

The High Efficiency Transformer-less PV Inverter Topologies Derived From NPC Topology

Lin Ma¹, Tamas Kerekes², Remus Teodorescu², Xinmin Jin¹, Dan Floricau³, Marco Liserre⁴

¹ School of Electrical Engineering
Beijing Jiao Tong University
No.3 of Shangyuan Residence
Haidian District, 100044
Beijing, China
Tel.: +86 / (10) – 5168 2512
Fax: +86 / (10) – 5168 2512
E-Mail: 05117293@bjtu.edu.cn
jinxm@bjtu.edu.cn
URL: <http://ee.bjtu.edu.cn>

² Institute of Energy Technology
Aalborg University
Pontoppidanstraede 101
9220 Aalborg East
Aalborg, Denmark
Tel.: +45 / 9440 9249
Fax: +45/ 9815 1411
E-Mail: tak@iet.aau.dk
ret @iet.aau.dk
URL: <http://www.iet.aau.dk>

³ Faculty of Electrical Engineering
University POLITEHNICA of Bucharest
313 Splaiul Independentei, 060042
Bucharest, Romania
Tel.: +4021 / 402 91 35
Fax: +4021 / 410 43 55
E-Mail: dan.floricau@upb.ro

⁴ Dipartimento di Elettrotecnica ed Elettronica
Politecnico di Bari
E. Orabona 4 – 70125
Bari, Italy
Tel.: +39 / 0805963912-433
Fax: +39 / 0805963410
E-Mail: liserre@gmail.com

Keywords

« Photovoltaic », « Multilevel converters », « Efficiency »

Abstract

The grid-connected photovoltaic (PV) systems are an important part of renewable energy sources and their integration is getting more and more widespread. In order to improve the efficiency, practicality and reliability of the PV systems, many kinds of new inverter topologies have been proposed to avoid using a grid isolation transformer.

The NPC topology and two other derived topologies are presented and analyzed in this paper. Validated by experiments, it has been proven that they are very suitable for using in transformer-less PV applications due to high efficiency, low leakage current and EMI.

Simulations using Simulink and the PLECS toolbox have been done for evaluating efficiency of different NPC topologies and some experimental results are presented in this paper to validate the operation of the different topologies.

Introduction

With the renewable power increasing, the grid-connected photovoltaic (PV) systems, in particular low power single-phase systems (from 1kW to 10kW), are becoming one of the most important parts in the DG (Distributed Generation) system. Meanwhile the low power PV systems are usually private systems, which need to give the users maximum profitability through high efficiency, long life time, low prices, small volume and safety.

In order to improve the efficiency of PV inverters and lower the system prices, the grid isolation transformers are usually eliminated (they are usually used for providing personal protection and avoiding leakage currents between the PV system and the ground). Thereby, many transformerless applications were proposed [1] including HERIC topology [2], FB with DC Bypass topology [3], H5 topology [4] and Neutral Point Clamped (NPC) topologies.

The NPC topology was introduced by Nabae, Takahashi and Akagi in 1981 [5] showing great improvements in terms of lower dv/dt in comparison with the classical 2-level full-bridge inverter. It was one of the inverter topologies connecting to the grid without using any transformer. Compared with the traditional 2-level PWM inverters, the NPC topology also can produce lower switch losses, harmonics and common mode current which significantly improve the efficiency of the inverters. The NPC topology was firstly used in motor drive systems to eliminate the common mode harmonics and improve the inverter efficiency. When the traditional PWM inverter is used to drive an AC motor, the common mode current, could flow through the stray capacitance between the stator and rotor, which is harmful to the motor and might cause increasing losses, premature isolation aging, and protections tripping. In the photovoltaic (PV) system, due to the large surface of the PV generator, its stray capacitance with respect to ground reaches values that can be quite high. This problem is similar to the AC drive system. The capacitor between PV array and the ground connection in the PV system is similar to the capacitor between rotor and stator in the AC motor drive system.

Because of the similarity between AC drive system and PV system, the NPC topology and its topologies derived also could be applied to PV systems. They are currently used by many companies for grid-connected PV systems.

In this paper, the NPC topology and another two derived topologies used for high efficiency PV inverters (Conergy NPC topology [6] and Active NPC topology [8]) are presented.

The comparison and control strategies of different topologies are also discussed. After showing some simulation and experimental results, a conclusion is given which proves that the topologies derived from NPC topology are suitable for PV application due to the high efficiency, low leakage current and good EMI behavior.

