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High-Efficiency Fault-Tolerant Three-Level SiC Active NPC Converter for Safety-Critical Renewable Energy Applications

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# Abstract:

Fault tolerance plays a critical role for power electronic systems in safety-critical applications such as the distributed generation of renewable energy. Particularly, multi-level power converters have been intensively utilized in medium-voltage or high-voltage distributed generations, the circuit topologies of which contain many more switching devices, leading to increased device failure probability. However, one main drawback with the majority of the existing fault-tolerant power converter topologies is the degraded efficiency due to the addition of the redundant phase leg or power semiconductor modules. A new 3-phase 4-leg fault-tolerant active neutral point clamped (ANPC) converter is proposed to tolerate switching faults under faulty condition, which also provides high efficiency under normal healthy condition by leveraging the redundant leg for current sharing with other main phase legs. In this paper, the efficiency of this fault-tolerant ANPC inverter will be investigated under the proposed switching schemes with the current sharing capability. The experimental results verify that this new 3-phase 4-leg fault-tolerant ANPC converter achieves higher efficiency under the current sharing switching scheme than that without current sharing, under normal/healthy operating condition.

# SECTION I. Introduction

With multilevel power converters being increasingly applied in medium-voltage or high-voltage distributed generation systems of renewable energy, the reliability becomes a major concern due to the utilization of numerous switching devices. For instance, in offshore wind turbine power plants and utility-scale battery energy storage systems, a failure in any single switching device could lead to system shutdown or even cascaded catastrophic disasters, in addition to significant downtime economic cost. Therefore, fast on-line fault diagnostic methods and fault-tolerant power converter topologies are required to be developed to ensure that the power electronic systems can autonomously switch into fault-tolerant operation mode if there are any switching faults. Many on-line fault diagnostic methods have been presented and investigated in the literature [1] [2] [3]. Therefore, the scope of this paper only focuses on fault-tolerant power converters. In the literature [4] [5] [6] [7], a number of fault-tolerant power converter topologies have been proposed and investigated, but the main drawback with these existing power converter topologies is the dramatic decreased efficiency under normal healthy conditions due to the device losses from the redundant switches or redundant phase legs. Such drawback may restrict the broad acceptance of the fault-tolerant power converters by industrial users due to the lower efficiency and possibly high cost.

[Figure 1: - 
The proposed A3L-ANPC power converter topology.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb1-p5-kateb-large.gif)

**Figure 1:** The proposed A3L-ANPC power converter topology.

Active neutral point clamped (ANPC) converter is introduced in [8] to overcome the issue of uneven loss distribution among the semiconductor switches in the conventional neutral point clamped (NPC) converters. The inherent fault-tolerant capability of the 3-phase 3-leg ANPC converter is investigated in [9]. However, it shows that the output voltage and output power of the 3-phase 3-leg ANPC converter have to be derated under certain fault-tolerant operation modes, which may not be allowed in many mission-critical applications, such as electric vehicles or more-electric aircrafts. In [10] [11], the authors proposed an advanced 3-level active neutral point clamped (A3L-ANPC) converter, as shown in Fig. 1, which can tolerate all the open-circuit switching faults and most of the short-circuit switching faults, with the capability of providing full voltage and full power. In this converter topology, an additional modular inverter phase leg is added between the dc-bus capacitor bank and the original three-leg ANPC inverter. If any of the switching devices in the original phase legs suffer from a device failure, the redundant phase leg can be utilized to replace the faulty devices or legs, as elaborated in [11]. Moreover, during normal operation (i.e., no fault condition), the redundant phase leg is fully leveraged for current sharing with other main phase legs to reduce conduction losses, rather than keep it in idle state which significantly increases conduction losses. However, the efficiency of this proposed 4-leg ANPC converter has not been thoroughly investigated in [10] [11]. Accordingly, in this paper, the efficiency of this proposed 3-phase 4-leg A3L-ANPC converter will be experimentally investigated in detail.

The remainder content of this paper is organized as follows. In Section II, the working principle of the proposed A3L-ANPC converter operated in the current sharing mode under healthy condition will be introduced. In Section III, experimental verification of the proposed A3L-ANPC converter and the associated efficiency comparison will be presented. In Section IV, conclusions based on the experimental investigation will be drawn. The fault-tolerant operation of the A3L-ANPC converter to various switching faults has been detailed in [11], and will not be repeated here.

