



Power Electronic Systems
Laboratory

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Proceedings of the 14th IEEE International Power Electronics and Motion Control Conference (ECCE Europe 2011),
Birmingham, UK, August 30 - September 1, 2011.

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Decentralized Active Gate Control for Current Balancing of Parallel Connected IGBT Modules

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Keywords

«IGBT», «Parallel operation», «Load sharing control», «Current sensor»

Abstract

In modern power converters operating at currents of few kA and voltages of several kV, Insulated Gate Bipolar Transistor (IGBT) modules are typically used. The increased power demand of modern inverters and rectifiers results in higher currents and voltages. Currents up to tens of kA and voltages up to tens of kV are required, which exceed the ratings of IGBT semiconductors currently available. Multiple IGBT modules can be connected in parallel or in series to provide the requested current or voltage rating.

Depending on the interconnection of the switches, parameter variations in the semiconductors and in the system, as well as tolerances and delay times in the gate driving circuits, an unbalanced current or voltage distribution may occur. Therefore, the IGBT modules are generally derated, which results in an increased number of devices and volume being required.

In this paper, a modular concept of a decentralized active gate control for current balancing of parallel connected IGBT modules is presented. It operates distributed to the gate drive units (GDU), the hardware and software configurations are independent of the system design and no restrictions on the number of parallel connected IGBT modules exist.

1 Introduction

The increased power demand of modern inverters and rectifiers operating at fixed system voltages of few kV results in higher currents. Values up to tens of kA are required, which exceed the ratings of IGBT semiconductors currently available. Multiple IGBT modules can be connected in parallel to provide the requested current rating.

In doing so, several factors may cause dynamic and static unbalanced currents of the parallel connected IGBT modules and can evoke unwanted system failures. Substantially, these are differences in the interconnection of the switches to the busbar and heat sink, parameter variations of the semiconductors, as well as tolerances and delay times in the gate driving circuits. In Fig. 1, a schematic overview of these quantities is shown, which are explained in the following.

Differences in the busbar connections lead to unequal current paths of the switches and thus to varied connection inductances L_{conn} and resistors R_{conn} [1–3]. An asymmetric system geometry leads to different thermal resistances R_{th} of the heat sink. Internal tolerances of IGBT and diode modules, i.e. differences in the Gate-emitter threshold voltages $v_{\text{Ge,th}}$ and Collector-Emitter saturation voltages $v_{\text{CE,sat}}$, the diode forward voltages v_f , the IGBTs transconductances g_m , the bonding inductances L_C , L_E , L_e and $L_{G,int}$ or the internal gate resistors $R_{G,int}$ as well as the internal capacitances C_{Ge} and C_{GC} , influence their switching and on-state behavior [3–6]. In addition, some of these parameters, e.g. g_m , $v_{\text{CE,sat}}$ and v_f , are temperature-dependent, which in combination with the different thermal resistances further affect the current balancing [7]. The switching and on-state behavior of an IGBT is controlled with the Gate Drive Unit (GDU), whereas the delay times t_{delay} and the gate currents i_G , e.g. defined by the GDU's supply

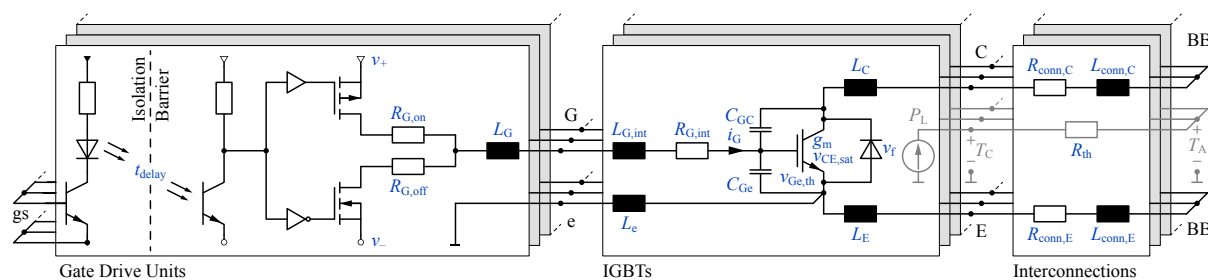


Fig. 1: Overview of the quantities responsible for the unbalanced current distribution of parallel connected IGBT modules related to the gate drive units, the IGBTs and the interconnections.

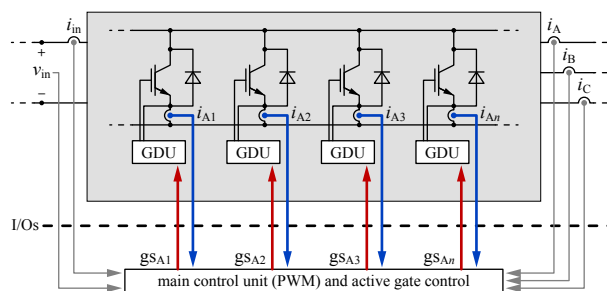


Fig. 2: Parallel connected IGBT modules as part of a converter with individual GDUs. Each gate signal (gs_{Ai}) is controlled by a centralized active gate control unit that measures all IGBT currents to ensure a balanced current distribution.

voltages v_+ and v_- , the gate resistors $R_{G,on/off}$ and the gate wiring inductances L_G , impact the current sharing substantially [8]. For that reason, the IGBT modules are generally derated, which results in an increased number of devices and volume being required.

