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Power Loss Research on IGCT-applied NPC Three-level Converter

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Abstract

IGCT has a broad application prospects in high power conversion such as flexible DC transmission due to its characteristics of high voltage and large capacity. Compared with IGBT it has a voltage and current level of 4.5kV/4kA and its slope resistance is less than IGBT's. In addition, due to the di/dt snubber circuit, IGCT's opening loss will be reduced. Because of improvement of IGCT performance, the loss of IGCT-applied three-level converter will have some new characteristics, so it is necessary to model the IGCT-type three-level converter. Based on piecewise linear curve fitting method, the IGCT switching loss mathematical model is established firstly. With its use in IGCT-type three-level converter loss model, a IGCT-type three-level converter mathematical model is established. If the model is applied in the ±200kV flexible DC transmission's calculation example, it can be concluded that the loss rate is 0.31%-0.78% when the power factor angle changes between 0 and π, while the loss rate of IGBT-type converter under same voltage level is 2%-3.5%, so it can be concluded that IGCT is more suitable than IGBT for use in high voltage and large capacity situation such as frequency control of motor speed and flexible DC transmission.

Keywords: *IGCT, three-level, loss model, power factor angle, flexible DC transmission*

1. Introduction

IGCT is the generic term of integrated gate drive circuit and the gate converter thyristor. Compared with IGBT, IGCT has several advantages: it has a higher voltage and current level (4.5kV/4kA), it also has a lower slope resistance [1]. Due to these advantages, IGCT has a broad application prospects in flexible DC transmission. Three-level will be a reasonable structure for the IGCT-type converter, because it not only raises voltage level, it also reduces the problem of excessive harmonic content. Three-level converter is simpler and more reliable than topology with more levels. Consequently, ABB will adopt the IGCT-type three-level converter in future medium voltage frequency control and flexible DC transmission project.

Currently, the loss of a IGBT-type converter has been analyzed systematically, but there is no profound analysis for a IGCT-type converter. In [2], circuit simulation using physical model is adopted, but the switching process is very short(less than 10us [3]) and very complex, so simulation step is usually set to 10ns. But it is not applicable in the simulation of flexible DC transmission. Another method is estimating the loss using the data sheet provided by the IGCT manufactures, but it cannot accurately calculate the loss of a converter [4]. The method adopted in this article is an extension of the piecewise linear curve fitting approach [5] and it takes the reverse recovery process of anti-parallel diodes and stray inductance of the line into consideration. On this basis, this article analyzes the IGCT-type three-level converter loss characteristics, and analyzes the impact of the switching frequency and power factor on loss.

2. The Switching Process of IGCT and diode

Because the voltage and current cannot change suddenly whether power devices are in turn-on or turn-off process, the switching loss caused can be expressed as:

$$E_{on/off}=\int_{t_0}^{t_0+\Delta t}V(t)I(t)dt \tag{1}$$

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Where Δt is the duration of turn-on or turn-off process, t_0 is the beginning time of turn-on or turn-off process.

2.1. The Turn-on Process of IGCT

In [3], the waveform of IGCT turn-on process had been drawn through experiment. The diagram obtained by curve fitting method is shown in Figure 1.

When IGCT is in the turn-on process, the current begins to rise only after the voltage almost declines to 0, so the turn-on loss is minimal. Because IGCT usually works under rated voltage, the loss can be considered only as the function of current. Assuming E_{on} is turn-on loss, i_L is the operating current, I_N is the test current provided by data sheet, E_{onN} is the corresponding turn-on loss, the turn-on loss under different current can be expressed as:

$$E_{T(on)} = \frac{i_L}{I_N} E_{T(on)N} \tag{2}$$

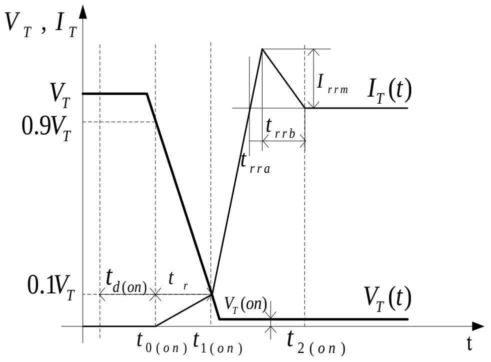


Figure 1. Diagram of the IGCT Turn-on Transient Waveform

2.2. The Turn-off Process of IGCT

According to the experimental waveforms in [3], the diagram of IGCT turn-off process is shown in Figure 2. The turn-off process is explained as follows.

