Power Electronic Modelling and Emulation of an Electrostatic Precipitator

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1   Summary / Abstract:

In this paper a power electronic emulation of an electrostatic precipitator is presented. Precipitator power supplies can be tested under real power and operating conditions up to 200 kVA. Energy consumption of the system is very low, because the energy which is drawn by the emulation converter is fed back into the power grid. Therefore, just the power losses have to be provided by the grid. It is possible to implement different precipitator models to verify real plant operation conditions or to optimize parameters for new precipitator designs. Precipitator power supplies can be tested as well in static as in dynamic operation points to verify the proper function of the device in the laboratory.

2   Introduction

In today's development processes it is a big advantage to have a test system available for the developed devices. Such test equipment exists for dedicated applications like motor inverters [1-4] and converters in complex systems like escalators[5]. The test system makes it easy to get an impression of the device under test and different states of the tested device can be emulated. Thus, the performance of a power supply can be tested under real power conditions during the development already. Herby, the power used during a system test can be recovered and fed back in to the power grid. That makes long term tests cheaper and more reliable.
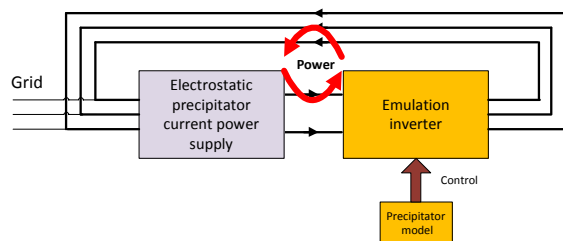

Fig 2-1: Block diagram of the device under test and the emulation inverter

Fig 2-1 shows a test of an electrostatic precipitator power supply. Basically, there are two different methods for the test of the power supply. The first system is the "hardware in the loop test system" for testing control unit of the converter. Here the control unit operation can be tested by using different precipitator types and scenarios. The IGBT pulses of the control unit are acquired and the precipitator current and voltage are emulated using a precipitator model. This test system can also be used for testing different precipitator models and high voltage transformer parameters.

The test system can be extended to a "power electronic hardware in the loop test system". In this system the real power supply of the precipitator is connected via a coupling network to an emulation inverter. During the test the energy produced by the precipitator power supply is absorbed by the emulation converter and fed back into the power grid. In the test scenario different precipitator models with adjustable parameters could be emulated. It is also possible to emulate recorded data of real precipitators.

3 Scope of Application

With the power hardware in the loop test system high voltage power supplies for electrostatic precipitators can be tested under realistic conditions in the laboratory. The device under test will be tested using realistic V/I-characteristics of an electrostatic precipitator. The device under test can work in different operating points. This was not possible in classic test systems using resistive loads.

During the test a real time precipitator model is calculated by the emulation system. In the model any parameters of the precipitator and the high voltage transformer could be considered. It is also possible to emulate recorded plant data to verify the ESPs power supply operation. Using the emulation system the controller and the control algorithm of the power supply can be verified, too.

4 The basic concept

4.1 Real Time Precipitator Model

The precipitator model is used for the two emulation strategies, the hardware in the loop system and the power hardware in the loop emulator. For the first test an easy model was implemented into the emulator shown in Fig 4-1.
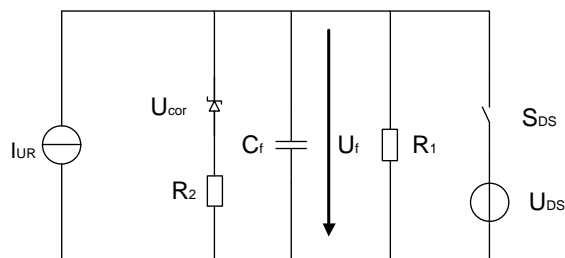

Fig 4-1: Simple electric model of the electrostatic precipitator

The precipitator model can be divided into three main functions. In the first state of the model the filter voltage U_f is low and the power supply starts feeding current I_{UR} into the precipitator. The voltage starts rising on the filter capacity C_f with a parallel resistance R_1 reproducing the dielectric losses in the model. The precipitator voltage in the precipitator can be calculated using equation(1.1).

$$U_f = \frac{I \cdot X_c \cdot R}{X_c + R} = \frac{I(s) \cdot R}{1 + R \cdot C \cdot s} \qquad (1.1)$$

After the voltage reaches a minimum corona voltage U_{COR} there is a second resistor R_2 in parallel R_1 representing the corona discharge current. By closing the switch S_{DS} electrostatic discharges could be produced as the precipitator voltage U_f drops down to U_{DS}.