In order to achieve an even current balancing, a symmetrical thermal layout and interconnection of the IGBT modules to the busbar should be ensured. The manufacturer commonly preselects the IGBT modules depending on the above mentioned parameters of the semiconductors [9]. For static current balancing and thermal stability IGBTs with a positive temperature coefficient should be used [10]. However, despite this costly classification, the maximal power rating of the IGBT modules must still be reduced. Another possibility is to insert additional components, such as series resistors or inductances, in the current paths [1]. The series resistors, however, result in additional losses and the inductances reduce the switching speed. Alternatively, the currents can also be balanced by controlling the switching and on-state behavior with the GDUs. In order to minimize delay times and costs a common GDU for all parallel connected IGBT modules can be used, if the IGBTs are matched [8, 11]. Individual gate resistors, common mode chokes or balancing cores must be used in such cases to reduce the influence of the different emitter voltages caused by the inductive coupling [8, 12]. An individual GDU is used for each IGBT module to avoid these coupling effects. In contrast to the common GDU, the delay time skews, the differences in the GDU's supply voltages and in the gate resistors have to be minimized [11]. The propagation delays result mainly from galvanic isolators such as optocouplers, which typically show delay skews of $60 - 100 \text{ ns}^1$, and the output stage of the GDU, whose delay time can vary in the range of $5 - 15 \text{ ns}^2$.

However, as proposed in previous papers [13–15], if an active gate control is applied, the inevitable delay times of the individual GDUs and the tolerances of $R_{G,int/ext}$ and $v_{Ge,th}$, resulting in different turn-on and turn-off times of the IGBTs [4], can be compensated. Thereby preselection and derating of the switching devices can be avoided. A schematic overview of a centralized active gate control is illustrated in Fig. 2. It can be seen that each current of the IGBT modules connected in parallel is measured by a central unit to detect the rising and falling edges of the current waveforms. Out of the measured delay times between the different IGBT modules, the centralized control unit (DSP / FPGA) adjusts the turn-on and turn-off times of the PWM-unit for each GDU independently to ensure simultaneous switching and a dynamically-balanced current sharing, which generally also results in a statically-balanced current sharing for IGBTs with positive temperature coefficient. If needed, in addition to the switching time control, the GDUs supply voltage can be controlled to ensure a statically balanced current sharing.

Usually the centralized gate control circuit is designed for a certain system configuration with a given number of IGBT modules connected in parallel, which makes subsequent modification unfeasible. Apart

¹ Avogo HFBR-Series optical links, optocouplers as Optek OPI1268

² IXYS IXD-430 Series

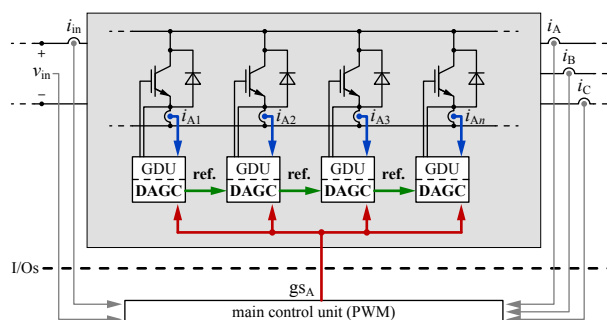


Fig. 3: Parallel connected IGBT modules as part of a converter with individual GDUs containing DAGC. Each GDU measures the current of its IGBT and gets a reference signal (current edge and/or amplitude value) from a neighbor GDU. Therewith, it controls the switching times to ensure a balanced current distribution.

from the costly isolated current sensors and the bidirectional cabling, in addition, the number of I/O-channels of the control unit or the maximum available calculation capacity is limited and probably can not meet the needed requirements.

In this paper, a modular concept of a decentralized active gate control (DAGC) [16] consisting of independent and equal GDUs for current balancing of parallel connected IGBT modules is presented, whereby the hardware and software configurations are independent of the system design and no restrictions on the number of IGBT modules connected in parallel exist. In contrast to the centralized control circuit, each GDU measures and controls the current of its IGBT module individually. In consequence, the control for the current balancing is distributed to all GDUs and no supervising control circuit is needed. However, a communication between the GDUs is naturally needed. The main control unit is only responsible for the control of the converter, i.e. the generation of the switching signals, and works independently of the parallel connected IGBT modules. In Fig. 3 the block diagram of the DAGC is shown.

In section 2, the DAGC is presented and the operating principle is explained in detail. One key component of its implementation is the current measurement including edge detection that is then investigated in section 3. The communication between GDUs, another essential integral part of the DAGC, is described in section 4. Finally, the performance of the DAGC is experimentally verified in section 5 by measurements with the developed hardware.

