GAMESA ELECTRIC · WHITE PAPER

Unlocking the hidden benefits of ultra-low THD inverters in solar and storage projects

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Executive summary

Harmonic losses represent a critical yet often underestimated factor impacting energy production efficiency in photovoltaic (PV) systems. This white paper examines the profound implications of harmonic losses on energy production, emphasizing the advantages of ultra-low THD inverter design such as the **Gamesa Electric Proteus** in mitigating these losses.

Historically, the significance of harmonic losses has been overlooked within the renewable energy sector. Even international standards are not adapted to the technological reality of today's inverters. However, recent research reveals that harmonic losses can lead to substantial reductions in energy production. Comparative analysis indicates that annual energy production with ultra-low THD inverters is up to 0.35% higher than with other standard inverters, attributable to their lower harmonic losses.

Beyond the immediate impact on energy production, harmonics can trigger mechanical vibrations, thus compromising the longevity of critical components such as transformers. An improper transformer design or elevated harmonic content may result in production losses exceeding 1% of the total energy output, underscoring the urgency for effective mitigation strategies.

The report highlights the pivotal role of the **Gamesa Electric Proteus** inverter in addressing this challenge. Through rigorous assessment by an independent technical advisor, Proteus inverters have consistently demonstrated significantly lower harmonic losses compared to alternative products. This distinction underscores the competitive advantage offered by Gamesa Electric in optimising energy production.

By prioritising harmonic loss reduction, stakeholders in the renewable energy sector can unlock substantial gains in energy output and operational longevity. Implementing ultra-low THD inverters such as the Proteus inverter not only enhances energy production but also safeguards critical infrastructure, ensuring sustained performance and profitability over the lifetime of the PV plant.

Introduction

The massive deployment of renewable energies poses multiple challenges for electricity grids. The rapid replacement of conventional synchronous generation by asynchronous distributed generation is forcing technologists to develop increasingly sophisticated renewable generation equipment with enhanced grid support capabilities.

In the case of solar photovoltaic generation and battery storage systems, the key element is the inverter, which is a power electronics device that not only converts direct current into alternating current but also acts as an interface to the grid and is the device that must provide advanced services both for grid stability and other smart grid-oriented services.

It is estimated that by 2030, more than 1,675,000 inverters or converters for distributed renewable generation will be connected to electricity grids around the world [3]. But there is one element associated with this renewable generation equipment that is often overlooked and is key to a stable grid: **harmonics**. In DC-AC inverter-based systems such as solar and storage, the introduction of harmonic distortion into the grid can be highly detrimental to the generation plant and to the grid in general.

This white paper delves into the harmful effects of harmonic distortion or THD and presents a case study comparing inverters with different THD levels to quantify their impact, showing the great advantages of inverters with ultra-low THD levels such as the **Gamesa Electric Proteus.**

What is THD?

THD stands for Total Harmonic Distortion. Solar photovoltaic power plants produce electricity in direct current (DC) but to feed this electricity into the grid, it must be converted into alternating current (AC). This is the main function of inverters, power electronics equipment that transform direct current into alternating current and act as an interface between the plant and the grid.

Inverters use semiconductors switching at high frequencies to make the DC-AC transformation using pulse width modulation or PWM. Basically, it is to mimic a sinusoidal by generating high frequency pulses with different amplitude and frequency.

As the switching frequency increases, the output current waveform is more similar to the ideal sinusoidal signal. Of course, even though the switching frequencies used are getting higher and higher, the resulting signal will not be perfect. These “imperfections” are the so-called harmonics and the percentage of distorted signal in relation to the total is the THD. In other words, THD is the ratio that measures the quality of the signal. The higher the THD, the more distortion the signal introduces, with **the highest harmonic content being close to the switching frequency.**

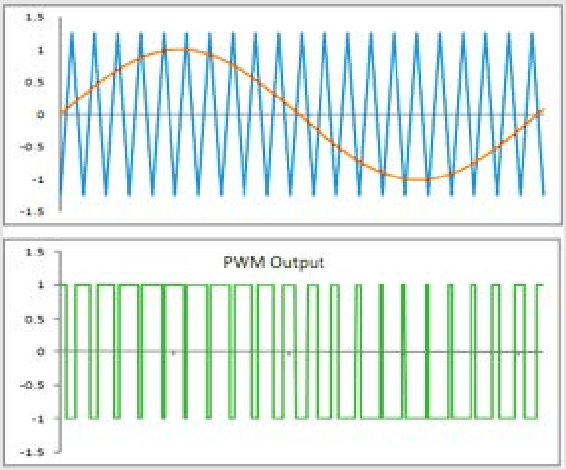


Figure 1: generic PWM output

The use of **pulsating signals** causes the resulting waveform **to deviate from a pure sine wave**

$$THD = \frac{Harmonics}{Fundamental} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \cdots}}{I_1}$$

$$I_{RMS} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + \cdots} \rightarrow THD = \sqrt{\left(\frac{I_{RMS}}{I_1}\right)^2 - 1}$$

Figure 2: THD mathematical definition [4]

Any nonlinear load in a power system (as inverters and rectifiers) is characterized by the above-mentioned introduction of a switching action and consequently signal interruptions. This behaviour provides signal with different components that are multiples of the fundamental frequency of the system (50 Hz or 60 Hz depending on the grid). These components are called harmonics.

