HIGH VOLTAGE HERCONE-SEMICONDUCTING COMMUTATION DEVICES FOR REA ELECTRIC POWER SUPPLY SYSTEMS

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Electric power supply systems for most applications in Radio and Electronic Engineering have a high operational voltage. The latter ranges from 1 .. 2 kV in the remote feed circuits of the unattended transmission stations up to 5 .. 15 kV in the electrovacuum SHF device power supply modules (e.g., traveling wave tubes, klystrons, etc.). To control and protect the operational modes of such power supply modules one has to use specialized HV commutation devices of relatively low power. Domestic electronic industry produces a variety of such devices such as vacuum contactor HVC-20, S1HV and S4G-1 high voltage switches, MCA-52141 and MCA-52142 magnetically excited contacts (a.k.a. MECs or hercones). However, none of these components completely satisfy the SDS of the high voltage communication systems. Per se, S1HV and S4G-1 can perform commutation only under zero current load condition; the operational time of HVC-20 is as large as 15 .. 20 ms; the mentioned MECs have a limited switching capacity (0.5 .. 2 mAmps).

At the same time, a typical requirement for a high voltage power supply module would be 0.001 .. 100 Amps in terms of switching capacity under 5 to 15 kV of operational voltage, at 0.0001 to 10 sec of fastresponse. Besides, a telecommunication designer is often challenged with a problem of providing a galvanic insulation of the different potential circuits.

The present paper addresses these issues and outlines the technical solutions based on the hybrid MEC and solid-state approach.

Conceptual solutions. The problem of the switching capacity increase can be generally solved by MEC synchronous commutation - for the AC applications, and by putting the MEC into the control circuit of the solid-state (amplifying) key - for the DC applications.

The synchronous commutation principle suggests sending out the control signal to the MEC synchronously with the sinusoidal current approaching zero. The problem, however, arises from the statistical deviation in the magnetomotive force of an individual MEC, so the synchronization module should allow for the operational parameter adjustment. Besides, the fastresponse degradation function should also be taken into account to eliminate a possible deviation in the zero current lead from the pre-determined value. Another, simpler method of the synchronous commutation is the so-called arc-free commutation, which can be implemented via shunting the MEC by a rectifier chain.

The control circuits of the high voltage hybrid MEC-solid-state amplifiers involving serially connected components triggered by a single MEC have to be reliably decoupled from one another to avoid mutual interference. One has to also account for the specific characteristics of the industrially produced solid-state components of certain types, such as a very low gain for a majority of the HV transistors.

The increase in fastresponse can be achieved through several strategies. The first one is to utilize a natural property of a MEC to switch-off faster than to switch-on. The second is to use a low voltage high speed MEC in the HV commutators through an appropriate circuit resolution. The third way is to eliminate or compensate the MEC transient bouncing, the duration of which constitutes the larger part of fastresponse and can not be ignored in the high voltage circuitry commutation. Finally, it is possible to use the traditional methods such as forced excitation of the commutator coil or geometric optimization of its magnetic circuit.

A high voltage galvanic decoupling between the different potential parts of the power supply module protection system can be effectively implemented through the *hercotrones* -- high voltage MEC based isolating interfaces [1,2].

The detailed discussion of the suggested conceptual solutions are given in the following sections.

The arc-free high voltage commutation device (Fig. 1) consists of the synchronizer SYN, two hercotrones H1 and H2 and the diode chain VD3. The output MEC in the hercotrone can be either of the closing-circuit, or the opening-circuit type. In the first case, the arc-free commutation is realized through the following sequence. H1 closes when the VD3 cathode potential is positive, the MEC conducting only the reverse current of the diode. H2 closes when the VD3 cathode potential is negative, the MEC being shunted by VD3. In the second case, the synchronization sequence of H1 and H2 is reversed. The synchronization is provided by the synchronizer, which includes the AC half-wave polarity identification module based on VD1 and VD2 diodes and the sequence synchronization module based on VS1 and VS2 thyristors. The sequence synchronization module provides that the signal to output I is applied prior than to output II. The switching capacity of the device is 0.5 Amps at 10 kV. The dimensions are 130x95x95 mm. Other variants of the synchronous commutation modules are discussed by us in [3,4].

