Small standard components strategy, twenty years later

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Abstract

In 1999, a PCIM keynote paper entitled “Power switch: the standard small components strategy” is presented. This paper deals with the advantages of the association of small standard components instead of bigger ones and illustrates this purpose with high voltage high current very fast switches with small components associates in matrix. Twenty years later, some of these switches are still working. The goal of the presentation is to give some examples of realization, to list the key points of the technology, especially the use of MOSFET in avalanche mode, and the dimensioning. The conclusion focuses on some opportunities of using new standard components in avalanche mode.

1 MOSFET MATRIX switches for pulsed laser application

In the 90’s, to provide higher reliability and lower cost for copper vapor laser for uranium enrichment application, CEA developed the replacement of high voltage hydrogen tubes (thyratrons) for these pulsed lasers by the association of thousands of small standard MOSFET [1].
MOSFET are associated in a matrix structure on PCB, and PCB are associated in series and in parallel.

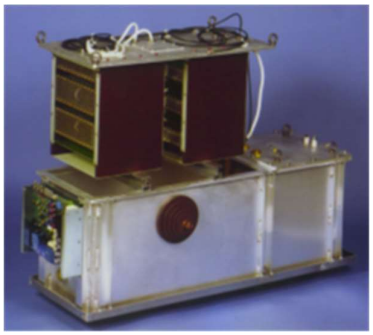


Fig. 1: 25 kV 2000 A switch for two thyratrons replacement

Because of intrinsic redundancy, this solution with MOSFET matrix proved a very high level of reliability. The calculated lifetime is 100 000 hours [2].

After this technology with the association of small standard components in matrix was extended to other components like thyristors.

2 Key points of the technology

The key points of the technology developed are:

- For components in series, voltage balancing is not necessary.
- For components in series, the mandatory requirement is only to keep the components in the safe operating area, by voltage clamping.
- For some MOSFET references the main part of the voltage clamping can be done by intrinsic clamping, in avalanche mode.
- Additional clamping can be done by high power Zener diodes, like Transils®, if necessary.
- The good criteria for avalanche clamping is not energy (as specified by some components suppliers) but a maximum level of current.
  This is the physical limiting parameter. Under the maximum level of current, the avalanche current spreads in silicon and the energy dissipation is analog to additional switching losses.
  If the maximum avalanche current limit is not respected, the current focus and the component fails.

- For components in series, a very good synchronization of the commutations at nanosecond level is necessary.
- A solution for the synchronization of the stages of components in series is to use a one turn/one turn pulse transformer with a high voltage silicon cable for the primary, toroid ferrites for the magnetic part and a small wire for the secondary. Toroid ferrites are referenced in potential on the associated stage, for example by a not insulated secondary wire. Ferrite toroid are implemented on the printed circuit board of the switch.

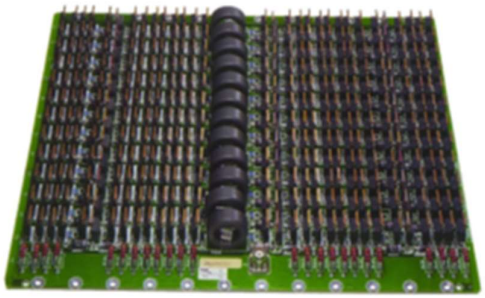


Fig. 2: 5 kV 1000 A switch with a Matrix of 350 MOSFETs

- The level of pulse current in the high voltage cable is some Amps, typically 3 to 5 Amps, and 200 ns duration. The high voltage cable can be a silicone one.
- For components in parallel in a stage, a very good synchronization of the commutations at nanosecond level is necessary.
- For very fast switch-on and limited drive current, a darlington structure can be used. In the figure 2, a high voltage silicon cable (not represented) is the primary of all the toroid ferrites in the center of the PCB. Three secondary (one turn ones) of the pulse transformer drive three driving MOSFET of a darlington structure. Each driving MOSFET is located in the middle of height MOSFET, to have four MOSFET at its right side and four at its left side. This structure and implementation provide very fast turn-on. Gate voltages are limited by zener diodes.
- For switch on switches for capacitor discharge a monopolar pulse is used for fast switch-on. There is no energy at switch-off.
- For switch on and off switches, bipolar pulses and an electronic for memorization drives each stages of transistors in series.
- For very high voltage switches, like 100 kV ones, cascaded toroid transformers are used with a high voltage cable (100 kV), a secondary lower voltage cable (20 kV) and ferrite toroid of the adapted diameter. The secondary cable goes throw the toroid ferrite on the printed circuit boards. Voltage reference is necessary for the secondary cable and all the ferrites parts for voltage repartition.
- In case of failure of one of the MOSFETs in parallel, the resistance of the failed MOSFET is around the same value as the R_{DSon}. If the drive can provide the turn-on and keep the on state for all the others MOSFETs of the defect stage, the global switch are still able to conduct the current but is unable to bear voltage. The switch is still operating with only the consequence of a lower maximum voltage. With a small safety margin the switch is failure tolerant with very high lifetime (100 000h for example in the pulsed laser application).
- For high voltage diodes, matrix of standard diodes are used in our application without any additional clamping if the following criteria is respected: diode avalanche maximum current should be more important than its nominal current. The experience proves the validity of this arbitrary design rule.
- Avalanche behavior of MOSFET and diodes depends of the design of components, so only qualification of the product is necessary but individual test of each component is not necessary.
- To provide a good current balancing between the components in parallel, low stray inductance and low cost, the switching components are soldered on a standard printed circuit board without any heatsink.
- Low cost current measurement is possible with resistors spread on the PCB in series with the MOSFET. The

