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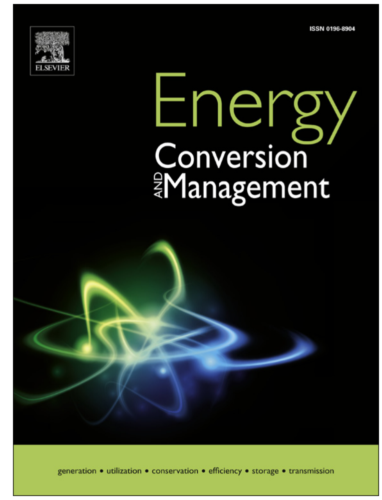

Performance of grid-tied PV facilities: a case study based on real data

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Performance of grid-tied PV facilities: a case study based on real data.

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Abstract

A new procedure is presented to analyse the performance of grid-tied PV facilities. It needs limited amounts of data that are easily sourced and is based on knowledge of the analyzed system and its mode of operation. The procedure is applied, in a case study, to compare real PV production at two 100 kWp grid-connected PV installations. Located in the same geographical region, the installation of these two facilities followed the same construction criteria -PV panels, panel support system and wiring- and the facilities were exposed to the same atmospheric temperature and solar radiation. They differ with regard to their inverter technology: one facility uses an inverter with an integrated transformer system and the other uses a transformerless inverter. The results show that the transformerless inverter system performed better than the isolated system by a factor of 1.2%, which, in economic terms, represents more than 2000 €/year.
Keywords: PV facilities, performance, transformerless inverter, isolated inverter.

1. INTRODUCTION

Renewable energy sources, which includes PV, will be essential for Europe to achieve its all-important objectives of reducing greenhouse gases and to guarantee decentralised energy production from local sources [1]. The solar PV market has seen spectacular growth over the recently years, a trend that is forecast to continue over coming years. Its main drivers are the reduction of PV generation costs and the introduction of new regulations to stimulate the use of renewable energy. The success of these policies relies on the cost-per-watt reduction of PV systems, in order to make PV energy more competitive with respect to traditional energy sources [2]. Importantly, there is huge potential for further reductions in the costs of generation: around 50% up until 2020. Depending on system size and irradiance levels, the cost of PV electricity generation in Europe could decrease from a range of 0.16-0.35 €/kWh, in 2010, to a range of 0.08-0.18 €/kWh, in 2020 [3]. The profitability of these investments has become a priority for both government and industry, although financial subsidies may slowly be removed as grid parity is gradually reached.

Various studies have been conducted on PV plant performance and its different elements [4-7]: the influence of PV module technology [8, 9], inclination [10, 11], inverter and control systems [12], sun-tracker system [13] and wiring [14] have been determined for experimental and real facilities,. They underline the relatively important role of all these elements in overall system performance.

One of the fundamental problems in any analysis of the energy performance of real grid-tied PV systems is the lack of reliable operational data over extended periods. Although owners of PV systems have an inherent incentive to ensure that their systems perform well, many homeowners and construction firms lack the necessary information and expertise to carry out this task effectively [15]. Some studies have been performed at experimental facilities equipped for data collection [12, 16-23]. Data from owners or maintenance services are very scarce and real PV systems are not usually monitored. Measurement systems at most facilities only record total production, which is necessary for invoicing the energy that is produced. In some cases, data are recorded in the inverter system after the conversion stage. Poor knowledge of technical and constructive features and their operational quality affects the visibility and image of renewable energy and hinders the optimization and predictive maintenance of PV plants that are already up and running. Very few studies using real data from the owners or operators have been published [24, 25]. The contribution of this study could help to fill this gap, encouraging owners and maintenance services to improve their facilities.

Various methodologies guide the design of grid-tied PV facilities based on the optimisation of such parameters as array distribution on the plot, use of sun tracker systems, type of connection to the inverter, and distribution of electrical protection. In any case, the PV array is connected to the network through a power processor: the inverter system. The essential function of the inverter is to extract the maximum power from the PV array and process it with maximum efficiency for transmission under appropriate conditions to the AC network. This involves the use of a suitable algorithm for Maximum Power Point Tracking (MPPT). As few conversion stages as possible should be used, as well as an appropriate signal that meets safety and quality requirements for injection into the network [26].