As a result, the final waveform of current or voltage is a composition (and hence can be discomposed) as an addition of waveforms with different frequencies; for a fundamental frequency of 50 Hz, the second harmonic frequency is 100 Hz, the third one is 150 Hz and so on.

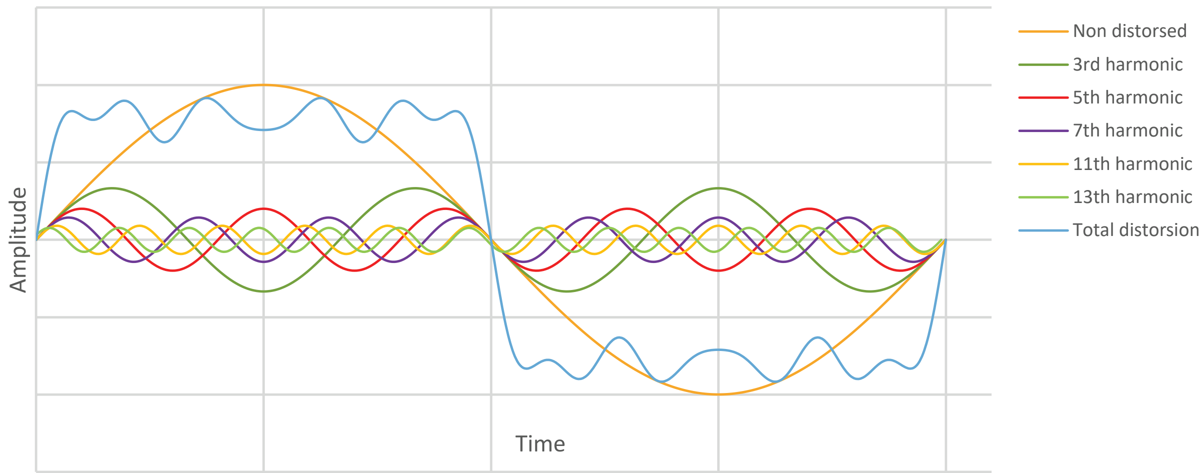


Figure 3: Example of harmonics and THD [4]

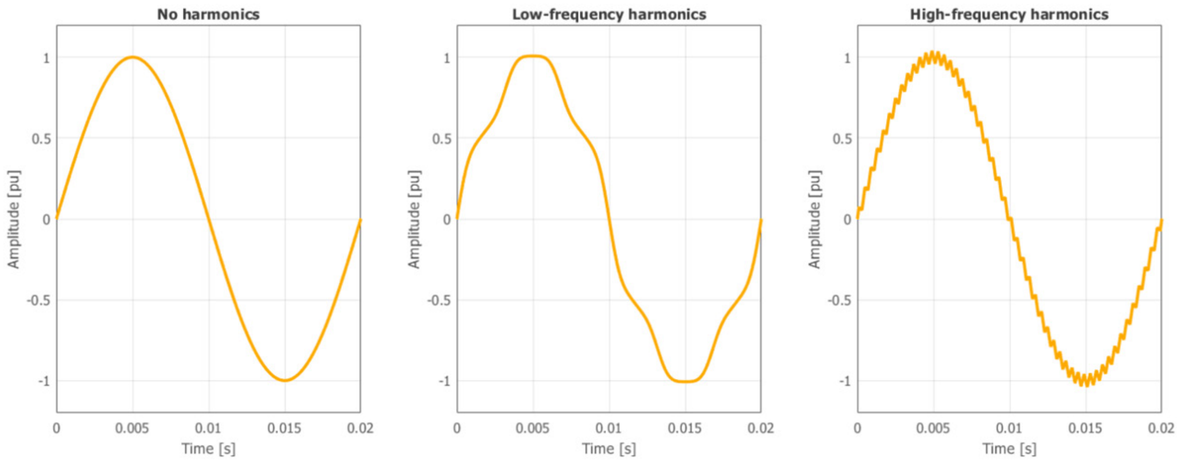


Figure 4: Example of harmonics effect in the signal

Effects of THD on solar photovoltaic plants

As we have seen, THD is a ratio that indicates the degree of distortion of the main signal due to the presence of harmonics. This distortion generates a multitude of problems in photovoltaic generation installations and in grids in general. We can group the undesired effects of harmonics into 3 main aspects:

Increased electrical losses

- Ohmic losses. Conductors and components suffer overheating and must be oversized since losses are equal to I^2R. Ideally active power only depends on the fundamental current (I_1) but when harmonics are present current effective value (I_{RMS}) is higher, so losses as well.

$$THD = \sqrt{\left(\frac{I_{RMS}}{I_1}\right)^2 - 1} \rightarrow I_{RMS} = I_1\sqrt{1 + THD^2} \rightarrow I_{RMS} > I_1$$

- Capacitors conduct high-frequency signals, more harmonics implies more losses.