2 Decentralized Active Gate Control

2.1 Operating principle

The DAGC [16] consists of equivalent and independent isolated GDUs, as shown in Fig. 3, where each GDU drives one IGBT. In addition to the gate drive output stage, the GDU contains mainly the same features as the centralized active gate control [13–15], i.e. a current measurement circuit and an independent digital control unit, e.g. FPGA, to control the turn-on and turn-off times as well as the switching behavior of the IGBT. The control to balance the currents of the parallel connected IGBT modules is therefore distributed to all GDUs and no supervising control circuit - as used in [13–15] or Fig. 2 - is needed. The main control unit operates independently of the parallel connected IGBT modules and the number of I/O-channels to the GDUs is reduced to just one single output signal common for all parallel connected GDUs and IGBT modules as depicted in Fig. 3.

In order to control the turn-on and turn-off times of the IGBT, which in general are different for each switch, the GDU_j has to measure the switching times, which could be calculated out of the time difference between the incoming PWM gate signal gs_A and the current edge of i_{A_j} measured by the current sensor and an edge detection comparator.

If the isolator's delay skews of the PWM gate signal are negligible, as it is the case for isolators based on electrical transformers [17], each GDU can control the turn-on and turn-off time independently to a predefined value without the need of communication. The challenge of these transformer-based signal isolators is the high voltage isolation, that is why optical isolators or links are typically applied.

The propagation delay skew for optical isolators is, as already mentioned, in the range of 60 – 100 ns neglecting aging effects. In such cases, it is insufficient to control the turn-on and turn-off times to a constant value. The control unit needs a reference signal containing information about the current imbalance between the driven and a second IGBT, e.g. the effective delay time between the two current edges or the amplitude difference after the turn-on switching transients, to adjust the switching times for balancing the currents.

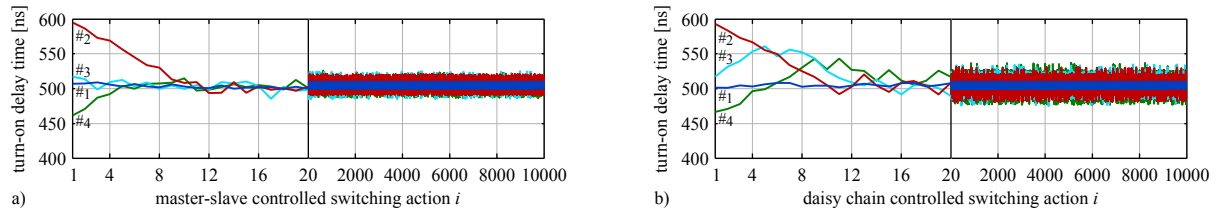


Fig. 4: Simulated turn-on delay times with DAGC using the a) master-slave and b) daisy chain control structure for 4 parallel connected IGBT modules based on individual sampling-jitter of the PWM gate signal input and of the current edge detection assuming digital control units operating at the frequency of $f_s = 100$ MHz.

Each GDU can directly provide the occurrence of its IGBT's current edge to another GDU, for example galvanically isolated with a signal transformer, where the control unit of the GDU receiving this signal is able to calculate a reference signal out of the effective delay time between the received and the own current edge signal. In this case, the propagation delay skew of this digital signal has to be minimized. Instead of transmitting the current edges, it is also possible to transmit the current amplitude, which is measured and sampled with an ADC directly after the turn-on switching transients, as a digital value to another GDU via a serial data channel. The receiving GDU calculates the reference signal as the amplitude difference between this received digital value and the one of the own measurement. Alternatively, each GDU could also directly measure the currents of the own and another IGBT with two current sensors to derive the needed reference signal without the need of communication.

As a reference either one IGBT current for all remaining GDUs (master-slave) or the IGBT current of the neighbor on the, e.g., left hand side (daisy chain) can be used. In the next subsections, these two control structures are analyzed and compared.

2.2 Master-slave control structure

In the master-slave control structure one GDU is selected as master and it provides to all other GDUs (slaves) the information needed for their reference signal calculation. Fast control dynamics and small temporary total switching time differences for all GDUs can be achieved with this topology because of the common reference for all slaves.

As the minimum temporal resolution is given by the operating frequency f_s of the digital control units, the slave GDUs can be synchronized on average to the master GDUs independently of each other within an interval of $T_s = 1/f_s$. Due to the individual clocks and sampling-jitter of the PWM gate signal and e.g. the current edge detection, a temporary total turn-on/off time difference for an arbitrary value of IGBT modules will typically get larger than T_s but smaller than $4 \cdot T_s$.

Due to stability aspects, it is proposed to change the controlled delay time in steps of the sampling time T_s per switching action, as the compensation of the entire measured delay time can lead to overcompensation and thus to ringing.

2.3 Daisy chain control structure

Instead of a common master for all slave GDUs, in the daisy chain control structure each GDU uses one, e.g. the left, neighbor as a reference (cf. Fig. 3). The most left GDU, finally, acts again as main master.

