Power Supplies for TESLA Modulators

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1 Introduction

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 be at maximum 16.8 MW. The pulse length is 1.7 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.

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.

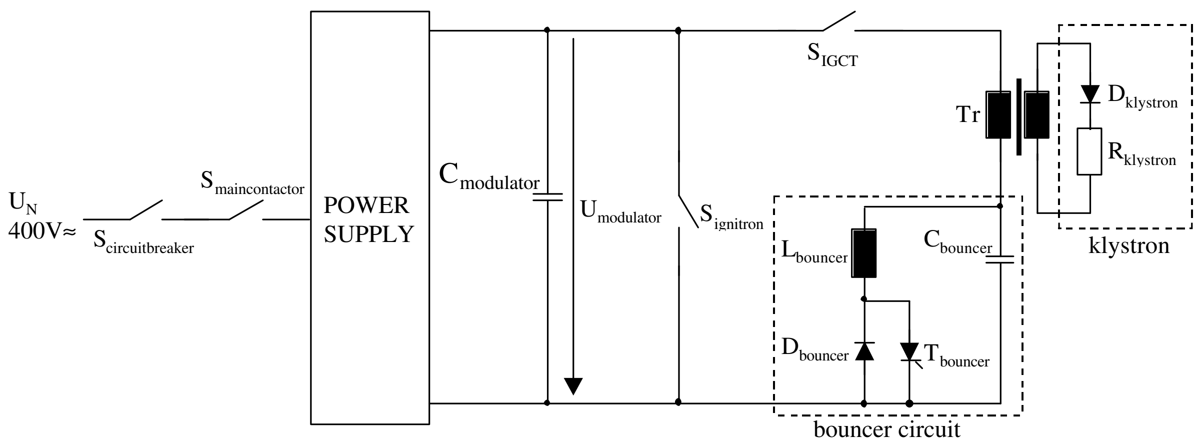


Fig.1: Principle schematic of the bouncer modulator

The specification for the modulators are

	Typical	Maximum
Klystron gun voltage	115 kV	120 kV
Klystron gun current	130 A	140 A
Electrical power	14.95 MW	16.8 MW
High voltage pulse duration	< 1.7 ms	1.7 ms
High voltage rise time (0 to 99%)	< 0.2 ms	0.2 ms
Pulse to pulse voltage fluctuation	< +/- 0.5 %	+/- 0.5 %
Pulse flatness during flat top	< +/- 0.5 %	+/- 0.5 %

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 cap 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 about 19 %. The principle can be seen in Fig. 2. To correct the voltage droop 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.

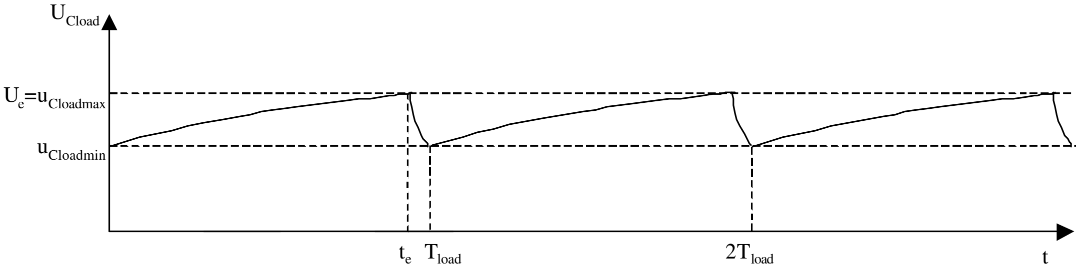


Fig. 2: Voltage curve form of the main capacitor bank in the modulator

3 High voltage power supply

There will be a 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 power supply cabinet is connected to the cabinet of the modulator. The size of the power supply will be 1.2m * 1.6m* 2m (l*w*h)

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 Disturbances to the mains

4.1 Pulsed power of the modulators

In the main linac 560 modulators are in operation. For the injectors another 24 are installed leading to a total sum of 584 modulators in operation. There are another 12 modulators in the main linac 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 8.8 GW at 5 Hz repetition rate1 GW for the intermediate pulses at 10 Hz repetition rate. This power is taken during 1.7 ms. During 200 ms respecting 100 ms the energy taken from the capacitors has to be recharged without disturbing the mains.

4.2 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 for TESLA can be taken from the diagram in Fig. 3. The value r is the number of voltage changes within one minute.

$$r\ (min^{-1}) = 5\ [s^{-1}] * 2 * 60\ s = 600$$

For this value d is <0.5%.

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 respecting 3.75% of the typical power. The remaining 10 power supplies are installed in another service hall having a separate mains connection point.