Different architectures have been described for PV inverters [27] and configurations for facilities [28] that offer reliable technical solutions, in view of local conditions. In all of them, the cost of the inverter together with the associated operating and maintenance costs, are between 10-15% of the total investment costs of a PV facility [12].

Grid-connected PV facilities must satisfy the standards issued by the utility companies and network regulators. In Spain, inverter systems were used with a transformer and a low voltage tie to the grid, up until the entry into force of Royal Decree 661/2007 [29], which permitted network connections with transformerless inverters. The consequent proliferation of systems that need new power transformer units, where the owner of the

PV system is responsible for implementation and maintenance costs, has led to the introduction of transformerless inverters at a lower cost for the plant. An obvious question that arises is the impact of these changes on energy performance and installation costs.

A new procedure is presented in this study to analyse the performance of grid-tied PV facilities. It needs limited amounts of data that are easily sourced and is based on knowledge of the analyzed system and its mode of operation. This procedure has previously been applied by the research group [24]. It is examined here in a case study, in order to conduct a comprehensive analysis of the influence of one of the key elements of PV facilities on their energetic and economic performance: the inverter system. Theoretical works [30] claim that transformerless inverter systems outperform isolated systems. Experimental measures are highlighted, as several factors affect the operation of an inverter that are difficult to predict by simulation alone. The present work uses two complete years of production data from real PV systems to test the extent to which this is true. Previous works [31, 32] have reviewed existing inverter technologies, but have not analysed the influence that the use of one system or another may have on energy efficiency and cost of installation.

2. BACKGROUND

PV inverters for inclusion in a transformer system at the conversion stage are classified as either isolated inverters, with galvanic isolation, or transformerless inverters. Kjaer et. al. [27] performed a comprehensive review of the requirements to be covered by the grid: detection of islanding operation, and system grounding of the inverter system, related to power quality, injection of DC current into the grid, among others. They also analyzed aspects related to cost, efficiency and the service life of the inverter. Galvanic isolation causes transformation losses, estimated at between 1% and 2%. Transformerless inverters perform better than isolated inverters. Additionally, low frequency transformers (LFT) increase the weight and the cost of the system in comparison with transformerless inverters [30]. In most modern facilities, the trend is to use High Frequency Transformers (HFT), which increase the performance of the inverter by up to 2% [33]. New topologies of transformerless inverters with high efficiency and low leakage currents to ground have been proposed [34-37]. Electrical leakage to ground due to the structure of PV arrays is another important issue, especially for transformerless facilities, if one of the terminals of the array cannot be grounded [36]. Current leakage to ground can be very significant, causing radiated and conducted electromagnetic interferences, distortion of the network signal and further losses to the PV system. It is therefore important to avoid hazardous ground potential gradients in transformerless inverters [38]. Table 1 presents a compilation of the pros and cons of both types of inverters.

Table 1

The three most important disadvantages of transformerless inverters (possibility of injection of DC to the network, current leakage to ground, and electromagnetic interferences) are properly solved in the most modern systems [39]. Their evident prevalence in the European market is due to their advantages in terms of cost, weight, size and performance [36].

3. THE FACILITIES

This case study involves two facilities (System 1 and System 2) located at the centre of the Spanish autonomous region of Castilla y León, at Herrera de Valdecañas (System 1) and at Magaz de Pisuerga (System 2), at a distance of 12.9 km from each other. The geographical coordinates of both systems are shown in Table 2. They stand on a gentle, south-facing slope that is conducive to natural air circulation, one of the most beneficial aspects for improving the panels' electrical production in summer time. Hence, the two facilities are subject to very similar environmental conditions, in terms of temperature, radiation, humidity, and wind speed. The area benefits from very favourable atmospheric conditions. Solar irradiation is estimated at approximately 1,450 Kwh/m^{2}year[40]. The ambient temperature range is between 4ºC and 20ºC and the number of cloudy days is very low [41]. Figure 1 presents photographs of both installations.

