High Voltage Pulsed Power Converters for the ESS Linear Accelerator

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***Abstract* – With new demands on lighter, cheaper and environmentally sustainable materials, the research has to go down to atomic levels in order to study the materials properties. This becomes possible with the European Spallation source (ESS), a research center based on the world's most power full neutron source. The accelerator Linac will accelerate a beam of protons with a peak power of 123 MW, due to the pulsing nature and strict standards a new design for converting power between the grid and the capacitor banks of the klystron modulators is developed.**

This is a popular summary of the master's thesis "High Voltage Pulsed Power Converters for ESS Linear Accelerator".

I. INTRODUCTION

The European Spallation Source (ESS) is an international research institution built by at least 17 European countries, with Sweden and Denmark as host nations. It will be located in Lund, Sweden, where it will be a research center based on the world's most powerful neutron source [1]. The project will enable new opportunities for improving material science research with positive impact on our everyday lives. With today's new requirements on lighter, cheaper and environmentally sustainable materials, the research has to go down to atomic levels in order to study the materials properties. This becomes possible with neutron research so that material science can develop and improve all the thousand products that are used in people's life [2].

Figure 1: The ESS facility [3].

In order to generate the electromagnetic fields in the cavities for beam acceleration, radio frequency (RF) power sources are required. The RF system converts AC grid power to RF power at either 352 or 704 MHz, which is the required frequency for different sections of the accelerator. In order to supply the accelerator with an average power of 5 MW, 4 % of duty cycle and a repetition rate of 14 Hz the RF system must supply over 123 MW in peak power. [3]

When designing the capacitor chargers, which are the first power converting steps in the modulators, there are several factors that have to be taken into account. This because of the connection to the low voltage AC-grid and the high power pulsing nature of the accelerator, the converter (modulator) topology together with the control loops need to be designed and dimensioned in such a way that international standards on power quality are met. With the chosen topology, see Figure 2, and advanced control loops, a flicker-free and sinusoidal current absorbing connection with unitary power factor is made possible. The approach will also provide a high efficiency and a modular based parallel formation, which will make a hypothetical expansion easily managed. Because of the low voltage connection and the module concept, all the components can be chosen from the conventional market and the structure will not require inclusion in oil tanks for insulation reason.

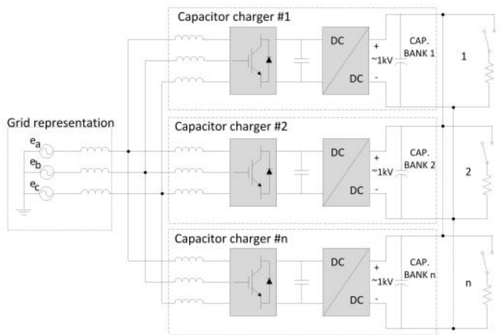

Figure 2: Block diagram of the capacitor charger concept, where the modulator consists of an Active Front End and a step down DC/DC - converter.

II. METHOD

The modeling and the simulations of the capacitor charger were implemented in *Matlab/Simulink*. All electrical components such as transistors, diodes, etc. are implemented with help of the *simPowerSys* library. The power losses for the converters are calculated separately with mathematical equations in a Matlab-script, this to get more flexible, faster and accurate calculations.

III. CONTROL STRATEGY

The controllers for the Active Front End (AFE) and the DC/DC-step down converter are separated into two completely independent controllers. In order to achieve a system that compromise between speed and stability the phase margin is chosen to 60˚ [4].

The AFE is an active 3-phase rectifier controlled by a couple of feedback loops. The main purpose of the conversion is to transform the source power at the AC side to a controllable DC load power. In order to simplify the control, transformations are established from the 3-phase AC representation to a two-vectored rotating frame. Due to the possibility of controlling the active and reactive power individually in both directions through the AFE, it's possible to adjust the power factor [5]. The AFE controller consists of a current control loop and a cascade coupled voltage control loop. An overview control concept can be seen in Figure 3.

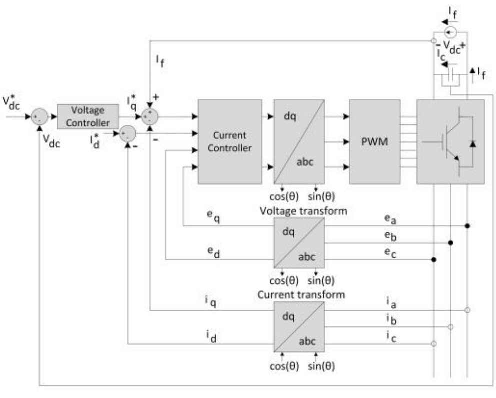

Figure 3: Block diagram of the AFE controller concept.

