INFLUENCE OF AVERAGE POWER FACTOR MANAGEMENT ON ACTIVE DISTRIBUTION NETWORKS

Luciano COCCHI
Alberto CERRETTI
Enel Distribuzione – Italy
luciano.cocchi@enel.com

Ettore DEBERARDINIS
CESI – Italy
ettore.deberardinis@cesi.it

Fabio BIGNUCOLO
Andrea SAVIO
Riccardo SGARBOSSA
University of Padova- Italy
fabio.bignucolo@dii.unipd.it

ABSTRACT

During the transmission and distribution process of electricity, technical power losses inevitably occur, depending on current flows along the lines which in turn are affected by the power factor resulting from loads and dispersed generation, as well as from both intentional capacitors and not intentional ones (MV cable shunt capacitance). The power factor has a direct influence on power losses and voltage profile.

The paper describes a first theoretical analysis to assess the influence of the power factor requirements when measured as average value and to compare how losses and voltage profiles may change considering the real "instantaneous" power factor. Starting from data coming from MV and LV customers and meters installed along lines, possible technical and regulatory countermeasures have been investigated to reduce network losses, taking into account also voltage constraints.

INTRODUCTION

It is well known that the reduction of reactive power flow in traditional distribution networks has several advantages of both a technical and economic nature.

The reactive power is a typically local phenomenon with consequences on the overall network, and thus, in order to minimize the impact resulting from the circulation of reactive power on the system, it is opportune that compensation interventions under the logic of the principle of subsidiarity are applied.

On traditional "passive" networks, to obtain losses reduction and to limit the voltage decrease to the load power absorption, loads usually need to be compensated (as close as possible to unity power factor). For the same reason capacitor banks are often installed in HV and MV networks. Generators, conversely, are usually requested to supply reactive power or to operate at unity power factor.

Unfortunately, as described below, the current Italian legislation evaluates an average power factor in a long period, typically the bill period (i.e. a month), being defined in presence of "passive" distribution networks. In this way, the reactive power behaviour of the end user is described through a global parameter, without information on the instantaneous reactive power exchange with the grid, which means network losses. Furthermore, the average power factor is evaluated considering only peak hours (named as F1, Monday-Friday, from 8.00 am to 7.00 pm) and hours with middle absorption (F2, Monday-Friday, from 7.00 am to 8.00 am and from 7.00 pm to 11.00 pm, and Saturday, from 7.00 am to 11.00 pm). Reactive exchanges during the night, on Sundays and in public holidays do not influence the average power factor computation. At present, average power factors lower than 0.9 involves penalties.

According to the Italian regulations[1], the average power factor is determined as:

$$cos\varphi = \cos\left[\arctan\left(\frac{E_{reac-net}}{E_{act-net}}\right)\right] \qquad (1)$$

where: $E_{act-net}$ is the total active energy absorbed from the network by the user in the first and fourth quadrant of P-Q diagram (Figure 1) during the bill period (F1 and F2); $E_{reac-net}$ is the inductive reactive energy absorbed from the network during the bill period (F1 and F2), measured only in case of absorption of active energy (first quadrant of P-Q diagram of Figure 1).

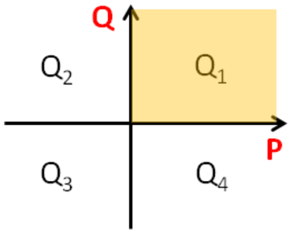

Figure 1: P-Q diagram

The end user is induced to oversize the reactive compensator, in order to avoid bill penalties by working on the fourth quadrant of the P-Q diagram. At present, compensating capacitors are installed either in combination with specific loads or at the Point of Common Coupling (PCC), without dynamic regulation. Even if the end user is heavily overcompensated, in particular during low load periods when high reactive power inversely flows on the distribution lines, no penalties are applied.

This measure, however, does not ensure a constantly modulated compensation according to the instantaneous generators and loads power factor operating values, so resulting in undesired current increase (due to the reactive component) on the network lines. Furthermore, the

---

[1] passive end users or active end users with their own load, different from the auxiliary services

measure of the power factor so conceived completely neglects the effects on the "natural" network capacitance (mainly due to MV cables permanently connected, widely employed to connect DER, whose effects may be particularly noticeable during the night). The effects are completely different on the LV, MV and HV networks, as they depend mainly on the R/X ratio (LV networks are predominantly resistive, whereas HV networks are mainly inductive).

