Competitive implementation of multi-kilowatts grid connected PV-systems with OKE4 AC modules

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ABSTRACT: The competitiveness of OKE4 based AC modules with traditional PV systems is compared. The performance of the OKE4 with respect to harmonics, power factor, EMC and monitoring facilities is equal or better than the performance of traditional systems. At system level the energy yield of an OKE4 based system is about 4.7-7.7% higher whilst the cost can be decreased by about 18% in comparison to a traditional system. The comparison applies to a system of about 2.2 kW.

1. Introduction

An AC module is a PV module with integrated DC to AC converter which generates grid conform AC power. Earlier presented papers indicated that AC modules are an interesting alternative for conventional grid connected PV systems as it offers possibilities to overcome problems with respect to high DC voltage levels, safety, cable losses, risk of DC arcs, fire hazard and protection. Moreover, PV systems based on AC modules are highly modular, which allows easy system expansion with units of about 100 Watts. This lowers the threshold for application by individuals. In view of these advantages of AC modules, a mini inverter for PV modules of about 130 Watts has been developed: the OKE4 inverter. A first small series was produced in the summer of 1995.

In this paper the competitiveness of AC-modules at system level is shown in the following aspects:

1. Performance with respect to power quality and electromagnetic compatibility.
2. Energy yield at system level.
3. Balance of system costs.

The gathered data for conventional systems - with one central inverter - and systems based on AC modules are presented and compared.

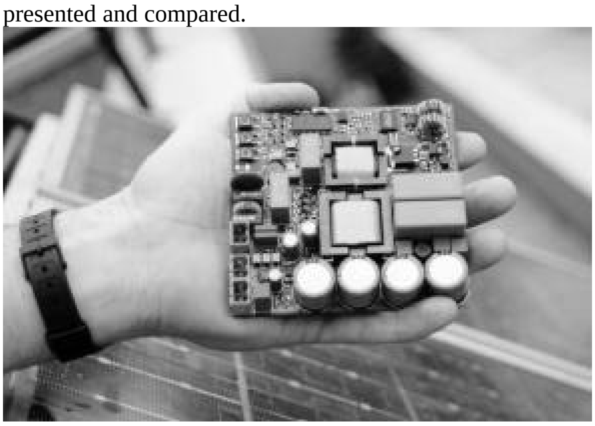

Figure 1.1. OKE4 inverter (not encapsulated)

2. Technical performance

In this section attention is payed to the performance parameters of the OKE4. In Section 2.2 the parameters of the OKE4 are compared with conventional inverters.

2.1. OKE4 inverter

The power quality of the OKE4 follows from the data presented in Figures 2.1 and 2.2. First in Figure 2.1 the power factor and total harmonic distortion is presented. It shows that the total harmonic distortion at full load is less than 3%, meeting the (future) IEEE standard. The power factor is > 0.9 at power levels exceeding 0.1 Pnom and approaches unity at high power levels.

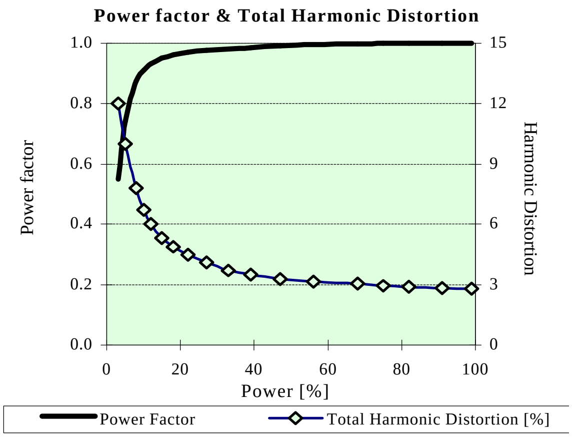

Figure 1.1. Power factor and Total harmonic distortion OKE4

Figure 2.2 shows individual line harmonics at 50 W output power. It is seen that all harmonics are below 2% of the fundamental. In the same figure the limits according to standard EN60555 for devices up to 500W are shown. Taking into account that for larger systems above 500W the limits increase proportionally with power, the results indicate that there is virtually no limit to the number of AC modules that can be paralleled.

