

Impact of Photovoltaic Generation on Energy Flows, Power Factor and Current Harmonic Distortion in grids with harmonics generated by the loads

Abstract

This document contains a study focused on the electrical analysis and power quality of a real-case industrial plant having **non-linear loads** and a **photovoltaic** generation system.

Plants of this type are currently very common: they are standard on new plants but are also widely used in the revamping of industrial production lines.

The telemetric survey carried out at Point of Common Coupling (PCC) highlighted **a common but often under-estimated** issue in modern plants with in-house production facilities.

When the PV system is operating at full capacity (meeting or exceeding the power consumption of the machinery), the active power drawn from the grid drops dramatically until it is reduced to zero or the flow is reversed. However, the loads continue to require the same amount of reactive power and to generate the same harmonic spectrum, leading to distortion of the power flows at the PCC and a deterioration in power quality.

As traditional photovoltaic inverters do not manage reactive power, and loads continue to 'distort' the grid, there is a drastic deterioration in the power factor (**$\cos\phi$**) and a sharp and sudden rise in harmonic distortion (**THDI%**) with the consequent risk of penalties on electricity bills, equipment malfunctions and the tripping or damage of installed power factor correction units.

The solutions are available: hybrid power factor correction or with detuning chokes, active compensation and harmonic filters. Essentially, the choice depends on **when** the company plans to install the Power Quality system and **how much** a production shut-down would cost the company.

1. Premise and Operational Context of the Case Study

This Power Quality study is based on a real-case analysis of electrical parameters recorded at an industrial facility specialized in precision machining. The plant's production cycle involves the use of computer numerical control (CNC) machine tools, machining centers, and variable-speed drives (inverters). Having installed a next-generation photovoltaic system, it serves as the ideal case study for examining the combined effects of photovoltaic self-consumption and nonlinear loads on electrical parameters at the Point of Delivery (PCC).

High-resolution telemetry analysis allows for evaluating the impact of bidirectional energy flows on system stability and defining optimal plant countermeasures.

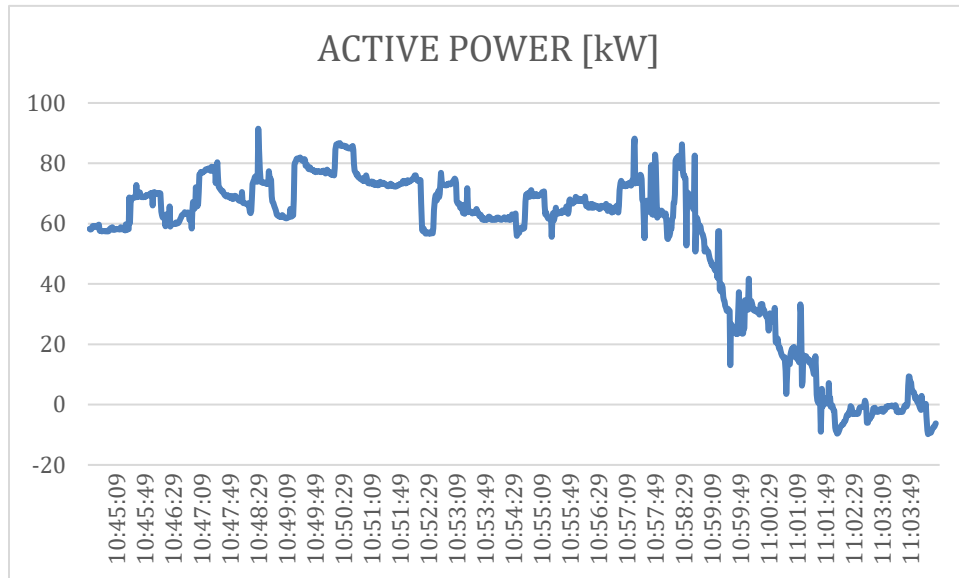
2. Introduction and Framework at the PCC

The interfacing of inverter-based photovoltaic generation (PV) systems to low and medium voltage distribution networks radically alters the energy regime at PCC. Under distorted operating conditions, the exchange profile can no longer be described solely by nominal power flows at nominal frequency (50Hz), but requires rigorous vector and harmonic analysis based on power vector algebra.