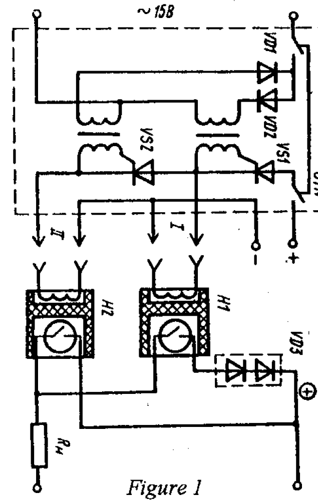

Figure 1

Hercone-thyristor commutation devices (Fig. 2) can be designed both for the AC and DC applications. The AC commutator is based on the anti-parallel thyristor couple [5]. The MEC current, in this case, is a short duration triangular pulse series, which appears at the beginning of each positive half-wave (see Fig. 3). The switching capacity of the MEC can, therefore, be based not on the nominal value of the control current but on the integral equivalent intermittent current defined by the following expression.

$$I_{emec} = 0.5 I_{irm} \sqrt{\frac{1 - Exp(-\frac{tp}{\tau})}{1 - Exp(\frac{-(tp+ts)}{\tau})}} \qquad (1)$$

where

I_{irm} - max value of the intermittent current;

tp, ts - duration of the I_{irm} pulse and the space;

τ - MEC heating time constant.

The above mentioned equivalent current can be represented by:

$$Ie = \sqrt{\sum_{1}^{1/n} t \int_{0}^{\sum t} i^2 dt}$$

Assuming that the pulse current is linear with respect to time, i.e.

$$Ip = \alpha t,$$

where $\alpha = Iop/t = const$, and Iop is the nominal opening current of the thyristor, one will get:

$$Ie=\sqrt{\frac{\int_0^t \alpha^2 x^2 dx}{t}} \qquad (2)$$

This latter expression evaluates to $3^{1/2}\, Iop$. By plugging (2) into (1), one gets:

$$Iemec = Iop\,/\,(2\; 3^{1/2}),$$

which is to say that the calculated MEC current is less than the thyristor nominal opening current almost by a factor of 3.5! Besides, it should be noted that the thyristor SDS gives not the actual value of the opening current but the maximum possible limit. Statistical analysis of the opening current distribution for the high power thyristors has shown that the average actual value of the opening current is usually less than the nominal value by a factor of 1.5 .. 2. The above considerations prove that the MEC parameters are well compatible with those of the medium and high power thyristors.

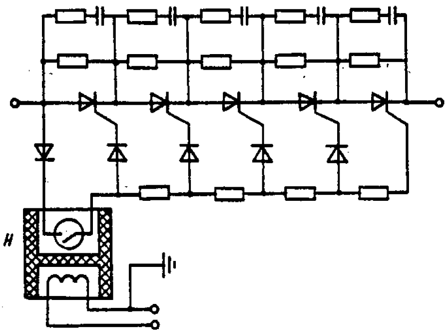

Figure 2

Using hercone-semiconducting devices as short circuiters in the protection systems of the high voltage electro-vacuum apparatus (such as klystrons) requires the fastresponse of the order of 50 .. 100 microseconds. The level of fastresponse is achieved by the circuitry shown in Fig. 4.

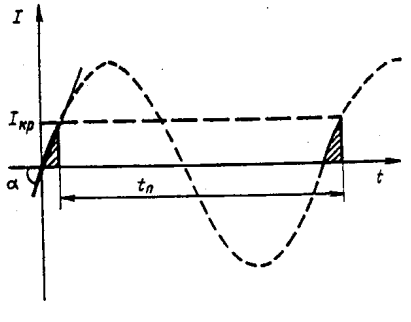

Figure 3

The principal component of this device is the miniature low voltage MEC of the MC-3 type. The MEC opens the primary circuit of the HV decoupling induction transformer, which results in the current pulse transformed through the secondary circuit to the thyristor control electrodes. Experimental investigations have shown that in order to reliably open five serially connected thyristors, the current in the primary winding has to be no less than 0.03 Amps under the voltage of about 3 V. The dimensions of the device are 100x85x30 mm.

