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Power switch : the standard small components strategy. From the state-of-the-art to future trends

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Abstract

In France, one joint program between Commissariat à l'Energie Atomique (C.E.A.) for the research part and COGEMA for the industrial application is the development of the Uranium Vapor Laser Isotopic Separation (SILVA).

The Power Electronic Laboratory from the C.E.A. in Pierrelatte is in charge of development on power supplies for Copper Vapor Lasers. For this specific application, the association of thousands of small standard components on printed circuit board is a cost-effective and reliable solution.

We will explain why this solution is a cost-effective and high-performance one for this application, as well as for industrial computer power supplies. Then we will set out some general rules.

Moreover, we will see that, in our particular case, the serial connection of a large number of components provides a very high reliability without over-cost.

Introduction

The Commissariat à l'Energie Atomique (C.E.A.) carries out French nuclear researches. One of its projects is the development of the Uranium Vapor Laser Isotopic Separation (SILVA). It's a joint program between C.E.A. for the research part and COGEMA for the industrial application.

The Power Electronic Laboratory from the C.E.A. in Pierrelatte is in charge of researches and developments on power supplies for SILVA and particularly on power supplies for Copper Vapor Lasers. This lasers are low energy high repetition rate pulsed powered.

This text is organized as presented below.

We will first introduce SILVA and its power supplies specifications. Among this, the issues of high voltage high current switches for 100 watts copper vapor lasers will be detailed.

Then we will draw a parallel with the case of specific power supplies for industrial computers in which small standard components on printed circuit board are used.

Our approach of high voltage switches will be explained and illustrated by the description of our high voltage high current power switches with MOSFETs matrix.

The cost-effectiveness of such a 25 kV 1600 A MOSFETs switch will be reported.

An important point will be to show how a very high reliability can be achieved without any additional cost.

Other switches, which have been designed with the same rules, will be described.

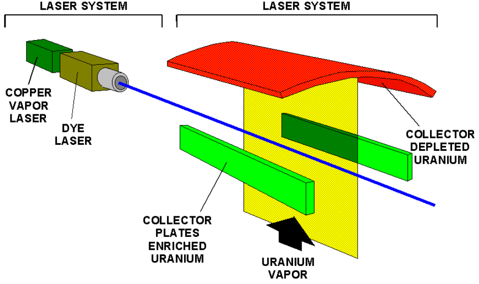
Finally, as it represents a key point of our studies, the remarkable performances of some small components will be considered.

1. SILVA power supplies specifications

The aim of SILVA is to replace the current Gaseous Diffusion uranium enrichment process, which is used in the EURODIF plant in PIERRELATTE.

In order to increase the U_{235} isotope rate to 3 or 4 per cent in uranium, the present Gaseous Diffusion process needs an electrical power of 3000 MW. This consumption could be largely reduced with SILVA process.

SILVA consists in a selective ionization of the 235 uranium isotope, using laser beams generated by dye lasers pumped by Copper Vapor Lasers (CVL).



A SILVA enrichment module includes a laser system, whose photons, after an appropriate optical conditioning, irradiate a metallic vapor obtained by intense focalized heating generated by an electron beam.

In order to reach optimal conditions, both luminous intensities of laser irradiation and vapor density of uranium atoms have to be adjusted. Several kilowatts of light per square centimeter are required, hence the need for pulsed lasers working at high repetition rate.

Copper Vapor Lasers (CVL) currently pump dye lasers working in the ranges which are needed for ionization scheme. Laser systems involving combinations of CVLs and dye lasers set in chains make possible the repetition rates which are needed in order to totally irradiate uranium atoms.

$^{235}U+$ photo-ions obtained by laser irradiation must be collected among a preponderant population of ^{238}U atoms. This is carried out by an electric field. Photo-ions are oriented towards polarized plates and then collected.

Power electronic is involved in SILVA for two kinds of power supplies :

- Copper Vapor Laser power supplies
- Electron beam power supplies for vapor generation

Copper Vapor Laser	**Electron Beam**
Pulses	Continuous
1600 A or 5000 A	6 A
25 kV or 60 kV	50 kV
200 ns pulse width	
5 kHz / 200 µs	
α = 0.1 %	
10 kW or 50 kW	300 kW
Jitter < 2 ns	
200 ns pulses width	Short-circuit

Common points of these power supplies are :

- **high power** (10 kW to 300 kW),
- **high voltage** (up to 60 kV),
- **very fast** (due to 200 ns pulses width or frequent short-circuit).

