A Novel Ultra Precise Solid State Pulsed Current Source for Kicker Magnets

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Abstract—For driving kicker magnets current sources generating current pulses in the range of some kA for a few hundreds of microseconds are required. In this paper a novel pulsed current source is presented consisting of a voltage pulse source (Modular Multi Level Marx Type Converter, \(M_3TC\)) to generate current gradients and a low voltage buck converter to compensate the parasitic voltage across the inductor during the flat top phase. This enables ultra precise pulse shaping. The operation principle is explained and the control of the system including the parasitic effects is presented. The results are validated by simulation and a prototype design is presented.

I. INTRODUCTION

To deflect particle beams in accelerators kicker magnets are utilized, which are influencing the electrical charged beam by magnetic fields. The generation of the strong magnetic fields requires high currents of several kA. Thus these magnets are operated in pulsed operation to reduce the consumed power losses.

The magnets have inductance values in the range of 2.15 \(\mu\)H [1] and 7.3 mH [2]. In order to generate a fast current pulses it is necessary to apply a high voltage pulse of several kA at the kicker magnet. For this purpose switches are required, that can handle both high currents and high voltages and have furthermore switching times below 1 \(\mu\)s. While in [3],[4] thyratrons are utilized to switch the current, in [2], semiconductors are used in combination with a resonant tank to generate the current gradient. Due to the limited power range of solid state devices, thyristors have been used to build the pulsed current sources. The flat top is generated by using a free-wheeling diode. Another approach is switching between a fast and a slow resonant tank to generate the pulse, presented in [5]. The droop of the current can be reduced by using larger resonant tanks or smaller parasitic resistors. Furthermore resonant circuits are necessary to switch off the thyristors.

In all these circuits the flat top of the current pulse is generated by designing a resonant tank such, that the current waveform fulfills the requirements. This results in large capacitors and thus very low resonant frequencies if the flat top has to meet small tolerances. There is no possibility to adjust the absolute output current or to influence the flat top behaviour of the current.

The ripple of the current at the flat top is caused by voltages applied across the kicker magnet’s inductance due to parasitic effects (1).

<table>
<thead>
<tr>
<th>TABLE I: Specifications of the proposed pulsed current source.</th>
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<tbody>
<tr>
<td>Nominal Output Current (I_N)</td>
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<tr>
<td>Kicker Magnet Inductance (L_{ms})</td>
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<tr>
<td>Current Rise Time (t_{rise})</td>
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<td>Flat Top Time (t_{flattop})</td>
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<tr>
<td>Current Decrease Time (t_{decrease})</td>
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<tr>
<td>Repetition Frequency (f_{rep})</td>
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<td>Voltage Pulses (V_{Pulse})</td>
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</table>
\[ v_L = L \frac{di_L}{dt} \] (1)

In this paper, a novel approach is presented, utilizing a low voltage buck converter to compensate the parasitic effects during the flat top. The large current gradients are generated by a Modular Multi-Level Marx Type Converter (\(M_3TC\)) [6] to apply bipolar high voltage pulses to the inductance (Fig. 2).

The proposed converter topology in section II is presented and the principle of operation is explained. The crucial issue is the controller system to generate the flat top, which is discussed in section III. The topology and the control is verified by simulations in section IV and a prototype design is presented in section V.

II. TOPOLOGY

The generation of a current pulse at the kicker magnet can be divided into 3 different phases:

1) Positive current gradient created by applying a positive voltage across the inductor
2) Flat top by setting \(v_L \approx 0\) V
3) Negative current gradient created by applying a negative voltage across the inductor

The current gradient is generated by a bipolar Modular Multi-Level Marx Type Converter introduce in [6]. A full bridge is utilized to connected the capacitor \(C_{M,i}\) either with positive or negative polarity to the load or bypassed. Because the rated voltage of the IGBT modules is limited, multiple modules are connected in series to increase the output voltage. For recharging, the capacitors of the \(M_3TC\) modules can be connected in parallel, thus only the voltage of one stage is required for recharging [6].

For improving the accuracy of the flat top the proposed source uses a buck-converter with a maximal load output voltage of \(V_{max} = 250\) V. This voltage is sufficient to compensate the parasitic voltage drop across the semiconductors and the winding resistance during the flat top, thus it is possible to apply \(v_L = 0\) V. To increase the output current and minimize the ripple, the buck converter is 6 times interleaved [7].

The full topology of the converter is depicted in Fig. 3.