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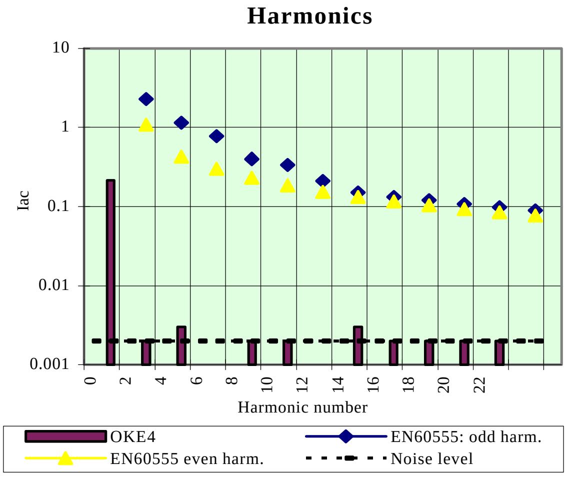
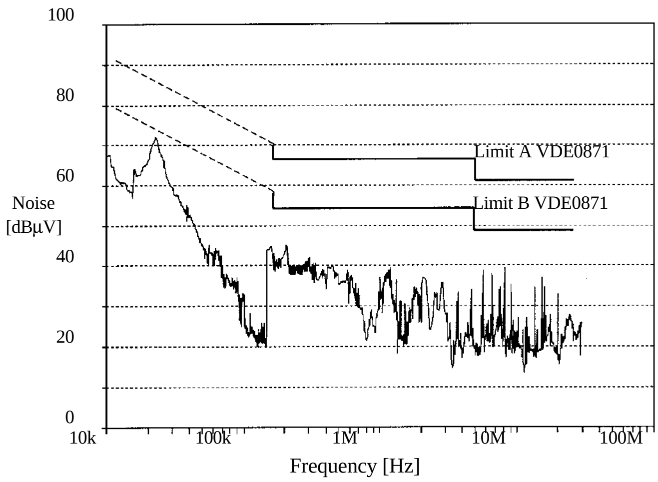
Measurements on the conducted electromagnetic noise are presented in Figure 2.3. It shows that the OKE4 meets the VDE0871 standards, limit B.



Source: Netherlands Energy Research Foundation, October 1995

Figure 2.2. Harmonics OKE4

To determine the behaviour of the AC module with OKE4 inverter for close-in lightning strokes, full scale lightning tests have been performed *by KEMA Transmission and distribution*, Arnhem. The AC module was subjected to a 10kA peak lightning stroke at a distance of 0.5 metres. The rise-time of the current was less than 3 µs. The di/dt of the current was therefore over 3.3 kA/µs which corresponds with the average values of a lightning stroke. The AC module was tested when it was switched off, switched on but not illuminated and switched on and illuminated. All results showed that the induced voltages remained within the design specifications of the AC module. Neither the module nor the OKE4 was damaged by the experiment.



(source: ECN, Netherlands Energy Research Foundation, October 1995)

Figure 2.3. OKE4 conducted noise

2.2. Comparison conventional inverters and OKE4

At ECN, Renewable Energy, a field test is started including 6 AC modules with OKE4 inverters. The results of the field test are up to now very satisfactory: the efficiency and power quality confirm the measurements performed in the laboratory. The efficiency of the OKE4 is presented in Figure 2.4, with a peak of approximately 92% at 22% of the power. The annual average efficiency determined according to Schmidt and Sauer [2] is 91.5%.

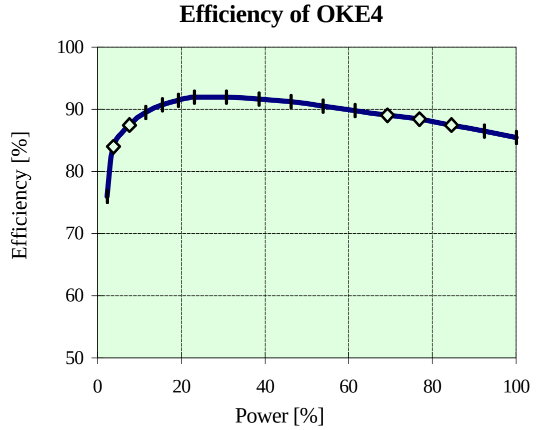


Figure 2.4. Efficiency of OKE4

In order to make a comparison between a conventional inverter and the OKE4, a hypothetical conventional inverter is introduced. The technical performance parameters of this inverter is a collection of the best values of existing inverters. The performance parameters of both inverters are presented in Table 2.1.