2. Issues of high voltage high current switches for 100 watts copper vapor laser

A 100 W Copper Vapor Laser needs a 10 kilowatts average power supply. The typical requirements for this power supply are 25 kV output peak voltage, 1600 A output peak current, 200 ns pulse width and 5 kHz repetition rate. The average power is 10 kW, but the peak power is more than 10 MW, while the duty cycle is 0.1%. **This value of duty cycle is very low.**

At first, the power supply was made with two thyratrons in parallel but the cost of this solution was too high considering individual cost and low lifetime of thyratrons (1000 h). The cost of two thyratrons is 10 000 EUROS and they have to be replaced after two months in case of 24 hours a day working.

Hundred watts copper vapor lasers are industrial lasers and the challenge was the replacement of the thyratron switch by a reliable and cost-effective semiconductor high voltage switch in the same place and with the same cooling system.

The laser is water-cooled and the thyratrons are in oil. There is a heat exchanger between oil and water.

A thyratron provides a very fast switch-ON in 20 ns. The dV/dt reaches 1 MV/µs.

The Copper Vapor Lasers are set in chain, so it's necessary to have a very good synchronization between the lasers. So the jitter between the laser pulse and the synchronization signal has to be better than two nanoseconds. This jitter is a very important specification in our application.

Because of jitter and cost aspect, it's not possible to use an IGBTs switch for long pulses generation and a magnetic modulator to accelerate the pulses because magnetic modulator need a very accurate pulse-to-pulse voltage regulation (<0.1%) to provide a very low jitter. In the industrial laser, the capacitor charging circuit provide a 1% regulation and it would have been necessary to change all the existing power supplies of the lasers to provide this 0.1% regulation.

The thyratron switch has a stray inductance about 200 nH. It's necessary to have the same value of stray inductance to provide a multi-resonant transfer between the main capacitor, this stray inductance, a peaking capacitor on the laser head and the laser inductance.

3. Specific power supplies for industrial computer

In power electronic, there are two different technologies to make a power electronic product.

For high power and high current power electronic, the industrial product is an association of mechanical parts and big modules on heat sinks or water plates, connected by bus bar.

For low current, the switching components are individual small components and the electrical connection is provided by a printed circuit board.

In specific power supplies for industrial computer, a domain we know, small standard solid-state components on printed circuit board are a cost effective and reliable solution.

Personal or industrial computers need low voltage low current power supplies. **Because of low current, less than 50 or 100 A, it’s possible to use PCB to conduct the current**. Because of low total power and high efficiency, the thermal losses per component are low. So it’s possible to have standard individual heat sink to cool the components. The other solution is to use an aluminum plate as a mechanical support and as heat sink for all the switching components. In fact, in this configuration, a better solution is to use some components in parallel to spread the thermal looses on the surface of the aluminum plate. For example, for a 5 V 50 A output, it’s possible to use three diodes in parallel instead of a big one. So the thermal losses are spread in three components with a distance between the three diodes. The three spread inductances have to be the same to provide a good current sharing. Another solution is to have three secondaries in parallel on the transformer and to provide the good sharing with the coupling between the primary and the secondary windings. A transformer is first a current transformer. The primary turns are in series and so have the same current. With a good coupling between the primary turns are the secondary ones, there is a mirror effect and the current in one turn of the primary creates the same current in the close secondary turn. So with such a design of transformer, with a good coupling between primary turns and secondary turns, it’s possible provide a very good sharing between three secondary windings.

In the case of specific power supplies for industrial applications, and because of the large number of different products, it’s very important to work with a small number of different components. It’s necessary to have a home standard with well-known good quality components provided by many suppliers. Having a few of different references is important for production, cost and product quality.