Figure 1

The PV panels at both facilities are FOTONA model-180D [42] and their technical specifications are presented in Table 2. A mobile structure adjusts the position of the panels according to the time of year, in order to optimize electrical production. Its design also helps to minimize the visual impact of the facilities. The maximum height of the panels (1.80 m) usually occurs during winter time and they can be lowered at other times of the year, using a manual system that can vary their angle of inclination by between 5º and 50°. This adjustment is performed every 26 days or so. Figure 2 presents the panel support system and Figure 3, its highest and lowest positions. This panel support system is a standard fitting in all facilities run by the same company [24, 25].

Figure 2

Figure 3

Table 2

The distribution of the panels in the plot determines the arrangement of the protection systems and wiring losses. Both facilities are structured in arrays composed of 14 PV panels grouped into 3 strings. Each string has a protection box, containing the protection elements (fuse and a 10 A switch). System 1 can generate 113.4 kW_p with 630 modules arranged in 45 groups each with 14 PV panels. The second facility, System 2, can generate 110.8 kW_p with 616 modules arranged in 44 groups. Groups of the array are connected in series that operate with a voltage of 515.2 volts (within the voltage range of the inverter). The current for each group is 4.89 A.

System 1 is located in a rectangular plot symmetrically distributed from South to North. The facility is structured in 15 rows, each with 3 PV arrays. System 2 is arranged in 15 rows with a different number of arrays: 3 rows of 1 array, 2 rows of 2 arrays, 3 rows of 3 arrays and 7 rows of 4 arrays. The protection boxes are located within the plot to minimize wiring losses.

Only one 100 kW inverter was selected for both systems: Sunny Central 100 SC (Indoor) [43] in System 1 and Sunny Central 100 HE (Outdoor) [44] for System 2. Their technical specifications are shown in Table 2. Both inverters are installed according to the manufacturer's instructions and use the same technology, except that System 1 has a transformerless inverter and System 2, an isolated inverter.

4. THE CASE STUDY

4.1. The analysis procedure

The proposed procedure involves a comparison that allows us to analyse the influence of different parameters on total plant performance, distributing data production at comparable quantitative intervals. It has previously been applied with some success

[24]. Total production data is used to analyse the performance of the facility. Detailed knowledge of wiring (location and connection of PV arrays, length and section of wiring) and of the technical specifications of both the inverter and the transformer systems is necessary.

The study began by comparing total electrical production, reducing all data to 100 kW_P. As very few facilities have radiation data in the exact area in which they are located, the first operation to perform is the estimation of global radiation levels in the area. In nearby facilities, it may be assumed that radiation will be the same for both plants. Several computer applications, such as PVGIS[40] or PVSyST[45], calculate average radiation levels at virtually any point on the map [46]. Nevertheless, the stochastic distribution of solar radiation can explain significant differences at nearby locations, although calculated radiation in this case was the same. An estimate of the actual incident radiation on an installation can be made from production data, the number of PV groups, the operating voltage and the maximum current, I_{PM}, in Peak Sun Hours (the equivalent number of hours per day when solar irradiance averages 1000 W/m^2, p.s.h.)

Wiring losses were calculated as a function of the wiring and the distance between the inverter and the measurement system (AC wiring losses) and the distances between the panels and the protection boxes, and the distance from the protection boxes to the inverter (DC wiring losses), for the maximum value of the electrical current flowing from the facilities.

Total production of each facility, $P_{C.S.}$, may be calculated from eq. (1):

$$P_{C.S} = P_{PVpanels} - E.L._{DC} - E.L._{inverter} - E.L._{AC} \quad \text{Eq. 1}$$

where $P_{PVpanels}$ are the PV electrical production in panels, $E.L._{DC}$ the DC wiring losses, $E.L._{inverter}$, the electrical losses in the inverter system and $E.L._{AC}$, the AC wiring losses. Applying equation 1 to both facilities and subtracting the respective results allows us to study the differences in the qualitative behaviour of the items in the equation.