- In transformers, harmonics means higher losses in windings (due to current) and in the core due to Eddy currents (proportional to frequency). It affects to transformer K-factor feature, the ability to withstand the heating effects due to non-lineal loads.

- “Skin effect”, the current flowing through a conductor tend to distribute to the surface as frequency increases. At higher frequencies the current is moved away from conductor center and is concentrated close to its surface, diminishing the effective conductive area and increasing the losses.

Shortened service life

- Harmonics cause mechanical vibrations and noise in magnetic components such as transformer and cables.

- Harmonics can cause resonances.

Poorer performance

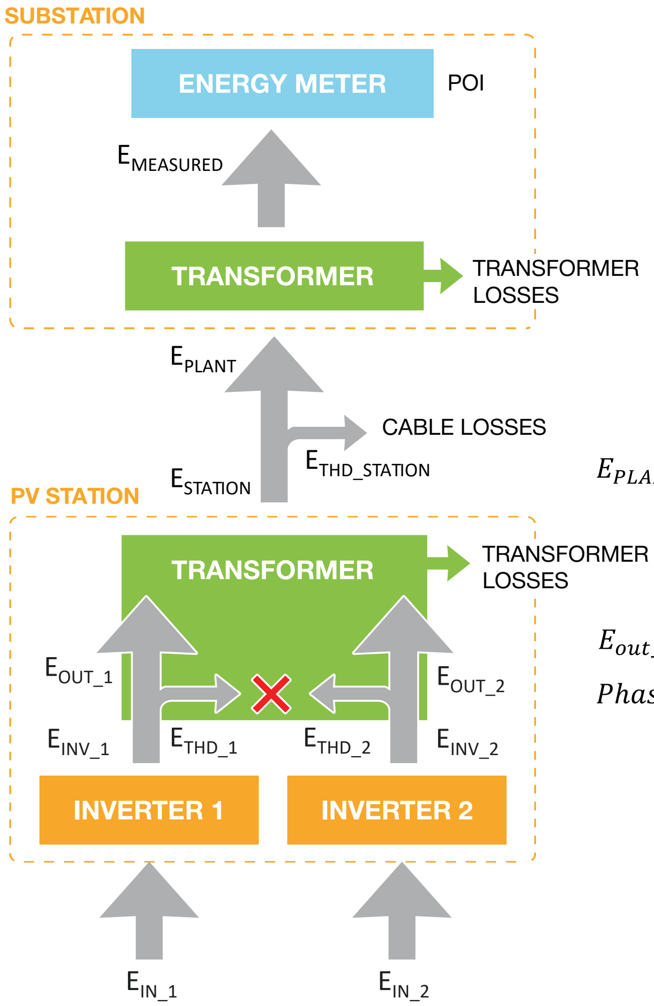
- Harmonics worsen the power factor. This means that more apparent power is required to obtain the same active power.

- Harmonics are the main cause of effects such as flicker that cause malfunctions in electronic devices.

- Electrical resonances, voltage or current fluctuations can, in extreme cases, trigger protections and cause the system to fail.

Case study: *PV Plant THD and its effect on total energy produced*

There are several techniques to reduce the THD at equipment output. In case of PV stations composed by multiple inverters in parallel operation, the *phase-shifting* is the most widely used; switching signals of all converters are slightly displaced in such way that harmonics due to switching cancel each other. The result is that the THD for the overall plant is lower than that generated by individual inverters.



$$E_{PLANT} = E_{STATION} + E_{THD\_STATION}$$

$$E_{out\_x} = E_{inv\_x} + E_{THD\_x}$$

$$Phase\ shifting\ \rightarrow\ E_{THD\_1} \approx -E_{THD\_2}$$

Figure 5. Energy evolution due to harmonics in a PV plant [4]

However, a low THD level at the output of the plant may lead to misleading conclusions as the harmonic distortion of individual inverters negatively impacts on yield, despite of the low plant THD.

Consider 2 PV stations (cases A and B) with same rated power and inner configuration (as described in previous figure) but with different harmonic spectrums; inverters of case A have lower THD than those in case B. The next graph shows the energy evolution of both cases taking into consideration only losses due to harmonics (rest of losses have been ruled out for simplicity).