# SECTION II. Current Sharing Capability Of The A3l-Anpc Converter

The current sharing characteristics of the A3L-ANPC converter is achieved by leveraging the redundant leg which can increase the overload capability and efficiency of the converter. Specifically, the redundant leg can be utilized to share the load current with three main phase legs under normal operating conditions. Current sharing capability is very beneficial in reducing the thermal stress in the outer switches (*Sx*1 and *Sx*4, where x=a, b, or c). Particularly, the outer switches in the converter have the largest thermal stress under the conditions of unity power factor and maximum modulation index [8]. However, it should be clarified that current sharing between the redundant leg and the three phase legs is only available at the six large voltage vectors.

## A. Current Sharing in Three-Level Mode

For the sake of explanation, the three-level voltage output states of the A3L-ANPC converter are defined as follows: P state (*Vd*/2), N state (−*Vd*/2), and O state (zero voltage). The large space vectors include P states and N states solely and the medium vectors and small vectors include at least one O state. Therefore, the redundant leg can output a P state or N state in the interest of sharing the current.

If the redundant leg outputs a P state or N state while another phase leg requires a O state, a dc-bus short-circuit fault may occur. To avoid a shoot-through fault, the redundant leg can only share current when large space vectors are used.

For instance, at the switching state of (P, N, N), the switches *Sr*1 and *Sr*2 on the redundant leg can be turned on to share the positive load current with the Phase-A leg, as shown in Fig. 2b. This capability is verified by the experimental results given in Fig. 3a and Fig. 3b. In Fig. 3a, the three line-to-neutral voltages, *Van*, *Vbn*, and *Vcn*, show the switching states of (P, N, N) and (P, O, N). Under the same operating condition, the load current sharing between the redundant leg and the Phase-A leg is demonstrated in Fig. 3b. It should be noted that the total load current is shared by the current flowing through *Sr*1 and *Sa*1 at the switching state (P, N, N). However, at the switching state (P, O, N), the current sharing strategy has to be disabled due to the necessity of using the redundant leg to output zero voltage for Phase-B leg. This is also shown in Fig. 3b where the load current equals the current flowing through *Sa*1. It should be pointed out that the current through *Sr*1 is represented by *iVNP* in Fig. 3b, where the subscript "VNP" refers to virtual neutral point. The similar current sharing strategy can be implemented for the other five large vectors, and will not be repeated here.

In order to further reduce the device conduction losses during current sharing mode, the lower neutral path of the A3L-ANPC converter can be turned on after the upper neutral path is turned on, as is shown in Fig. 2c. Firstly, the upper neutral path is turned on to build up the shared current. and then the lower neutral path is turned on to provide a quasi-zero voltage soft-switching for the lower neutral path. Assuming the on-state resistance of each SiC MOSFET as R during steady state, the resultant on-state resistance between the positive dc-bus and the Phase-A output terminal will be 2R when there is no current sharing as shown in Fig. 2a. Accordingly, the on-state resistance between the positive dc-bus and the output terminal would be 1.75R and 1.33R with different current sharing schemes as shown in Fig. 2b and Fig. 2c, respectively. Obviously, using the redundant leg for sharing the load current in normal operation can reduce the conduction losses significantly.

One potential concern during this operation mode is the overvoltage stress on the outer switches, such as *Sa*1 and *Sa*4. As shown in Fig. 2c, the bottom device *Sa*4 has to withstand the full dc-bus voltage during such current sharing mode, which should be paid spacial attention. If each device is not rated for the whole dc-bus voltage, using such parallel neutral paths should be forbidden.

## B. Current Sharing in Two-Level Mode

The current sharing characteristic of the A3L-ANPC converter can be utilized exclusively if the converter is operated only with large space vectors. In other words, the three-level A3L-ANPC converter has to be modulated as a two-level converter which is possible in normal operation or fault tolerant operation. However, the drawback of this mode is the increased harmonics in the output voltages, which may slightly degrade the performance of the load. If the two-level operating mode is acceptable for the application, current sharing in two-level mode can be utilized for overload, startup, and stall conditions, due to the increased overload capability of the A3L-ANPC converter.

