Multilevel Topologies for Stand-Alone 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 shows that versatile stand-alone renewable energy systems demand on at least one battery inverter with improved characteristics of robustness and efficiency, what can be achieved by using multilevel topologies. A compilation of the most common topologies of multilevel converters is presented and it is shown which ones are best suitable to implement inverters for stand-alone applications in the range of few kW. As an example, it was implemented a prototype of 3 kVA and peak efficiency of 96,0% was achieved.**

Keywords - **Multilevel inverter, renewable energy, stand-alone system.**

I. INTRODUCTION

Multilevel converters have been mainly used in medium or high power systems applications, such as static reactive power compensation and adjustable speed drives. In these applications, due limitations of current available power semiconductor technology, multilevel concept are usually the unique alternative because it is based on low frequency switching and also provides voltage and/or current sharing between the power semiconductors [1-4].

On the other hand, 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. Moreover, lower prices of power switches and new semiconductor technologies, as well as the current demand on high performance inverters required by Renewable Energy Systems - RES, have extended the applications of multilevel converters [5-10].

For the particular case of Stand-Alone Renewable Energy Systems - SARES, it is of common sense that it should be capable to supply alternating current (AC) electricity [11], thus providing compatibility with standard appliances that are cheap and widely available. In addition, due 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 [12-14].

According to these facts, it is evident that a device capable to convert a single DC voltage from a battery bank into AC voltage is a key element of most SARES. These 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, it is still a critical component to most SARES and the development of high performance inverters is even today a challenge [15-17].

Most small SARES for rural electrification present configurations that are variations of the complex hybrid systems presented in Fig. 1.

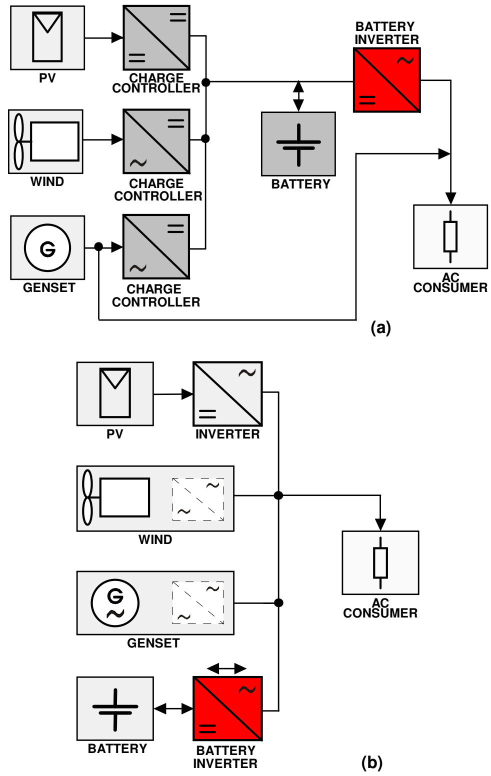

Fig. 1. Modular hybrid systems: (a) DC bus modular system; (b) AC bus modular system.

In both DC (Fig. 1.a) and AC (Fig. 1.b) bus configurations, since the generator does not operate continuously and considering the intermittency of the RE sources, then is possible to conclude that the battery-inverter should be designed to fully support the loads at some time periods. Therefore, independently of the system configuration, it is possible to identify that at least one "Strong" "Battery-Inverter" is required.

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 battery inverter, in order or importance, are:

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

This work investigates which multilevel topologies better fit the current demand of high performance battery inverters for SARES applications.

II. COMPILATION OF TOPOLOGIES

In this section, short reviews of the most common topologies are presented. Figure 2 shows the topologies considered in this work: (a) Diode-clamped; (b) Flying capacitors; (c) Cascade H-bridge; (d) Multiple transformer; (e),(f) variations of the Cascade H-bridge; (g) Multiple-source; (h) Multi-winding transformer; (i) Modular topology.

A. Diode Clamped topology

Proposed by Nabae et al., the inverter shown in Fig. 2.a is called as three-level NPC inverter [18]. It was the first widely popular multilevel topology and it continues to be extensively used in industry applications. Later, the NPC inverter was generalized for a greater number of levels, using the same concept of diode-clamped voltage levels, what resulted in the current designation of diode clamped converter [19]. As can be seen in Fig. 2.a, the 3-level NPC inverter uses capacitors to generate an intermediate voltage level and voltages across the switches are only half of the DC input voltage. Due to capacitor voltage balancing issues, practical diode-clamped inverters have been mostly limited to the original 3-level structure.

