A Real Time V_{ce} Measurement Issues for High Power IGBT Module in Converter Operation

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***Abstract*—A real time on-state collector-emitter *(V_{ce})* voltage monitoring is sensitive due to a stray inductance and a parasitic capacitance inside high power IGBT modules. An additional circuit used to monitor the on-state V_{ce} introduces small current into the module. Though the current is low in comparison to the converter current, the effect on gate driving signals cannot be neglected during worst case switching operations. The worst case situation is occurred during turn-on and turn-off period of the switches at low on-time of the IGBT. Furthermore, during this period, when the common terminal of the measurement circuit is not in contact properly, the consequences of the error will be higher by deteriorating the gate driving signals. This type of error may occur due to the vibration or during implementation of the measurement circuit in the converter. This paper presents the influence of the error into the measurement and shows the measurement of current and voltage transients during the converter operation. The selection of the components for the measurement circuit is also discussed. The effect in gate driving signals with and without the error events are presented. Finally, a real time V_{ce} measurement of IGBT module in the converter operation is presented.**

I. INTRODUCTION

The multi-chip high power insulated gate bipolar transistor (IGBT) contents parasitic inductance and capacitance due to layout and wire-bonding structure inside the package [1, 2]. The switching transient analysis shows major issues during turn-on and turn-off of the modules in a converter operation. The gate driving signals are influenced by the IGBT internal stray inductance [3]. In addition to this, the measurement circuit used for the condition monitoring of the power modules injects small current into the converter. This additional current has a bigger influence during worst case turn-on and turn-off of the IGBT. The worst-case transient occurs at the minimum turn-on time of the switching when the fundamental current is at a positive or a negative peak. Moreover, the noises will be even higher when the common terminal of the measurement circuit is not in contact properly during the converter operation. This is related to a practical problem which increases failure of the power modules due to a small error event.

Two major issues are identified during switching transients of the power modules even without implementing the on-state collector emitter voltage (V_{ce}) measurement board in the power converter. Firstly, the current overshoot occurs at turn-off of the freewheeling diode. Secondly, a voltage overshoot occurs at the turn-off of the IGBT [4]. It is necessary to consider the safe operating area due to parameter drift before and after accelerated power cycle test [5]. The reverse voltage capability of IGBT is not given. A careful selection of freewheeling diode and minimal stray inductance due to layout is required to avoid the occurrence of reverse voltage drop. The purpose of implementing the V_{ce} monitoring is to increase the reliability of the power modules. On the other hand, the error event such as loose connection only in the common terminal of the measurement circuitry could be a reason to reduce the reliability of the power modules. Due to this error event, the current flowing through the measurement components is high and this influences the gate driving signals by resonating it during turn-on and turn-off time. Consequently, the disturbed gate driving signals may short the upper and lower part of IGBT and also increases the possibility of latching-on the IGBTs across two legs of the converter. Even latter event occur, the converter is safely protected by turning-off the converter using overcurrent protection. However, this causes ageing of the module after frequent operations. Therefore, the measurement technique used to improve the reliability of the power module should not be a cause to increase the wear-out.

This paper shows experimental results of switching transients for the error event and for the normal operation of the converter. The switching transients during turn-on and turn-off for the worst case conditions are shown. Finally, the unaffected online and offline V_{ce} measurement using proposed V_{ce} measurement topology are presented.

II. PARASITIC IN IGBT MODULE

Silicon chips are connected in parallel to increase a high current capability in high power IGBT modules. As shown in Fig. 1, the cut section of 1000A module has 10 aluminum bond wires in IGBT and diode chips. The figure also shows

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layout of internal stray inductance and parasitic capacitance in the chip and the module. Each module has six identical sections of IGBT and diode chips as shown in Fig. 1.

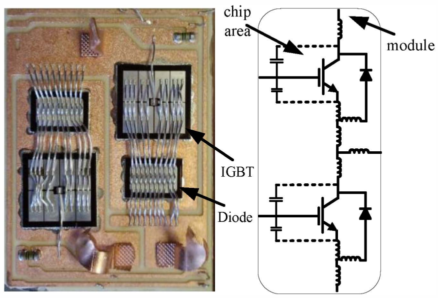

Fig. 1. Internal layout of stray inductance and parasitic capacitance in half bridge IGBT module

The passive parasitic components are distributed parameter and they are related to the substrate layout and chip arrangements in high power modules [1]. The power modules have two emitter contacts for the power and control signal to minimize the emitter inductance for the gate driving signal. A detail parasitic extraction is explained and concluded that the parasitic inductance mainly appears in the packaging terminal leads for the planar type packaging module in the literature [6].

