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Six Inch Thyristors for UHVDC

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SUMMARY

Phase control thyristors have replaced mercury arc valves in the 1970's and have gone a very successful way in world-wide HVDC transmission projects since then. The need for a dramatic increase of power transmission in China makes it necessary to raise the transmission power of HVDC systems far above the levels available today. ABB and PERI have a world-known leading record as suppliers of HVDC thyristors up to a silicon diameter of 5 inches, both in view of market share and reliability. To enable economical solutions for the new transmissions, is necessary to develop more powerful thyristors, which can be done on a 6 inch silicon diameter. ABB and PERI are commonly developing such 6 inch HVDC thyristors.

Design of a 6 inch thyristor has to be done with a high focus on the application-related requirements. Besides the needs for larger raw material silicon crystal disks with equal purity and homogeneity, which is by no means simple to realize, the thyristor performance has to be tailored to the needs of the more powerful UHVDC system. Besides the standard requirements of blocking capability, DC and surge current capability, thermal impedance and many more, the power loss inside the thyristor is of high importance. In the present work we analyze the different contributions to thyristor losses and ways to minimize their sum.

The first contribution is conduction loss. It is given by the on-state voltage drop at on-state current. An ABCD model formula can be used to assess the conduction loss. Turn-on energy gives rise to the second contribution and appears for each turn-on switching transition of the thyristor. It can be modeled on the basis of the photomask design of the thyristor by using a plasma spread velocity model, combined with the static on-state model. The third contribution is caused by the turn-off energy, which is released for each turn-off switching transition and which is tightly connected with the turn-off recovery charge of the thyristor.

Our investigations show that the increase of on-state current as needed for UHVDC systems dramatically increase the thyristor losses of a 5 inch thyristor beyond the levels which keep the thyristor within its acceptable thermal limits. A 6 inch thyristor with the same photomask structure has significantly smaller conduction losses, but the turn-on and turn-off losses in-

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crease. Nevertheless the total loss is smaller than in a 5 inch thyristor. A significant improvement is possible by optimization of the photomask structure, which reduces the turn-on loss to less than 50 % of its value before. The total loss therefore distinctly decreases when an optimized photomask structure is designed.

KEYWORDS

UHVDC, Six Inch Thyristor, Power Loss

1. INTRODUCTION

Since the 1970's, phase control thyristor valves have gone a successful way in replacing mercury arc valves by more powerful and more reliable means to control power conversion in HVDC systems. After a start from very small silicon diameters in those years, the available power rating has increased continuously. ABB has been the first company to develop thyristors of 5 inches silicon diameter for high power HVDC transmission. This enabled the Three Gorges transmission systems to become economical solutions for transmitted DC power levels of 3000 MW at ± 500 kV DC voltage. The next technology step, which will become a new power transmission standard in the world, has been found to roughly double the transmission power and to simultaneously raise the DC voltage to ± 800 kV. The preferred solution to reach this goal involves a larger DC and surge current rating of the thyristor, which requires an increase of the wafer diameter to 6 inches. This necessitates the major production equipment in the wafer factory, the assembly line and the test line to be upgraded. For preparation of such an upgrade, a firm basis needs to be laid by extrapolation methods for specifying the performance of the new product. The present work is based on empirical models and shows design calculations for predicting the power loss contributions of the thyristor under conditions relevant for HVDC systems.

2. POWER LOSS IN SEMICONDUCTORS

Before we start describing the model approaches for power losses in UHVDC thyristors, we like to show the contributions from the different states of operation of the device. In principle the thyristor can be in the off-state, in the turn-on transition, in the on-state or in the turn-off transition. In each state a contribution to power loss arises, but the related physical mechanisms are quite different in nature. In general the losses during the off-state are small compared to the other contributions and can be neglected.

