ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK045

BRANCH MODULE FOR AN INDUCTIVE VOLTAGE ADDER FOR DRIVING KICKER MAGNETS WITH A SHORT CIRCUIT TERMINATION*

J. Ruf†, M.J. Barnes, Y. Dutheil, T. Kramer, CERN, Geneva, Switzerland
M. Sack, KIT, Karlsruhe, Germany

Abstract

For driving kicker magnets terminated in a short circuit, a branch module for an inductive voltage adder has been designed and assembled. The module has been designed for a maximum charging voltage of 1.2 kV and an output current of 200 A considering the current doubling due to the short circuit termination. It features three consecutive modes of operation: energy injection, freewheeling, and energy extraction. Therefore, the topology of the branch module consists of two independently controlled SiC MOSFET switches and one diode switch. In order not to extend the field rise time of the kicker magnet significantly beyond the magnet fill time, the pulse must have a fast rise time. Hence, the switch for energy injection is driven by a gate boosting driver featuring a half bridge of GaN HEMTs and a driving voltage of 80 V. Measurements of the drain source voltage of this switch showed a fall time of 2.7 ns at a voltage of 600 V resulting in a voltage rise time of 5.4 ns at the output terminated with a resistive load. To meet both the rise time and current requirements, a parallel configuration of four SiC MOSFETs was implemented.

INTRODUCTION

At present, installations at CERN, for driving kicker magnets equipped with a short-circuit termination, comprise pulse generators based on transmission lines [1]. For some of these transmission-line based generators, a future replacement by an inductive voltage adder is currently under investigation. The inductive voltage adder comprises branch modules which are paralleled in layers for sharing the load current and stacked for adding up the voltage. The inductive voltage adder usually feeds into a matched load. Thereby, the match between the power to be fed into the load impedance and the power delivered by one module is made by an appropriate selection of the number of modules per layer and the number of stacked layers.

When driving a transmission line type kicker magnet terminated in a short circuit, with a low impedance source like an inductive adder, the following mode of operation can be used to deal with the reflections from the termination [2]. Initially, the generator outputs a voltage that travels as a wave along the connecting cable and the transmission line type kicker magnet. The wave is reflected at the short circuit termination and travels back to the pulse generator, causing a doubling of the current. Thereby, energy is fed into the system comprising the connecting cable and the kicker magnet and is stored as magnetic energy. Once the reflected wave reaches the pulse generator, the generator stops feeding energy into the system. Hence, the voltage over the output of the pulse generator settles to zero, disregarding losses. Finally, at the end of the pulse, the energy is extracted from the load.

* This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research.
† johannes.ruf@cern.ch

CIRCUIT TOPOLOGY OF THE BRANCH MODULE

In order to implement the functionality described above, the branch modules of the inductive voltage adder need to be equipped with an appropriate circuitry. Figures 1 and 2 show a simplified schematic with an appropriate arrangement of MOSFET switches, and a capacitor C_{pulse} to store initial energy. The circuit elements in Figs. 1 and 2 can each represent multiple paralleled components.

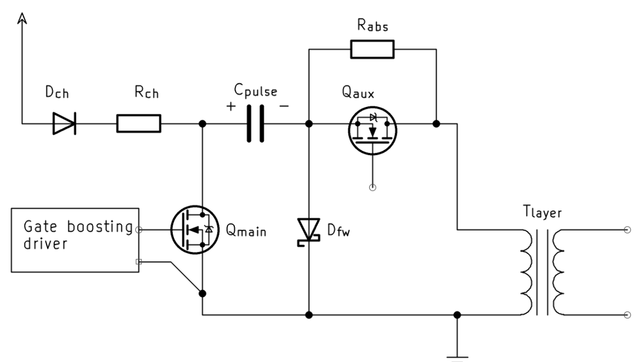

Figure 1: Simplified circuit diagram of one branch module with a resistor R_{abs} for dissipating the energy. (R_{abs} = 10 Ω; Q_{main} = 25μF; Q_{main}: 4 × G3R160MT17J; Q_{aux}: 2 × C2M0045170P; D_{fw}: 2 × GB25MPS17-247).