B. Flying Capacitor

The three-level flying capacitor topology, shown in Fig. 2.b, can be considered a good alternative to overcome some

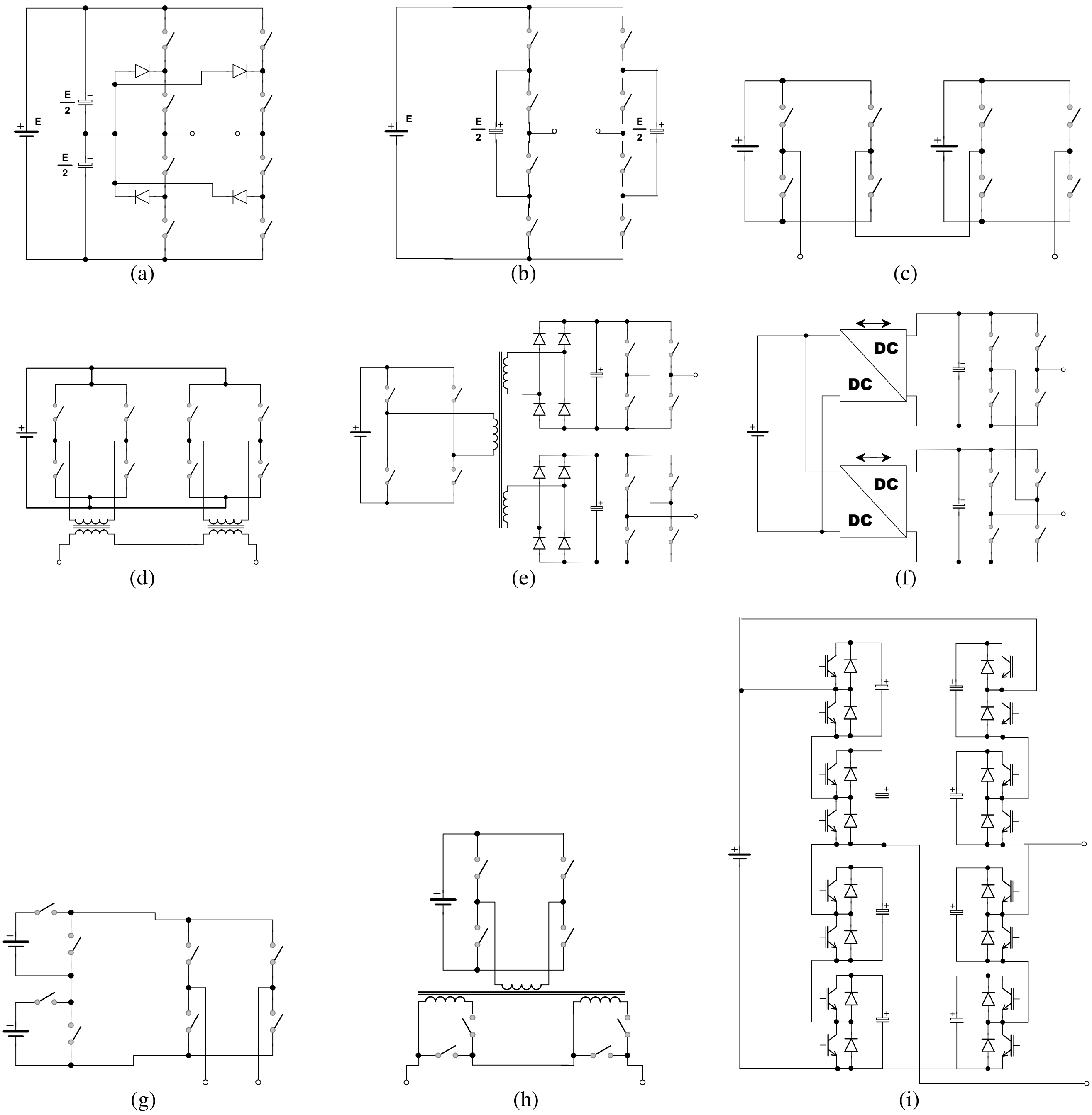

Fig. 2. Multilevel inverter topologies: (a) NPC; (b) Flying capacitors; (c) Cascade H-bridge; (d) Multiple transformer; (e),(f) variations of the Cascade H-bridge; (g) Multiple-source; (h) Multi-winding transformer; (i) Modular topology.

of the NPC topology drawbacks [20,21]. In this topology, additional levels and voltage clamping are achieved by means of capacitors that "float" with respect to the DC source reference. It does not require additional clamping diodes and also provides redundant switch states that can be used to control the capacitors charge even under loads with DC level [22]. Nevertheless, larger structures require relatively high number of capacitors and additional circuits are also required to initialize capacitors charge.

