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Containment of power losses in LV networks with high penetration of distributed generation

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Abstract: Power losses and their regulation is a key issue in modern electrical systems, especially in distribution networks. In the last few years, the number of distributed energy resources has grown dramatically, emphasising the importance of knowing in detail the operating conditions and the efficiency of low–voltage (LV) and medium-voltage (MV) networks. In particular, LV systems are often unbalanced networks experiencing a significant neutral current. This aspect could become more and more critical considering the distributed generation and its daily profile in comparison with the load typical time trend. The present regulatory prescriptions and rules for the connection of generators in the Italian context are discussed and then applied to a real LV case study network. Several scenarios are considered to analyse how distributed generators connection options and reactive power management strategies have influence on network losses.

1 Introduction

Power losses are inherently associated with the transmission and distribution of electric power. A traditionally adopted criterion for minimising such losses in distribution networks is the containment of the reactive power absorbed by end-users, through stringent limitations (and penalties) on the minimum allowed power factor (PF) (frequently evaluated as mean value in the bill period). This kind of regulation, with possible national variants, is enforced in the majority of the countries. The PF management has a great influence on both MV and LV network power losses, as well as on voltage profiles along MV distribution lines (especially overhead ones).

There is a serious concern whether this type of regulation, rightful in a passive or slightly active distribution network, would still be suitable in networks with high penetration of distributed generators (DGs) [1]. Consequently, nowadays the PF management for active users is requiring different rules, since the previous statement is no longer valid. The scenario is further complicated considering that the most recent National and International Grid Connection Rules (see for instance [2, 3]) impose DGs and storage systems to participate in the network voltage regulation by modulating their reactive power injection, with possible consequences on the loss-of-main protection effectiveness [4, 5].

Taking as reference the Italian context, which is one of the most advanced regulation frameworks for DGs connection in MV and LV networks, a real LV system is considered as a case study to investigate the effects of different DGs connection options (i.e. three- or single-phase, connection along existing feeders or through dedicated lines, etc.). Indeed, considering that the distribution system operator (DSO) is required to accept all the requests of connection by DGs in the distribution network, this paper evaluates the effects on losses of different DG connection scenarios.

The need of a more detailed knowledge of the distribution system (especially the LV network) is even more emphasised by the likely presence of reactive power flow. Since the reactive power provision by DGs could become a fundamental aspect for network management, knowing the effects that present connection rules have on power losses is essential.

2 Present regulation

The present regulation in European power systems foresees two approaches regarding the procurement of network losses [6]. In most of the European countries, the network operators are in charge of procuring the energy to cover network losses, therefore the associated costs need to be accepted by the regulator and introduced in the tariffs calculation. In other particular countries (e.g. Ireland, Portugal and Spain), the network losses are considered directly injected by the suppliers, therefore priced at the same price as load demands and treated as any other power imbalance. In Italy, following the first type of regulation, the Authority for Electrical Energy, Gas and Water (AEEGSI) prescribed the procedures that need to be followed by DSOs to assess their network losses. Among other prescriptions, one is to consider the network as passive (i.e. neglecting the distributed generation) when evaluating the power losses, resulting in an anachronistic method (DG impact on losses is neglected). The efficiency of a distribution network is then evaluated through a percent losses coefficient (LC) defined as

$$\mathrm{LC} = \frac{E_{\mathrm{losses}}}{E_{\mathrm{loads}}}(\%) \qquad (1)$$

where E_{losses} is the yearly lost energy (including both no-load losses and Joule losses), calculated using average power profiles for the customers, whereas E_{loads} is the total energy absorbed by loads. Applying this coefficient to different voltage levels in the network, AEEGSI specified the accepted losses for distribution networks, as summarised in Fig. 1 (values reported in black). In addition, commercial (i.e. non-technical) losses are evaluated as reported in the figure (in red, inside brackets). This kind of approach would be effective in evaluating the losses associated to passive

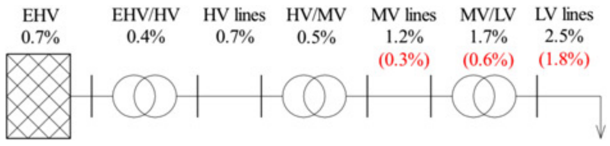

Fig. 1 *Losses coefficients declared by AEEGSI for point of connection [7], technical losses are reported in black, while values inside brackets are estimations of commercial losses*

customers having three-phase balanced generation. Differently, in distribution networks, and especially in LV systems, the connection of single-phase end-users and DGs is very common, with consequent imbalances in the power flows and therefore in the phase voltages, which means a not negligible neutral potential [7–9]. It is worth noting that single-phase DG units are typically realised by existing end-users, so the connection phase is directly defined.