From my point of view, in the case of specific power supplies for industrial computers, the main rules in order to make a high performance low cost product are :

- all connections by printed circuit board,
- a very few number of mechanical parts,
- specific mechanical parts are very expensive,
- a home standard of well-known components,
- some small standard components in parallel instead of a specific one,
- in this case, because of **natural cooling in air**, a good solution is to spread the thermal losses. It’s necessary to have **a sufficient surface for cooling**. So it’s not a good solution to concentrate the thermal looses and then to spread them on all the surface of a heat sink. It‘s a better solution to spread the thermal losses on all the cooling surface,
- it’s necessary to know the real limits of the technology of each component and the safety margin of the supplier,
- know-how is very important in the design of a power electronic product. Moreover this know-how is the key for performance, quality and reliability of the product and for the EMC.

In power electronic, we have a choice between two different technologies to make a power electronic product. Two of the criteria are the level of current and the technology of cooling.

For high current and water cooling, the industrial product is often an association of modules on water plates connected by bus bar.

For low current, the electrical connection is provided by a printed circuit board and the switching components are individual small components.

Current is the criterion, not the power. In case of high voltage, a 300 kW product may be a 50 kV 6 A buck regulator and the good criterion is 6 A, so printed circuit board is well adapted [1].

The limit between low current and high current depends on the frequency.

For high frequencies, because of skin effect, large thin plates have to be used. The switching components are also small components to provide fast switching and low stray inductance.

In this case, for example for a 300 kHz 200 kW induction application, an industrial solution is the association of some 20 kW converters in parallel, each of them made with some ISOTOP MOSFETs connected by printed circuit boards.

Another example we know is a 10 kilowatts high voltage high frequency power supply. A serial parallel resonant circuit is used. For this level of power, the primary current is low and is well adapted for a printed circuit board. The switching components are made with MOSFET in parallel. The buffer capacitors are small chemical capacitors in parallel. A good sharing of the average current in the chemical capacitors in parallel is provided by the design.

In fact we see that the average current of ten chemical capacitors in parallel is much higher than for a big one. The parasitic inductance of these capacitors in parallel is much lower. The lifetime of the ten capacitors in parallel may be the same than a big one, or may be better. About chemical capacitor reliability, there is a very common error between the failure rate and the life time.

In electronic, for most components there is no life limitation because there is no wear or chemical degradation and the key parameter for reliability is the failure rate. This failure rate is said constant, so an old component is said as good as a new one. This model is very right for silicon components without thermal cycling.

In electronic, only some components, like optical components and chemical capacitors, have a life limitation. In the case of chemical capacitors, this life limitation is due to the electrolyte evaporation. So this lifetime is dependent on the temperature. The lifetime is twice longer at ten degrees less. For a 2000 hours 105°C capacitor, the life time is more than 2000 hours at 105°C, 4000h at 95°C,… and 128 000 hours at 45°C.

The lifetime is 128 000 hours for one capacitor as well as for ten capacitors in parallel for the same technology.

These capacitors have also a failure rate and the failure rate of ten capacitors is ten times the failure rate of one capacitor.

There is no relation between this failure rate and the supplier lifetime specification.

It's a very common error to do confusion between the two values.

In fact, chemical capacitors haven't a good reliability only in the case of high temperature.

For room temperature, one capacitor only or hundreds of them in the same product have a good reliability.

Another example we know is a low voltage (10V) 300 A power supply with 1000 A 1 ms pulses. For this converter, a cost-effective solution with high performances is cells in parallel. Each cell is constituted of one low ESR chemical capacitor, a MOSFETs switch, a freewheel diode and an inductor.

4. Our approach of high voltage switches

In close collaboration with universities and particularly with the Ecole Supérieure d'Ingénieurs de Marseille (E.S.I.M.) [2], solid-state power supplies have been developed by the Laboratory to replace thyratrons in high voltage pulsed power applications. The main principle is serial [3] [4] or matrix connection of solid-state switch components.

Theoretical and practical results have also led us to a conception of high voltage switching supplies using serial or matrix connected fast components such as MOSFET and Insulated Gate Bipolar Transistors (IGBTs), made of :

- galvanic insulation by transformers between control signals and power,
- synchronous drive circuits by serial connection of the primaries of the transformers,
- standard components without individual test,
- individual voltages enclosed in safety margins by active or intrinsic avalanche clamping [5],
- modular design of 3 or 5 kV cards linked in series and industrially produced,
- distributed cooling either by forced ventilation or by oil.

