach for the definition of the load curves in NDS starts from the data relevant to the national energy consumption of MV and LV loads (respectively 106 TWh and 138 TWh [6]). As stated above, the NDS represent the 6.43% of the Italian HV/MV transformation capacity: applying this ratio to the national MV and LV load, the total $Energy^{MV}$ and $Energy^{LV}$ respectively delivered by NDS in the MV and LV networks are obtained.

Given the yearly load profile of the MV and LV loads ($load_{profile_i}^{LV}$ and $load_{profile_i}^{MV}$ as derived from Figure 4), the contractual power of each MV load ($Load^{MV}$ derived from the data sample) and the MV/LV transformer rated power ($Load^{LV}$, assumed relevant to estimate the LV networks withdrawals from the MV network), the following equations can be written:

$$Energy^{LV} = \sum_{i=1}^{60} k^{LV} * Load^{LV} * time\ step * load\ profile_i^{LV}$$

$$Energy^{MV} = \sum_{i=1}^{60} k^{MV} * Load^{MV} * time\ step * load\ profile_i^{MV}$$

where

- k^{MV} and k^{LV} represents either the usage factor and the coincidence factor of the loads;
- *time step* is equal to 146, representing the number of hours associated to each load profile.

By the mean of an iterative procedure, the coefficients k^{MV} and k^{LV} are computed: the results are $k^{LV} = 0.64$ and $k^{MV} = 0.27$, to be compared with the coefficient k previously calculated by the procedure 1 (see Figure 4).

POWER FLOWS AND DISPERSED GENERATION

The NDS, together with the relevant load curves built with the procedure described in the previous section, is the starting point to analyze the issues related to a high penetration of DG on the MV distribution networks.

A possible indicator to determine an abnormal quantity of DG on a network is the IPF on the HV/MV transformer. It is well known that, in the current distribution networks, the HV/MV interfaces are developed assuming that power flows in one direction (from HV to MV); as a consequence, the electric protection system and network automation are designed and operated accordingly.

Nowadays about the 15% of the Italian MV distribution networks reaches, in some particular conditions, an IPF condition [7]. The recently issued Italian standard for the connection of users to MV networks (CEI 0-16 [8]) suggests an acceptable limit for the IPF working condition equal to the 5% of yearly hours[2].

As a first step, this paper evaluates the correlation between the DG installed on a network and the yearly hours with an IPF: this analysis allows us to quantify how much DG can be connected to the electric distribution networks without exceeding a IPF threshold defined in terms of maximum yearly hours.

This information can be useful to better define the acceptable amount of DG power that can be installed in each MV network before incurring in the investments related to the improvement of the HV/MV interfaces.

Table 1 reports the IPF results for the NDS. For this analysis, the significant parameter is the hourly total power generated by the DG, while the number of generators effectively connected to the network can be neglected. For each IPF threshold (5%, 10%, 15%, 20% of yearly hours), the second row contains the maximum energy that can be produced by the generators connected to all the networks of the NDS without violating the defined threshold.

To convert these data in terms of rated power of generators connected, some hypotheses on the coincidence factors and the usage factors of each generator are required.

The worst case is the one in which all the generators are operated at their rated power; in this very conservative assumption the average GD accepted in each network of the NDS is reported in the third row. Both the procedures adopted for building up the network load curves are considered: the differences on the mean results are negligible.

PROCEDURE 1				
Threshold [%] of accepted IPF	20%	15%	10%	5%
GD installed [MW]	1422	1325	1243	1181
Average GD on each network [MW]	5,4	5,0	4,7	4,5
PROCEDURE 2				
Threshold [%] of accepted IPF	20%	15%	10%	5%
GD installed [MW]	1438	1348	1268	1206
Average GD on each network [MW]	5,4	5,1	4,8	4,6

Table 1: DG penetration vs. IPF accepted

Finally Figure 5 depicts the detail of the maximum rated power of the generators that can be connected to each network of the NDS with an IPF threshold equal to 5%.

2 Above this threshold, the same standard suggests that an improvement of substation infrastructures is necessary.

Each bar represents the percentage of the networks that can accomodate the relevant amount of DG without violating the constraint of an IPF threshold equal to 5%.
The results depict a different distribution of the acceptable DG w.r.t the IPF limit: the procedure adopted for the load curves definition has a direct influence on the amount of DG connected on each network into analysis.

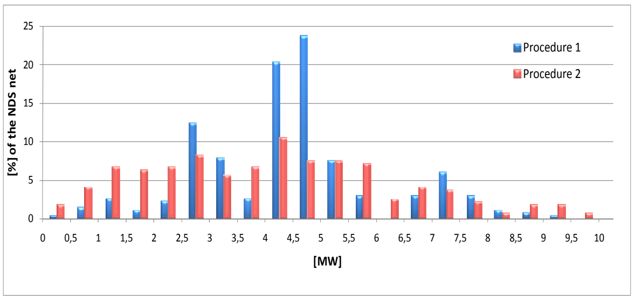


Figure 5: Dispersed generation that can be connected on each net allowing an inverse power flow in the 5% hours a year

If average values are considered, looking at the whole NDS (table 1), the results are quite similar between procedure 1 and procedure 2. It can be concluded that the two algorithms introduced are not suited for capturing the particular characteristics of each network; on the other hand, the results related to the NDS mean behavior (table 1) are not influenced by the procedure adopted. This makes the latter results useful for considering the opportunity of overcoming the issues related to IPF.

TECHNICAL REMARKS

In order to overcome the critical issues related to IPF condition the installation of adequate protection devices in the HV/MV power stations is needed. The possible critical conditions that deserve particular attention are:

1) loss of synchronism between the HV and the MV networks subsequent to the islanding of the whole MV distribution network (in presence of DG feeding all the load - IPF - the MV distribution network can operate isolated from the HV system);
2) presence of a fault on the HV side of the HV/MV transformer fed by the DG installed on the MV network.

To correctly manage these particular conditions, dedicated protections and automation devices nowadays not installed in the HV/MV Italian substations are needed. In particular, to protect the electric networks against the risk of a condition of type 1), a synchro-check device is required on the HV circuit breakers (provided that the islanded operation of a whole MV network is accepted).
To deal with the problem of point 2) it is necessary to install a zero-sequence maximum voltage relay on the HV busbar (with the relevant PTs, if needed).
Moreover the HV circuit breaker has to manage the interruption and the automatic reclosing for both multi-phase and single-phase switching.
The costs of updating protection devices (and possibly circuit breakers) can be roughly estimated in 50-250 k€ for each HV-MV substation. These figures are strongly dependent on the HV/MV substation current configuration (f.i, AIS or GIS). These costs are borne by the DNO and eventually included in the distribution tariff established by the Regulator and paid by the network users.

CONCLUSIONS

The aim of the present work is to analyze the power flows on the HV/MV interfaces over a time horizon of a "standard" year, in order to evaluate the occurrence of IPF situations.
The maximum amount of DG that can be connected to each MV network, without incurring in the investments related to the improvement of the HV/MV interfaces, is estimated. Different IPF thresholds are considered: the results, related to a large network sample representing about the 6% of the Italian MV networks, shows that the average amount of DG that can be installed on the MV networks without requiring any improvement (IPF threshold equal to 5%) is about 4,5 MW. A higher amount may induce more frequent IPFs making necessary to review the protection devices and logics installed on HV/MV interfaces and to bear the associated costs.
It has to be highlighted that some incentives for DNOs in order to allow a high penetration of DG in Italian MV networks are already in place (Order 348/07, [5]).

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