PULSE CABLES FOR XFEL MODULATORS

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Abstract

For the XFEL, housed in a single tunnel, most of the modulators will be placed in a central modulator building outside of the tunnel. The pulse transformers and the klystrons will be positioned inside the tunnel near by the superconducting linac. Therefore the energy has to be transported via pulse cables. These cables have lengths between 350m and 1.7 km. The power is up to 16.8 MW per pulse with a repetition rate of 10 Hz. In order to keep the rise time short and match the klystron impedance four 25Ohm cables will be put in parallel. A tri-axial design was chosen to prevent magnetic field outside of the cables in order not to disturb electronics or electron beam. A prototype of the cable was produced in industry and delivered to DESY. A set of four 1.5km long parallel cables is in test at present at one of the modulators of the TTF/VUV-FEL at DESY. The cable design criteria and test results are presented in this paper.

INTRODUCTION

The required RF for the superconducting cavities of the future XFEL (X-Ray Free Electron Laser) is generated in klystrons which are located inside the tunnel. The modulators that are supplying the klystrons with the pulsed power shall be placed outside of the tunnel in a central modulator building for reasons of maintenance and protection against the radiation. This constellation demands for cables that are transporting the pulsed energy into the tunnel. R&D work has been done to define what type of cable could be used and how to operate them. A prototype cable was manufactured and commissioned with a modulator in FLASH, the former TESLA Test Facility, where it is in operation for two years now.

MODULATORS

General Layout

The modulators are of the bouncer type. The principle was explained in detail in [4,5,6], here just a short overview will be given. In order not to take the pulsed energy directly from the mains, it is stored in a capacitor bank at the 10 kV level. Via a semiconductor switch this capacitor is connected to a transformer where the voltage is increased to the level of 120 kV for the klystron. During the pulse the capacitor bank has a voltage droop of 19 %. To compensate this, a so called bouncer circuit being a LC-resonant circuit is installed. The output voltage is the superposition of the two voltages

For the XFEL the pulse cable will be connected between modulator and transformer. The position of the klystron inside the tunnel determines the cable length to be between 350 m and 1500 m. The schematic can be seen in Fig. 2.

PULSE CABLE

Specification

The use of long cables for a pulsed high power application demands for a good performance of the cables. These demands are:

- No significant delay of the pulse
- Low distortion of the voltage wave form
- Low electromagnetic noise production
- Low losses
- Good fire resistance due to tunnel installation
- Radiation hardness
- High reliability
- Use of industry standards

Construction of the Cable

In order to compensate the magnetic field of the cables a tri-axial design was chosen. Here the high current leading conductors are the inner and the middle leads of the cable building a koaxial system. An additional solid shield is added. Fig. 1 shows a sample of the cable.

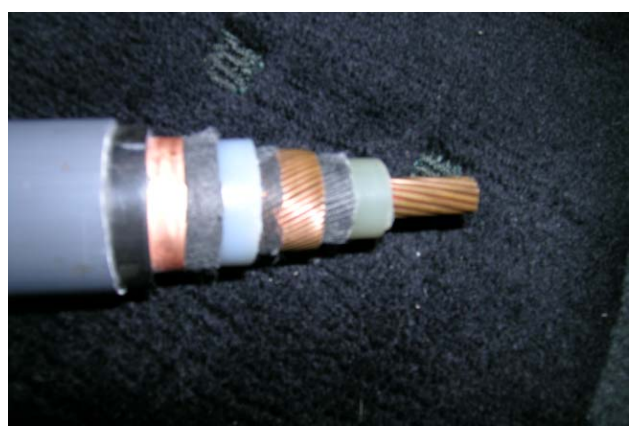

Figure 1: Pulse cable.

Simulations

The electrical behaviour of the combination of modulator, pulse cable, adaptation network and klystron was simulated with the Ansoft simulation software Simplorer.

