An Improved Method for Extracting Stray Inductance in IGBTS Dynamic Test Bench
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Abstract:
Stray inductance of Press Pack IGBTs’ (PPIs) dynamic test bench has great influence on dynamic test results. Thus, the stray inductance needs to be measured and calculated accurately. Conventional method cannot extract stray inductance accurately due to existence of nonlinear resistance in current path. Hence, a new method is proposed in this paper to extract stray inductance based on turn-off transient waveform and a following turn-on transient waveform. In this method, it is assumed that capacitor voltage and load current are constant during turn-off transient and the following turn-on transient, and then the stray inductance is extracted accurately by using gradients of both turn-off current and turn-on current at a given current value. This method eliminates the influence of nonlinear resistance in current path. To verify the proposed method, circuit simulation is carried out by using Synopsys Saber; furthermore, a dynamic test bench is developed, stray inductance of the test bench is extracted under different voltage level. Simulation and measurement results prove the effectiveness of the new method.

Keywords: Insulated gate bipolar transistors, electronic equipment testing, inductance measurement.

I.INTRODUCTION
Press Pack IGBTs (PPIs) are increasingly used in the transmission and distribution field, due to advantageous features of a higher cycling and thermal capability and ideally suited for series connection[1]-[3]. To test new PPIs module and have a comprehensive understanding of dynamic switching characteristics of PPIs under different working conditions are meaningful for application design; hence, a platform is needed to test dynamic characteristics of PPIs accurately [4]. Stray inductance of dynamic test bench is a key factor that affects dynamic characteristics of PPIs [5]-[6]. Thus, Dynamic parameters of Press Pack IGBT are tested with a special dynamic test bench, and usually the value of stray inductance of the test bench is given. For instance, datasheets of PPIs which produced by Westcode Corporation indicate that dynamic parameters are extracted under specified condition; the stray inductance of dynamic test bench is 200nH. Meanwhile, datasheets of StakPak IGBT of ABB Corporation also specify the stray inductance of dynamic test bench is 200nH. Parasitic inductance of test bench exist in power device modules, capacitor, copper interconnects, and busbars, etc. Much research effort has been reported on methods of extracting stray inductances and these methods can be divided into two categories. One is to extract parasitic inductance of each component separately by using mathematical computation or simulation approaches, which based on three-dimensional (3-D) finite element analysis[7]-[9] or partial element equivalent circuit (PEEC) method [10]-[13]. In addition, parasitic inductance of each part can be extracted by impedance analyzer [14]-[15], time domain reflectometry [16] or by using an extra oscillating circuit [17]. However, methods mentioned above can extract parasitic inductance of each part accurately, but mutual inductance between each part is ignored. Hence, extracting separately is inappropriate in identify total stray inductance of test bench. Another way to extract stray inductance of test bench is to use voltage overshoot and current gradient, and then the stray inductance is extracted as a whole. This kind of method is proposed in [6] [18], called conventional method in this paper, using formula \( L_s = \frac{\Delta u}{\left| \frac{di}{dt} \right|} \) to calculate the whole stray inductance in test bench. In [18], \( u \) is the overvoltage of IGBT; \( \frac{di}{dt} \) is the maximum IGBT collector current rate of change at turn-off. However, this method is not accurate in calculating stray inductance, because voltage drop on resistances and freewheeling diode in current path cannot be ignored; besides, the maximum collector-emitter voltage does not necessarily occurs at the same time when current gradient reaches its maximum. Hence, voltage difference \( u \) and current gradient \( \frac{di}{dt} \) need to be modified. Diode has forward voltage drop, and its resistance is nonlinear. Considering the influence of nonlinear resistances in current path, limitation of conventional method in calculating stray inductance is analyzed in this paper. Then, authors in this paper propose a new method to calculate stray inductance, which eliminates impacts of nonlinear resistances in current path. Simulation circuits with/without loop resistance are built; and stray inductance is extracted and compared by using conventional method and the new method. Moreover, a test bench is developed; stray inductance is extracted in different voltage level, and effectiveness of the new method is discussed in the end.