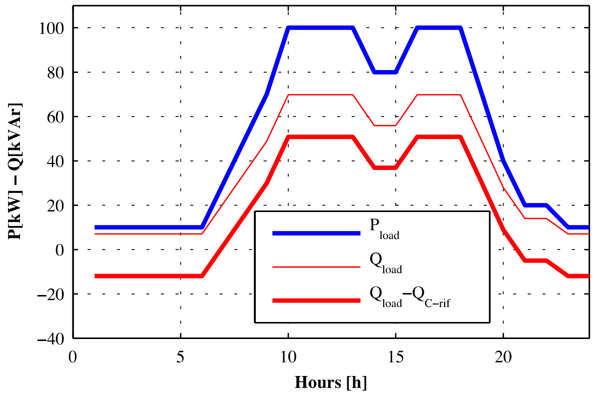

Figure 2: Hourly active and reactive power (with and without compensation) for a representative load

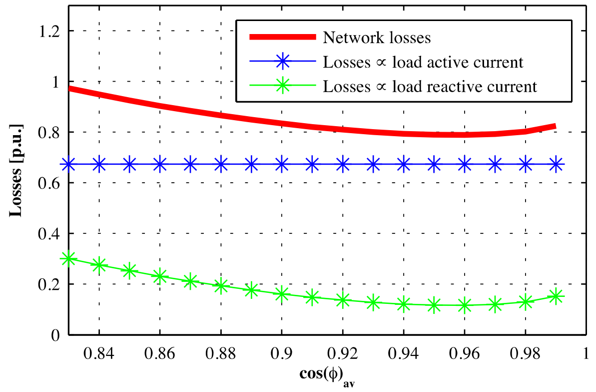

Figure 3: Correlation between end user mean power factor and network losses

Also the different features of ″primary energy source″, solar, wind, hydro, ORC, etc., lead to different considerations (in Italy, being solar source prevalent and being the present paper only a preliminary evaluation, only this primary energy source has been considered).
Considering a representative load as reported in Figure 2, where active and reactive power are reported with load convention, i.e.:

- $P > 0$ active power absorbed;
- $P<0$ active power generated;
- $Q > 0$ reactive inductive power;
- $Q< 0$ reactive capacitive power.

Figure 3 describes the correlation between the average power factor of the end user and the amount of daily network losses, as referred to the uncompensated case. The blue line represents the network losses caused by the active component of line current (not influenced by reactive compensation), while the overall line losses, reported in red, are also influenced by the reactive power flow (green line). It is important to note how an average power factor greater than 0.96 causes a network losses increase due to night inversion of reactive power flow, since in the present legislation no limits to capacitive reactive power absorption are considered.
Conversely, forbidding the night overcompensation, the network losses would decrease with the average power factor, even if increasing the average power factor to one requires dynamically adjustable reactive compensators (a fixed large compensator optimally operates in case of high load periods, but is frequently shut down to avoid reactive power inversion at the PCC).
The load curves measured at the LV bus of Enel's secondary substation are depicted in Figure 4.

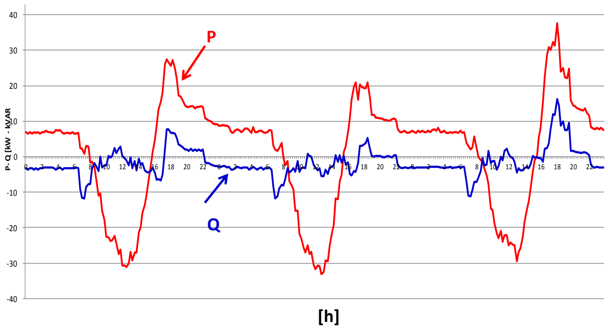

Figure 4: Load curve measures at the LV bus of secondary substation

Field measurements show that on the distribution network there is a capacitive energy flow during the night, demonstrating that the current method used to evaluate the average power factor is incorrect to reduce the reactive energy flow.
These measurements have to be considered as qualitative since one site only was partially monitored and there may be inaccuracies due to the absence of some data of electronic meter. Further more detailed measurements are underway.

IMPACT OF DISTRIBUTED GENERATION ON THE AVERAGEPOWER FACTOR

A passive user is characterized by active and reactive energy absorption. In order to minimize the reactive energy flow in the distribution networks, a threshold on the average power factor value of each single user is stated. Penalties are applied to users with average power factor lower than this threshold. Users have thus to install capacitor banks (denoted $C_{1\text{-rif}}$ in Figure 5) to compensate their average power factor and avoid penalties. The capacitor $C_{1\text{-rif}}$ is sized to guarantee a given average power factor level (usually not smaller than 0.9), although the instantaneous value may be significantly different.