Further experimental investigations of this device have led to the discovery of its unique property: under the condition of low anode currents and higher (by a factor of 10) primary circuit currents, the regular non-closing thyristors can be actively closed! The alternating polarity of the control pulses can be achieved by the change of the binary conditions of the MEC ("opened" to "closed" and vice versa). This effect is used in the fully controlled high voltage DC key with the switching capacity up to 0.05 Amps.

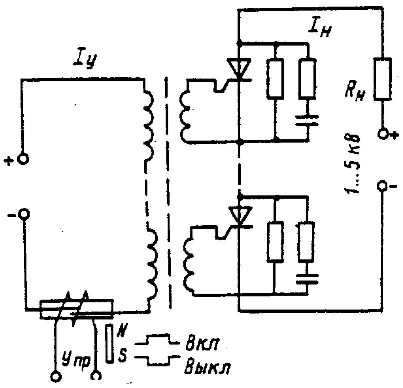

Figure 4

Hercone-transistor commutation devices have the highest potential from the standpoint of the communication equipment applications. Their usage, however, has a number of peculiarities, which are discussed below.

The designers of the high voltage solid-state commutation devices are traditionally focused at the HV transistors of the 2T828A, 2T839A or 2T713A type. However, the gain properties of these triodes are so low (2 .. 5) that for many parameter demanding applications their usage becomes questionable [8].

If a hercone-transistor device contains more than two serially connected transistors, their total control current (which is equal to the sum of the base currents) becomes practically comparable to the collector (load) current. The transistor power amplifier, in this case, becomes a nonsense. That is why the mentioned transistors can only be used for the simplest one-component applications [9].

One can obtain much better (in terms of switching power) results by compromising the operating voltage (e.g., $Uop = 0.8\ kV$ -- 2T506A) to a much better gain (30 .. 150). The increase in the number of the serial components is now compensated by a high gain. Besides, low dimensions and weight of these transistors (even if their number is twice as many as compared to the previously mentioned type) reduce the total dimension and weight indices of the commutation system. The switching capacity being at 15 kW.

For the super high voltage applications (e.g., 5 kV and 2 Amps - collector) involving more than 5 serially connected high gain transistors, the total base current still exceeds the maximum switching capacity of a high voltage MEC. The only remaining possibility to decrease the total base current is the cascade transistor circuitry [10]. The base circuit diodes eliminate the mutual interference of the serially connected devices and provide for the uniform distribution of the collector voltage in the static mode. The individual diode voltage is distributed according to the equation:

$$U_{VDi} = Ups\,(N - I)\,N^{-1} \quad (3)$$

where

Ups - the power supply voltage;

N - number of transistors in a serial chain;

$I = 1\ ..\ (N-1)$ - the ordinal number of a transistor from a positive terminal (see Fig. 5). Maximum reverse voltage of an individual triode should either be based on (3) or on the quantity of $Ups\,(1 - 1/N)$.

Another issue that has to be addressed in relation to the HV hercone-transistor commutation devices is the effect of the current pulsations caused by the MEC transient bounce (and amplified by the transistor) to the output (load) signal. The additional RC-chain (see Fig. 5) is one of the possible solutions. It is assumed that the capacitor gets charged during the first contact impact and provides a positive potential at the transistor bases during the first bounce. It then gets additionally charged during the second impact, etc. Thus, the compensating capacitor eliminates effect of the MEC bounce to the transistor output circuit and increases the fastresponse of the device. Fig. 6 features the oscillogram of collector current with (b) and without (a) the capacitor.

The parameter vector derivation of the RC-chain becomes somewhat specific. First, the capacitor has to be fully charged during the first impact of the MEC contacts t_1, which imposes the following condition on t_1:

$$t_1 \geq \pi RC \qquad (4)$$

Second, the power dissipated at the intercontact resistance of the MEC during the charge of the capacitor can not exceed MEC maximum switching capacity, i.e.

$$P_{MEC} \geq \frac{r_{MEC}}{t_1}\int_0^{t_1} i^2{}_c(t)\,dt \qquad (5)$$

where

r_{MEC} - MEC intercontact resistance;

$i_c(t)$ - free component of the capacitor charge current.

