GTO의 턴-오프 과도전류와 과도전류가 스위칭에 미치는 영향

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Tail Current and Its Effect on Turn-off Performance of Power GTO Thyristor

Abstract : In this paper the formation mechanism of tail current is analyzed and its effect on GTO turn-off performance is given. The conclusion is that the large tail current will considerably increase the turn-off loss E_{off} and cause the re-triggering during GTO's off-switching, therefore the best design criterion is that the tail current of power GTO must be as low as possible.

1. Introduction

In the past 30 years the Gate Turn-off Thyristors (GTOs) have reached up to 6kA/6kV. GTO is now promising power semiconductor device in the high power electronics application such as ac-dc-ac traction drive, static var. compensator(SVC), flexible ac transmissions(FACTs) etc. To have the best trade-off between on-state voltage drop (V_{TM}) and turn-off losses (E_{off}) for power GTO is still concerned by a lot of researchers. The E_{off} is mainly controlled by the tail current I_{tail} and the tail time t_{tail}. If the value of I_{tail} or t_{tail} is low, the E_{off} will be reduced. Actually the tail current play an important role in the GTO's off switching period. Since the reapplied voltage V_D goes up to high value, hence the higher value of I_{tail} will cause high E_{off} and finally result in GTO's high inner temperature especially at high frequency operation. Therefore the high I_{tail} will be harmful to the long-terms reliability for the power GTO. Some of GTO's failure phenomenon i.e. the re-triggering is mainly caused by excessive tail current I_{tail}. The best GTO should have low I_{tail}. It is necessary for us to understand the generation mechanism of the tail current I_{tail} and have the best way to prevent it

2. The generation of tail current

The basic structure of GTO device is shown in Fig.1. The tail time (t_{tail}) of power GTO, as shown in Fig.2, is equivalent to the last stage of GTO's turn off. It is defined as the times taken from point of peak tail current to the point of its 25%. The anode current flowing across the device at tail period is referred to as tail current. In general the peak value of tail current is defined as I_{tail}. Fig.3 explains the formation of tail current. After fall time (t_f) the gate-cathode junction J_3 is fully recovered to its reverse-blocking state and the main junction J_2 gradually recovers its forward blocking state. At this moment the cathode current I_k stops flowing.

Since

$$I_A=I_K+I_G \tag{1}$$

and I_K=0, therefore we can have

$$I_A= I_{tail}--I_G \tag{2}$$

i. e. the tail current flows to the gate across the forward blocking junction J_2. The most of tail current will come from the carrier recombination in the N-base since excess carriers located far away from J_2 in the N-base cannot extracted by the gate. In other words these excess carriers(holes) can only recombine with majority carrier(electrons). Too many carriers recombination forms the main parts of the tail current I_{tail}. If GTO's anode current increases, the excess carriers in the N base will be increased, resulting in higher tail current. Fig.4 shows the experimental verification of tail current at different anode current for same GTO device. It is very clearly that the tail current raises from 42A to 54A while tail time increases from 7.4μs to 9.72μs when I_A is increased from 310A to 600A.

Other factor to effect the tail current is the displacement current I_{dis} caused by the high rise rate of re-applied voltage dv/dt when the main junction J_2 recovers to its blocking state. Fig.5 shows the tail current changes with the variation of displacement current I_{dis}. Fig.5(a) gives the variation of anode voltage/anode current during turn - off. Fig.5(b) gives the variation of collector current i_{cl} of equivalent PNP transistor during GTO's turn-off. Fig.5(c) shows the variation of displacement current. The total tail current is the sum of i_{cl} and I_{dis} as shown in Fig.3. That is:

$$I_{tail} = i_{cl} + I_{dis} \tag{1}$$

The i_{cl} decreases exponentially during turn-off i.e. the expression is:

$$i_{cl} = I_{pk}\ exp(-t/t_{tq}) \tag{2}$$

where I_{pk} is the peak value of tail current, t_{tq} is the decay factor of tail current, which is related to the carrier lifetime τ_p and anode pattern. From the PNP transistor action we can have:

$$i_{cl} = \alpha_{pnp} \cdot I_A \tag{3}$$

Substituting Eq.(3) into (1), we have following equation:

$$I_{tail} = \alpha_{pnp} \cdot I_A + I_{dis} \tag{4}$$

According to the theory of PN junction we have:

$$I_{dis} = C_T \cdot dv/dt \tag{5}$$

and barrier capacitance of abrupt PN junction is as follows:

$$C_T = A\left[\frac{\varepsilon_r \varepsilon_0 qN}{2(V_D + V_A)}\right]^{1/2} \tag{6}$$

then we have

$$I_{dis} = k\frac{1}{V_A^{1/2}}\frac{dV_A}{dt} \tag{7}$$

In Eq.(7), $K = A \cdot [\varepsilon_r \varepsilon_0\ qN/2]^{1/2}$. From Eq.(7) it is clear that the magnitude and direction of I_{dis} is varied with variation of anode voltage V_A as shown in Fig.5(c). The variation tendency of tail current is mostly affected by the displacement current I_{dis}. For 600A/2500V GTO, the highest dv/dt is around 500V/μs during t_3-t_4 period. In this case $I_{dis} \doteq 0.9$A is much smaller compared to the totally tail current of several tens of amperes so as I_{dis} can be neglected. However the I_{dis} has very close relation to *dv/dt*, resulting in tail current variation with dv/dt. Fig.6 shows the test result of relationship between tail current and re-applied *dv/dt*. We can see that the maximum negative *dv/dt* is equivalent to the valley of anode current after fall time t_f.

After I_{tail} reaches the peak value I_{pk}, it will be damped as the exponentially with the time. If the I_{dis} is neglected, then

$$I_{tail} = \alpha_{pnp} \cdot I_A = I_{pk}\exp(-t/t_{tq}) \tag{8}$$

3. The effect of I_{tail} on GTO's turn-off

During tail period the higher tail current will cause too high turn-off losses E_{off} since the re-applied voltage V_D goes up high. The total E_{off} is composed of the power loss due to spike voltage (V_{DSP}) and power loss by tail current. Since the tail period is too much longer than the period of V_{DSP}, the power loss caused by tail current, is almost 80% of total E_{off}. The increase of tail current, and therefore E_{off}, will cause device temperature increasing and finally GTO will be failed. Fig.7 shows the comparison of tail current and tail loss with different type of GTO devices. It is clear that the No.1 GTO's has low tail current and low power tail loss compared to No.2 GTO. The result is that maximum turn-off current I_{TGQM} of No.1 GTO can reach very high. It is predicated that this GTO can operate safety in the high power application.

From the experimental results we have found that the GTO with high tail current is sensitive to retrigger during turn-off period. Since in this period GTO have almost turned-off and large tail current will bring GTO's internal into high temperature, resulting in higher leakage current of J_2. Subsequently, the J_3 will be positively biased. It will cause a few of fingers with non-uniformity to turn on firstly i.e. the retrigerring occurs. Fig.8 gives the typic retriggering waveform. At this moment GTO thermal destruction will result due to the localized spot overheated as shown in Fig.9.

4. The techniques to reduce tail current

From above discussion we know that the large tail current is harmful to GTO's safe turn off and reliability. It is necessary to reduce the tail current as low as possible. From equation (8), it is very clear that tail current I_{tail} is closely in proportion to the α_{pnp}. In order to reduce the tail current I_{tail}, the GTO must be designed to have low tail current. This is in accordance with the high turn-off gain of power GTO. There are two ways to reduce α_{pnp}: one is anode-shorts i.e. n^+ region is located between anode and N-base, and another is to reduce carrier lifetime τ_p by means of electron irradiation. However the control of electron irradiation will drastic increase the on-state voltage drop because the electron irradiation can penetrate the fully P-N-P-N structure. The best option is proton irradiation which can produce low-lifetime area in the N-base. If the low-lifetime area is located near anode junction J_1 then both low tail current and low on-state voltage drop can be obtained.