Let us begin with the on-state losses. The on-state losses can be calculated from the on-state voltage of a thyristor at given forward current and operation temperature. Fig. 1 shows typical on-state characteristics of an HVDC thyristor. The loss energy per pulse can be calculated by integrating the resulting momentary power over time, and the resulting power is the total energy per line cycle, divided by line cycle duration.

We next consider the turn-on process. Turn-on energy is the energy per turn-on process (per pulse), which is required to bring the thyristor into its conducting state. Fig. 2 illustrates the current and voltage waveforms appearing in reality. At $t = 0$ the thyristor is fired by a gate pulse. Electrons and holes now have to move into the base region to build up the plasma which will support the steady-state conduction characteristic of fig. 1. During this time the transient on-state voltage $V_D(t)$ is higher than in the steady state $V_T(t)$, and their difference is what makes up the turn-on energy. The current waveform is normally given by the circuit, and the thyristor can more or less quickly follow injecting carriers. Therefore, the turn-on energy will depend on di/dt at turn-on.

Finally, we consider the turn-off process. Here again, the conducting carriers need time to disappear. Part of them recombine inside the thyristor, but another part is extracted through the external circuit. The circuit then sees a reverse-recovery behavior as displayed in fig. 3. Here the carriers remain existing for a few tens of microseconds after current zero, while reverse voltage starts to rise. This leads to a momentary power dissipation, and its time integral

over one turn-off process makes up the turn-off energy. Again, the external current waveform, i. e. its di/dt, influences the size of the turn-off energy.

3. MODELING OF LOSS ENERGIES

The on-state voltage can easily be expressed in the form of an ABCD model:

$$V_T(I_T) = A + B \cdot I_T + C \cdot \log(I_T) + D \cdot \sqrt{I_T} \quad (1)$$

whereas V_T and I_T are on-state voltage and current and A to D are model parameters which can be found in thyristor data sheets. $V_T(I_T)$ can then be used to calculate momentary power dissipation and loss energy.

The turn-on energy can be obtained as follows. In a turn-on process, there will first be carriers injected axially from both anode and cathode, and the anode voltage V_D will collapse. A small current only flows at this time, and the corresponding loss energy is small compared to the following part and can be neglected. Next the carrier plasma, which has so far been located around the gate structure only, has to spread over the whole area. This is illustrated by fig. 4. This plasma spread process usually takes around 1 millisecond and makes up the major contribution of turn-on loss energy. The turn-on energy can be calculated by a model for the propagation speed of the plasma spread contour [1]:

$$v_p = v_0 \cdot j^n, \quad (2)$$

where v_p is the speed of propagation of the plasma contour, v_0 is a model parameter, j is the momentary current density in the actually conducting thyristor area and n is another model parameter that typically has a value of 0.5. v_0 can be determined from data sheets of thyristor suppliers as well. v_p is typically somewhat below 1 cm/ms for an HVDC turn-on process.

Turn-off energy finally can be estimated from data sheet information as well. [2] gives a summary of how to simulate current and voltage transients under given snubber conditions. Here we are interested additionally in how to scale the turn-off energy from a 5 inch to a 6 inch device. If we assume that the 6 inch device has the same carrier lifetime as the 5 inch device, we can approximate the energy loss increase by a factor f_{5-6} :

$$f_{5-6} = \left(\frac{6}{5}\right)^{2-m}, \quad (3)$$

where m is the power of increase of the recovery charge Q_{rr} in the data sheet of the thyristor, typically being 0.5 to 0.6.

4. DIFFERENT DESIGNS FOR 5 AND 6 INCH THYRISTORS

In the following paragraph we like to show the total power loss and the fraction of its contributions in different designs of high power HVDC thyristors. Fig. 5 shows the thyristor designs investigated. As a reference, we start with a 5 inch thyristor similar to the one in the Three Gorges HVDC projects. We have calculated the conduction loss according to (1), using the measured on-state voltage characteristics. The turn-on loss was calculated from (2) with v_0 derived from measured turn-on transients. The turn-off loss was finally obtained from a meas-

urement of the turn-off process as shown in fig. 6. Here we clearly see how the power dissipation starts to become significant when the reverse voltage rises. The loss energy is then its integral over time. The measurement, done at $V_R = 200$ V, was scaled to 50 % of rated voltage by a simple assumption of proportionality with voltage. The first and the fifth columns of fig. 7 show the resulting power loss contributions at $T_j = 90$ °C, two different values of di/dt and a DC current of 3000 A (as in the Three Gorges systems). It is not surprising to see that turn-on and turn-off power increase with increasing di/dt . On the other hand, the conduction power remains roughly the same.

