Wideband Transfer Function Measurements on IGBTs for Active Gate Driver Design and Transient Studies

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Abstract

IGBTs (Insulated Gate Bipolar Transistor) are used for power converters. For medium voltages about 3-60kV stacking of IGBTs is an interesting issue but lag of information from the data sheet makes it difficult to design active gate drivers [1], [2]. For these reason measurements of transfer functions has to be done for different conditions in voltages and currents. In relation to this also the IGBTs reaction to applied frequencies and transients is investigated in different states. With the achieved information's a model of the IGBT and hereby converters for transient studies can be made. With these studies parasitic components and their behavior can be included in the models. Studies on passive components like DC capacitors have been done in [3]. The paper describes the component theory in relation to higher frequencies. A measurement system (10Hz -1MHz) is designed and described to being used for lab measurements in order to verify the theory. The IGBT SKM100GB123D from SEMIKRON is used for the investigation. Results from the measurements are given and analyzes with respect to the theory are done.

1. Introduction

The common used symbol of an IGBT is seen in fig. 1 left. The collector current I_C is controlled by the gate emitter voltage as described in [1].

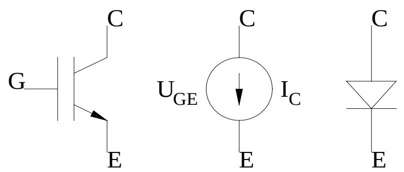

Fig. 1 – Schematic and two models of an IGBT

If U_{GE} is less than the threshold voltage U_T no current flow in the component. For a larger voltage the current is given as (1) where the IGBT acts as a voltage controlled current generator fig. 1 mid.

$$I_C = G \cdot (U_{GE} - U_T) \tag{1}$$

In (1) G is the trans conductance. When U_{GE} is larger than the matching load current the IGBT goes into saturation mode. Here it behaves as a diode fig. 1 right. The IGBT has also parasitic capacitance between the terminals as described for the diode.

The high voltage diode is a three layer semiconductor as shown in fig. 2. The terminals for the Anode and Cathode are connected with metal contacts to the semiconductor. This structure forms a capacitor with the semiconductor as dielectric material.

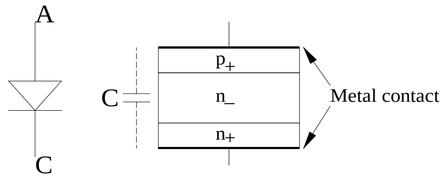

Fig. 2 – Schematic of the diode with parasitic capacitor

As seen in [4] the capacitance highly depends on the voltage across the diode. As an example it changes between 1150pF and 110pF for a voltage U_{RA} between 0.3V and 10V for the diode FFH50US60S FAIRCHILD. RURG5060 from FAIRCHILD is used in the rectifier setup for this paper.

2. Test setup for transfer function measurement on IGBT

A principle of the schematic for the transfer function measurement on the chosen IGBT is seen in fig. 3.

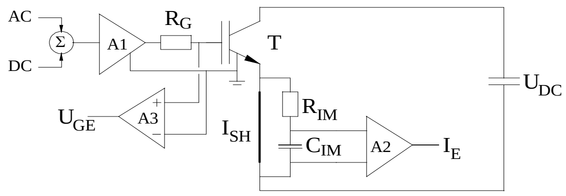

Fig. 3 – Schematic of the measurement system

T is the IGBT under test SKM100GB123D from SEMIKRON. It is driven from an analogue gate driver named A1 in series with $R_G = 15\Omega$ the recommended gate resistor from the manufactory. The gate driver is build up around LM7171 with an additional output stage.The input capacitance $C_{ies} = 6.6$nF for the IGBT forms a low pas filter with R_G where the cut off frequency $f_0 = 1.6$MHz is above the range of measurements. As well the U_{GE} is measured directly on the gate to eliminate the changes due to the cut off frequency. The DC input gives a U_{GE} gate emitter voltage above U_T the threes hold voltage of the IGBT and some voltage extra to set the collector current needed for the investigation. AC is an applied voltage with given amplitude and a frequency that change between 10Hz and 1.0MHz. This U_{GE} Create a DC current together with an AC current in the emitter. The U_{GE} is measured with the amplifier A3. The emitter current I_E pass a current shunt I_{SH}. The current create a voltage across the shunt where the shunt forms an RL circuit. A compensation circuit R_{IM}, C_{IM} with a time constant matching the RL in the shunt as seen in (2) correct the impedance.