Conventional NPC topology

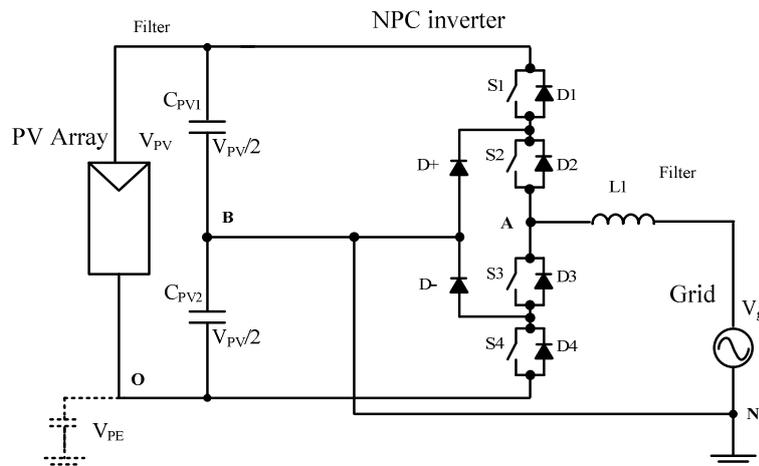


Fig.1: Neutral Point Clamped Half Bridge

Classical NPC topology is the most popular 3L topology. It is also very versatile and can be used in both single phase (full-bridge or half-bridge) and three-phase inverters. As presented in Fig.1, the NPC half bridge is composed by four switches and two clamp diodes. The main concept is that zero voltage can be achieved by “clamping” the output to the grounded “middle point” of the dc bus using D+ or D- depending on the sign of the current.

The control strategy of the NPC inverter is quite simple, since it has just two zeros states (0+ and 0). The commutation states and the switching PWM pattern of the NPC inverter are given by Table I and Fig.2, respectively. During the positive half cycle of the grid voltage, S2 is ON and only S1 switches at the switching frequency. Therefore, the dead time between S1 and S2 might be set to zero by using this PWM strategy. S3 and S4 work complementarily to S1 and S2, respectively.