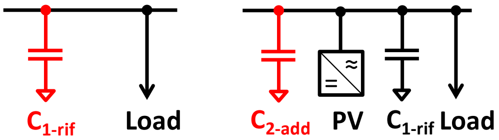

Figure 5: Capacitor for average power factor correction for passive end user and for active end user

A simplified example of passive user load curve is shown in Figure 2. The active and the reactive load demand (P_{load} and Q_{load}) and the reactive power exchanged with the network due to the presence of $C_{1\text{-rif}}$ (Q_{load} - $Q_{C1\text{-rif}}$, average power factor compensated to 0.9) are presented.
But what happen if a photovoltaic plant is added to this user plant?
Usually a PV generator injects only active power, whereas the load reactive demand is provided by either the main grid or the shunt capacitors. Since the load active power is partially self-produced, a reduction of active energy absorption from the network is expected if the local generation does not overpass the load requirement. The reactive energy is not modified. As a consequence, the resulting average power factor, measured at the PCC, decreases (Figure 6).

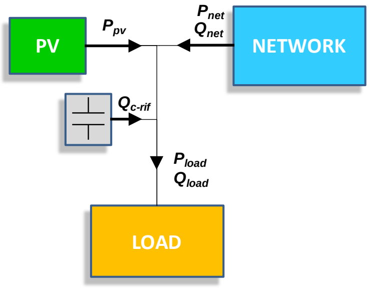

Figure 6: End user connection scheme in case of local generation in partial self-consumption

Indeed the average power factor is determined as in equation (1) above, where:

$$E_{reac-net} = \int (Q_{load} - Q_{c-rif}) dt \tag{2}$$

only for (P_{load}-P_{pv}) > 0 and (Q_{load}-$Q_{c\text{-rif}}$) > 0

$$E_{act-net} = \int (P_{load} - P_{pv}) dt \tag{3}$$

only for (P_{load}-P_{pv}) > 0

Therefore for maintaining an average power factor value greater than 0.9 with the PV plant in operation, it is necessary to add an additional compensating capacitor (denoted $C_{2\text{-add}}$ in Figure 5).
The resulting 24h curves (load+PV+Capacitors) are shown in Figure 7. The additional capacitor improves the daily average power factor by reducing the reactive energy exchange with the grid during the day (when the average power factor is evaluated according to current legislation), even if during the night undesired reactive (capacitive) energy flows into the network.
In case of unpredictable energy resources, the additional capacitor is quite difficult to be designed, in particular for seasonal variations (e.g. photovoltaic). In this case, all the possible configurations of load and generation trends have to be considered, since $C_{2\text{-add}}$ does not directly increase with the dimension of the plant. Defining R_{FV} as the ratio between the maximum generation and the maximum load requirement in terms of active power, Figure 8 shows the correlation between R_{FV} and the compensator size (without dynamic regulation), for different values of average power factor at the PCC.

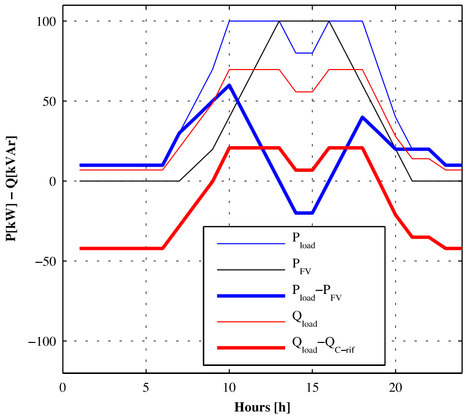

Figure 7: Active and reactive hourly power flow for an active end user

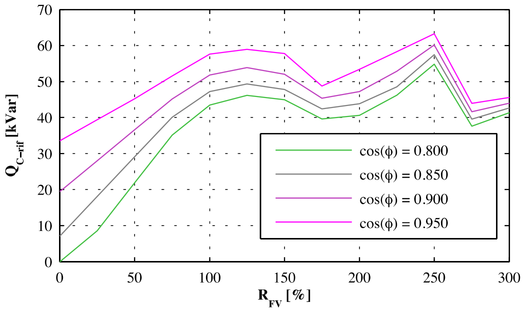

Figure 8: Additional compensator sizing in case of unpredictable generators

Considering that a PV plant may operate in the range between its maximum output and zero due to weather and seasonal reasons, $C_{2\text{-add}}$ has to be defined as the maximum value obtained varying the x-coordinate between zero and the maximum value of R_{FV}. Different curves can be obtained modeling different types of load.
This over-compensation, adopted by the user in order to avoid penalties, could have an impact on several network issues, such as:

- Sustained high voltage levels both during day (generation) and night (intentional and not intentional capacitors, neither load nor generation);
- Voltage regulation Q(V) issues (the higher is the voltage, the higher is the absorbed reactive power from generators to avoid overvoltage disconnection, the higher is the value of capacitors banks to increase the average power factor value, and so on);

- Increased risk of unintentional islanding (while DG units supply active power, the reactive power needed from the loads is supplied from the compensating capacitors) [6][7];
- Resonance problems;
- Increased network losses (due to constant reactive power circulation in the network).

