CURRENT DEMAND OF HIGH PERFORMANCE INVERTERS FOR RENEWABLE ENERGY SYSTEMS

Sérgio Daher*,**, Jürgen Schmid* and Fernando Antunes**
* University of Kassel - Germany Tel.: +49 / (561) - 804.6201 Fax.: 804.6434
** Federal University of Ceará - Brazil Tel.: +55 / (85) - 3366.9580 Fax.: 3366-9574
sdaher@secrel.com.br, jschmid@uni-kassel.de, fantunes@dee.ufc.br
www.re.e-technik.uni-kassel.de, www.dee.ufc.br

Abstract

This paper points out that versatile stand-alone renewable energy systems demand on at least one robust battery inverter. Despite of the employed system configuration, it is shown that the battery inverter should be capable to practically support all load demand. In practice, improved characteristics of reliability, surge power capability and efficiency are essential to guarantee long term and flexible operation for such systems. In addition, it is shown that these inverters can be optimized by considering the typical load profile commonly found in stand-alone applications. It is shown that multilevel topologies can be very suitable for these applications due to their inherent high efficiency and robustness. A prototype of 3 kVA was implemented and it has proved itself to be robust. Peak efficiency of 96.0% was achieved: value that is higher than similar high performance inverters currently available in the market.

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Keywords

Multilevel inverter, renewable energy, stand-alone system.

Introduction

Stand-alone Renewable Energy Systems - SARES are usually applicable when utility expansion cost is higher than the correspondent investment in a Renewable Energy System - RES. Despite of SARES size, location and explored RE resource, it is of common sense that it should be capable to supply alternating current (AC) electricity [1], thus providing compatibility with standard appliances that are cheap and widely available. On the other hand, most SARES include at least one DC voltage source that must be further converted into standard AC voltage source. Photovoltaic (PV) generators and most common energy storage devices are typical examples of DC voltage sources. According to these facts, it is evident that a device capable to convert DC voltage in AC voltage is a key element of most SARES.

The DC/AC converters, commonly referred as inverters, have experienced great evolution in the last decade due to its wide use in uninterruptible power supplies (UPS) and industry applications. However, they still to be critical components in most SARES and the development of high performance inverters is even today a challenge [2,3].

Multilevel and sine wave inverters are considered the state-of-the-art technology and several topologies are used to implement them. While for high power applications multilevel inverters are the best alternative (or, sometimes, the unique), for medium or low power applications a controversy takes place. Experts on high frequency converters point out the compactness and reduced cost that can be achieved by employing high frequency switching [4,5]. On the other hand, experts on low frequency

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converters claim that the very best efficiency and robustness belong to the topologies based on low frequency [6,7].
In fact, multilevel inverters offer all aimed features required by SARES applications. Nowadays, for small power systems (<10 kW), multilevel converters have been competing with high frequency PWM converters in applications where high efficiency is of major importance [8-11]. However, for the particular case of SARES, only few multilevel topologies can be applied due to the requirements of: 1) the topology must receive a single DC source input (from a battery bank); 2) the topology must be suitable to implement a high-resolution multilevel waveform (to avoid filter problems) and 3) the topology must support loads of unpredictable nature, such as half-wave loads. A detailed analysis of this problem is found in [12,13].

In this work, a high-efficiency multilevel inverter is proposed as one of the best solutions to the current demand on reliable and efficient inverters for SARES.

Typical Configurations

SARES range in size from small dedicated systems that provide few Wp, to complex mini-grid systems with peak capacities of more than a MWp. Most single consumer applications require up to some kWp and a variety of system configurations are commonly used to implement them [14,15].

Figure 1(a) shows a typical single source system, composed by a PV system with battery backup. As a general rule and due to the intermittent nature of almost all RE sources, most single consumer SARES include an energy storage device that is usually implemented by lead-acid battery banks [16,17]. The required inverter is fed directly by the battery bank, which usually presents a DC voltage in the range from 12 VDC to 96 VDC.