3 Reactive power management in LV networks

At present, for billing purpose, the Italian legislation defines the average power factor (APF) as the average value in a long-time period, typically the bill period (i.e. a month). Referring to this parameter, end-users larger than 16.5 kW adopt reactive power compensators (usually fixed capacitors banks) to avoid bill penalties. In this way, although effectively adjusting the APF, the risk of injection of reactive power by end-users arises, even if connection rules explicitly forbid it [1]. Discussions are underway to introduce penalties for the injection of reactive power by end-users [10], but this approach needs to be coordinated with the increasing involvement of distributed energy resources (DERs) in the network management [11].

As well known, distribution systems, in particular the LV ones, are characterised by cable lines with high R/X ratios. Nevertheless, reactive power contributions coming from DERs connected to these systems are going to play a significant role as they represent ancillary services for the network management. For this reason, the latest updates of connection rules for DERs have included schemes for the local reactive power control. In this paper, DERs connection scenarios are considered adopting the capability areas and local controls required by the Italian standard CEI 0-21 [3] reported in Fig. 2.

In particular, capability A is required for inverters with rated power P_r <11.08 kW (i.e. rated current lower than 16 A). They have to operate with instantaneous PF according to the PF(P) control in Fig. 2*b*. Referring to Fig. 2a, the reactive power Q is limited by the actual injected active power P (dotted red line), up to a limit value

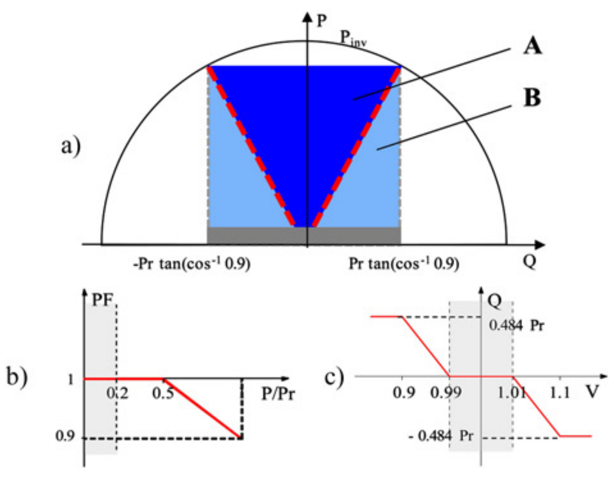

Fig. 2 *Local reactive power control:*
(a) Capability areas, ***(b)*** PF(P) control, ***(c)*** $Q(V)$ control

(grey band, typically 5% of the rated power), while the PF(P) control is disabled for $P \leq 20\%\ P_r$. The capability area B is applied to inverters with rated power 11.08 kW or above, which are required to be equipped with the $Q(V)$ local control depicted in Fig. 2*c*.

4 Load profiles

Load profiling is a pivotal activity for planning and operation of distribution networks. In planning, the accurate estimation of load profiles improves power flows calculations. In operation, since real measurements are combined with pseudo-measurements for state estimation, improving the knowledge of load profiles results in a more accurate estimation of network working conditions. Currently, TSOs and DSOs use load profiles that are often based on measurement campaigns performed many years ago which may reflect old consumption patterns no longer applicable to modem consumers. Typically, daily curves relevant to each consumer type (i.e. residential, agricultural, industrial o tertiary) have been produced by analysing real data obtained by first generation smart meters. Nowadays, new and more accurate measurements can be gathered from second generation smart meters and new load profiles (of both P and Q) can be produced. Such models must be capable to discriminate the single customer from the average and thus to find the differences within the same consumer type. Current load profiles associate to the same group of end-users, nominally homogeneous, the same behaviour and thus the same profile. This is a cause of inaccuracy since all customers of the same group have coincident peaks that are not real. This is particularly true for residential customers, whose time electric consumption is totally unpredictable and depends on many random parameters (e.g. how many persons are at home at the same time, how many appliances are contemporarily in use, which is the heating technology, etc.). Only a probabilistic approach can overcome all the difficulties on such load profiling [12].