5. Description of the high voltage high current power switches

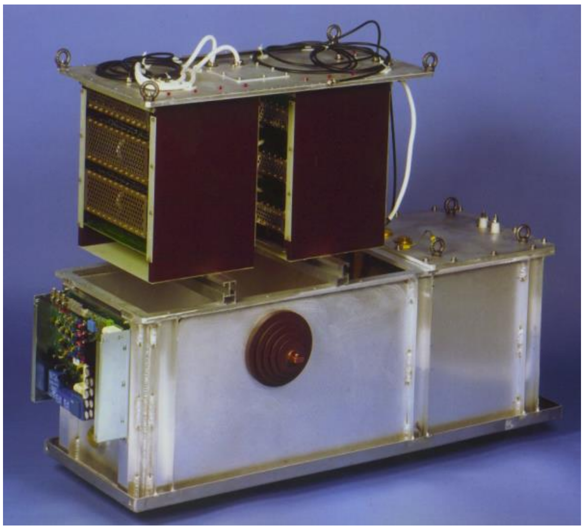
Development studies of the industrial products are made by CENTRALP under contract. This company has excellent experience in electrical power products. The main result of this collaboration is an industrial MOSFETs module switching 25 kV 1600 A.

MOSFETs switch is made up of about 350 IRF 840 MOSFETs. The matrix is designed about 27 in parallel and 13 in series. Suppliers of the MOSFETs are selected. There is no individual selection of components. Maximum current is more than 1000 A limited by MOSFETs.

Voltage specification for the board is 5 kV. Voltage drop is 20 ns typically. Jitter is less than one nanosecond.

350 MOSFETs board switching 5 kV 1000 A CENTRALP

For a copper vapor laser power supply, a 1600 A 25 kV switch is a design of two modules in parallel, each containing five boards in series.



25 kV 1600 A switch for laser CENTRALP

In the specific application of low energy high voltage fast switches with a high repetition rate, small standard components on printed circuit board are a good answer.

For a MOSFETs board switch the maximum current is 1000 A, but the duty cycle is about 0.1 %. So the average current is only 31 A. For such a level of current, printed circuit board is a good solution.

For a TO 220 package, the internal inductance is about 30 nH. There is 27 MOSFETs in parallel in each stage, so the total inductance of each stage (including connections to the others stages) is less than 1.5 nH. The total inductance of the 25 kV 1600 A laser switch is 200 nH. The main part of this inductance seems to be not the MOSFETs boards but the high voltage connection.

In a small component all internal inductances are low in comparison with the component capacitance. So the MOSFET switch-ON is very fast (<20 ns voltage fall time)

Printed circuit board is a high performance process with a very high level of quality and reliability. Each MOSFET has a resistor in its gate. This resistor is a SMC one and is mounted with an automatic process.

6. Cost and effectiveness of the MOSFETs 25 kV 1600 A switch

The cost of two thyratrons in parallel is 10 000 EUROS and they have to be replaced after three months in case of 24 hours a day working.

The cost of the 25 kV 1600 A switch for laser is about three pairs of thyratrons. So the replacement of a thyratron switch by a MOSFETs switch in a laser provided a return on investment in 9 months in case of 24 hours a day working.

For a new laser, the cost of a MOSFETs switch is about the same than a thyratron one with the same level of quality. The cost of the final laser is the same.

7. Reliability without any additional cost [6]

One of the main goal of the solid-state power supplies developed for SILVA is a very good reliability without any additional cost. The prototype of a pulsed power supply including 3500 MOSFETs has already been running 20 000 hours without any failure.

About twenty power supplies containing MOSFETs matrix have been produced and are used in copper vapor lasers. They have already run during a cumulative time of more than 70 000 hours without any failure. The MTBF (Mean Time Between Failure) is longer for this 3 500 MOSFETs product than calculated. The result of the calculation was 20 000 hours.

In fact, with this design, we have failure tolerance. We observe that the failure of one or some components is not a problem and that the global switch keeps the same behavior. For this design, with a small safety margin, the reliability of the module is very high because it is tolerant towards some components failures. One of the subjects of the laboratory is a basis study of reliability of components linked in series and in matrix [7].

In our case, we have failure tolerance, we have natural redundancy, **but without any additional cost, without over-cost**.

