The Three-Phase Power Supply for Low Ripple High Voltage in Conventional Technology

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1 Abstract

Electrostatic precipitators are supplied with high voltage direct current systems. For many applications one of the main requirements is the quality of the high voltage insofar, that the ripple has to be very low. Low ripple means a very efficient voltage time area rate. At a standard single phase high voltage system with grid frequency the ripple is significantly high. With the technological more sophisticated high frequency power supplies the quality of the high voltage can be driven to a maximum. Another solution to get high quality for the high voltage with simple conventional technology is to use a three-phase current system. The three-phase high voltage power supply combines the advantages of the so-called conventional (single phase) current systems, e.g. simple and robust technology for an appropriate price, with the advantages of the switched mode power supply systems, mainly the low ripple at the high voltage side.

2 Introduction

The functional principle of an electrostatic precipitator, to separate the particles from the waste gas by charging them, moving them out of the waste gas current and collecting them on the walls of the waste gas channel, is based on the high electric field strength within the waste gas channel. The high electric field strength is generated by the high electrostatic voltage which is connected to the waste gas channels.

There are certain requirements for the high voltage power supplies for the operation of an electrostatic precipitator:

- The high voltage shall be controllable over a wide range.
- Flash overs in the electrostatic precipitator shall be detected, the high voltage system shall react with an adjustable quenching behavior.
- The short circuit current shall be limited.
- Certain voltage shapes shall be available: There are ESP conditions which a smooth voltage with a low ripple is most sufficient for, at other conditions a high voltage pulse with a certain low voltage between the pulses (fill-in voltage) leads to better precipitation results.

3 High Voltage Power Supplies

To meet these requirements the power supplies to produce the high electrostatic voltage can be of different architectures:

- For small systems there exist high voltage cascade systems.
- For general applications there are built single phase grid frequency systems.
- For special applications there are used micro pulsing systems.
- For general applications with difficult conditions can be used either the three phase current grid frequency or the switched mode power supply systems.

3.1 The High Voltage Cascades

High voltage supplies with a diode capacitor cascade architecture are used for small electrostatic precipitators only (Figure 1). A diode cascade structure multiplies the input voltage by the number of stages which are connected in series.

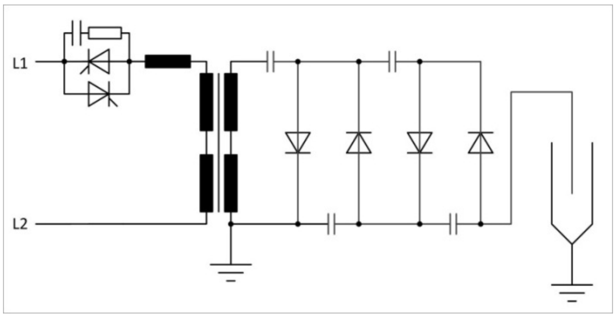

Figure 1: Schematic of the high voltage cascade; the series connection of the capacitor-diode-combinations multiply the output voltage by the number of combinations; modern high voltage cascades operate with transformer frequencies above 100 kHz

Theoretically with this structure there can be achieved every voltage height, which is of course limited by physically constraints. Practically a system with very many diode capacitor stages gets a very high internal resistance. Therefore the output current will be limited, which also limits the size of electrostatic precipitators.

3.2 The Single Phase System

The single phase high voltage power supply is the bread and butter supply for the electrostatic precipitators (Figure 2).