In Italy, the procedure for the assignment of time varying power coefficients to each customer of the LV network is suggested by AEEGSI and depicted in Fig. 3. Given the active power profile measured in a secondary substation (SS), typically with a 10 min resolution, and the energy absorbed by each load as monthly varying value (known for billing purposes), the power profile for each customer is evaluated as follows:

(i) Integrate the active power flowing through the SS to calculate the energy monthly provided to the LV network.
(ii) Given the monthly varying customer (E_C) and SS (E_{SS}) energies, calculate a month scaling factor as

$$k_M = \frac{E_C}{E_{SS}} \tag{2}$$

(iii) The active power profile over the year is then given by the application of the k_M scaling factors to the measured profile in SS.

The above-described procedure is obviously valid for passive networks, since it only considers energies measured for passive

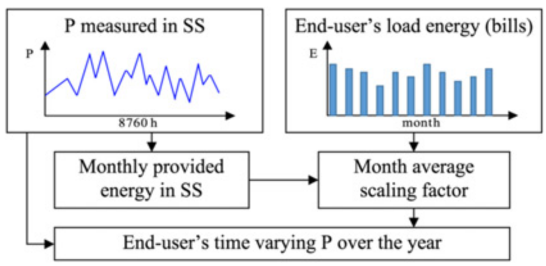

Fig. 3 *Procedure suggested by AEEGSI for calculating the yearly power coefficients for loads in a passive network*

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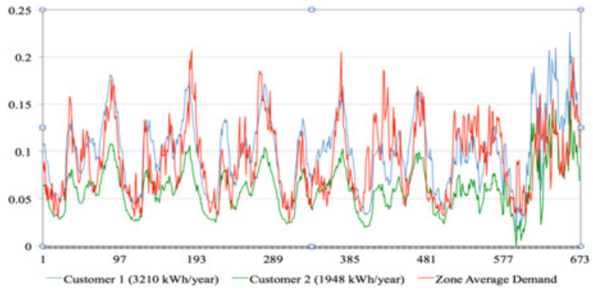

Fig. 4 *Estimated load profiles of two Italian residential customers and the zone average demand*

customers. Furthermore, no difference has been considered for customers of different type: the consumption profile shape of all the end-users supplied by the same SS is exactly the same of the measured one at the SS. Other European countries, for example the UK, for market competition purposes and in order to avoid the huge investment of putting half-hourly metering into every market customer, decided that customers below a certain size would be settled using load profiles and readings from customers' existing electricity meters.

A multi-linear regression analysis is used to calculate the quarter-hourly profile coefficients of eight customer classes, distinguished between domestic and non-domestic with different tariff rules, and other non-domestic classes [13]. Inspired by this methodology, quarter-hourly profile samples of a few hundred Italian residential users have been used. A regression analysis has been performed to estimate their demands (dependent variables of regression) starting from a couple of independent variables. Independent variables tested for this study have been daily maximum temperatures, day of the week, house surface, number of family components, annual salary and the number of appliances hold by the user. Preliminarily the users were subdivided by climate zone, then the 96 regression coefficients for each typical day of the year (i.e. working-day, semi-holiday and holiday for the four seasons) have been calculated. Fig. 4 shows the results obtained by using only the maximum day temperature and the day of the week as independent variables. The curves are the spring week profile of two customers of the same climate zone, together with the average zone demand simply calculated as the arithmetic average consumption among the customers of the same zone. The customer profiles are obviously quite similar but not the same, and not identical to the average curve. This means that customers belonging to the same group have different load profiles as they are in different areas. The impact on planning, energy loss estimation and state estimate is self-evident.

5 Case study

The case study network for this work is an Italian real LV distribution system composed by five feeders departing from the MV/LV transformer in the SS (Fig. 5). Feeder 3 (in green) is the most extended one, hosting 63 of the total 79 customers (total length of 4.4 km). Feeder 1 is a dedicated line for a customer connected at bus S1, while Feeder 5 is a dedicated line for the connection of a three-phase PV unit considered in one of the proposed scenarios. All the branches are composed by three phases plus the neutral conductor, which generally has a reduced section (at least half of the phase conductor section, with minimum of 16 mm^2). The cable types are reported in Table 1 and the compositions used in the case study network vary between 4×6 mm^2 and $3 \times 95 + 50$ mm^2. The MV/LV transformer has a 20/0.4 kV ratio and a rated power of 100 kVA. Its short-circuit impedance is defined by the short-circuit voltage $v_{cc} = 4\%$ and the short-circuit copper losses $p_{cc} = 1.47\%$. The magnetisation leakage and iron-core losses are $i_0 = 0.841\%$ and $p_0 = 0.32\%$, respectively.