figure 2 card has 24 resistors of one ohm. Each resistor is located in series with one of the 24 main MOSFET of the darlington structure.

- The 25 kV turn-on time in less than 20 ns, so the dV/dt is higher than 1 MV/µs. For EMC, the knowhow rules are the same as usual but several level of filter or protection and higher amplitudes of signal are necessary. For example, the current measurement has a maximum amplitude of 40 V and three common mode ferrite toroid and reference of the shielding are used between the resistors of the PCB and the command and drive PCB.
- For mock-up, the switch can be used in air with or without forced cooling, but for high repetition rate and long life, the high voltage switch has to be in mineral oil or a substitute of mineral oil. The main problem in air is the corrosion due to ozone generation. Forced oil cooling with heat exchanger is very efficient for transistor cooling and very high lifetime. Oil is absorbed by silicone cable so it's necessary to adapt toroid diameters to cable expansion.

3 Thyristor switch for crowbar application

For high voltage crowbar, protection of an application by short-circuit of the power supply, the use of small thyristors in parallel is interesting to provide high di/dt. Because of the plasma conduction spreading speed limitation around the gate, the di/dt of a thyristor has to be limited, for example to 100A/µs. With ten thyristors in parallel, the di/dt is 1kA/µs with the specified gate current.

To provide a good synchronization and higher di/dt than specified, a gate current of 2 Amps for some hundred on nanosecond is used. Using ten times the specified gate current is not a problem because of the very short duration of this initial pulse. This has no reliability impact.

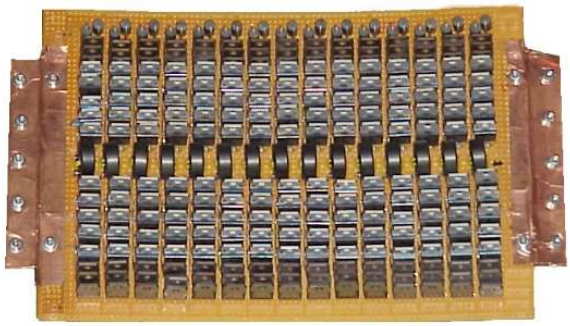


Fig. 3: First mock-up of 10 kV 10 kA switch with a Matrix of Thyristor

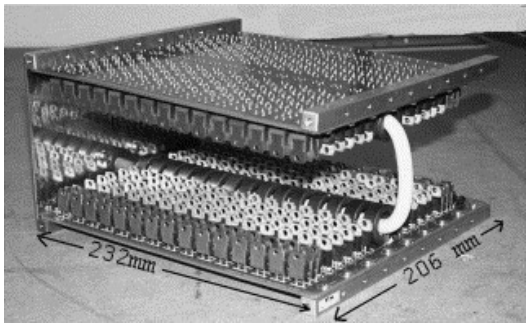


Fig. 4: 20 kV 10 kA switch with a Matrix of Thyristor and antiparallel diodes

On the figure 4, the toroid ferrites are in the middle of the card. The high voltage cable pass though the ferrites. Each stage has ten Thyristors in parallel and six diodes in antiparallel for the conducting the current oscillations. Two transil® diodes in series are used for voltage clamping when the switch is off, not to switch on the thyristors by overvoltage.

4 100 kV switch for series protection application

The first design of a MOSFET high voltage switch adapted to switch on and off and to be short circuit proof was designed for 60 kV and 500A for a +/- 30 kV half bridge [4].
The first high voltage MOSFET switches are for full capacitors discharge for pulsed laser application. In this application, a very fast switch-on is necessary, but there is no energy at switch off.
To provide a very fast switch-on and switch-off, a bipolar current in transmitted by the pulse transformer. The positive pulse is memorized in the gates capacitors of the MOSFET and switch-

on the switch. The negative pulse is used for switch-off. If the ON or OFF state has a long duration the charge in the MOSFET is refreshed by repetition of the positive pulse for ON state or negative pulse for OFF state.
To be short circuit proof, the gate voltage of the MOSFET is limited to ten volts. A MOSFET limits the short circuit current because of the current limitation of the gate channel. With ten volts gate voltage, the short circuit current is limited and can be clamped by the MOSFET by avalanche and some Transil® diodes in parallel.