The second and the sixth columns show the same result for the 5 inch thyristor when it is operated at 4000 A DC current. The power loss dramatically increases and can no longer be handled by cooling systems economically available. To realize this current, 5 inch thyristors of smaller voltage rating would be needed which would show significantly reduced loss energies in all contributions. This, however, would increase the overall cost of an HVDC system.

A better solution for 4000 A DC current and more is therefore a 6 inch UHVDC thyristor. Columns 3 and 7 show the resulting loss contributions as derived from the above models. If we leave the masks as they are on the 5 inch wafer, the total loss is smaller than in a 5 inch wafer at -1.5 A/ μ s and about equal at -4 A/ μ s. Besides this, however, a 6 inch device has much better access for a cooling system and can handle 1.4 times higher losses at the same junction temperature. With the design used here, the 6 inch thyristor will therefore even have a margin to go higher than 4000 A DC current.

Finally, we can further improve the efficiency of the thyristor by optimizing the gate structure for the wafer diameter increase from 5 to 6 inches. We then obtain columns 4 and 8 of fig. 7. It is impressive to see that by enlarging the gate structure as shown in fig. 5 (c) the turn-on energy can be reduced to less than 50 %, which gives a clear reduction of the total losses in the UHVDC thyristor.

5. CONCLUSIONS

In the present work we have discussed the contributions to power loss in an HVDC thyristor and have presented models for calculation of the different parts. In connection with the growing demand for ultra-high DC power transmission in China, we have discussed a calculation example for upscaling an HVDC thyristor for 3000 A DC current to a thyristor suited for UHVDC at 4000 A or more. It has turned out that 4000 A is only feasible with a 5 inch thyristor of reduced blocking capability, which increases the cost of an HVDC system. A 6 inch thyristor of full voltage was found to be a good solution, and optimization of the gate structure was seen to carry clear potential for reduction of total losses.

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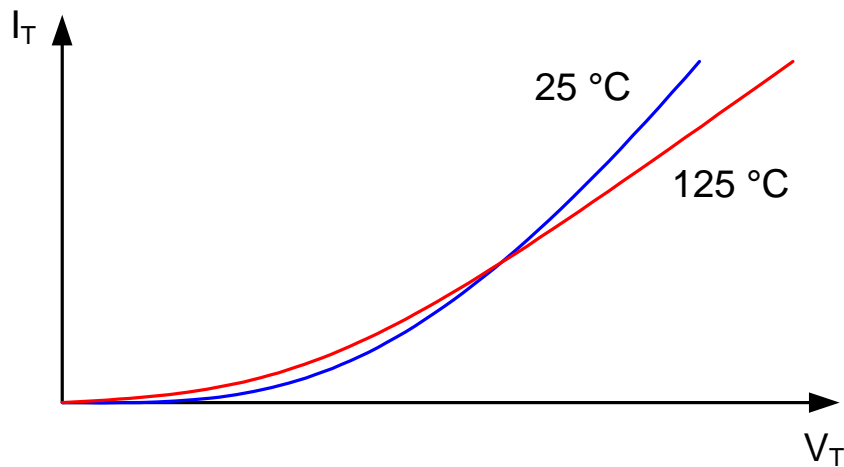


Fig. 1: On-state voltage (V_T) characteristics of an HVDC thyristor as a function of on-state current I_T and junction temperature T_j

