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IGBT : a solid state switch

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ABSTRACT

A Copper Vapor Laser Power Supply has been designed using a solid state switch consisting in eighteen Isolated Gate Bipolar Transistors (IGBT), -1200 volts, 400 Amps, each- in parallel. This paper presents the Isolated Gate Bipolar Transistor (IGBTs) replaced in the Power Electronic components evolution, and describes the IGBT conduction mechanism, presents the parallel association of IGBTs, and studies the application of these components to a Copper Vapor Laser Power Supply. The storage capacitor voltage is 820 Volts, the peak current of the solid state switch is 17,000 Amps. The switch is connected on the primary of a step-up transformer, followed by a magnetic modulator. The reset of the magnetic modulator is provided by part of the laser reflected energy with a patented circuit. The charging circuit is a resonant circuit with a charge controlled by an IGBT switch. When the switch is open, the inductance energy is free-wheeled by an additional winding and does not extend the charging phase of the storage capacitor. The design allows the storage capacitor voltage to be very well regulated. This circuit is also patented. The electric pulse in the laser has 30,000 Volt peak voltage, 2000 Amp peak current, and is 200 nanoseconds long, for a 200 Watt optical power Copper Vapor Laser.

1. INTRODUCTION

The reason for developing a solid state power supply instead of thyratron one originated in the reliability requirements of the Laser Isotope Separation Program at the Commissariat à l'Energie Atomique in France. The goal is 20,000 hours life time for the all power supply. The development study was realised by GEC-ALSTHOM under contract. This company has excellent experience in long life power electronic products, because of its railroad activity and through the development of the TGV. To ensure reliability, very good safety margins are taken for all the components and the design. The scale model was a 6 Kilowatt power supply for a 30 Watt Copper Vapor Laser. The prototype is a 40 Kilowatt power supply for a 200 Watt Copper Vapor Laser.

2. APPLICATION

For a 200 W Copper Vapor Laser the typical power supply requirements are:

- Supplied main voltage: 380 Volts +/-10% 50 Hz
- Output peak voltage: 33 KV
- Voltage rise time from 10% to 90%: ≤60ns
- Output peak current: 2000 A
- Current rise time from 10% to 90%: ≤60ns
- Pulse width: 200ns

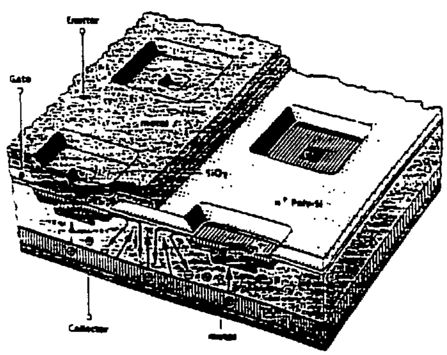
- Input averaged power processed: 40 KW
- Output averaged power: 20 KW
- Repetition rate: 5 KHz
- Jitter for 3σ: 4 ns
- Electric modelisation of the laser is a 4 ohms resistance and a 500 nano-henry inductance in series.

3. POWER SUPPLY PRINCIPLE

The principle on which this power supply worked is the following. A low voltage capacitor is discharged into a low leakage inductance step-up transformer by a Isolated Gate Bipolar Transistor (IGBT) solid state switch. The transformer output pulse is compressed by a ten ratio magnetic modulator. The storage capacitor is charged with an IGBT well-regulated resonant circuit. The input is a rectified and filtered three phase mains. The major part of the jitter comes from the magnetic modulator. Each stage delays the pulse of a time $t=S*\delta B/V$, where S is the magnetic material area, δB is the magnetic excursion, V is the inductance average voltage. To ensure the very low specified jitter, δB and V must be controlled. The resonant charging circuit must provide a 0.1 per cent pulse regulation. The magnetic excursion is $\delta B=Bs+Br$, where Bs is the saturation induction and Br is the remanent induction. A magnetic modulator reset is provided by a reflected energy recovery circuit.