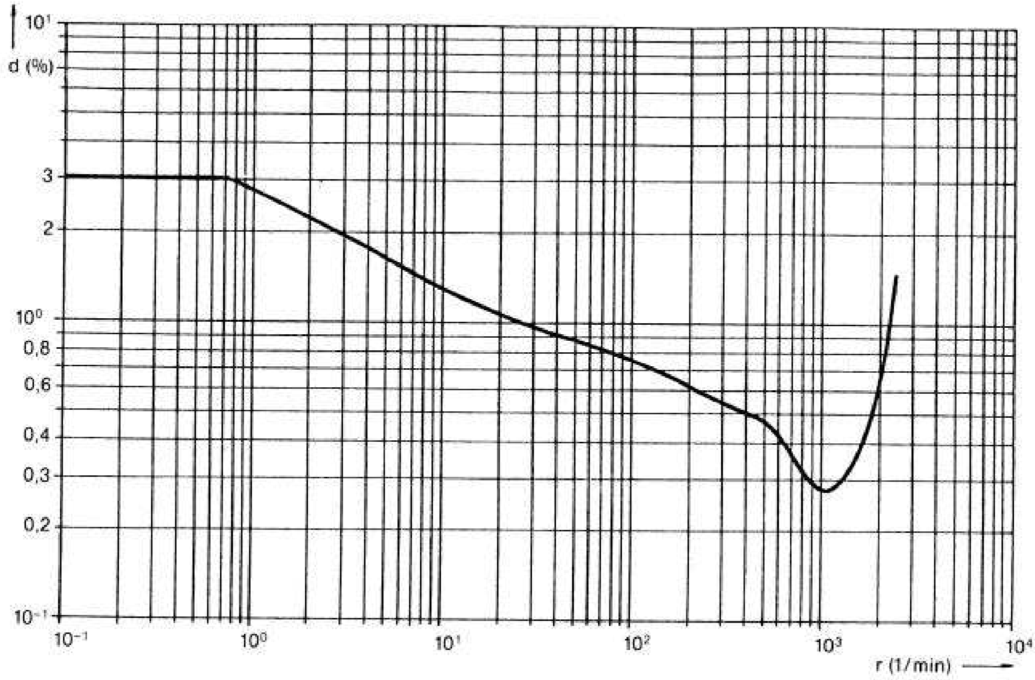


Fig. 3: Compatibility of regular repetitive rectangular voltage changes

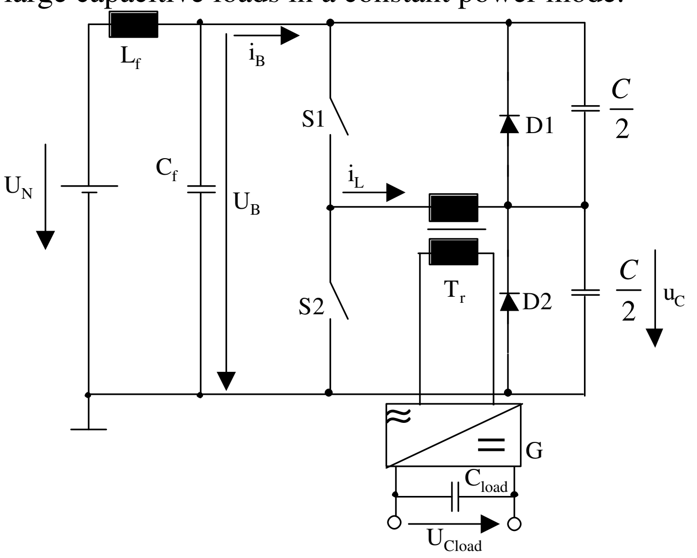
5 Types of power supplies

The given definition of the allowed distortions to the mains makes it impossible to use a variety of topologies of power supplies. The power supply 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.
Among other solutions described in [1,9] the following topologies have been investigated at DESY.

1) Series resonance sine converter
2) Series connection of buck converters
3) Hybrid power supply
4) SCR bridges in series with a diode rectifier

5.1 Series resonance sine converter

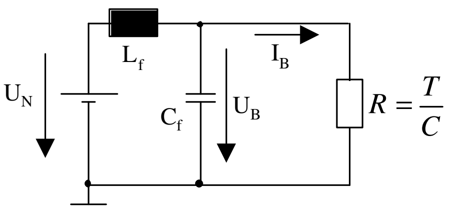
The power supply shown in Fig 4 was developed at DESY. This topology is known for small power supplies for auxiliary voltages. So far it has not been used as power supply to charge large capacitive loads in a constant power mode.



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. 4: Series resonance sine converter

The equivalent circuit according to the arithmetic average of the supply current I_B:



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 5: 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 – 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.

To describe the function of the power supply Fig. 6 is used.
Assumption: u_c=0V, I_L=0A and S_1 turning on
Because of the stray inductance L of the transformer the current i_L keeps zero while turning S_1 on (zero current switching power supply).Then the current i_L raises and the resonance capacitor C is charged. While charging the resonance capacitor C the supply current i_B is equivalent to the resonance capacitor current i_L.
When the resonance capacitor voltage u_C reaches the supply voltage U_B diode D_1 will start to conduct. The current i_L continues flowing forced by the energy stored in the stray inductance L of the transformer. Since the path of the current i_L is no longer through the resonance capacitor C and the supply current i_B equals zero.

The energy stored in the stray inductance L of the transformer will slowly be passed to the load C_{load} and the current i_L decreases linearly to zero.
After that a new cycle can start by turning S_1 off and S_2 on. The corresponding voltage and current waveforms can be seen in Fig.8. With each loading and unloading period the same amount of energy is transmitted from the primary side of the transformer to the main capacitor bank. This amount is the energy of the resonance capacitor loaded to the voltage U_B or unloaded to 0.