Usually, for a very high level of reliability, it's necessary to have redundancy and to pay the cost of this redundancy. It's so necessary to have some systems in parallel, more than necessary, to tolerate the failure of one of them. In the case of a powerful system with a lot of elements in parallel the cost of some elements in redundancy is not a problem. For a small system redundancy is very expensive because it's necessary to have two elements instead of one, or three instead of two.

In our case, the switch has only a small safety margin in voltage. There are 64 stages in series and only 8 of them are the voltage safety margin. This safety margin is only due to the design and is not an additional safety margin for redundancy. The failure tolerance of the switch is in the design of the switch and has no over-cost.

8. Other switches designed with the same rules

MOSFETs switches are industrial switches with a demonstrated high reliability. More than 200 boards have been produced. Other switches are in development [8] or are already used in some prototypes :

- IGBTs boards,
- DIODES matrix switches linked in series with the MOSFETs boards,
- THYRISTORS matrix switches including small standard thyristors, involving very low costs and high dI/dt,
- NANOSECOND solid-state switch.

Switches are serial/parallel associations of low-cost small standard semiconductor components on printed circuit board.

MOSFETs board switch specifications are :
5 kV, 1 kA for T<3µs duration.

IGBTS SWITCH

Using IGBT instead of MOSFET on the previous printed board provides a **3 kA** current commutation. IGBTs switch is not well adapted for very short pulses because of the silicon modulation delay [9]. This switch is better adapted for 1 µs to 10 µs pulses.

IGBTs board switch specifications are :
5 kV, 3 kA for 3<T<10 µs duration.

THYRISTORS SWITCH

MOSFETs and IGBTs have a silicon surface including thousands of cells in parallel. The conduction of the component starts on all the surface. There is no dI/dt limitation as in a thyristor. On a thyristor surface, the gate is located on a small part. At turn on, conduction plasma is created near the gate and diffuses slowly on all the surface. These is a critical current rate specified by supplier not to burn the component by localization of current on a small part of the component surface. The dI/dt depends of gate distribution on the surface. For high dI/dt the gate has to be interdigitated [10].

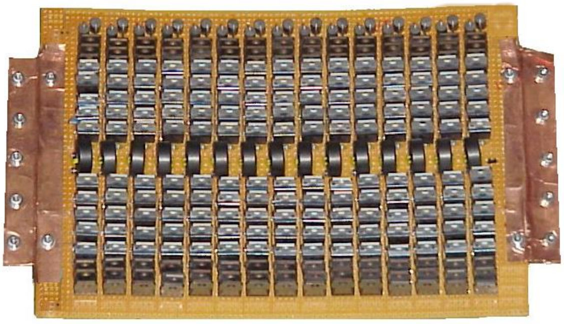
Thyristors switch is designed with small thyristors in parallel. The dI/dt specified for a small thyristor has the same level as a high current one. **Because of the parallel design, global dI/dt of thyristors in parallel is the sum of individual dI/dt.** Furthermore this specified dI/dt is given for a low gate current.

With an initial high level of gate current it is possible to reach higher dI/dt. A small thyristor, 12 A nominal current, is 100 A/µs specified. In fact, with a 2 A initial gate current, we measure a dI/dt of 1000 A/µs. With 30 thyristors in parallel the dI/dt calculated with supplier specifications is 3 kA/µs but the real limitation is higher than 30 kA/µs with high initial gate current.

With a switch of two boards in series with 150 thyristors each, we generate a **10 000 A** 20 000 volts pulse for a 100 µs duration.

With thyristors, the maximum current is dependent on pulse duration. For high power pulse, the temperature rise of the component is dependent on current and duration of the pulse. The temperature rise has to be limited to avoid cumulated thermal stress and failure.

Thyristors board switch specifications are :
10 kV, 10 kA for 100 µs duration and
dI/dt > 10 kA/µs.



DIODES SWITCH

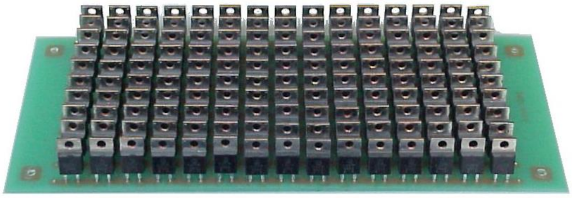
Only some diodes are avalanche specified. The laboratory made a high current low duration avalanche tester for power electronic components [11]. Some standard diodes have been selected. We selected the reference of one supplier and so the design of one type of diode.