C. Cascade H-bridge

This topology is composed by several H-bridge converters in a cascade connection. Fig. 2.c shows a 2-cell cascaded inverter.

The cascade topology allows the use of DC sources with different voltage values and high resolution multilevel waveforms can be achieved with relatively low number of components [23-27]. In addition, DC sources can be added or subtracted, what can increase the number of output levels.

Although the original cascaded topology requires several isolated DC sources, in some systems they may be available through batteries or photovoltaic panels, so it has been used to implement high efficiency transformer-less inverters [30,32].

D. Multiple transformers

Figure 2.d shows a multiple transformer topology composed by two cells. It is similar to the cascaded H-bridge topology, but the output of the isolation transformers are cascaded instead of cascading directly the H-bridge outputs. As a result, all H-bridge can be referenced to a same point and only one DC source is required.

Currently, there are available in the market some commercial inverters (for SARES applications) that are based on this topology [28, 29]. In practice these inverters have been proved to be very robust and reliable. One disadvantage of this topology is the fact that it requires several low frequency transformers.

E. / F. Other variations of the Cascade H-bridge

If only one DC source is available, then it is possible to use the topology shown in Fig. 2.e [31]. This topology is simple but losses in additional rectifier diodes can be significant and it does not support bi-directional power flow.

The topology shown in Fig. 2.f can be very efficient if soft-switching DC/DC converters are used [6]. On the other hand, this topology is based on high-frequency switching and inherent benefits of low frequency switching are lost.

G. Multiple-source

The multiple-source topology, shown in Fig. 2.g, uses several isolated DC sources to produce a rectified multilevel waveform which is latter converted in an AC multilevel voltage [33,34].

In practice, the multiple-source topology is one of the most efficient multilevel topologies currently available. It has been tested in some RES for more than 10 years and it has proved to be very efficient, robust and reliable [35]. The disadvantage of this topology is the fact that it requires several isolated DC sources and do not provide input-output isolation.

H. Multi-winding transformer

The multi-winding transformer topology can be considered as a variation of the multiple-source topology. A three-cell multi-winding inverter is shown in Fig. 2.h.

Unlike the multiple-source topology, it operates with a single DC input, what is achieved by the use of a multi-winding line-frequency transformer. It provides input-output isolation and, because it employs only one transformer, high efficiency can be achieved. The major disadvantage is the relatively high number of switches presented in the output stage. Additional information about this topology can be found in [36]

I. Modular topology

Figure 2.i shows an eight-module modular topology that was recently proposed for high power applications [37, 38].

III. TRIAL OF TOPOLOGIES

As discussed in the introduction of this work, most SARES require a single input battery inverter with improved characteristics of reliability, surge power capability and efficiency. In addition, such kind of inverter must be capable of work with loads of diverse nature, such as house appliances, and thus must produce an output voltage with acceptable waveform quality.

Taking into account these requirements, it is possible to define a list of characteristics required by a high-performance battery inverter, as presented in table I.

TABLE I
List of basic specifications required by a high-performance battery inverter topology.

Id.	Inverter characteristic	Priority
M1	**Single source input** Justification: *Required by standard designs.*	**Mandatory**
M2	**Mainly based on low-frequency switching** Justification: *Maximum robustness and efficiency can be achieved by using low-frequency switching.*	**Mandatory**
M3	**Capable to feed loads with DC level component** Justification: *Like the grid, it is desired that SARES must be capable to support loads of diverse nature.*	**Mandatory**
M4	**Suitable to implement high-resolution multilevel waveform** Justification: *The use of filters for low-frequency waveforms is not practical for these applications.*	**Mandatory**
A1	**Bi-directional (4-quadrant operation)** Justification: *Improve robustness.*	**Additional**
A2	**Input-output isolation** Justification: *Assures more flexibility.*	**Additional**

In accordance with Table I, the characteristics of all topologies shown in Fig. 2 are summarized in Table II. As can be seen in Table II, only 3 topologies attend all mandatory characteristics. While multiple transformer and multi-winding transformer topologies attend all characteristics, the H-bridge topology with multi-winding transformer does not support full 4-quadrant operation. In conclusion, the presented analysis shows that the multiple-transformer and multi-winding transformer topologies are the most suitable to implement high-performance battery inverters.

TABLE II
Characteristics summary of most common multilevel topologies.