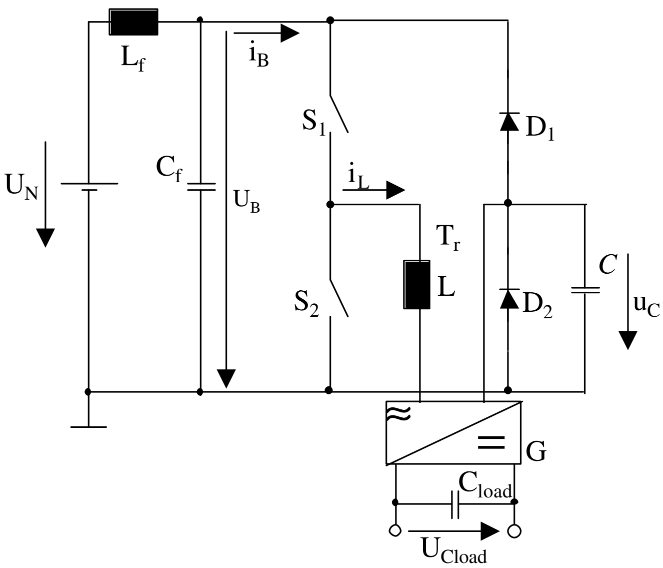


Fig.6: Series resonance sine converter with only one capacitor

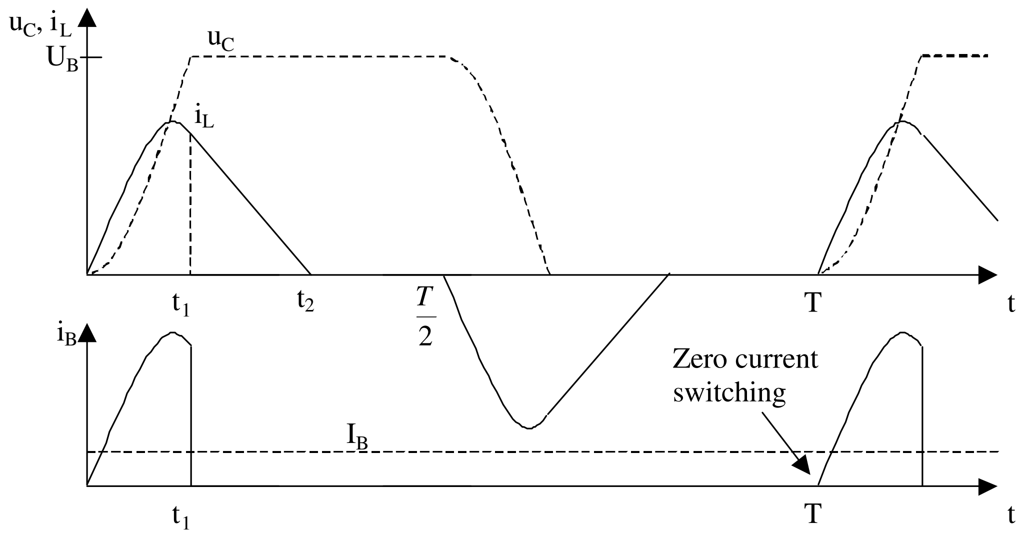


Fig.7: Voltage and current functions of the half-bridge

Please note that the current pulses are in the range of 20 kHz. They are filtered by the input filter and do not pass to the mains.

Derivation of the arithmetic average supply current I_B:

While charging the resonance capacitor C the supply current i_B is equivalent to the resonance capacitor current i_L. Therefor the charge Q taken from the power supply to the resonance capacitor C equals $Q = CU_B$.
The charge Q can also be expressed as follows:

$$Q = \int_0^T i_B \, dt = CU_B$$

Multiplication of the integral with the term $\frac{T}{T}$ with T = period time of the switching time:

$$Q = T * \left[\frac{1}{T} \int_0^T i_B \, dt \right] = CU_B$$

The term in brackets is equivalent to the average supply current $I_B = \frac{1}{T} \int_0^T i_B \, dt$.

$Q = T * I_B = CU_B$

The resulting expression for the average supply current is:

$$I_B = \frac{CU_B}{T} = \frac{U_B}{R} \text{ with } R = \frac{T}{C}$$

The voltage and current wave forms for the half bridge shown in Fig 4 are given in Fig 8. The same principle as for the half bridge is valid. The difference is that the frequency of the current it doubled and the currents are decreased. When one of the capacitors is loaded, the second capacitor is unloading and vice versa.

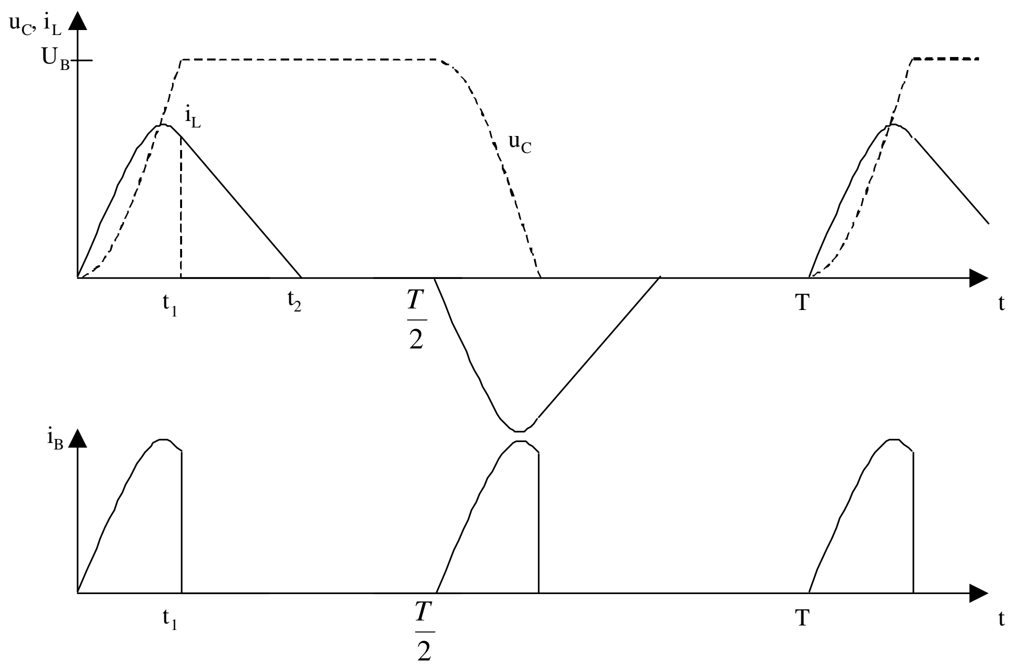


Fig 8: Voltage and current waveforms of power supply Fig. 4

The required power is with today's technique hard to fulfill with just one power part. A 300 kW prototype consisting of four modules having 75 kW each is going to be tested in TTF. One 75 kW module was tested successfully.

5.2 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 manufactured in industry. The units are now under construction an will be used for some of the TTF modulators. The power supplies are buck converters each 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. 9 shows the principle diagram of such a power supply.