$$\tau = \frac{L}{R} = R_{IM} \cdot C_{IM} \quad (2)$$

A voltage proportional with the current is picked up by A2. A2 and A3 are designed with the LM7171 and they need a similar transfer function in the operation area.
The trans conductance can then be find by (3).

$$G(f) = \frac{I_E(f)}{U_{GE}(f)} \quad (3)$$

The calculation in (3) is done by a FRA frequency-response-analyzer from N4L model PSM1735. The instrument is set up as a phase – gain measurement so the phase difference comes in degree and the trans conductance G in dB as seen in (4)

$$G_{dB} = 20 \cdot log\left(\frac{I_E(f)}{U_{GE}(f)}\right) \quad (4)$$

This is recalculated and a correction to the current measurement is done by the verification from paragraph 2.2.

2.1. Verify amplifier A2 and A3

By a test amplifier similar voltages are supplied to A2 and A3. The difference of the two output voltage is seen in fig. 4.

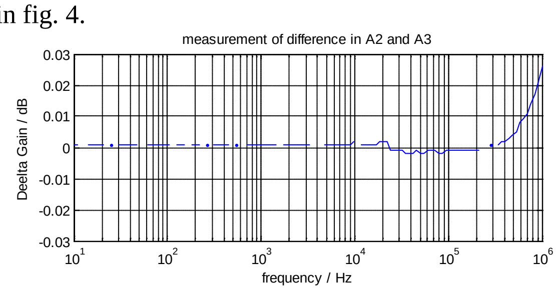

Fig. 4 – Difference of output voltage from A2 and A3

Fig. 4 shows that the difference between the two output voltages is less than 3mdB.

2.2. Verify the current measurement

A current generated with the amplifier model LPA05 from N4L and a front resistor is feted through the compensated current shunt. A measurement of the current is done with TCPA3000, TCP312 from TEKTRONIX. This is supplied to the FRA together with the output voltage from A2. Due to the shunt impedance R_{SH} = 20mΩ a gain of G = 20dB is given to the shunt current measurement. The transfer function is seen in fig. 5.

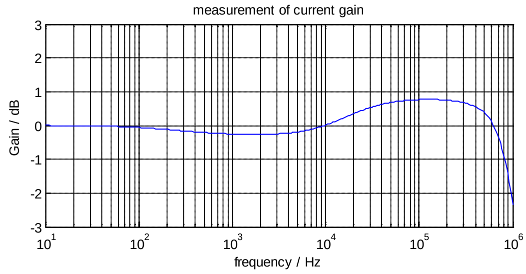

Fig. 5 – Transfer function of the current measurement

It is seen in fig. 5 that the measurement is correct within +0.8dB -2.4dB. This result is OK and is used to make correction of the current measurement from the IGBT.

In order to save space the phase measurement is not shown for the description of the set up.

3. Measurement of transfer function

The Transfer function of the IGBT is found from different settings of the U_{DC} voltage and the I_{DC} current in such a way that the loss in the IGBT does not become too large.

3.1. Changes in collector – emitter voltage

For this measurement where the dependency of U_{CE} is investigated a constant DC current of I_E = 6.0A is used. Table 1 shows the used U_{CE} voltage together with the low frequency trans conductance G_{low} and the cut off frequency f_0.

Table 1

U_{CE}	G_{low}	f_0
10V	45.4S	16.9kHz
15V	47.4S	15.5kHz
20V	49.4S	14.1kHz
25V	48.4S	15.5kHz
30V	14.8S	22.2kHz

In table 1 G_{low} is the low frequency trans conductance and f_0 is the frequency where G is reduced to -3dB as described in (5)

$$G_{-3dB} = \frac{G_{low}}{\sqrt{2}} \quad (5)$$

In the datasheet G = 45.7S at U_{CE} = 20V. This match well the result G_{low} from the measurement.
G as a function of frequency is seen in fig. 6 below.