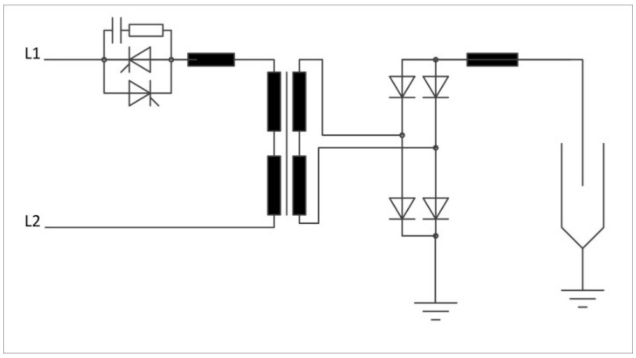

Figure 2: Simple functional principle of the single phase power supply; the grid frequency based input voltage is regulated by the thyristor set

Its architecture is rather simple. At the entrance of the power supply there is a current controller, mostly built by thyristor switches. The current flows through the primary coil of a transformer which produces at its secondary side a high alternating voltage. This secondary high voltage is rectified and put to the corona electrodes of the electrostatic precipitator. Between the precipitator and the rectifier normally there are put a damping resistor and a high frequency choke to protect the rectifier from the transients which occur at the flash overs within the ESP. The primary side of the transformer is normally protected by some kind of serial choke from over current, which may occur because of short circuit situations at the output of the high voltage supply. Every component of the single phase system is simple, the construction is old-fashioned and proven in use, hence the price is reasonable.

The output voltage has a significant ripple, especially when the ignition angle for the thyristor is small and the sinus wave is cut close to zero (Figure 3). However when the electrostatic precipitator is well dimensioned and the precipitator conditions are not too challenging, the single phase system does a sufficient job for cleaning the waste gas.

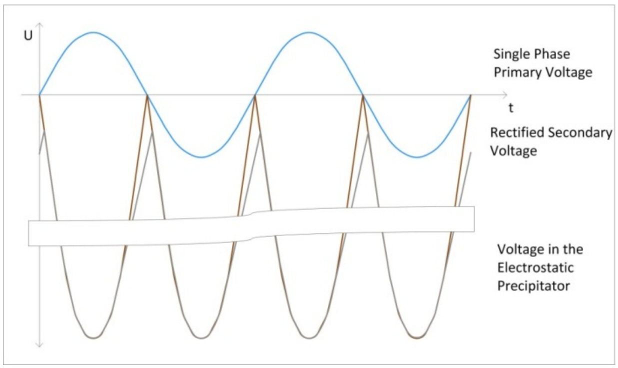

Figure 3: Input and output voltage of the single phase power supply; the resulting high output voltage has a significant ripple

3.3 The Micro Pulsing System

Micro pulsing systems are quite special in the market. They are a combination of two high voltage sources, from which one delivers a certain base voltage with especially low ripple and the second adds very short pulses with a length of about one hundred micro seconds (Figure 4) [1]. With this combination there can be reached very high voltages in the electrostatic precipitator. As is known, the Coulomb force is responsible inside the electrostatic precipitator for moving the dust particles out of the waste gas stream, and the Coulomb force depends primarily from the high voltage between the corona and the wall electrodes. In special applications, e.g. very high-ohmic dusts or situations with strong back corona effects, a micro pulsing system is quite sufficient, as it delivers a very high voltage for a strong Coulomb force, but the time of the pulse is too short to ignite a flash over caused by back corona effects.

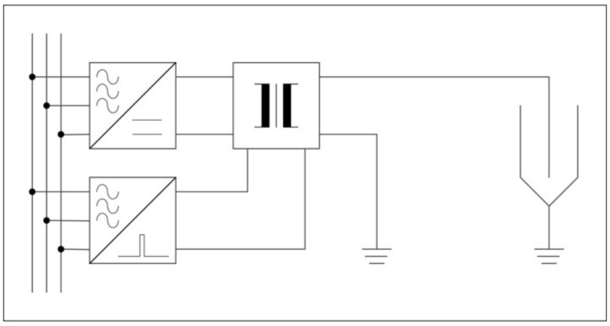

Figure 4: Principle of a Micro Pulsing System; two independent power sources are used for the direct current voltage and for the peak voltage and added together by a coupling network

3.4 The Switched Mode Power Supply System

There are some different kinds of high frequency based high voltage power supplies on the market, which are also known as switched mode power supplies (SMPS). Their main distinguishing value is the frequency of the transformer voltage. The structure of the high frequency power supply starts with an entrance circuit to rectify the grid voltage and build the intermediate voltage (Figure 5). From the intermediate voltage the IGBT output stage is supplied. The IGBT output stage provides a high frequency alternating current which is transformed into a high voltage. A rectifier with a following filter stage brings the high voltage to the electrostatic precipitator. Because of the high frequency in combination with the filter stage the output voltage of the high frequency system doesn't suffer from much ripple.

