A NEW KLYSTRON MODULATOR FOR XFEL BASED ON PSM TECHNOLOGY

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Abstract

Thomson Broadcast & Multimedia has been awarded with a contract from DESY to design and build a prototype klystron modulator for the XFEL project in Germany. This modulator will be built in pulse step modulator (PSM) technology. Such technology achieves a maximum flatness of the pulse without tuning of any high power components. The modulator will also have a built-in power regulation in order to ensure a constant power consumption and to prevent voltage flicker of the mains. The paper gives an overview of the principles of the modulator and presents the status of the design. It also includes simulation results showing the expected performance.

STATE OF THE ART

Modulators for long pulse, as required for XFEL, have some highly challenging requirements, making an economical adaptation of pulse forming network systems such as used for short pulses impossible. Today several technologies allowing long pulse modulation are under evaluation for the European XFEL and for the International Linear Collider (ILC).

Thomson developed the Pulse Step Modulator (PSM) technology more than 20 years ago as a solid state replacement for audio modulators (tube type) in radio broadcast transmitters. Since the beginning, Thomson recognised the potential of this technology for pulsed systems with variable pulse length. In the meantime, several modulators for pulse durations between 10us and 15s in the power range from 6 MW to 32 MW have been built by Thomson and are in operation. Typically PSM modulators are designed for a direct conversion of the required voltage, which may be as high as 160 kV. The required pulse current is typically less than 250 A.

REQUIREMENTS FOR XFEL

The modulator for XFEL is used to supply and modulate Multi Beam Klystrons. Due to the fact that the equipment in the accelerator tunnel is kept to a minimum, the klystrons will be placed in the accelerator tunnel, whereas all the modulators will be placed together in a common modulator hall at the accelerator start location. Thus the connection between the modulator and the klystron can be as long as 1700m. One of the challenges is to achieve a low pulse overshoot and to keep the short circuit energy below the limit in spite of such long cabling. Thus the design foresees a pulse transformer in front of the klystron with a transfer ratio of 1:12. This results in the modulator specifications as shown in Table 1.

Table 1: Modulator Specification

Pulse Voltage	2 -12 kV
Pulse Current	< 2000 A
Pulse Repetition Rate	1 – 30 Hz
Pulse Length	1.7 ms
Pulse Flat Top	1.5 ms
Pulse Flatness during top	< ±0.3%
Energy deposit in Klystron arc	< 20 J
Average Power	< 380 kW
Max. power variation on grid	10 kVA

Figure 1 shows a general simplified overview on the complete system.

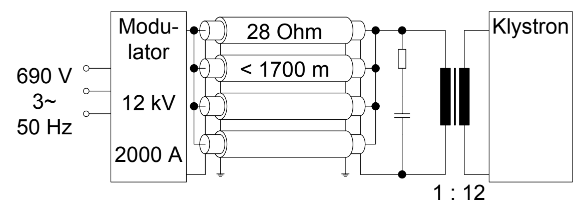

Figure 1: System Overview.

The pulse requirements as well as the low short circuit energies are easily fulfilled with a standard PSM system. To meet the special DESY requirements, the system needs further adaptations, as:

- Capability of inverse voltage for the pulse source (in order to allow the transformer to de-magnetise, the pulse source must allow for an adequate build-up of an inverse voltage. A PSM has an internal free-wheeling diode structure which prevents such an adequate build-up.
- Fulfilment of the short circuit requirement coupled with the long cable run.
- Energy storage capability (charged with constant power) to overcome the power variation requirements.

SYSTEM DESCRIPTION

The modulator will be built with 24 switching modules in series. Each switching module is designed to provide a minimum voltage of 545 V on the output. Thus the full output voltage can be generated with 22 modules in operation, resulting in a redundancy of 2 modules.