Topology	M1	M2	M3	M4	A1	A2
Diode clamped	Y	Y	-	-	Y	-
Flying capacitor	Y	Y	Y	-	Y	-
H-bridge (isolated DC sources)	-	Y	Y	Y	Y	-
H-bridge (+ multi-winding transformer) (Fig. 2.e)	Y	Y	Y	Y	-	Y
H-bridge (+ isolated DC/DC converters)	Y	-	Y	Y	Y	Y
Multiple transformer (Fig. 2.d)	Y	Y	Y	Y	Y	Y
Multiple source	-	Y	Y	Y	Y	Y
Multi-winding transformer (Fig. 2.h)	Y	Y	Y	Y	Y	Y
Modular	Y	Y	-	Y	Y	-

Table III shows the achieved design data and expected performance for the selected topologies.

TABLE III
Design data and expected performance for equivalent inverters (minimum p = 12).

	Fig. 2(e)	Fig. 2(d) / 3 Cells	Fig. 2(d) / 4 Cells	Fig. 2(h)
Number of cells	4	3	4	4
Maximum p	15	13	15	15
Transformers	1	3	4	1
Power switches	20	12	16	20
Capacitors	4	0	0	0
Diodes	16	0	0	0
Isolated drivers	8	0	0	8
Reliability	Medium	High	High	High
Surge Power	High	High	High	High
Efficiency	Medium	Medium	Medium	High
No-load Power	Medium	Medium	Medium	Medium
Competitiveness	Medium	High	Medium	Medium

It is important to note that evaluation of the expected performance parameters took into account the following:

- Reliability of the H-bridge inverter was lowered because of the presence of capacitors (usually, of electrolytic type) that must support all reactive power of inductive loads;
- Conversion efficiency of the H-bridge inverter is limited by the rectifier diodes;
- Conversion efficiency of the multiple-transformer/3 inverter is limited by the subtraction of levels and also by the use of several transformers. In addition, each transformer always carries total current at any instant;
- Conversion efficiency of the multiple-transformer/4 inverter is limited by the use of several transformers, and each transformer always carry all the load current at any time;
- Conversion efficiency of the multi-winding transformer inverter is considered high because it uses only one transformer and the load current is shared between transformer output coils and switches;
- Market competitiveness of the multiple-transformer/3 inverter is considered high because additional cost of the several transformers is compensated by the cost reduction provided by its reduced number of power devices and drivers.

The presented analysis shows that the multiple-transformer and multi-winding transformer topologies are the most suitable to implement high-performance battery inverters. It is also expected that the multi-winding transformer topology can achieve better efficiency than the multiple-transformer one if same rules and similar components are used in their design. Regarding cost, it is expected that a multiple-transformer inverter can present slightly lower production cost when compared to a similar multi-winding transformer inverter. Nevertheless, the better efficiency characteristic of the latter can justify the low cost difference.

IV. EXAMPLE OF APPLICATION

To validate the proposed analysis, it was implemented a 63-level inverter of 3 kVA (48 V_{DC} / 230 V_{AC} / 50 Hz), using the multi-winding transformer topology. Figure 3 shows the simplified schematic for the proposed 5-cell inverter.

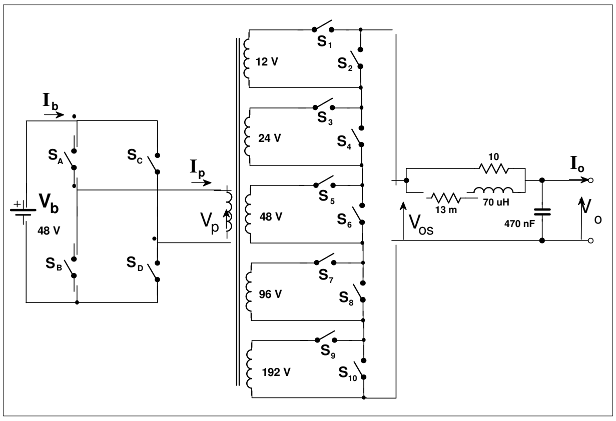

Fig. 3. Simplified schematic of the proposed inverter..

The output voltage waveform is shown in Fig. 4.

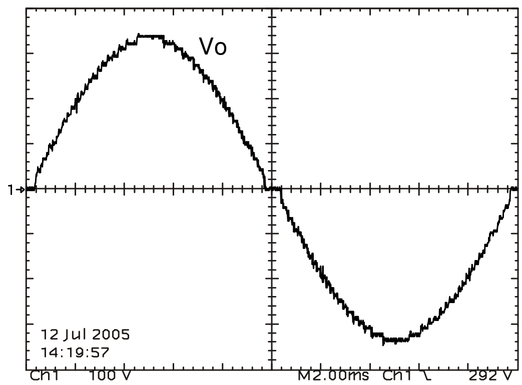

Fig. 4. (a) Output voltage at no-load condition.