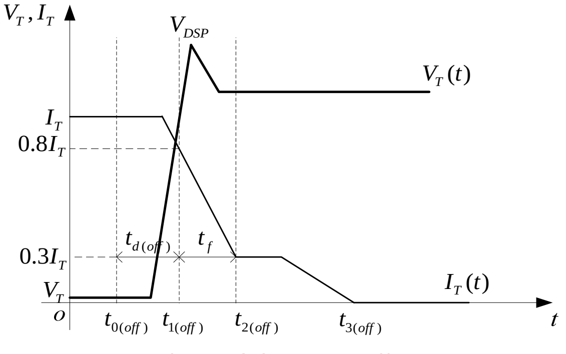


Figure 2. Diagram of the IGCT Turn-off Transient Waveform

Where, $t_{d(off)}$ is the turn-off delay which is the interval between sending turn-off signal and the current decreasing to $0.8I_T$, t_f is the fall time during which the current decreases from $0.8I_T$ to $0.3I_T$.V_{DSP} is the first voltage peak induced by line stray inductance [6]. Similar to the turn-on process, the turn-off loss is expressed approximately as the linear function of the current, because the current and voltage which are influenced by snubber circuit and stray inductance are not linear [7], and the turn-off time does not change proportionally with the current. The experiment in [3] also shows the approximate waveform is correct. Assuming that

E_{off} is the turn-off loss, i_L is the operating current, I_N is the test current provided by data sheet, E_{offN} is the corresponding turn-off loss, the turn-off loss under different current can be expressed as:

$$E_{T(off)} = \frac{i_L}{I_N} E_{T(off)N} \tag{3}$$

2.3. The Reverse Recovery Process of Diode

In the diode clamp three-level converter commonly uses fast recovery diode whose reverse current is minimal when turning-on, so the turn-on loss is far less than turn-off loss and can be neglected. The diagram of turn-off process waveform of diode is shown in Figure 3.

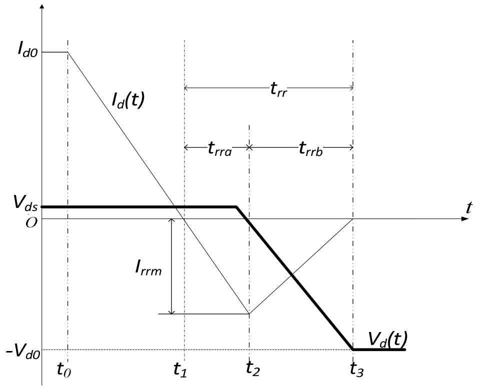


Figure 3. Diagram of the Diode Turn-off Transient Waveform

So the diode turn-off loss can be expressed as:

$$\begin{aligned} E_{d(off)} &= E_{d1} + E_{d2} \\ &= \frac{V_{ds}}{2}\left(\frac{I_{d0}^2}{\left|di/dt\right|} - \left|\frac{di}{dt}\right| K_D^2 t_{rr}^2\right) + \frac{1}{3}\left|\frac{di}{dt}\right| V_{d0} K_D (1 - K_D) t_{rr}^2 \end{aligned} \tag{4}$$

Where, $K_D=1/(1+S_D)$, $t_{rra}=K_D t_{rr}$, S_D is the softness of diode [8], trr is the reverse recovery time of diode.

3. Analysis of Three-level Converter Work Process

When the converter work steadily, the control signals for IGCT on bridge arms are shown in Table 1.

Table 1. Control Signal for IGCT

Output	VT1	VT2	VT3	VT4	Denoted as
+Ud/2	on	on	off	off	+1
0	off	on	on	off	0
-Ud/2	off	off	on	on	-1

Assuming that the power factor angle of receiving end is θ, load current is approximately sinusoidal, $i_L=I_m\sin(\omega t)$, load voltage $V=U_m\sin(\omega t+\theta)$, the relationship between the waveforms of current and voltage and the power devices operation status is shown in Figure 4.