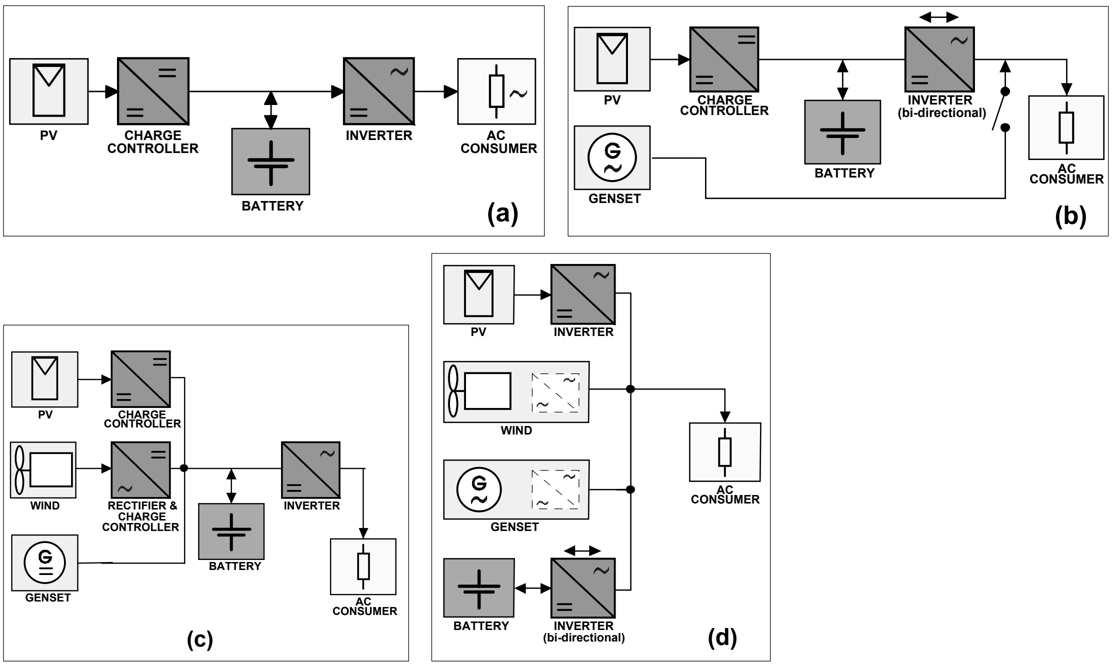

Fig.1: Typical configurations: (a) Single source system; (b) Hybrid system; (c) DC bus modular system; (d) AC bus modular system.

In many applications, a motor-generator set (genset) is combined with one or more RE source and a hybrid system is achieved, as illustrated in figure 1(b). For more complex hybrid systems, modular systems based on a DC bus or an AC bus have been proposed, as shown in figure 1(c) and figure 1(d), respectively. The configurations shown in figures 1(a) and 1(b) are modular and can be easily expandable to incorporate new power sources or even to compose a mini-grid system. Advantages and disadvantages of each configuration are discussed in [18].

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In the DC bus configuration, the inverter must be very reliable because it is the only alternative to generate regulated output AC voltage. Nevertheless, also in the AC bus configuration, the most critical inverter still to be the battery inverter, because the other modules (except for the generator) usually are not designed to support the surge power required by some loads (example: refrigerator). In close, it is possible to conclude that a “battery inverter” is required in all these configuations.

Inverters for SARES

Having in mind that SARES only make sense if they can be reliable and flexible, then all balance of system (BOS) components must accomplish with these characteristics. In this way, from the best of the author's knowledge, the most important characteristics of a RES inverter, in order or importance, are:

1. Reliability (most important);
2. Surge power capacity;
3. No-load consumption and efficiency.

Reliability

Reliability is the probability that a device or system will perform its specified function in a given environment for a specified period of time. Traditionally, reliability of a system has been presented in terms of Mean-Time-Between-Failures (MTBF) and it is usually modeled by a Bathtub curve.

Although inverters have experienced great evolution in the last decade, even today they still have the bad reputation to be considered one of the most critical BOS of a RES [19]. In the particular case of PV RE systems, in which PV modules can present an expected lifetime of 25 years [20], inverters still to be a critical component.

In response to the current demand on RES quality and increasing market competition, reliability concerns have gained more attention. Currently, while standard warranty up to 10 years are offered for grid inverters, manufactures are still timid to talk about expected lifetime of their stand-alone inverters. This fact shows how these components are critical and demand further improvements.

It is well know that voltage stress and temperature are factors that decrease lifetime of many components [21]. Considering this fact, it is expected that high efficiency (therefore lower working temperature) and stable (therefore less or more predictable voltage stress conditions) topologies, like the multilevel ones, can reach high degree of reliability.

Surge Power Capability

Systems capable to start a refrigerator or a conventional water pump are undoubtedly more useful than systems that can supply only well-behaved devices, such as lights, radio and television. This is why surge capacity can be considered the second most important inverter feature.

In general, for the same cost-benefit relation, inverters based on low-frequency switching present higher surge power capacity when compared to similar products based on high frequency switching. In fact, current available HF-PWM inverters usually present surge power around twice their rated power while inverters based on low frequency switching can easily present more than three times.