All the precipitator parameters are transformed to the low voltage side of the high voltage transformer. The parameters are calculated by the digital signal processor after entering the parameters of the transformer and the filter.

Even this model is a very simplified one for an electrostatic precipitator, it is possible to implement a more complex model. Different models could easily be verified using either the controller in the loop operation with the control unit or the emulation inverter.

4.2 Controller in the Loop Operation

For testing different operation conditions of the precipitator power supply control unit, the hardware in the loop test system has been implemented. In this test mode the control system is directly connected to the emulation unit. After a signal conditioning stage the IGBT driving signals are sampled in the emulator controller. From the gate pulses the output voltage of the power supply can be calculated. With the model both, the precipitator voltage and current are calculated and converted to analogue signals using a digital-analogue converter (DA-converter). The signals then are fed back to the control unit and into the current controller of the unit (see Fig 4-2).
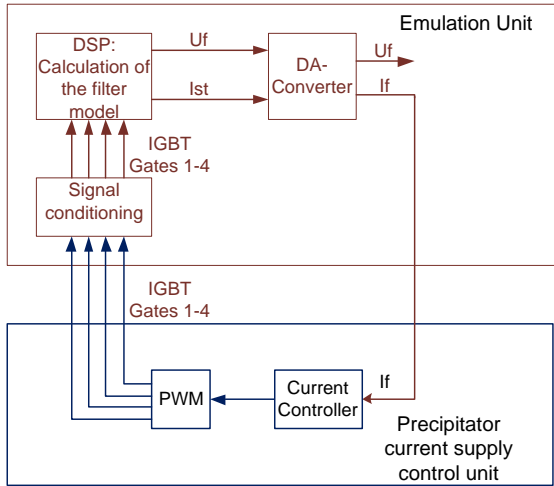
Fig 4-2: Block diagram of the hardware in the loop test system of the electrostatic precipitator

In the digital signal processor (DSP) of the emulation unit the precipitator model is calculated every 10us. After this time a new value for the current and voltage appears at the feedback. The model parameters of the precipitator and the high voltage transformer are calculated in the processor. Every parameter of the model can be changed during operation.

This test system has a great advantage in the controller development process. The electrostatic precipitator behaviour could be implemented and the reactions of the controller to different parameter changes could be checked. A second advantage for the controller development is that no power and currents are generated in the system. So the danger of damaging parts of the system is minimized.

4.3 Power Electronics in the Loop Operation

When using the power electronics in the loop operation a frequency converter is connected via a coupling network to the precipitator power supply. The energy absorbed by the emulation unit is fed back in to the grid by an energy feedback unit. The emulation unit of the test system was built as a two stage interleaved converter. With this converter it is possible to change the emulated voltage with a higher bandwidth. It prvides the possibility to drive higher power in the loop.
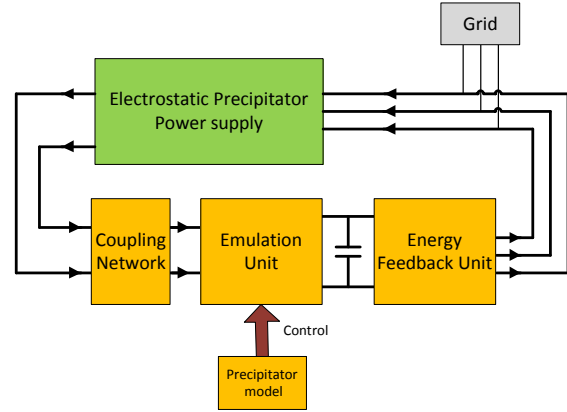

Fig 4-3: Assembly of the high voltage power supply with the emulation inverter

In this emulation strategy the same precipitator model, as described in section 4.1, is calculated by the control unit of the emulation inverter. Now the output of the emulated model is the precipitator voltage signal which is now used to control the emulation inverter. In this operation mode different models of the precipitator and the high voltage transformer could be implemented as well.

For the exact control of the precipitator voltage by the controller of the emulation unit the transfer function of the input inverter and the coupling network was calculated using state space averaging technique [6, 7]. After calculating and simplifying the transfer function and putting it into the laplace-space the transfer function can be written as shown in equation(1.2).

$$G_{str}(s) = \frac{U_f}{d} = \frac{-U_o \cdot (R_C \cdot C \cdot s + 1)}{\frac{L \cdot C}{2} \cdot s^2 + \frac{R_L \cdot C + 2 \cdot R_C \cdot C}{2} \cdot s + 1} \quad (1.2)$$

The transfer function in equation(1.2) shows a PT2-behaviour of the emulator system. This behavior and the poles and zeroes of the system can be cancelled by the voltage controller of the emulator. When using the pole and zero cancellation technique [8] almost any desired behavior of the emulator can be achieved.