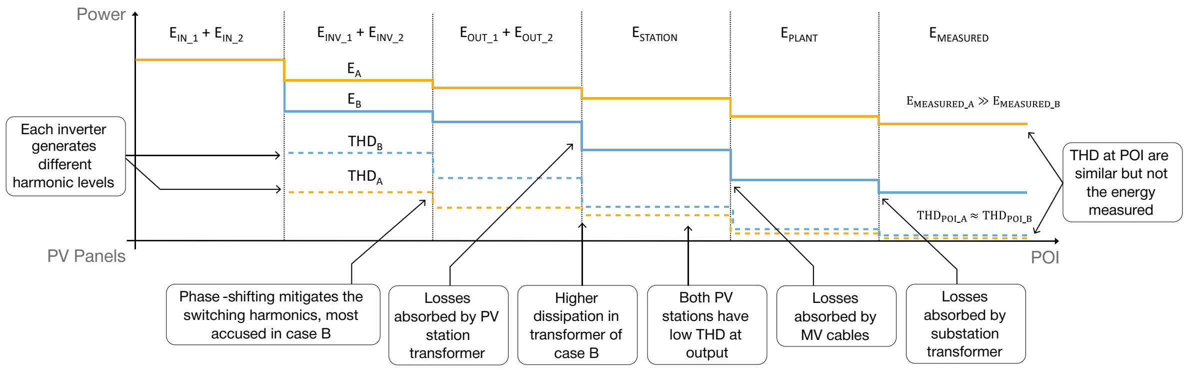


Figure 6. Comparison of THD and energy due to harmonics in 2 cases with different harmonic spectrum

Single inverters of case B converts higher amount of energy into high frequency components than case A. In case B the effect due to phase-shifting is most accused as well as the losses dissipated by PV station transformer, resulting in a PV plant THD close to case A.

It concludes that higher THD means less effective energy at POI, therefore the effect of harmonics of individual inverters impact on total yield although the PV plant is almost equally affected.

What are the THD levels defined in the standards?

As can be seen in the table below, there are several standards that set THD limits at the point of connection or PCC. The main ones are IEEE 519 and IEC 61000-3-2[1] which recommend a maximum value of 5%. The German and UK standards are more demanding and set the maximum at 3%.

Table 2. Current harmonics distortion limits of the PV systems.

The Standards	Type	Harmonic Order (h)	Distortion Limit	THD (%)
IEEE 1547 AS 4777.2 (Australia), GB/T (China), and ECM (Malaysia)	Odd	$33 < h$	<0.3%	<5%
		$23 \leq h \leq 33$	<0.6%	
		$17 \leq h \leq 21$	<1.5%	
		$11 \leq h \leq 15$	<2%	
		$3 \leq h \leq 9$	<4%	
	Even	$10 \leq h \leq 32$	<0.5%	
		$2 \leq h \leq 8$	<1%	
UK (EREC G83 Stds.)	Odd	h = 3, 5, and 7	<(2.3, 1.14, and 0.77)%	<3%
		h = 9, 11, and 13	<(0.4, 0.33, and 0.21)%	
		$11 \leq h \leq 15$	<0.15%	
	Even	h= 2, 4, and 6	<(1.08, 0.43, and 0.3)%	
		$8 \leq h \leq 40$	<0.23%	
IEC 61000-3-2	Odd	h = 3, 5, and 7	<(3.45, 1.71, and 1.15)%	<5%
		h = 9, 11, and 13	<(0.6, 0.5, and 0.3)%	
		$15 \leq h \leq 39$	<0.225%	
	Even	h = 2, 4, and 6	<(1.6, 0.65, and 0.45)%	
		$8 \leq h \leq 40$	<0.345%	

Table 3. Voltage harmonics distortion limits of the PV systems.

The Standards	Voltage Bus	Max. Individual Harmonics	THD (%)
IEEE 519	$(V \leq 1)$ kV	5%	8%
	$(1 \leq V \leq 69)$ kV	3%	5%
	$(69 \leq V \leq 161)$ kV	1.5%	2.5%
	$(V > 161)$ kV	1%	1.5%
IEC 61000-3-2	$(2.3 \leq V \leq 69)$ kV	3%	5%
	$(69 \leq V \leq 161)$ kV	1.5%	2.5%
	$(V > 161)$ kV	1%	1.5%

Figure 7: summary of THD levels defined in main international standards [1]

1. Only applies to equipment with a current per phase lower than 16 A.

In addition to the maximum recommended THD value, another key aspect in the standards is up to which harmonic is evaluated. And this is where the standards are most outdated as they generally evaluate up to the 50th harmonic, which translates to frequencies up to 2.5 kHz (or 3 kHz in 60 Hz networks). This frequency level is well below the switching frequencies of today's inverters.

These standards are not adjusted to the reality of today's technology, so that a commercial inverter can comply with the main standards and still generate high losses at high frequencies.

For this reason, the design of inverters aimed at achieving **very low THD** at **very high harmonics** is key. These are the so-called "ultra-low THD inverters" such as the **Gamesa Electric Proteus**, which, thanks to its design, achieves a THD of 0.7% at the 200th harmonic.