Fig. 5: 10 kV 500A Turn on, turn off and short circuit proof switch, diodes side
On the figure 5, the horizontally PCBs are the MOSFET ones, the vertically one is the antiparallel high voltage diode.

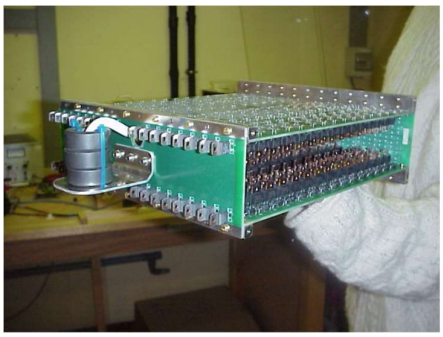


Fig. 6: 10 kV 500A Turn on, turn off and short circuit proof switch, high voltage transformer side
On the figure 6, the white silicone cable drives the two PCB. This cable and the ferrite toroid are voltage referenced in the middle of the two PCB. The high voltage cable (not represented) goes throw the toroid.
For Tore Supra, the existing Tokamak of Cadarache in France now named WEST (for Tungsten (W) Environment Steady-state Tokamak), a 100 kV 25 A version was developed.



Fig. 7: 100 kV 25 A Turn on, turn off and short circuit proof switch for Tore Supra.

5 Twenty years later

For Tore Supra, the existing Tokamak of Cadarache in France now named WEST (for Tungsten (W) Environment Steady-state Tokamak), two specific protection switches are developed [3]: a crowbar to short circuit a 40 kV bus continuous voltage and a high voltage very fast switch able to open the circuit to protect high power radiofrequency tubes (klystrons). The switch is designed for 100 kV.

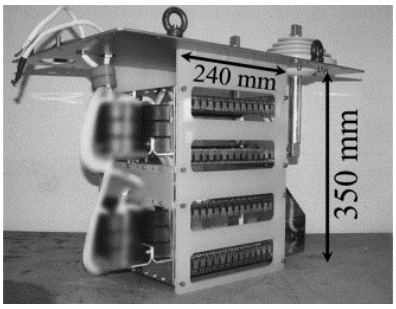


Fig. 7: 40 kV 10 kA Crowbar switch with thyristors Matrix
On the figure 7, we see the cascaded transformers with the high voltage silicon cable who goes throw the big toroid and the secondary silicon cable from these toroid to the other ones of the cards.



Fig. 8: Implementation of the protection opening switches (in the blue enclosures)

As indicated in the initial application of high frequency pulsed power supply for copper vapor laser, the developed MOSFET matrix switches proved to be failure tolerant and a 100 000 lifetime was calculated.
For other research application as Megajoule in Bordeaux or Tore Supra in Cadarache specific switches are designed. Twenty years later, some of these switches are still working.
The electronic design can provide failure tolerance, and the using of PCB in mineral oil provides a very efficient oxidation and corrosion protection for tens of years.

6 Conclusion

Twenty years ago, the development of this technology proves than for high voltage switches voltage balancing of transistors in series is not necessary, it is only mandatory to keep the transistors in their safety area by clamping.
The research work proves that some MOSFET of some suppliers have a good behavior in avalanche mode, and avalanche can be used in a design.
This research work proves that avalanche, energy is not a good criteria. The limiting physic parameter is the avalanche current. Components with the same references have the same level of maximum avalanche current for 200 ns and 2 µs avalanche duration. Energy is ten times higher.

Now, some transistor are specified in avalanche mode, not really the maximum avalanche current but energy at nominal current for example. This kind of specification illustrates a component with probably a good avalanche behavior.
Other components are specified in avalanche mode, but energy is specified for a lower current than nominal current. In this case, some avalanche tests seems necessary to know the real current limitation of the component in avalanche.
Now the maximum level of avalanche current is explained: the parasitic diode in a MOSFET is in fact a parasitic bipolar transistor with a short-circuit metallization between base and emitter. Maximum avalanche current is associated to the locally switch on of the parasitic transistor by second breaking, focus of the current and failure by burning of the zone.
Another publication at PCIM [5] presents a new development: 60 V 10 kA switch with MOSFET in parallel in avalanche mode, and describes the circuit and measurement for the test of MOSFET in avalanche mode. Avalanche test of maximum current are very easy to do.
Promising components for avalanche usage are SiC components, like SiC MOSFET.

7 References:

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