The model of the klystron with the nonlinear relation of voltage/current was developed. The pulse cable was modelled by the internal device of a transmission line

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with losses. However for the simulation of the tri-axial design three of theses models had to be combined according to the position inside the cable (Fig. 2):

1. transmission line formed by the inner to middle lead
2. transmission line formed by the middle lead and the shield
3. transmission line formed by the shield and the cable tray

Adaptation Network

In pulsed applications cable can cause problems due to reflections from the mismatch of impedances at the beginning and the end of the cables. The klystron with the nonlinear impedance as function of the voltage is an additional difficulty. The solution with the pulse cable is only possible due to the use of the pulse transformer. With the stray inductance of the transformer at the end the cable acts electrically like an open ended cable. This can be adapted with a resistance of the same value as the cable impedance Z_0. Since this resistor shall not build a second load in parallel to the klystron impedance a DC block in form of a capacitor has to be introduced. The variation of the capacitance changes the voltage step response.

Paralleling of Cables

Simulations showed that the cable impedance Z_0 had to be small in order to keep the rise time of the pulse high. Additionally the inner cable impedance shall match to the impedance of the klystron transformed to the 10 kV level. Therefore the cable impedance was chosen to be 6.5 Ω. The cable impedance depends on geometry and on the permeability ε_r of the insulation between the conductors. As insulation material cross-linked-Polyethylene (XLPE) with an ε_r of 2.5 was chosen since this has a high radiation withstand capacity. Therefore the Z_0 depends only from geometry. To decrease Z_0 either the diameter of the inner conductor has to be increased or cables have to be put in parallel.

The solution of paralleling the cables was chosen. Due to the long pulses and the comparatively long rise times of the pulse it is possible to use standard industrial production methods of medium voltage cables like the use of stranded bare copper conductors and semiconductor layers for the field smoothing. A Standard extrusion process for adding the semiconductor layers and insulation material are possible, insures a high reliability.

Four cables are put in parallel to form one system cable. The cross section of current lead is 75 mm² for the inner lead and the outer lead. This results to 300 mm² per lead for four cables.

Fittings and Intersection

For the fittings a construction with resistive field guidance was developed by the manufacturer. The advantages are the small volume of the unit and the low cost of a fitting. Although it is not foreseen to have intersections inside the tunnel these are developed for the case a cable has to be repaired.

Fire Resistivity

Since nearly 150 km cable will be installed inside the tunnel special care for the fire resistivity was taken. The cable was constructed according to the IEC 60332 category A. To achieve this an outer jacket of FRNC material (flame retardant non corosive) of 4.5 mm thickness was put around the cable. Additionally the solid shield protects the burnable XLPE from the flame.

COMMISSIONING

Low Voltage Turn On

When commissioning the cables with the modulator a low voltage was chosen. In this mode the current waveform has a church-like shape with a larger inrush current corresponding to the loading of the cable and the adaptation network. The amplitude corresponds to $I= U_{klystron}/Z_0$. When the cable is in steady state the modulator current corresponds to app. $I=U_{klystron}/Z_{klystron}$ at that working point. This proves that the resistance of the klystron at that working point does not affect reflections on the cable.

Short Circuit Test

Klystrons do arc during operation. In order not to damage them the allowed deposited energy is 20 J. During the pulse energy is stored in the cables and in the adaptation network. Inside the modulator a RC-network is installed in which the energy of the transformer and the cable is dissipated in case of an arc. This behaviour was tested with a test load which was shorted by an ignitron to simulate the arcing of the klystron. It was proven that the klystron is not endangered by the use of the cable.

High Voltage Pulse

The high voltage pulse was reached after a short commissioning. The voltage waveform is according to the specifications and there are no restrictions for the operation of the klystron.

PROBLEMS

Currents in the Shield

The di/dt of the main pulse generates a voltage spike between the middle lead and the shield. This is due to the parasitic inductance (L3 in Fig. 2) in the bouncer path. A pulsed current with an amplitude of 120 A is flowing. An adaptation network (R5, C5 in Fig. 2) has to be introduced into this path as well. This current spike can only be suppressed by changing the mechanics and thereby decreasing the parasitic inductance. Additionally with the existing bouncer a voltage is applied between the middle lead and the shield (GND level) in form of one sine wave with a frequency of 200 Hz. Since there is the adaptation network consisting of a RC-network, a current is able to flow. These currents are compensating themselves and can not be measured at the outside of the cable.