[Figure 2: - 
Current sharing capability in A3L-ANPC converter topology (a) No current sharing for Phase-A (b) Current sharing for Phase-A (c) Improved current sharing for Phase-A with two neutral paths.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb2-p5-kateb-large.gif)

**Figure 2:** Current sharing capability in A3L-ANPC converter topology (a) No current sharing for Phase-A (b) Current sharing for Phase-A (c) Improved current sharing for Phase-A with two neutral paths.

[Figure 3: - 
Current sharing capability in the A3L-ANPC converter, time scale 2ms/div (a) phase voltages (b) shared currents.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb3-p5-kateb-large.gif)

**Figure 3:** Current sharing capability in the A3L-ANPC converter, time scale 2ms/div (a) phase voltages (b) shared currents.

# SECTION III. Experimental Verification of the Efficiency Improvement

To investigate the efficiency of the proposed A3L-ANPC converter, a 50kW prototype was designed and implemented in the laboratory. The experimental setup for the A3L-ANPC converter is shown in Fig. 4. The A3L-ANPC converter prototype is comprised of 24 SiC MOSFETs (Model No.: CREE C2M0025120D, rated at 1200V/60A). A digital signal processor (DSP) TMS320F28377D was used to control the converter. A three-phase wye-connected RL load consisting of 3.3Ω resistors and 950*µ*H inductors are connected at the output of the inverter. The dc-bus voltage is 690V and the nominal output power in the test is 45kW at unity modulation index. The switching frequency and the fundamental output frequency were set to 20kHz and 60Hz, respectively. The input power of the converter was supplied by a high power diode rectifier that feeds the dc-link from the 3-phase 480V main supply.

In order to measure the input and output power of the converter, eight high frequency bandwidth voltage and current probes were utilized to collect data on the voltages and currents of the converter system. The input voltage data is collected by a Tektronix high voltage differential probe (model No. THDP0100). The three phase output voltages were measured by Tektronix high voltage differential probes (model No. TMDP0200). Both the dc input and the three-phase output currents were measured by the Tektronix TCP0150 current probes. An eight-channel mixed signal MSO58 oscilloscope from Tektronix was used to acquire the voltage and current data.

[Figure 4: - 
Experimental setup of the 3-phase 4-leg 50kW SiC A3L-ANPC converter.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb4-p5-kateb-large.gif)

**Figure 4:** Experimental setup of the 3-phase 4-leg 50kW SiC A3L-ANPC converter.

Equation (1) shows three sinusoidal duty ratios for the three-phase inverter with the Sine-PWM modulation strategy [7]:

[Figure 5: - 
Current sharing capability of the proposed A3L-ANPC converter at various modulation indices [12].
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb5-p5-kateb-large.gif)

**Figure 5:** Current sharing capability of the proposed A3L-ANPC converter at various modulation indices [12].

(1)

The modulation index *m* controls the magnitude of the converter output voltages, and *ω* sets the output angular frequency. Current sharing is only possible when all three phase legs output either P or N states. In other words, none of the phase legs can output an O state during the current sharing mode. The duty ratio of the current sharing over a switching cycle under the Sine-PWM Phase Opposition Disposition (POD) is shown in (2).

(2)

Fig. 5 shows the three dimensional current sharing capability of the A3L-ANPC converter under Sine-PWM-POD switching scheme at different modulation indices. Current sharing is always possible under the Sine-PWM-POD strategy, but with 50% the maximum sharing duration.

To calculate the experimental efficiency of the converter, the input and output voltage and current were measured to calculate the input and output power, as shown in Fig. 6. The Sine-PWM-POD modulation strategy is used to conduct the efficiency tests at different modulation indices.

The measured efficiency results of the A3L-ANPC converters are shown in Fig. 7. The efficiency for the A3L-ANPC inverter is calculated while running it with and without current sharing strategy between the redundant phase leg and the main phase legs at modulation indices between 0.5 to 1. The results confirm that the current sharing strategy increases the converter efficiency in the operation range.