II.EXTRACTION OF STRAY INDUCTANCE BASED ON EXPERIMENT
Fig. 1 shows the schematic circuit of dynamic test bench. Stray inductance is extracted by using voltage and current waveforms of turn-off and turn-on. DUT (Device under Test) in Fig. 1 is Press Pack IGBT under test, Diode is freewheeling diode.
A. Model of simplified freewheeling diode

Mostly, high voltage high power diode is pin diode [19], which means intrinsic region is sandwiched between a P-type and N-type region, as shown in Fig. 2(a). Equivalent circuit model of forward-biased pin diode is shown as Fig. 2(b); and Fig. 2(c) is the simplified equivalent circuit model of forward-biased pin diode. The simplify process is analyzed as follows.

\[ f = \frac{t}{\pi} \]

Where \( f \) is the equivalent frequency and \( t \) is the transient rise/fall time. Then, equivalent resistance of \( C_j \) is

\[ \frac{1}{\alpha C_j} = \frac{t}{2C_j} \]

As the capacitance of \( C_j \) is several pF, rise/fall time of switching current ranging from several hundred nanoseconds to several microseconds; according to (1), the equivalent resistance of \( C_j \) is much greater than \( R \). As a consequence, in the conditions of low frequency and large forward-biased current, equivalent circuit of pin diode can be simplified as shown in Fig. 2(c). But, the resistance of pin diode is not linear during switching process, which means resistance of freewheeling diode in IGBT dynamic testing is not linear.

B. Circuit analysis of dynamic test bench

Using the simplified model of pin diode, the equivalent circuit of dynamic test bench is depicted in Fig. 3. As shown in Fig. 3, \( U_{dc} \) is the no-load voltage of capacitor, \( r_j \) is the resistance of capacitor, \( L_2 \) is the parasitic inductance of capacitor and bus bar. \( L_{load} \) is the load inductance; \( r_1 \) and \( L_1 \) are the resistance and inductance of copper interconnects between bus bar and anode terminal of freewheeling diode. \( U_{bi} \) is forward threshold voltage of pin diode, \( r_2 \) is equivalent resistance of diode, \( L_d \) is parasitic inductance inside diode module; \( r_3 \) and \( L_3 \) are resistance and inductance of copper interconnects between cathode terminal of freewheeling diode and collector terminal of IGBT. Current \( i_c \) is collector current of IGBT under test, \( U_{ce} \) is collector-emitter voltage of IGBT, \( U_{ge} \) is gate driver output voltage. \( r_3 \) and \( L_3 \) are resistance and inductance of copper interconnects between emitter terminal of IGBT and bus bar. \( r_c \) and \( L_c \) are emitter resistance and emitter inductance. Effects of mutual inductance between the various parts are all considered in the inductance of each copper interconnects. Then, voltage drop of each component in equivalent circuit during switching performance is depicted in Fig. 4.

\[ U_{bi} = \frac{r_1 i_c + r_2 L_1}{r_1 + L_1} \]

\[ U_{ce} = \frac{r_3 i_c + r_4 L_3}{r_3 + L_3} \]

\[ U_{ge} = \frac{r_5 i_c + r_6 L_5}{r_5 + L_5} \]

\[ U_{dc} = \frac{r_7 i_c + r_8 L_7}{r_7 + L_7} \]

\[ U_{tot} = U_{bi} + U_{ce} + U_{ge} + U_{dc} \]
i_{off}, u_{off} is the collector-emitter voltage and i_{on} is the load current at the very same time.

C. Stray inductance calculation based on conventional method

Usually, resistance in the circuit of dynamic test bench, forward threshold voltage of freewheeling diode and nonlinear resistance of freewheeling diode are not considered when calculating stray inductance by conventional method. Therefore, stray inductance can be calculated by using turn-off waveforms

\[ L_s = \frac{u_{off} - u_{on}}{i_{off}} \]

(8)

Also, it can be calculated by using turn-on waveforms

\[ L_s = \frac{u_{on} - u_{off}}{i_{on}} \]

(9)

Through this method, one can calculate the stray inductance by measuring only capacitor voltage, collector-emitter voltage and gradient of collector current of DUT. However, limitation of this method is that impacts of nonlinear loop resistance is ignored, causing a certain degree of error as a result.

D. Novel method to calculate stray inductance of dynamic test bench

According to (4) and (5), when certain conditions are satisfied, stray inductance of dynamic test bench can be calculated accurately by eliminating the impacts of loop resistance.

Switching transient waveforms of voltage and current of DUT are measured, as shown in Fig. 5. Specifically, \( \delta t \) is time interval between two samples on Oscilloscope, \( t \) means testing time. Meanwhile, \( t_c \) is corresponding to the time when collector current of DUT is \( i_0 \) in turn-off process; \( t_f \) is corresponding to the time when collector current of DUT is also \( i_0 \) in turn-on process.