No-load Consumption and Efficiency

Efficiency characteristic is directly related to the overall efficiency of a system, and also indirectly related to system reliability (higher efficiency usually implies in lower working temperature and stress) and durability (for example, lower losses can result in shorter battery discharge cycles). Therefore, inverters for SARES should present high efficiency, what can be achieved trough the use of multilevel topologies.

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Load Profile and Inverter Efficiency Characteristic

The first two main parameters of the load profile that affects inverter specification are the peak demand and surge power. While the peak demand is easily estimated by simply summing the nominal power of all consumer appliances (worst case), estimation of surge power is difficult because many appliances do not have precise information about their startup transient. Common examples are refrigerators and water pumps, which present startup current of several times of their rated value.

As a fact, the average consumption of a rural property in Brazil has been estimated to be 45 kWh/month with surge power of 5 kW [22]. Considering that all consumption occurs within 2 hours in a day (worst case supposition), then peak power demand is equal to 750 W. In close, this application may require an inverter that should be capable to provide 750 W continuously and 5000 W of surge power, which will supply an average load demand of 63 W. This example makes clear that high performance inverters must present high surge power capacity and low no-load consumption.

Not less important, the energy distribution (as a function of the delivered power) is the third parameter that must be carefully observed. Figure 2 shows a typical example of such characteristic [23].

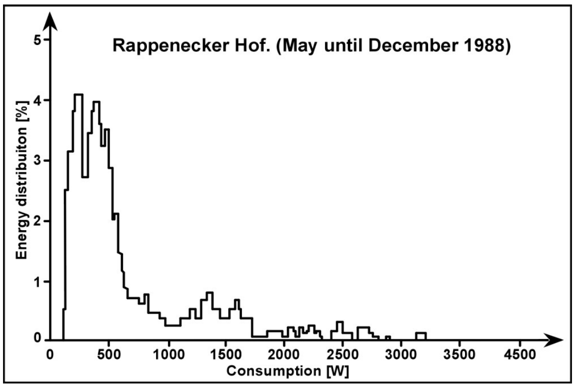

Fig. 2: Load profile of a typical stand-alone system (Rappenecker Hof [23]).

This characteristic is fundamental to correctly estimate the overall inverter efficiency under practical load condition. In fact, a typical SARES inverter process most energy at a fraction of its nominal power; thus its efficiency characteristic must be optimized in the low load region, even if this implies in efficiency reduction at rated power. Because of the relatively complex shape of the load profile, it is convenient to model the inverter efficiency characteristic by its no-load consumption (P_{nl}) and conversion efficiency (η_c) curve. Figure 3(a) shows how to calculate the equivalent conversion efficiency for a given conventional efficiency point.

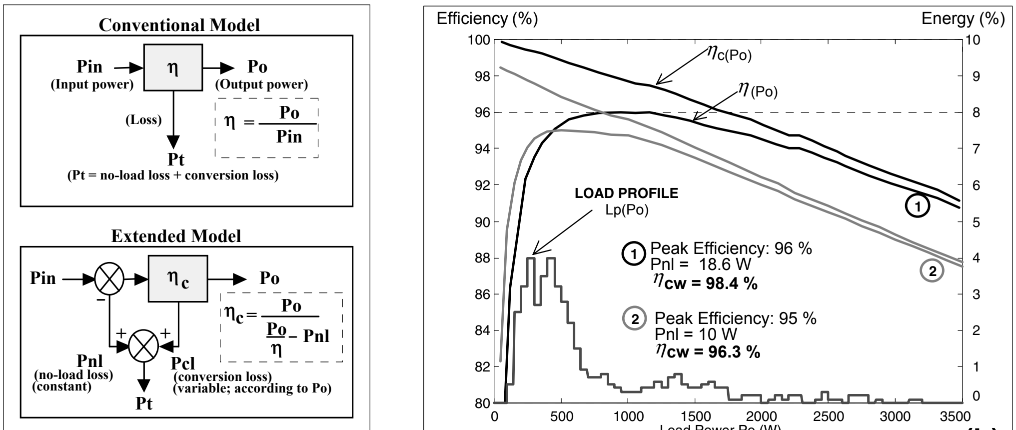

Fig. 3: (a) Conversion between conventional model and extended model; (b) Load profile and efficiency characteristic of two different converters.

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As it can be seen in figure 3(a), the extended model separates the no-load consumption from the conversion process. In consequence, for a given load profile, an inverter can be fully characterized by only two parameters: its no-load consumption and its mean weighted conversion efficiency (η_{cw}). The η_{cw} is the mean value of the weighted ηc curve (weighted by Lp), and can be calculated by equation 1.

$$\eta_{cw} = \frac{\int \eta_c(P_o).L_p(P_o).dP_o}{\int L_p(P_o).dP_o} \quad (1)$$

where: P_o is the inverter's delivered output power (W);
$\eta_c(P_o)$ is the conversion efficiency at P_o (%);
$L_p(P_o)$ is the load profile weight at P_o (%).