Table I: Switches States of NPC Half Bridge Inverter

	S1	S2	S3	S4
Positive	1	1	0	0
0+	0	1	1	0
0-	0	1	1	0
Negative	0	0	1	1

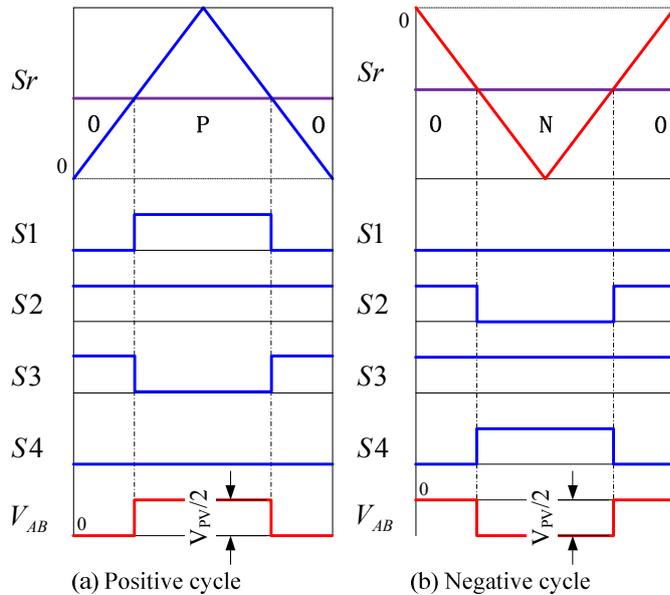


Fig.2: The switching states and output voltage of NPC inverter

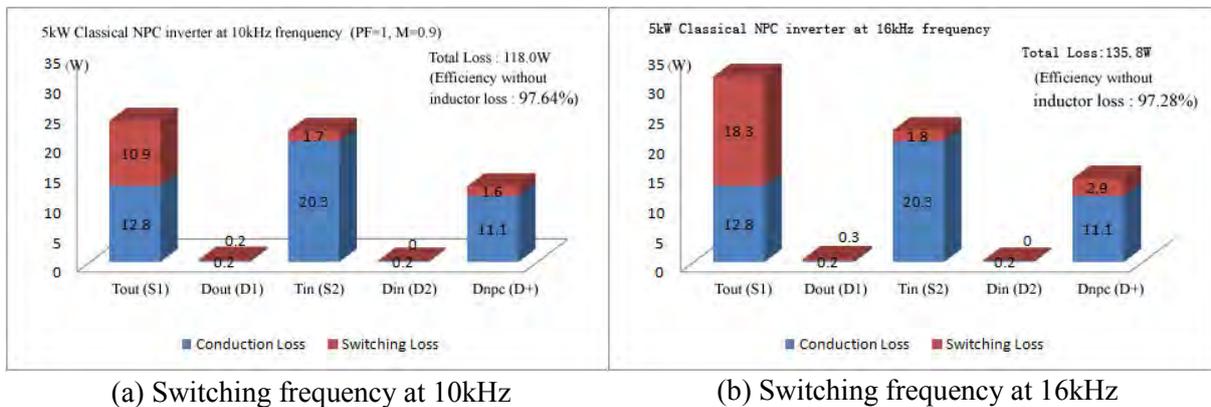


Fig.3: Switching losses of a 5kW NPC topology inverter at different frequencies, M=0.9 and PF=1

The main disadvantage of the NPC inverter is given by an unequal distribution of the losses in the semiconductor devices, which leads to an unequal distribution of temperature. Fig.3 shows the switching losses of a 5kW NPC topology inverter at different switching frequencies. This figure points out that the stresses due to switching losses on the outer switches S1 and S4 is higher than on the inner switches, especially at higher frequency (Fig.3b). As the switching frequency increases, the uneven losses distribution in the NPC inverter gets even worse.

For a PV system, the modulation index is often fixed when the DC bus and the grid voltage are given and the power factor also fixed at PF=1. The modulation index is usually set around M=0.9 with DC bus voltage VDC=400V (for full-bridge topologies) and grid AC voltage 230V (RMS).

In this paper all the simulation models of half-bridge topologies use a DC bus voltage of $V_{PV}=800V$ and a 220V (RMS)/50Hz AC grid voltage. The passive components are the same for all the simulated topologies. The switch model is based on the MITSUBISHI PM75DSA120 intelligent power module (IPM). The power rate is set to 5kW for simulation purposes. The switching frequencies are set to 10kHz and 16kHz (the commercial PV inverters normally use 16kHz, but 10kHz was used in the lab experiments).

As Fig.3 shows, the stress due to the total switching losses is stronger in the outer IGBTs (S1 and S4) than in the inner ones (S2 and S3). The conduction losses distribution is dependant of the modulation index (M). When $M=1$, the outer IGBTs exhibit the highest conduction losses stress. As both the conduction and switching losses overstress the outer IGBTs (S1, S4) respect the inner ones (S2, S3), the unbalanced losses distribution restricts the system power rate in case of high power applications.

Conergy NPC topology

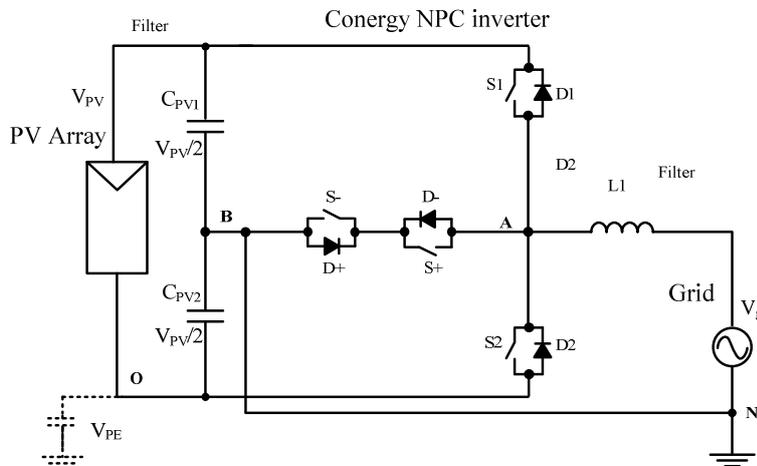


Fig.4: Conergy Neutral Point Clamped Half Bridge

A “variant” of the conventional NPC is a half-bridge with the output clamped to the neutral by using a bidirectional switch realized with 2 anti-series IGBTs as patented by Conergy [6].