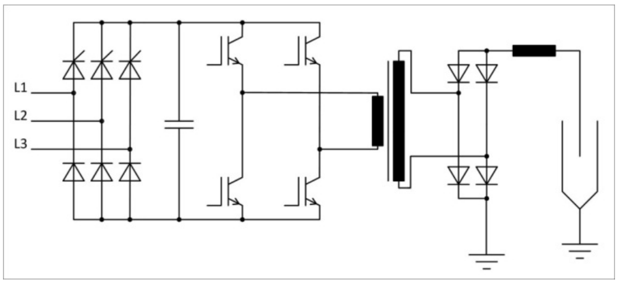

Figure 5: Principle of a Switched Mode Power Supply with the input rectifier stage, the intermediate circuit, the IGBT stage, the high voltage transformer and the high voltage rectifier; the high switching frequency of the IGBT stage in combination with electrical output filters results in a very smooth output voltage with a low ripple

Contrary to the thyristors, an IGBT power stage is able to switch off the current at any time, hence the reaction time of a switched mode power supply for an occurring flash over is quite short.

The main distinguishing value for the high frequency systems is their switching frequency in the IGBT stage. This frequency influences mainly the size of the transformer: The higher the switching frequency, the smaller the transformer can be, because the main inductance of the transformer can stay smaller at high frequencies (the main inductance is responsible for the no load cross current on the primary side of a transformer, Figure 6). On the other hand, the power loss of an IGBT stage consists mainly of two parts:

- The current dependent power loss at the IGBT is caused by the voltage loss over the IGBT during the conducting phase of the IGBT; there is a nearly linear relation between the system power and the current dependent power loss.
- The switching frequency dependent power loss is caused by the cross current through the IGBT bridge in the moment of the switching of the IGBTs; it increases linear with the number of switching cycles, i.e., a high frequency system has higher power losses in the IGBT stage than a lower frequency system.

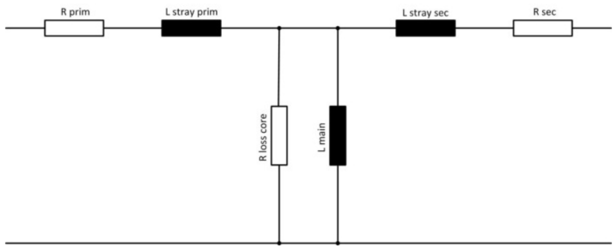

Figure 6: Principle circuit of the transformer; the size of the transformer depends on the frequency of the input voltage, as the reactive resistance of the main inductance L main depends linear on the frequency and determines mainly the cross current on the primary side

3.5 The Three Phase Current System

Three phase current systems are not very wide spread in the electrostatic precipitator market. They are from the architectural principle like the single phase systems, but they use all three phases of the supply grid, like the high frequency systems (Figure 7). Also similar to the high frequency system is the low ripple at the output voltage over a wide voltage range. The main differences between the three phase current and the high frequency systems are the sizes of the transformers, when the frequency of the switched mode power supplies is high enough to make a difference, and the behavior in case of short circuit in the electrostatic precipitator, i.e. in case of flash over, when the three phase current power supply is controlled with thyristors, as explained in the next paragraph.