As an example, using an approximation of the load profile given in figure 2, the calculated η_{cw} and respective efficiency curves (conventional and conversion) of a LF-based inverter (inverter-1) and HF-based inverter (inverter-2) are shown in figure 3(b), where it is possible to conclude:

1. Although inverter-1 peak efficiency is only 1% higher than inverter-2, it is 2.1% more conversion-efficient for the given load profile.
2. The conversion efficiency versus power characteristic can be approximated by a straight line. This fact suggests that the efficiency characteristic of an inverter can be completely described by only 3 numbers: its no-load consumption and the two coefficients of the line that better fits the ηc curve.
3. The conversion efficiency curve of inverter-1 approximately converges to the value of 100 %, while the inverter-2 characteristic converges to a value between 98 % and 99 %. This fact can be justified by the fact that inverter-1 is based on low-frequency switching and inverter-2 is based on high-frequency.

As it can be seen, the efficiency model proposed in this work can simplify the specification of the efficiency characteristic (only 3 parameters are required, instead of a complete plot or table), while it can be directly applied to a load profile in order to calculate the overall system efficiency. In practice, many inverters manufactures only give information about no-load consumption and peak efficiency, what is not enough to precisely estimate the overall efficiency under practical load conditions.

In fact, while grid-interactive inverters are highly standardized, there is a lack of standards for stand-alone inverters. Perhaps, the proposed model could be useful for future specification of standards.

The Proposed Inverter

The adopted topology is the multi-winding transformer topology and the proposed inverter is shown in figure 4. It is composed by 3 main components: one H-bridge converter, one multi-winding transformer and one output-stage.

The H-bridge converter receives voltage from a DC source, such as a battery bank, and generates a square waveform that is applied to the primary of the transformer. The transformer operates at line frequency and it has one primary and 5 isolated output coils of distinct voltages. The output-stage combines these partial voltages in order to produce the output voltage.

The number of levels that can be generated depends on the number of output-stage cells and also on their respective values. In this case, in which the output-stage is composed by 5 cells, the maximum number of levels (same polarity) that can be produced is $2^5 = 32$ levels (including the zero). This condition is achieved because all output-coil voltages are of distinct values and the set of all possible combinations does not present repeated values. Detailed description about the operation principle of the proposed topology can be found in [12,13].

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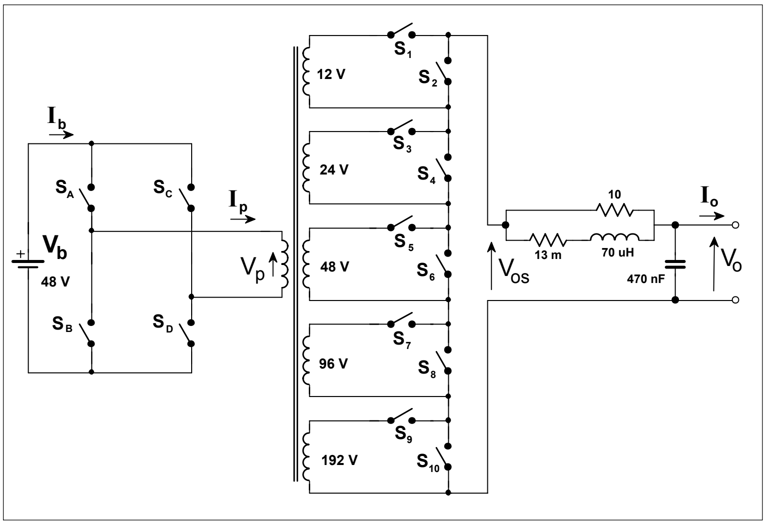

Fig. 4: The proposed inverter.

Prototype Specification

The adopted design specifications are listed in Table I.

Table I: Design specifications

Rated power	3000 VA
Rated input voltage	48 V
Output voltage	230 V_{CA} / 50 Hz
Voltage regulation	+5 % , -10 %
THD	< 5 %,

Although these specifications were arbitrary defined, they are based on the following facts:

- A 3 kVA inverter fits to several SARES applications and it is a reasonable value to validate the proposed topology. Also, several commercial inverters are rated to 3 kVA, and posterior comparison between the proposed inverter and similar products could be done;
- An input voltage of 48 V is suitable for a 3 kVA power rating (regarding current level). It can also be considered a standard value commonly found in SARES applications;
- Output voltage of 230 VAC / 50 Hz is the standard utility voltage in Germany, where the inverter had to be implemented and tested;
- The adopted values of voltage regulation and THD attend current utility standard limits, according to the European Standard EN 50160 and IEEE Std 519-1992, for example.