When changing the phase shift of the interleaved emulation unit, even dynamic changes of the precipitator voltage can be emulated.

4.4 Energy Recovery

The energy feedback can be archived in two ways. One solution is the coupling of the DC-links of the device under test and the emulation unit. When doing so, only the output stage of the device under test is used. The second way is the coupling of the converters thru the power grid. In this assembly the whole device under test is in operation.

When using the feedback over the power grid the grid current is controlled to a sine wave form, which has to be in phase with the grid voltage. Only the losses of the system must be fed by the grid. The main part of the energy is directly fed into the device under test.

5 Power Converter for Load Emulation

The power converter for the load emulation can be divided in two parts, the emulation- and the energy feedback unit. This converter is connected to the electrostatic precipitator power supply via a coupling network (see Fig 4-1).

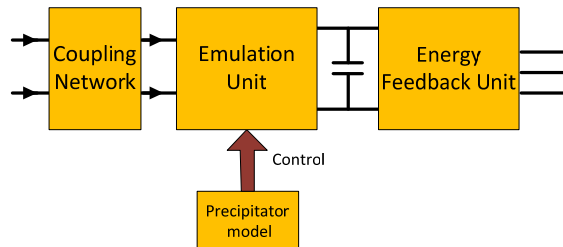## 5.1 Basic circuit description, block diagram

Fig 5-1: Block diagram of the test system

5.2 Topology of the emulator unit

The emulation unit of the power converter for the load emulation consists of a two stage interleaved boost converter shown in the right part of Fig 5-2. The converter can easily be expanded with further interleaved stages for higher power conversion rate of the converter or a better dynamic response.

5.3 Coupling Network

In the coupling network the ac-current of the current power supply is rectified and then the precipitator voltage is controlled on a capacitor shown in Fig 5-2.
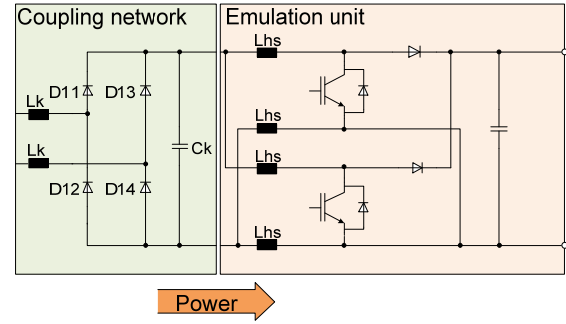
Fig 5-2: Block diagram and topology of the coupling network and the emulation unit of the test inverter

The capacitor voltage stands for the precipitator voltage transformed to the low voltage side of the high voltage transformer. Additionally, the parameters of the high voltage transformer could be changed in the emulation model.

5.4 Control

The emulated precipitator voltage is controlled by a digital signal processor (DSP). The transfer function of the coupling network and the inverter stage was calculated in section 4.2. With this transfer function a PIDT1-controller was calculated using the pole and zero cancellation technique described in [8]. The main transfer function of the controller can be seen in equation(1.3).

$$G_R(s) = \frac{K_R \cdot \left(T_N T_V s^2 + T_N s + 1\right)}{\left(1 + s\tau_1\right) \cdot s T_N} \quad (1.3)$$

With the factors of equation(1.3) the poles and zeroes in the converter transfer function are cancelled to get a PT1-Behaviour of the whole system G_W.

$$\omega_s = \frac{1}{\sqrt{\dfrac{L \cdot C}{2}}} \quad (1.4)$$

$$\vartheta_s = \frac{\dfrac{R_L \cdot C + 2 \cdot R_C \cdot C}{2} \cdot \omega_s}{2} \quad (1.5)$$

$$T_N = \frac{2 \cdot \vartheta_s}{\omega_s} \quad (1.6)$$

$$T_V = \frac{1}{2 \cdot \omega_s \cdot \vartheta_s} \qquad (1.7)$$

$$\tau_1 = R_C \cdot C \qquad (1.8)$$

When the parameters of the controller are set as in equation(1.4) to(1.8) the transfer function of the whole system G_W has PT1-behaviour, shown in equation (1.9)

$$G_W = \frac{-1}{\dfrac{T_N}{U_o \cdot K_R} \cdot s + 1} \qquad (1.9)$$

- Phase shifting technology

5.5 Grid Side Converter

The main task of the grid side converter is the control of the DC-link voltage to a constant value. The energy which is affiliated by the emulation inverter has to be fed back into the power grid and the device under test. The main energy is fed directly into the device under test. Only the losses of the inverters in the test have to be delivered by the grid.