There is no individual selection.

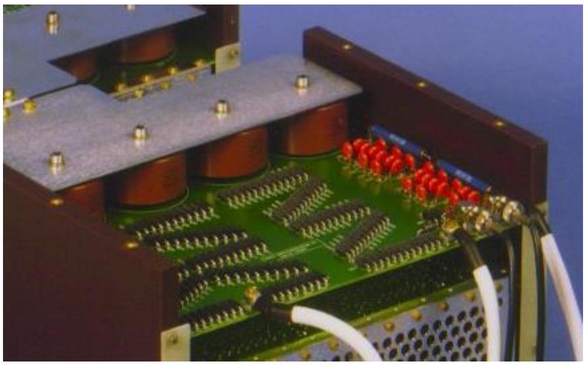
With these selected diodes we designed diode printed boards without any auxiliary clamping component or resistor to balance the different voltages.

Each high voltage diodes board is a 150 diodes matrix, 10 in parallel, 15 in series.

Diodes board switch specifications are : 15 kV, 1 kA, reverse recovery time t_{rr} = 50 ns.



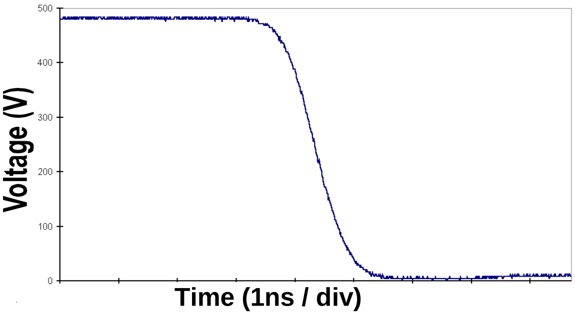
In the laser switch, a 3 A 60 kV diode is used between the transformer and the main capacitors. This diode is on the left part of the photograph.



On the right part of the photograph is the high voltage probe with two high voltage resistors and small standard capacitors in series. It’s a low cost solution for voltage measurement.

NANOSECONDE SWITCH

The nanosecond pulse is generated by a **standard MOSFET** turned on with a particular driver. The amplitude is very easily adjustable through the voltage on MOSFET. Voltage drop has 1 ns duration for a 500 V pulse in 50 ohms.



With this technology of driver it's possible to have MOSFETs in series, in parallel and in matrix. Now a 2 kV 1 ns fall time switch (in 50 ohms) is under development.

9. Some small components performances

Now standard MOSFET is a low cost component (about 1 EURO) with very high switching performances and a high level of reliability. We think that the real failure rate of some components is better than the standard value.

This level of reliability is very dependent on the supplier for the same reference. For example, we think the gate breakdown voltage dispersion is a good criterion. If the maximum gate voltage specification is 20 V, the breakdown voltage has to be upper than 60 V. For a supplier this voltage may be 64 V +/- 11 V, for the best one this breakdown voltage is **85 V +/- 1 V**. In fact for the best supplier the quality of the components is very high, there is no impurity defects. we think that the reliability of these two components with the same reference are very different. When a MOSFET produced by a supplier has a 50 ns fall time, another one with the same reference, but produced by another supplier, can have a 15 ns fall time. The evolution of MOSFETs is due to the micro-lithography process one

The safety area limits and avalanche

The limits of a silicon switch are :

- thermal limitation
- current limitation
- maximum voltage due to avalanche effect

The global thermal limitation depends of the case of the component and the cooling design.

Current limitation is due to the maximum channel current for MOSFET and IGBT, to limited base current for bipolar transistor, and is not limited for thyristor and GTO.

Maximum voltage is due to avalanche effect. If the voltage is too important, there is a creation of electron-hole pair in silicon because of electric field.

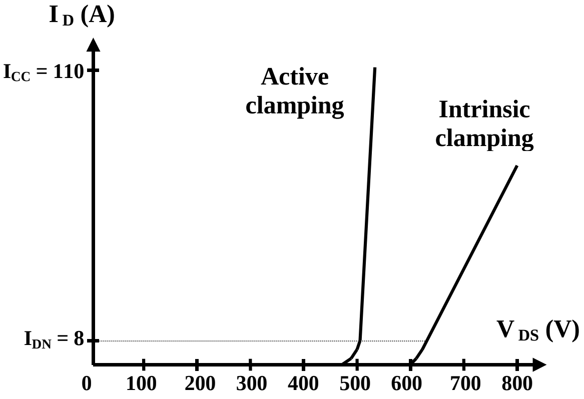
The security area is a supplier specification in which the component is said able to cut the current without destruction. This area is limited by the specified current, the maximum specified voltage and the thermal power limitation depending on the time.