The losses analysis has been conducted over an entire year, using hourly-varying power coefficients defining loads' absorptions and generators' active power injections.

As concerns load power profiles, the standard procedure proposed by the Italian Regulator and described in the previous section has been applied. This choice was done since the case study network was almost completely passive during the measurement period and data of customers different from residential were missing, thus the complete regression analysis could not be performed.

Referring to the procedure indicated by AEEGSI, the power profile at SS is shown in Fig. 6*a*, while Fig. 6*b* reports the monthly measured energy demands of five end-users. Generation

Table 1 Cable types data for the case study network in terms of: diameter Geometric Mean Radius (GMR) and DC resistance

Wire section, mm^2	*d*, mm	GMR, mm	R_c, Ω
6	3.000	1.168	3.300
16	5.200	2.025	1.210
25	6.300	2.453	0.780
50	9.400	3.660	0.386
70	11.000	4.283	0.272
90	12.700	4.945	0.206

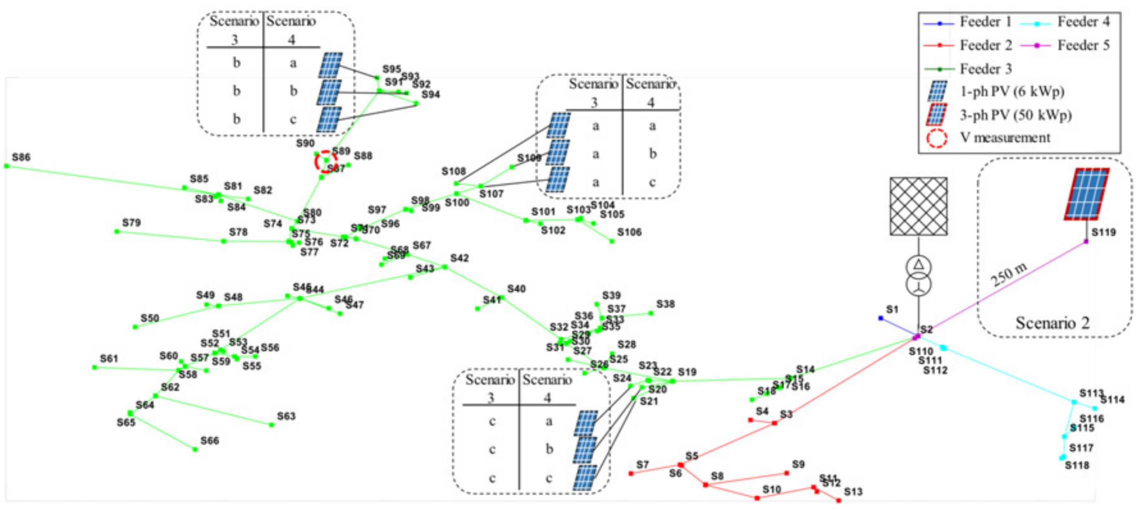

Fig. 5 *Case study LV network single line diagram. The three DG connection options are shown including 6 kWp single-phase units and a three-phase 50 kWp plant*