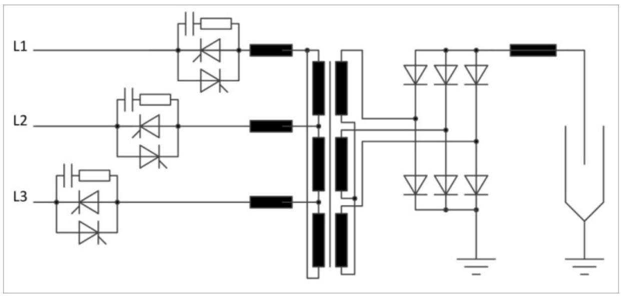

Figure 7: Principle circuit of the three phase current high voltage supply; the architecture is similar to the single phase system, the output voltage quality is comparable with the switched mode power supply systems; the input can consist of three sets of two thyristors each for a fully controlled thyristor bridge …

A three phase current power supply can be controlled by a so called semi-controlled thyristor bridge, which is indeed a thyristor-diode bridge, or by a fully controlled thyristor bridge.

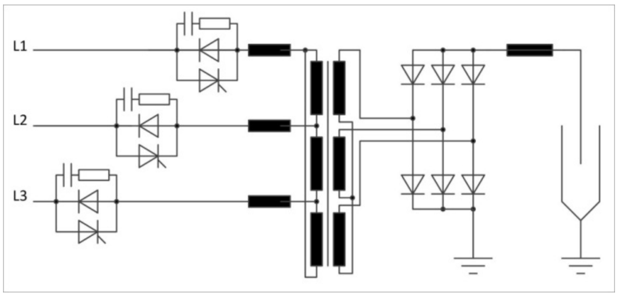

Figure 8: … or it consists of three sets of a diode and a thyristor each for the semi controlled bridge

The semi-controlled thyristor bridge consists of three thyristors and three diodes, which mean that only the positive half of the sinus wave is active controlled, the negative counterpart is connected by a diode (Figure 8). This means a ripple frequency of 150Hz and leads to a pronounced ripple amplitude, especially for small ignition angles.

A fully controlled thyristor bridge consists of six thyristors, hence all half waves of the three sinus can be controlled. This means a ripple frequency of 300Hz and a low ripple over a wide voltage range (Figures 9, 10).

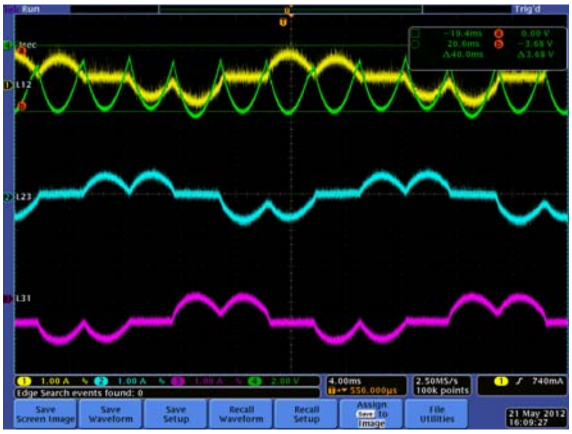

Figure 9: Oscillograph of the primary currents (red, yellow, blue) and the output voltage (green) of a three phase high voltage power supply with full controlled thyristor bridge; with an ignition angle of 25% the output voltage has 22% of the max. value …

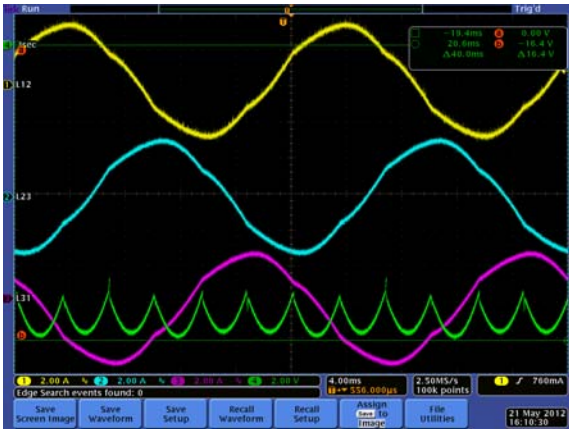

Figure 10: … and with 75% of the ignition angle the output voltage is 100% of the max value; the ripple is nearly without change over the dynamic range of 22% … 100%

Semi-controlled bridges are cheaper than the fully controlled ones, as diodes are cheaper than thyristors and the controller amplifier stage only has to get three ignition channels instead of six.