III. POWER CONVERTER TEST SET UP

Power converters are expensive and the most vulnerable parts in traction and wind turbine applications [7]. The physical size of the converters is evolving into smaller size to lower the cost. As a result, the power modules have to suffer larger thermo-electrical stress in real application. Furthermore, in wind turbine systems with the doubly-fed induction generator; the converter connected in the rotor side operates in maximum thermal stress zone most of the time at low frequency [8]. As the numerous previous research outcomes show a detectable variation in on-state V_{ce} due to thermal stress and failures of the device, this voltage gradient can be considered as a warning signal to detect an ageing and a failure of the module.

An H-bridge converter topology is used as shown in Fig. 2 in order to realize the thermo-electrical stress as in a real life application for wind power converter. The device under test (DUT) is connected to the control side power module through the inductors [9]. Moreover, to reduce the stress level in the control side, two control legs have been used in parallel and connected with DUT leg through the current sharing inductors. In Fig. 2, DU_H and DU_L are high side and low side IGBT and the corresponding diode of DUT. The current i_1 is divided in parallel using sharing inductors L_2 and L_3 in corresponding legs of the control side. Together with the total inductor the control side legs acts as a current source, hence large magnitudes of power is circulated between the switching devices. The voltage control in DUT leg is feed forward while the control legs are controlled in such a way that a sinusoidal current that fulfill the demand will flow between the DUT and the control legs.

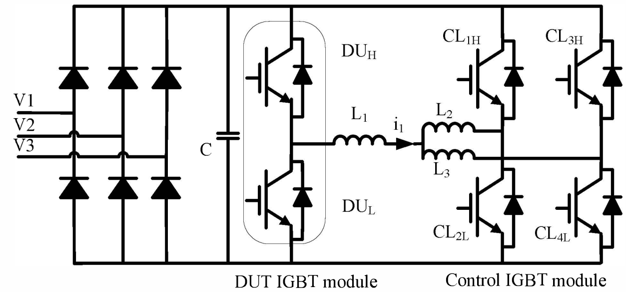

Fig. 2. The converter topology for test set up

The half bridge modules are used in the both DUT and control sides of the converter. The operating points of the converter for this test are given in table I.

Table I. The operating points of the power converter

Parameter	Value
DC link voltage (V_{DC})	1000V
Outpput voltage (V_{out})	315Vrms
Load current (I_L)	630Arms
Fundamental frequency(f_{out})	6Hz
Switching ferquency (f_{sw})	2.5kHz
Water temperature for cooling	80°C

A Danfoss Shower Power cooling system is used to maintain the steady temperature across the base plate of the power modules. The controller implemented in the cooling system is able to keep the water temperature at steady value.

Both online and offline measurement methods are implemented in the test set up. During offline measurement process, the normal PWM switching is disabled and a measurement routine is enabled. In which, a current is ramped up until it reaches peak value through the inductors and the corresponding switches turned-off and turned-on in respective time to read the on-state V_{ce} of the IGBT and diode. In each measurement process the offline measurement is enabled for 680µs to ramp-up and remove the measuring current.

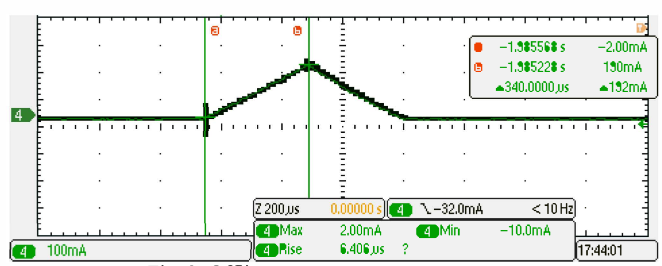

Fig. 3. Offline measurement process

In regards to the online measurement process, the converter is run at rated parameter in normal PWM switching operation. However, to eliminate the large data handling process, the measurement routine is enabled in every 5 minutes of operation. During the both measurement processes, the water temperature is maintained at 80°C with the maximum ±0.5°C variation.

