Unipolar Current Source for Arbitrary Waveforms

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Reto Schneider, Guido Blokesch and Marcel Frei
Ampegon AG, CH-5300 Turgi, Switzerland

***Abstract*—Particle Accelerator facilities need beam deflectors driven with high kA current sources capable of producing variable pulse forms. The ability to switch down unknown impedances, such as arcs, with controlled current outputs is anticipated to be highly beneficial for plasma and fusion applications. A novel, fully solid state pulsed current source, able to drive highly dynamic or inductive loads, is presented. Due to the modular architecture a high level redundancy and maximum performance can be achieved.**

I. Introduction

Current sources with power outputs up to several megawatts are key components for plasma sources and beam deflecting equipment. On one hand, plasma sources require a high peak voltage to ignite an arc and a stable current throughout the duration of the pulse. On the other hand in accelerator facilities the beamlines have to be divided in order to deflect the beam to energy boosters or to branch the beam, time limited to different user applications. Since, these operation cycles depends on the bunch train lengths and the repetition rates pulsed currents higher than 10 kA are required.

For low power sources, linear amplifiers or a combination of a linear amplifier and variable or switched voltage source are used. Conventional high power current sources are typically based upon resonant LC circuits. Consequently, long current pulses require low resonant frequencies and therefore voluminous and expensive resonant circuits. Resonant operation is often triggered by a thyratron or a thyristor switch, which does not allow an interruption in case of a failure. On the other hand, classical approaches such as simple buck converters are limited in terms of current shaping capability and losses, due to high switching losses of the medium voltage IGBTs. In this paper, a novel approach is presented, utilizing a 3-Level Converter and one or more Multi-Level Marx-Type Converters. This modular high power current source demonstrates optimum efficiency and a high repetition accuracy when used in industrial and scientific applications.

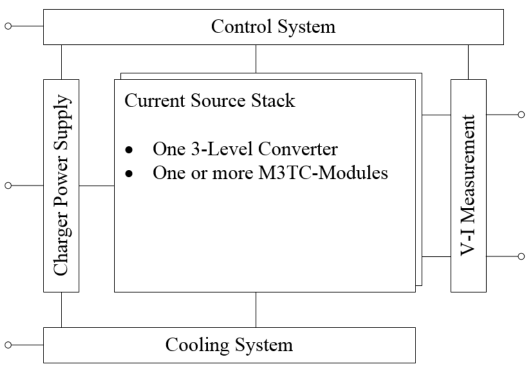

Fig. 1. Block diagram of the high power current source with several, parallel power stacks.

The proposed topology is presented in section II, where the principle of operation is also explained. Two applications are described in section III.

II. Topology

In 2011, a research project was started at the Laboratory for High Power Electronic Systems at ETHZ. It was focused on the development of high power current sources for the investigation of arcs in circuit breakers under transient conditions. The resulting topology is shown in Figure 1 and consists of one or more parallel current source stacks to achieve the specified output current. Each stack contains one 3-Level Converter and one or more Marx-Type Converter (M3TC) connected in series as shown in Figure 2. Consequently, the number of M3TC-Modules define the maximum output voltage [1].

The modular Multi-Level Marx-Type Converter is used to generate a stepwise output voltage. An M3TC module simply consists of a low ESR polypropylene capacitor and a half or full H-Bridge depending whether a unipolar or bipolar output voltage is required. To enhance the power to volume density, the IGBT switches in the H-Bridge are usually water cooled.

For controlling the output current pulse shape, a 3-Level Converter is used. The topology shown in Figure 2 is divided into a buck converter (upper two IGBTs) and a voltage level shifter (lower two IGBTs) supplied by an electrolyte capacitor bank. Due to the separation of high- and low frequency switches it is possible to minimize the switching and conduction losses [2].

A first prototype system of a pulsed current source supplying unipolar output currents up to 1.4 kA peak amplitude and pulse lengths up to 20 ms has been developed. A picture of this prototype system is shown in Figure 3. The measured output current showed that rise/fall times of 30 A/µs for resistive and 100 A/µs for inductive loads were achieved. The FPGA based control algorithm leads to a current ripple of less than 0.1 % and the pulse repeatability achieves better than 1E-4.