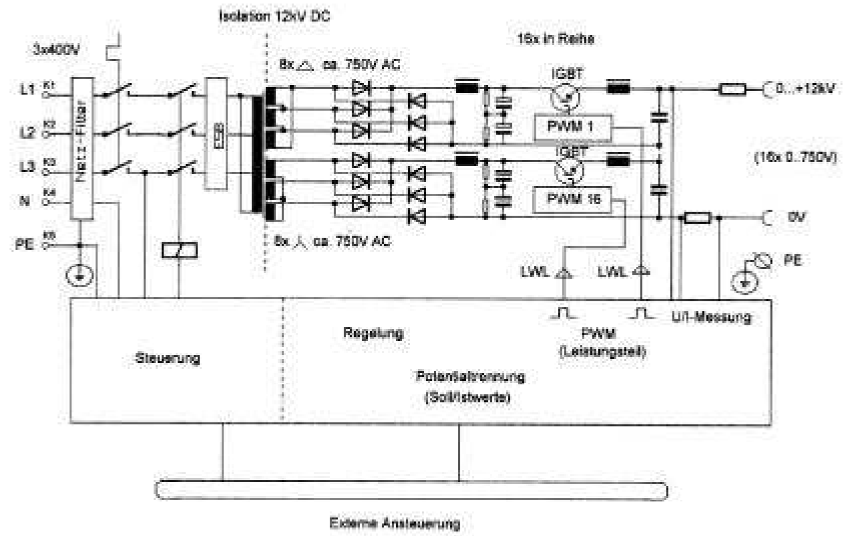


Fig. 9: Power supplies with stacked buck converters

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 transforms this into voltage and current values.

5.3 Hybrid power supply

When looking at the development in 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 10)

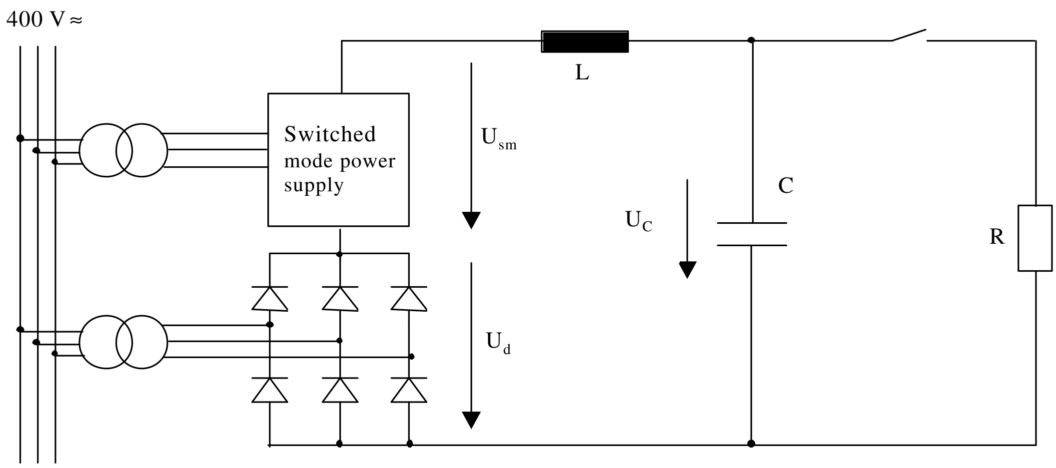


Fig. 10: Hybrid power supply

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.

5.4 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. shows A principle schematic is shown in Fig. 12. The voltage curves are shown in Fig. 13.

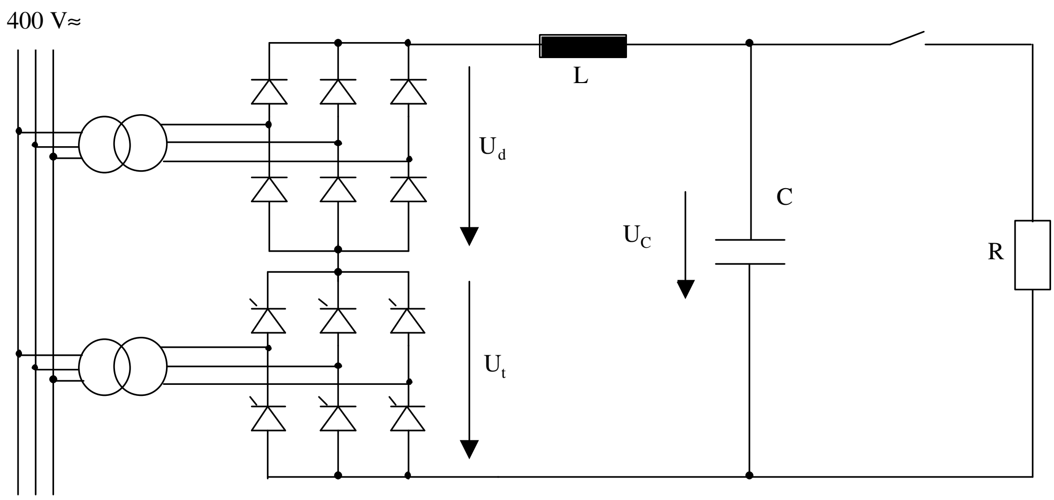


Fig.12: Series connection of a diode and a SCR bridge

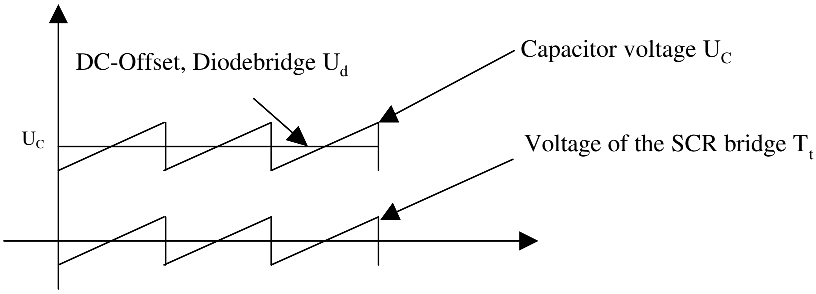


Fig. 13: Voltage curve of series connection of diode and SCR bridge

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.

