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XFEL MODULATORS WITH PULSE CABLES

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Abstract

The modulators of the European XFEL produce high voltage, at the 10kV level, having a power of up to 16.8 MW for 1.54 ms. The operation frequency of the superconducting linac is 10 Hz. The series production of the 29 modulators started in 2012. The first modulator began operation in 2014 and the start of linac was beginning 2017.

The R&D phase for the modulators started directly with the development of superconducting cavities. Besides the pulse generation, the modulator had to suppress the 10 Hz repetition rate in order not to disturb the grid. Another unique demand was the development of pulse cables. Since the power RF had to be generated in the tunnel, the klystrons were installed near the cavities. However, the modulators had to be installed outside of the tunnel for space, maintenance reasons and radiation concerns. This transmission of high power pulses via long cables is unique in the world and the suppression of EMI effects was mandatory. During the first year operation no EMI disturbances of other systems were detected and the modulator system works as expected.

INTRODUCTION

The superconducting European XFEL started the operation very successful in 2014 with the gun/injector operation and continued 2017 with the main linac. Multibeam klystrons provide the power RF for the acceleration. These receive a pulsed power of up to 16 MW for 1,54 ms at the 115 kV level. This power is generated from modulators operating at the 10 kV level. To convert the modulator voltage to the required HV, pulse transformers are used. The RF stations [1] are installed close to the linac along the accelerator; however, the modulators are installed in the central modulator hall aboveground. The reasons are lack of space in the tunnel, reliability, accessibility for maintenance, but also for radiation concerns. To transport the energy into the tunnel pulse cables had to be developed.

A long ongoing R&D process on modulators has been initiated at the beginning of the 1990s to develop the technologies fulfilling the demanding requirements for the operation of a large-scale machine.

TIMELINE

The development of long pulse modulators [2] started in parallel with the development of superconducting cavities in the beginning of the 1990s. The initial driver for the development was the so-called TESLA accelerator. The goal was the development of the superconducting cavities in order to build a 30 km long accelerator. The European XFEL uses the same technologies. To reduce the cryogenic load of the accelerator, the machine is operated in a pulsed mode. This led to the introduction of modulators that generate the pulsed power.

The first modulator was developed and built at Fermilab, Illinois [3] and shipped to DESY, Hamburg. The technology was the bouncer type. The energy is stored in capacitors. In combination with an LC resonant circuit a flat top pulse is generated. The testing and operation started in 1994 in the TESLA Test Facility (TTF).

The pulse generation to run the klystron worked very well and RF was supplied to operate the accelerator. At that time, mains distortions were detected as potential source for errors. The operation of the pulsing modulator could be measured in some HERA magnet currents in the 1-2 ppm region. Different approaches were evaluated to produce constant power power supplies to charge the modulator internal capacitors [4,5]. With further expansion of TTF, two more modulators were built and shipped to DESY in 1996 –1998.

At that time, the knowledge transfer between industry and laboratories for building such modulators was forced. The pulse-forming unit and the constant power power supply were separated and manufactured by different enterprises [5, 6].

With the decision of a one-tunnel solution for TESLA and the XFEL, a solution for the transmission of the high power pulses had to be found. It was obvious that the klystron/pulse transformer assembly had to be installed inside the tunnel, near the superconducting accelerator. Space inside the tunnel is costly and limited. Additionally, a relatively small, yet unknown level of radiation had to be expected. Therefore, it was decided to install the modulators in the central modulator hall aboveground.

The solution was the development of pulse cables [7, 8, 9], a quite challenging project hence the pulsed power of up to 420 MW had to be transported into and alongside the tunnel. This without disturbing any other electronics installed in the accelerator or influencing the beam under any circumstances. The proof of this solution was achieved in 2007 with a cable under operation along the FLASH accelerator without any problem.

