The Influence of IGBT Aging on the EMI of Traction Converter

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Abstract. The Insulated Gate Transistors (IGBT) is a kind of semiconductor that is prone to aging in power electronic equipment. After aging, the IGBT will not only degrade during its operating performance, but will also reduce the reliability of the electromagnetic compatibility (EMC) in its working circuits. This article summarizes and analyzes the aging mechanism of the IGBT and the impacts of the changed characteristic parameters raised by the aging on the characteristics of IGBT while working. The aging will lead to changes in the high-frequency parasitic parameters, which play an essential role in affecting the IGBT with high-frequency and high-power on the electromagnetic interference (EMI) of its working circuits. To further illustrate these issues mentioned above, a typical "AC-DC-AC" traction converter circuit is taken as an example, and adopt a simulation model of conducted interference of traction converter systems by using Saber sketch software to study the influences of the impacts of changes from aging parasitic parameters on EMI of traction converter circuits.

1. Preface

With the wide application of power electronic equipment in various fields, the reliability of the electromagnetic compatibility (EMC) of the equipment is becoming more important. However, due to the relatively high-frequency aging of the power electronic devices in use, the reliability of the EMC of power electronic devices will be reduced. In this sense, it can be said that the use and the further development of power electronic devices have been limited by the reliability of the EMC of the devices. In particular, the IGBT is one of the most widely used power electronic devices with the highest failure rate. As a commonly used semiconductor switcher, the IGBT is a semiconductor prone to aging in power electronic equipment [1], and is mostly used as a switcher in traction converter system of high-speed railway. To this point, the research on the reliability of EMC on the IGBT is of great significance in promoting the reliability of the operation of trains and reducing the high-frequency interference in circuits of traction converter systems.

At present, researches on the IGBT aging and the EMC are on devices and circuits. In devices, researches mainly focus on changes of the switching characteristics of the IGBT itself after the aging. In the part of the EMC, related researches are only involved in electromagnetic interference (EMI) without the impacts of the aging on the EMC during the normal operation of the IGBT. In circuits, researches on the IGBT EMC are still in their infancy, mainly studying the influences of certain parameters on characteristics of output in circuits.

A large number of studies have proved that too much high junction temperature and temperature gradient are the main reasons for the failure of the IGBT. So, we can conclude that thermal...
performance is a key index to measure the reliability of the IGBT. In reference [2], by adopting the technology of accelerating the degradation of performances, the paper analyzes the curves of the degradation based on the prediction tests on IGBT faults through the PXI measurement and control platform. The tests were conducted under sudden short circuits to see the degradation of the IGBT rather than its aging thermal performance. In reference [3], the paper, by using the data from measuring thermal resistance of the IGBT, shows the curve of dynamic changes of the thermal resistance by time-varying through fitting methods. Further, the paper obtains the parameters of theoretical thermal model of the IGBT by the curve. In reference [4], the paper builds parametric models of the IGBT by using the Simploter of ANSYS and analyzes the characteristics of the IGBT in its processes of opening and closing through the peripheral circuits of the IGBT built by the double pulse tests, which set a good reference for the research of aging of the IGBT. In reference [1], through the stimulation, the paper concludes that as the switching speed of the IGBT is becoming slower with the intensified aging, the threshold voltage becomes lower and the on state voltage drop becomes higher with the increases of temperature caused by large currents and lower with the decreases of temperature by small currents. At the same time, the paper, by analyzing the effects of the IGBT aging on voltage outputted by DC/DC based on the full bridge topology, concludes that the aging of the IGBT will make the frequency spectrum of the output voltage shift to a certain extent and the amplitude of some frequency points will change. In reference [5], the paper, through the 3D model of the IGBT module established by Ansoft Q3D software and the time-domain simulation model of PWM rectifier system involved with the parasitic parameters of the IGBT and the saber simulation software, concludes that the parasitic capacitance parameters of the IGBT module have a relatively great influence on common mode interference.

Based on the analysis of the key parameters of the degradation of the EMC of the working circuit of the IGBT after its aging, the paper, taking the typical AC-DC-AC traction converter circuits as an example, studies the influences of the changes in the parasitic parameters of the IGBT on the EMI of the traction converter circuits by the simulation made by Saber Sketch.

2. Aging mechanisms and influences of the IGBT

2.1. Aging mechanism

The failure mechanisms of the IGBT mainly include those of overvoltage, overcurrent, overheat and static [6], among which, the leading failure mechanism is that of overheat in the slow aging of the IGBT. The overheat can be divided into bond wire peeling and solder layer fatigue. Both of them happen because of thermal mechanical stress [7,8].