3.6 The Switching Components

One of the most important parts in the high voltage power supplies are the electronic switching devices, which can either be IGBTs (Insulated Gate Bipolar Transistors) or Thyristors rsp. SCRs (Silicon Controlled Rectifiers). The thyristor was developed in the late fifties of the last century. Since then it has been very successful, as it's working principle is rather simple. However, it has been improved over the years, the requirements for the control units have become more sophisticated (Figure 11).

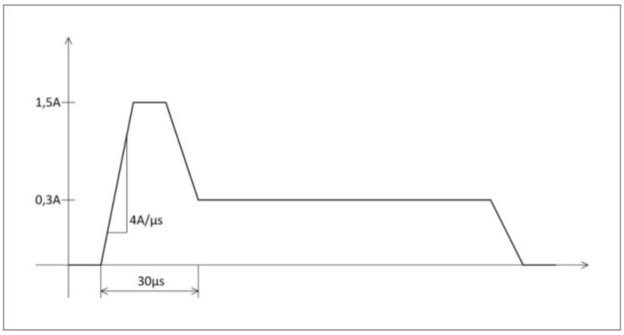

Figure 11: Shape of the ignition pulse for a modern thyristor; modern thyristors require a strong ignition current pulse with a fast switching on gradient [2]

But still the thyristor is a robust and reliable component. Its greatest disadvantage is that once it has been ignited, it will remain conducting until the current through it becomes smaller than the limit current for switching off. Hence a normal thyristor is only able to switch alternating current as a direct current does not become zero in regular time cycles. There is a special kind of thyristors, the so called GTO-types (Gate Turn Off) which can be actively switched off. But the switch off energy is quite high; hence this thyristor type is not very wide-spread; instead there are mostly used IGBTs nowadays.

The IGBT combines the advantages from a bipolar transistor, the very low conduction resistance, with the advantage of the field effect transistor, the very low switching energy. IGBTs are nowadays very wide spread in power electronic applications, they offer quite high performance with reference to the switching capabilities (voltage and current). Because of the low switching energy the driver circuits for the IGBTs are also rather small, compared to standard bipolar transistors. As the IGBT is a real transistor type, it can actively be switched off whenever it is necessary. Sufficient protection circuits take care that the IGBT does not suffer from overvoltage damage when switching off an inductive load.

The comparison of a thyristor switch (MCO740-22 with a specified reverse voltage VDRM = 2200V and a corresponding forward current ITDC = 1978 A) and an IGBT (FZ1800R17 with a collector emitter voltage UCE = 1700V and a corresponding collector current IC = 1800A) show the following results (Table 1) [3]. As can easily be seen, there are two main differences in the characteristics of the IGBT and the thyristor:

	MCO740-22	FZ1800R17
Offset Current	2mA	5mA
Onset Voltage	1,45V	1,8V
Power Loss at max. current	2868W	3240W
Switching Cycle Energy	10mJ	8mJ
Switch on Time	2,2µs	0,8µs
Switch off Time	375µs at Zero Cross	1,5µs
Overcurrent Capability	32kA for 10ms	7,5kA for 10µs

Table 1: Comparison of Thyristor and IGBT

- The switching off behavior of an IGBT enables it to switch off the current at every time very quick. Especially in the electrostatic precipitator applications this may become an advantage to avoid burning arcs after a flash over. For the thyristor the voltage has to cross the zero for a certain time until the thyristor becomes nonconducting.
- The overcurrent capability of the thyristor is much stronger than the capability of the IGBT; this makes the IGBT a sensitive component in the power electronic. Especially for the power supplies of an electrostatic precipitator where the short circuit situation happens more or less with every flash over the switching devices have to bear a heavy load.