Initially, the capacitor is charged via the circuit elements D_{ch}, R_{ch}, and D_{fw}. Thereby, D_{ch} prevents undesired discharging. To transfer energy from the capacitor to the load, consisting of the cable and the kicker magnet, both MOSFET switches Q_{main} and Q_{aux} are closed. Thereby, the transformer T_{layer} is part of the inductive adder and serves for combining the current originating from the branch modules of one layer. The output wave from T_{layer} travels through the kicker magnet to the short circuit. When the wave reflected from the short circuit reaches the module, switch Q_{main} opens, and the current commutates into the freewheeling diode D_{fw}. For extracting the energy at the end of the pulse switch Q_{aux} opens, and the energy stored in the load dissipates in the resistor R_{abs}. Alternatively, in order to recuperate the extracted energy back into the capacitor C_{pulse} a diode D_{rec}

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK045

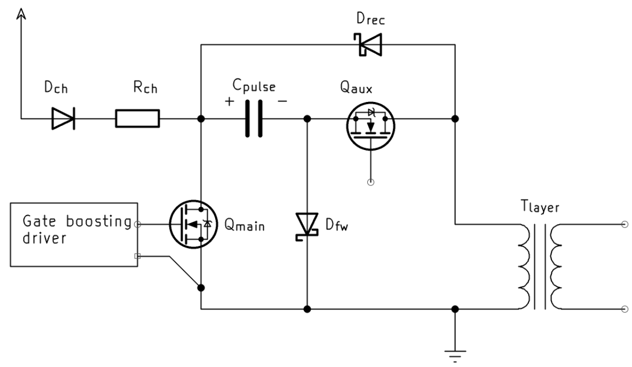

Figure 2: Simplified circuit diagram of one branch module with a diode D_{rec} for recuperating the energy. (D_{rec}: 2 × GB25MPS17-247. For other main circuit parameters see Fig. 1).

can be employed as shown in Fig. 2. During recuperation, a current path over capacitor C_{pulse} and diode D_{rec} is active.

The magnet fill time describes the time the travelling wave needs to propagate twice, i.e., forward and backward, through the short-circuit terminated kicker magnet. The field rise time comprises the magnet fill time and the rise time of the pulse. As a short field rise time is desirable, a fast rise of the pulse is crucial. Therefore, the MOSFET Q_{main} is driven by a gate-boosting circuit. It closes slightly after the switch Q_{aux} has closed and, therefore, defines the rise time of the initial pulse. In addition, its turn off defines the time for the current to commutate from Q_{main} to D_{fw}. MOSFET Q_{aux} is driven by a commercial gate driver and, hence, has a slower switching speed. Moreover, the gate driver for Q_{aux} features an insulation versus the ground reference for Q_{main}. The branch module has been designed for a voltage of 1.2 kV and a peak current of 200 A with a pulse repetition rate of 10 Hz. Switch Q_{aux} and the diode D_{fw} need to be capable of carrying this current. Hence, Q_{aux} has been implemented as two SiC MOSFETs of the type C2M0045170P [3] in parallel configuration. Similarly for the diode D_{fw} two paralleled diodes of the type GB25MPS17-247 [4] have been selected. The switch Q_{main} carries only the initial current before current doubling due to reflection of the wave front at the short circuit, i. e. 100 A. For this switch Q_{main} four paralleled MOSFETs of type G3R160MT17J [5] have been selected (see Fig. 3).

GATE-BOOSTING DRIVER

Figure 3 shows a simplified schematic of the implemented gate-boosting driver circuit. It features an additional capacitance (C_{gb}) in series to the gate, compensating the parasitic inductance of the gate circuit, and forming a capacitive divider with the gate capacitance [6]. A GaN-HEMT half bridge (Q_{gb1}, Q_{gb2}) is fed by a voltage of 80 V to compensate for the effect of the capacitive voltage divider. The resistors $R_{d,b}$ ensures equal current distribution among the four paralleled MOSFETs of Q_{main}. The resistors $R_{d,a}$ and $R_{d,b}$ also provide sufficient damping for operation without an overshoot of the gate voltage.

$$C_{gb} = \frac{C_g}{\frac{V_{gd}}{V_{g,nom}} - 1} \quad (1)$$

The capacitance C_{gb} can be calculated according to Eq. 1 based on effective gate capacitance C_g, the desired gate voltage $V_{g,nom}$, and the available gate driving voltage V_{gd}.

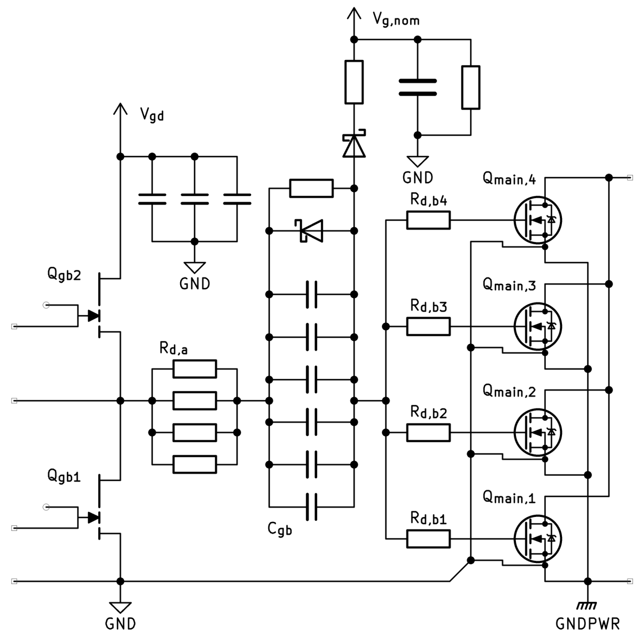

Figure 3: Simplified circuit diagram of the gate-boosting driver for Q_{main}. (V_{gd} = 80 V; $V_{g,nom}$ = 15 V; $Q_{gb1,2}$: GS66506T; $R_{d,a}$ = 0.75 Ω; C_{gb} = 2.52 nF; $R_{d,b1..4}$ = 3 Ω; $Q_{main,1..4}$: G3R160MT17J).