IV. REAL TIME V_{CE} MEASUREMENT TOPOLOGY

A diode based voltage measurement circuit is implemented to monitor the V_{ce} in the converter operation as shown in Fig. 4. Due to slow reverse recovery of the freewheeling diode of the module, the reverse voltage is crucial for the IGBT and for the monitoring circuit. Moreover, the transients during turn-on and turn-off of the IGBT also appear at the monitoring circuit. The transient suppression and voltage clamping diodes should behave faster than the transients of the module and bypass the transients to protect the measurement board. The operating principle of the monitoring circuit is described by Szymon et al [10].

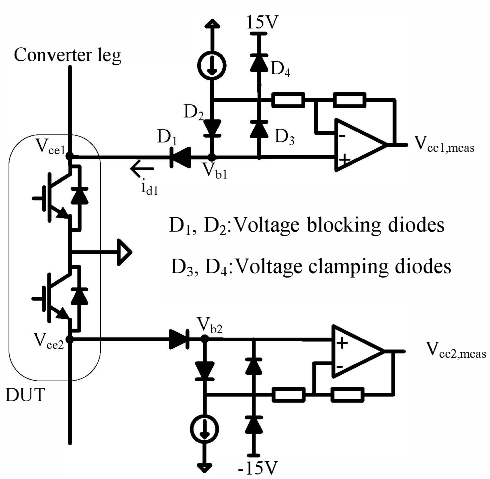

Fig. 4. Online V_{ce} measurement circuit

For Fig. 4,
V_{ce1}: Collector-emitter voltage for high side IGBT
V_{ce2}: Collector-emitter voltage for low side IGBT
V_{ce1},meas: Measured V_{ce1}
V_{ce2},meas: Measured V_{ce2}

A single circuit is implemented to measure the on-state V_{ce} of upper and lower part of the IGBT and the diode. In this paper, the worst case switching transient voltages are measured during turn-on and turn-off of the IGBT. The peak voltages are measured at collector emitter of the IGBT and the corresponding transient peak in the clamping diode at V_{b1} and V_{b2}. The reverse transients current flowing through blocking diodes D_1 is also measured in the worst case situation.

V. SWITCHING TRANSIENT

This section presents the gate-emitter and collector-emitter switching behavior of the IGBT without implementing the voltage monitoring circuit in the converter. The increase in gate bias voltage will increase the di_1/dt. The reverse recovery of diode is also a function of the di_1/dt. Consequently, the reverse recovery creates the over current stress to the IGBT and over-voltage stress to the diode, which ultimately creates electro-magnetic interference (EMI) problems in the converter.

A. Turn-On Transients

At positive current peak, when low side IGBT DU_L is suddenly turn-off, the current starts flowing through freewheeling diode on the upper side creating forward voltage drop, which is negative for the IGBT. Hence, the collector emitter voltage across DU_H is measured -80V due to a reverse recovery of the freewheeling diode as shown in Fig. 5. If the reverse voltage due to recovery is high, it could be critical operating point for the IGBT. The emitter stray inductance and commutation current rate of the diode may increase the reverse voltage. The equation (1) shows the relation for the increment in voltage with the variation in current flowing through the IGBT.

$$\Delta V_L = -L\frac{di_1}{dt} \qquad (1)$$

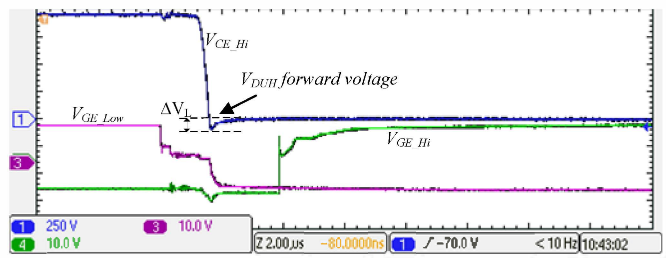

Fig. 5. Switching transient during turn-on of the IGBT

B. Turn-Off Transients

During turn-off of the DU_H, when the turn-off time starts at t_2 as shown in Fig. 6, the collector-emitter voltage rises to 1.2KV peak due to parasitic caused by miller capacitance. Though, duration of the peak is short, it is crucial for the IGBT. Due to the capacitance, the dV_{ce}/dt is high as shown in mathematical relation (2).

