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A high precision on-line detection method for IGBT junction temperature based on stepwise regression algorithm (October 2020)

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ABSTRACT The insulated gate bipolar transistor (IGBT), one of the most vulnerable component, is one of the most precious central component in the converter interior. High junction temperature will lead to device failure, which is the main reason of failure of power electronic system. Therefore, on-line high precision measurement of IGBT module junction temperature is the basis of life prediction and reliability evaluation of high-power power conversion equipment. In this paper, the principle of IGBT junction temperature extraction and the latest development of related technologies are summarized. In particular, the working principle and shortcomings of temperature sensitive electrical parameter (TSEP) method are summarized. The change of junction temperature will affect the inter-electrode capacitance in the internal structure of IGBT, which will cause the change of temperature sensitive electrical parameters. The single temperature sensitive electrical parameter method is easily affected by IGBT structure and inter-electrode capacitance. This paper presents an algorithm for high precision on-line detection of IGBT junction temperature. The parameter types are optimized by stepwise regression and the model is established accordingly. In this paper, IGBT: FF50R12RT4 is used as the experimental equipment. By comparing the junction temperature model established based on multiple linear stepwise regression algorithm with the junction temperature model based on traditional temperature sensitive electrical parameters, it is proved that the algorithm has better fitting degree and precision, and the algorithm can be used for high precision online extraction of junction temperature.

INDEX TERMS Temperature Sensitive Electrical Parameters; On-Line Junction Temperature Extraction; Stepwise Regression; Insulated Gate Bipolar Transistor; Reliability; Condition Monitoring

I. INTRODUCTION

Nowadays, energy conservation and environment protection highlight the central role of power electronics technology. As the most popular power electronic device, insulated gate bipolar transistors (IGBTs), a fast switching semiconductor device with easy driving and low ON-state voltage, have been extensively applied ranging from middle to high power areas, such as wind power, photovoltaic generation, electric vehicle, and high-speed railway [1-3]. With the increasing number of the IGBT, its reliability issue is becoming increasingly important [2], especially for the safety-critical and mission critical power converter applications [4-5].

Recently, there has been an increasing demand and interest in developing a method for establishing junction temperature model of IGBT [6-8], which has been proven to be a cost-effective means of reliability enhancement for conventional electrical equipment. Among different condition parameters, junction temperature directly indicates the IGBT safety margin, health status, and operation performance [11-12], but it is difficult to measure due to the encapsulated structure of the semiconductor device. By using the die itself as a temperature sensor, the temperature sensitive electrical parameters (TSEPs) based method shows promising and feasible way to indirectly measure the IGBT temperature on-line [6]. According to

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the characteristics of TSEPs, it can be divided into static TSEPs and dynamic TSEPs[7].

For the static temperature sensitive electric parameter method, including: small current saturation voltage drop method [8], large current injection method [9], driving voltage drop ratio method [10], collector opening voltage method and short circuit current method [11, 12].However, low current saturation voltage drop method requires specific low current, which not only increases the cost but also the measurement complexity. High current injection method can cause blind spot of detection. The collector opening voltage method has the risk of increasing the converter failure rate. It is relatively difficult to extract IGBT static parameters, so generally a static parameter is extracted primarily [7,13].

For dynamic temperature sensitive electric parameter method, including: threshold voltage method [14, 15], built-in temperature-sensitive resistance method [16]. In contrast, the measurement method of dynamic parameters is much more convenient. In literatures [17, 18], it is proposed to estimate IGBT's instantaneous junction temperature by using the rate of change of collector current di_c/dt at the turn-off transient process, and it is concluded that $(di_c/dt)_{max}$ decreases with the increase of junction temperature at the turn-off transient process. In literature [19], the rate of change of collector-emitter voltage at the time of turning-off is proposed, and the conclusion is that duce/dt at the time of turning-off is negatively correlated with junction temperature. However, due to the stray inductance and stray capacitance in the module, the measurement results have large errors. In literature [20-22], it is pointed out that when the junction temperature rises, the band gap width of silicon chip will decrease, and then the carrier will be more easily excited to open the gate and the V_{GEth} will decrease. In literature [23-25], it is pointed out that there is negatively correlation between t_{don} and junction temperature, while a positively correlated between t_{doff} and junction temperature. Bus voltage, bus current, gate drive and circuit parasitic effects are very important, which will have a great impact on the on-off delay time of IGBT elements. Reference [26] proposed that the gate internal resistance r_g (equivalent internal resistance of gate emitter capacitance) also increases with the increase of temperature, with high temperature sensitivity.

To sum up, we will mainly study the parameters in the switching process of IGBT (as the TSEPs-I_C-T model), because the switching parameters of IGBT are easily affected by junction temperature and can be easily extracted. From the relationship between the junction temperature and internal mechanism of IGBT, it can be found that the change of junction temperature causes the change of some interelectrode capacitance and inductance inside IGBT, which will change the parameters of the switching process. However, due to the low precision of the measuring equipment and the coupling between the parameters, the traditional temperature junction model based on TSEPs is prone to produce a large deviation. Therefore, a high precision on-line temperature detection modeling method is proposed in this paper -- the optimal model is determined by stepwise regression algorithm. The algorithm can be used to build junction temperature models for different IGBTs. It has good universality and is not easily disturbed by measurement errors.

