High Voltage Thyristors for Soft Starters

In spite of significant development of converters on the basis of fully controlled semiconductor stacks (IGBT, GTO, IGCT), today it's still technically legitimate and demandable to use "traditional" high power thyristors in stacks of controlled rectifiers as well as in soft starters for electric motors. Usage of thyristors is especially relevant in case of operating in AC network of 6/10 kV and higher, because the devices produced on the basis of such thyristors have no competition in price and energy efficiency (efficiency coefficient). That's why development and production of high voltage thyristors is of high interest. **D. A. Presnyakov, I. Yu. Vetrov, A. V. Stavtsev, A. M. Surma, Orel, Russia**

During last several years some manufacturers developed and put into production high power devices with voltage up to 6,5-8,5 kV necessary for high-voltage valves of electric converters operating in AC with 6 kV and higher. The blocking voltage level is still low to allow using only one thyristor in such stacks. That's why the stack consists of several series-connected semiconductor devices which requires operating synchronization of thyristors in such connections.

Unfortunately, along with increase of maximum allowed blocking voltage, reverse recovery voltage increases as well, which is quite typical for high voltage device. It's connected with the necessity to guarantee low voltage in off-state. For devices with 6,5-8,5kV voltage values of reverse recovery voltage and maximum value of reverse recovery current reach very high level, even with low value of current rate of rise.

In Figure 1 typical values for high voltage thyristors manufactured by various companies are shown. These values for thyristors with 6,5-8,5 kV reached the values when it's quite difficult to cross match damping and conforming RC-circuits.

Calculations and experiments show that full power of losses in damping RC-circuit, limiting the pulse spike of reverse voltage at recovery of the typical high voltage thyristor on the level of 0,75-0,8V_{RRM} in circuit with VDC~0,5V_{RRM} voltage is connected with reverse recovery charge by semi-empirical equation 1:

$$E_R \sim 1{,}5 Q_{rr} \cdot V_{DC}$$

where E_R = energy dissipating in resistor of RC-circuit in "turn on - turn off" cycle.

Taking the data shown in Figure 1 it's easy to see that power dissipated by damping circuit of high voltage thyristor can be compared with full power of losses of thyristor, which isn't optimistic at all concerning the complexity of stack cooling system as well as its efficiency coefficient.

Considering this the development of high voltage thyristors designed for series connection assemblies with some specific characteristics at reverse recovery:

- Minimized values of reverse recovery charge and current (on condition of low level of voltage in on-state);
- "soft" character of reverse recovery; usage of thyristors with soft reverse recovery allows to simplify the requirements to RC-circuit in case of providing acceptable level of peak voltage;
- adequacy of reverse recovery charges, as well as reverse recovery current form for thyristors used as series connected assembly; this allows to lower the requirements to conforming RC-circuits, and completely abandon it as perspective.