The main concept of this topology is that the zero voltage can be achieved by “clamping” the output to the grounded “middle point” of the DC bus by using S+ or S- depending on the sign of the current. The switching pattern for generating positive current is depicted in Fig.5. In the positive half cycle, S1 and S+ switch complementarily at the switching frequency. During the negative half cycle, S2 and S- switch at the switching frequency. In the whole process of the work period, the V_{PE} is clamped to $-V_{PV}/2$, no current will flow through the stray capacitance between DC- bus and ground.

Table II: Switches States of Conergy NPC Half Bridge Inverter

	S1	S+	S-	S2
Positive	1	0	0	0
0+	0	1	1	0
0-	0	1	1	0
Negative	0	0	0	1

The control strategy of Conergy NPC has only two zeros states as the conventional NPC topology. The switching states and the switching PWM pattern are given by Table II and Fig.5, respectively. Fig.6 shows the switching losses of a 5kW Conergy NPC topology inverter at different switching frequencies. It can be appreciated in this figure how the main switching losses stresses the outer IGBTs, S1 and S2.

As during the periods of S+ or S- turns on, the current across the S+ and S- is zero, whereas during the period of S+ and S- turn off, the voltage between the switch is zero, the processes turn on and turn off of S+ and S- are both soft-switching. All the switching losses stress S1 and S2.

Whereas the IGBTs S+ and S- with their anti-parallel diode exhibit more conduction losses than S1 and S2 as they conduct current during the zero state in both the positive and the negative cycle. The power losses unequal distribution is compensated by the double conduction losses in S+ and S-.

During the active states, just one IGBT (S1 or S2) exhibits conduction losses, so the total losses are less than in the NPC topology. As shown in Fig.6, the total power losses are about 20% lower compared with conventional NPC topology in the simulation results.

The Conergy topology has only four switches and better efficiency. Due to these facts it's a very suitable topology for low power PV system applications.

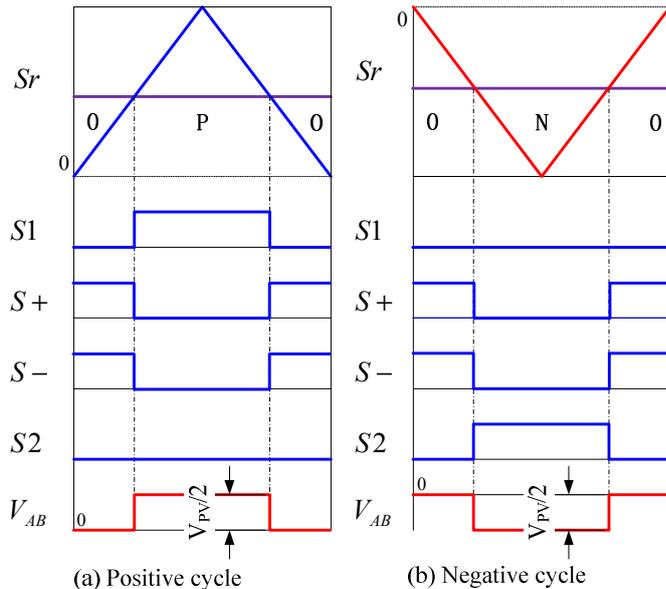


Fig.5: The switching states and output voltage of Conergy NPC inverter

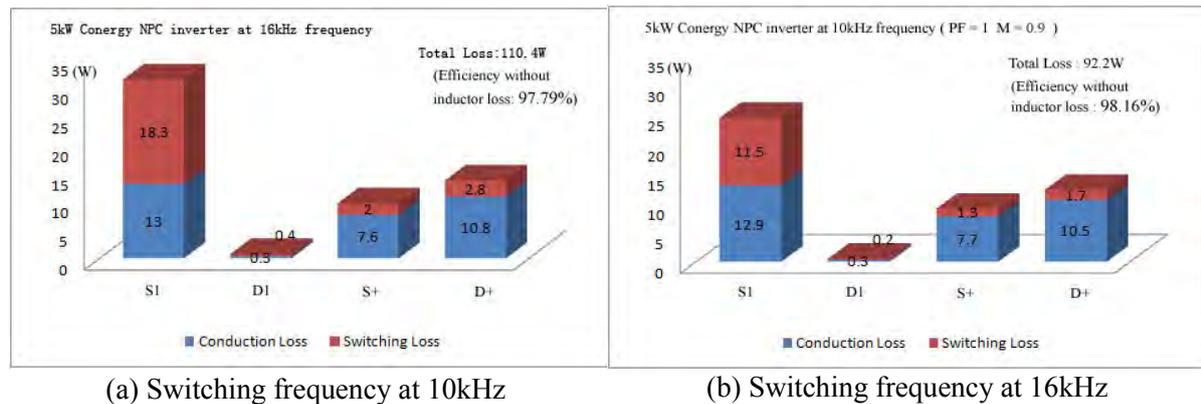


Fig.6: Switching losses of a 5kW Conergy NPC topology inverter

Active NPC topology

The ANPC topology inverter [8] is derived from the conventional NPC topology as presented in Fig.7. Two active switches with anti-parallel diodes are used for clamping.