3. Analytical Treatment and Power Flow Decomposition (P and Q)

From data acquisition, a clear deviation between active and reactive power behaviour is evident, as documented by following field charts.

3.1 Active power (P) Dynamics and Self-Consumption



- **Pre-photovoltaic stage:** Under initial conditions, the active power drawn from the grid entirely reflects the overall active load of the loads, setting around 60-90kW
- **Generation transient:** Starting at 10:58, the power rise of local PV generation injects active current in parallel with the loads. Based on the power conservation principle at the PCC node, the analytical relation is:

$$P_{grid}(t) = P_{load}(t) - P_{fv}(t)$$

Where:

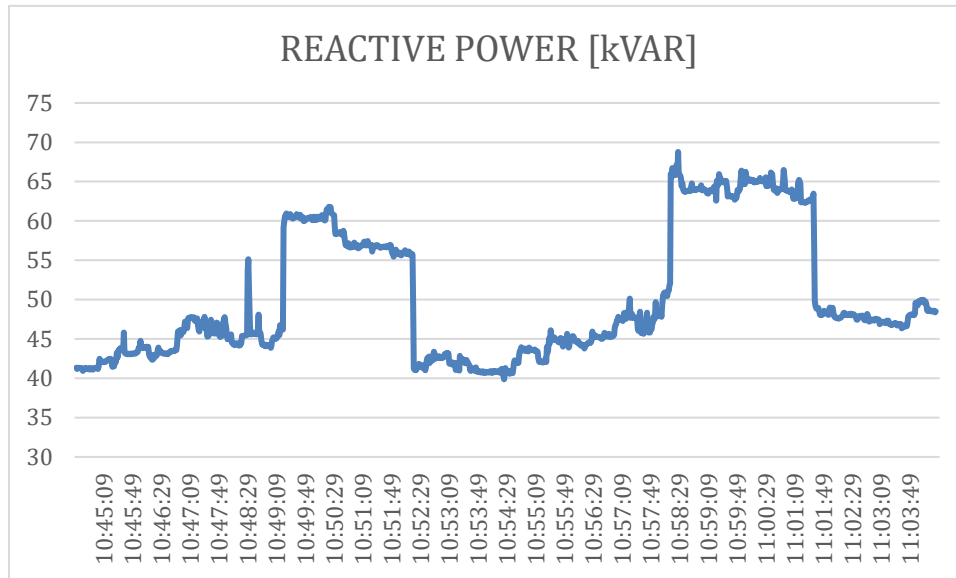
$P_{grid}(t)$ → Active power drawn from the distribution grid

$P_{load}(t)$ → Active power consumed by the loads

$P_{fv}(t)$ → Active power generated by the PV system

The collapse of P_{grid} withdrawal recorded in the chart toward zero and the transition to negative values (up to approx. -10kW) shows that P_{fv} momentarily equals and exceeds P_{load} , causing an active energy flow inversion toward the supplier grid.

