Fast Opening Switch Approach for High-Voltage Vacuum Tube Protection Application

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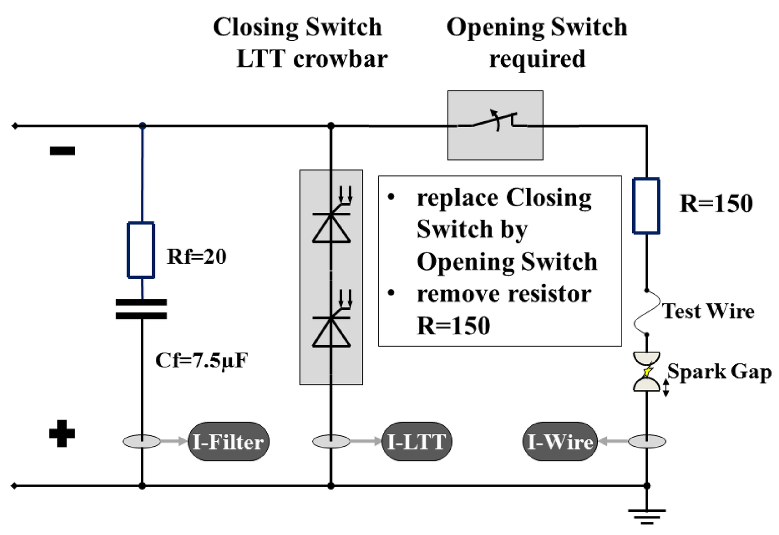
Initial Topology for Protection Application



The operation of high-power, high-frequency vacuum tubes requires an appropriate protection method to avoid significant damages during arcing. This paper describes a circuit topology to protect an Inductive Output Tube (IOT) which is expected to operate for accelerator applications. A preceding installation for testing the IOT operates the classic closing switch approach by means of Light Triggered Thyristors (LTT) with additional current limiting resistors .

Operating Conditions and Protection Requirements:

> Nominal Voltage : U = 48 kV dc
> Nominal Load Current : I = 3.8 A dc
> fault energy : W < 10 Joule

Operation Modes:

> Continuous Wave / DC Mode
> Long Pulse Mode : f = 1 Hz ; Duty Factor : D = (0.1…..0.5)

High Voltage Transistor Switch Module

Switch Module and Control Electronic

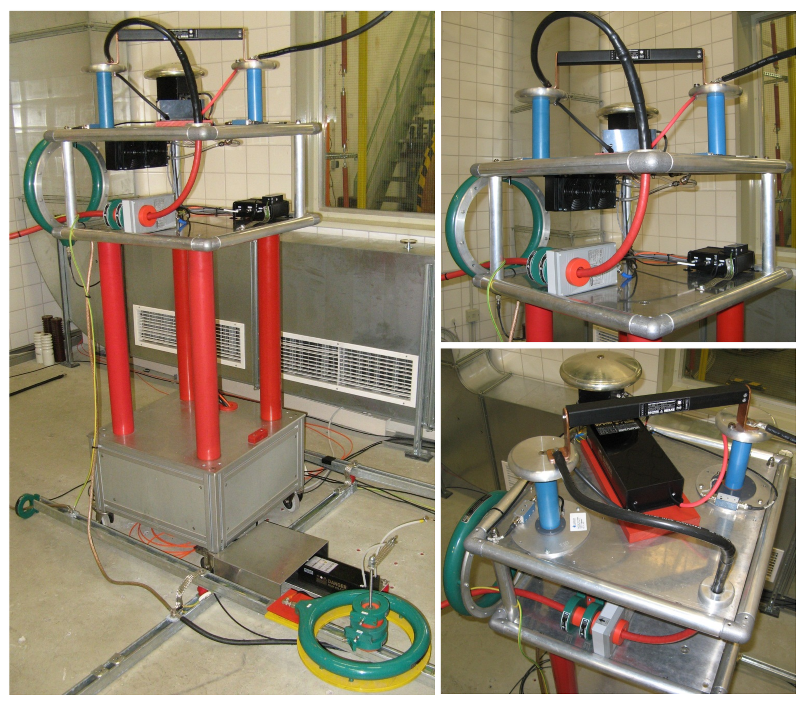
For fast switching operation a High-Voltage Transistor Switch based on MOSFET technology in combination with external control electronic is chosen (top). The module has been modified compared to the standard version by means of additional series diodes to protect the intrinsic body diodes of the MOSFETs from reverse current. Because of the heat load of dc mode operation, a direct liquid cooled version with an appropriate pump unit is deemed necessary (right).