Firstly, load of dynamic test bench is a large-value inductor, that is, if the time of switching off is short enough, the load current \( i_{load} \) can be considered to be a constant. But it should be noted that the minimal off-time cannot be too short to turn-off the DUT. Secondly, large capacitance value of capacitor allows the voltage drop very small during switching off transient and switching on transient; therefore, it can be assumed that no-load voltages of capacitor at both time \( t_f \) and \( t_c \) are equivalent. Last and most important, for a given freewheeling diode, whether the diode current is rising or falling, the equivalent circuit of diode is the same when current through the diode of the same magnitude and direction. That is to say, equivalent circuits of diode at time \( t_f \) and \( t_c \) are the same.

\[ u_{cc} = i_{off} = i_{on}; \text{ no-load voltage of capacitor and load current show no change from} \quad t_f \text{ to} \quad t_c \quad \text{which means} \quad u_{off} = u_{on} \quad \text{then one can calculate the stray inductance by solving} \quad (6) \quad \text{and} \quad (7) \]

\[ L_s = \left( U_{cc} - U_{on} \right) \int \left( \frac{di_{on}}{dt} + \frac{di_{off}}{dt} \right) \quad (10) \]

Advantage of this new method is that errors caused by nonlinear loop resistance are eliminated.

III. Method Comparison Based on Simulation

In this part, conventional method and new method are compared in calculating stray inductance based on circuit simulation. A. Stray inductance extracting based on conventional method

IGBT switching characteristic is analyzed by using Synopsys Saber, model of IGBT derived from 1700V/75A IGBT chip of ABB Corporation; model of freewheeling diode derived from 2500V/108A Fast-Diode chip of ABB Corporation. 1. Stray inductance extracting with zero loop resistance

Fig. 6 shows the simulation circuit without considering the loop resistance. Capacitor voltage is 1000 V, simulation step is 0.3 ns; meanwhile, the simulation step is limited to a range of 0.2 ns to 0.5 ns if step changes. Load inductance value is 800 μH, gate resistance is 20 Ω. Resistances in commutation loop are set to zero except freewheeling diode and DUT. Stray inductance in commutation loop is given 300 nH. Based on the simulation circuit in Fig. 6, stray inductance is extracted by using the switching waveforms. Fig. 7 shows the waveforms of collector-emitter voltage \( u_{ce} \) and collector current \( i_c \). Turn-off waveforms are shown in Fig. 7(a), when \( u_{ce} = 1514 \) V, the current gradient is 1.71 kA/μs calculated by CosmosScope, a component of Synopsys Saber software. According to (8), the stray inductance is calculated to be 300.6 nH.

Turn-on waveforms are shown in Fig. 7(b), when \( u_{ce} = 219.32 \) V, current gradient is 1.002 kA/μs. Then according to (9), the stray inductance is calculated to be 299.2 nH.

Simulation results indicate that, if the loop resistance in current path is zero, stray inductance extracted by conventional method is closed to true value; relative deviation of calculated result is about 0.36%.

![Fig.6 Simulation circuit without resistance](http://ijesc.org/)

Based on the analysis above, it can be summarized that, magnitude of load currents equal at time \( t_f \) and \( t_c \) which
Fig. 7 Switching waveforms. (a) turn-off waveforms, (b) turn-on waveforms.

2. Stray inductance extracting with the loop resistance considered

To verify the resistance has a non-negligible impact on stray inductance extracting, a simulation circuit with loop resistance is given in Fig. 8. Compared to Fig. 6, the only difference between these two circuits is the inductor in series with a resistor in Fig. 8, the resistance is 1Ω. Simulation results are shown in Fig. 9. According to the turn-off waveforms in Fig. 9(a) and (b), the stray inductance is calculated to be 293.3 nH; while the calculated result is 324.6 nH if using turn-on waveform in Fig. 9(b) and (9).

Hence, stray inductance extracted by conventional method shows obvious deviation with true stray inductance when resistance exists in the commutation loop. When extracting stray inductance by using turn-off waveform data, the deviation is -2.7%, a negative value indicates the calculated value is less than true value; the deviation is 14.9% when turn-on waveform data is used to extract stray inductance, a positive value indicates the calculated value is larger than true value.

Therefore, conventional method has limitation in extracting stray inductance when current path exist resistance and diode.

Fig. 8 Simulation circuit with resistance

Fig. 9 Switching waveforms. (a) turn-off waveforms, (b) turn-on waveforms.

B. Stray inductance extracting based on new method

Simulation circuit is the same as depicted in Fig. 8, software settings keep the same, turn off/on waveforms are also the same as shown in Fig. 10.

When turn-off and turn-on current are both 56 A, careful high magnification observation of these switching waveforms are shown in Fig. 10, which also shows the results processed by Synopsys Saber software. When turn-off current is 56 A, collector-emitter voltage is 1451.4 V, current gradient is -1.6907 kA/μs; meanwhile, when turn-on current is 56 A, collector-emitter voltage is 694.72 V, current gradient is 0.83933 kA/μs, then the stray inductance is calculated to be 299.1 nH according to (10).