4.2. Data analysis and classification

The two facilities under study – System 1 and System 2 – are the property of SOLARSAN S.L., which provided the data to the research group for this case study: total electric production, measured by the inverter and by the measurement system from both facilities over two years, 2009 and 2011: a total of 720 days with information on all seasonal periods. The study began by comparing electrical production at two available points, inverter and measurement system, reducing all data to 100 kW_P.

The technical specifications of the wiring in System 1 and System 2 for electrical AC and DC wiring loss calculations are shown in Table 3. The results presented in Table 4 are divided into DC and AC wiring loss. They take account of the estimated annual operating time for the area where the facilities are situated [40].

Table 3

Applying equation 1 to the facilities and subtracting, the difference in electric losses caused by the inverter, $E.L._{inverter}$:

$$\Delta E.L._{inverter} = \Delta P_{PVpanels} - \Delta P_{C.S.} - \Delta E.L._{DC} - \Delta E.L._{AC} \qquad \text{Eq. 2}$$

where, $E.L._{DC}$ and $E.L._{AC}$ represent the calculated differences in DC and AC electrical wiring losses, respectively. $P_{C.S.}$ and $P_{PVpanels.}$ represent the difference between total electrical production measured by the counter system and produced by the PV panels, respectively. From the manufacturer's specifications, a lower performance is estimated for an isolated transformer, so that the calculated $E.L._{inverter}$ should be a positive value.

As a first approximation, radiation [40] and temperature are assumed to be approximately the same at both facilities, given their proximity. That proximity means that they operate under very similar atmospheric characteristics [41]. This hypothesis also assumes equal production of PV panels ($P_{PVpanels}$=0). Figure 4 shows the 720 days under analysis, 76.7% of which present a positive value of calculated $E.L._{inverter}$. The number of days with positive values for the $E.L._{inverter}$ is greater than the number of days with negative values in all of the 24 months. Only in the months of lower production (December, January and February) do the number of days with positive and negative values converge. This confirms the working hypothesis, regardless of the electrical production facilities and the time of year under consideration.

Figure 4

To confirm the hypothesis that $P_{PVpanels}$=0, a detailed calculation of global radiation from the aforementioned procedure was performed. Differences in global daily radiation calculated from total production, working voltage, number of PV arrays and I_{PM} were between 3.608 and -2.540 p.s.h. The data were classified by homogeneity and all days in each interval are analyzed. As Figure 5 shows differences in global radiation, for most of the days under study, calculated between both facilities are within the shortest ranges. Analysing the days in the interval (-0.25,1) p.s.h., the $E.L._{inverter}$ has a positive value in 97% of cases. Only in 19 days was the performance of the transformerless inverter worse than the performance of the isolated inverter. Those days occurred when total production at the facilities was low, at below 100 kWh/day, so that both inverters were working at some distance from the MPPT.

Figure 5

As other factors will affect the variations in production at both facilities, a more detailed data analysis was conducted in which the calculated radiation levels were considered the same. For this study, days with differences in global calculated radiation lower than 0.125 p.s.h have been used. A total of 205 data items were within this interval and $E.L._{inverter}$ was only negative on 15 days, , when total production was lower than 100 kWh/day. For other values, assuming an average for the photovoltaic transformation of 14 % efficiency, (performance level of the PV panel specified by the manufacturer), then $E.L._{inverter} > P_{PVpanels}$, regardless of the sign of both magnitudes. The difference between $E.L._{inverter}$ and $P_{PVpanels}$ increased in the summer months, when production was greater, and was of the same order in the months of January and December, with very low production, when the inverters were operating outside the MPPT, a situation that is reflected in Figure 6.

Figure 6

Finally, a comparison between the values for $E.L._{inverter}$ and $P_{C.S}$ (Figure 7) reveals that both magnitudes continued to follow the same trend. This fact means that the unexpected negative values of $E.L._{inverter}$ are related to large differences in PV panel production, due to significant differences in global radiation, when the analysis is not applicable.