The materials of each layer inside the IGBT are mainly copper substrate, copper conductor layer, ceramic, silicon crystal chips and aluminum bonding wires, connected through solder layers, as shown in Figure 1. The linear thermal expansion coefficient of materials in each layer is shown in the Table 1. The aluminum bonding wire, working as a wire for the electrical connection of chips, is located in the outermost layer of the layered structure. When temperature changes, due to differences in CTE value of adjacent material layers, the size increment along the three dimensions of the materials is inconsistent, resulting in the coexistence of both normal stress and shear stress at the interface of the materials, as shown in Figure 2. In the working of the IGBT, the external temperature will fluctuate with the changes of temperature between day and night, weather, wind speed and other environmental conditions; at the same time, the alternating current flowing through the inside of the IGBT will usually produce losses in alternating power. Thus, we can conclude that under the dual influences from externally environment temperature and internal alternating losses, the actual operating temperature of the IGBT module is cycling, resulting in alternating normal stress and shear stress on the interface of multi-layer materials for a long time, the occurrence of cracks and layering from the gradual accumulation of thermal stress, as well as the deformed aluminum bonding wire under the influences of high temperature. After several years or decades, the aging gradually leads to the changes on electrical performance of the IGBT, eventually leading to the aging.
Figure 1. Each layer of the IGBT [9].

Table 1. Coefficient of Linear Thermal Expansion of Each Layer of Materials.

| Material                  | Coefficient of Linear Thermal Expansion (CTE) $1 / \degree C \times 10^{-6}$ |
|---------------------------|---------------------------------------------------------------------------------|
| Aluminum bonding wire     | 22                                                                              |
| Silicon wafer             | 3                                                                               |
| Solder layer              | 28                                                                              |
| Copper / Copper substrate | 17.5                                                                             |
| Ceramics                  | 7                                                                               |

Figure 2. The stress diagram of the IGBT.

The drop of the bonding wire will make the contact resistance and then the saturation conduction voltage drop, and the losses in conduction of the IGBT increase. At the same time, the current flowing through the other non-shedding bond wires will go up, adding more heat on the wires in turn, leading to an increase in the junction temperature, which will affect a series of temperature-sensitive parameters. The fatigue of solder layers usually occurs in the workplace where there is large temperature gradient. The sharp changes of internal junction temperature of the IGBT, i.e. from high to low temperature are easy to generate large thermal mechanical stress among different layers of materials with different thermal expansion coefficient. The stress causes the aging among solder layers with different materials within the chip, which is manifested as the solder layer cracks. The thermal mechanical stress generated by long-term temperature change gradually makes the cracks generated by early aging enlarge gradually, finally leading to unreliable connection or even delamination of two layers of materials connected by solder layers. Further, the effective connection areas among layers will decrease, the parasitic parameters will change, the thermal resistance will increase with higher temperature, and further the aging and faults of the IGBT will appear more quickly.

2.2. Effects of The Aging of The IGBT on Parasitic Parameters

The aging raised by overheat of the IGBT will lead to a slow turn-on and turn-off speed, decreases in
threshold voltages, increases in on-state voltage drop and changes in parasitic parameters[1], among which, the high-frequent parasitic parameters is an important factor that affects the EMI of the high-frequent and high-power IGBT and its working circuits. In this part, the paper will focus on the impacts of the aging of the IGBT on its high-frequent parasitic parameters. 

The parasitic inductance is in circuits in the form of wires or lead inductance with relatively small inductance value. And the IGBT aging has small impacts on the inductance value. So the effects of the parasitic inductance on the degradation of the system's EMC can be ignored. While the parasitic capacitance is parasitic inside the component, or between pin and ground of the IGBT, between lead and ground, and between leads. Therefore, the parasitic capacitance has greater impacts on the aging than parasitic inductance. Hence, changes in parasitic capacitance caused by the IGBT aging in circuits play a significance role in affecting the EMI of circuits.

The sharp changes of junction temperature inside the IGBT from high temperature to low temperature are very easy to generate large thermal mechanical stress between different layers of materials with different thermal expansion coefficient. This stress causes solder layers between different materials in the chip to age, which is manifested as the solder layer cracks. The thermal mechanical stress generated by long-term temperature change gradually causes the cracks generated by early aging to spread gradually, finally leading to unreliable connection or even delamination of the two layers of materials connected by solder layers. This will lead to the reduction of the effective connected areas between the layers and the changes of the parasitic capacitance.

