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SOFTGATE – An IGCT Gate Unit for Soft Switching

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Abstract

This paper presents an IGCT unit that has been tailored for emerging soft-switching high-power applications. Redefining the state-of-the-art design and driving concepts, the size and consumption of the proposed unit can be reduced significantly. The paper investigates the operation of the IGCT with this gate unit at a ground-breaking 5 kHz continuous switching frequency. The experiments reveal the operation specifics and conclude a reliable operation.

1 Introduction

For quite some time, integrated gate commutated thyristors (IGCTs) have been considered as robust, efficient, and reliable devices for hard-switching applications in sub-kilohertz range. Their lowest-in-the-class conduction losses, high reliability, excellent thermal-cycling capability, and large power density make the device a well established choice for applications not only in medium-voltage drives but also in high-voltage applications such as HVDC converters and solid-state breakers. However, it was not until recently, that they were re-discovered for soft-switching applications, such as resonant converters.

Although the slow-switching IGCTs might not appear as a good fit for the typical high-frequency operation, [1]–[3] have shown that the IGCT-based soft-switching converter can achieve remarkably high switching frequencies of several kilohertz. In fact, the main disadvantage of the device, being its high switching losses, is diminished due to the soft switching. Moreover, the naturally low conduction losses of the thyristor-based IGCTs can assure high conversion efficiency. As a consequence, the IGCT is likely a very good candidate for power-dense medium-voltage resonant converters for megawatt power range.

An envisioned application would be a medium-voltage dc transformer based on LLC resonant converter for future dc grids [4]–[6]. When operated in open loop near its resonant frequency, the LLC resonant converter topology naturally provides a very stiff voltage ratio, independent of the loading current [4]. Thus, the dc transformer is capable of transferring the power naturally according to the grid impedances, similarly to its ac counterpart. Furthermore, the voltage ratio can be set exactly by the turns' ratio of a compact medium-frequency transformer (MFT) that provides galvanic isolation and can integrate the required inductances by its stray and magnetizing inductances.

From the IGCT perspective, the LLC resonant converter enables a zero-voltage switching (ZVS) operation with low turn-off currents which can be set by the magnetizing inductance of the MFT without an influence of the loading. Hence, the switching losses of the IGCT consist only of the turn-off loss component that can be set very low by an optimization of the turn-off current for a sufficiently low value [3].

Although the gate-commutated thyristor (GCT) can be re-used "as is" for the soft-switching applications without any significant drawbacks, the standard commercial gate units, designed for hard-switched applications, are typically oversized in part but at the same time lacking the capability to operate efficiently at such high frequencies. To address this problem, the gate unit tailored for soft-switching applications of IGCT has been designed [7].

In the ongoing ERC Consolidator Grant Project *Empower*, we investigate different aspects of the

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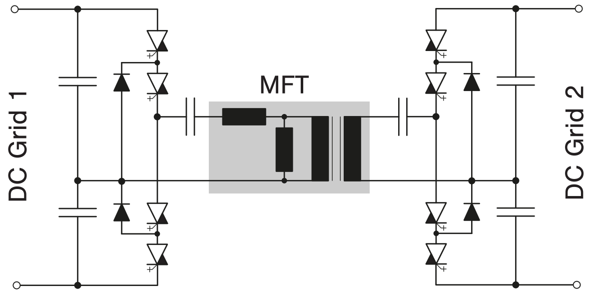

Fig. 1: The topology of the dc transformer demonstrator under development.

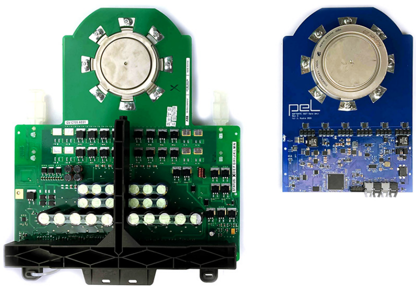

Fig. 2: Size comparison of the commercial gate unit (left) to the proposed SOFTGATE unit optimized for soft-switching applications (right).

feasibility of the dc-transformer concept and are developing a 5 kV/10 kV 0.5 MW demonstrator of the dc transformer as depicted in Fig. 1. To fully demonstrate the capabilities of the IGCT as a switching device, the dc transformer is concepted to operate at the ground-breaking 5 kHz switching frequency.