Due to the digital control units operating at the discrete sampling frequency f_s , the minimum control accuracy of the reference signal is again limited on average to $T_s = 1/f_s$ but the total temporary switching time differences for an arbitrary value of parallel connected IGBT modules is not explicitly limited.

In order to prevent unbalanced current sharing due to the sum of individual temporal resolutions T_s , the control procedure for the daisy chain structure must be modified for the case that the reference signal is based on the current edge delays. In a similar manner to maximum power point tracking algorithms, even if no delay time is measured, the switching times always have to be adjusted to find the optimum turn-on and turn-off times. As a dynamic tracking has to be implemented for the daisy chain control structure in this case, a change in time of one GDU also results in a change of time for all GDUs with lower priority. Therefore, compared to the master-slave control structure, this results in slower control dynamics and larger temporary total switching time differences.

2.4 Comparison of master-slave and daisy chain control structure

A simulation model considering individual clocks and independent sampling-jitter of the PWM gate signal input and the current edge detection of four GDUs was created for the master-slave and for the daisy chain control structure. If the control units on the GDUs detect the current edges in the same sampling

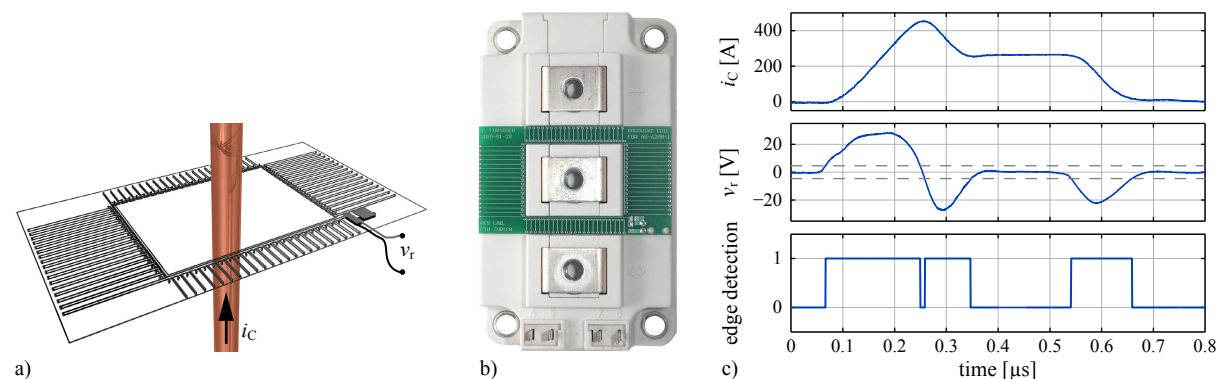


Fig. 5: a) Conductor carrying the current i_C enclosed by a PCB-Rogowski coil providing the voltage v_r . b) IGBT module (AG-62 mm package) and implemented PCB-Rogowski coil. c) Measured waveforms of the collector current i_C , the voltage v_r and the resulting logic output signal of the edge detection comparator.

interval, the delay time is not adjusted for the master-slave but arbitrary for the daisy chain control structure, otherwise the time of the delay stage was adjusted in all cases by one step of T_s . In Fig. 4 the simulated turn-on times of all four IGBTs are depicted in dependency of the switching action.

As already expected, with respect to the achievable accuracy, the master-slave control structure results in faster control dynamics than the daisy chain structure, has a non-minimum phase character and smaller temporary switching time differences as shown in Fig. 4. However, the daisy chain control structure offers the advantage of shorter, symmetrical and more natural communication paths between the GDUs. Therefore, the hardware realization for the daisy chain control structure is more feasible.

3 Current measurement

Independent of the mentioned possibilities to communicate the information, needed to derive the reference signal, from one GDU to another, or the implemented control structure (master-slave or daisy chain), each IGBT current or, as will be shown, at least its edges have to be measured to generate the reference signal.

In general, the current edge detection is made with a high speed comparator, which compares the measured IGBT current with a certain threshold value [15], that can be set to an arbitrary value, but has to be below the measured peak current and identical for all GDUs. The output power of a converter and also the IGBT current amplitudes can vary in a wide range, i.e. from zero to the nominal value. Therefore, depending on the actual current level, the threshold value of the high speed comparator should always be adjusted to $\hat{i}_C/2$, which is less reliable and more complex to realize than a fixed threshold value.

The current slope for converters within a power range of several 100 kW to MW is typically in the range of few $\text{kA}/\mu\text{s}$ [3, 5, 18], whereas the slope is mostly independent of the switched current value [19]. Therefore, in order to detect the current edges with a fixed threshold value, the current edges respectively the current derivatives di_C/dt can be used instead of the real IGBT current i_C . However, depending on whether the IGBT is turned-on or off, the measured di_C/dt can be either positive or negative. Thus, for the detection of the rising and falling current edges two independent high speed comparators have to be used. As the current slopes during turn-on and turn-off are in general different, two different threshold values can be used.