Figure 7

5. RESULTS AND CONCLUSIONS

A new procedure to calculate the performance of a grid connected PV system has been proposed. The procedure has been used to analyse two grid-tied PV plants over two full years of operation under real conditions. The analysis is based on a few parameters that are easily obtained from the management of the plant. We have studied the influence of two different inverters in use. Located in neighbouring geographic areas, both facilities experience similar meteorological conditions. The same criteria was followed for the installation of the two systems: use of the same PV panels and wiring layout, and minimization of electrical wiring losses before and after the inverter system. The facilities only differ with regard to the type of inverter they use: the inverter is from the same manufacturer and uses the same technology, except that System 1 has a transformerless inverter and System 2 an isolated inverter. A detailed analysis of the losses due to the wiring and the operation of the inverters has been completed on the basis of actual production data, measured at the inverter outlet and in the counter system. This analysis has shown that the transformerless inverter has habitually fewer operational losses than the isolated inverter, regardless of the radiation conditions and the time of the year under consideration. The performance of the transformerless inverter is estimated to be 1.2% higher than the isolated inverter. As annual production at each installation is valued at €60,000 over 30 years of operation, the use of the transformerless inverter implies a total saving of €20,000. The cost of the transformerless inverter is 10% lower than the isolated inverter and the associated costs of operation and maintenance and the occasional errors detected at both facilities are equal over the two years of this study (100% operational days for both systems). The experimental results confirm the theoretical predictions discussed in the literature and presented in the introduction section, which claim that transformerless inverters present greater energy efficiency than the isolated inverter. We may therefore conclude that the transformerless inverter system is more profitable from both an economic and energetic point of view and that its installation will imply shorter repayment schedules.

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Nomenclature section

$E.L._{AC}$	AC wiring losses.
$E.L._{DC}$	DC wiring losses.
$E.L._{inverter}$	Electrical losses caused by the inverter system.
HFT	High Frequency Transformers.
I_{PM}	Maximum power Current
kW_p	kW peak
LFT	Low Frequency Transformers.
MPPT	Maximum Power Point Tracking.
p.s.h.	Peak sun hour
$P_{C.S}.$	Total electrical production of each facility measured at the counter system.
$P_{PVpanels}$	PV electrical production in panels.
PV	Photovoltaic.
V_{PM}	Maximum power Voltage
W_P	Peak power
$E.L._{AC}$	Calculated differences in AC wiring electrical losses.
$E.L._{DC}$	Calculated differences in DC wiring electrical losses.
$E.L._{inverter}$	Calculated differences in the inverter electrical losses
$P_{C.S}.$	Calculated difference in the total production.
$P_{PVpanels}$	Calculated differences in PV electrical production at panels.

Figure captions:

Figure 1: (a) System 1 at Herrera de Valdecañas and (b) System 2 at Magaz de Pisuerga, Castilla y León.

Figure 2: Panel support system. Detail of mechanical support.

Figure 3: Panel support system. High and low panel positions.

Figure 4: Distribution of days with positive and negative values of calculated $E.L._{inverter}$ throughout 2009 and 2011.

Figure 5: Distribution at regular intervals of the differences in daily global radiation (p.s.h.) calculated between the two facilities: System 1 and System 2.

Figure 6: Comparison between $E.L._{inverter}$ and $P_{PVpanels}$, (KWh/day), and total production of System 1.