Ten years ago, with bipolar transistors, the safety area was very small. With MOSFETs and IGBTs the specified safety area is a square with the maximum specified voltage on one axis and the maximum nominal current on the other. In fact, the real safety area is higher and the components are short-circuit tolerant (within some limitations). Now, for MOSFET the specified safety area goes over maximum specified voltage, and it’s possible to go to avalanche voltage with a current limited to nominal current.

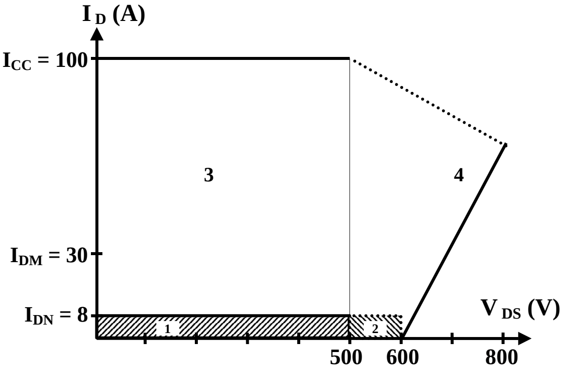
Nowadays, the real safety area of some new components is very large.Year after year, the real security area is more and more important for MOSFET and IGBT.

For a small MOSFET in a TO 220 package, the nominal current is 8 A, the maximum specified current is 32 A. The maximum specified voltage is 500 V. The current limitation in case of short-circuit is 100 A, and the component is able to cut this current with 500 volts between drain and source. The avalanche voltage is 600 volts and the component is specified to be able to cut his nominal current with avalanche clamping.

In fact, the components have very good performances far beyond the specifications. These curves concern a 8 A component in case of active clamping and in case of avalanche (intrinsic) clamping [11].



In fact the real safety area of a 8 A MOSFET is :



-Area 1 is the specified safety area.

-Area 2 is the avalanche specification.

-I_{DM} is the pulsed current.

-Area 3 is the safety area up to short-circuit limitation in the worst case.

-Area 4 is the part of the safety area up to the avalanche limitation.

In fact, there is a dangerous area for the very high level of current, more than 60 A, for voltage above the specified voltage.

This MOSFET has not only a square security area but also a very important accidental safety area. It’s possible to work without snubber if the maximum current is limited by the design of the product.

Our personal hope for the close future (and it seems to be possible) could be to dispose of a component with a square safety area limited on one side by the short-circuit current in the worst case, and on the other side only by the controlled avalanche voltage.

Conclusion

SILVA is a very specific application with very specific power supplies specifications. Our answer for this problem is the association of very standard components in a very standard process. In this context, the industrial product is a cost-effective solution, which provides a very high level of reliability. This reliability has no over-cost because it’s due to the series concept and the design and not to an additional redundancy.

Small standard components have often a very high level of quality and reliability because of mass production. Their real performances are far upper the specifications.

With the concept of small standard components on printed circuit board, the designer has a lot of free parameters to make the design. With his know-how, he has the possibility to do a lot of optimizations. He is less dependent than with a module in which the internal design of the components fixes the parameters.

Furthermore the concept of small standard components on printed circuit board has a lot of very different applications. For many of them, this freedom on the parameters is a real advantage to design the product.

Because of mass production, the standard components are very close to the physics limits. For MOSFET, the safety area is very large and there is only a small dangerous area. The component may be used with avalanche clamping.

For us, avalanche is very interesting. For diodes the avalanche tolerance allows serial connection without any additional component. It’s a great advantage in my application. Generally speaking, avalanche tolerance provides safety margin.

We think that a component without avalanche tolerance has a conception defect. For diodes the design itself provides the avalanche tolerance or not.

Our personal hope for the close future is to dispose of components with square safety areas limited only by the controlled avalanche voltage.

For some components it seems to be possible.

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