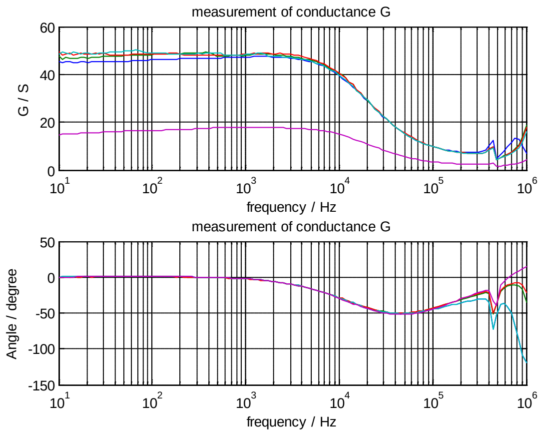

Fig. 6 – Trance conductance G with U_{CE} as a parameter and I_E = 6A

Above 15kHz the conductance decrease but independent on the voltage level.

3.2. Changes in collector current

For this measurement where the dependency of $I_{E,DC}$ is investigated a constant DC voltage of U_{CE} = 30V is used. Table 2 shows the used $I_{E,DC}$ current together with the low frequency trans conductance G_{low} and the cut off frequency f_0.

Table 2

$I_{E,DC}$	G_{low}	f_0
1.0A	14.8S	20.3kHz
2.0A	25.6S	18.4kHz
3.0A	30.5S	18.5kHz
4.0A	36.0S	15.5kHz
5.0A	40.5S	18.5kHz
6.0A	44.3S	16.9kHz

As expected from the datasheet G increase with increasing emitter current $I_{E,DC}$ for small currents.

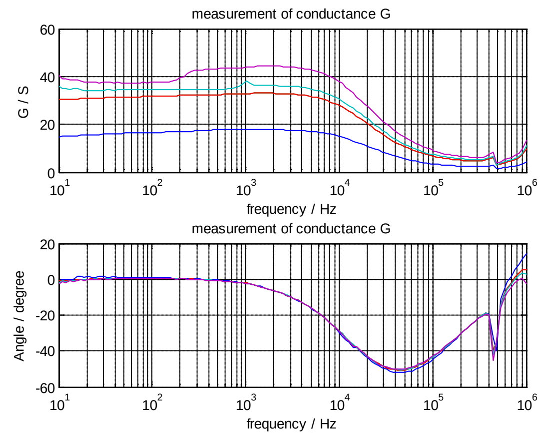

Fig. 7 – Trance conductance G with $I_{E,DC}$ as a parameter and U_{CE} = 30V

For frequencies above 10kHz the trans conductance decrease. This match the expected switching frequency of 10kHz to 20kHz for the IGBT.

3.3. DC trans conductance G_{DC}

Measurement of the trans conductance G_{DC} by using a triangle voltage to the gate is seen in fig. 8. The measurement is done by capture U_{GE} and I_E in time and then plot I_E against U_{GE}. Fig. 8 show the result for a triangle frequency of f_{tr} = 100Hz.

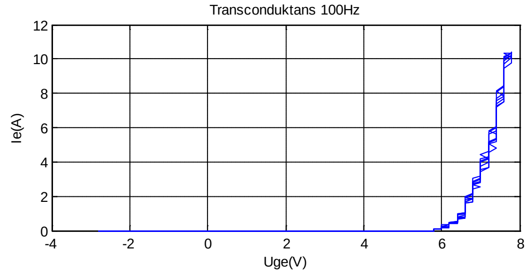

Fig. 8 – Trance conductance G_{DC} at 100Hz.

Again G_{DC} is increasing with increasing current. It is also seen that there are symmetry with increasing and decreasing current.

In fig. 9 G_{DC} is seen with a triangle frequency of f_{tr} = 10kHz.

