Investigation of Three-Level ANPC IGCT Converter for Industrial Medium-Voltage Drives

Jingxuan Zhang*

Electrical and Instrument Department, China Huanqiu Contracting and Engineering Corporation, Beijing, 100039, China

*Corresponding author’s e-mail: 2301638438@qq.com

Abstract. High-power three-level neutral-point-clamped (NPC) integrated gate commutated thyristor (IGCT) voltage-source converters have been widely used in industry applications. The novel three-level active neutral-point-clamped (ANPC) IGCT voltage-source converters can provide three additional switch states compared to the the NPC counterparts. Thus, the ANPC converter can increase the rated power compared to NPC. In this paper, the switching states of the three-level ANPC IGCT voltage-source converters are illustrated. The commutations and power loss distribution of the IGCT devices are investigated. The strategy is implemented on a high power three-level ANPC voltage-source converter equipped with 4.5kV/4kA IGCT devices. The experimental results prove that the three-level ANPC voltage-source converter has higher power density compared to the conventional NPC counterparts.

1. Introduction
Medium-voltage high-power converters have been widely used in industry applications. For example, they can be applied to motor drives for steel rolling mills, pipeline pumps, high speed Maglev vehicle, offshore wind power plant and so on. In recent years, medium-voltage high-power converter has become one of the hot topics in power electronics area. The power semiconductor devices that widely used in medium-voltage high-power converters mainly include gate-turn-off (GTO), insulate gate bipolar transistors (IGBTs) and integrated gate commutated thyristor (IGCT) due to their excellent switching characteristics.

The topologies that utilized in medium-voltage high-power converters can be grouped into three categories: Voltage-Source converter (VSC), current-source converter (CSC) and cycloconverter (CCV) [1]-[2]. For high-power applications, there are two CSC topologies always used in industrial drives: the load commutated inverter (LCI) and the CSC with full-controlled semiconductor device. The LCI has drawbacks include high total harmonic distortion of input current and low input power factor. The drawback of CCV is low dynamic performance. Compared to CSI and CCV, high power VSC fed drives have developed quickly and occupied higher market share over the last decade. The classical two-level VSC is not suitable for medium-voltage drives due to the voltage limits of the semiconductor device. Multilevel-VSC technology is dominant in higher voltage and higher power applications. Several topologies have been proposed for multilevel-VSC, among which, the cascaded H-bridge (CHB) and the neutral-point clamped (NPC) have been commercialized by major manufacturers including ABB, Siemens, Toshiba, GE and so on. For the CHB converter, each cell should be fed by a separated dc-link voltage source which is achieved by phase-shifting transformer with multiple secondary windings and corresponding rectifiers. Thus, the CHB converter has
drawbacks like high costs and low power density. The three-level NPC (3L-NPC) VSC has several advantages over CHB including low power density, common dc bus capability, high reliability and so on. With which, the 3L-NPC VSC has been widely used in medium-voltage high-power drives. Furthermore, it can be seen that the IGCT is more suitable for three level medium-voltage high-power converters compared to IGBT.

The drawback of 3L-NPC VSC is the unequal power losses of semiconductor devices. With which, the semiconductors device with the most switching losses will limit the maximum power of the converter. Thus, the three-level active neutral-point-clamped (ANPC) topology has been developed to improve unequal power losses distribution performance of the conventional NPC converter [3]-[5]. The 3L-ANPC VSC have two additional full-controlled semiconductor switches in each phase leg compared to NPC, which can provide more commutations state and increase the maximum output power. In this paper, the switching states of the three-level ANPC IGCT converters are illustrated. The commutations and power loss distribution of the IGCT devices are investigated. The strategy is implemented on a high power 3L-ANPC VSC equipped with 4.5kV/4kA IGCT devices. The experimental results prove that the three-level ANPC voltage-source converter has higher power density compared to the conventional NPC counterparts.

2. Switching state and operation principle of 3L-ANPC IGCT VSI converter
The topology diagram of the 3L-ANPC IGCT VSC is given in Fig. 1. As shown in Fig. 1, two IGCT switches (T5 and T6 for phase A) are added in antiparallel to the clamped diodes (D5 and D6 for phase A) in each phase compared to the NPC counterpart. The 3L-ANPC VSC can provide six effective switching states that allow the phase current to flow in both directions. The switching states of phase A of the 3L-ANPC VSC are summarized in Table 1.