Six working states within a period are shown in Figure 5.

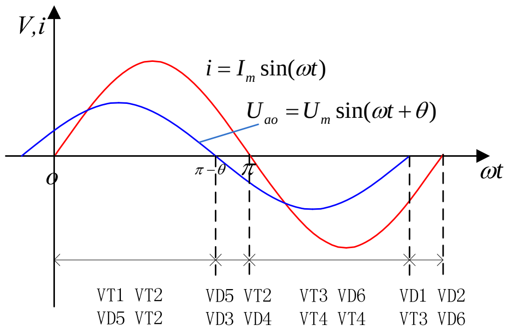
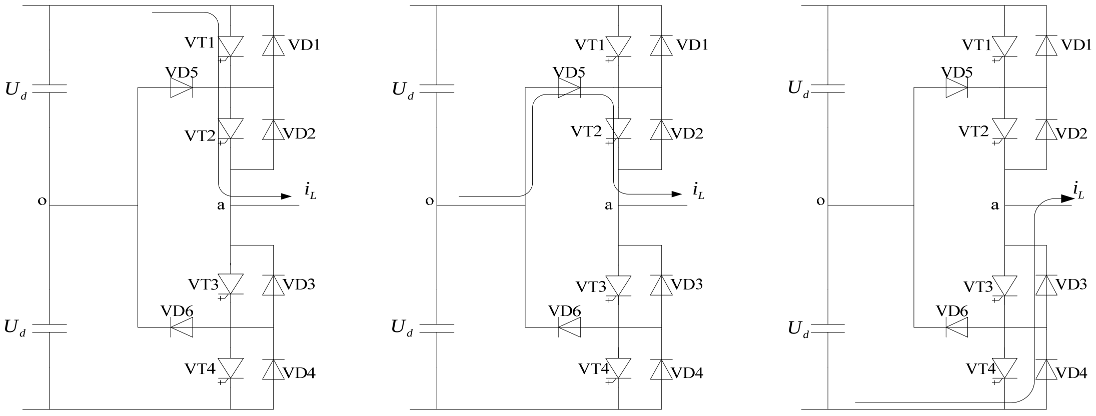
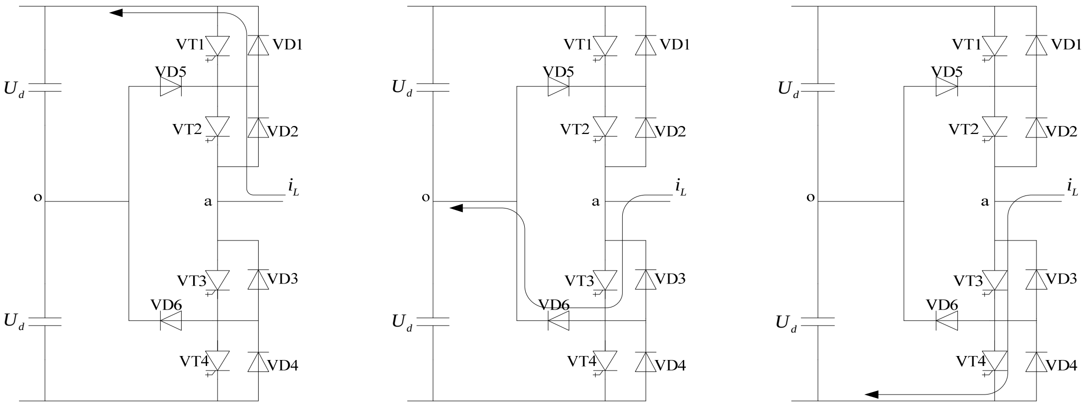


Figure 4. The Relationship between the Load's Voltage and Current and the Device Operation Status



(a)State 1,i_L>0 (b) State 0,i_L>0 (c) State -1,i_L>0



(d) State 1,i_L<0 (e) State 0,i_L<0 (f) State -1,i_L<0

Figure 5. The Flow Path of the Load Current under Different Switch State

The calculation of duty ratio of power devices: This article adopts cophasal carrier modulation [9, 10] which means the carriers are on top of each with the same phase. This modulation method produces a minimum harmonic in line voltage output, as shown in Figure 6.