4. IGBT DESCRIPTION

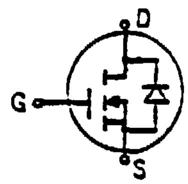
In Power Electronics, there are two main components where the surface consists in tens of thousand of cells per square centimeter. These two components are the Metal Oxyde Semiconductor Field Effect Transistor (MOSFET or MOS) and the Isolated Gate Bipolar Transistor (IGBT). The difference between the two components is the base substrate. A N^- substrate is used for MOS and a P^+ substrate for IGBT. It is the same surface with many cells in parallel.



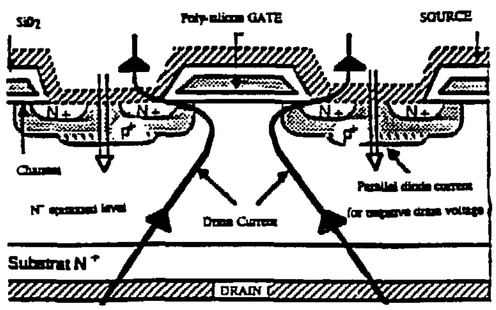
Semiconductor block diagram of an IGBT cell

The number of cells on a MOS surface is something like 40,000 cells per square centimeter for a high voltage component and 400,000 cells per square centimeter for a very low voltage one.
In Power Electronics, MOS, IGBTs are microlithographic products as Random Access Memory (RAM) is in Microelectronics. Designs are very similar.

First, we will study the MOS conduction mechanism.



The drain is the positive electrode
The gate is the control electrode..
The source is the common negative electrode.



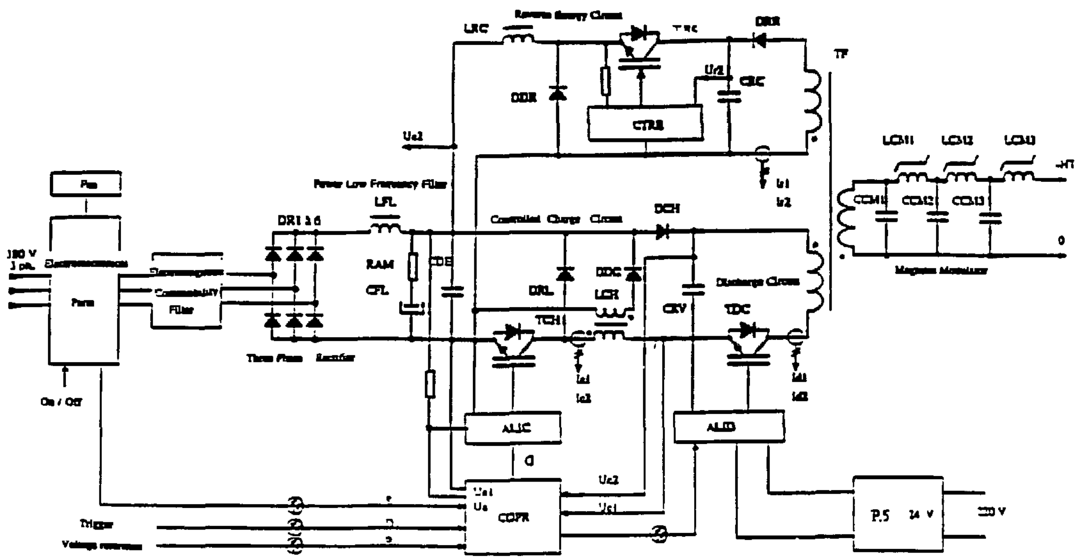
When a MOS switch is off, the voltage is sustained in the silicon by a depleted zone where the conduction electrons were extracted. There is a local space charge with an internal field.

To switch on the MOS a positive charge must be supplied to the gate. So a negative charge conduction channel appears in contact with the dielectric oxide in the silicium. The conduction channel provides conduction electrons, which fill the depleted zone.

When the MOS is on the current flows through both the N^- zone and the conduction channel. A high resistance value is maintained because of the silicium resistivity. It is the Rds_{on} parameter. A high voltage MOS needs a thick N^- layer to allow the depleted zone to grow. So, high voltage MOS have high resistance value. For low voltage MOS, the major part of the Rds_{on} is the channel one, so the cell size must be minimized. For high voltage MOS, the major part of the Rds_{on} is the N^- layer one, so the cell size is not very important. Rds_{on} is directely proportional to maximum voltage to the power of 2.5. These components have no interest for high voltage , high power applications.

