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Design and Implementation of a Three-Phase Active T-Type NPC Inverter for Low-Voltage Microgrids

Rick Chen[1], Ying-Yu Tzou[2]

[1]AcBel Polytech Inc., Taiwan
[2]Institute of Electrical Control Engineering, National Chiao Tung University, Taiwan
Email: yytzou@mail.nctu.edu.tw

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Abstract

This paper presents the design and implementation of a 3 kVA three-phase active T-type neutral-point clamped (NPC) inverter with GaN power devices for low-voltage microgrids. The designed inverter is used in a battery-based energy system (BESS) for power conversion optimization in applications to low-voltage microgrids. A modular design method has been developed for the design and implementation of the AT-NPC inverter. Experimental verification has been carried out based on a 3-kW three-phase T-Type NPC grid-connected inverter. FPGA based digital control technique has been developed for the current control of the three-level three-phase grid inverter. A maximum efficiency of 98.49% has been achieved within a load range from 50% to 75%.

Keywords

Active T-Type NPC Inverter, Modular Design Methodology, Loss Analysis, Efficiency Optimization

1. Introduction

Multi-level converters (MLC) have been traditionally adopted for static power conversion and motor drives in medium voltage applications [1] [2]. Although various converter topologies have been developed for medium voltage applications, the three-level neutral-point clamped (NPC) converter topology is the most frequently selected for industrial applications due to its advantages of simplicity and reliability [3] [4] [5]. With the advances of modularized power devices developed for the implementation of active T-type NPC inverters [6] [7] [8] [9], AT-NPC inverters are becoming a competitive choice for PV inverters and

motor drives in low voltage applications [10]-[15].

2. T-Type NPC Inverter

The 3-level active T-type NPC inverter, as show in **Figure 1(b)**, provides an additional middle point of its DC-link voltage for its voltage switching, and thus the inverter voltage is reduced to half compared with the conventional 2-level inverter as shown in **Figure 1(a)**. The reduction of voltage switching level provides advantages such as lower switching losses, smaller filters for both the dc-link capacitor and output filters, lower EMI and leakage current, higher power density with improved efficiency.

The drawbacks of the AT-NPC inverters are extra AC switches with their corresponding isolated gate drives are required, more sophisticated PWM strategy and balancing control scheme are required. However, with the development of new generation wide bandgap (WBG) semiconductors such as Gallium Nitride (GaN) and Silicon Carbide (SiC), and the high-performance advanced FPGA embedded microprocessors, an active T-type inverter phase leg may become a standard power module for the implementation of an idea renewable power conversion system.

Vertical GaN devices provide advantages such as high voltage blocking capability, very low conduction resistance with very small footprint, and high operating temperature, but still exists a major challenge for reliable mass production.

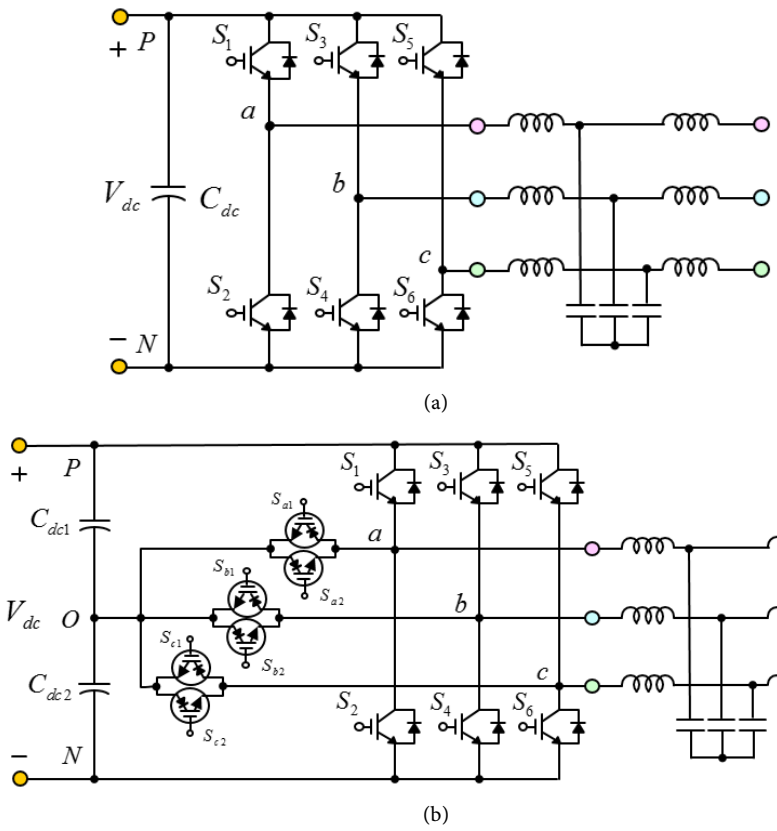


Figure 1. Schematics of (a) 2-L and (b) 3-L active T-type NPC inverters.