Table 2.1. Comparison of technical performance parameters of hypothetical conventional inverter and OKE4

	OKE4	Conventional inverter
Annual average efficiency [2]	91.5%	92%
Harmonics - conformity EN60555 - total harmonic distortion	 yes 3%	 yes 5%
Power factor	0.99	0.99
EMC: conformity to VDE0871	A and B	A
MPPT efficiency	> 0.98 [1)]	0.99
start-up power (% of Pnom)	(10-15 W/m2) 0.3%	30 W/m2
stand-by power (% of Pnom)	0.002%	?
susceptibility to lightning (10 kA @ 3.3 kA/µs @ 0.5m)	no damage	?
Monitoring facility	included	?

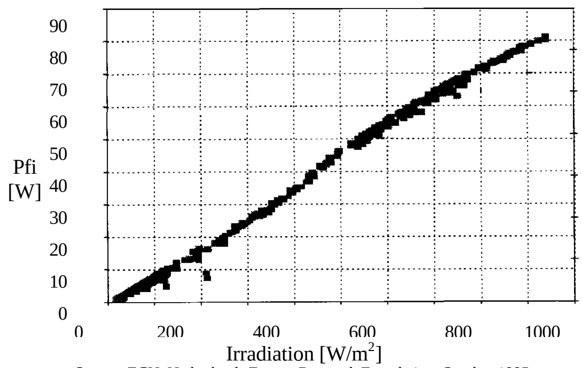
1) Laboratory test after recent modification

The figures in Table 2.1. show that with respect to efficiency the hypothetical inverter slightly out performs the OKE4. In all other aspects the OKE4 performs comparable or better.

3. Energy yield at system level

3.1. AC module with OKE4 inverter

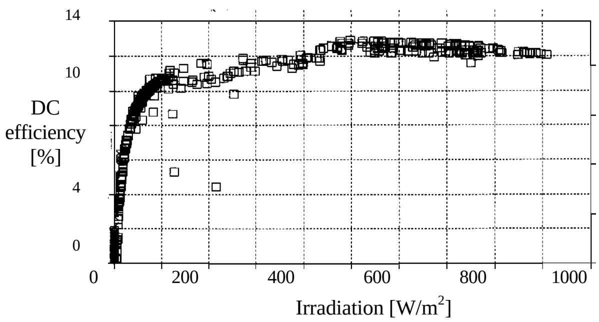
The system output of an AC module, based on field measurements performed at ECN, are shown in Figure 3.1, whilst the system efficiency follows from Figure 3.2. Not corrected for any external factors like temperature, the measurements show that system efficiency is about 12%. Figure 3.2. shows that the inverter will start generating power at an irradiation of 10-15 W/m^2 when connected to a PV module of 100 Wp (< 0.4 W at 24 V). Figure 3.2 also shows that the MPP tracking was not performing optimal. Based on these results the MPPT software, which is incorporated in the microprocessor of the OKE4, has been changed recently. Currently the adapted software for MPPT is being tested at ECN .



Source: ECN, Netherlands Energy Research Foundation, October 1995
Measurements performed in period 08.10.95-15.10.95

Figure 3.1. System output AC module with OKE4 inverter

The stand-by losses are so low that they cannot be measured exactly: they are calculated to be less than 0.003 W. The energy loss during one year stand-by (365 night) is compensated within 10 minutes of full sunshine when the OKE4 is connected to a PV module of 100 Wp.



Source; ECN, Netherlands Energy Research Foundation, October 1995

Figure 3.2. System efficiency of AC module with OKE4 inverter

3.2. Comparison of conventional systems with AC modules with OKE4 inverter

The energy yield of PV systems with one central inverter is compared with a system based on AC modules with OKE4 inverter. Different kinds of losses can be discerned. For the electrical system it concerns: mismatch losses, cable losses, diode losses and inverter losses.

The losses for both systems are presented in Table 3.1. The mismatch losses refer to the losses at system level and do not include mismatch losses at module level. For conventional systems with identical modules the mismatch losses are more than 2% because of differences in temperature and solid angle [6]. In most of the conventional systems the mismatch losses will be higher as the PV modules are not perfectly identical.

Table 3.2 shows that the losses of and OKE4 based system are much lower than the losses of a conventional PV system.