Let's consider the problems in more details, which may occur when developing

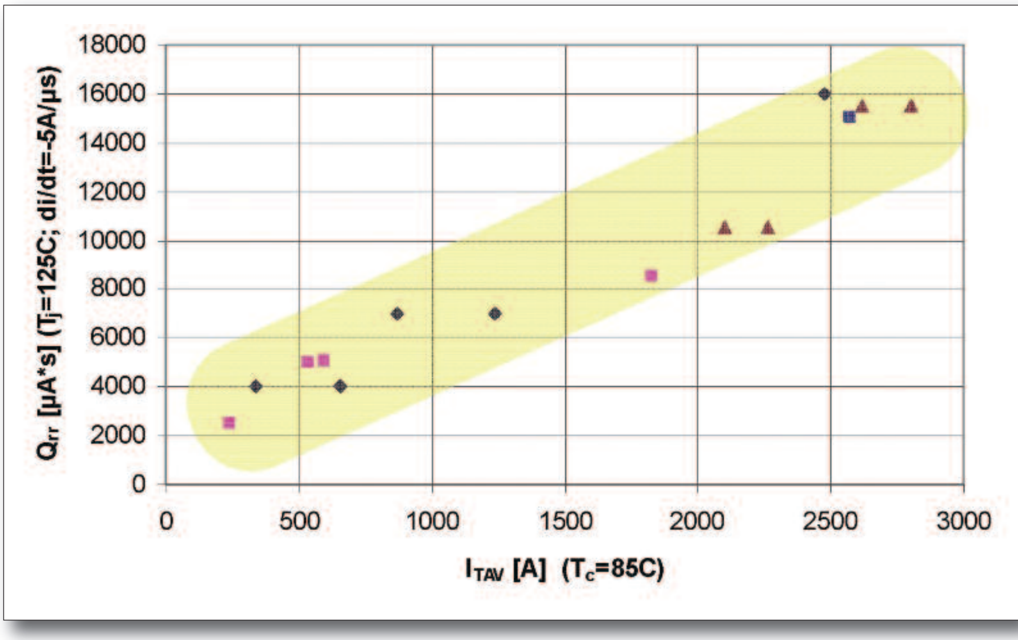


Figure 1: Dependence of average current in on-state and reverse recovery charge for high voltage (6,5-8,5 kV) thyristors manufactured by various companies (average current: pulse waveform - half-wave sine time length 10 µs, 50 Hz frequency, thyristor case temperature 85°C; reverse recovery charge: temperature of semiconductor element 125°C, rate of rise 5 A/µs, reverse voltage $V_{R(DC)}$~ 0,5-0,8V_{RRM})

and producing such devices and series connected assemblies on its basis, using the example of thyristors and stacks produced by Proton-Electrotex JSC.

High voltage thyristors adjusted for usage in series assemblies

It's clearly known that value of reverse recovery charge depends on value of accumulated charge of excess electrons and holes in n- base layer of thyristor, and also on recombination rate of this accumulated charge. For high voltage thyristors, which recover at low rate of rise of anode current, the second factor is more crucial. Indeed during rate of rise of anode current the bigger part of excess carriers recombinate. Thus there is some optimum value of effective life time of carriers in n-base of thyristor, which allows achieving low reverse recovery charge with relatively low value of voltage rate of rise in on-state.

To reach the optimum value of carriers' life time in n- base of thyristor the technology of accelerated electrons and protons irradiation of silicon elements is used. However, there are some additional options to lower the value of reverse recovery charge. If we lower the maximum concentration of atoms of acceptor dopant in p- base of thyristor, this will lower reverse recovery charge by means of transferring part of excess electrons accumulated in n- base into n+ emitter, same to the process in diode. In thyristor with highly doped p- base, as a result of transistance, there isn't any electrons transfer from n- base, but excess holes injection into n- base what leads to relative increase of reverse recovery charge.

Thyristors produced by Proton-Electrotex JSC have quite low doped p- base (as a rule maximum concentration of acceptors - (1 or 2)*10^{16} cm^{-3}) [1]. This allows to lower reverse recovery charge without any influence on voltage rate of rise in on-state.

To guarantee the required dU/dt - durability for thyristors with low doped p-base, special configuration of distributed cathodic diversion is used.

"Softness" of reverse recovery S is very significant characteristic, which can be shown as quotient of duration of rate of rise of reverse current (t_f) and time of delay of reverse voltage applying (t_s) in the process of reverse recovery of thyristor according to equation 2:

$$S = t_f / t_s$$

It's known that increase of reverse recovery softness can be reached with lowering of concentration of excess carriers near anode p- emitter. There are two ways to achieve it:

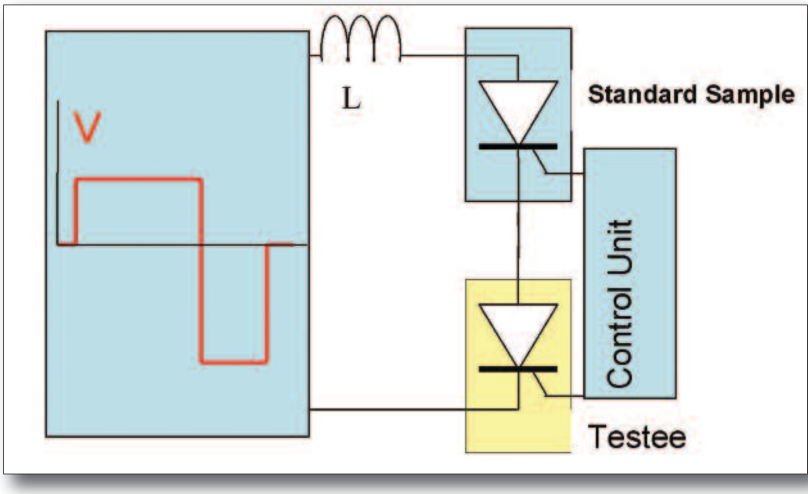


Figure 2: **Basic diagram of equipment for final presorting of thyristors by reverse recovery characteristics**