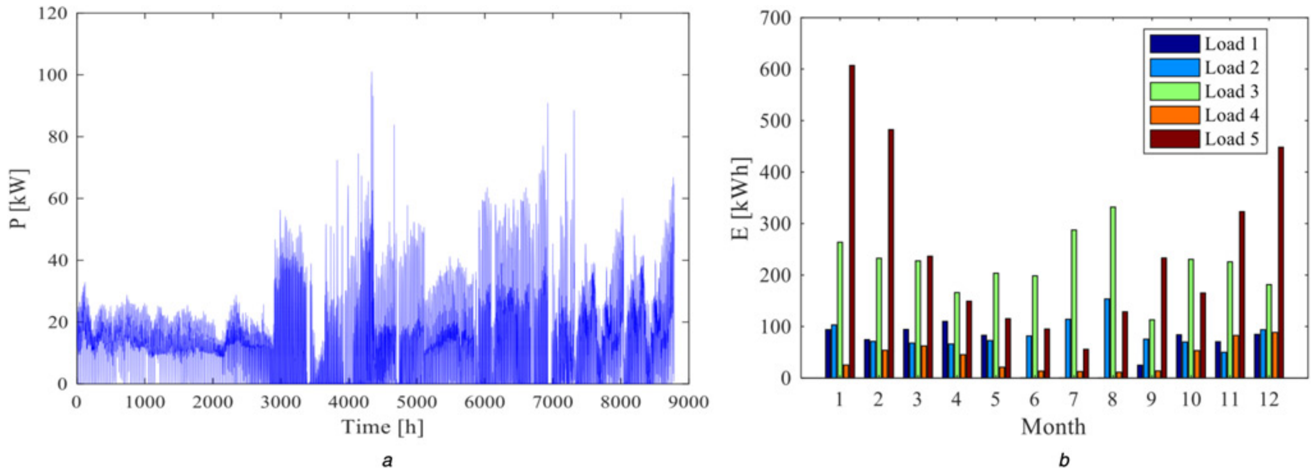

Fig. 6 *Active power variability*

(a) Active power profile at SS, **(b)** Monthly registered energy absorbed by five loads taken as example

data for the PV units have been estimated from typical seasonal PV production trends. Loads and generators connected to the network are either single- or three-phase: the overall yearly absorption of loads (123.4 MWh) is divided in 46% for single phase and 54% for three-phase customers (PF = 0.9), whereas the connection of generators is one of the hypothesis of the analysis. In addition to the passive configuration (Scenario 1), three active network scenarios are introduced, namely:

(i) Scenario 2 (concentrated generator): a 50 kW PV plant is connected through a dedicated line directly departing from the SS (Feeder 5).
(ii) Scenario 3 (dispersed generators, unbalanced connection): nine single-phase PV units (each with rated power of 6 kW) are connected to the network as shown in Fig. 5, in groups of three; all the DGs of a group are connected to the same phase;
(iii) Scenario 4 (dispersed generators, balanced connection): the same single-phase PV units of Scenario 3 are considered, but each group of DGs is balanced on the three phases.

Results of the simulations over 1 year are reported in Table 2 highlighting the outcome in terms of losses, separated between the component due to the SS transformer and to the lines. Variations in brackets are referred to the base case. As it could be seen comparing the losses on the transformer and on the lines, the transformer terms are generally higher (about 70% of the total) due to the transformer no-load losses (i.e. magnetisation leakage and iron-core losses), which are uncorrelated with its actual loading but rather to the feeding voltage, therefore remain almost unaltered during the entire period.

The left-hand side of Table 2 considers DGs operating at PF equal to 1. In Scenario 2, the losses component associated with LV lines obviously rises with respect to the passive case (+10.1% due to Feeder 5), while the losses reduction on the transformer (−4.0%) are ascribable to the power flow compensation during the PV production hours (inversions of the active power flow on the SS rarely happen).

In Scenario 3, an active power production similar to that in Scenario 2 is considered, but in this case obtained through the connection of nine single-phase units as shown in Fig. 5. Since all the DGs of the same group are connected on the same phase, this kind of connection strongly affects the load flow unbalance in the system, causing a significant increase in losses related to the lines (+78.18%). This consequence is mainly due to the increased current flowing on the neutral conductor.

To highlight this, Scenario 4 reports the case in which the DSO reconfigures the phase connections of the single-phase DGs, locally balancing the generators. A significant share of the load is now supplied by DGs (reducing the power flow through the SS). However, since DG units are connected away from the SS, where branches are usually realised with cables with smaller sections, Scenario 4 experiments an increase in line losses (+10.3%) in comparison with the passive condition (Scenario 1).

Without reactive power regulation, both Scenarios 2 and 4, although considering different DG connection options, lead to similar results in terms of network losses, with a slight decrease mainly involved by the power flow reduction on the transformer. However, this result strongly depends on the DG penetration level, so it cannot be generalized.

