POWER SUPPLIES FOR TESLA MODULATORS

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Abstract
Modulators are used to generate the pulsed power for the klystrons of the superconducting linear accelerator TESLA. They produce rectangular high voltage pulses of up to 120 kV. The electrical power during the pulse is typically 15 MW and can maximally be 16.8 MW. The pulse length is 1.6 ms with a repetition rate of 5 Hz, for app. 10 % of the modulators it is 10 Hz. This leads to a needed pulsed power of 8.9 GW. It is obvious that this energy can not be taken from the mains directly. Therefore it is stored in capacitor banks to be released during the pulse. Power supplies are needed to recharge the capacitor banks and to decouple the low repetition rate from the mains. The electrical supply companies have very strict rules of the amount of distortions that are allowed to be produced by a customer especially in the frequency range below 25 Hz (flicker frequencies). To meet these rules the power supplies have to operate in constant power mode. Different types of power supplies have been investigated to check a possible use for TESLA

1. INTRODUCTION

TESLA klystrons require high voltage pulses of up to 120 kV with a pulse power of up to 16.8 MW. The pulse length is 1.6 ms with a repetition rate of 5 Hz, 10 % of the klystrons are working a 10 Hz repetition rate. The pulses are generated in modulators. In order not to take the pulsed energy from the mains these modulators store energy which is released during the pulse. The energy storage is then constantly loaded from the mains. To do so different types of power supplies have been investigated for the use in the modulators.

2. BOUNCER MODULATOR

Beside other designs the bouncer modulator is the most promising solution for the modulators in respect to cost and ease of design. Fig. 1 shows the principle schematic with the main capacitor bank, a semiconductor switch, the pulse transformer, the bouncer circuit and the HV power supply. For safety reasons ignitrons are installed to quick discharge the main capacitor bank in case of failure in the klystron.

To generate the HV pulses the main capacitor bank is charged to a voltage at the 10 kV level. Via the semiconductor switch the pulse transformer is connected to the capacitor bank. With the step up ratio of 1:12 the voltage is transformed to the 120 kV level.

During the pulse the voltage of the main capacitor droops for about 19 %. The principle can be seen in Fig. 2. To correct the voltage droop during the pulse to +/- 0.5% a bouncer circuit is used. This is a resonant LC circuit which creates a low frequency sine wave which is triggered slightly before the main pulse. The main pulse is positioned in the linear part of this sine wave. The sum of both voltages is a rectangular voltage of the desired parameters. With the use of the bouncer the stored energy inside the modulator is decreased.