5.4.1 SCR bridge with single phase control

The power of the SCR supply can be calculated:

P: real power
Q: reactive power
S: apparent power
Q_1: fundamental reactive power
Q_0: harmonics reactive power
S_1: fundamental apparent power
α: trigger angel

$$P = U_{di} * I_L * Cos\ \alpha$$
$$Q = \sqrt{Q_1^2 + Q_o^2}$$
$$S = \sqrt{P^2 + Q^2}$$
$$Q_1 = U_{di} * I_L * Sin\ \alpha$$
$$S_1 = U_{di} * I_L$$
$$Q_0 = 0{,}31 * U_{di} * I_L$$

The correspondence of the reactive power to the real power in dependence of the trigger angle is shown in Fig.14.

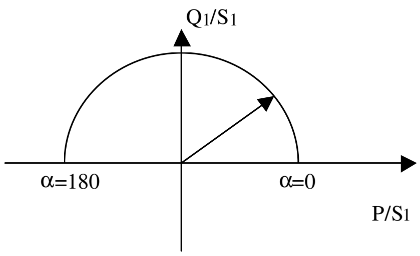


Fig. 14: Real and reactive power in dependence of the phase angle α

The overall real power is: $P = P_{\text{thyristor}} + P_{diode} = U_{dit} * I_L * Cos\alpha + U_d * I_L$

For a constant power α can be calculated: $\alpha = Arc\cos((\frac{P}{I_L} - U_{did}) * \frac{1}{U_{dit}})$

The arccos function is only valid when $\frac{P}{I_L} - U_{did} * \frac{1}{U_{dit}}$ is between –1 and 1.

If the relation

$$\frac{P}{U_{did} + U_{dit}} \le I_L \le \frac{P}{U_{did} - U_{dit}}$$

is not valid, no phase shift angles can be calculated for a constant power mode.

The simulation shows that a constant power mode is possible when having a nominal voltage of 3 kV of the SCR supply.
The power diagram is shown in Fig. 15. The power was calculated in periods of 20 ms the repetition rate is 10 Hz.

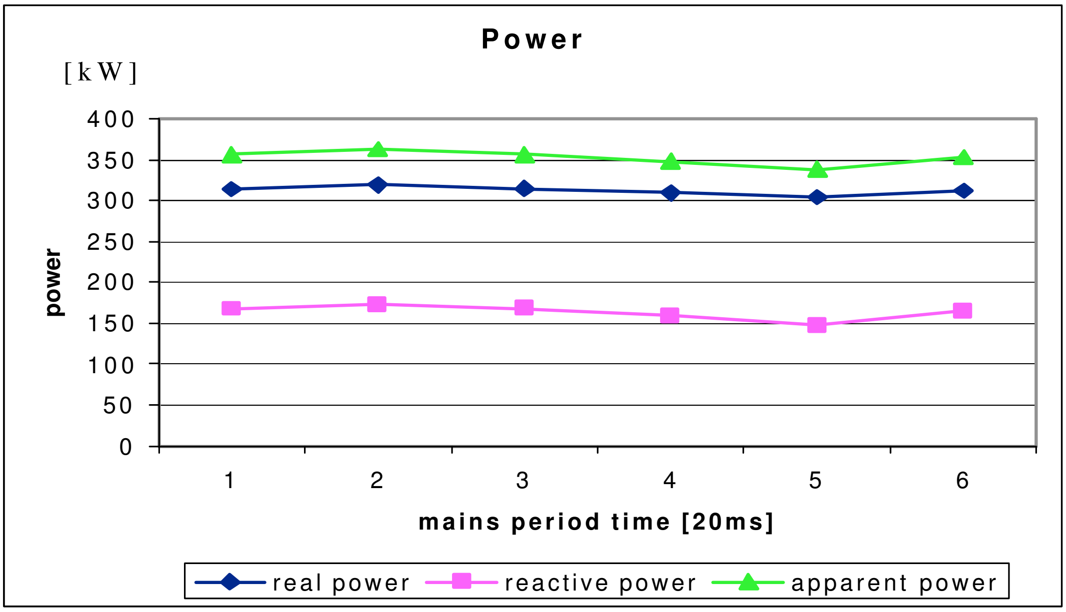


Fig.15: Power diagram of a series connection of a diode and SCR bride α(P)

5.4.2 SCR bridge with sequential phase control

In literature the half regulated B6 bridge can be found as topology to produce low reactive power. In the B6 bridge either the anode or the cathode SCRs are replaced by diodes depending whether the rectifier mode or the inverter mode is driven. When using SCRs instead of diodes and varying both phase angle it is possible to regulate the reactive power in the region between half controlled bridge and full controlled bridge. This type of regulation is controlled sequential phase control. The real/reactive power diagram is shown in Fig. 16. The simulation results are shown in Fig. 17.

The formulas to calculate the power are:

$$P = \frac{U_{di}}{2} * I_L * (\cos\alpha_1 + \cos\alpha_2)$$
$$Q = \sqrt{Q_1^2 + Q_o^2}$$
$$S = \sqrt{P^2 + Q^2}$$
$$Q_1 = \frac{U_{di}}{2} * I_L * (\sin\alpha_1 + \sin\alpha_2)$$
$$S_1 = U_{di} * I_L$$
$$Qo = 0{,}31 * U_{di} * I_L$$

P: real power
Q: reactive power
S: apparent power
Q_1: fundamental reactive power
Qo: harmonics reactive power
S_1: fundamental apparent power