Pump Unit PU2

Main Parameters Switch Module

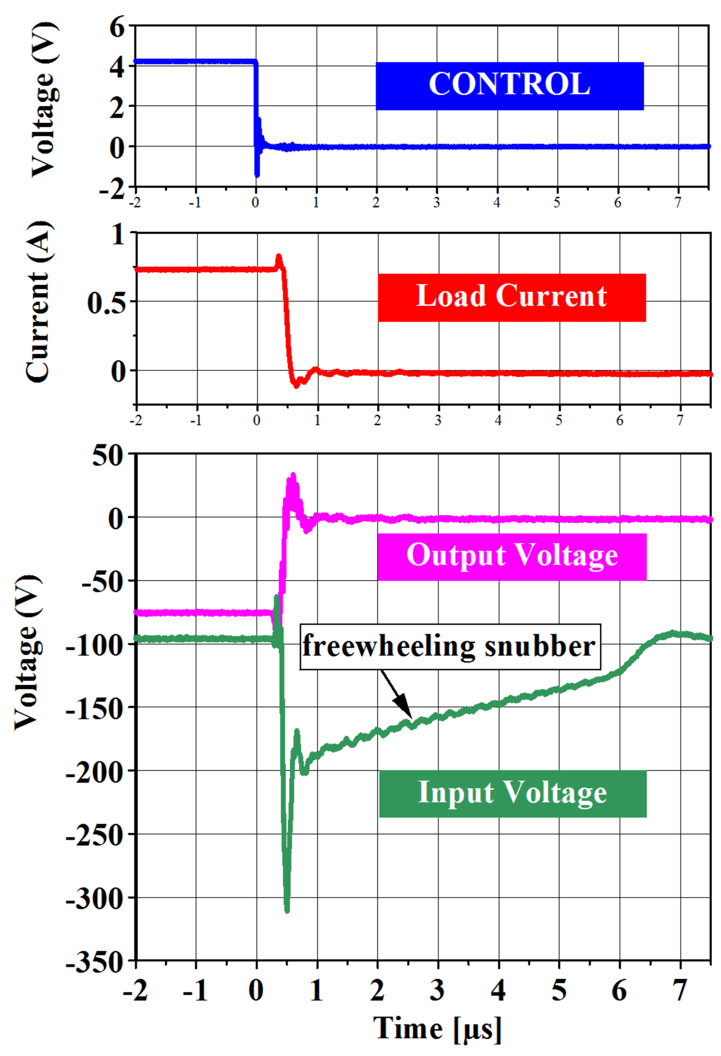
HTS 701 - 10 - LC2		
Specification	Value	Unit
Max. Operating Voltage	70	kV DC
Max. Isolation Voltage	100	kV DC
Max. Turn On Peak Current	100	A
Max. Continuous Load Current	4.75	A DC
Operating Voltage Range	0…70	kV DC
Turn-On Dealy	250	ns
Turn-On Rise Time	50	ns
Turn-Off Rise Time	80	ns
Coupling Capacitance	46	pF
Natural Capacitance	20	pF