At the same time, increases in junction temperature caused by aging directly affect changes in carrier mobility in semiconductor, which will indirectly lead to changes in the junction capacitance of PN junctions. And the separation and dislocation among layers of materials will also cause changes in the original parasitic capacitance. For IGBT, the aging mainly affects the parasitic capacitance between gate and collector, and between gate and emitter. The changes of parasitic capacitance will affect the characteristics of on and off of the IGBT, and then the EMI of the working circuit.

3. The extraction of the IGBT model parameter

3.1. The IGBT Model Based on Parasitic Parameters

The IGBT Equivalent Model [10] with parasitic parameters inside the IGBT is shown in Figure 3, including the main parasitic parameters of the IGBT. The model accurately reflects changes in currents and voltages and the behavioral characteristics of the IGBT during charging and discharging of the IGBT.

![Figure 3. The parasitic parameter model of the IGBT.](image)

Among them, $C_{gd}$, $C_{gs}$ and $C_{ds}$ respectively represent gate drain capacitance, gate source capacitance and drain source capacitance, all of which are parasitic capacitance inside the IGBT; and $L_g$, $L_d$ and $L_s$ are lead inductance of gate, drain and source respectively.
3.2. The Extraction of the Parasitic Capacitance of the IGBT

To extract the junction capacitance parameters inside the IGBT, further divide the non-linear capacitance in Figure 3 and thus acquire an equivalent circuit model involved with the junction capacitance inside the IGBT, as shown in Figure 4. The meanings of each capacitance parameter are shown in Table 2.

![Figure 4. The equivalent circuit model of the IGBT.]

**Table 2. The Parasitic Capacitance of The IGBT.**

| Parasitic Parameters | Name                                      |
|----------------------|-------------------------------------------|
| \( C_{OX} \)         | overlapping oxidation capacitance         |
| \( C_{GDJ} \)        | depletion layer capacitance               |
| \( C_{GD} = C_{OX} + C_{GDJ} \) | gate-drain capacitance                     |
| \( C_{DSJ} \)        | source-drain capacitance                   |
| \( C_{GS} \)         | gate-source capacitance                    |

Due to the junction capacitance inside the IGBT, when the IGBT gate is charged, a displacement current will be generated inside the IGBT. At this time, even if the IGBT gate voltage is lower than the threshold voltage \( V_T \) and thus the IGBT is off, the displacement current inside the capacitance at the port will be detected. With the combination of \( C_{gd} \) and \( C_{gs} \), the gate current \( I_g \) is as follow:

\[
I_g(t) = C_{gs} \frac{dV_{gs}(t)}{dt} - C_{gd} \frac{d[V_{gs}(t) - V_{ge}(t)]}{dt}
\]

(1)

During the gate charging process, the rising process of \( V_{gs} \) will be divided into three stages. According to data from voltage and current waveform of these three stages and the forum (1), the parasitic capacitance parameters of the IGBT can be deducted: \( C_{GS} \) and \( C_{OX} \), the threshold voltage \( V_T \), trans-conductance coefficient \( K_T \), and gate-drain overlap area \( A_{GD} \) of the IGBT as well.

The solution expressions for the variable capacitance of \( C_{GDJ} \) and \( C_{DSJ} \) are shown in Figure 4:

\[
C_{GDJ} = \frac{A_{GD} \varepsilon_{si}}{[2\varepsilon_{si}(V - V_{GS})/qN_B]^2} \quad (2)
\]

\[
C_{DSJ} = \frac{(A - A_{GD}) \varepsilon_{si}}{[2\varepsilon_{si}V/qN_B]^2} \quad (3)
\]

In the forum, \( A_{GD} \) is the overlapped gate-drain area; \( \varepsilon_{si} \) is the dielectric constant of silicon; \( q \) is the amount of electronic charge; \( N_B \) is the doping concentration of the base region; \( V \) is the applied voltage; \( V_{GS} \) is the gate voltage.
4. Modeling and simulation analysis

According to the aging analysis and parameter extraction, in this section, taking the traction converter circuits as the object in research, analyze the influences of changes of parasitic capacitance caused by the aging of the IGBT in circuits on the conducted interference of common mode and differential mode of "AC-DC-AC" traction converter systems by simulation.

4.1. Simulation Circuits

The traction converter system circuits are built in saber shown as in Figure 5.