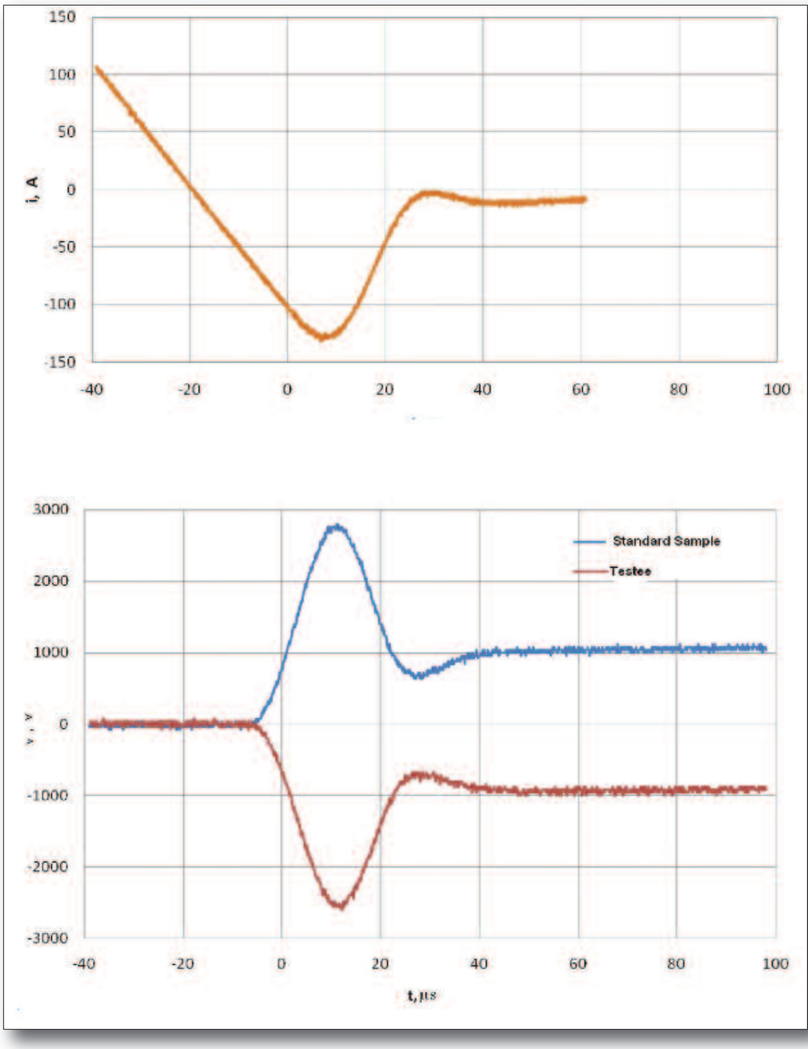


Figure 3: **Typical dependences of reverse recovery current (upper) and voltage of testee (lower graph) and standard sample thyristors using equipment for final presorting by reverse recovery characteristics**

- Lowering of injection efficiency of anode p- emitter; this can be achieved by lowering the maximum concentration of acceptor dopant as well as carriers' life time in highly doped area of p- emitter layer;
- local decrease in life time in the layers of n- base and low doped p- emitter joining anode p-n junction.

Proton-Electrotex JSC uses both ways to achieve the desired results for thyristors.

Firstly, relatively low doped p- emitter layers are used. This allows reducing reverse recovery surge current and increasing softness of reverse recovery. More than that, as proved by calculations and experimentations, for such thyristors low temperature dependence of time and reverse recovery charge is very characteristic. Secondly, when it's necessary to reach soft reverse recovery special technology of carrier life time regulation based on proton irradiation. This technology allows locally decrease carriers' life time in the layers joining the p-n junction.