A. Principle of Operation

The operation of the current pulse generator is controlled by a state machine, which uses 4 different states to generate the output current shown in Fig. 4. Additional states are used for recharging the system.
During first state 0 (Idle), all switches are turned off and the output current $I_{\text{out}}$ is zero. To generate a positive current gradient, state 1 is used and the switches $S_{i, 1}$ and $S_{i, 4}$ ($i = 1..3$) are turned on. Thus a positive output voltage $3 \cdot V_{M, i} + V_C$ is applied across the inductor $L_m$ (c.f. Fig. 4.b) and accordingly the current rises. Because the current is conducting through $C_{\text{out}}$ the has to be charged and hence the voltage controller is operating and generating a constant voltage gradient (Fig. 4.c and e). After reaching the nominal output current, switches $S_{i, 4}$ are turned off and $S_{i, 3}$ is turned on resulting in 0 V output voltage of the $M_3TC$ converter (state 2). The buck converter is generating a voltage $V_C$ at $C_{\text{out}}$ equal to the voltage drop caused by the conduction losses of the IGBT and parasitic resistances (Fig. 4.c). In state 3 the output current is reduced to 0 A by applying a negative voltage at $L_m$ ($S_{i, 1}$ off, $S_{i, 4}$ on). Having reached $I_{\text{out}} = 0$ A the state machine changes back to state 0 and the recharging and balancing of the voltages can be performed.

III. CONVERTER CONTROL

The top-level control is performed by a state machine, described in section II-A.

The $M_3TC$ converter is controlled by a time based modulation. Using a 100 MHz clock the resolution of one time step is $\Delta t = 0.86 \mu s$. By switching not all stages at the same time, the resolution can be enlarged to $\Delta t_{\text{single}} = 0.86 \mu s = 0.29 \mu s$. But this accuracy is limited due to the jitter of the transmission of the switching signal from the control system to the IGBT module. The duration of state 1 is not adjusted during the voltage pulse, but the current at the end of the voltage pulse is measured and the switching times are adjusted for the next pulse.

The control circuit for the buck converter system is depicted in Fig. 5. It uses an inner voltage controller to adjust the voltage $V_C$ at the capacitor $C_{\text{out}}$ and an outer loop current controller for the current $I_{\text{out}}$. The voltage controller uses a PID controller to enable fast transients. The controller frequency is equal to the resulting switching frequency of the buck converter $f_{\text{comp}} = f_s \cdot n = 120 \text{ kHz}$. The good transient behaviour is necessary because $V_C$ has to be adjusted within 100 µs.

The current controller uses a PI controller with a large integrator part. As it is only working during state 2 it does not have to generate fast transients but constant output currents. Thus the calculation frequency is only $f_{\text{comp, curr}} = 10 \text{ kHz}$. The chosen controller parameters and the effect on the system is shown in Fig. 7, showing that the voltage controller is working up to $f_c = 21.3 \text{ kHz}$ with a damping factor $Q \approx 1.3$ while the current controller is slower with $f_c = 408 \text{ Hz}$ and $Q = 0.3$ (c.f. Fig. 7).

To reduce the remaining ripple on the output current caused by switching and tolerances of the components, the ripple cancelation method by optimal interleaving described in [7] is applied.

IV. SIMULATION RESULTS

One stack of the proposed converter system, as shown in Fig. 1, has been simulated by using GeckoCircuitsTM having

![Fig. 6: Control model of the buck converter system including the kicker magnet as load.](image)

![Fig. 7: Bode plot of the voltage $V_C$ controller and the current $I_{\text{out}}$ controller.](image)
the additional buck converters can be operated interleaved to the other ones. This leads to a controller frequency of the inner voltage compensator of 360 kHz. Hence the outer current controller can be operated at higher frequencies, too, resulting in a higher accuracy.

V. Prototype Design

A system has been designed for a kicker magnet specified in Table I, consisting out of 3 stacks each providing an output current of $I_{\text{out,stack}} = 1.85$ kA. The detailed design process of the $M_{\text{f/TC}}$ and the buck converter system are described in [6], [7]. The control is performed by a FPGA based control platform. The components are listed in Table II and a 3D CAD model is presented in Fig. 1.

VI. Conclusion

In this paper a novel high pulse current source is presented with a nominal output current of 1.85 kA having a repetition accuracy of $1.025 \cdot 10^{-4}$ and a flat top accuracy of $1.5 \cdot 10^{-3}$. It uses a combination of a bipolar high voltage source to generate the current gradient and a low voltage buck converter to generate the flat top by applying $V_L = 0$ V across the kicker magnet’s inductance. The design has been validated by simulations and a prototype system has been presented.

REFERENCES