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# MAGY: AN INNOVATIVE HIGH VOLTAGE - LOW CURRENT POWER SUPPLY FOR GYROTRON

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From the electrical point of view, the body and the anode of high power gyrotrons behave as capacitive loads. A highly dynamic power supply is, therefore, hard to achieve. The MAGY concept (Modulator for the Anode of a triode type GYrotron) embodies an innovative solution to manage the capacitive current ensuring a very low ripple on the output voltage. It consists of a series of independent, bi-directional and regulated DC sources. Compared to existing topologies, this solution requires a smaller number of power modules. It avoids internal high frequency modulation and simultaneously offers high resolution of the output voltage and a wide range of operating scenarios.

Keywords: body power supply, anode power supply, gyrotron

## 1. Background

Gyrotrons are one of the additional heating systems planned for ITER with 26 units initially foreseen delivering a total of 20MW of RF power to the plasma. These high power gyrotrons can use two different types of electron gun: the diode type and the triode type.

Both types of gyrotrons operate with a depressed collector. An electrode, called the body, is placed between the microwave output and the collector to slow the electrons beam without intercepting it. In the triode arrangement, an anode is placed close to the cathode to regulate the beam current.

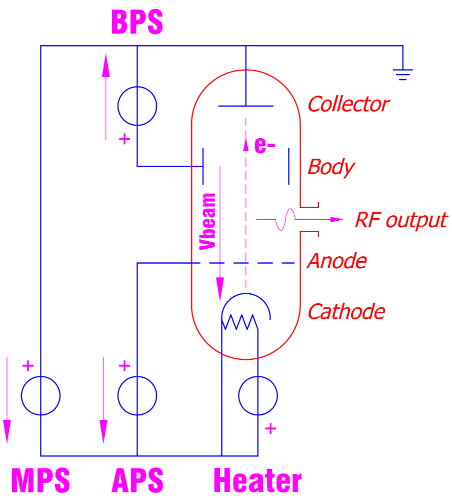


Fig.1 Power supplies for a gyrotron of the triode type

Figure 1 presents a configuration supplying the electrodes of a triode type gyrotron. In this topology, the anode power supply (APS) is referred to the cathode and the accelerating voltage (Vbeam) is the sum of the output voltages of the body power supply (BPS) and the main power supply (MPS). Thus, the BPS only provides part of the beam voltage, whereas the beam current is provided by the MPS alone.

## 2. Specifications of the power supply

From the connecting scheme of figure 1, it is possible to envisage a common design for both low current power supplies (APS and BPS) since only the nominal output voltage is different.

The MAGY modulator uses a modular concept where higher output voltage is achieved by adding power modules. Table 1 and table 2 summarize the power supply specifications, based on the ITER gyrotrons requirements, as a compromise between the specifications of a BPS and those of an APS.

Table 1: DC output voltage and current specifications

| Item | | Value |
|---|---|---|
| Output voltage range | | 0..40kV |
| Output DC current | | 0..50mA |
| Ramp up time | 10-90% | 100µs -1ms |
| DC Resolution | 0.5% | 200V |
| DC Accuracy | 0.5% | ±200V |
| Voltage ripple | 0.5% | ±200V |
| Overshoot | 1% | ±400V |
| Load Characteristic | R = | 0.8..50MOhm |
| | C = | 1..3nF |
| Isolation test voltage | 2xVmax | 80kV |
| Emergency switch off time | | <10µs |
| Energy delivered to the load in case of an arc. | | <10J |
| Arc voltage and equiv. charge | | 100V, 100mAs |
| Operation duration | h/d, d/w | 10/24, 5/7 |

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Table 2: Output voltage square modulation

| Item | | Value |
|---|---|---|
| Modulation voltage depth | | 0..40kV |
| Frequency | target | 0..5kHz |
| Rise Time | target | 30µs |
| Settling Time | target | 10µs |
| Overshoot | 1% | ±400V |
| Duration | | 1' each 2' |

## 3. Design of the power supply

The main concept is to construct a power supply with a series of independent, regulated, bi-directional DC sources avoiding any switching (like PWM) at the module output.

In order to minimize the number of modules, each should provide as high a DC voltage as possible. Several modules, providing smaller DC voltages, are then added to increase the resolution in the output voltage. This topology is known as asymmetric multilevel converter [1].