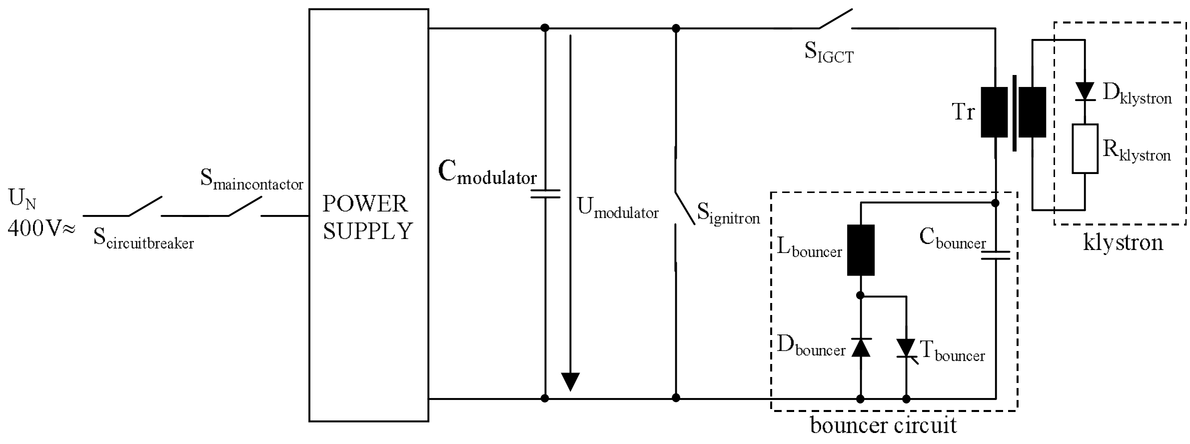


Fig.1: Principle schematic of the bouncer modulator

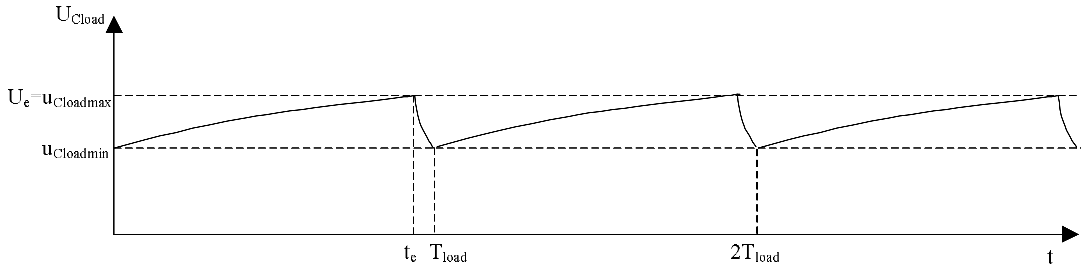


Fig. 2: Voltage curve form of the main capacitor bank in the modulator

3. DISTURBANCES TO THE MAINS

3.1 Pulsed power of the modulators

In TESLA 584 modulators will be in operation. Another 12 modulators are in stand by mode ready to start operation in case of a failure of the working units. 519 modulators operate with the 5 Hz repetition rate. The other 65 modulators will have a repetition rate of 10 Hz. This leads to a typical total peak pulse power of 8.9 GW at 5 Hz repetition rate and 1 GW for the intermediate pulses at 10 Hz repetition rate. This power is taken during 1.6 ms. During 200 ms respecting 100 ms the energy taken from the capacitors has to be recharged without disturbing the mains.

3.2 Allowed distortions to the mains

The German standard VDE 0838 or the equivalent European standard EN 61000 defines the amount of distortions that are allowed to be produced by a consumer of electrical energy. These distortions are defined as relative voltage changes d with

$$d = \frac{\Delta U}{U} \approx \frac{\Delta S}{S_{sc}}$$

d = allowed relative voltage changes

U= mains voltage

ΔU= variation of mains voltage

ΔS = variation of power due to the modulators

S_{sc} = short circuit power of the mains

In general no consumer of electrical energy is allowed to produce more than 3 % of voltage variation to the public mains. For low repetitive changes below 25 Hz this value is even more decreased. Voltage changes below 25 Hz are seen as changes in the luminance of the electric light. Since the human eye is very sensitive to these changes this appears as flickering light. These frequencies are called flicker frequencies. The value d can be achieved from diagrams in the standards. For the 5 Hz repetition rate the value d is < 0.5 %.[3,8]

TESLA will have a distributed electrical power supply system with a voltage of 20 kV. With the short circuit power S_{sc} of app. 200MVA per service hall the allowed power variation can be calculated to:

$$\Delta S < 200MVA * 0{,}005 = 1MVA$$

In each service hall up to 100 modulators are to be installed. The typical real power consumption is assumed to 15 MW per hall. Therefore each modulator shall not produce more the 10 kVA variation over the entire time between the pulses. With a nominal input power of 150 kW this leads to an allowed variation of 6.5 % of this value including the reactive power changes.

For the 10 Hz operation the curve of relative voltage changes has a minimum. The allowed voltage variation is decreased to d = 0.25 %. The number of modulators working at the 10 Hz level is low. There are 55 modulators installed in the service hall on the DESY site. The power supplies have an allowed variation of 3 % of their nominal power. The remaining 10 power supplies are installed in another service hall having a separate mains connection point.

4. TYPES OF POWER SUPPLIES

4.1 General assumption

There will be one power supply for each modulator. It will have a standard 400 V three phase input. The output voltage will be 12 kV_{DC}. The nominal power will be 150 kW for the 5 Hz and 300 kW for the 10 Hz repetition rate. The typical power needed for the 5 Hz operation is 120 kW. The power supplies will be built in modules. By this a high reliability and a good maintainability is given.

The advantages of having one power supply per modulator are:

- very high redundancy in the rf system. A failure of a modulator or a power supply does not affect any other modulator
- a failure in a single power supply module will not turn down the modulator
- each power supply can be regulated independently with a high regulation dynamic
- at the low voltage level switch gear is available as low price commercial of the shelf component.
- in case of replacing or working at the power supplies no further high voltage safety requirements are given

During operation the power supply has to meet two requirements:

- The main capacitor bank has to be recharged to an accurate value of voltage in order to obtain the same voltage at the klystron from pulse to pulse. The accuracy has to be +/- 0.5 %.
- The low repetition rates of 5 Hz and 10 Hz have to be suppressed in order not to produce disturbances to the mains.

