ADVANCED HIGH FREQUENCY SWITCHING TECHNOLOGY OF OK4 AC MODULE INVERTERS BREAK THE 1 US$/WATT PRICE BARRIER

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ABSTRACT: AC modules offer a lot of advantages compared to traditional central inverters. Although the price-to-performance ratio can compete with those of central inverters, potential buyers perceive the price as too high. Therefore, NKF focused on developing an AC module inverter with a lower price. This has resulted in a 100 Watts inverter, the OK4-100, that was introduced for the wholesale price of less than 1 US$ per Watt. Whereas other AC module inverter manufacturers increase the inverter power to reduce the price per Watt, NKF decided to decrease both power and price to respectively 100 Watts and US$ 100. In spite of its very competitive price the OK4-100 is still a high quality inverter meeting all general quality and safety standards; it even sets up new records regarding efficiency, annual yield and dimensions. Compared to other AC module inverters the annual yield is at least 3% higher, while it also can compete with central inverters as the losses at system level are less.

Keywords: Inverter -1: AC-Modules - 2: Cost reduction - 3

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 overcomes problems with respect to high DC voltage levels, safety, Ohmic 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. Because of these advantages AC module inverters have been developed by several companies.

However, the price of these inverters were too high to be able to compete with traditional central inverters. Therefore, NKF focused on developing an AC module inverter with a competitive price. This has resulted in a 100 Watts mini inverter, the OK4-100, that was launched on the market in June 1997 for the wholesale price at large quantities of US$ 100, i.e. 1 US$ per Watt. Besides a European version, the OK4E-100 (230 Volts, 50 Hz), also a US-version (OK4U-100, 115 Volts, 60 Hz) and a Japanese version (OK4J-100, 230 Volts, 60 Hz) has become available. The OK4-100 is the first of a family of low cost, high quality AC-module inverters.

In this paper the following aspects of the OK4-100 will be discussed:

- technical performance,
- field performance and annual yield,
- economics compared to other inverters, and
- certification of AC modules and AC module inverters.

Figure 1: The OK4E-100, the European version of the OK4-100

2. TECHNICAL PERFORMANCE

In this section the performance parameters of the OK4-100 will be presented.

In order to attain a competitive price-to-performance ratio special attention was paid to the increase of the efficiency aiming at optimisation of the annual energy yield. This has resulted in a maximum efficiency of 94% at 40% of the maximum input power, as shown in Figure 2. In spite of the optimisation for 40 Watts DC, the efficiency at full power is still around 89%.

The efficiency at low input power of the predecessor of the OK4-100, the OKE4, ranged from 76% at 3 Watts to 88% at 10 Watts [8]. Figure 2 shows the efficiency of the OK4-100. The efficiency at low input power has increased significantly: 86% at 3 Watts and 91% at 10 Watts.

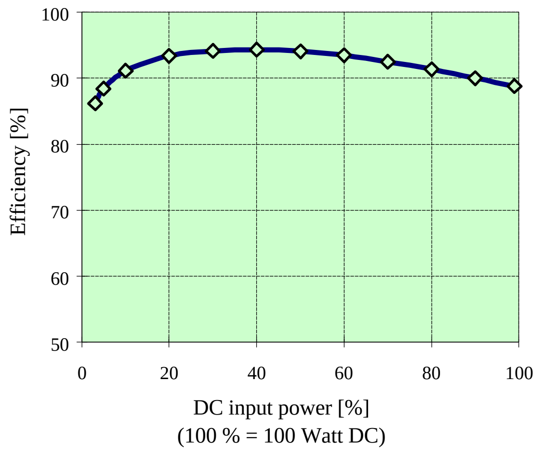

Figure 2: Efficiency of OK4-100, optimised for maximum annual yield.