The ANPC topology, in contrast to the conventional NPC converter, has more than one way to clamp the midpoint. The upper clamping path results from turning on S2 and S5 and the lower clamping path from turning on S3 and S6. The current can be conducted through both clamping ways in both directions.

The distribution of the conduction losses during the zero states can be controlled by the selection of the different NPC paths. The switching losses could be also controlled by the selection of different commutation states.

There are many different PWM strategies for Active NPC control by using different zero states and conduction paths [7]. In this section, natural double frequency PWM strategy [8] is introduced.

Papers [7], [8] show a PWM strategy named Double-Frequency ANPC control which naturally doubles the apparent switching frequency. In comparison with the other ANPC PWM strategies, the DF-ANPC strategy has four zero states: 0+1, 0+2, 0-1 and 0-2 (Table III). For the zero voltage states, different control sequences could be used with different losses distribution needs.

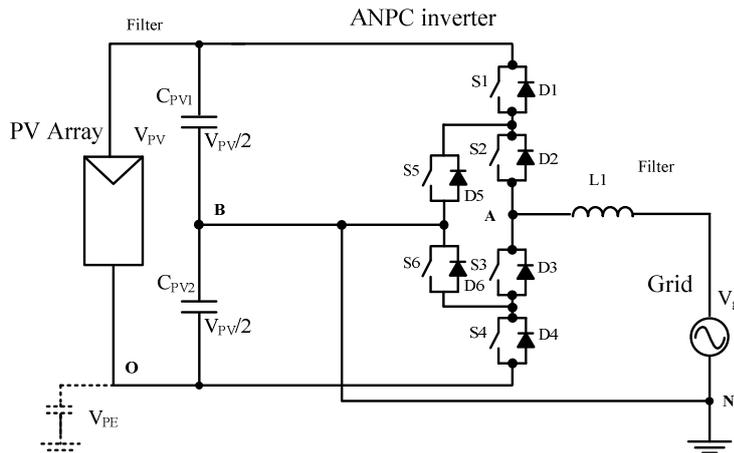


Fig.7: Active Neutral Point Clamped Half Bridge

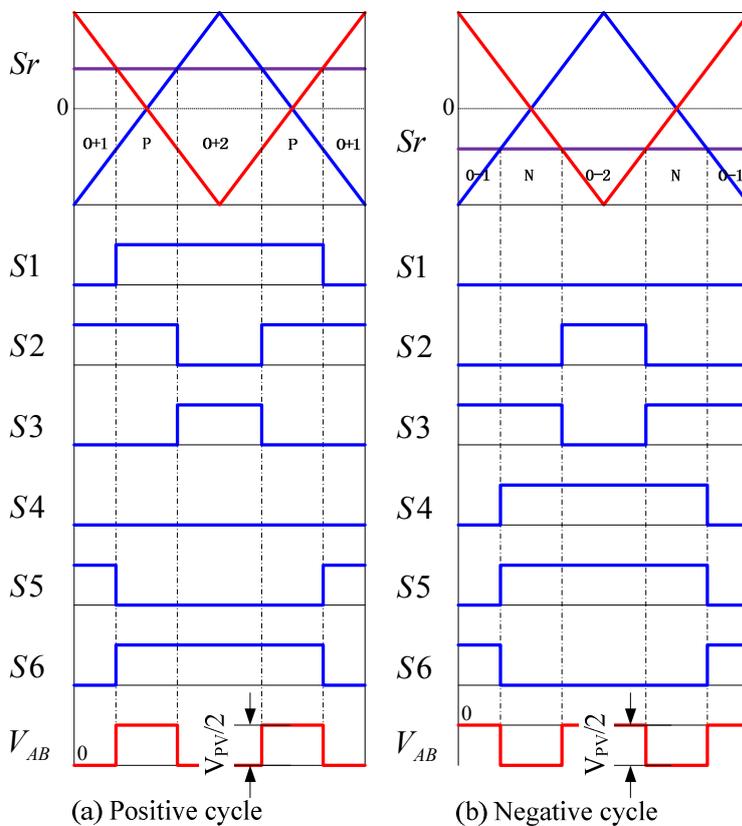


Fig.8: The switching states and output voltage of ANPC-DF strategy

The reference voltage is compared with two carrier waves that are phase-shifted by $T_s/2$. As there are two active states in a half cycle, this ANPC control strategy naturally doubles the apparent switching frequency. As there are two positive and two negative active states during one switching period, the output voltage has an apparent switching frequency equal to $2f_s$.