3.7 Power Losses

Mainly there have to be considered three different types of power within an alternating current system:

The real power is the power which is transformed in a different kind of power, e.g. in heat, in mechanical power, in field force etc. The real power occurs when in the AC system the voltage and the current are in phase (Figure 12). The multiplication of the moment voltages and currents always leads to a positive result for the power, the power flow is always in the same direction.

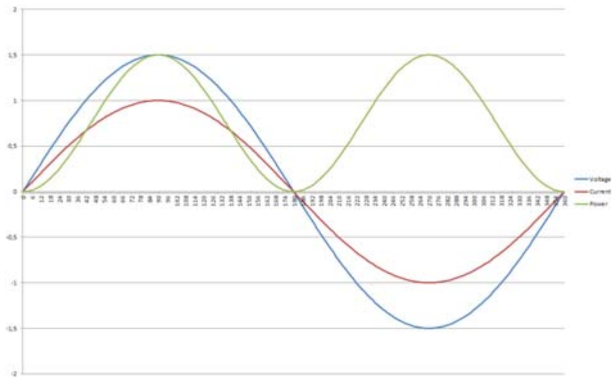

Figure 12: Alternating voltage (blue) and current (red) are in phase, they cross the zero line at the same moment; the power (green) which momentary values are the product of the momentary values of voltage and current is always positive over the whole period; the power from the supply system is always flowing in one direction

The reactive power is the power which is stored in a system for a while and flows back to the power source. The reactive power is a typical phenomenon of AC systems with inductive or capacitive loads; inductivities and capacitors are used for power storage. The reactive power occurs in the AC system when the voltage and the current are different in phase (Figure 13). The multiplication of the moment voltages and currents leads to positive and to negative results for the moment power values, which means, that the power is going back and forth within the system. In principle reactive power does not have an influence onto the power balance as it does not leave the system, but the flowing currents cause a real power loss at the lines as there do not exist non-loss lines in normal systems. Hence the lines have to be dimensioned not only for the real power current, but also for current of the reactive power part.

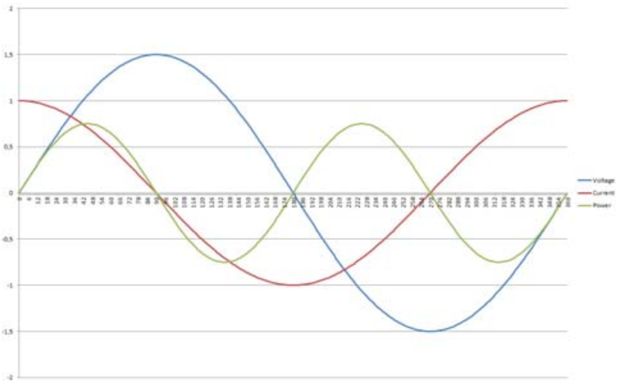

Figure 13: Alternating voltage and current with a phase difference of 90°, the current is earlier in the position than the voltage in this example, it goes ahead; the power gets negative and positive values, it stays in the system and is not converted into different kinds of power

The apparent power is the sum of the real and the reactive power. As they are not in the same direction in the vector diagraph, they have to be added as vectors (Figure 14).

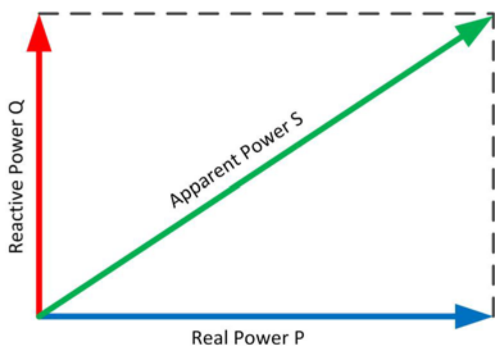

Figure 14: Vector diagraph of the relation between real, reactive and apparent power; as the vectors are not in phase, they have to be calculated geometrically, i.e. their values and angles have to be considered