Table 3.1. Energy efficiency aspects (in % of Pnom)

	OKE4	Conventional system
Losses:		
- Mismatch	0%	2-5%
- Cable	0.3%	2.5%
- String diodes	0%	1%
- Inverter	8.5%	8%
Total losses	8.8%	13.5-16.5%
Other aspects		
- starting power	0.3%	0.5%
- stand-by power	0.002%	?

Moreover, in case the inverter of a conventional system has a defect, none of the PV modules will be able to deliver energy to the grid. Monitoring results of the thousand roofs programme in Germany showed that system failures had a considerable effect on the annual yield. A defect in the inverter caused 65% of the total number of registered failures, where it took more than seven days to correct the fault for 53% of the failures [1].

4. Balance of system costs

Concerning the balance of system costs of inverters and the associated electrical system, data are obtained from R&S, Renewable Energy Systems, Eindhoven [7]. The data, that apply to grid connected, roof integrated systems of 2.2 kWp per house (one array), are presented in Columns 1 and 2 of Table 4.1. The size of the project is 100 houses. The costs of the different components of the electrical system of a PV system are given in Table 4.1. Costs related to modules, mounting, transport, insurance, etc. are not listed in the table as these are the same for both systems. It should be noted that the costs of the different components strongly depend on the type of roof integration and the detailed electrical layout of the system. Moreover, costs of installation and engineering, as well as other costs depend on the size of the project.

In Column 1 of Table 4.1. the costs are given for the electrical system of a conventional PV system of 2.2 kW and using an inverter designed for PV systems of 1800 Wp. Thus, in the system design use is made of undersizing of the inverter (82%). In the second column the costs of the same system are given, but now using AC modules of 100 Wp with the OKE4. However, the OKE4 was designed for PV modules of 100-130 Wp. Thus, a third column was added to Table 4.1., that reflects a realistic comparison of the costs of both systems, assuming 14 PV modules of 157 Wp each (undersizing of 83%) and using a price of an OKE4 inverter of Dfl 250,- for 1996.

The figures in Table 4.1 show that AC modules with OKE4 are cost competitive in comparison with conventional systems with one central inverter.

Moreover, in Table 4.1. some costs related to PV systems are not included. First of all it concerns the saving of bypass diodes that are not needed anymore in a PV system based on AC-modules. Secondly, in larger projects a lot of attention is payed to monitoring to gain insight in the performance of the PV system. The OKE4 enables a simple, easy to use and above all very economical monitoring system, which will save monitoring costs. Further, PV systems with AC modules will be more safe than systems with central inverter because of the absence of DC sub-systems. Finally, maintenance activities will become more simple with the use of AC modules with an OKE4 inverter.

Table 4.1. BOS prices of electrical part of PV system (2.2 kWp), prices per Wp

	(1)	(2)	(3)
	One central inverter [Dfl]	22 AC-modules of 100 Wp (1995) [Dfl]	14 AC-modules of 157 Wp (1996) [Dfl]
Inverter	1.80	2.75	1.59
Connection to grid	1.30	0.70	0.70
Installation and engineering	1.85	1.75	1.75
TOTAL	4.95	5.20	4.04
in % of column 1	100%	105%	82%

Thus, it can be concluded that using AC modules with OKE4 inverter decreases the costs of the electrical part of a PV system with at least 18%. When also additional advantages of the OKE4 are considered this percentage is far higher. Especially monitoring costs will drop, while also the costs of maintenance will decrease.

5. Other aspects

One of the main advantages of the OKE4 that is difficult to express in terms of costs concerns safety. Traditional PV systems show problems with respect to high DC voltage levels, risk of DC arcs, fire hazard and protection. These safety problems are overcome by using AC modules.
Moreover, AC modules offer the possibility to use PV systems on roofs and facades of buildings of which the angle of irradiation varies. While in conventional systems this would be quite cumbersome because of different irradiation angles.

6. Conclusions

In Section 2 it is shown that with respect to power quality, EMC and efficiency the technical performance of the OKE4 is without any doubt comparable with existing, conventional inverters.

Calculations in conjunction with measurement results show that PV systems with AC modules are more competitive than traditional multi-kW PV systems. At system level a cost reduction of about 18% can be realised, whilst at the same time the energy output increases with 4.7% to 7.7%.

AC modules will therefore significantly contribute to cost reduction of electricity generated by PV systems and the wide spread application of PV. Thus, it might be concluded that indeed PV systems based on AC modules with an OKE4 inverter are a better approach for multi-kW systems.

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