### 3.1 Quantification of the output voltage

The criteria defining the DC voltage of the smallest module follows from the output voltage requirements, in particular, the voltage accuracy required and the permissible voltage ripple.

In contrast, the voltage of the largest module is limited by existing power electronics components. Based on available semiconductors, it was decided to fix the maximum voltage of the DC link to 1600V, using IGBTs rated to 2500V.

The specifications in table 1 indicate that a negative output voltage is not required so a push-pull commutator of the DC voltage is sufficient i.e. a full H-bridge is not required.

This leads to the following design: the nominal DC link voltage of the smallest module is fixed at 100V. There will be three modules rated at 200, 400 and 800V, followed by 24 modules rated at 1600V. Thus, it is possible to cover the range from 0 to 39.9kV in steps of 100V.

The output stage of the modulator will comprise a total of 28 modules. It must be pointed out that this is a demonstration design. An industrial product would also include redundant modules.

### 3.2 Modulator principle

The power is drawn from the network through a conventional rectifier feeding the primary inverter, working at a switching frequency of 10 kHz that supplies all the power modules via individual transformers, as shown in figure 2.

On the transformer secondary, a controlled rectifier regulates autonomously the DC voltage that is switched by the output stage. These three functions, rectification, energy storage and output switching, are integrated onto the same electronic board.

At the output of the power supply, a simple filter, composed of an inductor and resistor in series, limits the peak current that appears when a voltage step is applied to the capacitive load.

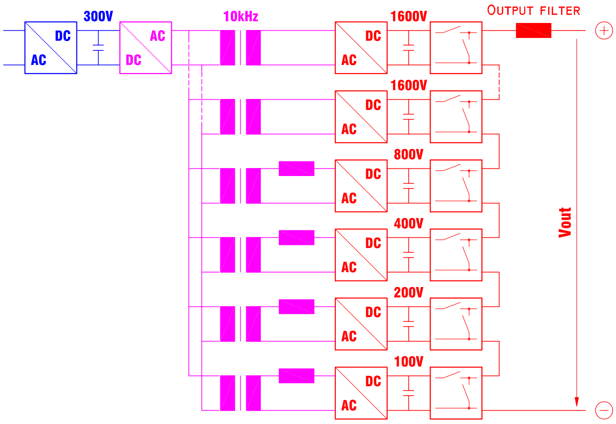


Fig.2 Schematic diagram of the MAGY modulator

The major innovation in this design consists using a medium frequency bi-directional controlled rectifier to feed the DC link.

This principle allows any modulation strategy on the output of the power supply since the bi-directional rectifier compensates for any variation in the DC link. Furthermore, the use of medium frequency transformers decreases significantly the size and the weight of the power supply.

### 3.3 Controlled rectifier

The rectifier, illustrated in figure 3, consists of an inverter leg connected to a capacitor bank with a connection at the midpoint.

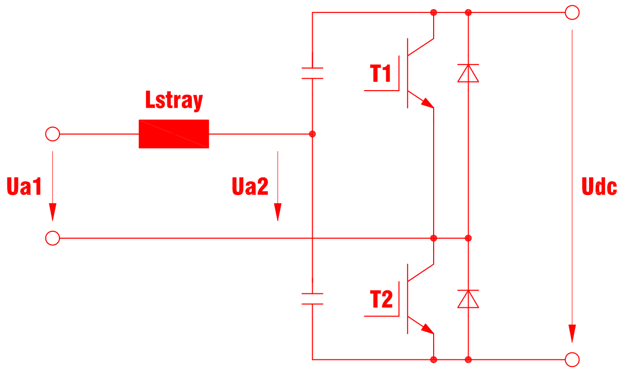


Fig.3 Schematic diagram of the rectifier

By acting on the phase shift between the primary voltage Ua1 of the transformer and the voltage Ua2 applied on the secondary winding it is theoretically possible to achieve any value of DC voltage. In practice, the maximum (similarly the minimum) DC voltage is reached when the current through the transformer reaches its nominal value.

The inductance $L_{STRAY}$ on figure 3 is the short-circuit inductance of the transformer. However, an additional inductance placed on the secondary may be mandatory for the modules that operate at reduced voltage, since an identical transformer is used for all voltage modules.

### 3.4 Power board

The power board, shown on figure 4 has the topology of a full bridge inverter. The first leg is used as the active rectifier and the second leg for the output stage. The capacitor bank, i.e. the DC link, is mounted locally. The auxiliaries are fed by an isolated current loop common to all the power modules.