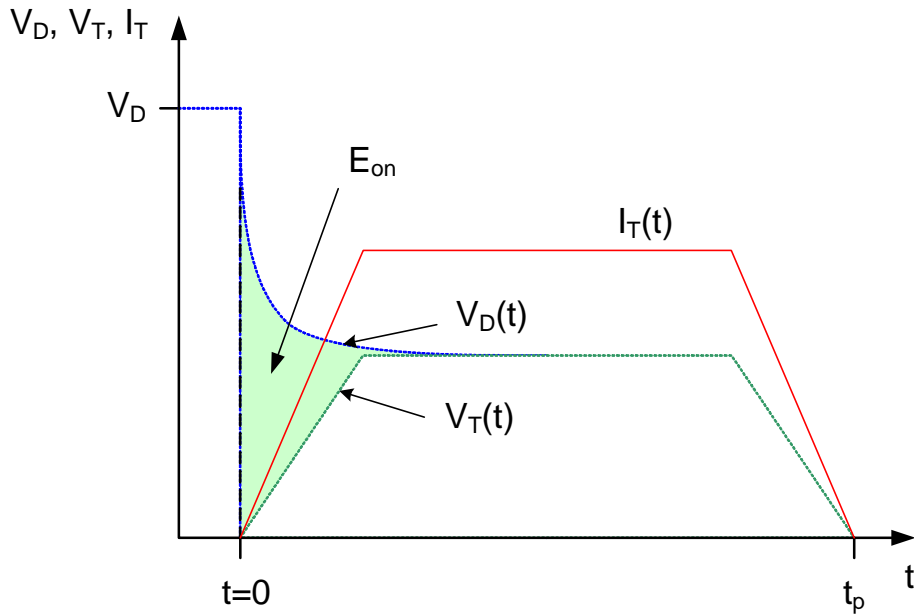


Fig. 2: Current and voltage characteristics of an HVDC thyristor in the turn-on process. The shaded area indicates the transient on-state voltage contributing to turn-on energy.

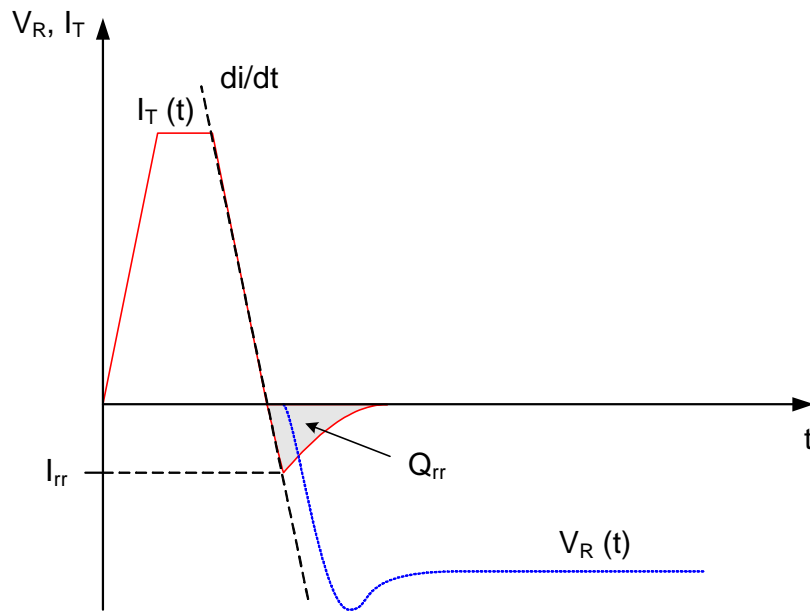


Fig. 3: Current and voltage characteristics of an HVDC thyristor in the turn-off process. The conduction current I_{TR} is being turned off at a given di/dt . The thyristor remains conductive until I_{rr} and then depends to gradually reduce its current to zero. Meanwhile the reverse voltage builds up, and their product forms the turn-off power and energy.