Prototype Implementation

Figure 5(a) shows the block diagram of the implemented prototype and figure 5(b) shows the final implementation, where it can be identified all components previously labeled in figure 5(a).

The use of toroidal shape allowed the transformer to present low no-load losses (13.0 W @ 48 Vrms - squared wave), reduced weight (32 kg) and size (diameter of 32 cm, height of 13 cm). This transformer is a customer type that was designed (standard rules, using Si-Fe GO laminations of grade DIN VM89-27) and manufactured by a specialized company (using automatic winding machine).

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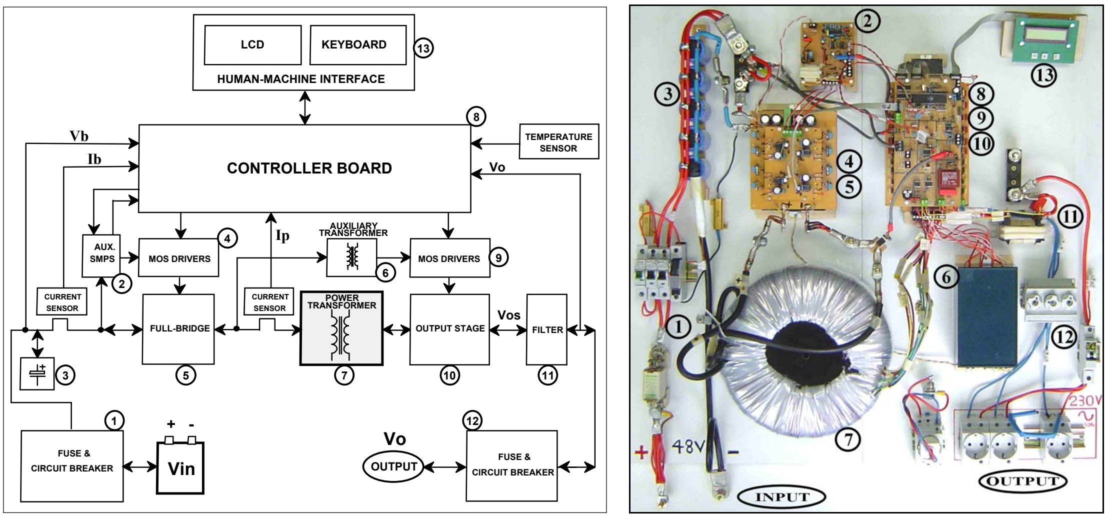

Fig. 5: (a) Block diagram, showing all components; (b) Prototype top view.

All output-stage switches must be capable to operate with AC voltage and current. In practice, these AC switches were implemented by two MOSFET´s connected in series in a source-to-source configuration. Table II shows all specifications of switches and snubbers used in the implemented prototype.

TABLE II: Component data for main power switches and snubbers

Stage	(V)	MOSFET DATA				Z_n (V)	R_n (Ω)	C_n (nF)
		Reference	V_{ds} (V)	I_d (A)	R_{ds} (mΩ)			
FB	48	2x IRFP2907	75	2x 209	4.5/2	66	330	470
Cell 1	12	IRF3205	55	110	8	22	120	47
Cell 2	24	IRF3205	55	110	8	33	330	47
Cell 3	48	IRF2807	75	82	13	66	330	47
Cell 4	96	IRFP260N	200	50	40	130	470	47
Cell 5	192	APT30M40	300	76	40	250	470	47

Experimental Results

The output voltage waveform is shown in figure 6(a). As it can be seen, the experimental output waveform approximates a perfect sinusoidal shape, apart from the distortions near zero crossing. These distortions correspond to a fixed time of 700 μs, where the output voltage is forced to be zero, and it is used to control transformer-unbalancing.