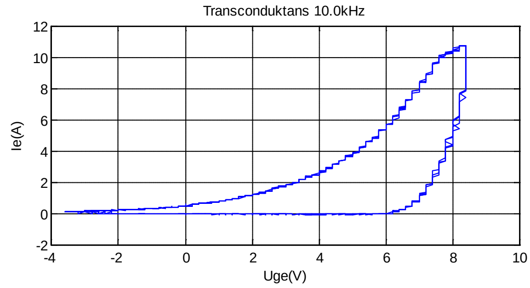

Fig. 9 – Trance conductance G at 10.0kHz.

When the frequency is increased to 10kHz a hysteresis phenomenon is observed. The I_E is seen in fig. 10.

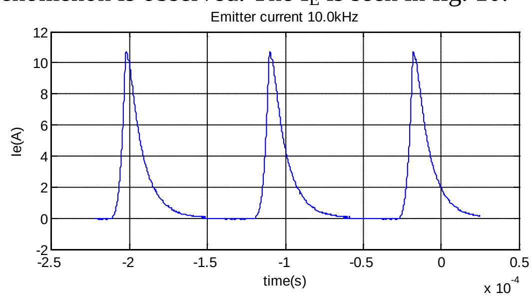

Fig. 10 – Current I_e for a triangle U_{ge} voltage.

The slope of the current is different for increasing and decreasing current.

From the data sheet rise time t_r = 70ns and fall time t_f = 70ns for I_E = 75A and gate driver voltages U_g = ±15V. R_g and C_{eis} forms an RC circuit means that the change in voltage is three times larger for turn off than for turn on means that G is 3 times less for turn off than for turn on.

3.4. Discussion

The investigation shows that the IGBT behave different trans conductance G for low and high frequencies where in general the trans conductance G decrease with high frequencies. Also it is shown that G at higher frequencies has different values for turning on and off.

When stacking IGBTs the U_{CE} have to be controlled [1] but this only involved small change in current that can be controlled with an active gate driver even for a trans conductance G = 1-5S. There is a tendency that G increase for frequencies above f = 500kHz but this have to be investigated further.

4. Test setup for measurement of transients in a diode rectifier

The diagram of the rectifier used for the transient investigation is seen in fig. 11.

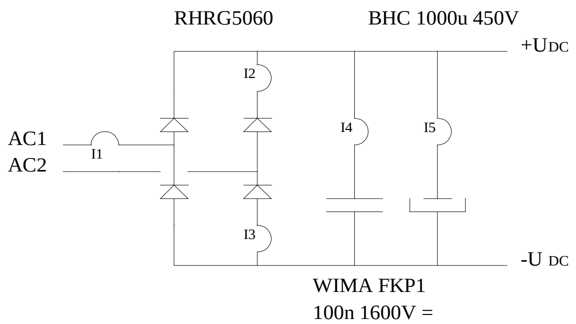

Fig. 11 – Single phase rectifier with fast diodes and a high quality smoothing capacitors

The rectifier is built of four diodes type RHRG5060 from FAIRCHILD two capacitors one fast capacitor of 100nF type FKP1 from WIMA and an electrolytic capacitor of 1000µF 450V from BHC.

To create transients discharging of a fast capacitor is used. This is done with a relay as shown in fig. 12.

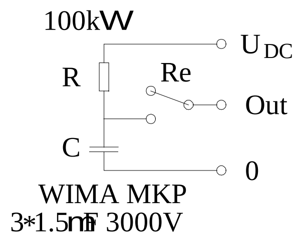

Fig. 12 – Capacitor with a relay to create a transient

The capacitance C is made with a parallel connection of three 1.5µF series MKP from WIMA.

4.1. AC input voltage and currents

With the rectifier loaded with 3Ω at the DC side input voltage and current are delivered from the amplifier LPA05. The result of input voltage U_{AC} input current I_{AC} and the dc voltage U_{DC} is seen in figure 13.