The calculation of the apparent power leads to the total current flow in the system. The cabling and the components of the switching cabinet have to be dimensioned with reference to the current of the apparent power. The relation between the real, the reactive and the apparent power is as follows:

$$S^2 = P^2 + Q^2$$

There are several factors defined which describe the indicating relations of power in alternating voltages:

The power factor is a number which shows the relation between the absolute value of the real power and the apparent power. The power factor is "1" when the real power is similar to the apparent power, it becomes "0" when the real power vanishes and only reactive power remains. In a system which does not only consist of pure sine waves of one single frequency, the power factor is also influenced by the form factor and the crest factor.

$$f_P = \frac{|P|}{S}$$

The active factor is the relation between the real power and the apparent power of a pure sine wave. In systems with harmonic waves, a system of sine waves with frequencies which are multiplied with an integer compared with the base frequency, the active factor for each of the sine waves can be different to the others. Hence the power factor and the active factor are different for non-sinusoidal systems.

$$f_A = \frac{P}{S}$$

The form factor of an alternating voltage shape is the relation of the root mean square value (RMS) to the average rectified value (ARV) of the voltage.

$$f_F = \frac{\sqrt{\frac{1}{T} \cdot \int_{t_0}^{t_0+T} f^2(t)dt}}{\frac{1}{T} \cdot \int_{t_0}^{t_0+T} f(t)dt}$$

The crest factor is the relation of the peak value to the root mean square value of an alternating voltage.

The distortion factor gives some information about the relation between the sine amplitude of the basic frequency and the amount of amplitudes of the harmonic waves, i.e. the integer frequency multipliers of the basic frequency. Each voltage shape, especially oscillating voltages, can be described of an infinite number of partial sine waves by the so-called Fourier-analysis. The Fourier-analysis can be used to calculate the distortion factor of any oscillating voltage, e.g. rectangular or cut sine waves. The distortion factor is “0” when the voltage is a pure sine wave.

4 Technical Comparison of the Three Phase Current System and the Switched Mode Power Supply System

The architecture of the three phase current system and the switched mode power supply can be distinguished mainly by the intermediate circuit and the following IGBT switch bridge which is part of the SMPS but not necessary in the three phase current system (Figure 15).

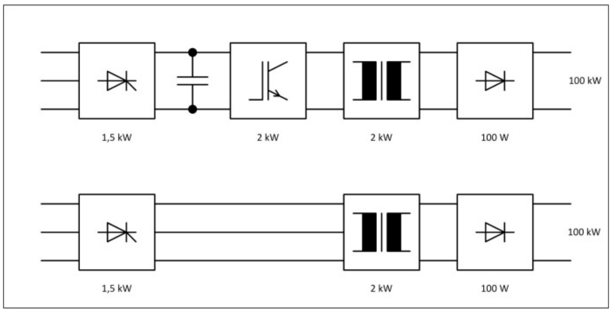

Figure 15: Two Gate Models of the switched mode power supply (above) and the three phase current power supply (below); as can be seen easily there is one more sink of real losses in the switched mode power supply

To put through a certain power from the supply grid to the electrostatic precipitator the power has to pass the input rectifier rsp. the thyristor bridge. Behind the transformer the power has to pass the high voltage rectifier to reach the electrostatic precipitator. The power losses in the rectifier and in the thyristor bridge rsp. as well as in the transformer and the high voltage rectifier can be considered to be nearly similar. For the switched mode power supply there is the IGBT switch bridge in front of the transformer to convert the DC voltage in the intermediate stage into AC voltage for the transformer. In the IGBT switch bridge occur additional real losses. They can be considered to be at least as high as the losses in the entrance rectifier or even higher.