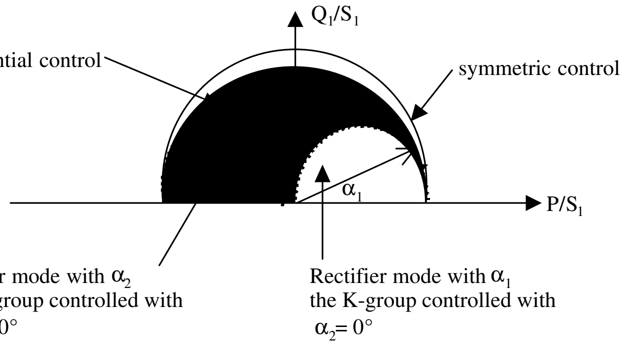


Fig. 16: real and reactive power in dependence of the phase angles α_1, α_2

The total power can be calculated with

$$P = P_{diode} + P_{thyristor}(\alpha_1, \alpha_2)$$
$$Q = Q_{diode} + P_{thyristor}(\alpha_1, \alpha_2)$$

With

$$P = U_{dit} * \frac{I_L}{2} * (\cos\alpha_1 + \cos\alpha_2) + U_{did} * I_L$$

$$Q = \sqrt{(U_{dit} * \frac{I_L}{2} * (\sin\alpha_1 + \sin\alpha_2))^2 + (0{,}31 * U_{dit} * I_L)^2} + 0{,}31 * U_{did} * I_L$$

$$\cos\alpha_1 + \cos\alpha_2 = \left(\frac{2 * (P - U_{did} * I_L)}{U_{dit} * I_L} \right)$$

$$\sin\alpha_1 + \sin\alpha_2 = \sqrt{4 * \left[\frac{(Q - 0.31 * U_{did} * I_L)^2}{(U_{dit} * I_L)^2} - 0.31^2 \right]}$$

In the simulation it is shown that the power supplies fulfill the requirements of low changes in apparent power nevertheless the regulation requires a lot of difficulty mathematics. Due to the arccos functions the values for α, α_1, α_2 are defined only in a small area.
Both power supplies require a large filter choke to smooth the loading current. In spite of the very good price this type of power supply is not taken.

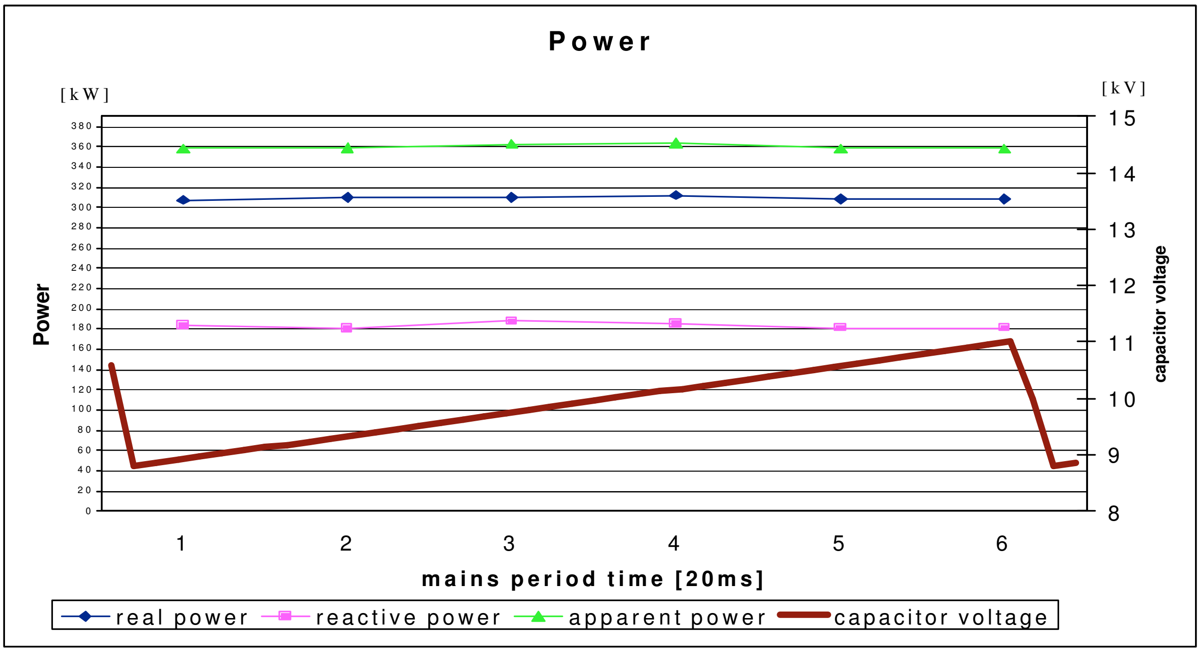
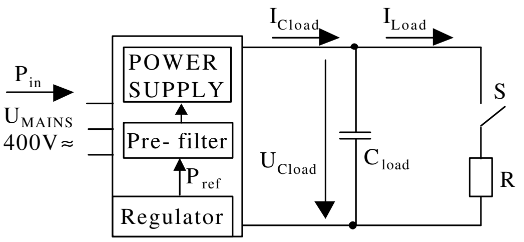


Fig.17: Power diagram of a series connection of a diode and SCR bride with sequential control

6 Regulation

The regulation is a major part of a constant power power supply. The voltage of the capacitor bank at the trigger time of the pulses has to have a pulse to pulse repetition accuracy of +/-0.5%. This in combination with the demand of constant power requires a digital regulation. To be able to react on variations of the mains, temperature effects or non linear behavior of components the regulation is self learning. A simplified modulator circuit is shown in Fig. 18.



R	Klystron
S	high voltage switch
C_{load}	main capacitor bank
U_{Cload}	capacitor voltage
P_{in}	input power

$$W_{Cload} = \frac{1}{2} C_{load} * U_{Cload}^{2}$$

Fig. 18 Simplified modulator circuit

6.1 Principle of regulation

The regulator contains a RAM wherein the charging curve of the capacitor voltage U_{Cload} is stored. It is driven according to the RAM curve. A fast regulator ensures that the RAM curve and the capacitor voltage U_{Cload} are equal despite of even fast voltage variations of the mains voltage U_{MAINS} . For this reason it is obvious that the final voltage $U_e = U_{Cload}$ at time t_e remains the same at each charging cycle because it equals the well known RAM curve. Fig. 19 shows again the voltage curve of the main capacitor bank.