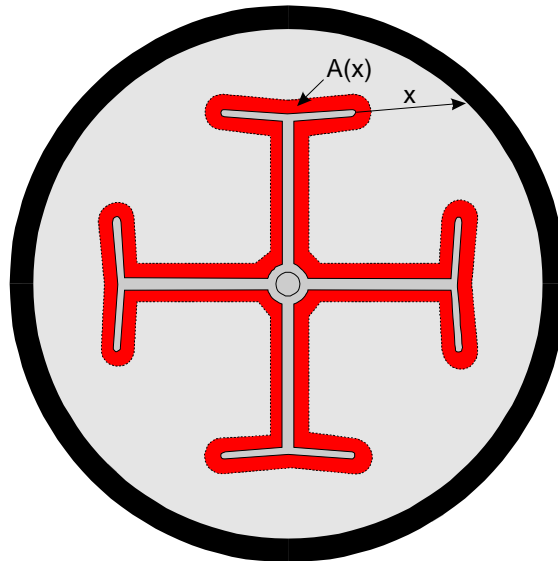


Fig. 4: Plasma spread at turn-on of an HVDC thyristor. Initially, an area close to the contour of the gate structure in the wafer contains electron-hole plasma; this plasma (red area) then spreads from there over the full wafer, e.g. along direction x , and covers a conducting area $A(x)$ for each value of x .

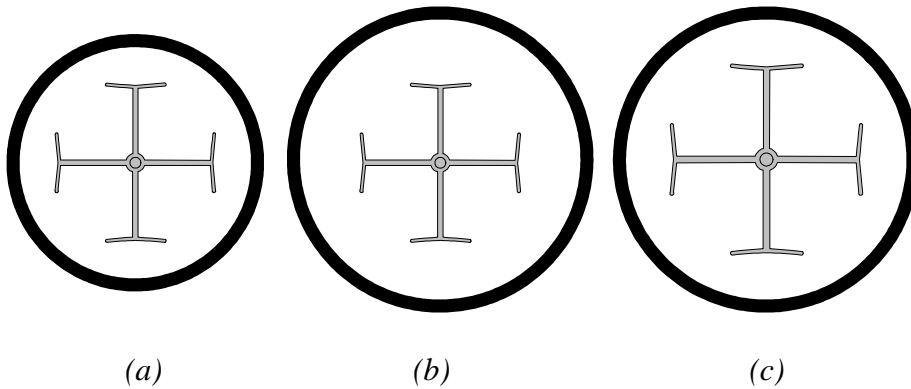


Fig. 5: Gate patterns for 5 and 6 inch HVDC thyristors. (a) 5 inch thyristor, (b) 6 inch thyristor with gate pattern of 5 inch thyristor, (c) optimized 6 inch thyristor pattern.