IGBTs have the same surface as MOS but the substrate is a P^+ layer. When the IGBT switches on, the channel provides conduction electrons. The Collector (Drain for a MOS) current appears. This first phase is similar to the MOS one. But the P^+ substrate provides conducting electrons and holes. The resistivity of the N^- epitaxied layer decreases. This is the N^- epitaxied layer modulation. The speed of this phenomenon is fast. The corresponding time is negligible for a two microseconds long pulse. IGBT is a high voltage, high current component because of the modulation. The cellular surface provides a high speed complete conduction of all the chip. There is no plasma speed limit and dI/dt limitation as in thyristors.

5. POWER SUPPLY DESIGN



5.1. Electromechanical parts

The power supply input consists of a main contactor to connect the power supply. Auxiliary low voltages are generated. The fan is supplied. The main chemical capacitors current charge is limited by three resistors. These components are by-passed by an auxiliary time contactor for normal operation.

5.2. Electromagnetic Compatibility Filter

An electro-magnetic filter limits the mains reinjection of high frequency currents.

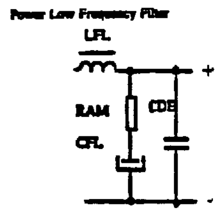
5.3. Three Phase Rectifier

The three phase rectifier consists in three diode pair modules with their snubbers.

5.4. Power Low Frequency Filter

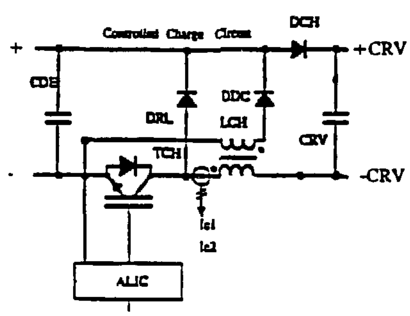
Low frequency harmonics are filtered by chemical capacitors. A high value inductor makes the pulses of the mains absorbed current longer. This magnetic power factor corrector limits the input root-mean-square (r.m.s.) current.

5.5. Main High Frequency Decoupling Capacitor



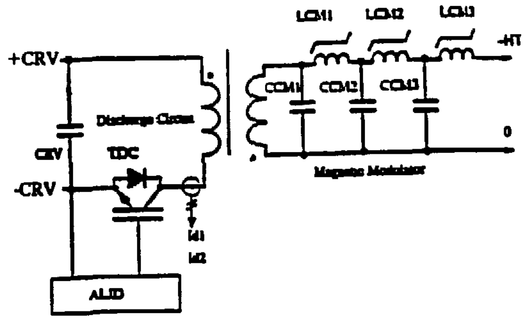
Electro-chemical capacitors are high value capacitors. This technology is well adapted for a low frequency power filter, but the specified maximum r.m.s. currents are very low because the Equivalent Series Resistor (ESR) value is high and so provides an internal thermal rise and the capacitor MTBF (Mean Time Between Failures) decreases rapidely with temperature. Main high frequency current is supplied by a polypropylene low value capacitor. This plastic technology is a high r.m.s. one. An additional resistor in series with the electro-chemical capacitor forces the r.m.s. current into the polypropylene capacitor.

5.6. Controlled Charge Circuit



The capacitor charge voltage is regulated to provide the jitter requirements. The charging circuit[5] consists of a resonant circuit. When the Isolated Gate Bipolar Transistor (IGBT) switches on, the capacitor voltage rises. When the reference voltage is reached, the IGBT switches off. The conduction of the leakage inductance current is provided by the free-wheel diode. To prevent the inductor storage energy from over-charging the capacitor, a coupling winding free-wheels this magnetic energy. The secondary diode switches on and the magnetic storage energy goes back to the main capacitor. The diode CRV prevents the storage capacitor from discharging when the IGBT is off.

5.7. Discharge Circuit



The discharge circuit consists of the storage capacitor, the discharge IGBTs, the transformer, and the secondary capacitor. When the IGBTs switch on, the capacitor storage energy is transmitted to the secondary capacitor. The resonant inductance is the transformer leakage inductance. If n is the step-up transformer ratio, and CVR the primary capacitor, the secondary capacitor is CRV/n^2 for providing the impedance adaptation. The IGBT switch is open when the resonant current reaches zero. The control circuit provides this function.