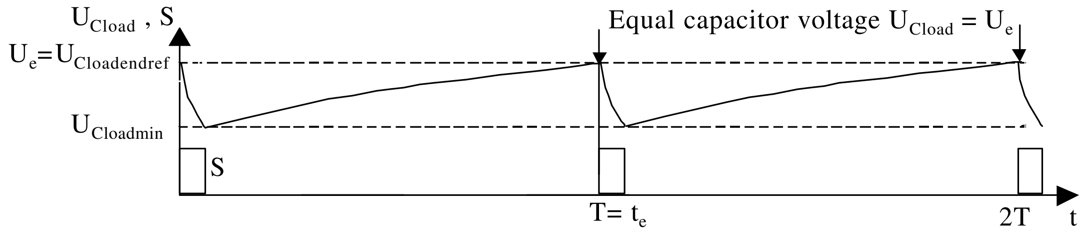


Fig. 19: Voltage curve of the main capacitor

For achieving constant input power a learning process is introduced. A voltage charging curve for C_{load} is determined. With this curve the final charging voltage equals the nominal voltage ($V_{capend}=V_{capendref}$). This charging curve is stored in the memory. The possible starting curve is shown in Fig. 20.

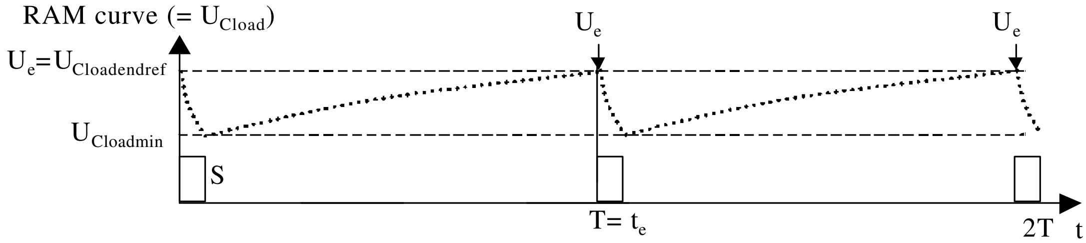


Fig. 20: Stored reference charging curve of the capacitor

With this reference charging curve the input power is not yet constant but looks e.g. like the curve shown in Fig. 21. The aim is to have a constant power. With the self learning algorithm the stored reference curve is modified in such a way that the reference values are increased or decreased until the input power is constant.
The result of the learning process is equal output voltage $U_{Cload} = U_e$ = constant after each charging cycle T and constant input power consumption $P_{in} = P_{average}$ = constant.

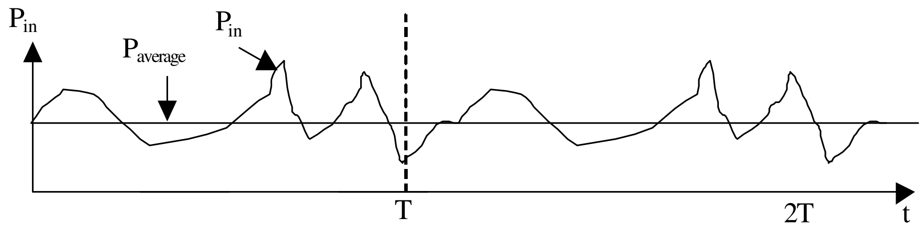


Fig. 21: Input power of the modulator

6.1.1 Regulation with unit RAM curve

To be independent from changes in the charging time T (changes in repetition rate) or the output voltage U_e a unit curve is stored in the RAM. By this it is not necessary to relearn this curve in case of change. The unit charging curve is simply scaled to the real time and voltage axis.

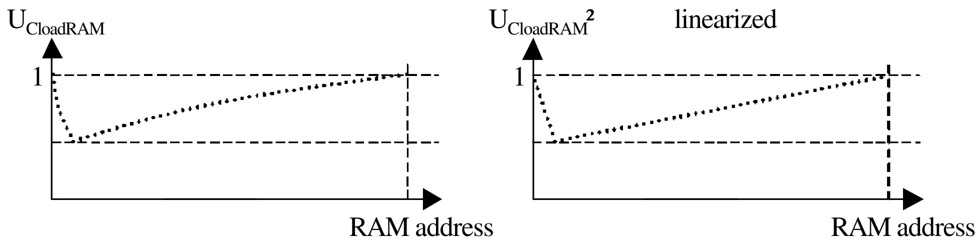


Fig 22.: RAM curves of the capacitor reference curves

To linearize the regulation the capacitor voltages are used as squared values. This is because the energy stored in the capacitor C_{Load} is proportional to the squared capacitor voltage U_{Cload}^2
The linearized curve is stored as RAM curve.

$$W_{Cload} = \frac{1}{2} C_{load} * U_{Cload}^2$$

$U_{Cloadref}^2(t)$ (reference curve) is the linearized reference value of the squared capacitor voltage $U_{Cload}^2(t)$ (actual curve) .

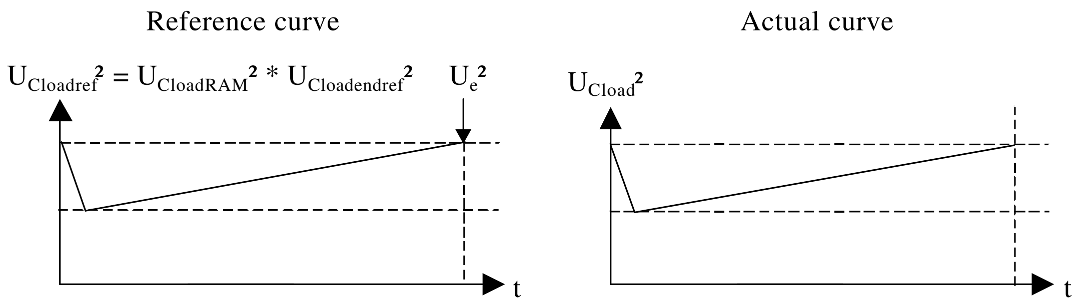


Fig. 23: Linearized and scaled reference curve and monitored curve

The reference value $U_{Cloadref}^2$ and the linearized squared capacitor voltage U_{Cload}^2 are passed to a P(I) regulator.