High Voltage Test Setup

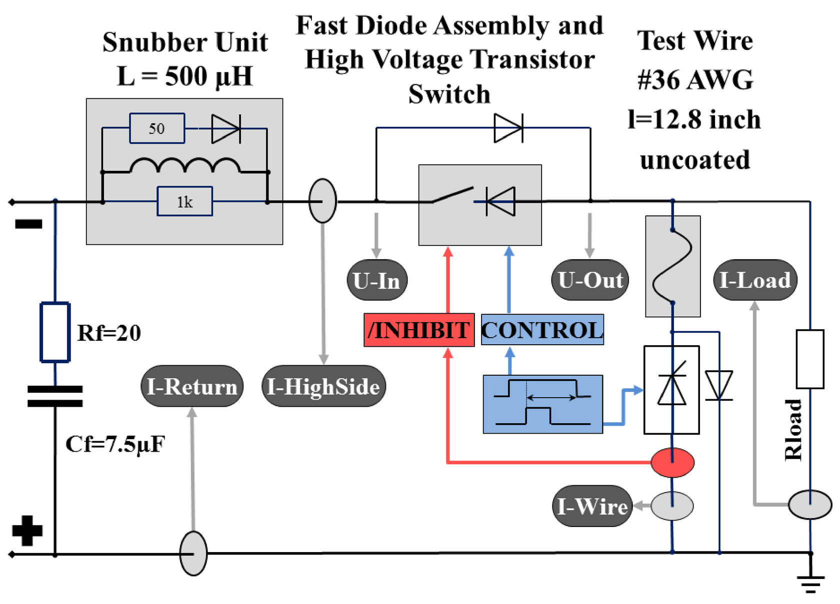


The test setup installation inside a high voltage room is shown above. For more flexibility during testing air insulation is preferred. The main components are located on the mounting deck. Top story with the switch module, diode assembly, pump unit and voltage dividers. Beneath active radiator, high side current monitors, control electronic and interface electronic. The insulation level of 50 kV dc for the high side current monitors is accomplished by means of a high voltage cable (red). On floor the short circuit thyristor module and low side current monitors.