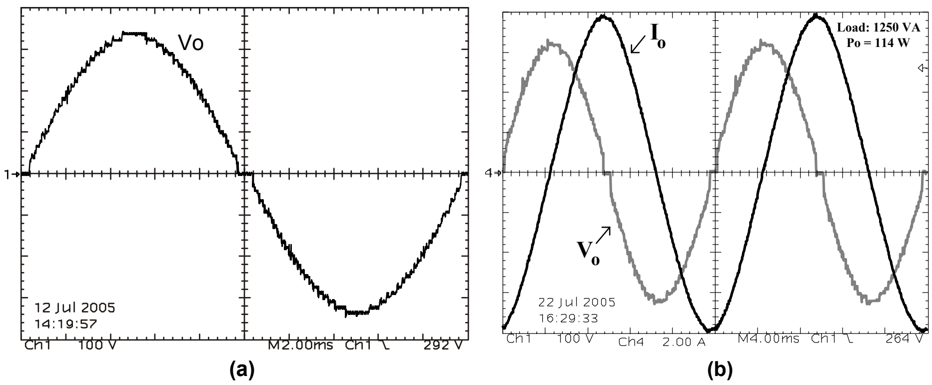

Fig. 6: (a) Output voltage at no-load condition; (b) Waveforms for operation under inductive load.

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Operation of a nearly pure inductive load is presented in figure 6(b), where it is possible to verify that the load current is delayed by almost 90 degrees.

A refrigerator is commonly desired in residential applications and it is known to be a problem in many small stand-alone systems due to its high startup current. Figure 7 shows the waveforms acquired at the startup of a refrigerator. At steady state operation, the measured current was 1.0 A (RMS), while the current at startup is approximately 10.6 A (RMS). Thus, even this small refrigerator may require 2.4 kVA at startup.

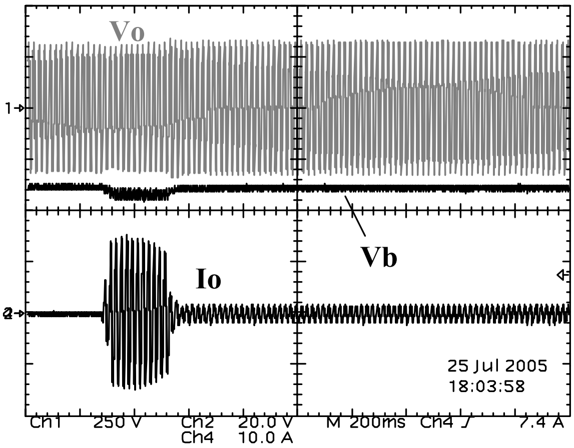

Fig. 7: Waveforms for a refrigerator startup.

The efficiency versus output power characteristic curves of the implemented prototype are shown in figure 8(a). Peak efficiency of 96.0 % at an output power of 945 W was measured for an input voltage of 48 V. Figure 8(b) shows how the no-load losses are internally distributed.

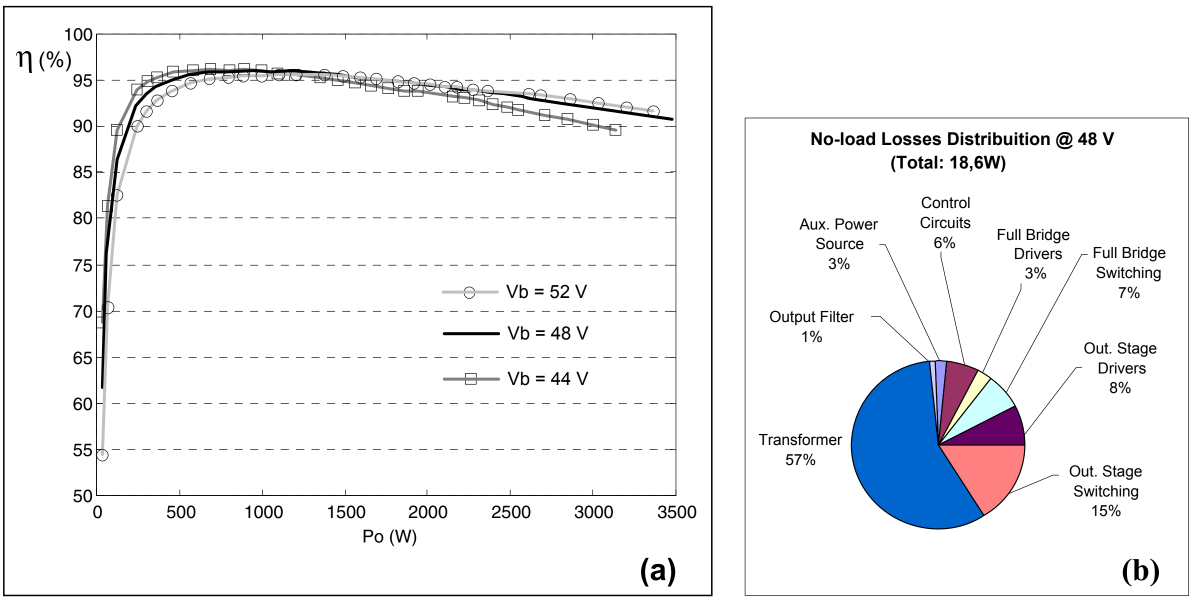

Fig. 8: (a) Efficiency x output power characteristic (resistive load); (b) No-load losses distribution.