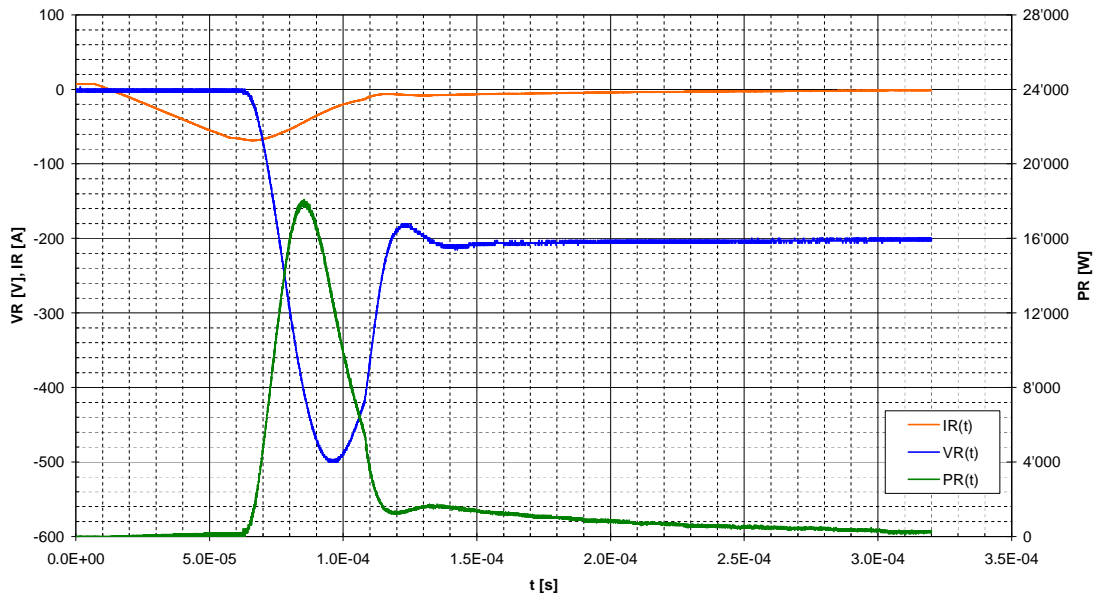


Fig. 6: Turn-off measurement of a 5 inch thyristor with anode current, reverse voltage, power dissipation and energy loss transients at $di/dt = -1.45 \text{ A}/\mu\text{s}$, $V_R = 200 \text{ V}$ (commutation voltage) and $T_j = 90 \text{ }^\circ\text{C}$ (junction temperature)

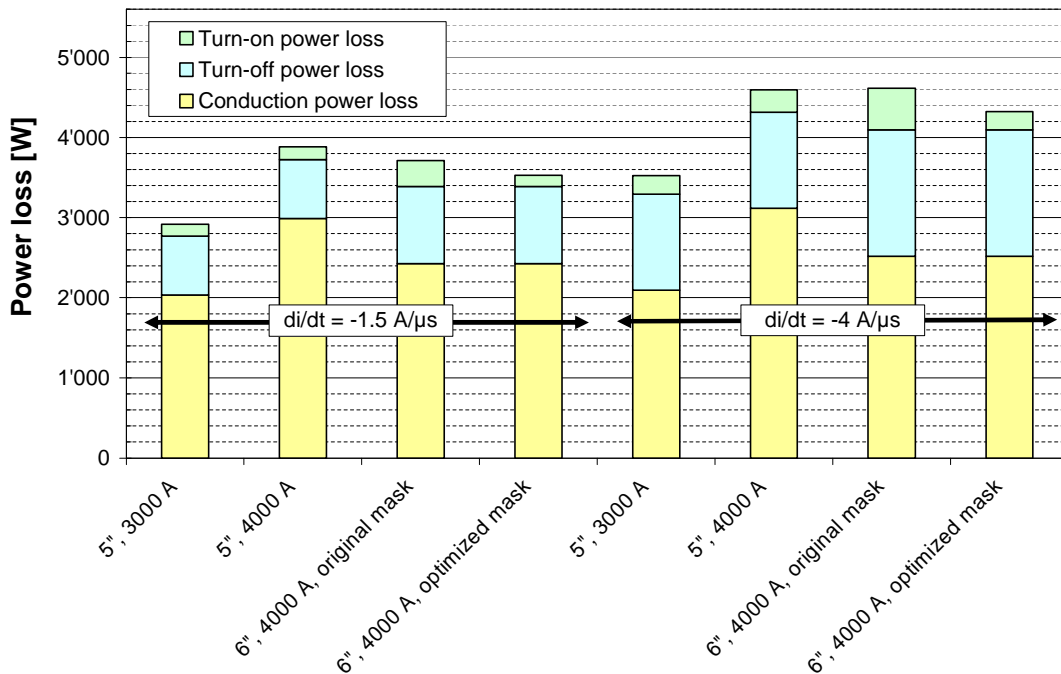


Fig. 7: Power loss contributions at 50 Hz line frequency and 90 °C junction temperature for two different values of di/dt and different thyristor diameters as well as different gate structure designs (photo masks)