On the other hand, lateral GaN-on-Si devices are a promising alternative. A High-electron-mobility transistor (HEMT), also known as heterostructure FET (HFET), is a field-effect transistor incorporating a junction between two materials with different band gaps. GaN HEMT power devices can achieve low on-state resistance and high-speed switching performance, and provides a possibility to miniaturize the connected power filter components with sophisticated digital control techniques [16]-[21].

3. Implementation and Experimental Results

Practical implementation issues of the AT-NPC inverters using advanced WBG power semiconductor devices have got attentions in recent years [22] [23]. There still left many design and implementation issues for the integrated design and control of the AT-NPC inverters with innovative power semiconductor devices and advanced SOPC control technologies. This paper presents the design and implementation of a 3 kW three-phase 3-L AT-NPC inverter using the GaN HEMT power semiconductor devices from Transform. **Table 1** gives some key parameters of the designed inverter.

An FPGA-based predictive control scheme has been developed for the current control and efficiency optimization of the designed three-phase T-type NPC grid-tied inverter. T-type inverter has the features of low conduction losses, low switching losses and superior output waveform quality. These benefits will become significant as the switching frequency decreases. The proposed control scheme is very promising for high power applications. The 3LT2C basically combines the advantages of the 2-level converter such as low conduction losses and small part count with the advantages of the 3-level converter such as low switching losses and superior output voltage quality.

We adopt a modular design method for the design and implementation of the AT-NPC inverter. The converter is designed with a half-bridge AT-NPC inverter as a basic power module. A basic power module includes its own input and output filter, gate drive circuits, protection circuits, sensing and control interface circuits, and a local FPGA-based current controller. Other converters can be constructed with several basic AT-NPC modules. **Figure 2** shows the modularized grid converter design methodology.

Table 1. Parameters of the constructed 3L AT-NPC inverter.

Parameters	Symbols	Values
Nominal output power	P_n	5 kW
Grid voltage	V_g	220 VAC
DC-link voltage	V_{dc}	5380 VDC
DC-link capacitance	C_{dc}	2 × 470 μF in parallel
Switching frequency	F_s	48 kHz
Inverter-side inductance	L_1	1.2 mH
Grid-side inductance	L_2	0.4 mH
Output filter capacitance	C_f	22 μF