Keys to ultra-low THD inverter design

The Gamesa Electric Proteus inverter achieves ultra-low levels of harmonic distortion or THD even at high frequencies, with levels of 0.7% at the 200th harmonic, including the switching frequency harmonics, thanks to a design aimed at mitigating these harmonics and supported on 3 main pillars:

HARDWARE

An accurate design of compact and passive low-pass filter at output of the power stage ensures the blocking of any high frequency component. All components have been designed to achieve the best tuning in terms of cutoff frequency. Proteus converters also include a high frequency (HF) filter that attenuate high frequency harmonics not considered by international standards.

SOFTWARE

The use of proper hardware assures the current distortion is below international limits. However, it's possible to reach further by using of special control algorithms based on the *selective harmonic cancellation* and advanced switching strategies which minimize undesired components.

VALIDATION

Gamesa Electric ensures the proper integration of its equipment in any conditions, performing studies at very high frequencies, measuring harmonics corresponding to frequency of 125 kHz for a 50 Hz grid and 150 kHz for a 60 Hz grid. This presents several advantages:

- Transformer manufacturers uses the information to fine-tune their designs.
- Skin effect, and its associated losses. is most acute at higher frequencies.
- Minimize the possibility of electrical resonances at those frequencies.

All these measures result in the Proteus inverter's compliance well above the requirements of international standards. Graphically, it can be appreciated the huge differences of measured values respect to limits.

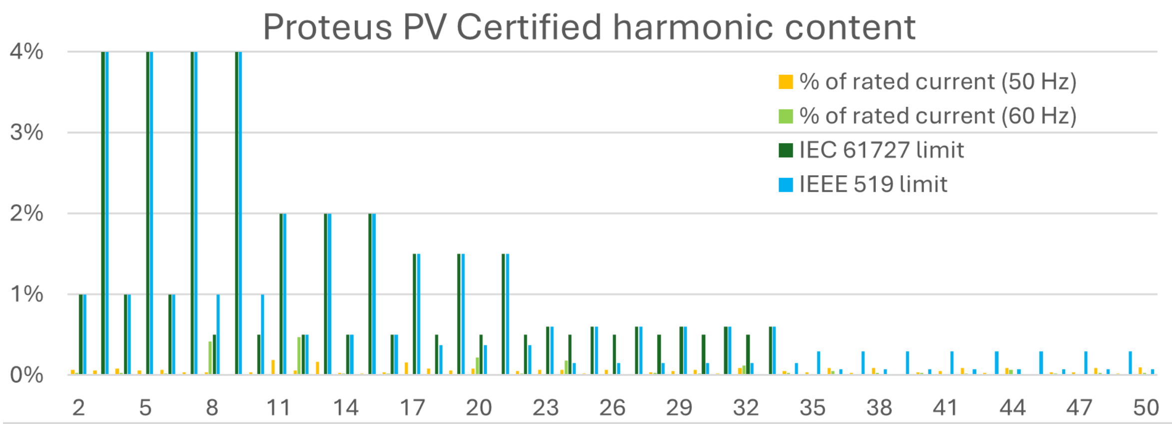


Figure 8. Comparison of converter harmonics with limits of international standards [4]

Furthermore, all measures for the certification were repeated at different load levels resulting a **total harmonic distortion lower than 1% at any load level** for harmonics up to 50th (equivalent to 2,5kHz).

Grid frequency	33% of rated power	66% of rated power	100% of rated power	IEC 61727 limit	IEEE 519 limit
50	0.6%	0.4%	0.5%	5%	5%
60	0.5%	0.5%	0.8%	5%	5%

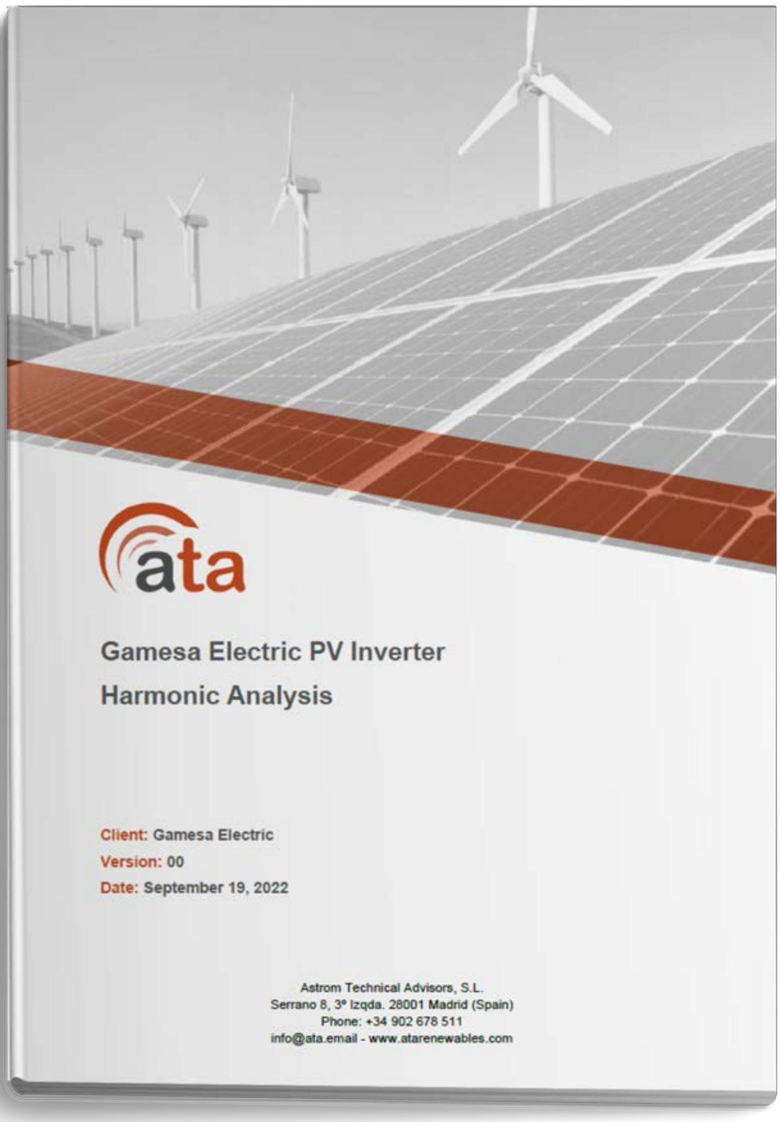
Table 1. THD certificated at different load levels (data from certificate) [4]