The grid currents are controlled to be sinusoidal and in phase with the phase voltages to only affiliate active power. All harmonics produced by the device under test were cancelled by the active front end of the emulation inverter. To avoid a feedback in the emulated currents between the device under test and the emulation inverter a galvanic isolation is inserted on the grid side of the emulator using a 1:1 transformer.

5.6 Topology, Block diagram

The energy feedback unit contains of a B6 IGBT bridge and a transformer for galvanic isolation between the two inverters.
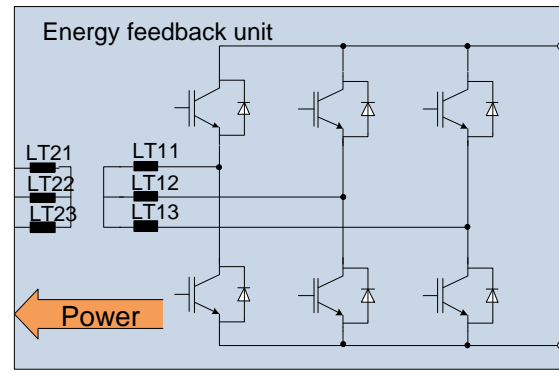

Fig 5-3: The grid side converter contains of a B6 IGBT inverter and a transformer for galvanic isolation

5.7 Control

The DC-link voltage of the emulator is controlled by a voltage and current controller in cascaded mode adapted by a harmonic controller shown in Fig 5-4.
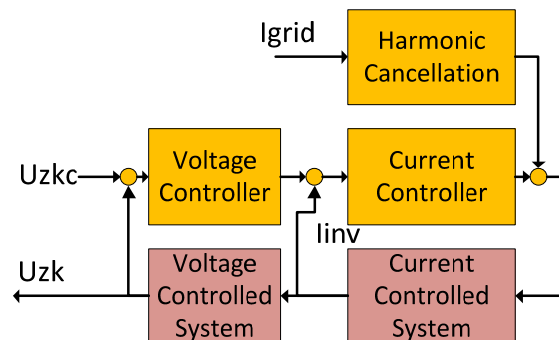

Fig 5-4: Block diagram of the control system of the grid connected power inverter

The voltage controller of the cascaded mode calculates the current which has to be fed out of the emulation converter. The current is controlled by a current controller in the inner loop of the cascaded mode control system. This has the advantage that the emulator current can be controlled modulated in phase and amplitude by the harmonic cancellation control. The cascaded mode control only controls the basic frequency currents. The harmonics of the power converter are controlled by the harmonic cancellation unit.
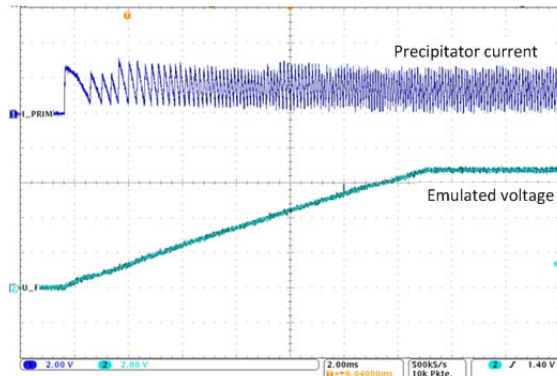
5.8 Harmonics Compensation

The harmonic cancellation unit in the control system shown in Fig 5-4 controls the harmonics of the grid current. It regulates the phase current in phase with the voltage and

cancels all the harmonics on the grid current (see Fig 6-4).

6 Experimental results

6.1 Controller in the Loop results

Fehler! Verweisquelle konnte nicht gefunden werden. shows the charging of the precipitator capacity with constant inverter current. The emulated model is described in section 4.1.
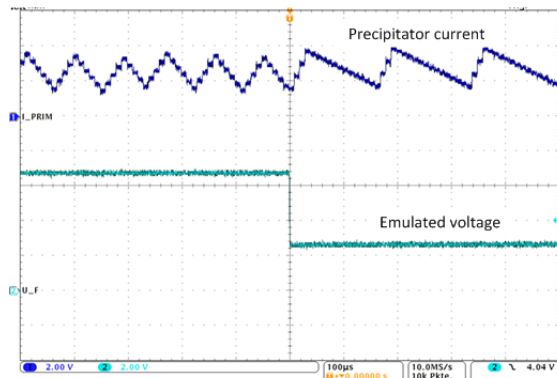

Fig 6-1: Precipitator output current after a strong change of the voltage

In Fig 6-1 the change in the filter current after a step of the emulated voltage can be seen. This effect happens after an electric discharge of the filter capacity. The shape of the emulated current changes immediately after the voltage change. Due to the current control of the device under test the average current is kept constant during change of the voltage. In Fig 6-1 also the small steps of the calculation time of $t_C = 10\mu s$ can be seen.