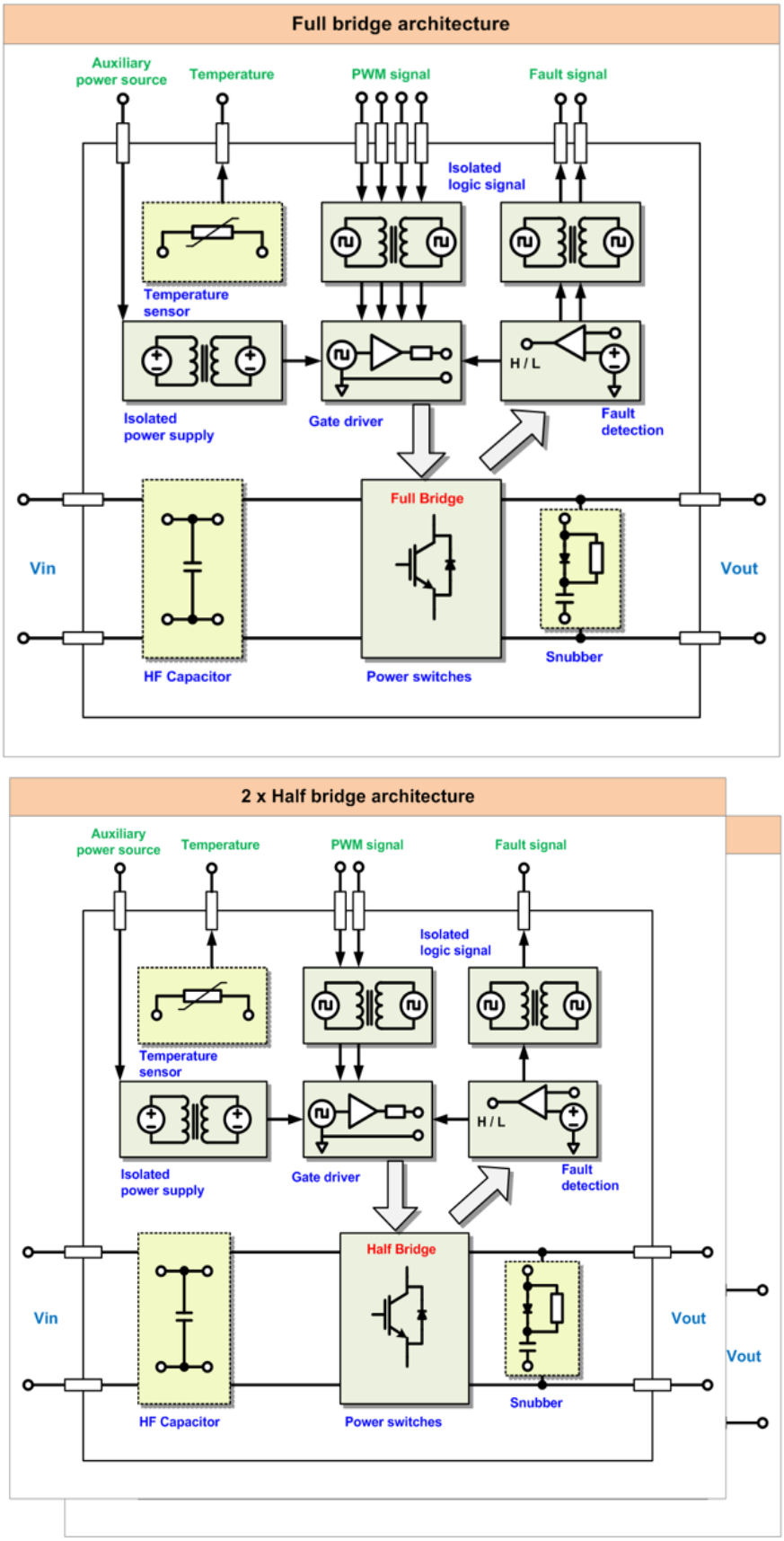
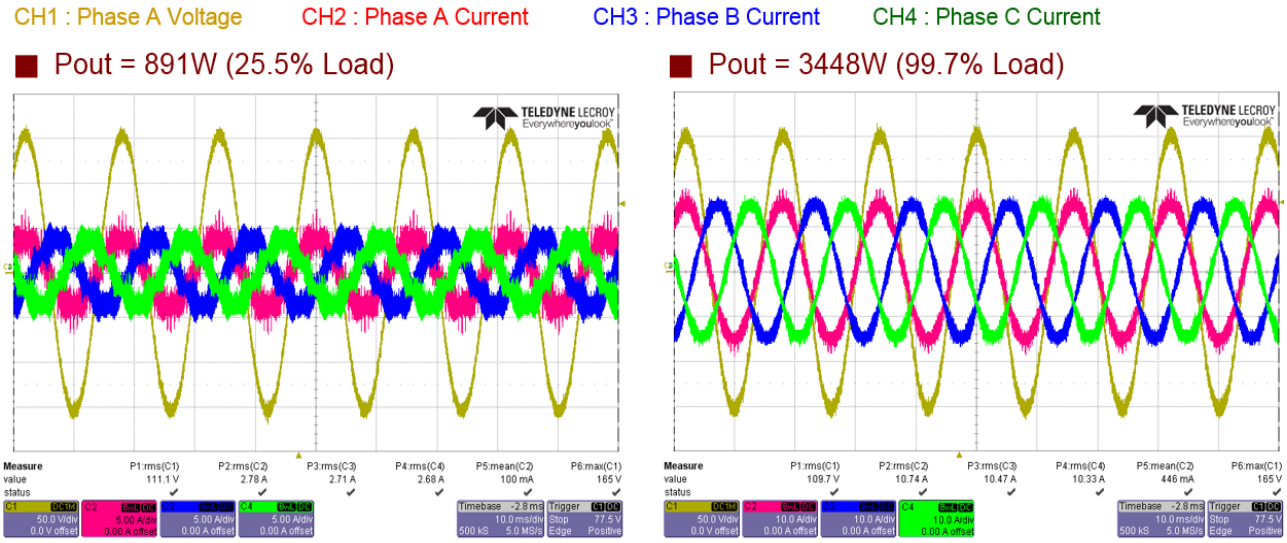


