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 SKM100GB 123D 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].

\[ I_C = G \cdot (U_{GE} - U_T) \] (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 mid. 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](image)

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](image)

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 $C_{ies} = 6.6nF$ for the IGBT forms a low pas filter with $R_G$ where the cut off frequency $f_0 = 1.6MHz$ 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.

\[ \tau = \frac{L}{R} = R_{IM} \cdot C_{IM} \] (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).

\[ G(f) = \frac{I_G(f)}{U_{GS}(f)} \] (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)

\[ G_{dB} = 20 \cdot \log \left( \frac{I_G(f)}{U_{GS}(f)} \right) \] (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 fett 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 \( R_{sh} = 20m\Omega \) a gain of \( G = 20dB \) is given to the shunt current measurement. The transfer function is seen in fig. 5.

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>
<thead>
<tr>
<th>( U_{CE} )</th>
<th>( G_{low} )</th>
<th>( f_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10V</td>
<td>45.4S</td>
<td>16.9kHz</td>
</tr>
<tr>
<td>15V</td>
<td>47.4S</td>
<td>15.5kHz</td>
</tr>
<tr>
<td>20V</td>
<td>49.4S</td>
<td>14.1kHz</td>
</tr>
<tr>
<td>25V</td>
<td>48.4S</td>
<td>15.5kHz</td>
</tr>
<tr>
<td>30V</td>
<td>14.8S</td>
<td>22.2kHz</td>
</tr>
</tbody>
</table>

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)

\[ G_{-3dB} = \frac{G_{low}}{\sqrt{2}} \] (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.
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>
<thead>
<tr>
<th>$I_{E,DC}$ (A)</th>
<th>$G_{low}$ (S)</th>
<th>$f_0$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>14.8</td>
<td>20.3</td>
</tr>
<tr>
<td>2.0</td>
<td>25.6</td>
<td>18.4</td>
</tr>
<tr>
<td>3.0</td>
<td>30.5</td>
<td>18.5</td>
</tr>
<tr>
<td>4.0</td>
<td>36.0</td>
<td>15.5</td>
</tr>
<tr>
<td>5.0</td>
<td>40.5</td>
<td>18.5</td>
</tr>
<tr>
<td>6.0</td>
<td>44.3</td>
<td>16.9</td>
</tr>
</tbody>
</table>

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

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 $f_{tr} = 100Hz$.

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

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 $U_g = \pm 15V$. $R_g$ and $C_{gw}$ 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 transconductance $G = 1-5S$. 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.

![Diagram of the rectifier](image)

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.

![Diagram of the capacitor with relay](image)

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

The capacitance $C$ is made with a parallel connection of three $1.5\mu F$ series MKP from WIMA.

4.1. AC input voltage and currents

With the rectifier loaded with $3\Omega$ 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.

![Graph of AC input voltage and currents](image)

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.

![Graph of AC input voltage and currents](image)

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

![Graph of transient from AC side](image)

Fig. 15 – Transient from the AC side. Top input current $I_{1}$ (blue) Electrolyte current $I_{5}$ (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 increases fast to about 7V. A voltage of 10V gives an inductance given by (6)

\[ L = \frac{U}{di/dt} = \frac{10V}{30A/\mu s} = 333nH \]  

(6)

Surprisingly nearly all current runs in the electrolytic capacitor. Dynamically the DC voltage increases with 2V showing an inductance of about \( L_D = 66nH \).

Then the DC side is pre-charged to 5V. The result of the transient is seen in fig. 16.

\[ f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} \rightarrow L = \frac{1}{(f \cdot 2 \cdot \pi)^2 \cdot C} = \frac{1}{(167kHz \cdot 2 \cdot \pi)^2 \cdot 4.5\mu F} = 200nH \]

(7)

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 have 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