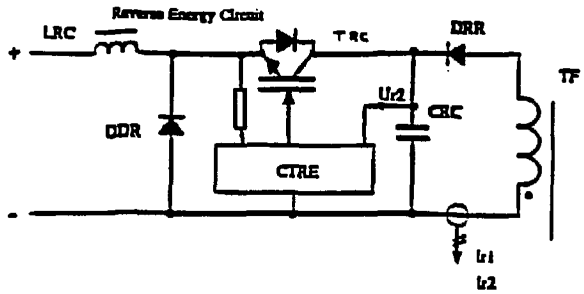
5.8. IGBT Switch

The main switch consists of 18 high voltage IGBTs in parallel. The specified maximum voltage is 1200 Volts. The continuous current is 400 Amps. The specified peak current for a one millisecond long pulse is 800 Amps. These components have been characterized in over-current use. For long life operation, a peak current of 1000 amps has been chosen. The current pulse length is 2 microsecond. The peak discharge current is 17,000 Amps. The storage capacitor voltage is 820 Volts. A stripline design permits the current to be well shared out in the eighteen IGBTs.

5.9. Magnetic Modulator

The first stage of the magnetic modulator[1] is an amorphous magnetic material design because of the length of the discharge pulse. The second and the third stages consist of ferrite designs. The three stages have no reset auxillary windings. The reset of the magnetic modulator is provided by a patented reflected energy circuit.

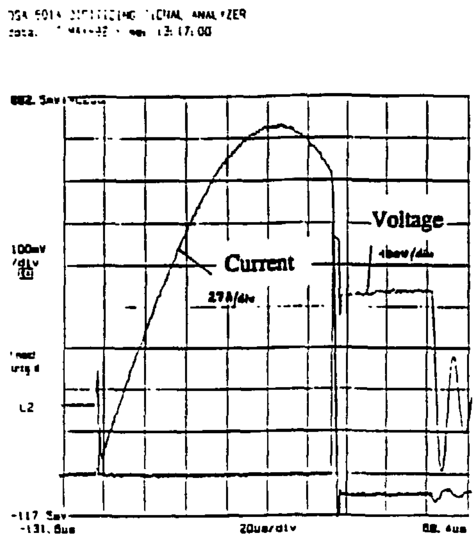
5.10. Reflected Energy Circuit[4]



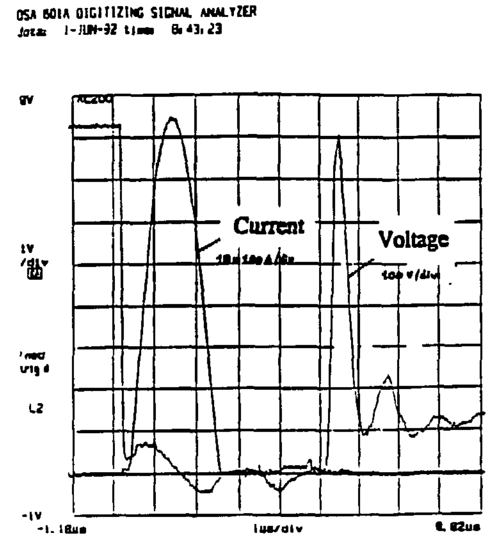
The Copper Vapor Laser (CVL) electrical equivalent circuit is a resistance in series with an inductance. So a part of the inductance magnetic energy goes back to the magnetic modulator. The current keeps the same direction, the voltage is reversed. The IGBTs are open so the reflected energy is forced into the third winding. The diode DRR conducts. A resonance appears between the capacitors CCM and CRC. The values of these components are adapted. The transit time is smaller than the first stage saturation to saturation magnetisation time. The resonance inductance is the transformer leakage inductance. When the CRC capacitor voltage rises, the IGBT TRC switches on. The CRC reflected energy is transfered to the main capacitor through LRC inductor. When CRC voltage decreases to a reference voltage, the IGBT TRC switches off, and CRC voltage is this reference voltage. The diode DAR prevents the recharge of CRC capacitor. The LRC current free-wheels by DDR. For the following pulse, CRC voltage is the reference voltage. So the resonance between CCM1 and CRC is not a total transfert. A controlled energy is stored in CRC, so the same energy is not transfered. This energy creates an inverse saturation and resets the magnetic modulator.