The switching losses distribution during the positive half cycle is analyzed here. As shown in the Fig.8, in the positive half cycle, there are two active periods with $V_{AO}=V_{PV}/2$ during the positive half cycle. During the first period, when S1 turns on, S2 keeps on state from the zero state to the active state, the switching on losses stresses on S1. When S2 turns off, S1 keeps on state from the active state to the zero state, therefore S2 withstands the switching off losses stress. During the second period, the situation is opposite, i.e., the S2 takes the turn on losses and S1 takes the turn off losses.

By means this switching strategy, the switching losses are distributed more uniformly among inner and outer IGBTs as presented in Fig.9.

Compared with the conventional NPC topology, the efficiency does not improve. However, the power losses distribution problem is improved by using the ANPC control strategy.

Table III: Switches States of DF-ANPC Half Bridge Inverter

	S1	S2	S3	S4	S5	S6
Positive	1	1	0	0	0	1
0+1	0	1	0	0	1	0
0+2	1	0	1	0	0	1
0-2	0	1	0	1	1	0
0-1	0	0	1	0	0	1
Negative	0	0	1	1	1	0

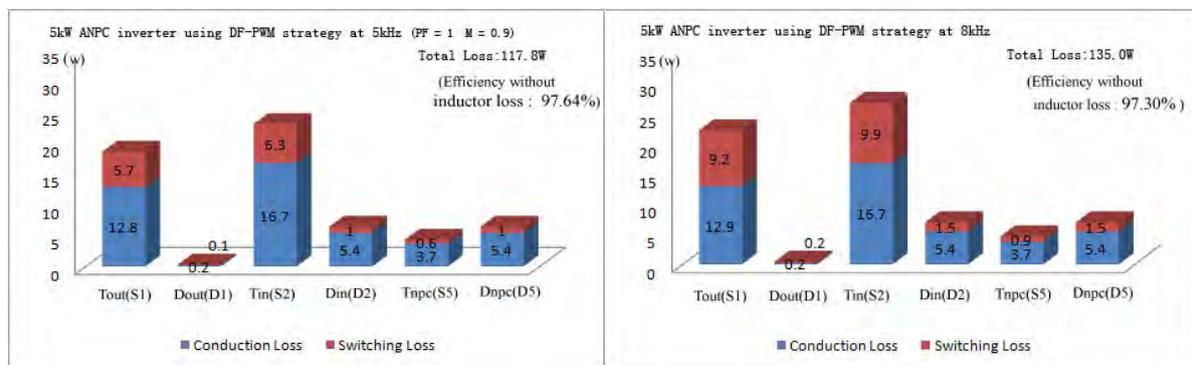


Fig.9: Switching losses of a 5kW DF-ANPC topology inverter

Experimental results

The experimental tests setup is constructed by MITSUBISHI PM75DSA120 intelligent power modules (IPM) and the system parameters are shown in Table IV. The YOGOGAWA WT3000 Precision Power Analyzer is used for calculating the efficiency of the different inverters.

Due to the fact that the IPM used in the experiments encases two IGBTs of a single leg, the power losses distribution cannot be measured in each single switch. Therefore the experimental results are focused on evaluating the conversion efficiency of the tested topologies. These experiments reveal that overall efficiency of the Active NPC and the conventional NPC topologies are quite similar.