The start-up power has decreased to less than 0.15 Watts. This implies that any DC power above 0.15 Watts will be converted to AC power. This overall increase of the efficiency, especially at low input power combined with the extremely low light operation, has a large impact on the annual yield and thus on the price-to-performance ratio. This will be discussed in more detail in sections 3 and 4.

Moreover, the stand-by power i.e. the power dissipated at the AC side when the inverter is not working, is only 0.003 Watts.

The significant increase of the efficiency of the OK4-100 has not weakened other performance parameters. On the contrary, both power factor and harmonic distortion have been improved and easily meet general quality standards.

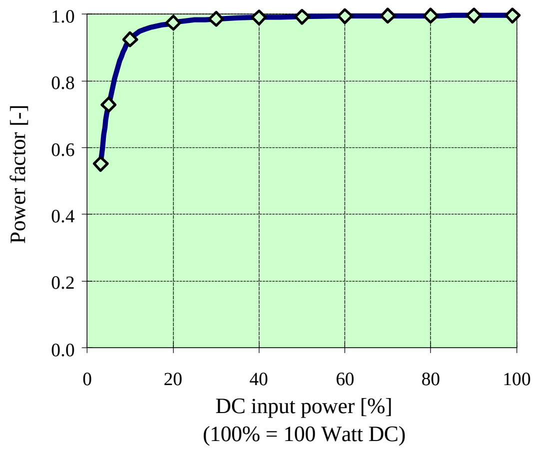

Figure 3: Power factor of OK4-100

In Figure 4 the harmonic distortion of the OK4-100 is presented. It shows that at full load it is less than 3%, meeting the future IEEE standard. Moreover, it easily meets the European standard, the EN60555; the individual line harmonics are below 2% of the fundamental [11]. It indicates that in view of harmonics there is virtually no limit to the number of AC modules with OK4-100 that can be paralleled.

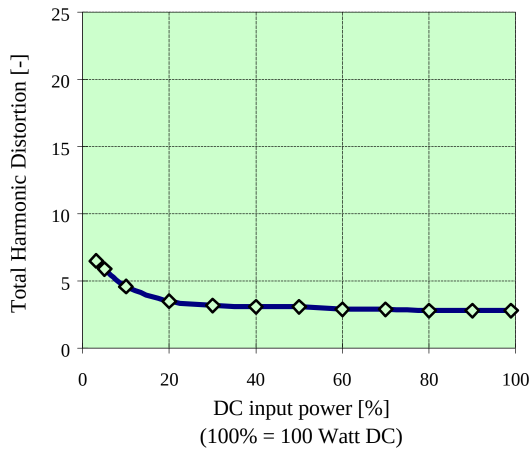

Figure 4. Total harmonic distortion (THD) of OK4-100

3. FIELD PERFORMANCE AND ANNUAL YIELD

At the Netherlands Energy Research Foundation, ECN in Petten, a field test with OKE4 inverters is running since 1995. The algorithm used for the Maximum Power Point Tracking (MPPT) in the OK4-100 is the same as used in the OKE4. The MPPT efficiency is shown in Figure 5.

In order to assess the annual yield of the OK4-100 actual irradiation data of Zandvoort, The Netherlands collected in the period July 19, 1994 - July 18, 1995 [9] were used. To visualise the effects of the shape of the efficiency curve on the annual energy yield, the frequency distribution of the available output power of a typical 100 Watts PV module was estimated. The result is presented in Figure 6.