The deviation between calculation result and true value is about 0.3%, which means the method proposed in this paper can accurately extract the stray inductance in the commutation loop.

Fig. 10 Calculation of stray inductance based on switching waveform. (a) turn-off waveforms, (b) turn-on waveforms.

C. Comparison of calculation result based on different methods

Changing the resistance in current path, stray inductance is calculated based on conventional method and new method proposed in this paper. Still, stray inductance in simulation circuit is 300 nH, relative error between calculating results and true value shows in table 1. According to the simulation results in table 1, deviation of calculation results and true value increases along with the increasing loop resistance. While using the method proposed in this paper, deviation almost has no relationship with loop resistance. Based on the novel method, a test bench is developed, and stray inductance of PPIs dynamic test bench is measured and calculated.

TABLE I

<table>
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<th>Relative error based on different methods</th>
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<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
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<td>(%)</td>
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<tr>
<td>turn-off</td>
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<td>8.2</td>
<td>10.2</td>
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<td>(%)</td>
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<td>(%)</td>
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IV. EXTRACTION OF STRAY INDUCTANCE OF PPIs DYNAMIC TESTBENCH
A. Dynamic test bench
Schematic of test circuit is shown in Fig. 1, the test circuit is realized in a power stack, see Fig. 11. The press pack IGBT is T0600TB45A (4.5kV/600A) produced by Westcode Corporation, clamping force is 20kN and relative error is 3%. Experiments are carried out at room temperature, discharge capacitor is a metal film capacitor, and its capacitance is 6000μF. Using the diode in IGBT module as a freewheeling diode; the IGBT module is DIM800NSM33-A000 produced by DYNEX.

Testing Oscilloscope is Tektronix DPO4104B, voltage probe for gate voltage measurement is TPP0500, time delay is 5.2ns; high voltage differential probe for collector-emitter voltage measurement is THDP0100, time delay is 16.7ns, current sensor is Rogowski coil, time delay is 30.2ns. Turn-on gate resistance is 8Ω, turn-off gate resistance is 1Ω, and gate voltage pulse interval is 30μs.

B. Calculation of current gradient
Compared to simulation results, experimentally measured waveforms are not smooth, especially at a high sampling rate. Hence, a special method is needed to calculate the rate of current change.

1. Turn-off waveforms
Turn-off waveforms are shown in Fig. 12(a), which indicates that turn-off current shows linearity only in a very short period of time. Turn-off current cannot be fitted by polynomial fitting method. Considering hole diffusion current density during the constant voltage transient is given by [21]

\[ J_i(t) = \frac{J_i(0^\circ)}{J_{\text{keff}}} + 1 \exp\left(\frac{t}{\tau_{\text{off}}\beta} - \frac{J_i(0^\circ)}{J_{\text{keff}}}\right) \]  

where \( J_i(0^\circ) \) is the current immediately after the switching voltage is reached. Obviously, collector-emitter voltage of IGBT in Fig. 12(a) shows no constant, but overvoltage peaks. Hence, construct a time domain function of turn-off current,

\[ i_i(t) = f(t) + g(t) \]  

where

\[ f(t) = \frac{\alpha_i}{\alpha_i + \alpha_{\beta}e^{-\alpha_i\beta}} + \beta \]  

\[ g(t) = \sum_{j=0}^{n} a_j t^j \]  

Derivation of the function \( i_i(t) \) is the gradient of current.

2. Turn-on waveforms
Previous studies have shown that the derivative/slope of the collector current \( i_c \) during switching on can be approximated as [22]

\[ \frac{di_c(t)}{dt} \approx \frac{V_{C G} - V_{th}}{R_C(g_m + L_s)} \]  

In (8), \( V_{C G} \) is gate voltage, \( R_C \) is gate resistance, \( g_m \) is collector-source capacitor, \( g_m \) is transconductance, \( L_s \) is the parasitic inductance in current path when switching on.

Turn-on waveforms are shown in Fig. 12(b). Gate voltage waveform in the figure indicates that \( V_{C G} \) is not constant when the collector current is rising. Hence, the rate of current change is a time varying function; and collector current is approximately linear but not strictly linear. In this paper, polynomial fitting method is used to fit switching on current curves, and then the derivatives of polynomial expressions are current gradients.

C. Experiment results
Using the dynamic test bench as shown in Fig. 11, waveforms are measured in two different voltage levels, since experiment in different voltage offers comparable results; and then the stray inductance is calculated individually.