In the following these phenomena are briefly described.

NETWORK ISSUES

High voltage values

In a distribution network without Distributed Generation, the voltage profile decreases along the feeder. However, connecting local producers, the voltage profile is no longer monotonic and may even give rise to serious over-voltages because of active power supply from peripheral areas.

Furthermore, as for voltage quality standards, the steady-state voltage limits in distribution system are ±10% of the nominal voltage (EN 50160). The voltage variation along a feeder can be expressed with the following simplified formula $\Delta V = r\Delta P + x\Delta Q$, where r and x are the resistive and the reactive parts of the line impedance respectively (considering the electrical connection from local nodes to the network point with “infinite” short circuit power). In a LV line the voltage variation mainly depends on the active power flow since $r >> x$, whereas in a MV line the voltage variation depends on both active and reactive power flow ($2\ r \sim x$ in case of overhead lines).

Considering DG (e.g. photovoltaic generation), during the day the voltage could rise because of active power injection, while in the night the voltage, especially in MV feeders, may rises because of reactive capacitive power flow (see Figure 7). As a consequence, during the night the voltage rises also in the LV feeders due to the higher voltage values on the primary winding of MV/LV transformer (the voltage does not drop along the LV feeder because of low load absorption). This phenomenon can be controlled during the day in LV feeders by reducing the supply of active energy or increasing the load (e.g. using battery storage).

Problem for voltage regulation Q(V)

The DG requirements Q(V) will not be so much effective in LV feeder in reducing high voltages caused by active power injection from DER (only P(V) could be effective). Conversely, in generators connected to the MV network, where additional compensating capacitors for average power factor correction are installed, the voltage regulation could get into an instability process in case the Q(V) requirement is activated, involving the disconnection of the DG plant for different reasons:

- active power production and consequent increase of the PCC voltage;
- power factor reduction due to partial active power self-production;
- capacitive energy flow required by the compensating capacitors to increase power factor average value;
- absorption of inductive power from the generators through Q(V) (like and induction generator) to try to reduce this excessive voltage value before plant disconnection.

Obviously, the maximum generator capability will be soon reached with final generating plant disconnection.

Further, there is the risk to trigger, inside the plant, an uncontrolled exchange of reactive power between shunt capacitors, always connected, and the generator operating with Q(V) requirement.

Unintentional islanding

Unintentional islanding is the electrical phenomenon in a portion of a power network disconnected from the main supply, where the local loads are entirely supplied by the local embedded generation and where the voltage and frequency levels are maintained within permissible limits around nominal values. The generated and load (plus losses) power should balance exactly in terms of both active and reactive power.

The rising of reactive capacitive power installed in the plants (e.g. for addition capacitor) increases the risk of unintentional islanding because of higher probability of reactive power balance.

The actual efforts of TSOs and DSOs in the European region are oriented to avoid the unintentional islanding due the presence of DG and battery systems. In the future standard EN 50549 1/2 and in the actual Italian standards CEI 0-16 and CEI 0-21 (CEI is Italian standardization body), the activation of a delay in active response to frequency deviation and the voltage support through reactive power are provided, with the scope of reducing the probability of the unintentional island operation.

Network losses

Technical losses depend on the characteristics of the components and the current magnitude. In details, technical losses vary in proportion to the resistivity of the conductor and in quadratic form with magnitude of the circulating current in the network.

The power factor correction carried out aiming to increase the value of the average power factor can lead to a losses reduction in peak hours but at the same time may increase the losses for the contribution of $Q_{capacitive}$ (increasing current magnitude during the night).

In Figure 9, the behavior of network losses, evaluated using the passive network as base reference, is correlated with the end user average power factor in active operation and the parameter R_{FV}, designing the capacitor bank for the highest obtainable production ($R_{FV,max}$).

Allowing overcompensation, if the end user adopts large capacitor bank to avoid penalties, an undesired increase of network losses is appreciable. Again, the specific points identifiable in the figure depend on the specific load trend (domestic, commercial, industrial) and lightly on the site location in terms of solar availability and generating trends. In case overcompensation is forbidden, no increase in power losses is expected, remembering that increasing the average power factor means the use of compensators with dynamic regulation.