Since a current measurement has to be implemented at least once on every GDU, a simple and cheap but anyhow accurate solution is needed. Two promising approaches are described in the following paragraphs.

3.1 Rogowski coil

The Rogowski coil is basically a coreless coil that encloses the conductor, whose current has to be measured. Due to the magnetic coupling M between the Rogowski coil and the enclosed conductor, similar to a transformer with a single primary turn, a variation of the current i_C results in a variation of the magnetic field, whereby based on Faraday's law a voltage v_r is induced in the coil [15] as per (1):

$$v_r(t) = M \cdot \frac{di_C(t)}{dt} \quad (1)$$

The induced voltage v_r is proportional to the derivative of the current, whereas the mutual inductance M between the Rogowski coil and the conductor depends on the geometry and the number of turns

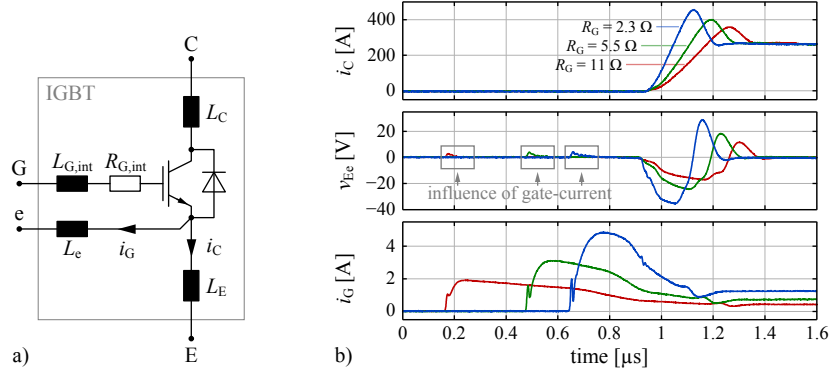


Fig. 6: a) IGBT's internal bonding inductances and gate resistor. b) Measured waveforms of the collector current i_C , the voltage between power-emitter 'E' and auxiliary-emitter 'e' terminals v_{Ee} and the gate current i_G during the turn-on switching transients for different external gate resistors $R_{G,on}$.

of the coil. In general, the Rogowski coil can be wound on a flexible or on a rigid bobbin. In order to construct a reproducible and flat measurement setup for each IGBT module, a PCB-Rogowski coil was implemented as depicted in Fig. 5 a) and b). The Rogowski coil can be designed for the given specifications and can easily be reproduced with the same signal behavior due to the tight tolerances during the PCB manufacturing process. As a GDU has to be connected to an IGBT as close as possible, the PCB-Rogowski coil could be combined with the GDU's PCB to minimize the overall size. In Fig. 5 b) the designed PCB-Rogowski coil and the associated IGBT module (Infineon FF450R12KE4) are depicted. The Rogowski coil consists of 80 turns, its mutual inductance was measured to $M = 7$ nH and the upper bandwidth is approximately $f_u \approx 70$ MHz.

In Fig. 5 c), measured waveforms of the IGBT current i_C and the output voltage of the Rogowski coil v_r are depicted. This voltage is directly used for the current edge detection by comparing it to a positive and negative reference value (dashed lines) with a comparator. During the turn-on transients a second detection signal may result after commutating the current from the diode (cf. Fig. 5 c)). As only the first positive comparator signal for turn-on and the first negative one for turn-off are considered after a gate signal transition, this additional pulse does not affect the control.

In addition, the voltage v_r can be actively integrated with an integrator circuit [20] in parallel to the current edge detection to measure the IGBT current during the switching transients. This signal can then be sampled with an A/D-converter after the switching transients to provide an amplitude information that could also be used to derive a reference signal needed for the DAGC.

3.2 Emitter inductance

The internal connections of an IGBT module, i.e. bonding wires and screwed terminals, cause parasitic inductances as shown in Fig. 6 a). Although these parasitics lead to a degradation of the switching behavior and therefore are unwanted, they can be used for current measurement if the emitter terminal is split into a power-emitter 'E' to connect the power circuit and an auxiliary-emitter 'e' to connect the GDU. Based on the relation between current and voltage of an inductor, the resulting voltage v_{Ee} between the power- and the auxiliary-emitter terminals is given by the inductances L_E , L_e and the derivatives of the gate and collector currents according to (2):

$$v_{Ee} = -L_E \cdot \frac{di_C}{dt} + L_e \cdot \frac{di_G}{dt} \quad (2)$$

Based on the used IGBT's datasheet (Infineon FF450R12KE4) the inductance values L_E and L_C are each in the range of 10 nH, similar to the mutual inductance value of the designed Rogowski coil. The total emitter-inductance $L_E + L_e$ was measured to 50 nH, which results in an auxiliary-emitter-inductance of 40 nH. Therefore, neglecting the gate resistors and the external series inductance of the gate driver circuit and assuming a gate inductance $L_{G,int} = L_e$ and a GDU supply voltage of ± 15 V, in the worst case a voltage of ± 15 V respectively a gate current slope of ± 15 V/40 nH = ± 375 A/ μ s can be measured between the emitter terminals 'E' and 'e' at most, when the GDU is turned-on or off. The measured voltage induced by the gate current thus shows, even in the worst case consideration where all mentioned external parasitics are neglected, a smaller amplitude than the voltage induced by the collector current.