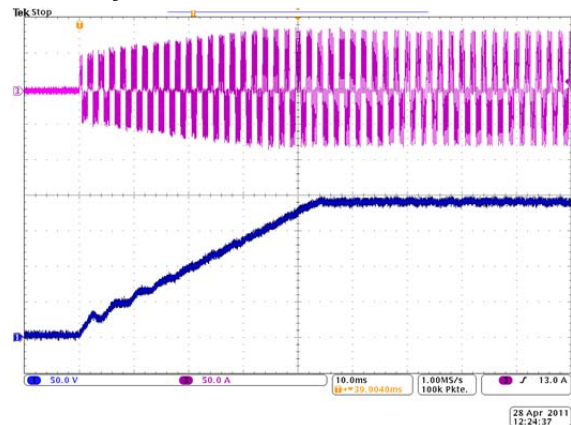## 6.2 Power Electronics in the Loop System

Fig 6-2: Precipitator current (purple) and voltage (blue) using a simple precipitator model in the power hardware in the loop system

Fig 6-2 shows the charging of the precipitator capacity when the precipitator's power supply is switched on. The voltage rises to the value, where the extended resistance of the corona losses in the model becomes active. After this state the increase of the voltage is fairly low.

When zooming into the current and voltage of Fig 6-2 a better impression of the precipitator power supply output current and the emulated voltage can be seen in Fig 6-3
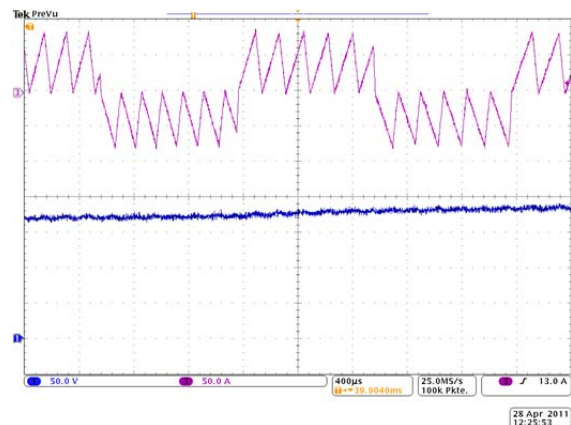

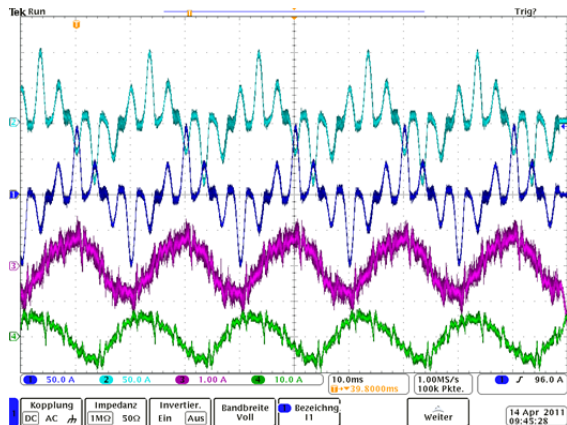Fig 6-3: Precipitator current (purple) and voltage (blue)

Fig 6-4: inverter (blue and turquoise) and grid (purple and green) currents of the energy feedback part of the emulator

Fig 6-4 shows the output currents of the grid side converter of the test system and the grid currents during the test. In this picture it has to be considered that the grid currents have a peak value of $\hat{I}_{Grid} = 10A$ and the emulation inverter output currents have a peak current of $\hat{I}_{INV} = 60A$. During the test of the precipitator power supply the main energy of the experiment is fed directly into the device under test.

7 Conclusion

In this paper a platform for testing electrostatic precipitator power supplies is presented. With two different emulation strategies simplified and complex precipitator models can be emulated. With such an emulation system the precipitator power supply control unit and its inverter system can be fully tested. The parameters of the precipitator model and the high voltage transformer can easily be changed during the test. It is possible to include more parameters into the model such as temperature, fluid mechanic parameters, chemical analysis of fuel (e.g. coal data), electrical wind etc... Also measured data of an existing electrostatic precipitator can be emulated.

During the emulation the energy used by the device under test is affiliated by the emulator and fed back in to the power grid. So the energy consumption of the whole system is very low. This has an advantage when performing long time measurements.

9 Literature

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