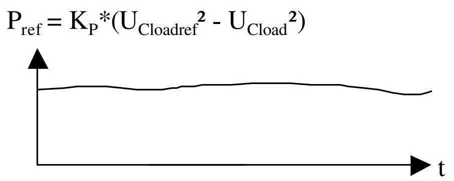


Fig. 24: Output signal of the regulation

The signal P_{ref} is the signal steering the power consumption of the power supply (Fig.23). It is necessary that the actual input power P_{in} is proportional to the steering signal P_{ref} ($P_{in} \sim P_{ref}$). In some power supplies a pre- filter has to be used to ensure that $P_{in} \sim P_{ref}$. Droops of the mains voltage U_{MAINS} are the most disturbing error signals for the P(I) regulator. The pre-filter in the proposed power supply for TESLA guarantees the independence of the input power P_{in} from the mains voltage U_{MAINS} ($P_{ref} \sim P_{in} \neq f(U_{MAINS})$).
The hardware of the regulation is based on a programmable ALTERA device. The device contains the complete regulation software, the pulse firing generation of the switched mode power supply and the interlocks for the power supply. The designed board is able to work in local mode. A VME interface allows to communicate with a control computer to feed in pre-calculated curve forms for the modulator. By this the learning time is decreased.

The regulation scheme is shown in Fig. 25.

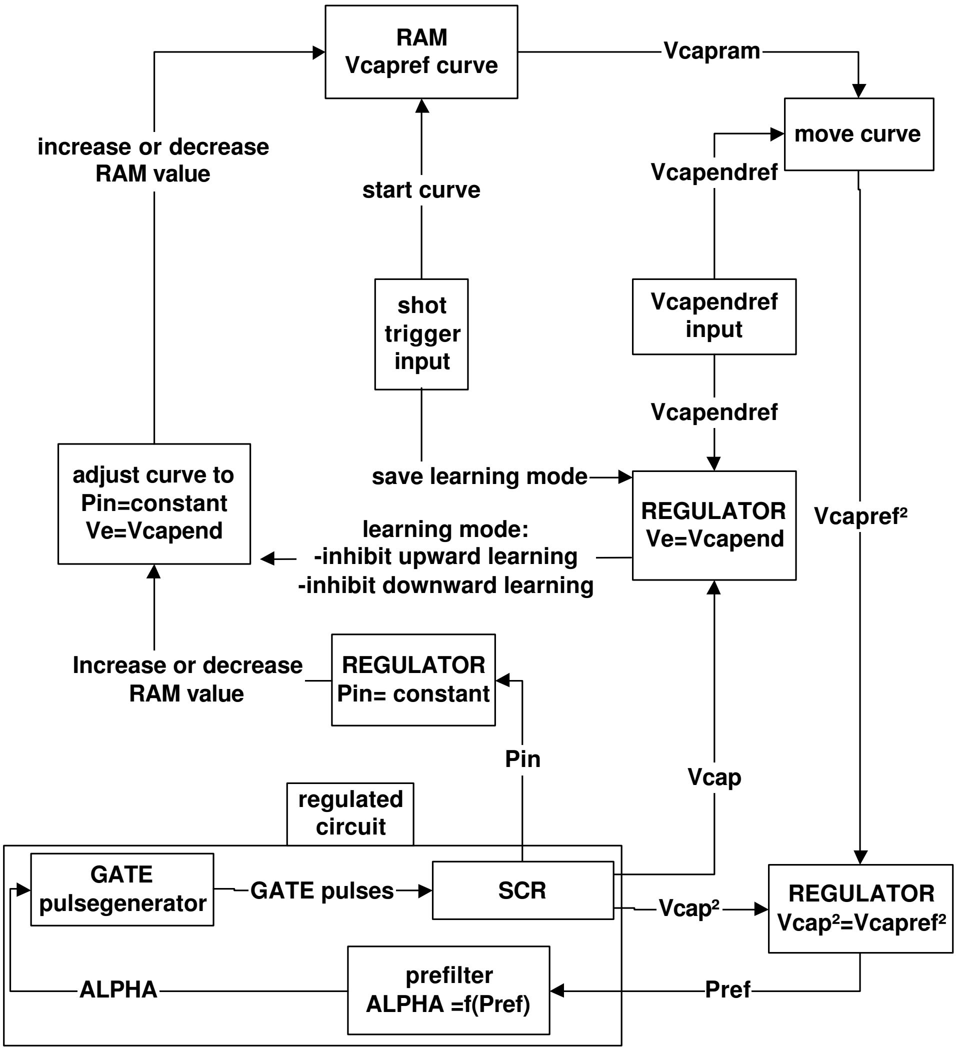


Fig. 25: Block diagram of the self-learning regulation

7 Summary

Different types of power supplies are possible to fulfill the requirement of low disturbances to the mains. A switched mode power supply, the resonance converter was developed for the high voltage high power operation and successfully tested at DESY TTF. The next type of switched mode power supply used in TTF is a series connection of low voltage buck converters. As outlook for future power supplies with lower costs the hybrid power supply, a series connection of a diode bridge and a switched mode power supply, was investigated and give good results in simulation. A further cost reduction just using SCR technology is possible in simulation but has draw backs for real power supplies since the regulation is very complicated.

8 Literature

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