However, as the two induced voltages in (2) have a different polarity and the gate of the IGBT has to be partially charged or discharged before the IGBT starts switching, the two induced voltages appear at different times and can easily be separated, e.g. by blanking out the induced negative voltage caused by

the gate current during the turn-on respectively the induced positive voltage caused by the gate current during the turn-off switching transients as shown in Fig. 6 b).

Except for polarity, amplitude and the short voltage spike due to the gate current, the measured emitter voltage v_{Ee} equals the voltage v_r induced in the Rogowski coil. In spite of this signal distortion, the emitter voltage v_{Ee} has the major advantage, that for the current edge detection no additional sensing hardware, e.g. a Rogowski coil, is needed. However, in comparison to the Rogowski coil, the voltage v_{Ee} is clamped to the auxiliary-emitter 'e' and is not floating like v_r leading to more complex current measurement and edge detection circuits.

3.3 Overcurrent protection

As for both presented current measurement methods the current derivative di_C/dt is measured, the IGBT current during the switching transients or for short pulses (some $10 \mu s$ [15]) can be measured with an additional active integrator circuit integrating the current derivative [20].

This simple and low cost measurement circuit can be applied to protect the IGBT from overcurrent during the switching transients. Due to high-pass characteristic and non-idealities in the integration circuit, the current of longer pulses and also DC-components cannot be measured correctly by this method. The protection of the IGBT after the switching transients thus can be achieved by simple desaturation detection [21], where the saturation voltage $v_{CE,sat}$ of the IGBT is monitored. This protection method can only be activated a few μs after the switching transients, when the gate is fully charged. The combination of these two protection functions leads to a simple solution to protect the IGBT current during switching transients as well as during on-state. As the value of i_C is available at the integrators output on the GDU during the turn-on transients, the use of a complex multi-level desaturation detection to identify an overcurrent already during the ends of the transients, as proposed by [22], can be avoided. In addition, by monitoring the real current value during the switching transients, an exact current trip value can be ensured.

In case of an overcurrent detection on the GDU, the own IGBT can be soft turned-off. To reduce delays for the turn-off of the parallel connected IGBTs, the protection signal can be transmitted to all further parallel connected GDUs, as well as to the main control unit to ensure a safe turn-off operation of the whole system. A single electrical protection bus on the non-isolated side of all GDUs connected in parallel and the main control unit can be applied to avoid multiple signal paths thereby.

4 Communication

The measured current edges or current amplitudes have to be transmitted between the GDUs. In this section, the general requirements of the communication channels are identified and possible implementations are presented.

In general, the power terminals of parallel connected IGBT modules are joined to a low inductive busbar, as shown in Fig. 1, with a common emitter potential and collector potential respectively. The GDUs, however, are connected to the IGBT's auxiliary-emitter 'e', whose potential v_e can vary individually for each GDU, depending on the switching behavior, i.e. the gate and collector current time derivatives, in accordance with (2). To transfer the edge or amplitude information from one GDU to another, a galvanic signal isolation has to be applied. As the voltage between the power- and auxiliary-emitter $v_{Ee} = v_E - v_e$ is usually in the range of some tens of volts and the voltage between two GDUs is always less than $2 \cdot v_{Ee}$, which is typically well below 100 V, the isolation requirements concerning electric strength and common-mode immunity are low.

Depending on the type of transmitted signal - current edge or sampled current amplitude - different types of isolators have to be applied as described in the following.

4.1 Current edge signal

For the transmission of a current edge signal, a galvanic isolation with a isolation voltage of at least 100 V and a minimum amount of propagation delay and delay skew is needed. A ferrite core signal transformer with a high magnetic coupling thus can be used [17]. Compared to opto- or magnetocouplers, the propagation delay of such signal transformers, defined by the parasitics, can be neglected. Assuming a comparator output signal with a length of several 100 ns to $1 \mu s$ and a pulse voltage of 3.3 V, only a very small ferrite core signal transformer with a few number of windings is needed to avoid saturation of the core. In order to achieve perfect reproducibility and to minimize costs, a tiny PCB-transformer with high magnetic coupling was implemented on the GDU to isolate the current edge signal (cf. Fig. 7 - ④). It consists of a ferrite E- and I-core combination (Epcos ELP 14 Series N87) with a core cross-section of $A_C \approx 14 \text{ mm}^2$ and 3 turns around the core's center leg for the primary and secondary windings in different PCB-layers. The delay time of this implemented signal transformer was measured to $t_d \approx 1 \text{ ns}$.