![Fig. 1. Topology diagram of the 3L-ANPC IGCT VSC.](image)

| States | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $U_{in}$ |
|--------|------|------|------|------|------|------|--------|
| $+$    | 1    | 1    | 0    | 0    | 0    | 1    | $+U_{dc}/2$ |
| $0P_1$ | 0    | 1    | 0    | 0    | 1    | 0    | 0      |
| $0P_2$ | 0    | 0    | 0    | 1    | 0    | 0    | 0      |
| $0N_1$ | 1    | 1    | 0    | 0    | 0    | 0    | 0      |
| $0N_2$ | 1    | 1    | 0    | 0    | 0    | 0    | 0      |
| $-$    | 0    | 0    | 0    | 1    | 1    | 1    | $-U_{dc}/2$ |

As can be seen from Table 1, there are four different zero switching states that can be utilized in the 3L-ANPC including $0P_1$, $0P_2$, $0N_1$ and $0N_2$. If the phase current flows through the positive phase leg, the switch state is called $0P$. There are two different upper zero states: $0P_1$ and $0P_2$. For $0P_1$ and $0P_2$, the states of $T_2$ and $T_3$ are both active. The difference between $0P_1$ and $0P_2$ is the on-off state of $T_4$. The on-off state of $T_4$ does not change the conduction path but affects the switching loss distribution.
The lower zero states 0N₁ and 0N₂ can be analysed in the same way. Based on the analysis above, it can be seen that the phase current can flow in both directions across the upper and lower paths of the neutral.

![Commutations of the positive bus in the 3L-ANPC IGCT VSC (iₐ >0): (a) Type I (+↔0P₂), (b) Type II (+↔0N₁), (c) Type III (+↔0N₁)](image)

**Table 2. Device switching losses distribution for 3L-ANPC IGCT VSC.**

| Type | Commutation | T₁ | T₂ | T₃ | T₄ | T₅ | T₆ |
|------|-------------|----|----|----|----|----|----|
| I    | +↔0P₂       | ✓  |    |    |    |    | ✓  |
| III  | +↔0N₁       | ✓  | ✓  |    |    |    | ✓  |
| II   | +↔0N₂       | ✓  | ✓  | ✓  |    |    | ✓  |
| II   | 0P₂↔↔       | ✓  | ✓  | ✓  |    |    | ✓  |
| III  | 0P₁↔↔       | ✓  | ✓  | ✓  |    |    | ✓  |
| I    | 0N₂↔↔       | ✓  |    |    |    |    | ✓  |

3. **Commutations and power loss distribution analysis**

The transitions between the non-zero switching states and the zero switching states affect the switching losses distribution of the IGCTs and diodes. The loss distributions of different commutations are shown in Table 2. As can be seen from Table 2, the commutations can be divided into three types: Type I, Type II, and Type III. Fig. 2 shows the three commutations between the positive state “+” and the zero states with positive phase current (iₐ >0). These commutations are listed to show the difference between the three commutation types and illustrate their influence on the loss distribution of the 3L-ANPC converter.

The circles in Fig. 2 represent that the corresponding IGCT or diode will produce switching losses in the commutation. As shown in Fig. 2a, turn-off of T₁ and turn-on of D₃ during commutation +↔0P₂ and turn-off of T₁ and turn-on of D₃ during commutation 0P₂↔+ will produce switching losses. Fig. 2b shows that T₁ and D₃ will produce switching losses during Type II commutation. Fig. 2c shows that T₅ and D₃ will produce switching losses during Type III commutation. Based on the analysis above, it can be seen that switching losses between IGCT T₁ and T₅ as well as diode losses between D₅ and D₃ can be distribute by selecting different commutation types.

4. **Simulation and Experimental results**

The three-level ANPC converter is modelled in Matlab/Simulink. The loss model of the 4.5kV/4kA IGCT device is based on the datasheet of 5SHY55L4500. The dc bus voltage of the converter is 5000V. Simulations are performed to verify the power loss distribution performance of ANPC. Fig. 3 shows the comparison of power losses of the NPC and ANPC three-level converter. From Fig. 3, it can
be seen that the maximum power loss of the semiconductor devices in 3L-ANPC VSC can be reduced about 20% compared to that of the conventional NPC counterparts.

Fig. 3. Simulation results of the power loss distribution of different 3L-IGCT converter.

Fig. 4. Power module of the 3L-ANPC VSC  Fig. 5. Output voltage and current waveform of the VSC

Basing on the simulation, a high power 3L-ANPC VSC equipped with 4.5kV/4kA IGCT devices is constructed with the power module shown in Fig. 4. Experiments with three-phase inductance load are carried out to verify the power loss distribution effect. The output voltage and current waveform of the inverter side is presented in Fig. 5. As can be seen from Fig. 5, the maximum power is about 10.5MVA, which is 16.7% higher than the commercial 3L-ANPC VSC products. The experiment results prove that the 3L-ANPC IGCT VSC can increase the rated power by power loss distribution.

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