The proposed gate unit is significantly smaller in size (see comparison in Fig. 2) and has significantly lower consumption compared to hard-switching IGCT gate units. The smaller size is a significant advantage as the unit size poses great restrictions on the complexity and the volume of the stack. The lower consumption is advantageous because it enables a utilization of smaller external gate-unit power supplies that have to be isolating working medium voltage.

This paper introduces the specific challenges of the 5 kHz operation of IGCT gate units. It presents the novel gate unit, tailored for soft-switching operation, and explains its working principles. Furthermore, the necessary changes to achieve the 5 kHz operation are investigated as well. Finally, the measurements for 5 kHz operation are presented and studied in detail, drawing conclusions about operation specifics but also proposing further improvements for the future development.

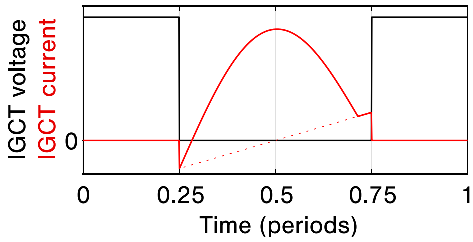

Fig. 3: Example loading of a reverse-conducting IGCT applied in a LLC-converter-based dc transformer. The dotted line represents the magnetizing current component.

2 LLC Converter Operation with IGCTs at 5 kHz

In the typical operation of the LLC-converter-based dc transformer, the waveforms from Fig. 3 apply to the IGCT. In the figure, it can be seen that the current waveforms comprise two components: one (almost) linear component, imposed by the magnetizing inductor in the resonant tank, and one (almost) sinusoidal component, related to the stray inductance and the resonant capacitance. Since the dc transformer is operated in an open loop at the switching frequency below the resonant frequency, it can be observed in Fig. 3 that the sinusoidal half wave is finished before switching takes place. This has two very important implications on the switching losses of the converter:

- The turn on of the IGCT occurs as zero-voltage switching since the negative value of the magnetizing current forces the antiparallel diode to open before the IGCT is turned on.
- The turn off of the IGCT is a hard turn off. However, the magnitude of the turn-off current can be selected to a desired value by adjusting the magnetizing inductance. Moreover, since only the resonant component of the current contributes to the transferred power and decays before the switching event, the turn-off current value is independent of the dc transformer loading and thus, can be optimized for minimum losses.

Since the switching losses play the dominant role in the 5 kHz operation, it is vital to optimize the turn-off current value for minimum turn-off losses. Fig. 4 shows a characterization of the IGCT switching losses as a function of the turn-off current. It can be

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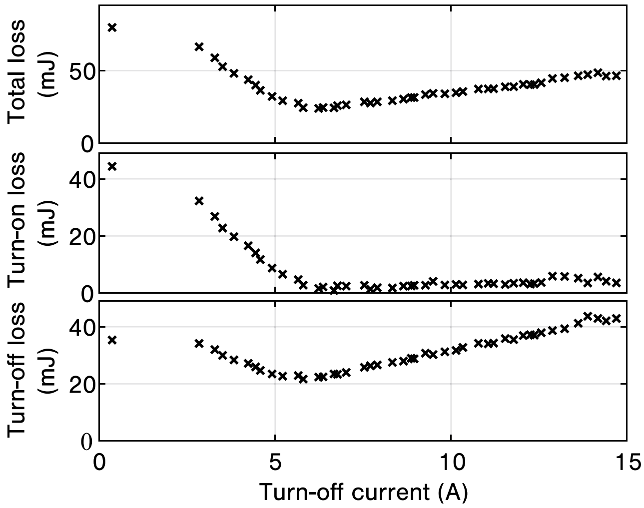

Fig. 4: Characterized switching losses of the utilized GCT as a function of the turn-off current. The dc-link voltage is 2.5 kV and the applied dead time is 14 µs.

clearly seen that the minimum total losses (for the given dead time and device) are not at zero current (the case of zero-current switching with a classical series-resonant converter) but at a higher value near 7 A. This is because lower values of current do not manage to charge the parasitic capacitances of the IGCTs within the switching dead time and thus, an inrush peak is generated at the turn on of the complementary IGCT. This causes not only turn-off losses in the IGCT but the turn-on losses in the complementary IGCT as well.