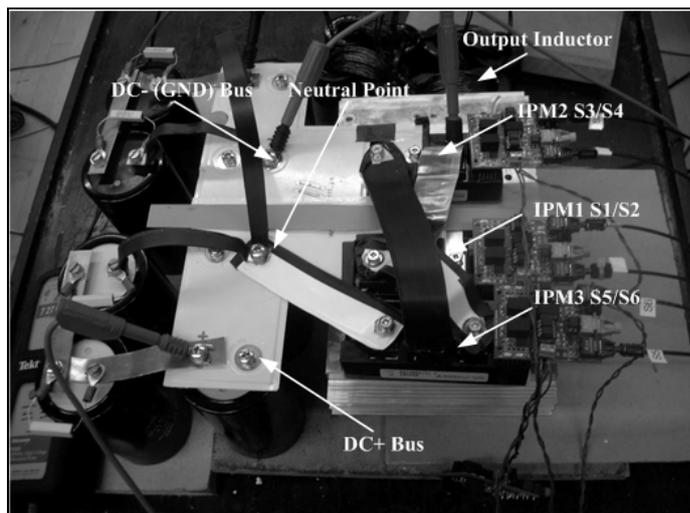


Figure 10 Experimental equipments

Table IV: System Parameters

Quantity	Value	Comment
Line frequency	50Hz	
Carrier frequency	10kHz	DF Active NPC 5kHz
Output filter L	2mH	
C_{DC}	1000uF	Each level
Rated DC voltage	800V	400V each level
R_{Load}	15 Ω	
Switches	PM75DSA120	MITSUBISHI IPM

Table V: Efficiency experimental results

Input Power (kW)	0.5kW	1.0kW	1.5kW	2.0kW	2.5kW	3.0kW	3.5kW	4.0kW	4.5kW
NPC Efficiency (%)	94.98	95.87	96.38	96.71	96.85	97.06	97.17	97.25	97.23
Conergy NPC Efficiency (%)	95.34	96.18	96.62	97.05	97.14	97.42	97.47	97.60	97.67
DF Active NPC Efficiency (%)	94.60	95.82	96.35	96.72	96.94	97.08	97.20	97.29	97.34

In simulation, the inductor losses were neglected. In the experiments however, the overall efficiency got 0.45% lower when a second 2mH inductor was added to the original 2mH output filter (total 4mH).

In simulation, as shown in Fig.6, the efficiency of the Conergy NPC was 98.16% (neglecting the filter losses). If the estimated filter losses are included (0.45%), then the efficiency decreases to 97.7%, which matches to the experimental results detailed in Table V.

Likewise, as shown in Fig. 3, the efficiency of the NPC was 97.64% from simulation (neglecting the filter losses). If the estimated filter losses are included (0.45%), then the efficiency decreases to 96.2%, which matches the experimental results detailed in Table V.

From the experiments, the efficiency curves for the tested topologies are given in Fig.12. The efficiency of the Conergy NPC topology is about 0.5% higher than in case of the NPC topology. The efficiencies of the Active NPC and conventional NPC are almost equal.

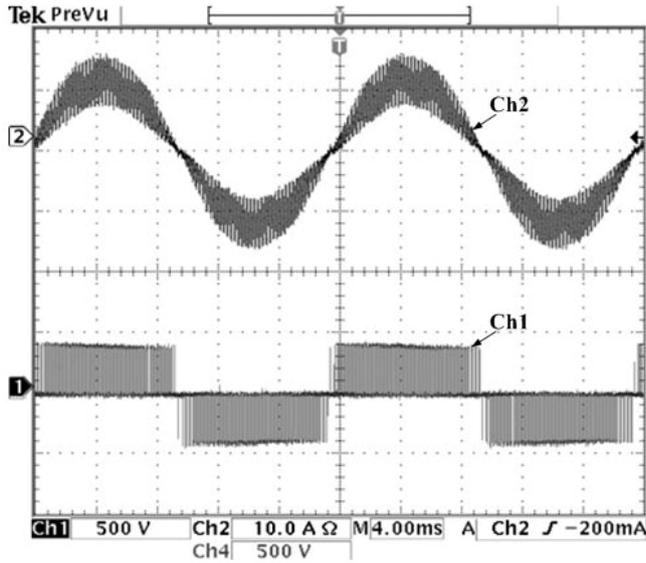


Fig.11: Conergy NPC Output waveform
(Ch1 VAB CH2 Output Current)