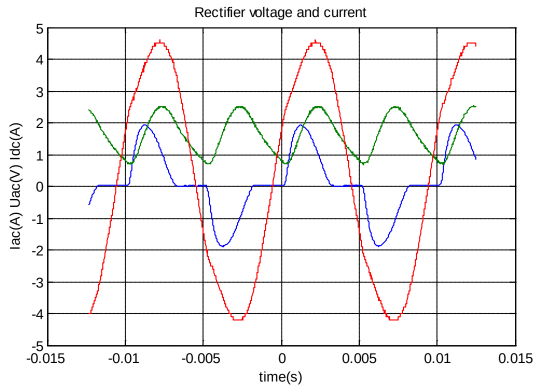

Fig. 13 – Voltage U_{AC} read U_{DC} green and current I_{AC} blue input for a frequency of 100Hz.

Fig. 13 shows a normal operation for the low frequency of 100Hz. This is expected especially with these fast diodes. With a frequency of f = 100kHz the operation changes as seen in fig. 14.

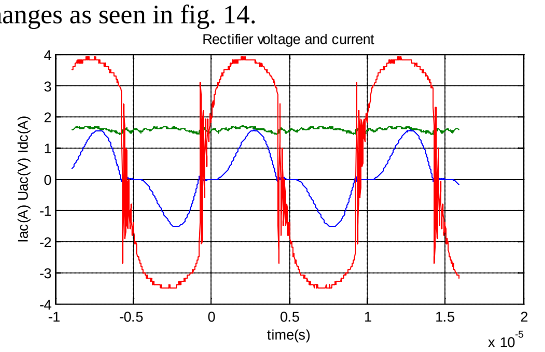

Fig. 14 – Voltage U_{AC} read U_{DC} green and current I_{AC} blue input for a frequency of 100kHz.

The inductive behavior is now seen in the current and a larger forward voltage drop across the diode can be observed. Also a resonance is seen at the input voltage when the current becomes zero. The resonance is formed by the inductance between the amplifier and rectifier together with the capacitance of the diodes.

4.2. Transients from AC and DC side

Fig. 15 shoves the result of discharging the WIMA capacitors from fig. 12. The voltage at the capacitor is 10V. The DC voltage is 0V.

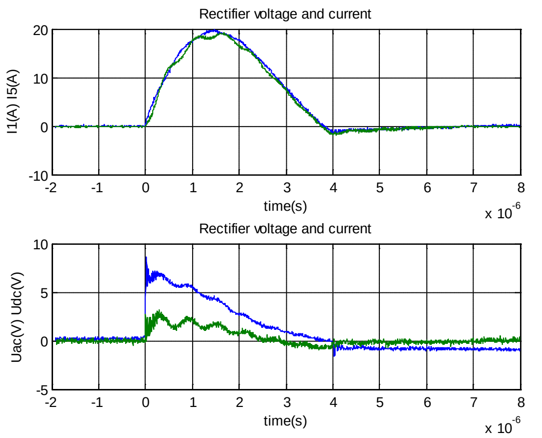

Fig. 15 – Transient from the AC side. Top input current I1 (blue) Electrolyte current I5 (green). Bottom input voltage (blue) and DC voltage (green). 0V at the DC side. Variable names come from fig. 11.

From fig. 15 it is estimated that the current increase with 30A/µs. The voltage at the input increase fast to about 7V. A voltage of 10V gives an inductance given by (6)

$$L = \frac{U}{di/dt} = \frac{10V}{30A/\mu s} = 333nH \qquad (6)$$

Surprisingly nearly all current runs in the electrolytic capacitor. Dynamically the DC voltage increase with 2V chowing an inductance of about L_S = 66nH.
Then the DC side is pre charged to 5V. The result of the transient is seen in fig. 16.