Additional measures carried out by Gamesa Electric show a very low distortion even at **very high frequencies** with a THD at 125 kHz results in **1.0%** (935Vdc) and **1.1%** (1300Vdc).

Case study: *Quantifying the benefits of ultra-low THD*

As explained previously, the harmful effects of harmonics can be grouped into 3 groups: reduced lifetime, poorer performance and higher losses. It is this last aspect that we are going to quantify with a practical case study.

For this purpose, we have been assisted by the independent technical advisor ATA, which has carried out a theoretical study to estimate the production losses in 2 scenarios.



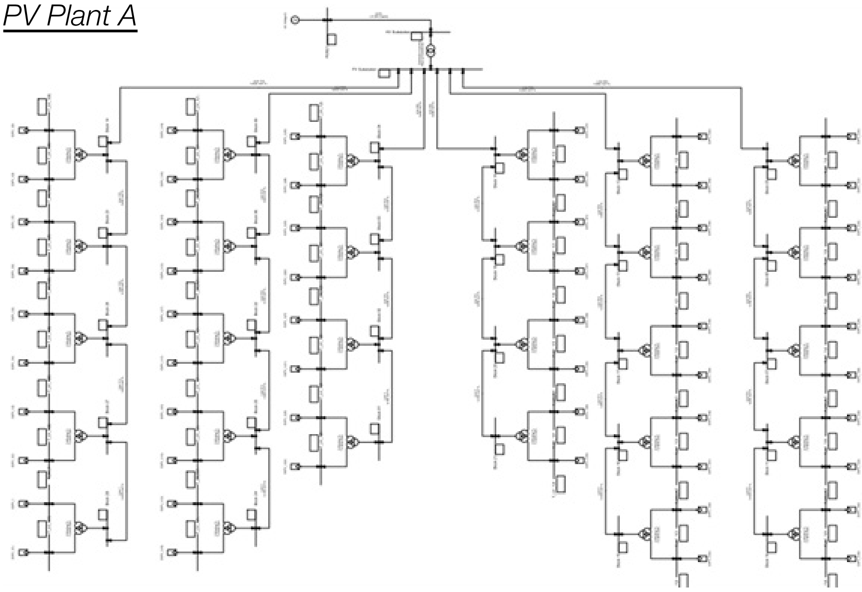
The methodology and tools used were as follows:

Plant A: Australia	Plant B: Spain
220.52 MWdc	49.99 MWdc
210 MW	48.75 MW

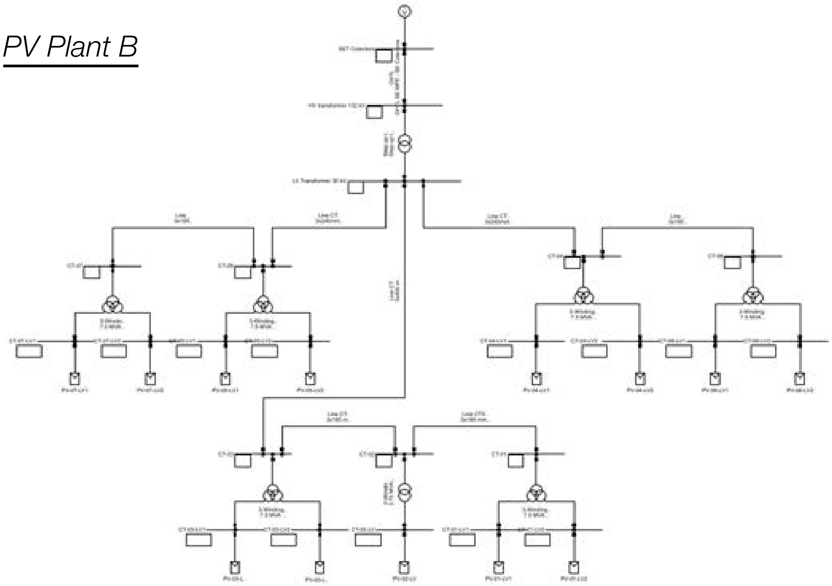
1. Definition of the 2 simulation scenarios