It's very crucial to have identical reverse recovery characteristics for thyristors. And it's very important to have same surge current and reverse recovery charge, as well as identical characteristic of current dependence on time. This can make it possible to avoid using RC-circuits when assembling thyristors.

In accordance with above mentioned it's clear that to have identical characteristics of reverse recovery it's necessary to provide high precision of doping profile and life time distribution of carriers in semiconductor elements. Identity of dopants distribution is provided by high level of production of semiconductor elements technology, precise control of carriers' life time becomes possible with help of special technology of electron and/or proton irradiation.

To achieve low variation of reverse recovery parameters the following process flowsheet is used:

- Step 1. Presupposition for achieving low variation of reverse recovery characteristics - providing high identity of dopant profiles in produced silicon elements, which is achieved by thoroughly worked-out technology. This step provides the repetition of reverse recovery current form, temperature dependences of reverse recovery characteristics.
- Step 2. Precise control of reverse recovery parameters (reverse recovery time, reverse recovery current, reverse recovery charge, softness) with help of electron and proton irradiation. This step provides additional correction of reverse recovery time and charge to lower the variation of these characteristics in group. Combination of electron and proton irradiation allows simultaneously adjust softness.
- Step 3. Final presorting with equipment that provides the possibility to run tests of reverse recovery of two and more series connected thyristors in mode close to operational.

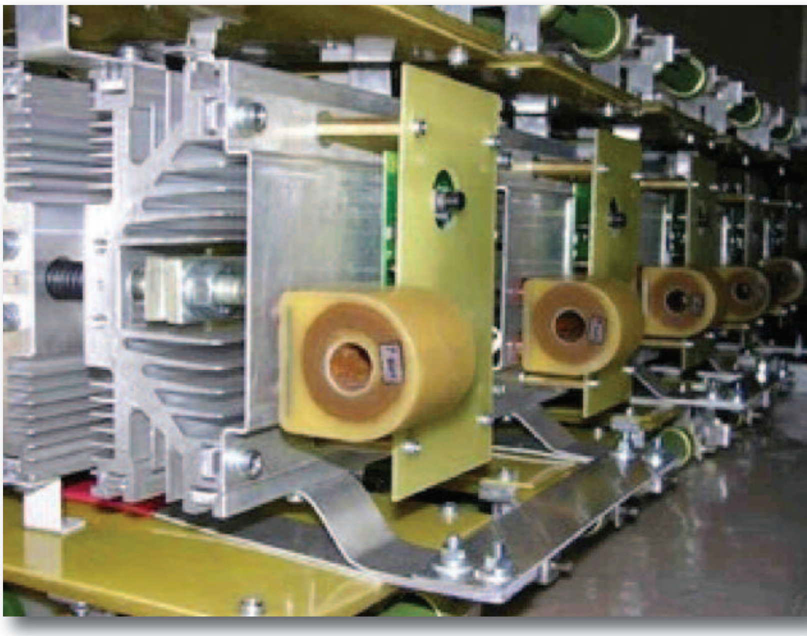
The scheme of equipment necessary for such tests is shown in Figure 2. Presorting is done during test of each and every thyristor in series connection with standard sample. Pulse power supply provides positive voltage distribution to the switched-on thyristors, and current, going through the inductive reactor L, linear reaches the necessary value. Voltage polarity changes and two series connected thyristors reverse recover.

And the fitting criterion of reverse recovery characteristics of device to the standard sample is voltage distribution applied to the thyristors during the whole process of reverse recovery equally between testee and standard sample. Typical dependences of reverse recovery current and voltage of testee and standard sample thyristors are shown in Figure 3.