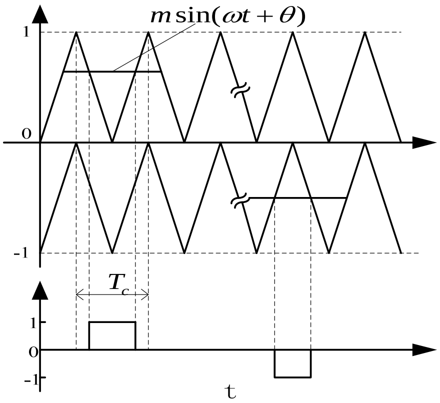


Figure 6. Cophasal Carrier Modulation PWM and Duty Ratio

The calculated duty ratio using regular sampling method [11] is shown in Table 2.

Table 2. Duty Ratio of Switch Device

Phase voltage	Voltage level	Duty ratio	Denoted as
>0	$+U_d/2$	$m\sin(\omega t+\theta)$	D1
	0	$1-m\sin(\omega t+\theta)$	D2
<0	0	$1+m\sin(\omega t+\theta)$	D3
	$-U_d/2$	$-m\sin(\omega t+\theta)$	D4

4. The Model of Three-Level Converter Loss

4.1. Switching Loss

Due to different current in every IGCT switching process, the switching loss is the function of I_{T0}.The forward voltage drop is also different, but it changes little and its range has little effect on the switching losses. Therefore it can be considered to be a fixed value which can be considered as the average value of saturation voltage drop and collector-emitter voltage under rated current. Assuming that $I_{T0}(k)=I_m\sin(\omega t_k)$, where tk is the moment of every switch, so:

$$P_{switch}=\frac{1}{T}\sum_{k=1}^{n}[E_{on}+E_{off}(I_{T0}(k))] \tag{5}$$

But this calculation method is very complicated, it should be simplified which means averaging every switching loss on the carrier's period, then integrating the average loss. This method can determine the converter loss within the permitted tolerance [12].Take VT1 for example:

$$P_{switch,VT1}=\frac{1}{2\pi}\int_{0}^{\pi-\theta}\frac{E_{T(on)}+E_{T(off)}(I_m\sin(\omega t))}{\omega T_c}d\left(\omega t\right) \tag{6}$$

Where T is the period of modulating wave, Tc is the carrier's period, ω is angular velocity of modulation wave. In a the same way,

$$P_{switch,VT2}=\frac{1}{2\pi}\int_{\pi-\theta}^{\pi}\frac{E_{T(on)}+E_{T(off)}(I_m\sin(\omega t))}{\omega T_c}d\left(\omega t\right) \tag{7}$$

$$P_{switch,VD3/VD4} = \frac{1}{2\pi}\int_{\pi-\theta}^{\pi} \frac{E_{D(off)}(I_m \sin(\omega t))}{\omega T_c} d\left(\omega t\right) \tag{8}$$

$$P_{switch,VD5} = \frac{1}{2\pi}\int_{0}^{\pi} \frac{E_{D(off)}(I_m \sin(\omega t))}{\omega T_c} d\left(\omega t\right) \tag{9}$$

Where, the applied voltage on every power device when turned-off is $U_d/2$.In a three-level converter, the characteristics of four switching devices on every bridge are almost identical and the diodes also have the same characteristics. Assuming the load is symmetrical three-phase load, so $\mathrm{P}_{\mathrm{switch,VT1}} = \mathrm{P}_{\mathrm{switch,VT4}}$, $\mathrm{P}_{\mathrm{switch,VT2}} = \mathrm{P}_{\mathrm{switch,VT3}}$, $\mathrm{P}_{\mathrm{switch,VD5}} = \mathrm{P}_{\mathrm{switch,VD6}}$, $\mathrm{P}_{\mathrm{switch,VD3/VD4}} = \mathrm{P}_{\mathrm{switch,VD1/VD2}}$.