Introducing the reactive regulation of DGs (right-hand side of Table 2), the *Q(V)* control introduced in Scenario 2 (three-phase 50 kW PV unit) causes a significant variation of power losses respect to the not regulated case. The yearly analysis demonstrates that the *Q*(*V*) action (reactive power absorption to compensate the local voltage higher than the rated value) increases the current magnitude on both the dedicated line and the transformer, resulting in a losses increase of around 10.8% in comparison with

Table 2 Losses results for the four scenarios simulated

	Without *Q* regulation of DGs				DGs supplying *Q* regulation			
	Transf., MWh	Lines, MWh	Total, MWh	LC, %	Transf., MWh	Lines, MWh	Total, MWh	LC, %
Scenario 1 (base case)	3.701	1.097	4.798	3.89%	—	—	—	—
Scenario 2	3.552 *(−4.0%)*	1.208 *(+10.1%)*	4.760 *(−0.8%)*	3.86% *(−0.0%)*	3.589 *(−3.0%)*	1.683 *(+53.5%)*	5.273 *(+9.9%)*	4.27% *(+0.4%)*
Scenario 3	3.541 *(−4.3%)*	1.955 *(+78.2%)*	5.495 *(+14.6%)*	4.46% *(+0.6%)*	3.556 *(−3.9%)*	1.955 *(+78.3%)*	5.511 *(+14.9%)*	4.47% *(+0.6%)*
Scenario 4	3.531 *(−4.6%)*	1.209 *(+10.3%)*	4.741 *(−1.2%)*	3.84% *(−0.1%)*	3.545 *(−4.2%)*	1.2329 *(+12.4%)*	4.778 *(−0.4%)*	3.87% *(−0.0%)*

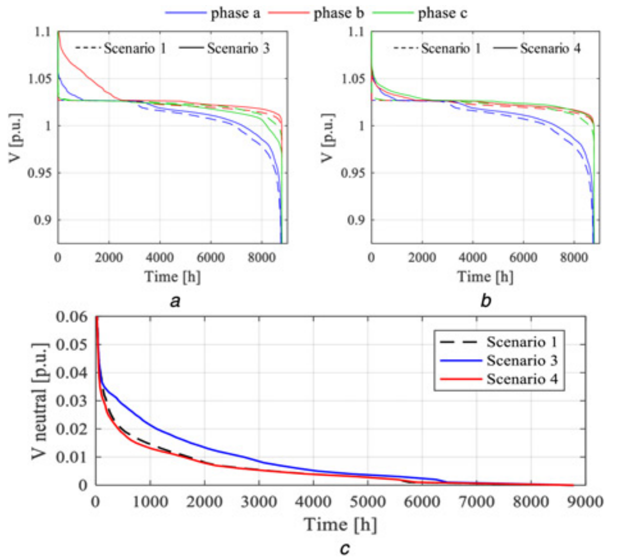

Fig. 7 *Duration curves of phase voltages and neutral potential at bus S89*

(a) Comparison between phase voltages in Scenario 1 and 3, ***(b)*** Comperison between phese voltages in Scenario 1 and 4, ***(c)*** Neutral potential in Scenario 1, 3 and 4

the case without regulation. Differently, in the other two scenarios, the *PF*(*P*) control causes very limited alterations of the reactive power flow, leading to slight variations of losses in the case of reactive power modulation (+0.3–0.8%). In Fig. 7, an analysis of both the phase voltages and the neutral potential is reported through duration curves regarding Scenarios 3 and 4. Looking at the phase voltages at node S89, Scenario 3 results in a higher voltage unbalance, in particular related to higher voltage values (Fig. 7*a*). The effect of the phase reconfiguration in Scenario 4 leads, along with a limited unbalance, to reduced values of the voltage deviation (Fig. 7*b*). Fig. 7*c* confirms that the neutral potential rises in Scenario 3 as an effect of the increased current flow on the neutral conductor.

6 Conclusions

The paper shows that the connection of DG does not necessarily lead to a reduction of annual energy losses. To make the study more realistic, advanced techniques for load profiling have been used. The worth of the models is that even though customers belong to the same group, each one has its own individual load consumption.

With the aid of a significant case study, it has been showed that losses are influenced by the DG penetration level, the connection topology, the type of generating units (single phase), the profile of energy consumption, the unbalance of load and generation and the reactive power flows (consequent to the adopted reactive power management strategies).

In particular, the paper demonstrates that reactive power regulations applied to DGs connected to LV networks could have a role in sensibly increasing the network losses. In addition, the reactive power exchanged by LV DGs, together with the concept of ‘APF’ having influence on end-users’ reactive power behaviours, could impact on voltage regulation in upstream MV networks.

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