This equipment can be used for testing the assembled high voltage valves on basis of series connected thyristor stacks. As a result of the above mentioned technologies in production it made it possible to have thyristors with relatively low reverse recovery charge, low temperature dependence, as well as high softness of reverse recovery. Typical

Thyristor Type	T543-250	T653-500/630	T473-1000/1250
Silicon element diameter, mm	40	56	80
Allowed average current, A (current pulses halfwave sine, time length 10 μs, frequency 50 Hz, case temperature 85°C)	250	500-630	1000-1250
Repetitive voltage in off-state, reverse voltage, V	4600-6500	4600-6500	4600-6500
Reverse recovery charge, μC, (semiconductor element temperature 125°C, current rate of rise 5A/μs, reverse voltage $V_{R(DC)}$= 0,5V_{RRM})	2500-3500	4000-6000	6000-8000
Reverse recovery charge variation by group	In accordance with customer's demands from ±5% to less than 1%		
Reverse recovery softness S	1,0-1,3	1,0-1,3	1,0-1,3

LEFT Table 1: Typical characteristics of high voltage thyristors adjusted for usage in series assemblies



BELOW Figure 4: KT5.11-800 stack for usage in soft starters of electric motors operating in AC networks of 6 kV

characteristics of high voltage thyristors adjusted for usage in series assemblies are shown in Table 1.

Series stacks for usage in soft starters of electric motors

New high-voltage thyristors adjusted for usage in series connection are used for series connected stacks - KT5.11-800, designed for usage in soft starters of electric motors operating in AC network of 6 kV (see Figure 4). The stack consists of thyristors with 6,5 kV blocking voltage and presents the complete unit - AC stack equipped with drivers, power units, conforming circuits and heat sinks, it's basic diagram is shown in Figure 5. Thyristor groups, forming direct and reverse stacks are controlled separately by fiber optic line.

The stack can be used in AC network of 6 kV, as well as in other networks with peak values of direct and reverse voltages up to 11 kV, and provides maximum starting current of electric motors up to 400 A.

Literature

[1] Applying Proton Irradiation for Performance Improvement of Power Semiconductors, Power Electronics Europe 3/2011, pages 35 - 38

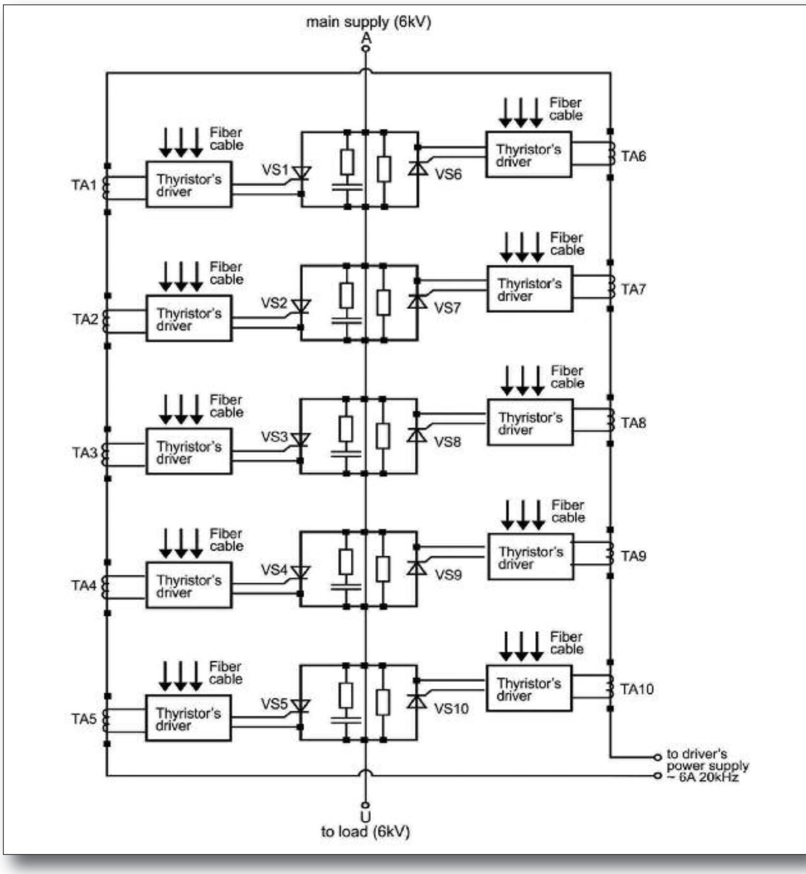


Figure 5: Basic diagram of KT5.11-800