4.2 Topologies of the power supplies

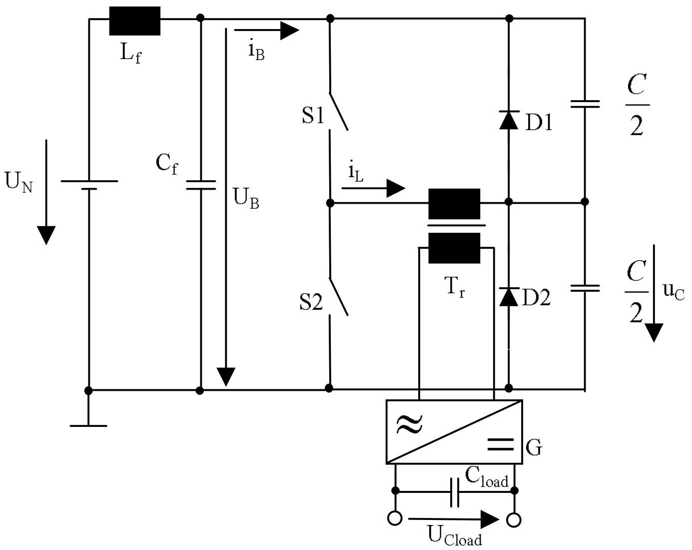
The given definition of the allowed distortions to the mains restricts the topologies of power supplies. The power supplies used in the first prototypes of the modulators at TESLA Test Facility are primary regulated SCR bridges with transformer and secondary diode bridge. This can not be used for TESLA due to the large variation in reactive power. Three phase rectifiers using SCRs like B6 bridges cannot be used for the same reason. Switched mode power supplies in the needed power and voltage range have recently come to the market and are available from industry. Additionally a digital regulation has to be introduced to fulfill the requirement for the constant power consumption.

Among other solutions described in [1,8] the following topologies have been investigated at DESY.

- Series resonance converter
- Series connection of buck converters
- Hybrid power supply
- SCR bridges in series with a diode rectifier

4.3 Series resonance converter

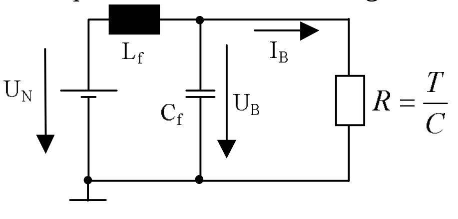
The power supply shown in Fig 3 was developed at DESY. This topology is known for small power supplies for auxiliary voltages. So far it has not been used as power supply to charge large capacitive loads in a constant power mode.



G	Rectifier
i_B	supply current
i_L	primary current of the transformer
u_C	voltage of the resonance capacitor
U_{Cload}	output voltage to the switch of the klystron
i_{Bt1}	current i_B at the time t1
L	primary stray inductivity of the transformer
U_B	supply voltage
f	resonance frequency of the resonant circuit of L and C
ü	gear ratio of the transformer and rectifier
T	period time of the switching frequency of S1 and S2
C	resonance capacitor
U_B	supply voltage
U_N	line voltage

Fig. 3: Series resonance sine converter

The equivalent circuit according to the arithmetic average of the supply current I_B is shown in Fig.4:



T	period time of the switching frequency of S1 and S2
C	capacity of the resonance capacitor
R	equivalent resistance of the switch mode power supply
U_B	supply voltage
U_N	line voltage
I_B	average supply current i_B

Fig 4: Equivalent circuit of the power supply

The equivalent circuit of the switch mode power supply is a resistor R which is constant when the period time T of the switching frequency f (10 kHz– 20 kHz) is constant. This resistance is independent of the capacitor voltage U_{Cload} and the pulse repetition rate of the modulator. By this the input power is (in a wide range) independent from the voltage of the main capacitor bank of the modulator.

4.4 Buck converter

To achieve the high voltage level of the main capacitor bank it is possible to stack a group of low voltage power supplies. This topology is used for power supplies that are manufactured in industry. These units are now under construction and will be used for some of the TTF modulators. The power supplies are buck converters having a nominal voltage of app. 750V each. 16 modules are stacked to deliver the required voltage of 12 kV. The transformer has a 400 V input and 16 outputs of which 8 outputs are in delta, the other 8 outputs are in star to get less mains harmonics. Fig. 5 shows the principle diagram of such a power supply.