Therefore, the switching loss of three-level converter can be expressed as:

$$P_{switch} = 3(2P_{switch,VT1} + 2P_{switch,VT2} + 2P_{switch,VD5} + 4P_{switch,VD3/VD4}) \tag{10}$$

4.2. On-state loss

The static characteristics of on-state power devices is the key to calculating the on-state loss of three-level converter [13]. IGCTs work on saturation region when they are on, so its static characteristic can be expressed as:

$$V_{VT} = R_{VT} i_c + V_{T0} \tag{11}$$

Where R_{VT} is the slope resistance, V_{T0} is the saturation voltage drop which is independent of the collector-emitter current.

In the same way, the static characteristics of diode can be expressed as:

$$V_{VD} = R_{VD} i_c + V_{F0} \tag{12}$$

Where, R_{VD} is the slope resistance of diodes, V_{F0} is the threshold voltage of diodes.

Taking VT1 for example, the calculation process of a power device of the three-level converter loss is explained as follows. Within a carrier's period, the VT1 loss can be expressed as:

$$E_{VT1} = (R_{VT} I_m \sin(\omega t) + V_{T0}) I_m \sin(\omega t) D_1 T_c \tag{13}$$

According to [14-16], (13) can be transformed into differential forms. The mean power of VT1 within a period is the integral of energy's differential within the on-state period, so the mean power loss of VT1 is:

$$P_{VT1} = \frac{1}{T}\int dE_{VT1} = \frac{1}{2\pi}\int_{0}^{\pi-\theta} (R_{VT} I_m \sin(\omega t) + V_{T0}) I_m \sin(\omega t) D_1 d(\omega t) \tag{14}$$

In the similar way, the on-state loss of VT2, VD3/VD4, VD5 under PWM modulation is:

$$\begin{aligned} P_{VT2} = \frac{1}{2\pi}[&\int_{0}^{\pi-\theta} (R_{VT} I_m \sin(\omega t) + V_{T0}) I_m \sin(\omega t) \cdot 1 \cdot d(\omega t) + \\ &\int_{\pi-\theta}^{\pi} (R_{VT} I_m \sin(\omega t) + V_{T0}) I_m \sin(\omega t) D_3 d(\omega t)] \end{aligned} \tag{15}$$

$$P_{VD3/VD4} = \frac{1}{2\pi}\int_{\pi-\theta}^{\pi}(R_{VD}I_m \sin(\omega t) + V_{F0})I_m \sin(\omega t)D_4 d(\omega t) \tag{16}$$

$$\begin{aligned} P_{VD5} = {} & \frac{1}{2\pi}[\int_{0}^{\pi-\theta}(R_{VD}I_m \sin(\omega t) + V_{F0})I_m \sin(\omega t)D_2 d(\omega t) + \\ & \frac{1}{2\pi}\int_{\pi-\theta}^{\pi}(R_{VD}I_m \sin(\omega t) + V_{F0})I_m \sin(\omega t)D_3 d(\omega t)] \end{aligned} \tag{17}$$

In a three-level converter, four switch devices and diodes in every bride have the identical characteristics, so $P_{VT1}=P_{VT4}$,$P_{VT2}=P_{VT3}$,$P_{VD5}=P_{VD6}$,$P_{VD3/VD4}=P_{VD1/VD2}$. Therefore, the total on-state loss is:

$$P_{on} = 3(2P_{VT1} + 2P_{VT2} + 2P_{VD5} + 4P_{VD3/VD4}) \tag{18}$$

The expression of on-state loss indicates that the on-state loss is related to load current, static characteristics of power devices, modulation ratio (m) and power factor angle (θ).

4.3. Comparison with the Experimental Results

Compared to the experimental results in [3], the fitted value is very close to them, as shown in Table 3. All the tolerances are within 4%, so the loss under other current values can be determined by the fitted curve.

Table 3. The Contrast between Experimental Value and Fitted Value

Current(A)	500	1000	1500	2000
Experimental(on;J)	0.31	0.45	0.62	0.83
Fitted(on;J)	0.30	0.46	0.62	0.84
Experimental(off;J)	3.2	5.6	7.4	9.2
Fitted(off;J)	3.3	5.6	7.3	9.2