With the start of the European XFEL project in 2005, the modulator technology had to be adapted for a series production of 27 modulators plus two spares. The tender procedure was such that a prototype of the modulator had to be built. After acceptance, the vendor would be eligible for taking part in the bid for tender of the series produc-

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tion. At DESY Zeuthen a test stand was erected to examine the different modulators to their performance, their correspondence to the specs. In addition, improvements had to be done [10]. At that time, a new topology was introduced. It was the pulse step modulator by Ampegon [11]. The modulators were tested a few thousand hours. During this time several improvements, especially on EMI problems were done. These occurred when operating the modulator with the pulse cable.

2011 the bid for tender was launched and the series production started. Oct. 2012 Ampegon delivered the first and by the end of 2014 the last modulator of the series. The commissioning on resistive load was done from 2013 until 2015.

The operation with the first two modulators for the gun and injector started in 2014. The operation of the linac started in 2017.

MODULATORS

Specification

- Max. klystron gun voltage: 120 kV
- Max. klystron gun current: 140 A
- Primary Voltage 10 kV
- Primary Current 1680 A
- High voltage pulse length: 1.7 ms
- Pulse repetition frequency: 10 Hz
- Max. ripple on flat top +/- 0.3 %
- Max. pulse power: 16,8 MW
- Average power: 300 kW
- Number of modulators : 27

Topology

The topology of the modulators for the XFEL is pulse step modulation (PSM) by Ampegon [5]. Stacked independent voltage sources generate the required output voltage, forming the pulse. These voltage sources are built in power modules that have individual potential free 3-phase input, an input stage to charge the internal storage capacitor and an IGBT output bridge, which connects the module to the HV output. Via pulse-width-modulation operating at a switching frequency of 20 kHz, a fine

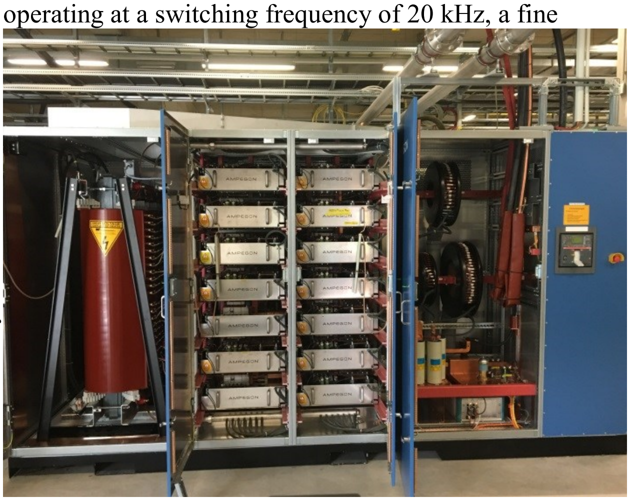

Figure1: Modulator of XFEL.

adjustment of the output voltage is possible. In total 24 units are mounted per modulator. With this setup and a well-designed filter on the HV output, shown in Fig.1, it is possible to achieve a final flat top ripple of 30Vpp on the pulse voltage of 10 kV.

Connection to the Grid

The pulsed operation of the modulators may induce undesired voltage changes to the grid (flicker). These fluctuations cause changes in the brightness of lamps and are potential sources for disturbing other electrical devices connected to the grid. DIN EN 61000-3-3 defines the allowed level of voltage changes. The 10 Hz repetition rate is very close to the minimum of the allowed distortions.

The input circuit of the modules are designed to cope with this 10 Hz pulsing power. The input transformer has a three phase input voltage of 690V and 24 independent output windings, allowing the stacking of the voltages. These windings are in delta-wye configuration. In combination with a B6 input diode bridges and a DC-link circuit on each power module, a low harmonic content of the current is achieved and only very small reactive power is generated.

From the DC-link a boost converter charges the constant power into the storage capacitors. Independent from the pulses, the constant power is transferred from DC-link circuit to the storage capacitors without fluctuation.