Third, during the discharge of C over t_{12} (the first bounce duration), the free component attenuation of the voltage drop across the base resistors should not exceed the maximum acceptable voltage drop at the collector load, i.e.

$$\frac{U_{l\min}}{U_{ps}} \geq Exp(-\frac{t_{12}}{R_b C}) \qquad (6)$$

where

$$R_b = (\sum_{i=1}^{N} \frac{1}{R_{bi}})^{-1}$$

epresents the equivalent resistance of the transistor base circuits. Integrating (5) and solving the resultant based on (4) defines the value of the compensating capacitor:

$$C = \frac{t_1}{U_{ps}} \sqrt{2 \frac{P_{MEC}}{\pi r_c}}$$

After a simple transformation of (6), one can get minimal resistance of an individual base resistor:

$$R_{b\min} = \frac{t_{12}}{NC(-\ln U_{l\min}/U_{ps})}$$

The fastresponse of the described device (with the HV MEC of the MCA-52141 type) is about 300 microseconds, which is sufficient for most applications.

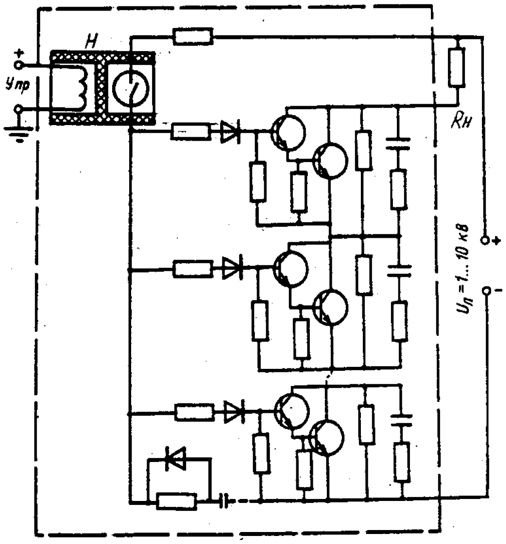

Figure 5

One can reach even higher (up to tens of microseconds) fastresponse level implementing the circuitry shown in Fig. 7 [11]. The basic feature distinguishing this technical solution is the low voltage MEC, which can now be put in parallel to the base-emitter junction of the transistor chain, since the voltage drop across the latter even for the high power triodes does not exceed a few volts. Another principle difference is that the MEC is now of the opening-circuit type. Due to the fact that under the optimal magnetic system design [12], the opening-circuit miniature low voltage MECs have a fastresponse of the order of tens of microseconds, and to the fact that operational time even for a low frequency transistor does not exceed a few microseconds, the total fastresponse of the device becomes very high. It should be noted that the switch-off mode of this commutation device is associated with some power loss (through the opening circuit MEC). However, in most cases its magnitude (10 W) is negligible as compared to the switching capacity (100 kW) of the device.

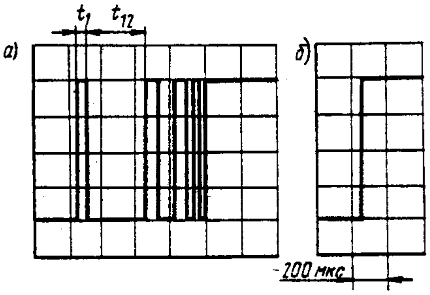

Figure 6

The mass and dimension indices of the hercone-transistor commutation devices are 0.25 kg and 90x45x20 mm for the pulse mode applications, and 0.4 kg 100x100x45 mm -- for the stationary mode applications.

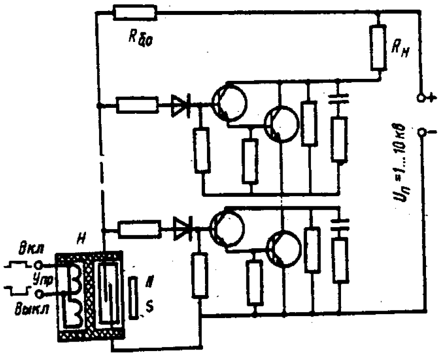

Figure 7

The practical implementation of the described design solutions has been performed by the "INVENTOR" Science and Technology Enterprise (Kharkov, Ukraine).

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