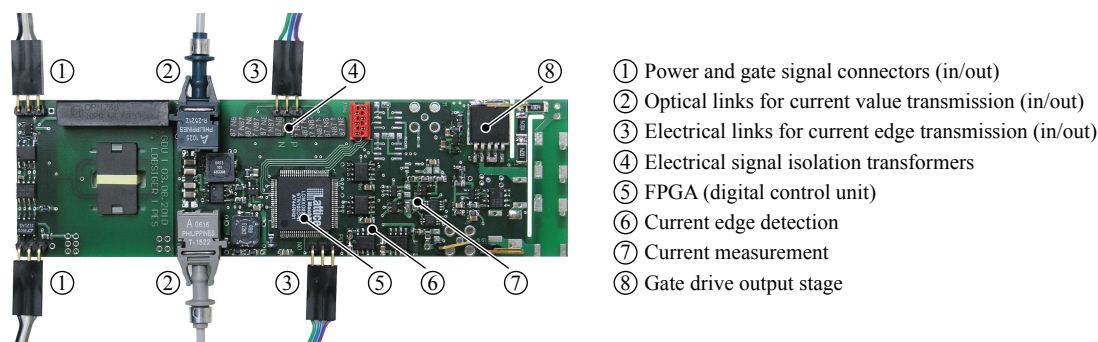


Fig. 7: Developed GDU containing the DAGC functionality.

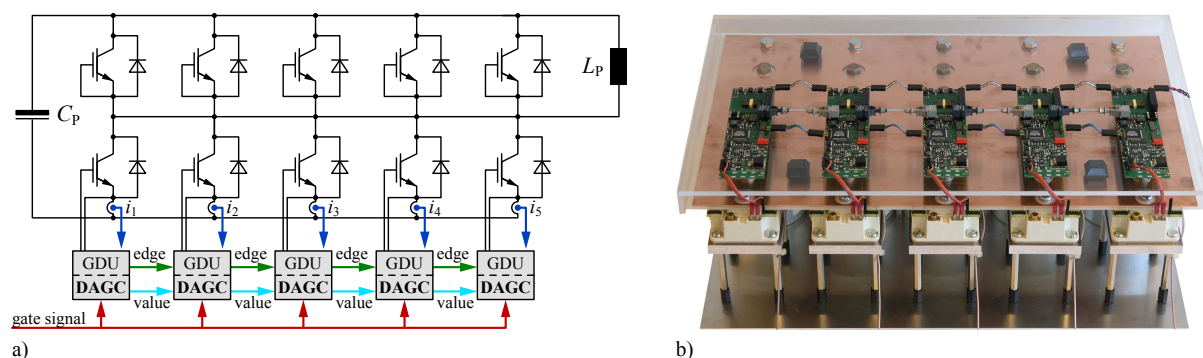


Fig. 8: a) Schematic of the test setup hardware and the block diagram of the particular GDUs, the current measurements and the communication channels. b) Top front view of the test setup hardware (without pulse inductor). Top: five interconnected GDUs, middle: isolated busbar, bottom front: 5 parallel connected IGBT modules with PCB-Rogowski coils, bottom back: DC link capacitors.

However, to compensate this delay time, an identical transformer could also be inserted between the own edge detection comparator and the control unit of a GDU.

4.2 Current amplitude signal

To transmit a sampled current amplitude value, e.g. with an 8-bit resolution, a digital communication channel between GDUs must be implemented. An asynchronous serial bus is the easiest way to implement such a communication as therewith only one connection is needed. In contrast to the current edge communication, the transmission of the current amplitude is not as time-critical, since the digital signal has to be transmitted only within one switching period (typ. around $100\ \mu\text{s}$ for 10 kHz switching frequency) resulting in a rather low minimum data rate. The galvanic isolation requirements of 100 V allow to use magnetocouplers, optical links or even optocouplers. This kind of communication can therefore be implemented easily due to the low requirements concerning propagation delay and isolation voltage.

5 Experimental results

5.1 Hardware setup

An isolated GDU was developed, as shown in Fig. 7, that contains the DAGC functionality: a digital control unit (FPGA), current measurement circuits with edge detection by either a Rogowski coil or the IGBT's emitter voltage difference and communication interfaces to transmit current edges and sampled current amplitudes between GDUs both in a daisy chain control structure.

To verify the proposed DAGC, a test setup consisting of a film capacitor DC link C_P (up to 1 kV, 1.6 mF), 5 parallel connected Infineon FF450R12KE4 IGBT half-bridge modules (1.2 kV, 450 A) driven by the developed GDUs, an air-core pulse inductor L_P ($53\ \mu\text{H}$) and a low inductive busbar interconnecting all components was built. Its schematic is shown in Fig. 8 a) and the realized hardware corresponding is depicted in Fig. 8 b). With this setup, multiple pulse tests for up to 5 parallel connected IGBT modules can be performed to measure and analyze the current sharing during turn-on and turn-off switching transients. To measure the currents of all the IGBTs, Rogowski coils, as illustrated in Fig. 5 b), are implemented in the hardware setup.