Figure 7: Number of days per month when the value of $P_{C.S}$ and $E.L._{inverter}$ follow the same pattern (positive or negative). The figure reveals that incoherent values of $E.L._{inverter}$ are related to differences in PV panel production

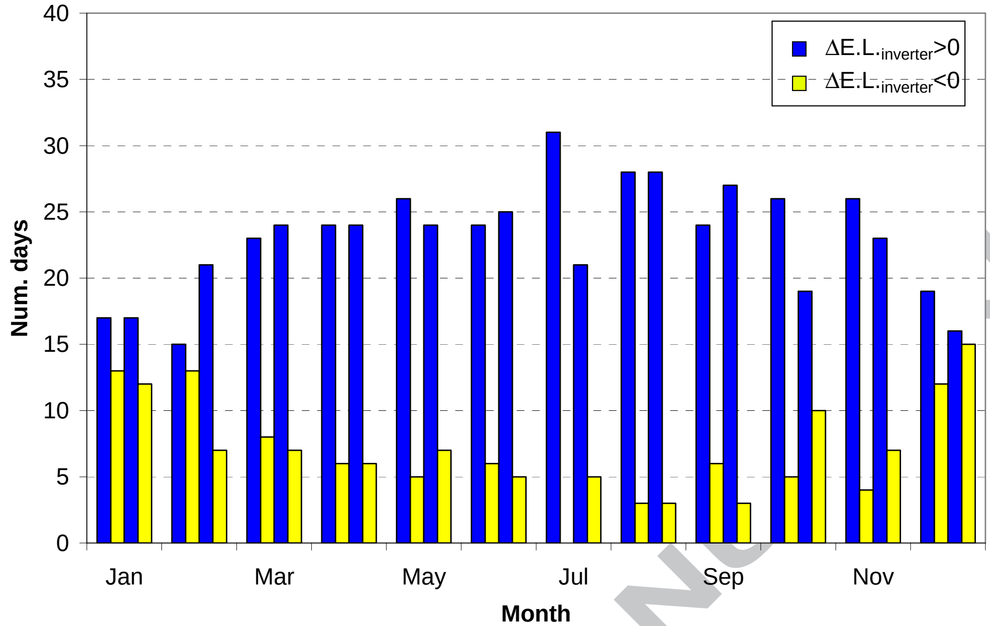
Figures

Figure 1: (a)

Figure 1: (b)

Figure 2

Figure 3



40
35
30
25
20
15
10
5
0
Num. days
Jan
Mar
May
Jul
Sep
Nov
Month
ΔE.L.inverter>0
ΔE.L.inverter<0