Snubber Unit Freewheel Operation at Low Voltage

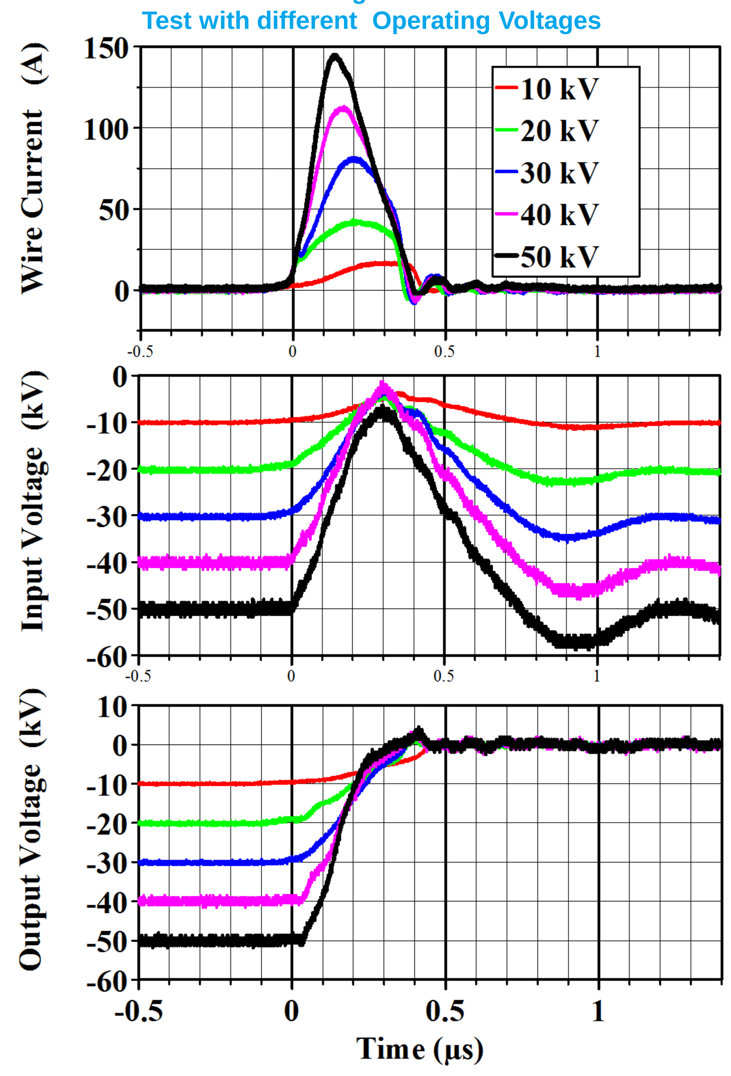


Protection Circuit Topology for Short Circuit Wire Test and Initial Results

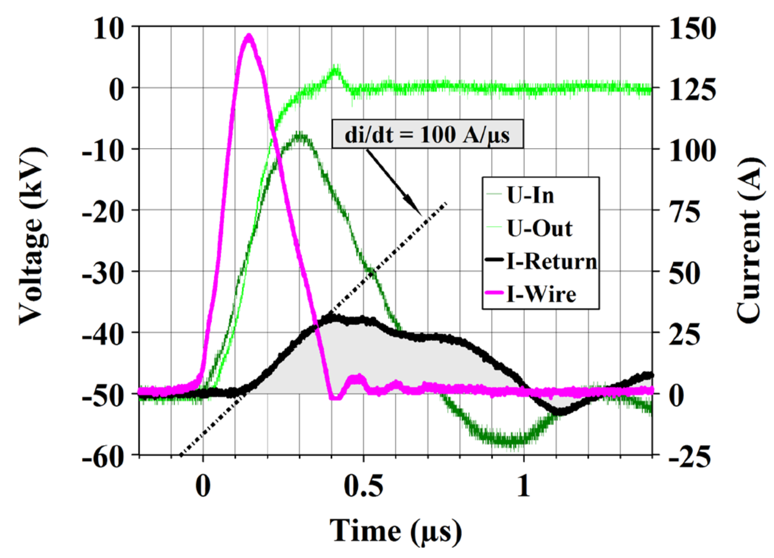


The topology is characterized by using a series connected switch module completed with essential snubber extensions. A 80 kV Fast Diode Assembly (FDA 800-75) antiparallel connected to the module bypasses possible reverse current. A wire test has been prepared to prove that the energy transfer during arcing is well below the 10 Joule limit allowed. An uncoated #36 AWG copper wire with a length of 12.8 inch has been specified by the manufacturer of the tube. Closing the short circuit a fast high voltage thyristor module (HTS 800-100-SCR) is used. The ratings of this module (80kV and 1 kA for 100µs) are sufficient for the overvoltage and pulse current expected during testing. To prevent the thyristor module from reverse transients an additional Fast Diode Assembly (FDA 800) is added. The wire test was repeated many times at nominal voltage without any degradation of the wire.

Current and Voltage Waveforms of the Wire Test with different Operating Voltages



Snubber Unit Decoupling Feature

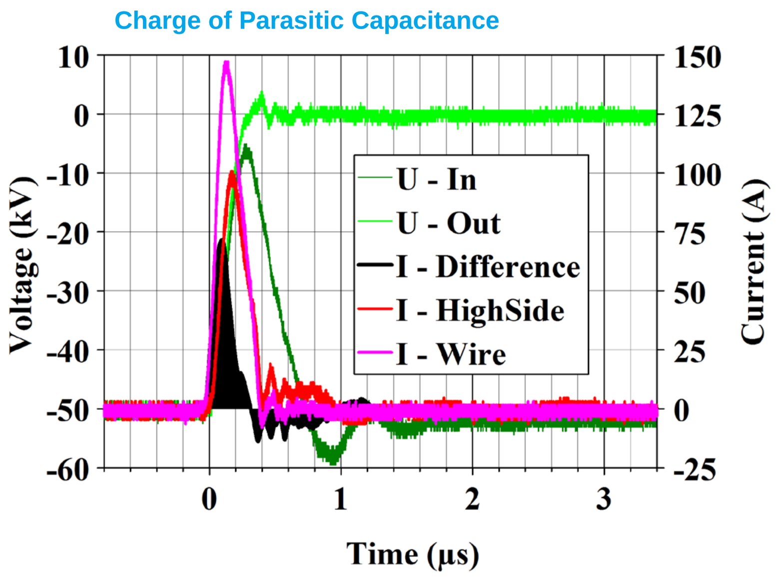


The operation of the High Voltage Transistor Switch (HTS) for short circuit conditions (tube arcing) is only possible with an additional series connected snubber unit. This unit limits the rate of short circuit current rise during arcing by means of an appropriate inductance. The HTS has to be switched off during arcing by the control electronic fast enough before reaching a critical current level that might damage the output transistors.

To prove the essential decoupling function of the snubber unit, the return current with respect to wire current was measured during short circuit operation. The waveforms are given above. The current rise of return current correlates the expected value of 100 ampere per microsecond. For proof of principle the parasitic oscillations observed are not considered within this context.