To enable the 5 kHz operation, the magnetizing current magnitude has been reduced to only 16 A. This value was selected to account for some variability in the device due to manufacturing and temperature variations. Moreover, additional margin is required to account for the prolonged turn off due to the preflooding effect, which becomes pronounced at such low turn-off currents.

3 Implications for the Gate Unit

The presented waveforms from Fig. 3 have also significant implications on the design of the gate unit. Compared to the typical IGCT gate unit for hard switching, the proposed gate unit has to be capable of switching at a significantly higher frequency (5 kHz in contrast to typical subkilohertz frequencies). However, the turn-off current is overproportionally lower. As a consequence, the charge to turn-off the device is lower as well. Thus, overall, the loading of the turn-off channel of the gate unit is likely significantly reduced compared to hard-switching applications.

Furthermore, it can be observed in Fig. 3 that the rate of rise of the current during the turn on is heavily limited due to the inductance in the resonant tank. Not only does this enable an operation of the IGCTs without a clamping circuit [2], [3] but it also implies that the current is build up slowly in the IGCT during the turn on. While a conventional hard-switched device has to turn on currents with a $\mathrm{d}i/\mathrm{d}t$ up to 1 kA/µs, the IGCT in the proposed dc transformer application does not experience a $\mathrm{d}i/\mathrm{d}t$ higher than 30 A/µs. Since the current in the device is increased with significantly slower rate, the thyristor cells within the GCT have significantly more time to be opened uniformly (without causing the hotspotting problems due to unequal distribution of turn on currents). As a consequence, the GCT applied in the soft-switching applications can be turned on with a significantly lower gate current turn-on pulse.

4 SOFTGATE Gate Unit

To exploit the special properties of the studied soft-switching applications, the “SOFTGATE” gate unit for 68 mm GCTs has been developed ([7], Fig. 6). Because of the aforementioned lower loading of the gate unit during the turn off, the (size-dominant) turn-off channel has been reduced. Furthermore, because of the lower requirements on the turn-on pulse magnitude (and retrigger pulse magnitude), the turn ON channel, the retrigger channel, the positive-gate-voltage backporch channel, and the negative-gate-voltage backporch channel, typically present on the gate units [8]–[10], can all be integrated into a single “ON stage”. This novel topology of integrated stages can be observed in Fig. 5, represented by the T-type NPC power-stage topology with a nonlinear inductor L_{on}. Overall, the proposed driving topology reduces the size, the consumption, and the complexity of the gate unit.

Furthermore, the gate unit provides additional means of protection such as one-time turn off of high current with a cool-off time (tested up to 1.5 kA), an interlock fibre-optic link between the devices, and an cathode-to-anode voltage measurement to recognize a failure of the device by using the properties of ZVS [7].

In the following, the functionality of the gate unit

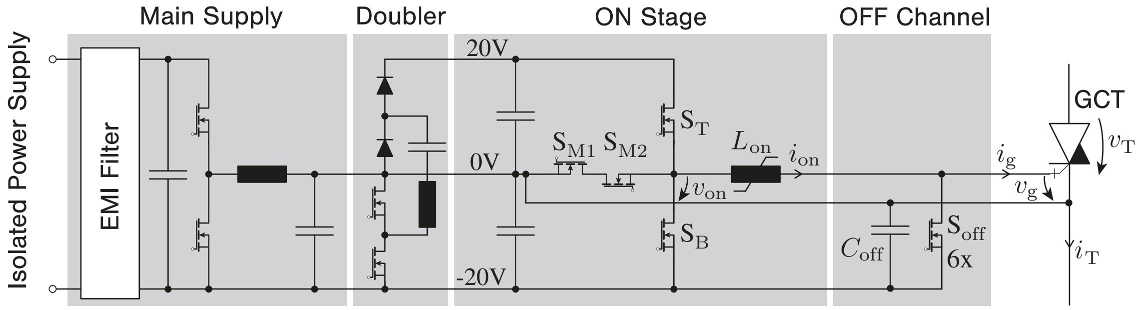

Fig. 5: Hardware topology of the power stages of the SOFTGATE unit.