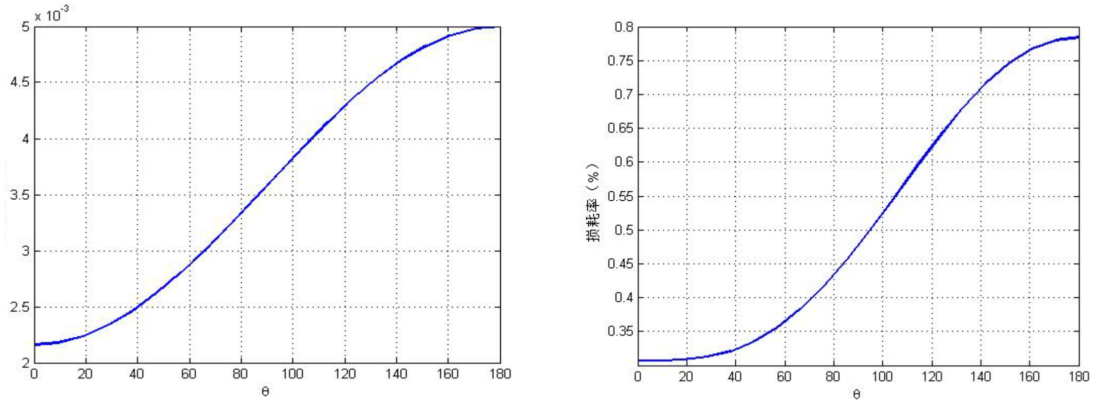
5. Example of Loss Calculation and Analysis

The IGCTs used in the loss analysis are 5SHX 26L4503, its rated voltage and current is 4500V/2200A and its off-state resistance is 90kΩ. The anti-parallel diodes and clamping diodes are 5SDF 28L4520. The loss is calculated in the model of ±200kV three-level flexible DC transmission system and is compared to the loss of the corresponding system which adopts IGBT. This article is mainly concerned with the influence of power demand in AC system on loss. Assuming that every valve bank is consisted of 50 IGCTs in series, equalizing resistance is 9kΩ, the modulation ratio(m) is 0. 95, the load current rms is 1400A (IGCT), the AC power is 285MVA, the range of power factor angle is [0, π], the carrier frequency (f_c) is 800Hz, the consequence of (10) and (18) calculated by MATLAB is shown in Figure 7.

As shown in Figure 6: (1) The switching loss of IGCT is far less than its on-state loss, because its turn-on loss is very small and the switching frequency is low. (2) The switching and on-state loss increase with the power factor angle, because more current flows from the anti-parallel diodes when the power factor angle increases. Because the current of IGCT-type converter can reach 2kA, higher rating fast recovery diodes are required. These diodes' loss in reverse recovery process and their slope resistance all exceed IGCT. These are the different from IGBT-type converter. The loss of IGBT-type converter decreases with the increase of power factor angle, because the loss of fast recovery diodes used in three-level converter is lower than IGBT. (3) Compared with the IGBT-type converter under the same voltage level, the IGCT-type converter has a noticeably lower loss. The loss rate of IGCT-type converter is 0.31%-0.79%,and the corresponding value of IGBT-type converter is 1.23%-3.42% and the load current is only 1kA.The detailed contrast is shown in Table 4.

Table 4. The Relationship between Power Loss Rate of ±200kV Three-level Converter and the θ

θ	0°	45°	90°	135°	180°
IGCT（%）	0.31	0.33	0.48	0.68	0.79
IGBT（%）	3.42	2.98	1.61	1.43	1.23



(a) Switching loss rate (b) On-state loss rate

Figure 7. The Relationship between Power Loss Rate and Power Factor Angle

6. Conclusion

It is difficult to calculate the loss precisely because the switching process only lasts for several microseconds. This article uses the IGCT parameters provided by the datasheet to build a mathematical model of switching loss of IGCTs with current changes. This method provides the foundation for the calculation of the converter loss. Then, the model of switching loss and on-state loss of three-level converter is built based on the analysis of the three-level converter working principal. Finally, the model of total loss is built. Using this mathematical model to analyze the IGCT-type flexible DC transmission system, this article obtains new characteristic that the loss of IGCT-type converter is far less than the IGBT-type converter. Therefore, IGCTs are more suitable than IGBTs in large-capacity high-pressure situations such as flexible DC transmission. IGCT has a lower switching loss and on-state loss than IGBT with a larger capacity, so it further improves the economics of the flexible DC transmission. IGCT will has a broad application prospects in the future.

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