Opening Switch Approach for Protection Application, Lessons learned …

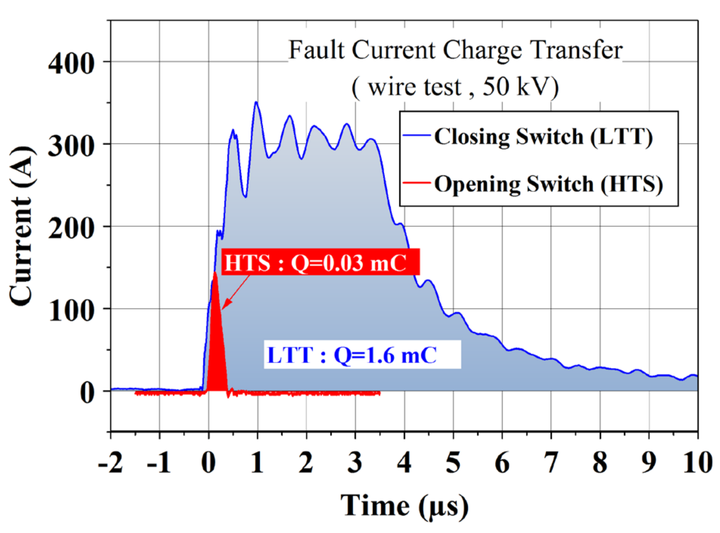
Charge of Parasitic Capacitance



The current peak measured through the wire at nominal voltage exceeds the maximum peak current specified for the switch module. This was an initial concern for further tests. An additional measurement of the current pulse at high side gives significant deviation compared to the low side measurement for the wire. An example of the resulting voltage and current waveforms is given above.

Obviously additional charge transfer by parasitic capacitances within the test topology is responsible for this effect. Based on the measured current deviation, the calculation of the transferred charge at nominal voltage gives approximately 225 pF for the capacitance considered. The high side measurement proves that short circuit operation fits the 100 ampere current rating of the switch module.

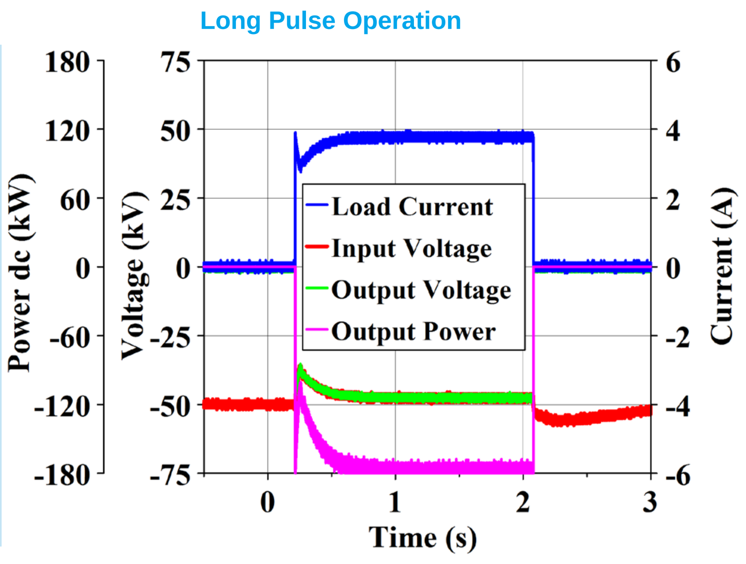
Fault Current Charge Transfer



To demonstrate the significant improvement achievable with the new opening switch approach compared to the preceding closing switch crowbar the charge (Q) transferred through the test wire has been identified. In the figure above the charge transfer through the test wire for both opening and closing switch during wire test at nominal voltage are presented.

It is important to recognize that the opening switch topology operates without any series connected current limiting resistors. This is of special importance to reduce the additional heat loss during continuous wave and long pulse operation of the tube.

Long Pulse Operation



Due to power limitations with the dummy load long pulse operation was only possible for a preliminary demonstration by applying On-Off command to the opening switch. An example is given in the figure above. The drop at the beginning of the pulse is caused by the ineligible power supply, which is optimized for clean dc operation only. To improve this situation an appropriate upgrade is underway.

At the final design the long pulse mode will be controlled by the RF drive of the IOT. The opening switch has to withstand all resulting load conditions only and finally to protect the tube in case of arcing.

Conclusion

The initial test results of this work prove the feasibility of the opening switch approach based on compact semiconductor modules for tube protection applications. The requested maximum fault energy **< 10 joule** can be accomplished easily. In general there is significant potential of this circuit topology to achieve even smaller fault energy levels. This work is considered as a first step taken to prove the principle.

For further investigations and development there are some complex details left to be solved:

> The very fast switching speed of the MOSFET module under high voltage conditions causes significant interaction with stray capacitances and leakage inductances of the circuit topology. An improved construction of the circuit layout has to avoid possible resonant transients intrinsically.

> For a very compact mechanical design alternate housing and cooling methods of the switch module in strong relation to the snubber unit needed have to be investigated.

> High side current sensing for fault level detection and fast /INHIBIT command is the preferred solution. Solving the contradiction of sensitivity and robustness against electromagnetic interference is a challenging task. The availability of fast current monitors with dc capability is mandatory.

> The overall reaction time of the system is **400 ns** for now. Further improvement, if desired, is possible with a redesign of the external control unit to get faster response time for the /INHIBIT interface.