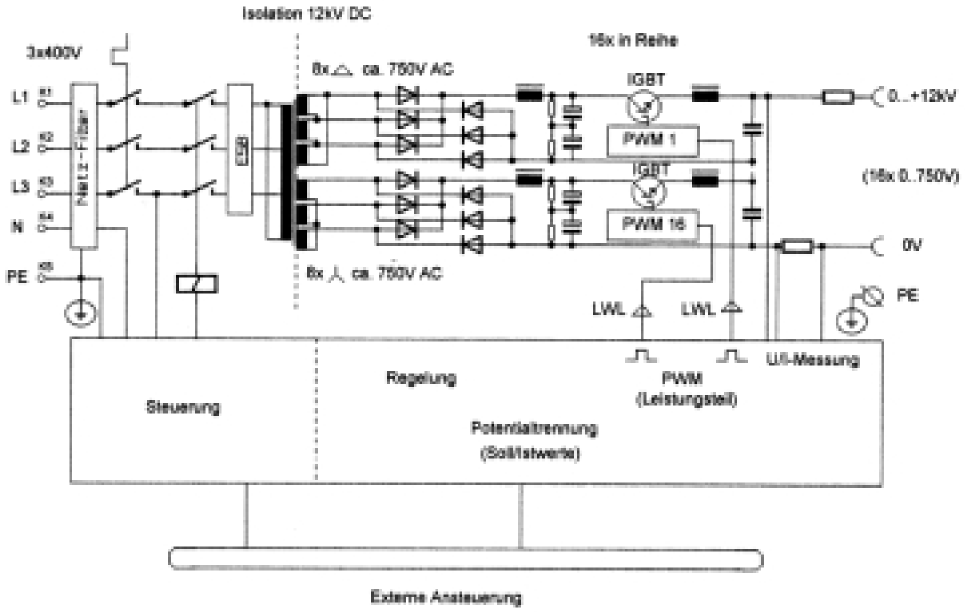


Fig. 5: Power supplies with stacked buck converters

The buck converters are working with a Pulse Width Modulation (PWM). The overlaid regulation for the voltage and the constant input power is accomplished on an external board that is developed and provided by DESY. The internal regulation of the power supply is a power regulation. The units will receive the power reference signal from the DESY regulation and transform this into voltage and current values.

4.5 Hybrid power supply

When looking at the development of the cost of switched mode power supplies a permanent decrease can be seen. In the last 5 to 10 years the prices have been reduced by a factor of two. Nevertheless they are still high in comparison with SCR or diode technology. Therefore another solution is considered. This is the hybrid power supply.(Fig 6)

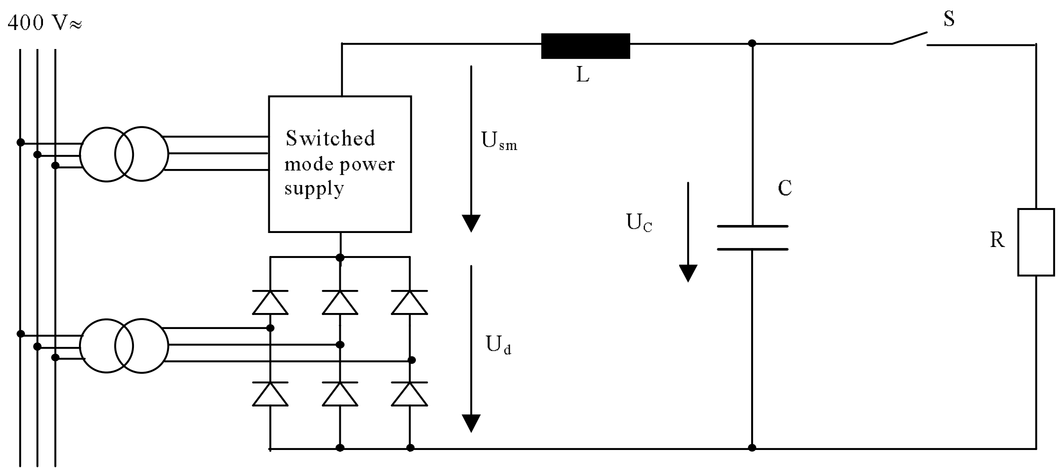


Fig. 6: Hybrid power supply

Basic idea

When looking at the waveform of the capacitor bank voltage of the modulator (Fig. 2) this can be splitted into two parts. There is a constant DC part and a part of varying voltage. The basic idea is to produce the constant DC part with an unregulated diode rectifier. The changing part will be produced by a switched mode power supply e.g. a buck converter. By this combination the full regulation dynamic of the switched mode supply can be used. Since the price of the diode rectifier is app. 40 % to 50 % of the price of a switched mode supply, an overall price reduction of 20 % to 30 % seems possible depending on the chosen value of the DC voltage. The principle is proven in simulations.