Fig. 10 shows the waveform of tail current decay for GTO 600A/2500V (T_j=25℃). In Fig. 10(a), symmetrical GTO has no anode-shorts to extract the excess carrier in the N base so that tail current is very high(near 60A) and tail time is up to 30μs. The power loss P_{off} is calculated to 40kW. Fig. 10(b) shows the tail current decay for GTO 600A/2500V with anode-shorts structure. Its tail current is only 20A and tail current is 15μs, moreover the calculated P_{off} is 10 kW. Fig. 10(c) shows the tail current of 5MeV proton irradiated anode-shorts GTO with same rating. Clearly the tail current decay more fast than other GTO devices. Its I_{tail}/t_{tail} is only 15A/μs and power loss is much low. The conclusion is that the combination of anode-short and proton irradiation can be best option for GTO design.

References :

[1] M. Bakowski, N. Galster et.al, "Proton Irradiation for Improved GTO Thyristors", Proc. ISPSD'97, pp.77 80, 1997.

[2] Bleicher H. et. al. "The Effect of Emitter shorting on Turn-off Limitations and Device Failure in GTO Thyristors under Snubberless Operation", IEEE trans. on Electron Devices, 1995, 42(1), pp. 178-187.

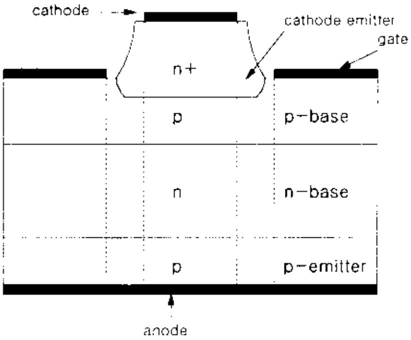


Fig. 1 Basic symmetrical structure of GTO

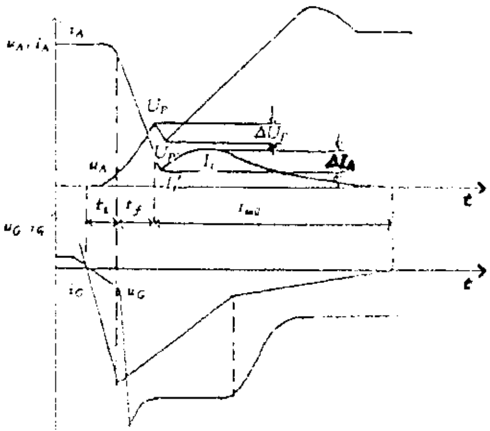


Fig. 2 Turn-off waveform of GTO

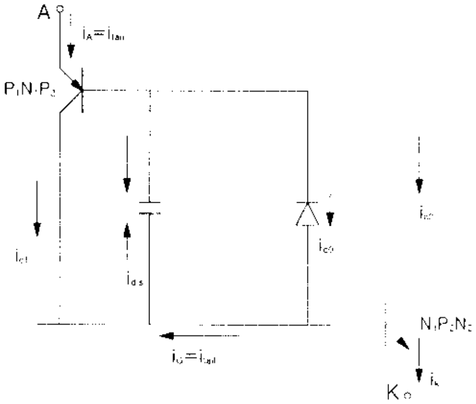


Fig. 3 Schematic diagram of the tail current

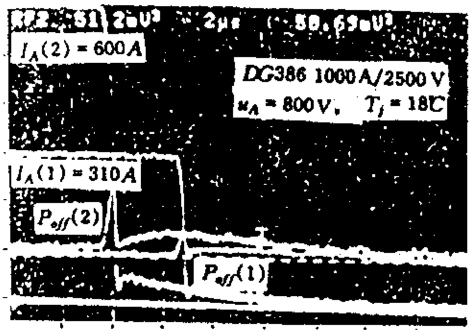


Fig. 4 Comparision of tail current under different anode current cindition

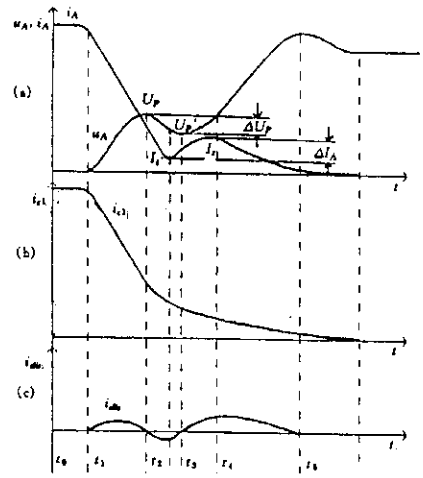


Fig. 5(a). Turn-off waveform of GTO
Fig. 5(b). The i_c of PNP transistor
Fig. 5(c). Displacement current of J_2