MEASUREMENT RESULTS

For initial tests, one module has been directly connected to a resistive load without a transformer. Figure 4 shows a photo of the test setup. The value of the resistive load has been selected to be 10.8 Ω; this results in a current corresponding to the designed operating point of the module in an inductive voltage adder before the arrival of the reflected wave front. The current through the load has been measured by means of a shunt resistor with a bandwidth of 1.2 GHz. For voltage measurements voltage probes of type 10076C [7] and tpp0500 [8] have been employed. The measurements were performed with an oscilloscope with a bandwidth of 500 MHz. This results in a rise time of the voltage measurement setup of approximately 1 ns [9] which is considered to be sufficiently fast for the measurements.

The tests have been performed at a voltage of 600 V as well as at the rated voltage of 1.2 kV. Figure 5 shows the voltage at the gate of one of the MOSFETS comprising Q_{main}, measured where the gate and kelvin-source leads enter the housing: it rises within 2.8 ns to a voltage of 15 V. The voltage between the drain and source of one of the two center MOSFETs exhibits a fall time between 90 % and 10 % of

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK045

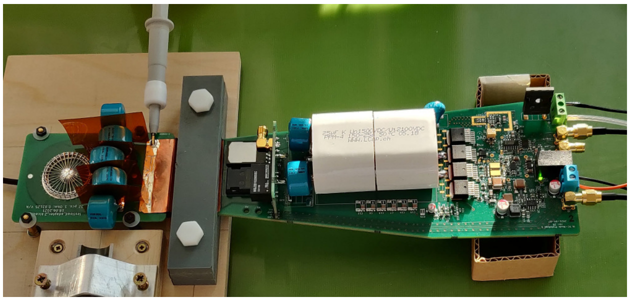

Figure 4: Photo of the test setup.

2.7 ns for a charging voltage of 600 V and 3.4 ns for a charging voltage of 1.2 kV as shown in Fig. 6. Figures 7 and 8 show the voltage and current measurements at the output of the module. The rise time (10 % to 90 %) for both voltage and current has been measured to be 5.4 ns for a charging voltage of 600 V and 5.0 ns for a charging voltage of 1.2 kV as shown in Fig. 7. For the tests the total pulse length has been adjusted to 400 ns. The pulse to pulse amplitude stability with this initial test setup has been measured to 461 ppm over 1032 pulses at 1.2 kV.

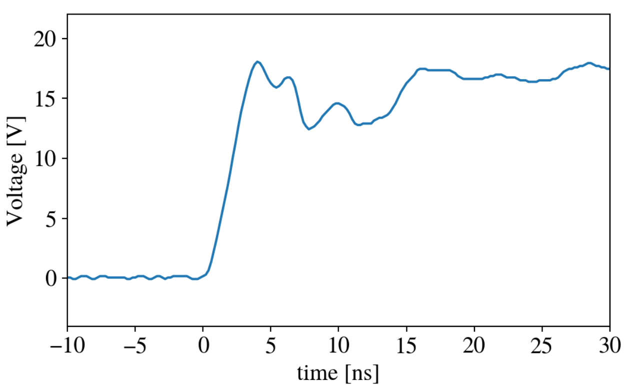

Figure 5: V_{gs} of MOSFET Q_{main}.

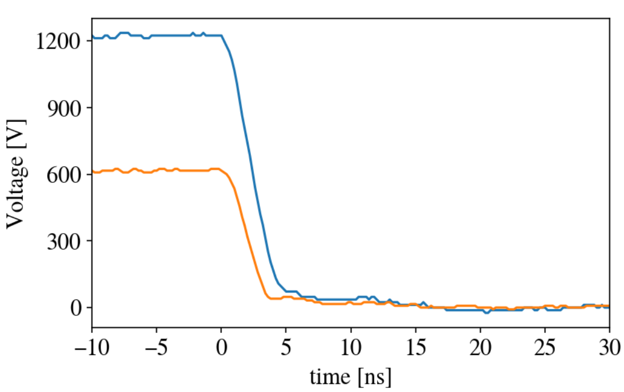

Figure 6: V_{ds} of MOSFET Q_{main} for a charging voltage of 600 V (orange) and 1.2 kV (blue) both with a resistive load of 10.8 Ω.