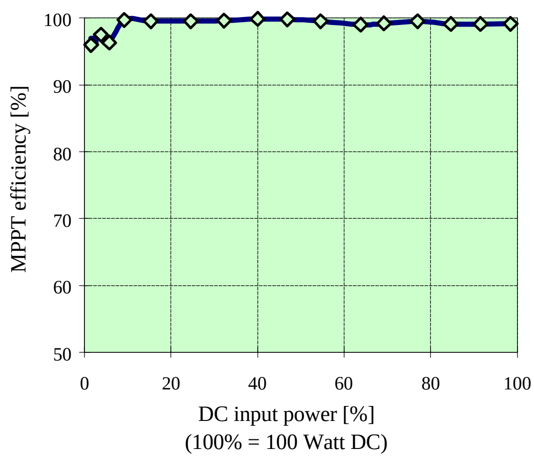

Figure 5: MPPT efficiency of OK4-100

The area under the upper curve represents the annual available DC energy of the PV module. The area under the lowest curve represents the energy losses of the OK4-100 inverter at the given input power assuming a perfect MPPT. Based on these data the annual average inverter efficiency of the OK4-100 was assessed at 91.5%, To be able to compare these results with other inverters, the efficiency curve assessed by ECN was used [11].

4. ECONOMICS

4.1. Introduction

In this section the economics of the OK4-100 is discussed and compared with both other commercially available AC module inverters and central inverters.

4.2. Comparison with other AC module inverters

The OK4-100 is currently the cheapest AC module inverter available on the market for PV modules of 100 Watts. However, when comparing the OK4-100 with other AC module inverters, the annual yield is decisive next to the price itself. As a comparison the losses of another commercial available AC module inverter are presented in Figure 6. This inverter has about the same peak efficiency as the OK4-100; at power levels of more than 70 Watts it even is higher. However, this effect is fully undone by the fact that the efficiency of the OK4-100 at lower power levels is significantly higher.

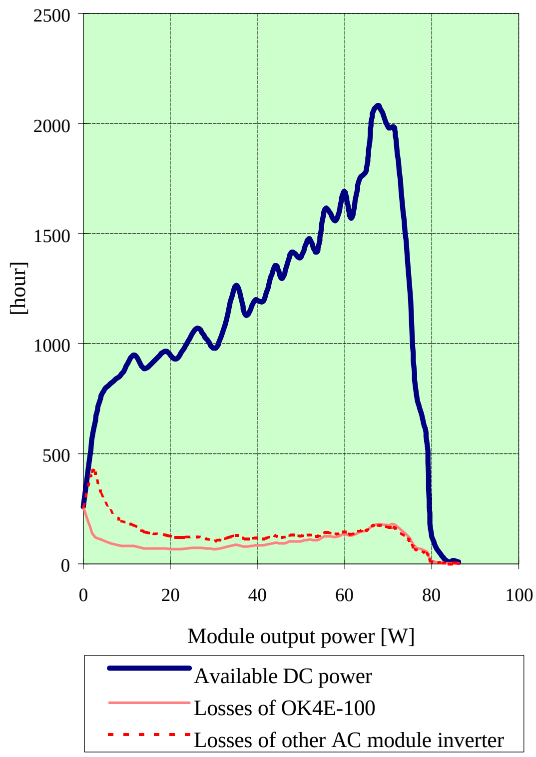

Figure 6: Frequency distribution of available power and inverter losses

4.3. Comparison with central inverters

In order to compare the OK4-100 with bigger inverters, especially the losses at system level need to be considered. Earlier presented papers indicate that losses at system level caused by mismatch, cables and string diodes range from 5.5 to 8.5% [6, 7, 8]. Thus, by using AC modules the output of the PV system will increase. At the current price level of PV modules of US$ 4 per Watt, each percent loss costs 0.04 US$ per Watt for a 100 Wp PV system. The economic value of an efficiency improvement of 5.5 - 8.5% is therefore 100 • 0.04 • 5.5 = US$ 22 to 100 • 0.04 • 0.085 = US$ 34. Thus, the OK4-100 is still competitive with larger inverters even when the OK4-100 is US$ 0.22-0.34 per Wp more expensive. The current price of the OK4-100 at larger quantities of only US$ 1 per Wp, implies that it can be compared with a price of a large inverter of US$ 0.66 to US$ 0.78 per Wp.

Moreover, the BOS costs of the electrical part of PV systems need to taken into account. Earlier presented papers [7, 8] indicate that especially the cables costs and costs related to installation and engineering drop when using AC modules.