3.2 Constancy of Reactive Power (Q) and Magnetisation



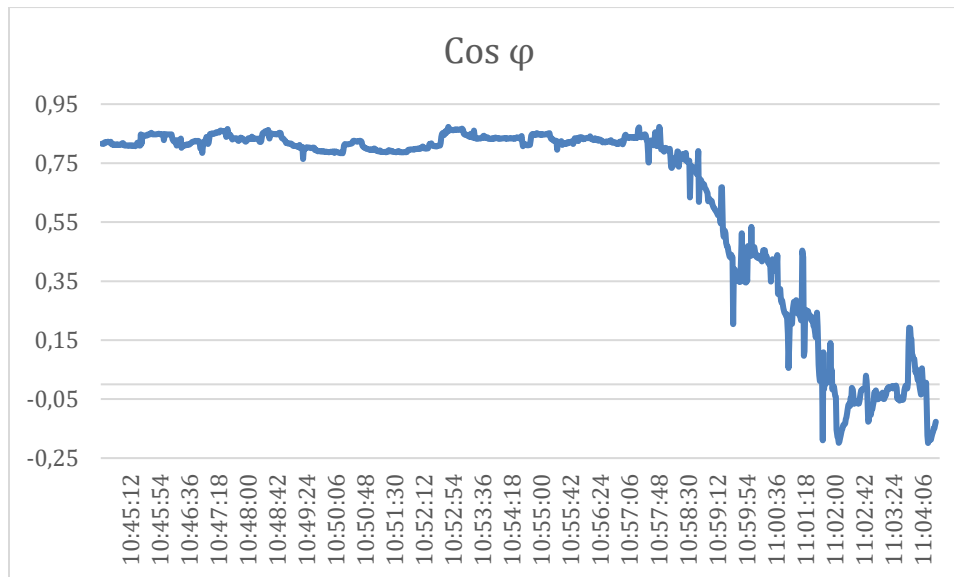
- **Stability of Q:** Reactive power Q_{grid} remains stationary within the 40 - 70 kVAR (with an average level around 50 kVAR). The plant's inductive loads (asynchronous motors, ecc.) continue to require the same inductive reactive power to generate the concatenated magnetic flux.
- **Absence of inverter contribution:** Since standard photovoltaic inverters typically are set at a power factor close to 1, they do not supply magnetizing reactive power. Consequently, the Q demand does not benefit from photovoltaic contribution and relies entirely on the supply grid, completely decoupling from the trend of P_{grid} .

4. Power Factor and $\cos\varphi$ decrease

The sudden degradation of the total power factor derives directly from the geometric variation of the power triangle (or the complex apparent power S plane, where D is distortion power):

$$\cos\varphi \approx \frac{P}{\sqrt{P^2 + Q^2 + D^2}} = \frac{P}{\sqrt{P^2 + Q^2}}$$

With P decreasing towards 0 against $Q \approx \text{constant}$, the phase shift angle $\varphi = \arctan(Q/P)$ tends to 90° , causing $\cos\varphi$ to collapse toward values close to zero and extreme capacitive/inductive transitions, as highlighted in the chart..



5. Advanced Harmonic Distortion Analysis: The THDI% Surge.

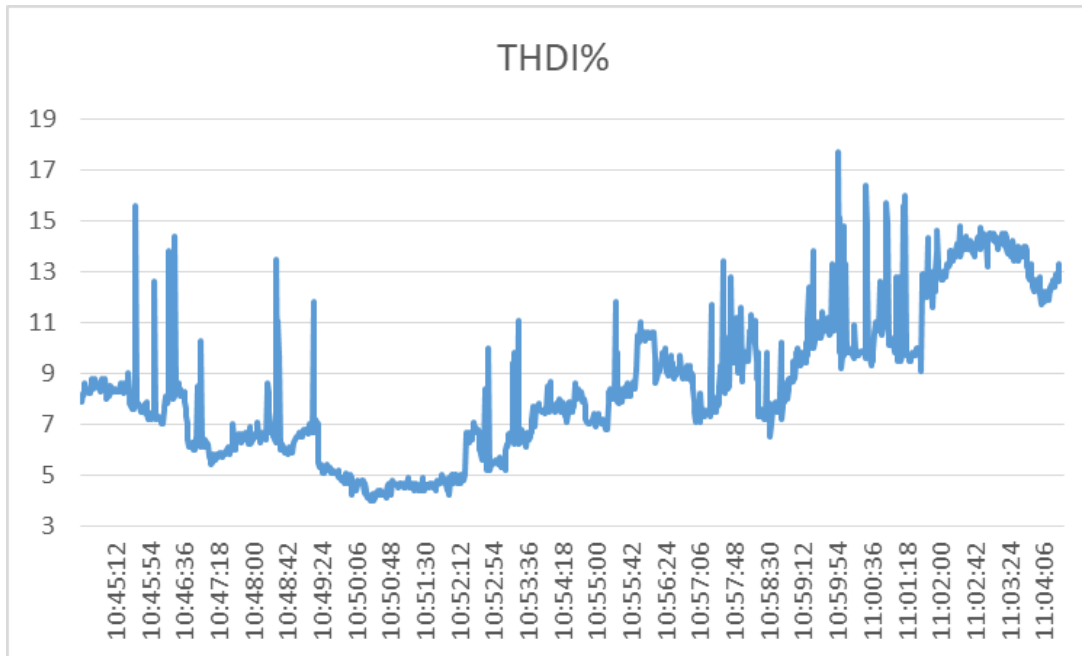
THDI% chart shows a marked increase from 4-8% values up to peaks exceeding 17-18% during maximum self-consumption.