Further on the three phase current system works on the grid frequency level, which is usually 50 … 60Hz. Hence the components which are used, e.g. the transformer core, can be made of simple material for a reasonable price; also the connecting cables are standard cables for grid technology off the shelf. It is not necessary to care about the special cable requirements or place the power switch close to the transformer rectifier set in an unkind environment, e.g. on the roof of the electrostatic precipitator.

The higher real losses in the switched mode power supply lead to a high effort in cooling systems, usually realized by electromechanical fans with all the disadvantages which are included with that parts: limited lifetime, additional real power to drive them, high maintenance efforts.

Finally, the request of a transformer rectifier set for a new primary or secondary voltage or power range takes several days at the construction desk to get the new product and does not start a completely new development with all the challenges new product developments are accompanied with.

A realistic comparison shall not disregard to discuss the difference in the power factor. The power factor of a switched mode power supply stays under normal conditions well over 0,92, while the power factor of the three phase current power supply can go down below 0,8.
The power factor stays rather constant at the switched mode power supply, as between the inductive parts of the system and the power input there is placed some kind of rectifier and the intermediate capacitor.
The power factor at the three phase current system depends mostly on the load, as behind the thyristor block there is mounted the current limiter choke. For maximum load situations the power factor is about 0,86 … 0,9 (depends on the system parameters), the lower the load situation will become the lower also the power factor will be. But the influence of the low power factor in combination with a very little load current to the supply grid is not that high.

5 Application samples

In general a high voltage power supply for an electrostatic precipitator reacts simply to the electrical attributes of the electrostatic precipitator, which always depend on a variety of parameters, like the temperature of the waste gas, the resistivity and permittivity of the dust, the chargeability of the particles, the consistency of the waste gas and the particles etc. The higher the voltage is over the gas area between the discharge and the wall electrode, the stronger are the electric field force and the Coulomb force. The systematic limitation of the voltage is given by the flash over point which always depends on the actual ESP situation.
The current which flows through the electrostatic precipitator when there is connected a voltage source, might be useful or disturbing. This also depends on the situation in the ESP. If high current values become disturbing, one of the measures for improvement is the so called pulsating modus. In the pulsating modus the high voltage is

switched on for a short time and the gap between the pulses is filled with a significantly lower voltage, the so called fill in voltage (Figure 16).

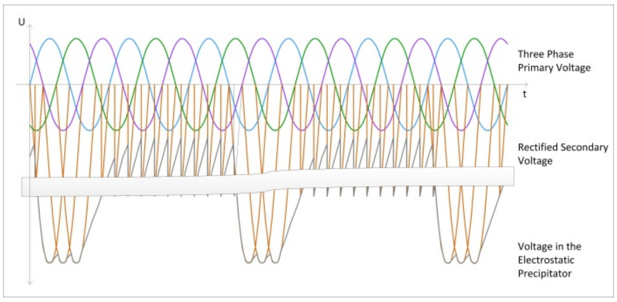

Figure 16: Pulsating voltage shape with a three phase current system: full half waves and cut sine waves for fill in voltage are switched behind each others

It has been discovered many years ago, that a smooth voltage for the field force is more efficient than a voltage with high ripple as produced by the single phase systems, often called the conventional types. This smooth voltage may be produced by a switched mode power supply or a three phase current system, there is no significant difference in the outlet dust rate. The smooth voltage seems to be of advantage, even when it is applied for the fill in voltage in the pulsating modus. In this case also the three phase current systems and the switched mode power supplies are performing more satisfying than the single phase systems.

There are application samples, when a three phase current system is installed instead of a single phase system, which indicate clearly that the precipitation efficiency can be improved significantly, but the improvement of the precipitation efficiency may cause higher or lower energy turnover. This depends on the situation in the ESP the operation mode (continuous voltage mode or pulsating mode) is adapted to.

6 References

[1] V. Reyes et al: 4th generation of Coromax pulse generators for ESP's, 12th ICESP 2011, Nuremberg

[2] Ixys: Data sheet of MCO740, January 2006

[3] Infineon: Data sheet of FZ1800R17HP4, June 2012