Besides the OK4-100 offers some interesting monitoring features. It has a built-in computer interface which allows monitoring of each AC module; total kilowatt-hours delivered, internal inverter temperature, AC output current, utility grid AC voltage and DC voltage of the PV module is available via a RS485 port. This will cut the costs of monitoring equipment, which is generally used for larger PV systems. Moreover, it has field adjustable voltage and frequency limits.

5. CERTIFICATION OF AC MODULES

5.1 Why certification

All equipment connected to the electricity grid has to comply to national and/or international standards for electrical safety and the EMC-CE directive. Hence, AC modules have to comply to these standards as well, just as any other electric device. Special for AC modules is that these devices generate energy, whereas normal devices consume energy.

Compliance to the EMC-CE is mandatory. Safety aspects and a safe interconnection with the utility grid is normally required by national codes and/or a requirement from the utilities. The need for a certification for AC modules is clear as these devices will (in future) be installed by normal consumers which are not familiar with electricity.

5.2 Some history

In 1995 two AC modules of Dutch manufacturers were introduced on the market. In conjunction with these manufacturers and support of NOVEM, KEMA started the process for defining the KEMA-KEUR™ certification. After an intensive interpretation of the present standards and codes, KEMA defined a set of standards to which AC modules have to comply to. Regarding the EMC-CE directive following standards are applicable: EN 61000-3-2, EN 60000-4-2-, EN 61000-4-4, EN 60000-4-5, EN 6000-4-11, ENV 50141, ENV 50140, EN 55014 and EN 55104. For safety aspects the IEC 950 (EN 60950) is chosen as the main product related standard. Regarding the electrical installation of AC modules the IEC 364 standard is appropriate.

Special for AC modules is the protection for islanding. Based on the Dutch experience with several decades of small power generators connected to the low voltage grids, a voltage and frequency window is defined as an adequate way of protection against islanding.
Special attention is also given to the safety aspects of AC modules. The array with solar cells is working at a relatively low DC-voltage level. Since class II modules do not exist, the inverter has to work as a safety barrier. This

implies that the inverter has to meet the demands of a "safety transformer". Special measures have to be taken to have a safe electrical and mechanical barrier between the DC side and the AC side. This barrier must be intact even when one or two electrical components in the inverter have failed. Severe tests and evaluations of the design of the inverter have to prove that this safety barrier is and will remain intact.

This set of interpreted codes was given for approval to the Dutch Council of Accreditation. This approval was granted in mid-1996. All AC modules that are or will be sold on the Dutch market have to comply to the KEMA-KEMA™.

5.3 Present status and future

Now the KEMA-KEUR™ is available the Dutch AC modules are submitted for an approval. A detailed description of the content of the KEMA-KEUR shall be made available soon, and submitted to international bodies like CENELEC and IEC. The OK4-100 AC module inverter is submitted for an official certification.

6. CONCLUSIONS

In Section 2 it is shown that the efficiency of the OK4-100 has improved significantly, without weakening quality parameters. On the contrary, both the power quality and harmonic distortion have improved. Without any doubt these can be compared with existing, conventional large inverters. The data presented in Section 3 and 4 show that the OK4-100 is very cost competitive, both with other AC module inverters and central inverters.

In Section 5 certification is considered. It is shown that it is very important, especially for AC modules, that safety standards are drawn up. It is crucial for the OK4-100 that it will meet the KEMA safety standard.

The presented data show that the OK4-100 can both compete with other AC module inverters and traditional, central grid connected inverters. It sets up new records regarding efficiency, annual yield, dimensions and price. By cutting down the price to 100 US$ for one inverter, i.e. 1 US$ per Watt the threshold to invest in PV is considerably lowered, and the last barrier for large scale implementation of AC module inverters has overcome.

7. ACKNOWLEDGEMENTS

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