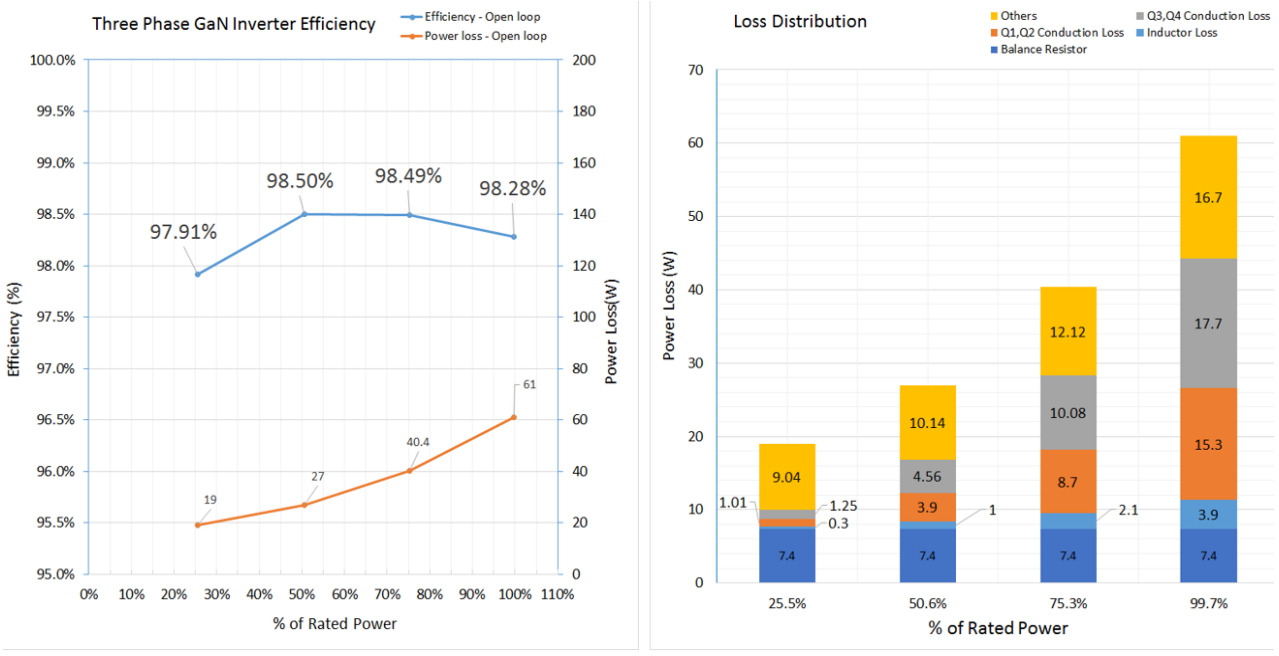
Figure 2. Modularized grid converter design methodology.

Loss model based on a defined switching waveforms and device characteristics can be used for the efficiency analysis of inverters [24] [25] [26]. The inverter is designed to be operated with a wide range of adjustable switching frequencies from 3 kHz to 60 kHz. **Figure 3** shows the experimental results of measured output current of the designed 3 L AT-NPC inverter at different loading conditions. **Figure 4** shows the measured efficiency and loss distribution as functions of load. A maximum efficiency of 98.49 has been achieved within a load range from 50% to 75%.



(a) (b)

Figure 3. Measured output current at different load conditions.



(a) (b)

Figure 4. Measured efficiency and loss distribution.

Efficiency optimization with adjustable switching frequency and adjustable DC-link voltage can be carried out with a programmable FPGA-based inverter controller. The designed inverter is tested with a nominal switching frequency of 48 kHz. Efficiency performance measures are functions of load current, switching frequency, and dc-link voltage. For the selected power devices, conduction loss plays a dominant role for ratings above 70%. Experimental results suggest that an efficiency optimization strategy is required to reduce the conduction losses above a specific load ratio while to reduce the switching losses when the load is lower than this specific load ratio.

4. Conclusion

This paper has presented the design and implementation of a 3 kVA three-phase active T-type neutral-point clamped (NPC) inverter with GaN HEMT power devices for low-voltage microgrids. For the selected power devices, conduction loss plays a dominant role for ratings above 70%. Experimental results suggest that an efficiency optimization strategy is required to reduce the conduction losses above a specific load ratio while to reduce the switching losses when the load is lower than this specific load ratio. A maximum efficiency of 98.49% has been achieved within a load range from 50% to 75%.

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