The Switching Module

The module diagram is shown on Figure 2. The input circuit is based on the standard PSM modulator. After the DC rectifier, a boost converter is installed as a constant power converter. This converter boosts the rectifier

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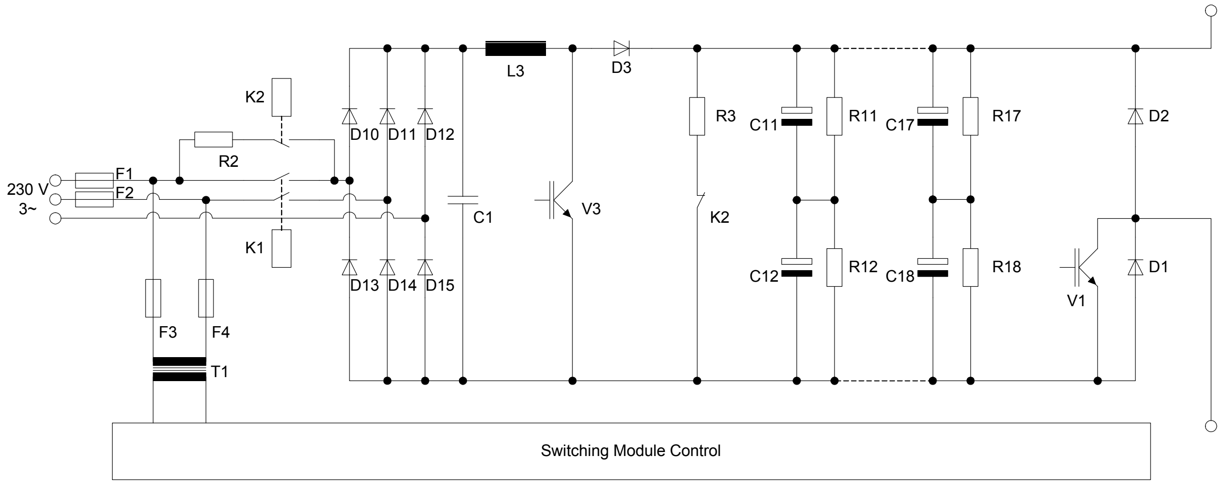

Figure 2: Switching Module Diagram.

voltage to charge up the storage capacitor C11 to C18. The regulation loop of this converter is made to regulate constant power. The storage capacitor consists of a bank of electrolytic capacitors with a total capacitance of 20 mF. The capacitor is charged up to 700 V peak voltage prior to the pulses and is discharged during the pulse to minimal 550 V. The output switching element consists of an IGBT rated 1200 V / 2400 A. The IGBT is planned to be switched with 20 kHz switching frequency in order to have a high frequency spectrum to simplify filtering. Special care was taken on the evaluation of the IGBT type.

Inverse Modules

It is foreseen to include an active de-magnetisation mode in the system. This is made in a two-quadrant configuration, which allows to set inverse voltage with forward current. A total of 4 two-quadrant modules is sufficient to allow full de-magnetisation for a duty cycle up to 14%, which exceeds the requirements by far. In order to achieve maximum modularity the two-quadrant modules are not built as special modules but as a combination of standard modules with an additional phase leg for the inverse operation. The so-called inverse module consists of an IGBT-diode combination and is switched off between the pulses in order to actively discharge the magnetic stored energy from the transformer back into the storage capacitors.

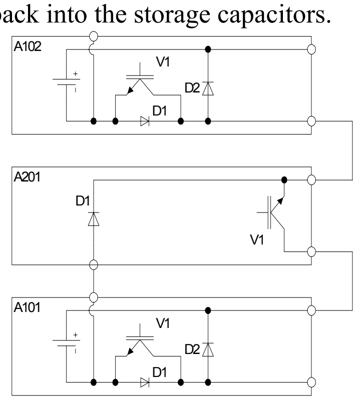

Figure 3: Inverse Modules in Series Connection.

In addition to maximum modularity, this concept also gives maximum redundancy as the loss of any module, even inverse modules, still allows the system to continue operation. The system must be stopped only if a standard module and its partner inverse module both fail due to the inverse voltage and power flow.