This phenomenon is rigorously explained by the mathematical formulation of current THD:

$$THD_I\% = \frac{\sqrt{(\sum I_h^2)}}{I_1} \times 100$$

Where I_1 is the RMS value of the fundamental current component and I_h are the harmonic components of order h . The percentage increase in THDI% is not due to an absolute increase in harmonic amplitudes, but rather to the sharp drop of the denominator (the fundamental I_1):

- **Collapse of the fundamental current at the PCC:** The photovoltaic system locally supplies the active power at fundamental frequency demanded by the load, drastically reducing the fundamental current I_1 flowing through the electrical meter from the grid.
- **Relative stability of harmonics current:** The non-linear loads of the plant continue to inject harmonic currents that close towards the grid. Since I_1 decreases drastically while the numerator remains nearly constant, or slightly decreases, the percentage ratio undergoes strong increase.



6. Plant Criticalities, Resonances, and Power Quality Solutions

The concurrence of the $\cos\phi$ decrease and the THDI% increase led to severe plant criticalities:

- **Insufficiency of conventional power factor correction systems:** Traditional varmetric controllers based on upstream CT readings may lose reference measure and incorrectly switch capacitive steps due to the distortion and bidirectional flow of currents. Furthermore alarms due to low I_1 are tripped
- **Harmonic resonance risk and amplification:** The presence of power factor correction capacitors in parallel with the substation transformer short-circuit inductance in the presence of a high harmonic spectrum (THDI% > 15%) can cause high-frequency parallel resonance phenomena, resulting in dangerous harmonic current amplification and thermal overload of the capacitors.

7. Conclusions

In this specific case, the customer's problems were resolved by

installing a new AAR/6 series power factor correction equipped with "anti-resonance" inductors, tuned to a resonance frequency of 189 Hz corresponding to a detuning factor $p=7\%$.

This replacement was necessary for safety reasons, as the existing power factor corrector, (manufactured by another company), was neither equipped with reactors nor with overcurrent protection.

Installation of an active filter (AHF) high-efficiency (SiC MOSFET technology)

The customer obligation was not to exceed 6% THDi% on defined production lines.

Summarizing the various features of the solutions currently available in our product portfolio:

Solution	Item	Resonance protection	Inductive PFC	Capacitive PFC	Harmonics reduction	Effect on the grid	
						Cos φ	THDi%
	Standard APFC	✗	✓	✗	✗	✗ *	✗
1	Detuned APFC	✓	✓	✗	✗	✓	✗
2	SVG	✓	✓	✓	✗	✓	✗
3	HSVG	✓	✓	✓	✗	✓	✗
4	AHF	✓	✓	✓	✓	✓	✓
5	HAHF	✓	✓	✓	✓	✓	✓

* Inefficiency caused by the APFC's disconnection tripped when THDi% levels are above the allowed threshold

The choice depends on the customer's needs, which can be summarized as follows:

- **Ensuring the safety of the network and efficiency of capacitive power factor correction**
Solution 1: Install detuned power factor correction (APFC) based on the harmonic content (AAR/xxx series)
- **Maintaining the efficiency of both capacitive and inductive PFC (issues with reactive power injection into the grid)**
Solution 2: SVG for systems requiring low reactive power
Solution 3: HSVG for systems requiring high reactive power and with significant THDi
- **Prevent malfunctions or unintended shutdowns of production equipment by staying within regulatory limits (CEI 0-16, IEEE 519,)**
Solution 4: AHF for systems requiring high harmonic compensation currents but not requiring power factor correction (Cos φ)
Solution 5: HAHF for systems requiring medium-to-high compensation currents and power factor correction (Cos φ)

The choice between a "pure" active device and a hybrid one is essentially economical related on the required power for factor correction and the distortion current to be compensated. For large loads, the hybrid option is more cost-effective