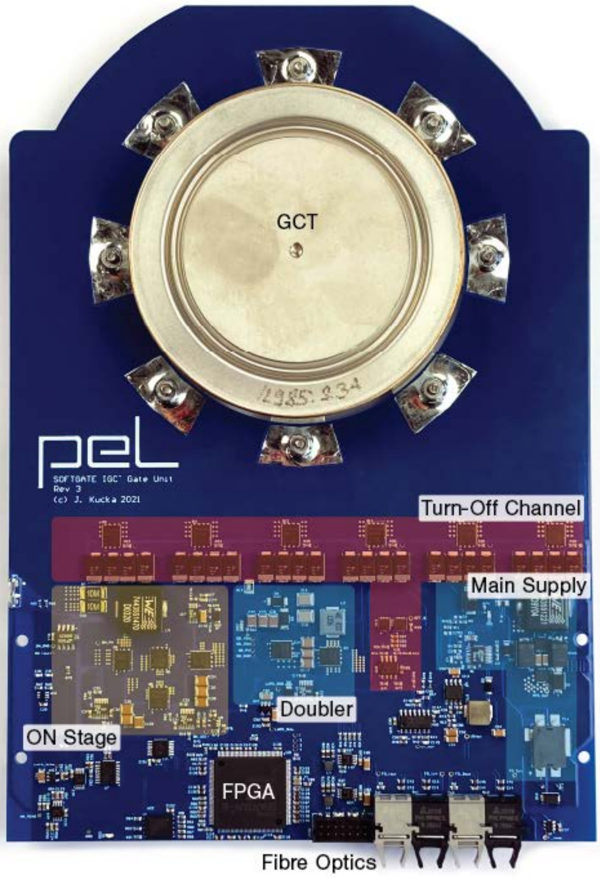

Fig. 6: Photo of the designed gate unit with highlighted power stages.

stages (Fig. 5) will be briefly explained. For more detailed explanation of the hardware design and the functionality, please refer to [7].

4.1 OFF Channel

The off-channel, consisting of parallel-connected MOSFETs $\mathrm{S_{off}}$ and a capacitor bank C_{off}, has a sole purpose of connecting the gate of the GCT to -20 V potential to turn it off and to keep it off.

When the turn-off channel is activated during a conduction state, a large amount of charge is ex-

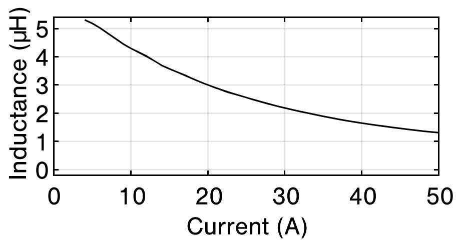

Fig. 7: Measured characteristic of the ON stage nonlinear inductor.

tracted from the gate. Hence, the capacitor bank capacitance was designed to be C_{off} = 2.5 mF. The parallel-connection of six MOSFETs minimizes the parasitic off-channel inductance to 1.2 nH and provides a high-current emergency turn-off capability.

4.2 ON Stage

The ON stage represents one of the main novelties of the gate unit, as it is capable of integrating the funcionalities of several conventional power stages. The main principle of the power stage is that the three-level T-type NPC stage is capable of generating positive, negative, and zero voltage levels at its output (represented by voltage v_{on}). This, in turn, enables an option to exactly control the current i_{on} buffered by the nonlinear inductor L_{on}.

The nonlinear inductor L_{on} was selected to have a high inductance during low currents (to enable the control of back-porch current with an acceptable switching frequency) and to have a low inductance during high currents to enable a faster build up of turn-on and retrigger gate-current pulses. The measured characteristic is shown in Fig. 7.

4.3 Power Supplies

The gate unit is, as common, supplied from an external isolating power supply, providing a voltage bus ranging from 25 V to 40 V. A buck converter

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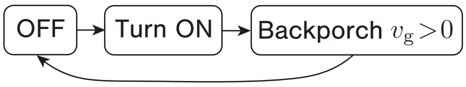

Fig. 8: Finite-state machine describing the gate unit operation modes implemented in the 5 kHz gate unit firmware.

stage ("main supply") is utilized to stabilize the internal -20 V bus. To generate the third voltage level, a resonant voltage doubler is employed as depicted in Fig. 5.

5 Adaptations for the 5 kHz Operation

Before operating the gate unit at the target 5 kHz switching frequency with a very low magnetizing current, a few characterizations had to be done.