In addition, the proposed prototype was also capable to successfully operate non-linear loads, such as microcomputers and half-wave loads (up to 1500 W). Thanks to its bi-directional characteristic and also to the implemented control to prevent transformer unbalancing, no problems were observed while operating these loads.

A summary of the main characteristics of the prototype and some commercial inverters is shown in table III.

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TABLE III: Comparison of inverters

No.	Inverter	Power (VA)	η_{pk} (%)	No-Load (W)
1	**Implemented prototype**	**3000**	**96.0**	**18.6**
2	Phoenix 48/3000/35	3000	95.0	10.0
3	Dakar 48/3000/50	3000	90.0	4.8
4	SMA Sunny Island 3324	3300	94.5	22
5	Trace SW3048	3300	95.0	16.0
6	Xantrex SW2548	2500	95.0	<20

As it can be seen in table III, the implemented prototype presents the best peak efficiency (96.0 %). In comparison with an inverter of 95.0% (at the same output power), the apparently small difference of 1% corresponds to loss reduction of 20%. At the end, this saving can imply in lower working temperature and consequently longer lifetime.

Regarding no-load consumption, the proposed inverter presents a reasonable value if it is considered that it competes only with inverters 2 and 5. In fact, inverter 3 can not be used as reference because its poor efficiency characteristic and inverters 6 and 4 probably present higher no-load consumption allied to worst peak efficiency.

Considering the typical load profile presented in figure 2, conclusive investigation can be done by observing figure 9.

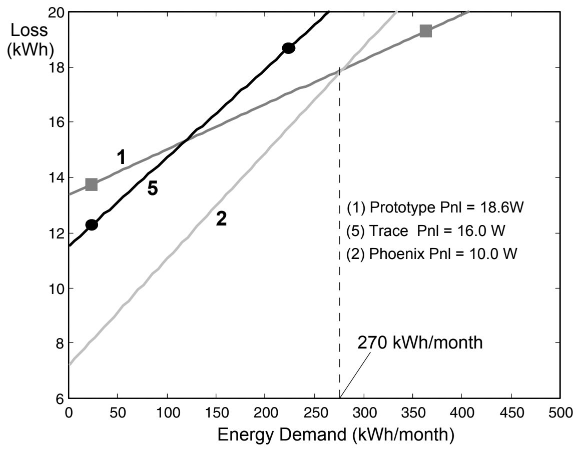

Fig. 9: Monthly energy loss versus processed energy.

As it can be seen in figure 9, inverter-2 present lower loss for any energy demand of up to approximately 270 kWh/month (average: 375 W), and above this value the proposed inverter is more efficient. In comparison with inverter-5, the proposed inverter present better efficiency for any energy demand above approximately 120 kWh/month.

Conclusions

This work shows that SARES demand on inverters with improved characteristics of reliability, capability to start heavy loads and efficiency; all these benefits can be achieved through the use of multilevel topologies, such as the adopted multi-winding-transformer topology. According to the typical load profile of SARES, the battery inverter should be optimized to the operation at light load conditions, once these systems operates most of the time with a fraction of their rated power. The proposed efficiency model is an interesting approaching that can be applied to this optimization process analysis and can also be useful to the better specification of the inverters for these applications. The implemented prototype presented peak efficiency of 96.0% and could be considered a top-efficiency inverter for the power range of about 3 kVA. Considering a typical load profile and in comparison with similar high-quality commercial inverters, it was found that the implemented prototype can achieve the best efficiency performance for any load demand greater than 270 kWh/month.

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References

[1] W. Durisch, S. Leutenegger and D. Tille, “Comparison of Small Inverters for Grid-Independent Photovoltaic Syst.,” Renewable Energy, No. 15, pp. 585-589, 1998.

[2] A. B. Maish et. al (Sandia National Laboratories), "Photovoltaic System Reliability," in Proc. of the 26th IEEE Photovoltaic Specialists Conference, Anaheim - California, October 1997.

[3] A. Pregelj, M. Begovic, A. Rohatgi, “Impact of Inverter Config. on PV Syst. Reliability and Energy Production,” in Proc. of the 29th IEEE Photovoltaic Specialists Conf., New Orleans, Louisiana, May 2002.

[4] E. Hiraki et al, "Zero-Voltage and Zero-Current Soft-Switching PWM Inverter with a Single ARDCL Cell," in Proc. of the IEEE 36th Annual Power Electr. Spec. Conf. - PESC05, Recife-Brazil, pp. 798-803, June 2005.