[Figure 6: - 
Measured waveforms of the fault-tolerant A3L-ANPC converter for efficiency measurement. Testing conditions: unity modulation index; scope time scale is 20ms/div; modulation scheme: Sine-PWM-POD.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb6-p5-kateb-large.gif)

**Figure 6:** Measured waveforms of the fault-tolerant A3L-ANPC converter for efficiency measurement. Testing conditions: unity modulation index; scope time scale is 20ms/div; modulation scheme: Sine-PWM-POD.

[Figure 7: - 
Measured efficiency comparison in different modulation indices at switching frequency of 20kHz.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/8791938/8807448/8807616/kateb7-p5-kateb-large.gif)

**Figure 7:** Measured efficiency comparison in different modulation indices at switching frequency of 20kHz.

# SECTION IV. Conclusion

Fault-tolerant capability is very critical for power converters applied in safety-critical applications such as wind turbine or photovoltaic power generations. To overcome the drawback of the low efficiency in existing fault-tolerant power converter topologies, the efficiency of the proposed A3L-ANPC converter was investigated in experiments. This paper verifies that the current sharing scheme using the redundant phase leg in the A3L-ANPC converter improves the efficiency under normal operation, which provides a promising solution for such multilevel converters to be used in the applications where both the reliability and efficiency have high priority.

# References

1. J. Lee, K. Lee and F. Blaabjerg, "Open-switch fault detection method of a back-to-back converter using npc topology for wind turbine systems", IEEE Transactions on Industry Applications, vol. 51, no. 1, pp. 325-335, Jan 2015.

2. L. M. A. Caseiro and A. M. S. Mendes, "Real-time igbt open-circuit fault diagnosis in three-level neutral-point-clamped voltage-source rectifiers based on instant voltage error", IEEE Transactions on Industrial Electronics, vol. 62, no. 3, pp. 1669-1678, March 2015.

3. X. Ge, J. Pu, B. Gou and Y. Liu, "An open-circuit fault diagnosis approach for single-phase three-level neutral-point-clamped converters", IEEE Transactions on Power Electronics, vol. 33, no. 3, pp. 2559-2570, March 2018.

4. W. Zhang, G. Liu, D. Xu, J. Hawke, P. Garg and P. Enjeti, "A fault-tolerant t-type three-level inverter system", 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, pp. 274-280, March 2014.

5. S. Ceballos, J. Pou, J. Zaragoza, E. Robles, J. L. Villate and J. L. Martin, "Fault-tolerant neutral-point-clamped converter solutions based on including a fourth resonant leg", IEEE Transactions on Industrial Electronics, vol. 58, no. 6, pp. 2293-2303, June 2011.

6. H. Ben Abdelghani, A. Bennani Ben Abdelghani, F. Richardeau, J. Blaquire, F. Mosser and I. Slama-Belkhodja, "Fault tolerant-topology and controls for a three-level hybrid neutral point clamped-flying capacitor converter", IET Power Electronics, vol. 9, no. 12, pp. 2350-2359, 2016.

7. R. Katebi, J. He, W. A. Khan and N. Weise, "Efficiency improvement of fault-tolerant three-level power converters", 2018 IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1054-1059, 2018.

8. T. Bruckner, S. Bernet and H. Guldner, "The active npc converter and its loss-balancing control", IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 855-868, June 2005.

9. J. Li, A. Q. Huang, Z. Liang and S. Bhattacharya, "Analysis and design of active npc (anpc) inverters for fault-tolerant operation of high-power electrical drives", IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 519-533, Feb 2012.

10. R. Katebi, A. Stark, J. He and N. Weise, "Advanced three level active neutral point converter with fault tolerant capabilities", 2016 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1-7, Sep. 2016.

11. R. Katebi, J. He and N. Weise, "An advanced three-level active neutral-point-clamped converter with improved fault-tolerant capabilities", IEEE Transactions on Power Electronics, vol. 33, no. 8, pp. 6897-6909, Aug 2018.

12. R. Katebi, J. He and N. Weise, "Investigation of fault-tolerant capabilities in an advanced three-level active t-type converter", IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 1, pp. 446-457, March 2019.