4.6 SCR supply with diode rectifier

The same basic idea as for the hybrid supply is assumed. Here the switched mode supply shall be replaced by SCR technology to further reduce cost. The voltage of the diode rectifier is at 10 kV. The SCR has to be in inverter mode at the beginning of the loading period to decrease the voltage. At the end of the loading period the power supply has to add voltage. A principle schematic is shown in Fig. 7. The voltage curves are shown in Fig. 8.

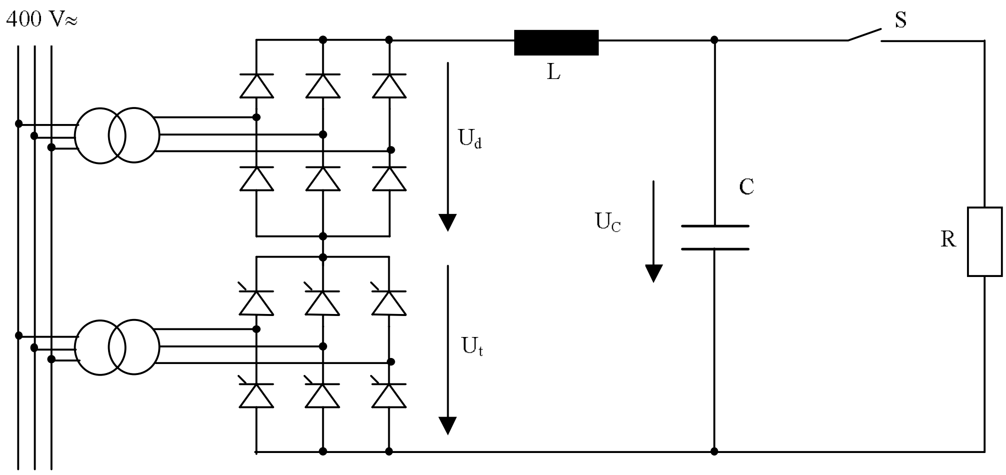


Fig.7: Series connection of a diode and a SCR bridge

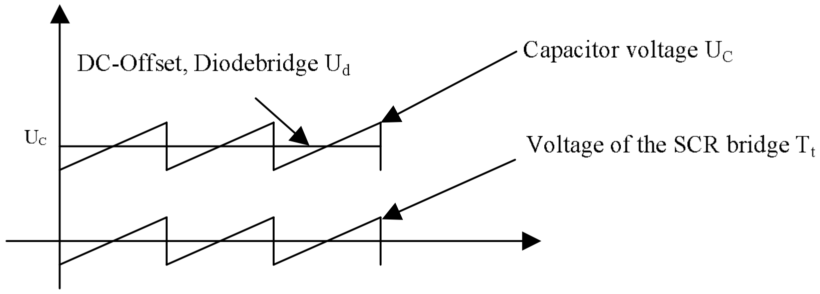


Fig. 8: Voltage curve of series connection of diode and SCR bridge

Here two versions are possible:

- The SCR power supply has a single phase angle control
- The SCR power supply is driven in sequential phase control

Both solutions have to take care for the reactive power of the SCR supply in order to keep the distortions of the mains low.

5. CONCLUSION

The low repetition rate of TESLA with the high pulsed power lead to hard specifications for the power supplies. Different types of power supplies have been investigated in terms of functionality and price. The result is that there are good solutions. The most convenient type with respect to regulation dynamics is the switched mode power supply but the price is still high. A good compromise is the hybrid power supply, a series connection of a diode bridge and a switched mode supply, since low price and good regulation abilities are combined. The third topology is the series connection of a diode bridge and a SCR rectifier. The drawback here is the large filter choke that has to be introduced to smooth the DC current. The regulation for this power supply is difficult.

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