[5] P.T. Krein, R.S. Balog and X. Geng, "High-frequency Link Inverter for Fuel Cells Based on Multiple-Carrier PWM," IEEE Transactions on Power Electronics, vol. 19, no. 5, September 2004.

[6] K. A. Corzine and J. R. Baker, ”Multilevel Voltage-Source Duty-Cycle Modulation: Analysis and Implementation,” IEEE Transactions on Industrial Electronics, vol. 49, no. 5, pp. 1009-1016, Oct. 2002.

[7] F. Z. Peng, “A Generalized Multilevel Inverter Topology with Self Voltage Balancing,” IEEE Transactions on Industry Applications, vol. 37, no. 2, pp. 611-618, March-April 2001.

[8] H. Ertl, J. W. Kolar and F. C. Zach, “A Novel Multicell DC–AC Converter for Applications in Renewable Energy Systems,” IEEE Transactions on Industrial Electronics, vol. 49, no. 5, October 2002.

[9] B. Ozpineci, L.M. Tolbert and Z. Du, "Optimum Fuel Cell Utilization with Multilevel Inverters," in Proc. of the IEEE 35th Annual Power Electronics Specialists Conference - PESC04, Aachen, pp. 4798-4802, 2004.

[10] M. Calais, V. G. Agelidis and M Meinhardt, "Multilevel Converters for Single-Phase Grid Connected Photovoltaic Systems: An Overview," Solar Energy, Vol. 66, no. 5, pp. 325-335, 1999.

[11] L.M Tolbert and F. Z. Peng, “Multilevel converters as a utility interface for renewable energy systems,” in Proc. of the IEEE Power Engineering Society Summer Meeting, vol. 2, pp. 1271-1274, 2000.

[12] S. Daher, "Analysis, Design and Implementation of a High Efficiency Multilevel Converter for Renenable Energy Systems", Doctor Thesis - Universität Kassel - Germany, June 2006.

[13] S. Daher, J. Schmid and F.L.M. Antunes, "Design and Implementation of an Asymmetrical Multilevel Inverter for Renewable Energy Systems", in Proc. of the COBEP 2005, pp. 199-204, Recife, 2005.

[14] Institut für Rationelle Energiewandlung - IEE-RE, "Photovoltaic Systems Technology" , Script, Universität Kassel, Kassel - Germany, 2003.

[15] F. Trieb, O. Langniß and H. Klaiß, "Solar Electricity Generation - A comparative View of Technologies, costs and Enviromental Impact," Solar Energy, Elsevier Science Ltd, vol. 59, pp. 89-99, 1997.

[16] M. I. A.-H. Ibrahim, "Decentralized Hybrid Renewable Energy Systems - Control Optimization and Battery Aging Estimation Based on Fuzzy Logic," Doctor Dissertation, Universität Kassel - Fachbereich Elektrotechnik/Informatik, Kassel - Germany, May 2002.

[17] J. Nickoletatos and S. Tselepis, "Evaluation of literature search and results of survey about lifetime expectancy of components, in particular the energy storage systems in existing RES applications", ENK6-CT2001-80576 (Research funded in part by The European Commission in the framework of the Non-Nuclear Energy Programme JOULE III), Center for Renewable Energy Sources (CRES), Pikermi/Attiki- Greece, April 2003.

[18] M. Ross, "Bus Configurations in Hybrid Systems Part I - What they are," Hybridinfo - The semi-annual newsletter on photovoltaic hybrid systems in Canada, Issue 7, Summer 2004.

[19] W. Bower, "Inverters - Critical Photovoltaic Balance-of-system Components: Status, Issues, and New Millennium Opportunities," Progress in Photovoltaics Applications Res. Appl. 8, pp. 113-126, 2000.

[20] M. A. Green, "Silicon Photovoltaic Modules: A Brief History of the First 50 Years", Progress in Photovoltaic Research and Applications, published online in Wiley InterScience (www.interscience.wiley.com), DOI: 10.1002/pip.612, John Wiley & Sons, Ltd, 2005.

[21] Hitachi Ltd., "Reliability Handbook," ADE-410-002, Rev. 1.0, Japan, January 2002.

[22] L. A. ROSSI, "Modelo avançado para planejamento de sistemas energéticos integrados usando recursos renováveis," Doctor Thesis - Escola Politécnica, Universidade de São Paulo, São Paulo - Brazil, 1995.

[23] J. Müller, "Untersuchung und Optimierung von StuffenInvertern für Photovoltaik-Anlagen", Doctor Thesis, Fernuniversität / Fraunhofer-Institut für Solare Energiesystem, Freiburg - Germany, 1994.

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