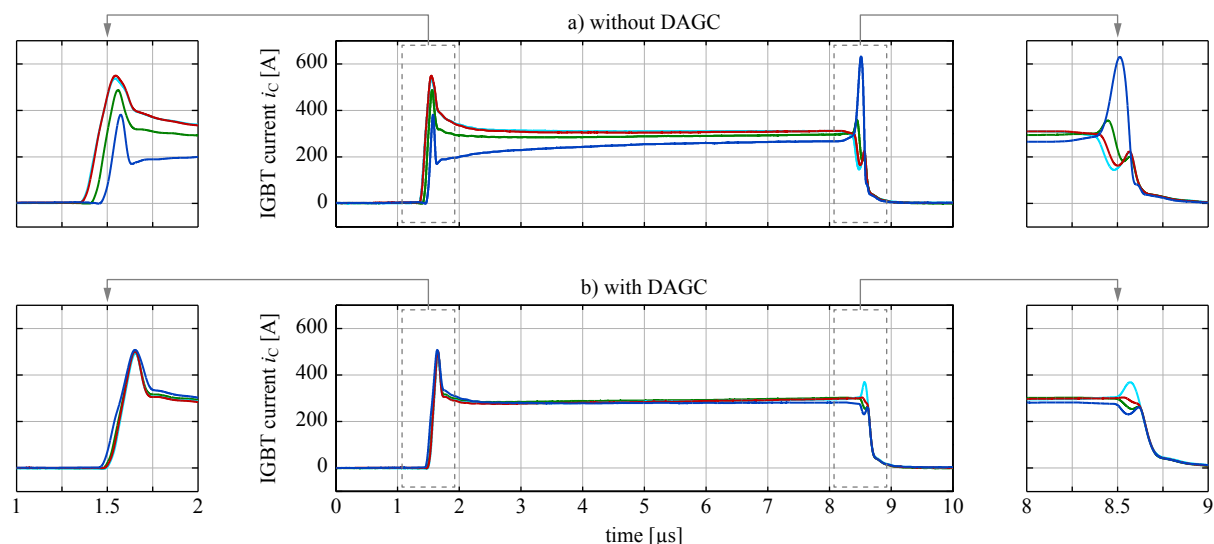


Fig. 9: Measured IGBT currents a) without and b) with current amplitude DAGC ($f_s = 100$ MHz) based on the actively integrated emitter voltage difference v_{Ee} . The current waveforms have been generated by means of measuring the implemented PCB-Rogowski coil's voltages (cf. Fig. 5) and integrating them digitally on a PC. The gate signal delays of all 4 IGBTs have been adjusted to $t_{\text{delay}(1,2,3,4)} = 100, 0, 20, 50$ ns in both cases.

5.2 Measurements

The current distribution of 4 parallel connected IGBT modules was measured for hard turn-on and turn-off switching transients in a multi pulse test to demonstrate the performance of the DAGC. The gate signal delays of all 4 IGBTs have been adjusted to constantly $t_{\text{delay}(1,2,3,4)} = 100, 0, 20, 50$ ns. A sequence of 20 pulses was performed after which the current sharing has been measured.

Without DAGC, the constant gate signal delays are not compensated, thus an unbalanced current distribution, as shown in Fig. 9 a), results. With DAGC ($f_s = 100$ MHz) and amplitude control based on the actively integrated emitter voltage difference v_{Ee} implemented on all GDUs, the delays of the gate signals are compensated by the control units. As a consequence, the current distribution is transiently and statically almost completely balanced for all 4 IGBT modules as depicted in Fig. 9 b). If the DAGC is implemented with the edge instead of the amplitude control, also based on the emitter voltage difference v_{Ee} , a similar current distribution is achieved.

It has to be mentioned, that due to the individual clocks of the control units and the sampling jitter of the PWM gate signal inputs, the DAGC is an ongoing control action where the delay times for all IGBTs may vary individually around the optimal average delays, what results in temporary slightly less balanced currents. This consequence could be minimized by increasing the FPGA's clock frequency f_s .

6 Conclusion

In this paper, the decentralized active gate control, a modular concept to balance the currents of parallel connected IGBT modules, is presented. The distributed control units on the GDUs adjust the switching times to achieve a dynamic current balancing by means of the implemented measurement and communication capability. Thanks to the modular concept, adding or removing IGBTs to and from the parallel connection without giving up the DAGC is very simple as no changes in the GDU's hardware and software have to be executed.

For the required current measurement functionalities two simple, cheap and accurate implementations are shown, whereupon in one solution the IGBT itself is used as current sensor and no additional sensing element is needed. Realization possibilities for the two different types of communication (edge or amplitude) have been investigated.

To experimentally verify the performance of the proposed control, GDUs with implemented DAGC, current measurement and communication channels have been developed. It has been shown that the DAGC is able to compensate the initially existent delay times for the parallel connected IGBTs enabling a balanced current distribution.

In addition to the DAGC, the digital control unit on the GDU can be applied for advanced driving methods of the IGBT. Adjusting di_C/dt or dv_{CE}/dt by a controllable output stage and improved protection functions can be handled simultaneously by the digital control unit.

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