Common mode ringing of the modulator

By measuring the current with a current probe around the set of four cables a significant disturbance occurs only at the switching times. The frequency is app. 1 MHz. This disturbance is also measurable as magnetic field.

The noise is assumed to be generated by parasitic elements inside the modulator. It is possible to damp the magnetic field by an aluminium shield of 1 mm thickness around cable and cable tray. Here further investigations have to take place to detect and eliminate the source.

Common grounding

One problem in our test assembly is the short ground connection between the modulator and the transformer. The cable has been connected in between this combination. Therefore parasitic currents can easily bypass the cable and flow directly between the components without being forced into the cable.

FUTURE IMPROVEMENTS IN DESIGN

Changes in Cable Construction

The cables for the XFEL will be of the same construction. However the shield will have a larger cross section. According to [6] the cut off frequency of the cable will be lowered. This means that the cable will force currents with frequencies higher than the cut off frequency back into the cable instead of letting it flow through ground construction.

Changes in the Modulator Design

The design of the modulator will to be changed:

1. The bouncer circuit has to be installed into the positive output of the modulator. The middle lead will be at ground potential. By this 200 Hz-current in the middle lead and the shield disappears.
2. The already existing choke will be positioned at the output of the modulator in order to suppress high frequency ringing.
3. The mechanical design has to be improved to minimize parasitic capacitances and inductances.

SUMMARY

Cables for the pulsed application of XFEL have been developed, manufactured and commissioned in FLASH, former TTF. Pulse cables with a length of 1.5 km are working for a period of nearly two years now. It is possible to transmit the high pulsed power. There are EMI problems which are traced down to the mechanical construction of the test assembly. However further investigations have to take place for optimization.

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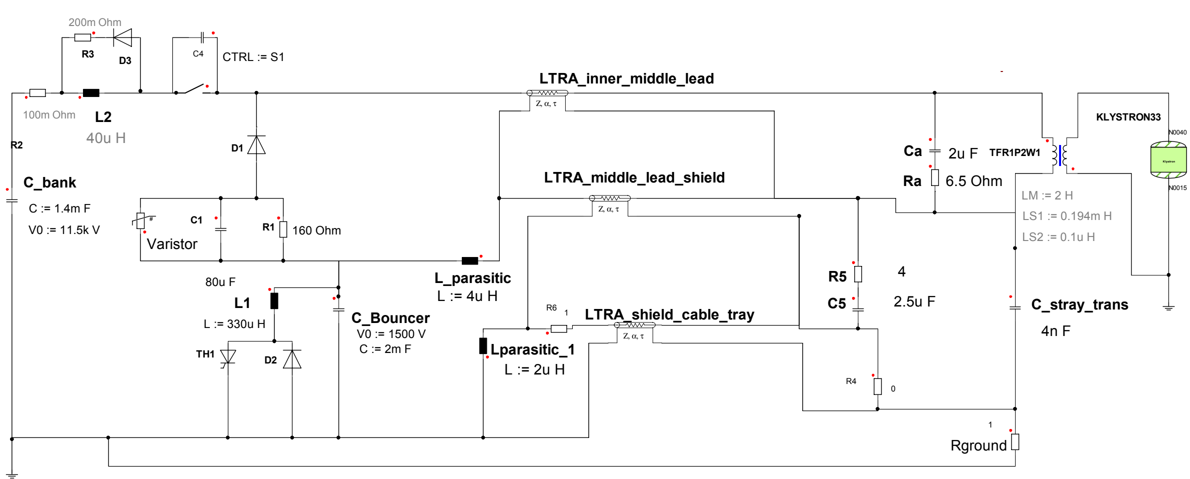

Figure 2: Simulation model of the modulator, pulse cable, adaptation network and klystron.