Figure 4

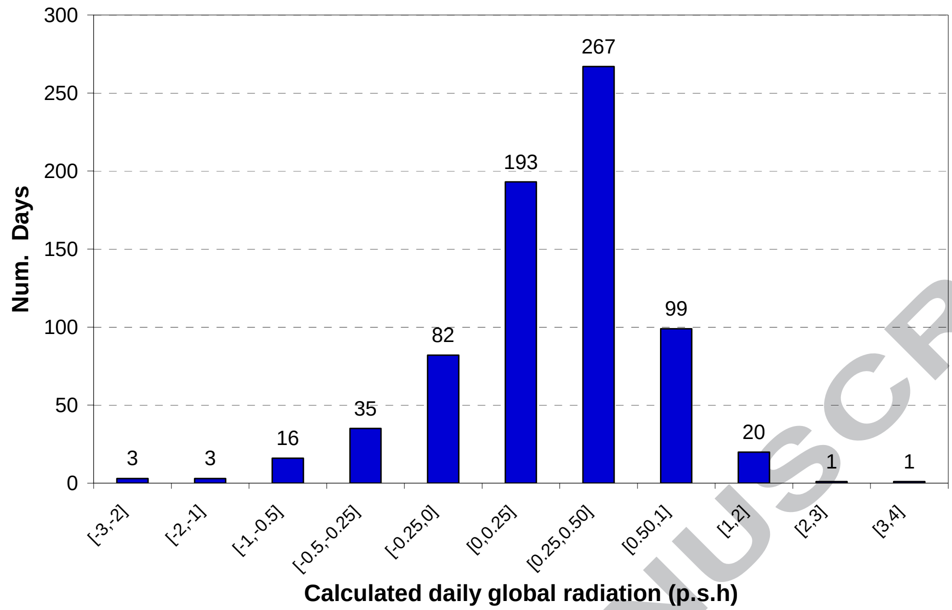
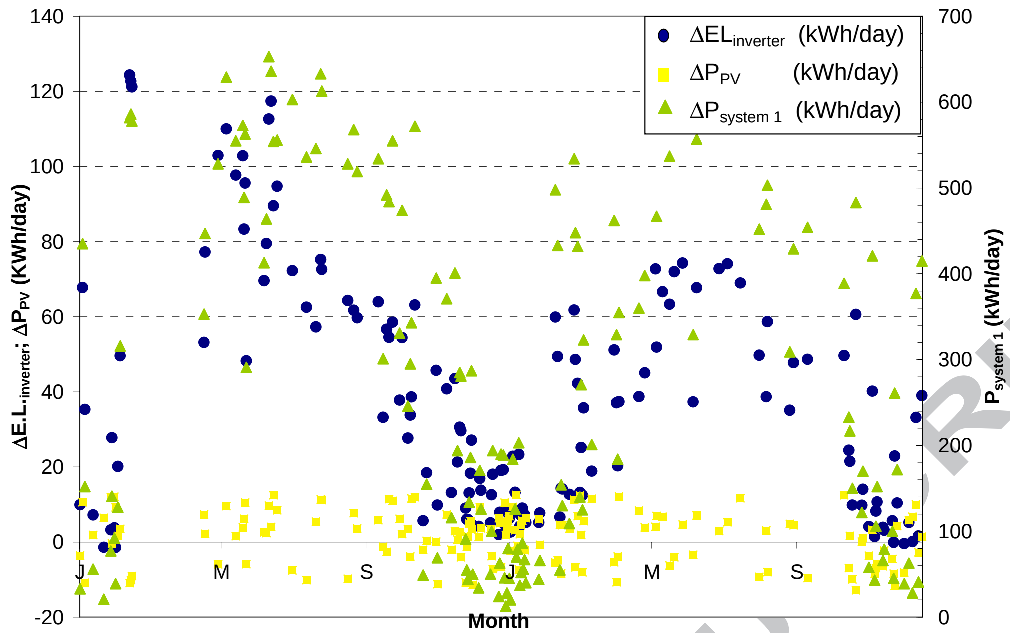

300
250
200
150
100
50
0
Num. Days
267
193
99
82
35
16
3
3
20
1
1
[-3,-2]
[-2,-1]
[-1,-0.5]
[-0.5,-0.25]
[-0.25,0]
[0,0.25]
[0.25,0.50]
[0.50,1]
[1,2]
[2,3]
[3,4]
Calculated daily global radiation (p.s.h)

Figure 5



140
120
100
80
60
40
20
0
-20
ΔE.L.inverter; ΔPPV (KWh/day)
700
600
500
400
300
200
100
0
Psystem 1 (kWh/day)
ΔELinverter (kWh/day)
ΔPPV (kWh/day)
ΔPsystem 1 (kWh/day)
J
M
S
J
M
S
Month