6. RESULTS

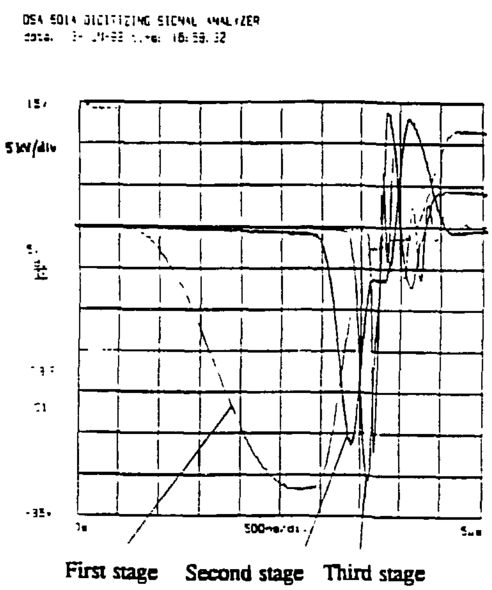
Peak voltage : 27 KV
Peak current : 3000 V
Stored energy : 8 Joules.
Injected energy : 3.75 Joules
Reflected energy : 1.1 Joules
Efficiency : 55 %
Injected power : 18.7 KW for a 5 KHz repetition rate
Voltage rise time : 60 ns
Current rise time : 58 ns
Short circuit current : 5000 A
Power supply output inductance : 330nH
R.M.S. jitter, σ : 0.47 ns
Jitter for 3σ : 1.4 ns
Peak to peak jitter : 3.1 ns
Input power factor : 0.9



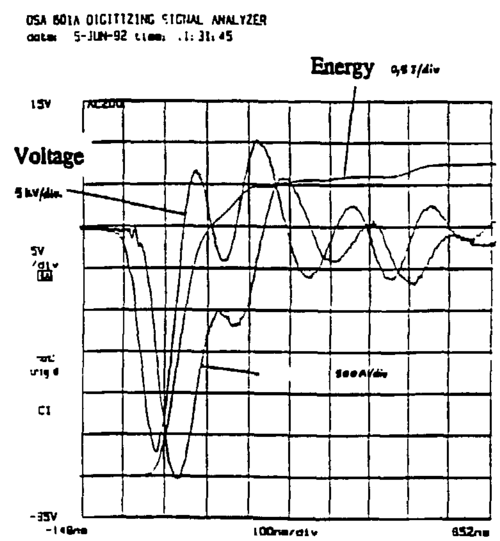
Charge circuit



Discharge circuit



Magnetic modulator capacitors voltages



Output

7. CONCLUSION

The Isolated Gate Bipolar Transistor consists of thousands of cells in parallel. This high level of interdigitation allows a high speed conduction mechanism. There is no current speed limit due to conduction plasma extension speed, like in thyristors. The power supply main switch consists of eighteen Isolated Gate Bipolar Transistors in parallel. The peak current of each component is only 1000 A for a 2 μs long pulse. The manufacturing specifications are 400 A continuous current , and 800 A pulse current for 1 millisecond long. A magnetic assistance in series with the Isolated Gate Bipolar Transistors minimizes losses in the components. The model was a 6 Kilowatt power supply for a 30 Watt Copper Vapor Laser. The prototype is a 40 Kilowatt power supply for a 200 Watt Copper Vapor Laser. The reset of the magnetic modulator is done by part of the reflected energy of the laser through a patented circuit. So, the magnetic modulator has no additional windings, and any Direct Current (DC) reset current generator.

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- M. Neu and M. Gidon from CEA, France
- The members of the Laser Development Section

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Assignee: Commissariat à l'Energie Atomique, France
Patent number : 5,079,689 Filed: Nov. 15, 1990

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Assignee: Commissariat à l'Energie Atomique, France US Patent: Filed