Transformer

A single multi-secondary transformer is used to supply all modules. The transformer will be built in dry-type technology with resin casted secondary windings. The choice of 690 V mains voltage allows to build the transformer in such a way that it can be used on common 400 V mains for factory testing by simply wiring the primary in a different vector group.

Filter Network

The operation of the system with a PWM modulation requires a low pass filter output network. The purpose of this network is to filter out the switching frequency and its harmonics. As a PSM system has a phase shifted control between the individual modules, the switching noise is quite low compared to other types of switched mode power supplies. Thus the filter can be kept small and quite simple.

One possible solution for the final filter network is shown in Figure 4.

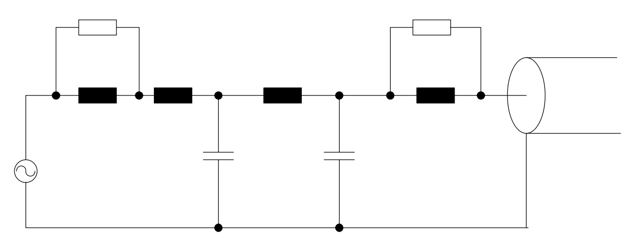

Figure 4: Filter Network.

The resistors in the filter help to damp cable oscillations under load short circuit conditions. A remaining task is to optimize the filter in order to achieve the maximum performance. The fine tuning will be made during the first system tests.

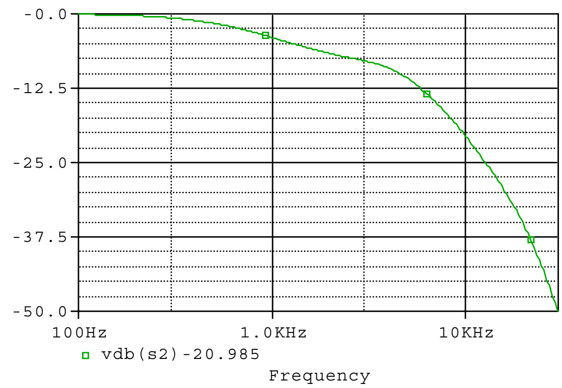

Figure 5: Filter Frequency Response.

EXPECTED PERFORMANCE

Pulse Shape

A digital filter built in the control system compensates the roll-off effect of the filter network and results in optimized pulse performance. It delivers a fast rise time and low overshoots. Typical pulse shapes achieved with such a digital filter are shown in Figure 6.

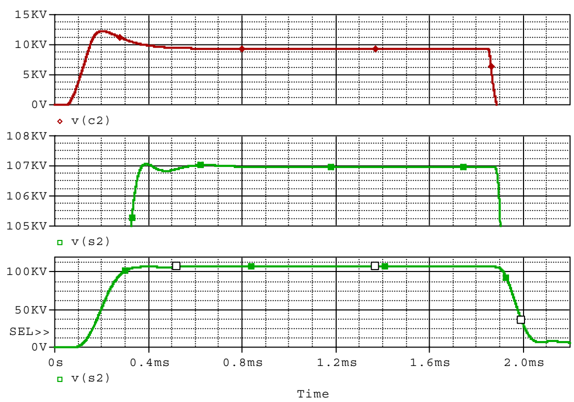

Figure 6: Pulse performance. Top: Source Voltage (after digital filter) Middle and Bottom: Klystron Voltage

Short Circuit Energy

The inverse modules are also useful to limit the energy deposited into a klystron arc. In case of a short circuit all IGBT including the inverse modules are switched off. The inverted voltage then helps to discharge the energy out of the filter inductors. This mechanism was already implemented for klystron modulators and is patented by Thomson [1]. Simulation shows maximum short circuit energy of 18 Joule.

RECENT STATUS

Thomson will assemble prototype switching modules before autumn 2007 and test them individually. The complete system will be assembled and ready for testing by spring 2008. The first system will undergo a full factory testing prior to delivery to the DESY site at Zeuthen in Germany. At DESY the system will be tested in a full system configuration including cable, pulse transformer and klystron.

REFERENCES

[1] European Patent EP1553686, High voltage DC power supply and method of operating such high voltage DC power supply