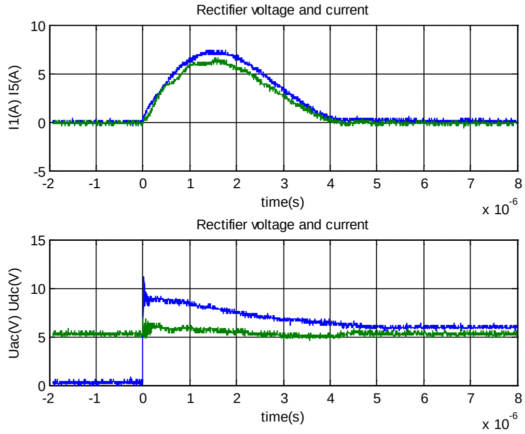

Fig. 16 – Transient from the AC side. Top input current I1 (blue) Electrolyte current I5 (green). Bottom input voltage (blue) and DC voltage (green). U = 5V at the DC side.
A similar result as in fig. 15 is seen. The slope and the peak value of the current change do to the pre charging of the DC side.
Then the transient is given at the DC side with a short circuited AC side. The result is seen in fig. 17.

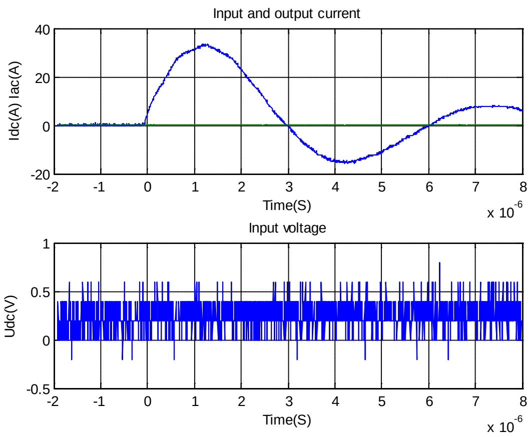

Fig. 17 – Transient from the DC side. Top input current DC (blue) output current AC (green). Bottom input voltage (blue) and DC voltage (green). Short circuit AC side.
From the DC side there are no forward voltages so the current slope di/dt increase to 60A/µs. With this frequency the inductance can with (7) be found to

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} \rightarrow$$

$$L = \frac{1}{(f \cdot 2 \cdot \pi)^2 \cdot C} = \qquad (7)$$

$$\frac{1}{(167kHz \cdot 2 \cdot \pi)^2 \cdot 4.5\mu F} = 200nH$$

Here the frequency with damping is used. The estimation of the inductance is correct within 10% due to the tolerance of the capacitor.
The reason for the small inductance is that an exact di/dt for the equation (7) is difficult to get from fig. 15. It is also seen from fig. 17 that no current is running in the AC side.
With components of a good quality the du/dt at the DC side is very small this means that the parasitic capacitances in the diodes are so small that they do not contribute to a current transmission in the diodes. This is valid even that there are no voltages across the diodes so the capacitances have the maximum value.

4.3. Discussion

In the previous section it is seen that transients pass the diode rectifier without larger forward voltage drop and the belonging charge is stored at the capacitors. There is no significant voltage rise at the DC side means that this is low inductive.
A transient from the DC side of the rectifier gives no contribution to the current at the AC side for the reason that the parasitic capacitors in the diodes are small compared with du/dt at the DC side when the current pulse charge the capacitors.

5. Conclusions

Measurements of the transfer function equivalent with the trans conductance G of an IGBT has been done. It is shown that G depends on the current level but do not depend on the voltage level. It is shown that G decrease for frequencies above f = 15kHz. The G for high frequencies f = 500kHz tends to increase but this has to be investigated further. The G for high frequencies is large enough for active gate drivers. At last it is shown that G is different for positive and negative current slopes at higher frequencies f = 10kHz.
For rectifiers with fast diodes it is shown that transients in the range of 1MHz can pass the rectifier. With quality capacitors transients do not affect the DC voltage and hereby this kind of disturbances does not pass to the AC side through the parasitic capacitors in the diodes.

6. References

[1] T.W. Rasmussen, "Active Gate Driver for dv/dt Control and Active Voltage Clamping in and IGBT Stack", Proceeding on CD, EPE, Dresten Germany, 11-14 September 2005, 0189

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[4] FFH50US60S FAIRCHILD, http://www.farnell.com/datasheets/1863430.pdf