First, to estimate the feasibility of the long-run operation, the gate current during the turn-off have been recorded in a few pulse operation. Although the switching frequency is high, the IGCT turn-off current is low at only 16 A. Consequently, the rms current of the turn-off channel has been estimated to be only 8.63 A, which is well below the design maximum of the capacitor bank of 47 A [7]. Moreover, the charge supplied to the gate is only 0.3 mC, which corresponds to only 0.12 V variation on the -20 V bus, which is almost negligible and guarantees a long-term safe operation.

Furthermore, the first tests have shown that such low value of magnetizing current conducted by the integrated anti-parallel diode at the beginning of the period is not sufficient to generate enough voltage to avalanche-break the PN junction near anode. As a consequence, the retrigger pulse and negative backporch operation are both not necessary and, as will be discussed in the next section, might even cause additional losses. To prevent this, both have been disabled in the gate unit firmware, greatly simplifying the gate unit operation, as displayed in Fig. 8.

6 Experimental Results

To test the IGCT (including the gate unit) in a resonant operation, the resonant test setup from [3] was utilized. While this setup, shown in Fig. 9, does not process any power on its own, it is capable of emulating the same conditions for the IGCT as it

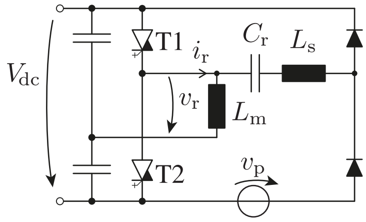

Fig. 9: Utilized IGCT resonant test setup emulating the LLC resonant converter operation.

Tab. 1: Test setup configuration

DC-link voltage	2.5 kV
Magnetizing current	16 A
Switching frequency	5 kHz
Resonant frequency	6.3 kHz
Dead time	15 µs

would have experienced in an LLC resonant converter. In the setup, the dc-link voltage can be set by a high-voltage low-current source V_{dc} and the magnitude of the resonant peak can be set by a high-current low-voltage source v_p. The magnetizing current magnitude can be set by the choice of the magnetizing inductor L_m. The parameters of the test setup configuration can be found in Tab. 1.

In Fig. 10, the experimental results captured for the IGCT during the resonant operation can be seen for both no-load operating condition and maximum-load operation. During the no-load operation, no resonant current is applied (as this component transfers power) and only the linear magnetizing current component is visible. The maximum-load operation is limited by the voltage capability of the voltage source v_p and is characterized by a 320 A peak resonant current. Assuming that the IGCT would be applied on the 5 kV side of the dc transformer from Fig. 1, this operation point represents a power transfer of roughly 420 kW.

The gate voltage v_g and on-stage voltage v_{on} have been measured by passive probes. The gate current i_g has been recorded using four miniature Rogowski coils *PEM CWT Ultra-mini* placed around the four gate connection points of the GCT. The GCT voltage v_T and GCT current i_T have been measured using standard medium-voltage differential voltage probe and a high-current Rogowski coil, respectively. All waveforms were recorded via an eight-channel Yokogawa oscilloscope.

Observing the waveforms at the no-load condition (Fig. 10 left), the operation of the gate unit can be