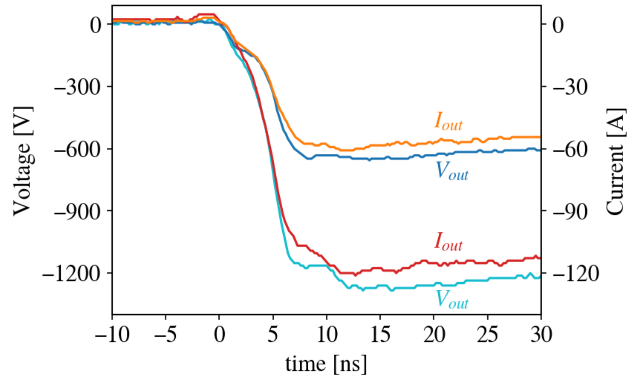

Figure 7: Output voltage and load current of the branch module for a charging voltage of 600 V (blue and orange) and 1.2 kV (cyan and red), both with a resistive load of 10.8 Ω.

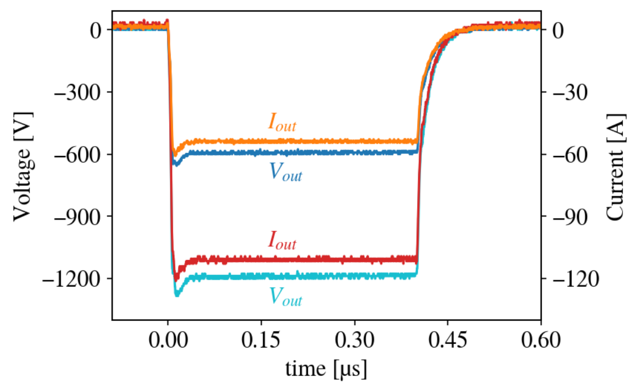

Figure 8: Output voltage and load current of the branch module for a charging voltage of 600 V (blue and orange) and 1.2 kV (cyan and red), both with a resistive load of 10.8 Ω.

CONCLUSION

A branch module for an inductive voltage adder for driving a kicker magnet terminated in a short circuit has been designed and built. It features two active SiC MOSFET switches and a diode switch. A gate driver for MOSFET Q_{main} featuring gate-boosting allows for operation with a fast rise time. The module has been tested connected to a resistive load. At a voltage of 1.2 kV and a current of 110 A a rise time of 5.0 ns has been measured. As the next step the module will be tested with a replacement load emulating a kicker magnet terminated in a short circuit.

ACKNOWLEDGEMENTS

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research.

REFERENCES

[1] M.J. Barnes, *Kicker Systems*, Proceedings of the CAS–CERN Accelerator School, Vol. 5/2018, CERN-2018-008-SP CERN, Geneva, 2018.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK045

[2] J. Ruf, M. J. Barnes, T. Kramer, and M. Sack, "Requirements for an Inductive Voltage Adder as Driver for a Kicker Magnet with Short Circuit Termination", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 3521-3524. doi:10.18429/JACoW-IPAC2021-WEPAB351

[3] CREE, *Datasheet C2M0045170P*, Rev. -, 04-2018, https://assets.wolfspeed.com/uploads/2020/12/C2M0045170P.pdf, retrieved 25/05/2021

[4] GeneSiC, *Datasheet GB25MPS17-247*, Apr. 20 Rev 1.4, http://www.genesicsemi.com/sic-schottky-mps/GB25MPS17-247/GB25MPS17-247.pdf, retrieved 22/01/2021

[5] GeneSiC, *Datasheet G3R160MT17J*, Rev 21/Feb, http://www.genesicsemi.com/sic-mosfet/G3R160MT17J/G3R160MT17J.pdf, retrieved 15/03/2021

[6] M. Sack, M. Hochberg, D. Herzog, and G. Mueller, *Fast SiC-MOSFET Switch with Gate Boosting Technology*, PCIM Europe digital days 2021; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2021, pp. 1-7.

[7] Keysight, *InfiniiVision Oscilloscope Probes and Accessories*, Rev May 18, 2021, https://www.keysight.com/fr/en/assets/7018-06695/technical-overviews/5968-8153.pdf, retrieved 29/04/2022

[8] Tektronix, *TPP0500 & TPP1000 500 MHz and 1 GHz 10X Passive Probes Instructions*, Revision A, https://download.tek.com/manual/TPP0500-TPP1000-Instructions-RevA-071280901.pdf, retrieved 29/04/2022

[9] A. Schwab, *Hochspannungsmesstechnik*, zweite Auflage, Springer Verlag Berlin Heidelberg New York, 1981.