PULSE CABLE

Requirements

The requirements for cables for a pulsed high power application were described in [10]. At the start of the project, the requirements were not defined, but an optimum had to be found. These demands were:

- No significant delay of the pulse
- Low distortion of the voltage wave form
- Low electromagnetic noise
- Losses <2%
- Good fire resistance due to tunnel installation
- Radiation hardness
- High reliability <1 failure in 15 years
- Use of industry standards for production

Construction and Production of the Cable

To meet these requirements a tri-axial cable was chosen. Fig. 2 shows a sample of the cable. The inner conductor, at the high voltage level, leads the main current. The return path is via the middle conductor. Due to this construction the magnetic fields generated by the high current are eliminated. Both conductors are built by stranded copper wire.

The shielding is realized with a solid copper foil. Besides the EMI behaviour, this is mandatory for the fire resistance.

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For the production process, the materials were specified very closely since the electrical length of a cable is depending on the material properties. To ensure best tolerance and quality, all insulation materials were purchased at the production start.

Since intersections are potential trouble sources all cables have been produced with the final length. Therefore each cable length was pre-calculated with an overlength of only 15 m per cable. The length was precisely cut during the production process. After production, each cable was measured mechanically and by an electrical measurement using the transmission time to verify that the cable had the required length. It showed that both measurements corresponded within 1 m.

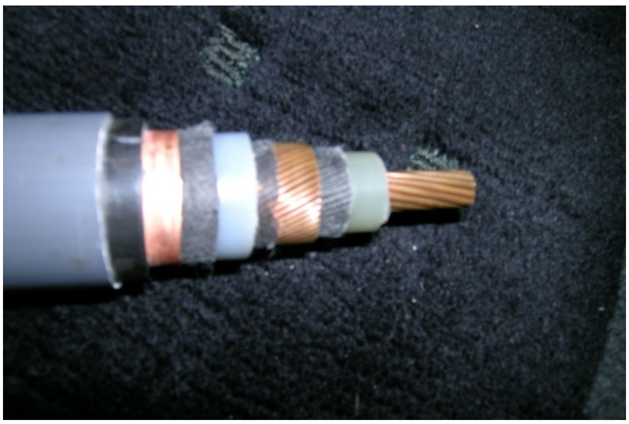

Figure 2: Pulse cable.

Installation of the Cable

The cable were routed from the aboveground modulatorhall via the shaft building into the tunnel. Four single cables were installed as a bundle, forming one system cable per modulator. The lengths of the cables were between 200 m up to 1.7 km. In total 106 km of cables were installed by an externally hired enterprise over a time period of 6 months including the installation of cable trays. One technician was trained on the mounting of the terminations to ensure the same quality of every unit. During this mounting process, the cable ends had to undergo a special heat procedure for 8 hrs. This is a preaging which prevents from shrinking of the material.

Adaptation Network

Each cable requires an adaptation network built of several RC-circuits to suppress reflections. These networks were purchased independently. Differing from the prototypes in the test stands, an additional compartment in the housing of the transformer was foreseen.

FINAL IMPROVEMENTS ON EMI

Many EMI tests and improvements have been performed at the test modulators. The final verification had to be repeated with the large-scale installation in the XFEL. Two types of problems occurred. The measurement in the tunnel showed too high level of noise. The typical common mode frequencies deriving from the switching of the modules were measured in metal structures along the tunnel. Additional EMI filters led to a complete suppression of this noise.

The second problem was detected as high 50Hz-current in the grounding system. This was generated by magnetic fields of the AC cabling to the modulator. The choice of a 3-phase sector cable with shield solved this problem.

SUMMARY

After years of R&D of RF stations, solutions were ready for series production. The testing of modulators in DESY Zeuthen was very successful. For the modulator series production only minor changes were made. The series of 27 modulators was built with PSM topology. The construction period for the series has lasted three years. In parallel, the pulse cables were purchased and installed inside the XFEL tunnel. The use of pulse cables was seen very critical at early states of the project due to possible EMI-effects. This has turned to be no issue and they are working without causing any problems in the tunnel. The first year of operation was very successful.

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