Figure 6

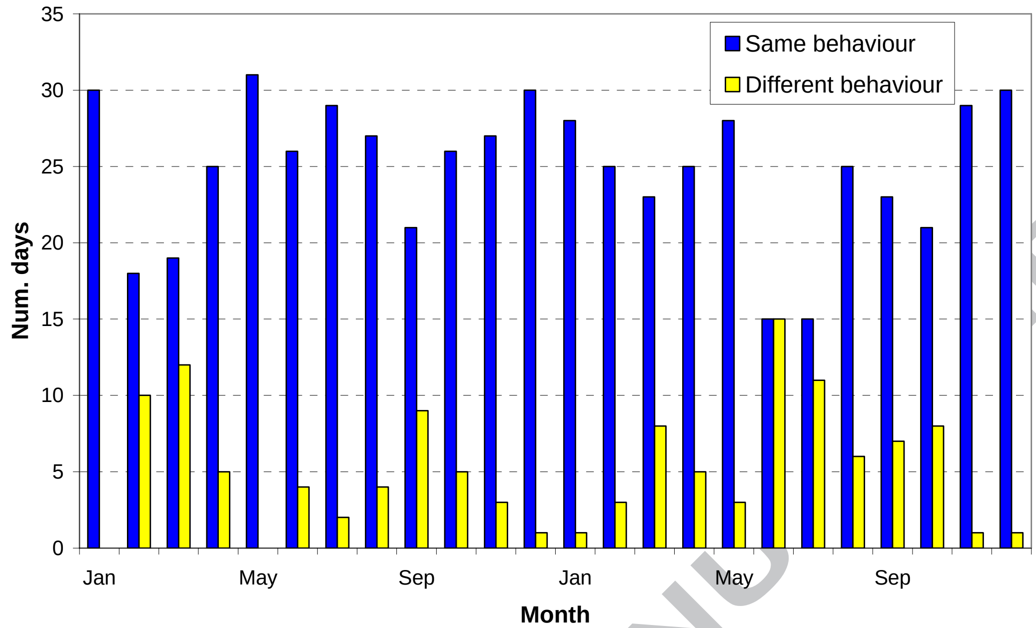

35
30
25
20
15
10
5
0
Num. days
Same behaviour
Different behaviour
Jan
May
Sep
Jan
May
Sep
Month

Figure 7

Tables:

Table 1: Advantages and disadvantages of isolated inverters and transformerless inverters for PV facilities

Transformerless inverter	**Isolated transformer inverter**
- Stronger electromagnetic impact. - Higher performance - Lower weight and cost. - Small size - Additional electrical protection systems.	- Lower Electromagnetic Interferences. - Isolated Input and output voltage - Lower performance

Table 2: Geographical positions and technical specifications of both systems case study

	System 1	System 2
Longitude	41º 59´ N	42º 03´ N
Latitude	4º 24´ W	4º 12´ W
Sea Level	720 m	829 m
PV panels	FOTONA 180D	
V_{PM} (V)	36.8	36.8
I_{PM} (A)	4.89	4.89
W_P (W)	180	180
Performance	15%	15%
Tolerance	2-5%	2-5%
Nº panels	630	616
Nº groups	45	44
V_{group} (V)	515.2	515.2
Facility power (kW)	113.4	110.88
Inverter	SMA Sunny Central 100 SC	SMA Sunny Central 100 HE
W_{DC} (kW)	105	103
W_P (kW)	115	115
V_{DC} (V)	100	1000
I_{DC} (A)	235	235
Nº inlet DC	3	3
V_{AC} (V)	400	300
I_{AC} (A)	145	193
T. range (ºC)	-20,+50 ºC	-20,+50 ºC
Performance (%)	96.6	98.5
Trafo info	With trafo	Transformer-less
Protection [a)]	IP 20	IP 44, IP 54

a) from IEC 62052-11:2003. Electricity metering equipment (AC) – General requirements, tests and test conditions -- Part 11: Metering equipment

Table 3: Technical specifications of System 1 and System 2 wiring.

		Length (m)	Section (mm^2)	Max. current (A)
System 1	DC wiring	20	10	4.85
	DC wiring	20;75	10;50	4.85;73
	DC wiring	20;40	10;50	4.85;73
	DC wiring	15	50	73
	AC wiring	2	70	145
System 2	DC wiring	33	10	4.85
	DC wiring	26	10;50	4.85;73
	DC wiring	20	10; 50; 50	4.85;73;73
	DC wiring	13	10	4.85
	DC wiring	30	50	73
	AC wiring	60	120	192

Table 4: Experimental data of electrical production of System 1 and System 2, measured at the inverter outlet and the counter system and the calculated DC and AC wiring losses.

	Total electrical production (inverter system) kWh	Total electrical production /counter system kWh	DC wiring losses kWh	AC wiring losses kWh
System 1	285112	275371	11118.4	1771.2
System 2	280676	278017	29554.8	9611.5

A new procedure to analyse the performance of PV facilities is presented.

It only requires limited amounts of data that are easily sourced.

Data sets on production were collected over two complete years.

The transformerless inverter outperforms the isolated inverter.