The DigSilent diagrams for each plant are as follows:

PV Plant A



PV Plant B



2. Definition of injected harmonic spectra

To compare different inverters, 4 harmonic spectra up to harmonic 198th have been generated for all power levels:

No-loss Case
Assuming no harmonics.

Base Case: Gamesa Electric Proteus
Spectrum obtained from the accredited laboratory measurement for the VDE 4110 standard [2].

Case A
Standard commercial Inverter incorporating a high frequency filter with high attenuation.

Case B
Standard commercial Inverter incorporating a high-frequency filter with medium attenuation.

Case C
Standard commercial Inverter incorporating a high frequency filter with low attenuation.

3. Simulations in DigSilent Power Factory

To calculate the losses caused by harmonics in each case.

4. Simulations in PVSyst

To estimate plant yield with and without losses. The results for each scenario are as follows:

No-loss Case energy differences (%) - PV Plant A (220.5 MWdc)			
Base Case	VS Case A	VS Case B	VS Case C
0.002%	0.038%	0.088%	0.326%

No-loss Case energy differences (%) - PV Plant B (50 MWdc)			
VS Proteus	VS Case A	VS Case B	VS Case C
0.002%	0.040%	0.094%	0.350%

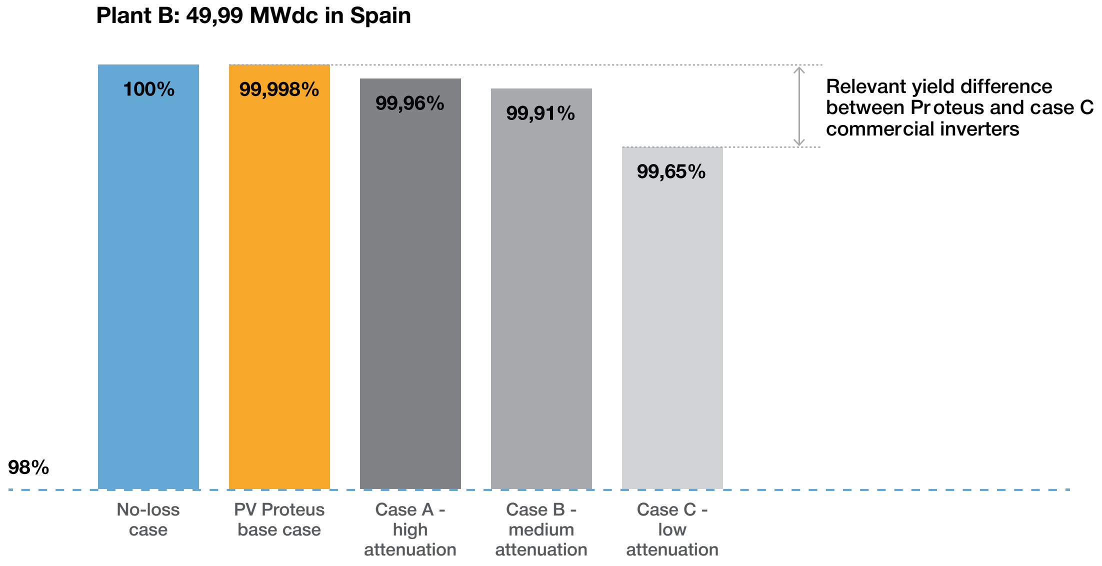


Figure 9: Yield differences in Plant B. Energy production differences are very relevant between PV Proteus and other commercial inverters

As can be seen in the results, harmonic losses in the base case using Gamesa Electric Proteus inverters with ultra-low THD are practically negligible, while in the case of inverters with low attenuation filters, despite being able to comply with the standards, losses reach up to 0.35% of the total production .

If we translate this difference between a Proteus inverter and a Case C-type inverter into euros, we see that the extra annual income can be very significant:

Plant A simulation:
Proteus up to **0,32%** more energy

Energy Price (€/MWh)	Annual extra revenues per MW plant A	Annual extra revenues plant A (210 MW)
50	**415** €/MW/yr	**87,154** €/yr
100	**830** €/MW/yr	**174,308** €/yr
150	**1,245** €/MW/yr	**261,462** €/yr
200	**1,560** €/MW/yr	**348,616** €/yr

Plant B simulation:
Proteus up to **0,35%** more energy

Energy Price (€/MWh)	Annual extra revenues per MW plant B	Annual extra revenues plant B (48.75 MW)
50	**390** €/MW/yr	**19, 011** €/yr
100	**780** €/MW/yr	**38,021** €/yr
150	**1,170** €/MW/yr	**57,032** €/yr
200	**1,560** €/MW/yr	**76,042** €/yr

Considering that solar plants are designed to operate for a minimum of 25 years, the extra income generated by plants with ultra-low THD inverters is very significant and far exceeds a higher initial investment to ensure the lowest level of losses.