$$\Delta V_H = L\frac{di_1}{dt} + V_{CE\_Hi} \qquad (2)$$

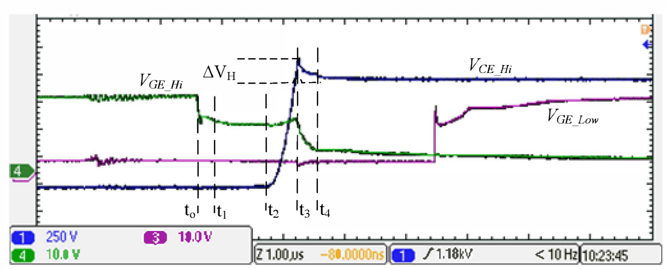

Fig. 6. Switching transient during turn-off of the IGBT

For Fig. 6,
t_o turn-off process initiates
t_1 clamped voltage in the driver
t_2 turn-off time starts
t_3 peak collector emitter voltage
t_4 turn-off process completes

As shown in Figure 6, when the turn-off process starts V_{GE} is active clamped nearly to 3.2V voltage for 1.6µs to reduce the

dV_{ce}/dt during turn-off from time t_1 to t_2. This active clamping feature is used in the modern gate drivers for the high voltage module [11]. During turn-off due to miller capacitive effect, the slope of the collector emitter voltage (V_{ce}) can be obtained using the following relation (3).

$$d\frac{V_{CE}}{dt} = -\frac{I_G}{C_{GC}} = -\frac{V_{GG}-\left(V_{th}+\frac{I_1}{g_m}\right)}{C_{GC}R_{G(OFF)}} \qquad (3)$$

where

- I_G gate current
- C_{GC} gate collector parasitic capacitance
- V_{th} threshold voltage
- g_m transconductance gain
- $R_{G(off)}$ turn off gate resistance
- V_{GG} turn-off voltage of the gate drive supply
- i_1 collector current

C. Transient Measurement

In this section the current and voltage transients during the worst cases turn-on and turn-off of the IGBT are presented with the use of the voltage monitoring circuit. Initially, the transient results are shown for the error event when the common of the measurement circuit is not in contact properly. Then the error is corrected and no influence to the gate driving signal from the measurement part is shown during the converter operation.

The transient peak voltages are shown in Fig. 7 at the high side IGBT collector-emitter terminal and at the blocking diodes is presented at different current level from Fig. 4. The converter was operated at $1000V_{DC}$ during the measurement. The transient peaks are not only crucial for the IGBT safe switching operation but also creates error in the real time voltage measurement. Fig. 7 shows the reverse voltage peak across the high side IGBT V_{ce1} and V_{b1} as shown in figure 4. The V_{ce1} peak is similar with and without implementation of the V_{ce} measurement board in the converter.

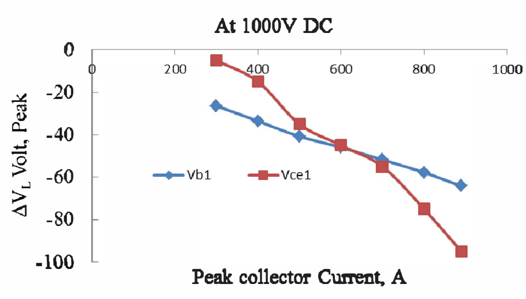

Fig. 7. The voltage transients measured at IGBT and clamping diodes (Vb1 and Vce1 defined of Fig. 3)

The additional current injection from the measurement circuit and its affect to the transient voltage cannot be avoided. Moreover, the current flows through the gate-emitter signal and produces ringing and noises in the gate driving signal. Consequently, this creates a short circuit between the high side and low side of the IGBT. The current transient measured at the measurement circuit i_{d1} (Fig 4) is shown in Fig. 8 at different current level before the improvement.