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. The Total Harmonic Distortion - THD was lower than 4% for any number of levels between 31 and 63, and the output voltage regulation was implemented by simply changing the output number of levels.

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 5 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.

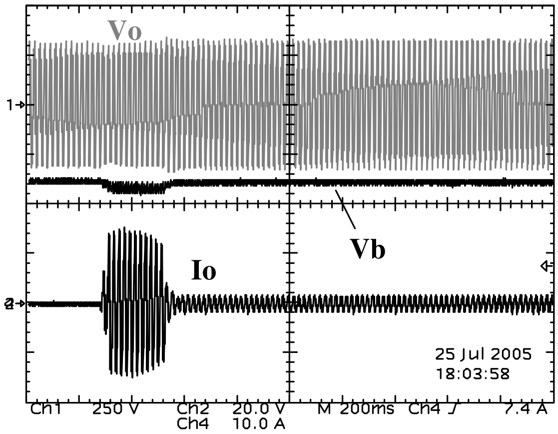

Fig. 5. Waveforms for a refrigerator startup.

Figure 6 shows the prototype operation under a sequence of resistive load steps (0W ➔ 500W ➔ 1000W ➔ 3000W ➔ 2500W ➔ 1500W ➔ 0W). As can be seen, despite of the large changes in the battery bank voltage (V_b) and also in the input and output current (I_b and I_o), the converter was capable to produce a stable output voltage (V_o).

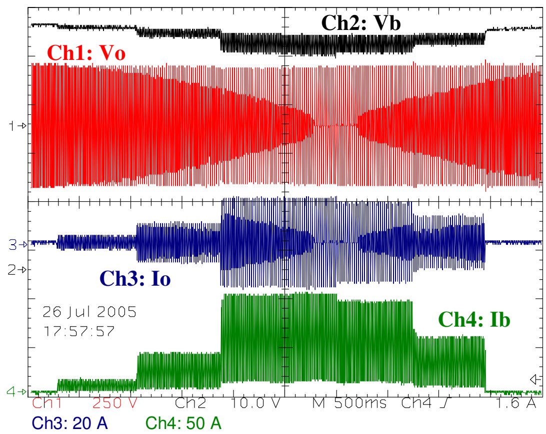

Fig. 6. Sequence of load steps.

The efficiency versus output power characteristic curves of the implemented prototype are shown in Fig. 7. Peak efficiency of 96.0 % at an output power of 945 W was measured for an input voltage of 48 V.

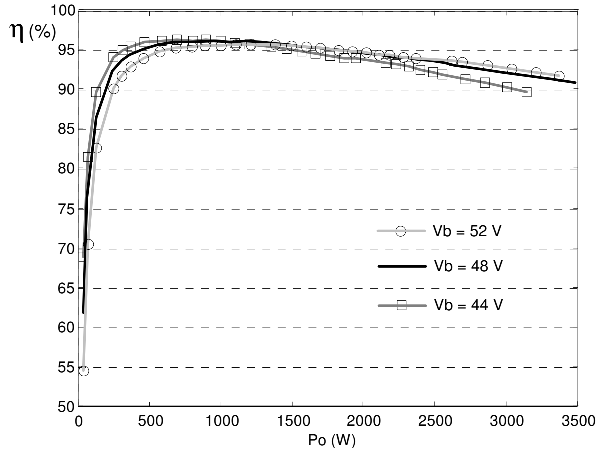

Fig. 7 Efficiency x output power characteristic (resistive load);

V. CONCLUSIONS

Most SARES stores energy in battery banks in order to overcome the intermittence problem commonly found in RE sources and a special battery inverter is necessary to guarantee continuous operation. Even more, it was concluded that either DC or AC bus based systems demand on at least one reliable and robust battery inverter, which should be capable to directly attend the consumer AC loads. It is proposed that this current demand on high-performance battery inverters can be reached by using multilevel topologies, and it is shown that the most suitable topologies are the multiple-transformer and the multi-winding transformer. The implemented prototype is based on the multi-winding transformer topology and has proved itself to be robust, presenting peak efficiency of 96.0%. The proposed inverter can be considered a top-efficiency inverter for the power range of about 3 kVA.

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