CONCLUSION

Low THD has direct advantages such as lower losses and higher revenues, and indirect ones as more reliability for transformers and increased grid stability.

All these factors combine to have a positive impact on the LCoE of the plant, which is difficult to quantify due to the lack of technical information and standards on harmonics at high frequencies.

References

[1] Power Quality Assessment of Grid-Connected PV System in Compliance with the Recent Integration Requirements - Ali Q. Al-Shetwi 1,2 , M A Hannan 2,* , Ker Pin Jern 2 , Ammar A. Alkahtani 1 and A. E. PG Abas

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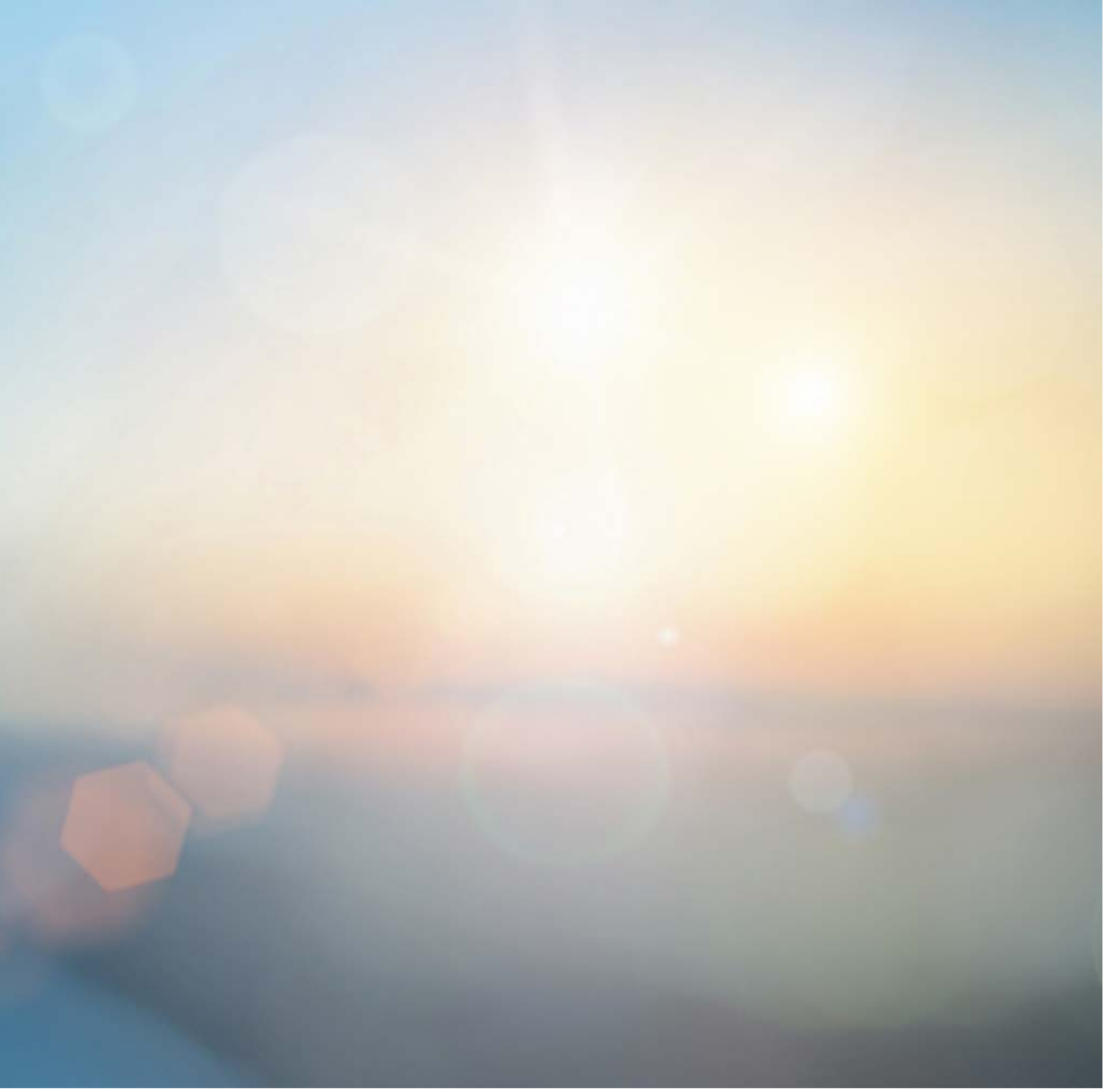

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