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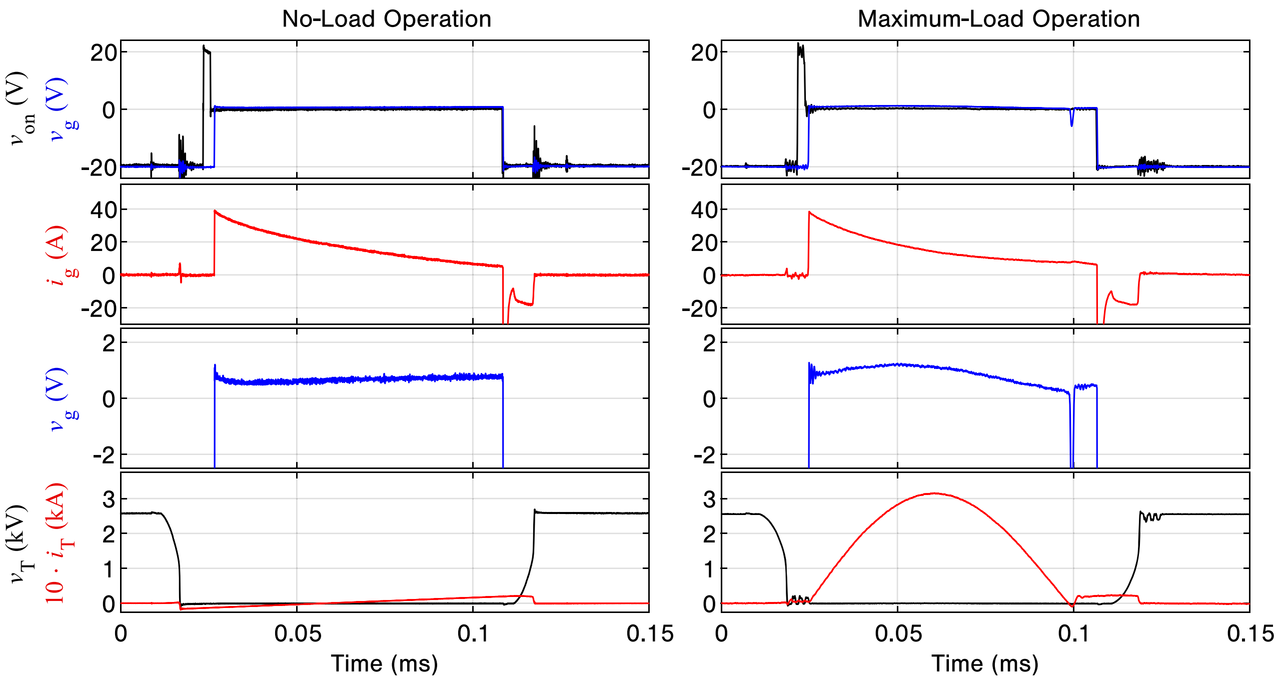

Fig. 10: No-load and maximum-load resonant operation of the IGCT. The gate voltage v_g in the third graph represents a zoomed-in waveform from the first-graph. All waveforms are filtered with a 25 MHz low-pass filter.

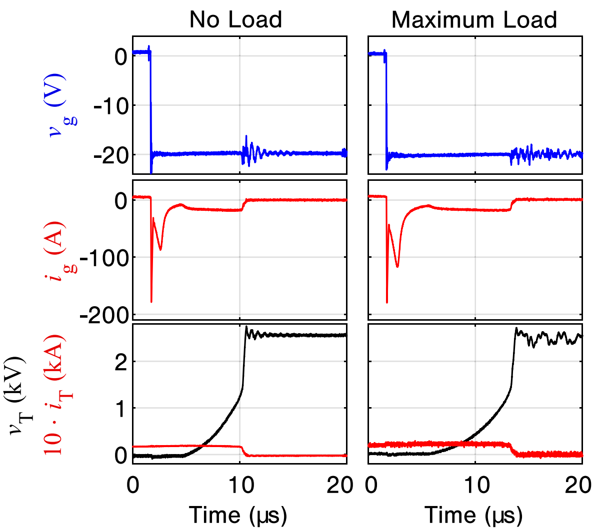

Fig. 11: Turn-off detail of no-load and maximum-load resonant operation of the IGCT. The waveforms are not filtered.

explained. At the very beginning, the gate driver is in the off state and consequently, the gate voltage v_g equals -20 V. Similarly, the on-stage voltage v_{on} is kept at -20 V potential to keep the voltage drop over the inductor L_{on} at zero. Once the turn-on signal is received via the optical fibre, the “Turn ON” state is activated (ref. to Fig. 8). During this state, the off channel is still active but the on stage already starts to generate voltage (v_{on} is either 0 V or 20 V) to generate a positive voltage drop over the inductor L_{on} (20 V or 40 V, respectively). This way, the current through the inductor i_{on} is built up rapidly within a turn-on delay of 3 µs. After this constant time delay, the “backporch” state is activated (ref. to Fig. 8) and the off channel is deactivated, which leads to rapid commutation of the inductor current from switch S_{off} into the gate, generating the turn-on pulse in the gate current i_g. Typically, in this state, the gate current is actively controlled via the 20 V and 0 V potential of the on stage after the initial pulse has decayed to a value of several Amperes. However, the 5 kHz operation does not leave enough time for the gate current to decay sufficiently and thus, this mode of operation is never present and the on-stage voltage v_{on} is kept at zero until the command for the IGCT turn off is received via the optical fibre. This forces a transition to “OFF” state (ref. to Fig. 8), which activates the off channel and both the gate voltage v_g and the on-stage voltage v_{on} become -20 V. This in turn, generates a large negative peak at the gate current that removes the free charges from the gate and enables the GCT to build up the blocking voltage.