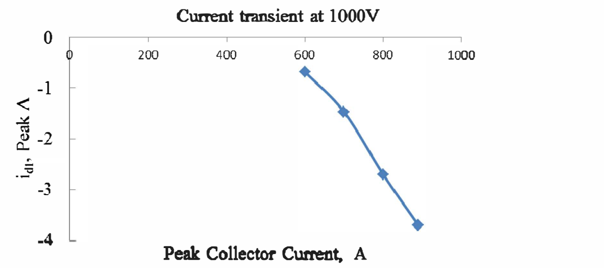

Fig. 8. The current transients measured at blocking diode i_{d1} (shown in Fig. 4)

Before improving the performance of the measurement circuit board, the gate driver signal was influenced by the current as shown in Fig. 9. As a result, the gate pulse is ringing as shown in Fig. 9. The gate transient voltage peak is recoded as 21.6V during turn-on process. The high V_{GE} is crucial for IGBTs, as the gate oxide has limited voltage capability.

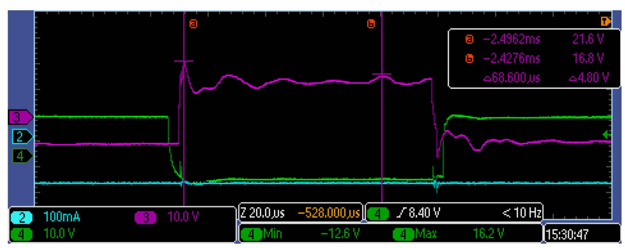

Fig. 9. A disturbed gate driving signal

For Fig. 9,
Blue: inductor current L_1
Green: gate voltage V_{GE} low side IGBT
Magenta: gate voltage V_{GE} high side IGBT

In addition to above mentioned short circuit in the leg, the transients may lead to false switching across the legs of the converter. This problem is witnessed during testing of the voltage monitoring circuit as shown in Fig. 10.

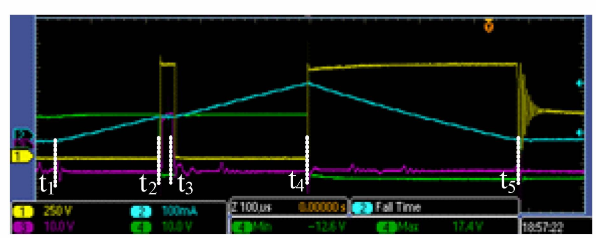

Fig. 10. A short circuit event due to false switching across legs

For Fig. 10,
Blue: inductor current L_1
Yellow: collector-emitter voltage V_{ce}
Green: gate voltage V_{GE} low side IGBT
Magenta: gate voltage V_{GE} high side IGBT

Due to this event, the low side control IGBTs (CL_{4L} and CL_{5L}) continuously latched on when the high side DUT IGBT is turned-on. Hence, the current in the inductor is continuously rising until the overcurrent protection is activated. Fig. 10, shows the current and gate driving signal before the events. At t_1, the current changes a slope because of the control side IGBTs are being latched. The current did not rise instantaneously due to high inductance between the DUT and the control side. At t_2-t_3, the high side DU_H is not conducting and the low side DU_L IGBT is conducting. The low control side IGBTs are still latched, hence the current is steady. Since turn-on time period of low side DUT is short in comparison to high side DUT, the decrement of current is small. After t3, the high side DUT is conducting and low side control IGBTs are latched, hence the current is keep increasing. At the end of this interval, the rise in current stopped due to the overcurrent protection, which is implemented in the controller. At t_4 and t_5, the protection system is activated. Hence, the power supply and gate driver signals are turn-off.

After correction on the performance of the measurement board, the transient current flowing through the measurement diodes is reduce to 40mA peak, and also the gate driver signals are not affected as shown in Fig. 11.

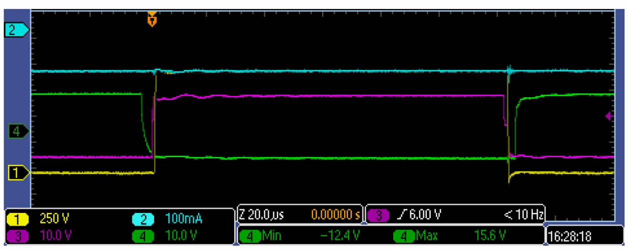

Fig. 11. A good gate driving signal

For Fig. 11,
Blue: inductor current L_1
Yellow: collector-emitter voltage V_{ce}
Green: gate voltage V_{GE} low side IGBT
Magenta: gate voltage V_{GE} high side IGBT

VI. V_{CE} MEASUREMENT

The on-state voltage V_{ce} can be measured in online and offline as discussed above. In offline measurement, the normal PWM switching of the converter is turned-off and a measurement routine is reinforced to measure the V_{ce} evolution due to wear-out of IGBT module after certain cycles of operation.