The DC/DC-converter is a one-quadrant step down converter with control of current, voltage and power. The main purpose is to control the power from a steady DC-source voltage to a load that in this case is pulsing. Because of the pulsing nature a completely new-developed power control is implemented to only affect the DC-source with a constant power. For safety and in order to assure correct voltage levels for all semiconductors a voltage control is implemented to prevent too high or too low voltages. The power control and voltage control are coupled together with a switch that with a smart logic decides which control should be active. The switch is connected to a current control and Pulse Width Modulator (PWM) before connecting to the system. An overview block diagram can be seen Figure 4.

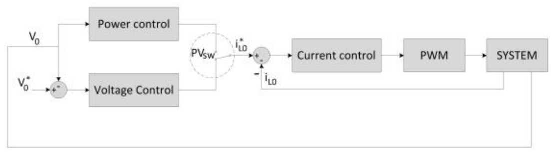

Figure 4: Block diagram of the DC/DC-step down controller concept.

IV. RESULTS

The main focus has been on fulfilling the IEC standards regarding power quality, 61000-3-2 and 61000-3-3 for rated currents below 16 A, together with active power regulation, sinusoidal current absorption from the grid and high voltage precision at the output.

Power losses and efficiencies in this application are estimated with mathematical expressions. The AFE and DC/DC are calculated separately and then merged for a full system result. The efficiency is 93.85 % with a switching frequency of 7.5 kHz but can be significantly higher with a reduced switching frequency.

Table 1: Efficiency of the power converter (AFE and DC/DC).

Frequency	Efficiency @50 kW	Efficiency @100 kW	Efficiency @200 kW
3 kHz	96.88 %	97.06 %	96.92 %
5 kHz	95.21 %	95.60 %	95.55 %
7.5 kHz	93.13 %	93.79 %	93.85 %
15 kHz	87.00 %	88.41 %	88.81%

The IEC 61000-3-2 concerns the limitation of current harmonics injected into the low voltage grid. According to the standard, the second harmonic is the strictest, which is below 2 % compared to the 50 Hz fundamental. All current harmonics presented in Table 2 is far below this limit.

Table 2: AC-line current harmonics level compared to the 50 Hz fundamental.

Harmonic Order	Harmonic @50 kW	Harmonic @100 kW	Harmonic @200 kW
2	0.07 %	0.11 %	0.07 %
3	0.05 %	0.11 %	0.05 %
5	0.16 %	0.2 %	0.16 %
7	0.09 %	0.1 %	0.09 %
9	0.03 %	0.04 %	0.03 %
$11 \leq n \leq 39$	< 1.5 %	< 1.5 %	< 1.5 %

The IEC 61000-3-3 concerns a standard regarding voltage fluctuations, voltage changes and flicker on applications connected to the low voltage grid. According to the standard, flicker level for voltage changes at 14 Hz shall not exceed 0.3 %. Flicker levels in Table 3 are calculated during pulsing based on connection to a 250 kW rated power transformer.

Table 3: Flicker level compared to the nominal voltage.

Power level	Flicker level
50 kW	0.0078 %
100 kW	0.019 %
200 kW	0.059 %

Simulations have been done in order to verify that the system behaves as expected and fulfills the requirements. From Figure 5 the following results are achieved:

- The current absorbed from the grid is sinusoidal shaped with a high frequency switching ripple on top.
- The power is constant with reactive power compensation, when the output load is pulsing at steady state.
- The output voltage precision is better than 0.1 % at the first pulse and better than 0.01% at steady state.

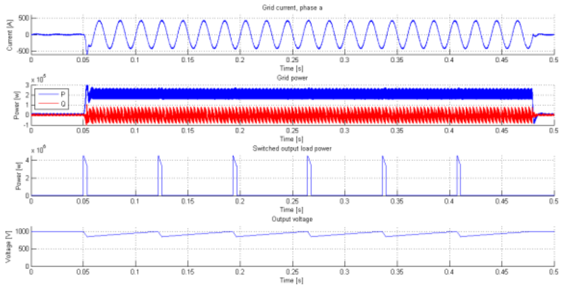

Figure 5: Plots from 200 kW simulations with output quantities; Grid current in phase a, active and reactive grid power, switched output load power, output voltage.

V. CONCLUSIONS

The strictest IEC standards, 61000-3-3 and 61000-3-2, for flicker and low harmonic currents content are applied, where the rated currents are lower than 16 A. This application sinks up to 4 MW in a pulsing pattern and has nominal sinusoidal currents up to 300 A and still fulfills these strict standards. Power drawn from the grid is active only and constant when the load is pulsing and the output voltage precision better than 0.1%.

The power losses and efficiency for the system are dependent mainly on switching frequency for the transistors. Conduction losses are merely a fraction of the total loss and the smallest contributing part of these two. A reduction of switching frequency down to 5 kHz could be considered since the accuracy margin is significantly good.

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