It is important to mention that the magnitude of the gate current is only 40 A, which is roughly three-to-four times lower than that of conventional units (e.g.,

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[8] utilizes 150 A turn-on pulse). As discussed in Section 3, this is possible because the $\mathrm{d}i/\mathrm{d}t$ of the anode current during the turn on is greatly limited by the application.

Comparing the no-load 5 kHz operation from Fig. 10 to the 1.44 kHz operation from [7], not only it can be observed that the typical switched back-porch operation is never reached within the short time, but also it becomes obvious that the extremely low magnetizing current magnitude of 16 A is not sufficient to generate sufficient voltage on the integrated antiparallel diode so that the PN junction near the anode avalanche-breaks. Consequently, the gate voltage never becomes negative during the on state of the GCT. This means, as mentioned in the previous section, that the negative-gate-voltage backporch operation is not necessary and neither is the generation of the retrigger pulse.

Comparing the maximum-load operation (Fig. 10 right) to the no-load operation, it can be concluded that the operation steps of the gate unit are practically the same: “OFF” state, “Turn ON” state, “backporch” state without the necessity to generate voltage pulses, following by the “OFF” state again. However, after taking a closer look at the GCT terminal waveforms, two important differences can be recognized: First, an oscillation in the current of the antiparallel diode can be observed during the dead time. While the diode current is not anymore linear, it can be still concluded that the turn on happens at zero current and practically zero voltage. Second, the gate voltage becomes negative for a short period of time near the time of 0.1 ms. This is caused by the reverse-recovery charge of the rectifying diodes (visible as a negative dip in the GCT current i_{T}) and is present also at the real LLC resonant converter. In a typical gate unit operation, this occurrence would first activate the negative backporch operation and then active the retrigger pulse. While the retrigger pulse is an important feature, which, similarly to the turn-on pulse, ensures that all thyristor cells are uniformly open before current is diverted to the GCT, in this particular application it is not necessary. This is because, after this occurrence, the GCT anode current i_{T} remains low, only to be turned-off a short moment after. Consequently, in this case, the retrigger pulse would unnecessarily preflood the GCT which would have negative impact on the turn-off performance and would only increase the losses in the GCT and

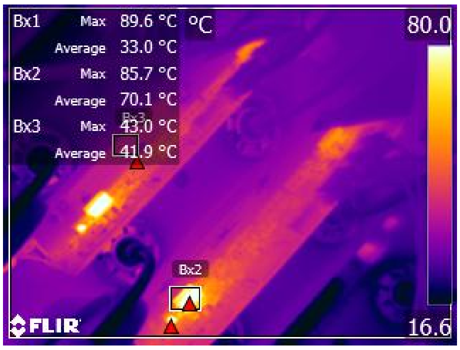

Fig. 12: Temperature measurement at the stack in a continuous 5 kHz operation. The picture has been taken remotely after 60 minutes of operation to ensure steady state.

in the gate unit. Finally, as observable in Fig. 10 (and Fig. 8), both the negative-gate-voltage backporch operation and the retrigger pulse have been disabled for this application. It should be noted that the short negative gate-voltage pulse at time 0.1 ms slightly increases the gate current, which is, however, acceptable.

Fig. 11 shows the detail of Fig. 10. Here, the detail of the turn off can be observed. After the gate voltage is forced to be negative, a short reverse recovery is visible in the gate current. After, the anode current is fully commutated on the gate, which enables a build up of the anode-to-cathode voltage. Since the anode current is very low, the anode voltage is built up relatively slowly. Comparing the no-load operation (Fig. 11 left) to the maximum-load operation (Fig. 11 right), the pre-flooding effect can be clearly observed, as the turn-off transient takes almost 50 % longer for the maximum-load operation. As mentioned in Section 2, this should be taken into account when selecting the magnetizing current (it can be seen that at the maximum load operation, the turn-off delay is already close to the dead time).

In Fig. 12, the thermal picture taken in a steady state (after 60 minutes of operation) can be seen. The ambient temperature during the measurement was 30 $^{\mathrm{o}}$C and no external cooling of the gate unit was applied in the cabinet. While two hotspots (one at shunt for measuring the current i_{on} and one at the inductor L_{on}) can be recognized in the figure, overall, a good thermal design and a long-period stability of the proposed gate unit can be stated.