A. *Offline measurement*

The on-state V_{ce} evolution can be used as a wear-out indicative parameter of the IGBT module. However, this method is required to turn-off a normal switching operation of the converter, which is not practical to implement in field application. Fig. 12 shows on-state voltage evolution at 550A for low side diode while converter is running at full power level. The step increment in voltage also indicates a failure of the module, mostly due to bond wire lift-off. The power module is run close to 5100K cycles in a converter operating parameter as shown in Table I continuously for 10 days. At the end of the cycle, the module is failed to operate and exploded during the test.

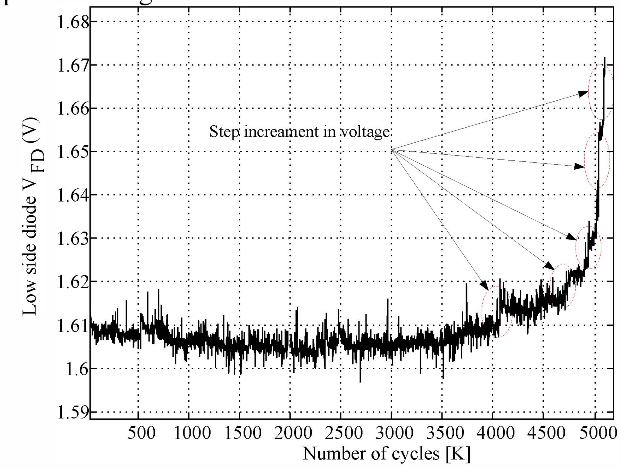

Fig. 12. On-state V_{ce} evolution at 550A measured offline

B. *Online measurement*

Fig. 13(a) shows current through inductor, (b) shows on-state voltage for low side IGBT and corresponding diode and (c) shows high side IGBT and corresponding diode while converter is running at full power.

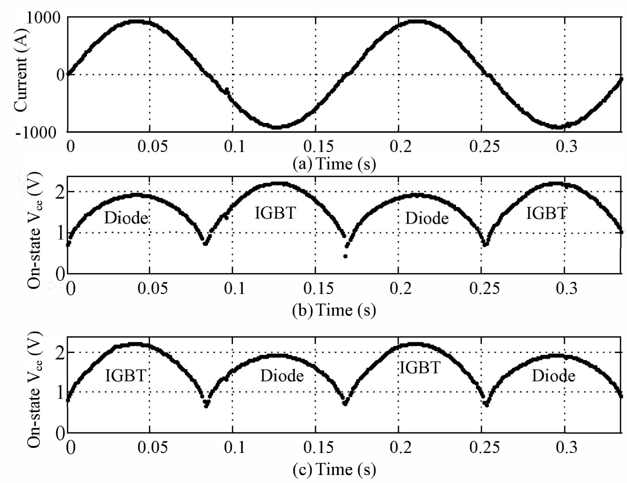

Fig. 13. A real time measurement (a) Current (A), (b) Low side IGBT and diode on-state voltage (V_{ce}) and (c) High side IGBT and diode on-state voltage (V_{ce})

This measurement technique can be implemented in field application without disturbing the normal operation of the power converter.

VII. CONCLUSION

The online measurement of on-state voltage monitoring of IGBT module in converter operation is in priority due to various advantages such as junction temperature monitoring, wear-out status monitoring, short circuit protection, over-load protection etc. This paper presents the switching transient in the high power IGBT module specifically to highlight the practical issues for the implementation of the voltage monitoring circuit. The possible effect on gate driving signals from the current injection of the monitoring circuit is demonstrated in the worst case situation. The performance of the monitoring circuit is corrected and no influence in the gate driving signal is demonstrated after long hours of operation. Finally, the offline and online on-state voltage and current measurement are demonstrated for high power converter using the proposed V_{ce} monitoring circuit.

ACKNOWLEDGMENT

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