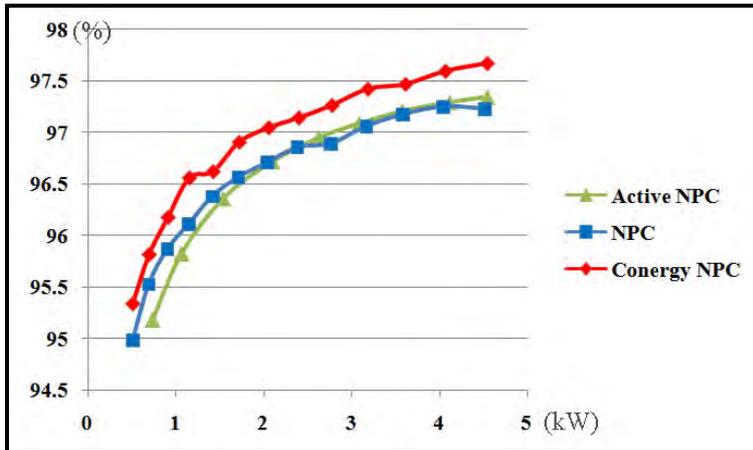


Fig.12: Efficiency curves

Conclusion

The topologies derived from the NPC topology showed very high performances both in the experimental and the simulation tests conducted in this work, which make them very suitable for transformer-less PV applications due to their high efficiency and low leakage current and EMI. The Conergy-NPC topology has a slightly higher efficiency in comparison with NPC topology, due to the fact that only one switch is conducting during the active state. Therefore, the Conergy NPC topology is suitable for low power PV system applications. Moreover, the simple structure and few components are both attractive for commercial application. However, the switches S^+ and S^- are not similar to the clamp switches of the Active NPC topology. Those two switches exhibit more power losses and need to switch $V_{PV}/2$ voltage. In the experiments, the distributed inductor also caused more stress to the switches S^+ and S^- . The ANPC topology, which uses different modulation strategies, has a better power losses distribution. Thus, the ANPC topology is suitable for the high power transformer-less PV system applications. The modulation strategy is a key issue in this topology. As $S1$ and $S5$, $S4$ and $S6$, $S2$ and $S3$ (active states) could not be ON at the same time (see Fig.7), the dead time setting needs to be carefully considered.

Table IX. The comparison of NPC topologies

	Conventional NPC	Conergy NPC	Active NPC
Device Count	4 Switches & 2 Diodes	4 Switches	6 Switches
Efficiency	High	Higher than NPC and ANPC	High
Losses Distribution	Unbalanced	Unbalanced	Balanced

Table IX shows the main characteristics of the 3 different NPC topologies. Conergy NPC has the best efficiency and lowest number of components. The Active NPC topology has the best power losses distribution balance. The NPC topology is currently used by Danfoss Solar Inverters in a three-phase configuration with multi-string boost converter. The Conergy-NPC topology is currently used on the PV inverter market by Conergy in the IPG single-phase string inverter series. The NPC topology and other ones derived from the NPC are becoming widely used in PV systems due to their high performance.

References

- [1] Kerekes, T. Teodorescu, R. and Borup, U, "Transformerless Photovoltaic Inverters Connected to the Grid [C]," Applied Power Electronics Conference, APEC 2007 - Twenty Second Annual IEEE, Feb.25.2007-March.1.2007, Page(s):1733-1737.
- [2] Schmidt, Heribert – European Patent Application, Pub No.03009882.6, Pub. Date: 15.05.2003
- [3] Gonzalez, R.; Lopez, J.; Sanchis, P.; Marroyo, L, 'Transformer-less Inverter for Single-Phase Photovoltaic Systems [J]', Power Electronics, IEEE Transactions on Volume 22, Issue 2, March 2007, Page(s):693 – 697.
- [4] Matthias Victor – United States Patent Application, Pub No.US2005/0286281 A1, Pub. Date: 29 Dec 2005
- [5] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point-clamped PWM inverter [J]," IEEE Trans. Ind. Applicat., vol. 17, Page(s): 518–523, Sep./Oct. 1981
- [6] Knaup P – International Patent Application, Pub No. WO 2007/048420 A1, Pub. Date: 3 May 2007
- [7] D. Floricau, E. Floricau and M. Dumitrescu; "Natural Doubling of the Apparent Switching Frequency using Three-Level ANPC Converter [C]", Nonsinusoidal Currents and Compensation, 2008. ISNCC 2008. International School on 10-13 June 2008 Page(s):1 – 6
- [8] Thomas Brückner, Steffen Bernet and Peter K. Steimer, "The Active NPC Converter for Medium-Voltage Applications [C]", industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005 Volume 1, 2-6 Oct. 2005 Page(s):84 - 91 Vol.