Finally, the power consumption of the SOFTGATE gate unit was compared to that of the commercial

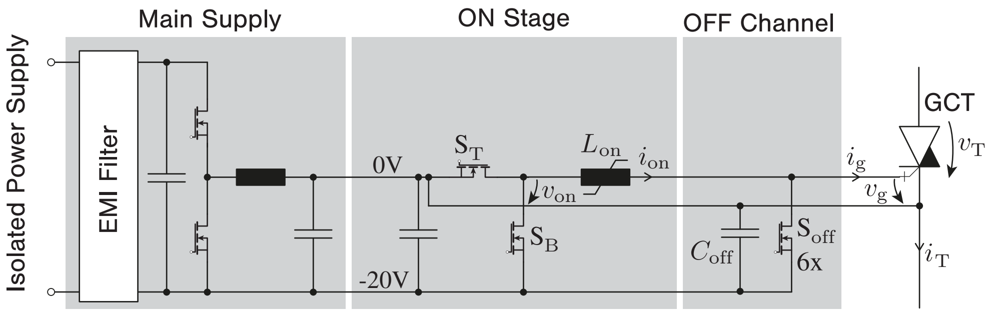

Fig. 13: Potential further simplifications of an IGCT gate unit for 5 kHz low-magnetizing-current dc transformer application.

gate unit from Fig. 2 left. While the consumption of the commercial gate unit at 5 kHz maximum-load operation was measured to be 58 W, with the SOFTGATE gate unit, the power consumption was only 40 W, demonstrating the advantage of the proposed gate unit.

7 Discussion on a Possible Simplification of the Gate Unit

Considering the fact that no retrigger mode is utilized and the backporch operation never reaches the switched operation when the gate unit is operated at 5 kHz with extremely low turn-off currents, a further simplification of the gate unit can be proposed. This is depicted in Fig. 13.

As Fig. 13 shows, the ON stage topology can be simplified to use only two levels: the 0 V and -20 V potentials, as the +20 V potential is currently utilized only during the build up of the turn-on pulse (see Fig. 10). As a consequence, the current i_{on} in the inductor L_{on} is built up more slowly as only 20 V can be imposed on the inductor instead of the 40 V. Nevertheless, this additional turn-on delay can be accounted for in the upper layer controller.

Furthermore, as the 20 V potential is not necessary, the resonant doubler can be removed from the topology as well.

Finally, the proposed simplification is expected to further reduce the size and the consumption of the unit and also improve the reliability of the circuit. However, it should be noted that such gate unit would be tailored exactly for the given application and the given switching frequency, leading to reduced flexibility.

8 Conclusions

This paper has presented the SOFTGATE gate unit that has been tailored for a soft-switching operation to be utilized in an LLC-converter-based dc transformers for future dc grids. When tailoring the unit for the given application, it can be shown that the driving topology can be simplified and many power stages can be integrated. This leads to a higher power density of the gate unit, a smaller size, and a lower energy consumption. This is expected to simplify the mechanical design of the stacks for the IGCTs and poses lower requirements on the gate unit power supplies that have to isolate the working voltage.

The main focus in this paper has been put on the feasibility of the 5 kHz switching frequency of an IGCT fitted with the SOFTGATE gate unit. To enable this ground-breaking frequency, it has been demonstrated that the magnetizing current has to be selected to a proper low value. Furthermore, it has been observed that the retrigger pulse is not only not necessary for such low magnetizing currents but might even become counterproductive as the reverse-recovery current from rectifier side could falsely trigger the retrigger pulse, preflooding the GCT before the turn off and increasing its losses. A one-hour thermal experiment has confirmed the general feasibility of the 5 kHz operation with the SOFTGATE gate unit.

Moreover, based on the observations, further simplifications of the gate-unit driving topology have been proposed. These simplifications are expected to improve the main metrics such as power density, consumption, and reliability, for the cost of further specialization – making the gate unit useful only for a thin range of switching frequencies.

Finally, the paper demonstrates that tailoring the gate unit for the dc transformer application improves the gate unit properties and that the IGCT is a good fit for medium-frequency soft-switching applications.

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