1. Testing voltage 500 V
Gate voltage, collector-emitter voltage and collector current during switching off are shown in Fig. 12(a); switching on waveforms is shown in Fig. 12(b).

By using curve fitting, when turn-off current of IGBT is 90.5 A, collector current gradient is -0.179 kA/μs, voltage of collector-emitter is 554.7V. Additionally, when IGBT turn-on current is 90.5 A, collector current gradient is 0.531 kA/μs; voltage of collector-emitter is 394.5 V.

According to conventional method, calculation result of stray inductance of dynamic test bench is 305.7 nH if using turn-off current waveform and (8); or the result is 300.7 nH if using turn-on current waveform and (9). Based on the method proposed in this paper, stray inductance is calculated to be 225.6 nH. 2. Testing voltage 808 V Experimental waveforms are shown in Fig. 13(b). Based on curve fitting, when turn-off current of IGBT is 105A, current gradient is -0.1829 kA/μs; at the very same time, voltage of collector-emitter is 863 V. Additionally, when turn-on current of IGBT is 105A, current gradient is 0.6318 kA/μs; and the collector-emitter voltage is 679 V. According to conventional method, calculated result of stray inductance is 300.7 nH if using turn-off current waveform and (8); or the result is 204.3 nH if using turn-on current waveform. Based on the method proposed in this paper, the calculated result is 225.8 nH.
Based on the above analysis, stray inductance of PPIs dynamic test bench is extracted from different experimental voltage level, results show a good consistency based on new method; the stray inductance of dynamic test bench discussed here in is about 225.8nH.

When using the new method to calculate stray inductance of dynamic test bench, voltage difference and current gradient have to be calculated accurately; hence, voltage probe calibration and current probe calibration is very necessary before experiment.

In addition, no-load voltage of bus capacitor at time t_f is assumed equal to no-load voltage at t_e in Fig. 5. This assumption is correct if differences of these two voltages are negligible, but actually, tail current may leads to a large discharge of capacitor. Fig. 14 shows the discharge of capacitor at turn-off transient and turn-on transient.

For a given current i_n, discharge of capacitor is Q_t after time t_f in turn-off transient; discharge of capacitor is Q_e before time t_e in turn-on transient. Hence, voltage drop from time t_f to t_e is

\[ \delta U = \frac{Q_t + Q_e}{C} = \frac{1}{C} \int_{t_f}^{t_e} idt \]  

(17)

Based on experimental data, voltage drop can be calculated. When testing voltage is 500V, \( \delta U \) is about 0.026V; when testing voltage is 808V, \( \delta U \) is about 0.027V. Hence, voltage drop from t_f to t_e is negligible in extracting stray inductance.

Load current is shown in Fig. 15, when testing voltage is 500V, percentage change of load current from time t_f to t_e is about 0.87%; when testing voltage is 808V, percentage change of load current from time t_f to t_e is about 0.81%. Therefore, change in load current is negligible in stray inductance extraction.

**Fig. 12** Switching waveforms of PPIs. (a) turn-off waveforms, (b) turn-on waveforms

**Fig. 13** Switching waveforms of PPIs. (a) turn-off waveforms, (b) turn-on waveforms

**V. DISCUSSION**

Based on the above analysis, stray inductance of PPIs dynamic test bench is extracted from different experimental voltage level, results show a good consistency based on new method; the stray inductance of dynamic test bench discussed here in is about 225.8nH.

When using the new method to calculate stray inductance of dynamic test bench, voltage difference and current gradient have to be calculated accurately; hence, voltage probe calibration and current probe calibration is very necessary before experiment.

In addition, no-load voltage of bus capacitor at time t_f is assumed equal to no-load voltage at t_e in Fig. 5. This assumption is correct if differences of these two voltages are negligible, but actually, tail current may leads to a large discharge of capacitor. Fig. 14 shows the discharge of capacitor at turn-off transient and turn-on transient.

**Fig. 14** Discharge of bus capacitor. (a) turn-off waveforms. (b) turn-on waveforms

**Fig. 15** Load current.

**VI. CONCLUSION**

Based on circuit analysis of IGBT switching transient, this paper proposes to extract stray inductance by using both turn-off transient waveform and the following turn-on transient waveform. Compared to the conventional method, this method is superior because mutual inductance of each part in test bench is included and the impact of nonlinear resistor in current path is excluded. The experimental results show that the stray inductance value extracted does not change along with test voltage level, current level and rate of current
change. Thus, the proposed method is effective to extract stray inductance of IGBT dynamic test bench.

VII. REFERENCES