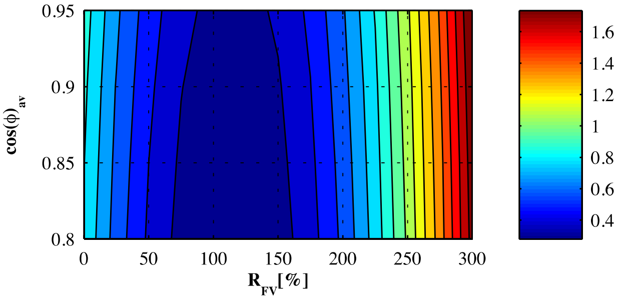

Figure 9: Influence of average power factor on network losses for different DG penetration levels

Finally, increasing the value of the average power factor does not mean achieving the best efficiency in terms of network losses if fixed compensators are considered. In general, the reduction of technical losses with embedded DG may be much lower than expected, or even, on some lines, the losses could increase.

Resonance phenomena

The series connection of an inductance and a capacitance will result in a very low impedance in a certain frequency range, close to the resonance frequency. This effect is called series resonance. If harmonic voltage- or current-sources excite such resonance circuits, an amplification of voltages and currents may occur which can disturb, overload or even destroy network components.

Adding a photovoltaic plant to a pre-existing load, the end user is induced to increase the compensating capacitors in order to avoid penalties, possibly increasing the probability of resonance problems. The inductive reactance changes proportionally with the frequency ($X_L = j\omega L$) while capacitive reactance is inversely dependent on the frequency ($X_c = \frac{-j}{\omega C}$).

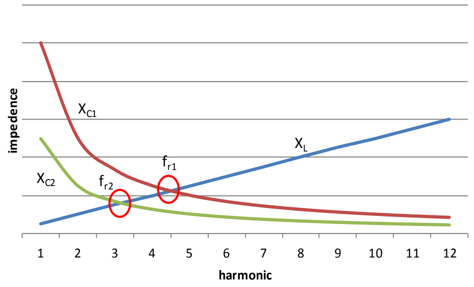

Figure 10: Inductive reactance and capacitive reactance dependence with harmonic frequency

In Figure 10, it is possible to appreciate that increasing the magnitude of the capacitors, the resonance frequency decreases (capacity $C_1 = C_{1\text{-rif}}$ while capacity $C_2 = C_{1\text{-rif}} + C_{2\text{-add}}$ with reference of Figure 5).

CONCLUSIONS

The article describes the consequences of a system of anachronistic measurement that had its rationale when distribution networks were completely passive, consequences which may range from :

- permanent high voltage on distribution networks with disconnection of generating plants during maximum production;
- loss of EN 50160 and contractual constraints with end users;
- increase of probability of uncontrolled islanding being the active power supplied by generators and reactive one by capacitors;
- increase of network losses due to continuous reactive power exchange between networks and generators.

It should be noted that this reactive power will be injected also in the HV system, with increased problems in the control of energy flows.

The article describes qualitatively some of the side effects of smarter grid management on a consolidated issue, like power factor management. No solution is presented, only the general framework. Even if this article is only a first step of a wide work still to be done, it appears clearly that the power factor concept requires a deep revision, involving technical aspects, legislation, regulation and Network Codes.

REFERENCES

[1] CENELEC TS 50549-1 and TS 50549-2, “Requirements for the connection of generators above 16 A per phase”, Part 1 and Part 2, 2014.

[2] CEI 0-16, “Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company”, 2011-12.

[3] CEI 0-21, “Reference technical rules for the connection of active and passive users to the LV electrical Utilities”, 2011-12.

[4] CEI EN 61642, “Industrial a.c. networks affected by harmonics -Application of filters and shunt capacitors”, First Edition1998.

[5] L.Cocchi, A. Cerretti,C. Pezzato, C. Noce, E. Deberardinis, R.Nicolini, "New ancillary services required to electrical storage system for correct network planning and operation " *CIRED 2015 Lyon conference.*

[6] N. Cammalleri, A. Cerretti, L. D’Orazio, C. Pezzato, C. D’Adamo, V. Bufano, E. De Berardinis “Risk of uncontrolled islanding on active distribution networks: short-term countermeasures taken by EnelDistribuzione” *CIRED 2015 Lyon conference.*

[7] F. Amadei, A.Cerretti, M. Coppo, P. Mattavelli, R. Sgarbossa, R. Turri. “ Temporary islanding operations of MV/LV active distribution networks under fault conditions”, Proc. 49th Universities' Power Engineering Conference (UPEC 2014). Cluj-Napoca, Romania, 2-5 September 2014.