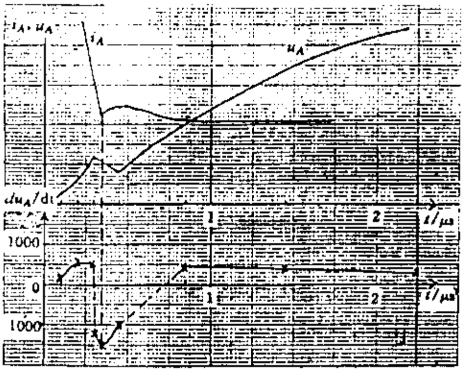


Fig. 6 The relationship of I_{tail} and du/dt

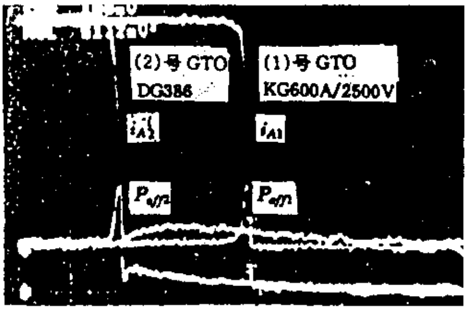


Fig. 7 Tail current of different type of GTO

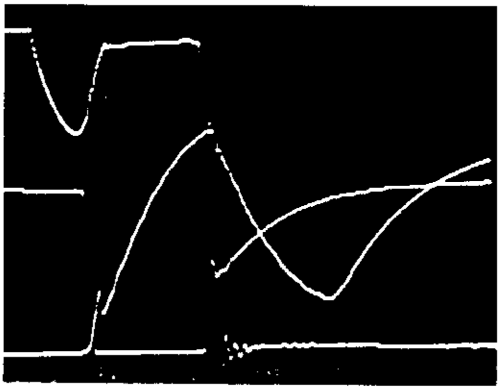


Fig. 8 Retriggering waveform of GTO (I_A=600A, T_j-125℃)

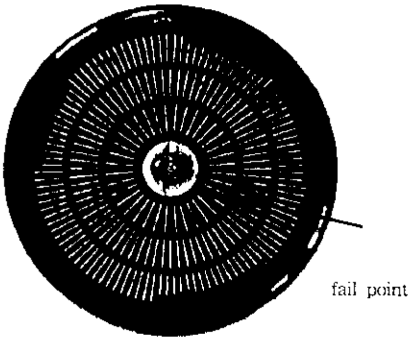
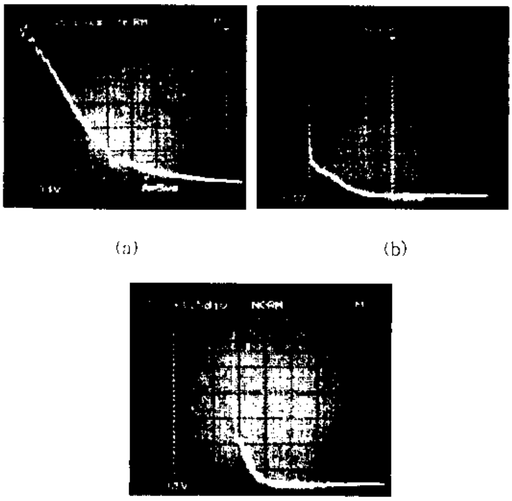


Fig. 9 The failure spot of retriggering of GTO



(a) (b)

(c)

Fig. 10 Tail current for different GTO
(I_A=10A/div, t=5μs/div)