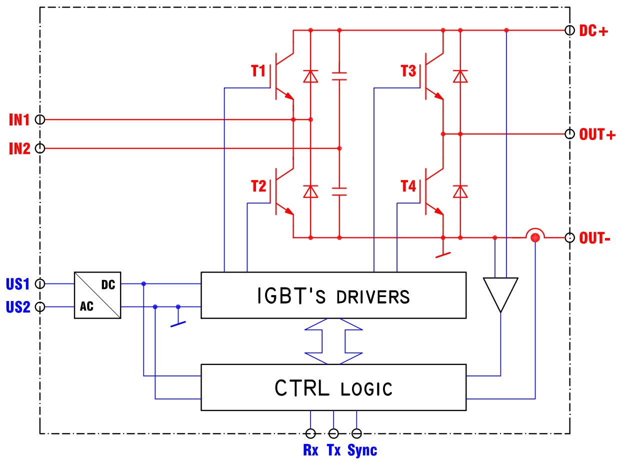


Fig.4 Bloc diagram of a power board

A special feature of this board is that it can also be used for the primary inverter. For the MAGY modulator, four boards used as the primary inverters are required to share the power consumption of the power supply.

### 3.5 Transformer

The transformer is the most critical component of the present design. It must withstand the voltage between the power supply outputs and the primary inverter that, for a BPS, is referred to ground.

For the APS, it must be possible to refer the negative pole to the cathode of the gyrotron. The primary inverter must be fed through an additional isolating transformer or every transformer of the power module must be able to withstand the cathode voltage (the preferred solution)

Particular attention must be paid to the parasitic capacitances of the transformer. The parasitic capacitance of the secondary winding could cause oscillations of the current flowing into the transformer, and the sum of the capacitances between the primary and secondary of all transformers is summed with that of the load and thus decreases the achievable slew rate on the power supply output voltage.

The nominal current of the transformer is an important parameter of the modulator design since a higher nominal current allows the operating voltage range of the power module to be extended, as has already been mentioned, and also allows the voltage of the DC link to be varied more quickly.

Although these issues are important, the short-circuit voltage ratio is the most important parameter in the transformer specifications. For a given operating point of the power module, the current waveform depends on the stray inductance and the short-circuit resistance. Thus, the short-circuit impedance determines the peak current that the IGBT must be able switch off.

### 3.6 Power dissipation

Compared to the low power delivered to the load resistance, the dissipation inside the modulator is relevant when considering the input power from the grid. Various phenomena contribute to the power losses in the modulator.

There are the losses resulting from the energy transferred to the load capacitance when a voltage step is applied. These losses are independent of the current waveform and may be minimized by switching off the modules in the same sequence as they were switched on.

Switching losses of the semiconductors are, for the selected components, mostly due to the IGBT's current tail when switching off. They depend on both the DC link voltage and the current to be switched off. The output filter is intended to optimize the output current waveform and thereby reduce the losses on the output stage. Losses of the rectifier are minimized when the stray inductance of the transformer increases.

Finally, one must not forget the losses in the transformers and those of the input inverter, particularly when the modulator is placed into a cabinet.

### 3.7 Control system

The control system is divided into two parts: the onboard control and the overall control system. Communication between the modules and the overall control system is based on a full duplex series protocol, using two optical fibers. The synchronization signal required for the rectifier control has no dedicated fiber. It is extracted from the time interval between two words of the data stream, whereas the state of the module output is controlled through a third fiber.

The onboard control system includes regulation of the DC link voltage, supervision of the IGBT's driver status, over-current and over-voltage protections and activation of the output stage. It also provides a simplified debugging mode: with two single boards working as primary inverter and rectifier, respectively, this test mode allows a verification of proper operation of a module outside the main control system.

The supervisory control system must regulate the output voltage of the power supply and to ensure the interface with the external world. No specific hardware development is foreseen for this item; Thomson Broadcast and Multimedia (TBM), the industrial partner, will provide a system that is already used in other products.

### 3.8 Operational scenarios

The MAGY modulator is suitable for a large number of operational scenarios due to the asymmetric topology and the continuous provision of the references for the DC links to the power modules.

For instance, for small voltage modulations, the lower voltage modules must be used. In contrast, when the modulator must modulate from 100% to 0%, it is better to divide the output voltage reference by an integer number of module.