![Simulation circuit diagram of traction converter system.](Image)

The traction transformer inputs 1500V as converters reduced from the AC-side 25KV voltage. The four quadrant pulse rectifiers adopt two-level topology. The DC in the middle includes filter inductance $L_1 = 0.8\text{mH}$, filter capacitance $C_1 = 3\text{mF}$, support capacitance $C = 9\text{mF}$. The inverter also adopts two-level topology. PWM control strategy is adopted for the rectifier and inverter to provide control pulse for the IGBT. The control circuit is shown in Figure 6 and Figure 7. The calculated value of the IGBT model parameters is shown in Table 3: the switching frequency is 1250Hz; the load end adopts simple Y-shaped three-phase inductive load, and $L_{load} = 47\text{mH}$, $R_{load} = 10\Omega$.

![Schematic diagram of PWM control of four-quadrant pulse rectifier.](Image)

![The principle diagram of inverter PWM control.](Image)
Table 3. Parameter Calculation Values.

| Parameter | Extract Value |
|-----------|---------------|
| $C_{GS}$  | 23nF          |
| $C_{GD}$  | 40nF          |
| $K_p$     | 30.4A/V       |
| $V_T$     | 7.9V          |

Due to the long time period and randomness of the IGBT aging, in the simulation, randomly select three IGBTs, increase their gate-collector parasitic capacitance $C_{GD}$ and gate-emitter parasitic capacitance $C_{GS}$ with an increase of 20% and simulate how changes in the parasitic capacitance of these three IGBTs after the aging will affect the conducted interference of the common-mode and differential-mode of the traction converter system.

4.2 Conducted Interference of Common Mode and Differential Mode of Systems

Since most of the auxiliary power supply systems of the existing EMU are powered from the intermediate DC of converters, the conducted interference on the DC bus will be directly coupled to the auxiliary power supply systems, which will further add interference to the sensitive equipment powered by the auxiliary power supply systems in the vehicle. In this regard, it is of great significance to study the effects of aging of the IGBT on the conducted interference of common mode and differential mode of the DC bus side.

The conducted common-mode and differential-mode of voltages of the DC bus side are calculated from the LISN network, a coupling and decoupling circuit that acquires and matches impedance of conducted disturbance signals to transmit the signals to receivers. The calculation formula of the common-mode voltage $V_{CM}$ and differential-mode voltage $V_{DM}$ are as follows:

$$V_{CM} = \frac{V_{x1} + V_{x2}}{2}$$

$$V_{DM} = \frac{V_{x1} - V_{x2}}{2}$$

The comparison diagram of the spectrum waveform of the conducted common mode voltage before and after aging obtained by simulation is shown in Figure 8 and Figure 9. It can be seen from the diagram that in the frequency band between 10kHz and 3MHz, the amplitude of common mode voltage decreases from -10dBV to -80dBV, accompanied with higher harmonics. Before and after aging, the spectrum of common mode voltage of DC bus side is shifting to a certain degree in the spectrum of common mode voltage in some frequency bands, but there is no significant increase in the spectrum amplitude. In the frequency band from 0.08GHz to 2.7GHz, the spectrum amplitude of the conducted common mode voltage after aging significantly increases by about 11dB.

The comparison diagram of spectrum waveform of conducted differential mode voltage of DC bus...
side before and after aging obtained by simulation is shown in Figure 10. It can be seen from the figure that between 10kHz and 3MHz in the frequency band, the amplitude of differential mode voltage varies from -20dBV to -100dBV, showing a trend of attenuation as a whole and accompanying by higher harmonics. The spectrum amplitude of differential mode voltage on the side of DC bus before and after aging increases obviously (about 10dB) in some frequency bands, especially from 200kHz to 400kHz and 600kHz to 2MHz. It can be seen that the increases of parasitic capacitance caused by the aging will make the conducted interference of high-frequent differential mode of DC bus go up as well. The interference will be directly coupled to the auxiliary power supply systems through DC bus, and may further impose interference on sensitive equipment powered by the auxiliary power supply systems in the vehicle.

5. Conclusion

Through the simulation model of traction converter systems and the analysis of aging mechanism and aging characteristics of the IGBT, the paper analyses the influences of parasitic capacitance on conducted interference of common mode and differential mode of traction converter systems. The results from the simulation show that changes in parasitic capacitance caused by aging IGBT will affect the conducted interference in the working circuits of IGBT: shifting to a certain degree in the spectrum amplitude from 10kHz to 3MHz of common mode voltage of systems after changes of parasitic capacitance; significant increases about 11 dB in the range from 0.08 to 2.7GHz. From 200 to 400kHz and from 600kHz to 2MHz, the spectrum amplitude of differential mode voltage of systems increases obviously about 10dB. It is proved that changes in parasitic parameters after the IGBT aging will lead to the degradation on EMC of traction converter circuits.

6. References

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Figure 10. Spectrum comparison of differential mode voltage (10 kHz-3 MHz).
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