III. Applications

The modular approach of the high power current source enables a wide range of applications in industrial and scientific environment.

A. Particle Accelerator Magnets

The particle beam in an accelerator facility has to be injected into, transferred between and extracted from storage rings. The deflection angle depends on the magnetic field which is generated using an electromagnet supplied by a pulsed current with magnitudes up to several thousand amperes. For example, septum and bumper magnets are used to deflect a beam into the beam chamber.

Typically, thyristor switched resonant circuits are used to generate pulses up to 20 kA. Such currents are achieved by a full or half sine pulse shape with lengths between 100 µs and a few milliseconds. Since the deflection requires a constant magnetic field, only a small part of the sine wave is used.

With this novel current source, it is possible to generate any current pulse shape with a high flat-top and pulse-to-pulse accuracy. This will tremendously increase the system efficiency and also reduce the impact of the magnetic field on the surrounding system. Furthermore, with the proposed topology the pulse length can be adjusted easily. This is, together with fast fall and rise times, a key demand for Free Electron Lasers (FEL), in order to achieve a fast beam distribution and low beam distortion. A similar possible application is the deposition of atoms on a substrate (ion sputtering) which is widely used in thin-film technology.

B. Arc Power Supply

Fusion energy research and the development of high voltage DC (HVDC) circuit breakers have created a demand for power supplies which can ignite and control a highly dynamic current. For example, in the production of plasma for fusion energy research, gas must be ignited by an arc power supply. These arcs are ignited by applying a short pulse of several kV to an ignition electrode connected to the supply tube. Subsequently the arc current has to be kept constant. On the other hand, the optimization of HVDC circuit breakers requires the arc which arises while opening and closing to be modelled, for which experimental research is required. To develop such a modelan experiment, a high power current source is necessary.

The classical approach, as for example using a simple buck converter for generating high current pulses, is limited in terms of current shaping capability and losses, due to the very high switching losses of the IGBTs.

In comparison the advanced control algorithm of the novel current source allows an arbitrary output current even during rapid changes of the load impedance. In addition, the modular approach allows to include a droop compensation as well as redundant power modules.

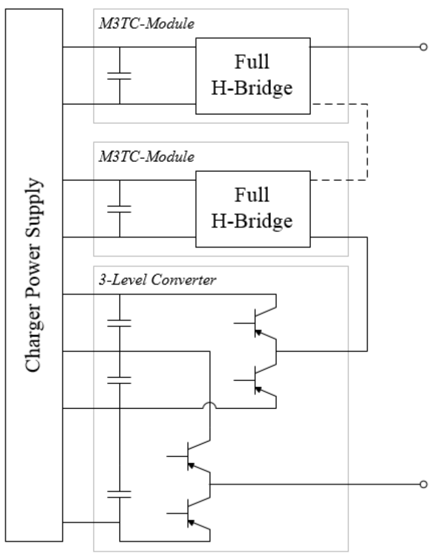

Fig. 2. Block diagram of one current source stack able to supply an output current of 1.4 kA. The output voltage depends on the number of M3TC modules.

Fig. 3. Prototype of a unipolar current source with a maximum output current of 1.4 kA and voltage of 5.5 kV.

IV. Conclusion

Due to the modular approach of the novel high power current source, the topology can be used for accelerator magnet applications, and as modular arc power supply. In contrast to existing solutions for particle accelerator magnets, the output current can be modulated with any arbitrary waveform to achieve less beam distortion and high efficiency. The advanced control algorithm guarantees a low current ripple, fast rise and fall times as well as an excellent pulse repeatability. Therefore, the output current can be controlled even with high dynamic loads such as an arc and mainly inductive loads.

References

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[2] C. Carstensen, "Unacuso a unipolar arbitrary current source for a hardware-in-the-loop test bench," Ph.D. dissertation, ETHZ Laboratory for High Power Electronic Systems, 2012.