When the user needs a slow variation of the modulator output voltage, it is possible to modify the voltage reference of the dc links in real time and, thereby, to act smoothly on the output voltage.

## 4. Performance

Based on the simulation results shown in figure 5, with 3nF connected at the modulator output, a 1600V module can be switched on or off every microsecond. Therefore, the target value of 30 µs, for the rise time from 0 to 40kV, should be attainable.

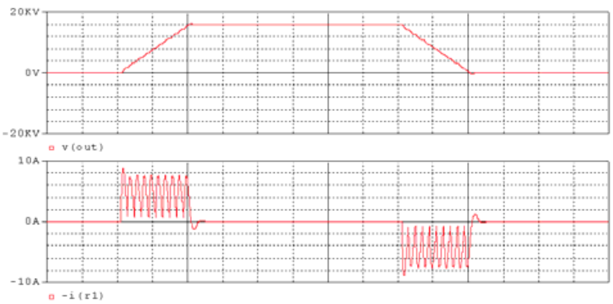


Fig.5 Simulation result with 10x1600V on a 3nF load: Output voltage and current through the filter, 5µs/div.

All preliminary tests and all simulations conclude that the ripple of the MAGY modulator during a flat top pulse will be very low, i.e. <100V.

## 5. Status of the project

To date, the first prototypes of the power module have been delivered and a new transformer prototype will be available soon. Drawings of the mechanical enclosure are available and demonstrate that the footprint of the MAGY modulator is smaller than alternative modulators. Figure 6 shows the installation of all the equipment in a cabinet that accommodates the isolation distances (dimensions LxHxW: 1.0x2.0x1.3m).

The resources allocated at the beginning of the project do not allow the construction of a complete modulator. However, the power module can be intensively tested using the debugging mode implemented in its control system. The transformer will also be submitted to an extensive testing program.

It has been agreed to build a complete power supply prototype, including its control system, in the framework of an ongoing collaboration project between TBM, CRPP and the Swiss Secretariat for Education and Research. The first results of future developments are planned before end 2011.

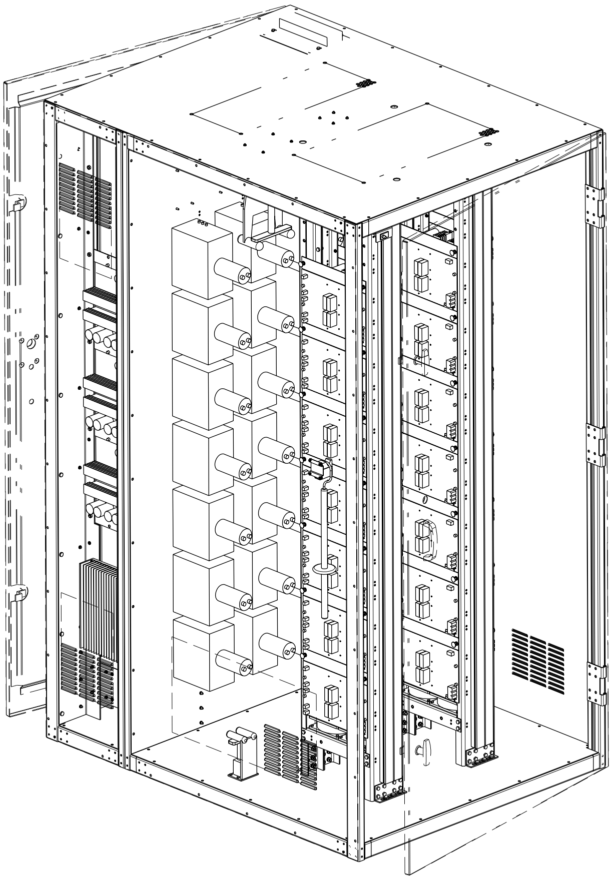

Fig.6 Mechanical integration of the power supply

## 6. Conclusions

The series of regulated DC sources ensures a high dynamic drive on capacitive load and the absence of switching (PWM) on the output of the power modules results in a very low output voltage ripple.

Compared with a modulator that reproduces the well known PSM structure developed by TBM [2], the number of modules in a MAGY modulator is lower, as is the required space for the installation.

Thanks to an asymmetric topology and an advanced control system, the MAGY modulator allows flexibility in the operation scenarios of state-of-the-art gyrotrons.

In summary, for demanding loads, high output quality and low ripple, the MAGY modulator offers an effective solution in a small volume.

## Acknowledgments

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