The remaining sections are arranged as follows: the principle of extracting junction temperature with traditional thermal sensitive parameters is analyzed in chapter II; the proposed IGBT junction temperature modeling algorithm based on stepwise regression is described in detail, including backward stepwise method and forward stepwise method, as well as the modeling process in chapter III. Experimental validation is conducted in Section IV to evaluate the performance of the method for IGBT junction temperature detection with high accuracy. Finally, Section V provides a brief summary of the paper.

II. Relevant TSEPs

The internal structure of IGBT is shown in FIG. 1 [27], NPNP structure. The structure of IGBT is similar to MOSFET with vertical structure. IGBT is composed of a vertically structured MOSFET with a highly doped P+ injection layer added to the drain electrode. The transistor collector region, the transistor base region and the transistor emission region are composed of P+ substrate, N- drift region, N+ buffer layer and P region. The PNP triode consists of collector, base and emitter. IGBT is a composite structure of MOSFET and PNP triode, which has the advantages of high input impedance and low on-voltage drop.

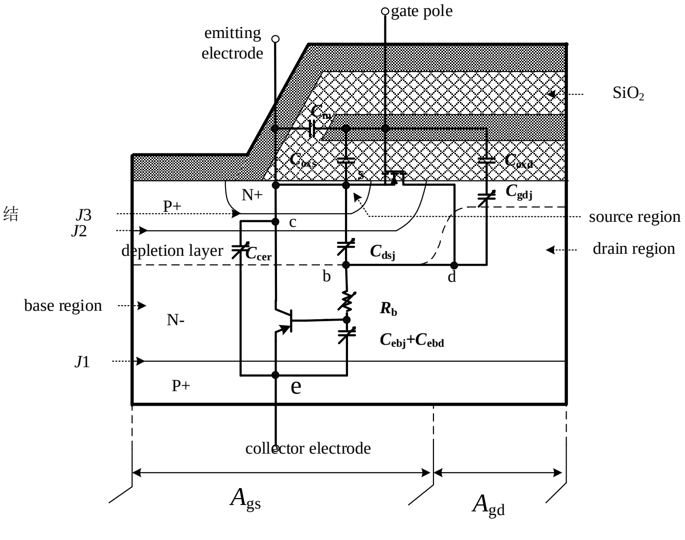

FIGURE 1. Structure diagram of IGBT

There are also some parasitic capacitors and resistors inside IGBT, besides the power MOSFET and triode, which are marked in the corresponding positions in FIG. 1 [28].

There are some parasitic capacitances in the IGBT, including: metallized capacitor C_m, source-gate oxide

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capacitor C_{oxs}, gate-drain oxide capacitor C_{oxd}, gate-drain depletion capacitor C_{gdj}, drain-source depletion capacitor C_{dsj}, collector emitter C_{cer}, Emitter-base distributed capacitor C_{ebj}, emitter- base diffusion capacitor C_{ebd}. There are some parasitic resistances, including the base resistance Rb. Among them, Cm and C_{oxs} are connected in parallel to form the gate-emitter capacitance of IGBT. Then C_{oxd}, C_{gdj} and (C_{ebd}+C_{ebj}) are connected in series to form the gate-collector capacitance of IGBT. These parasitic capacitors will be affected by the junction temperature, and the switching process of IGBT will be greatly changed. The mechanism of each TSEPs is different (affected by interelectrode capacitance and Interelectrode inductance). However, when the internal temperature distribution is uneven or part of the structure is damaged, there will be a large error in single TSEP-T model. On this basis, this paper selects a number of TSEPs to fit the high-precision junction temperature in the switching process, including the turn-off delay time T_{doff}, current fall time T_{fi}, current rising time T_{ri}, voltage rising time T_{rv} and turn-off loss E_{off}. It will be proved in the following text that the accuracy of junction temperature extraction can be improved by the model established with multi-TSEPs. [28].

A. The influence of junction temperature on the turn-on process and the expression of parameters

In the process of turn-on, it is mainly composed of four stages. Parameters such as trun-on delay time, current rising time and turn-on loss can be extracted. The states of IGBT in each stage are shown in Figure 2 respectively:

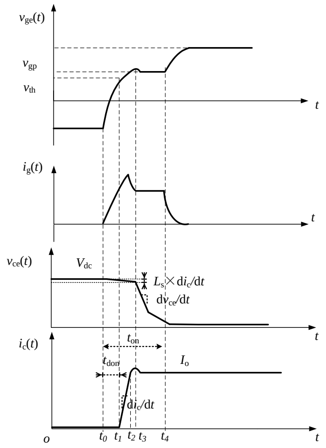

FIGURE 2. **Voltage and current waveform during IGBT turn-on process**

Phase I (t_0~t_1): gate delay phase. The voltage of IGBT gate changes from V_{goff} to V_{gon}, and the drive power supplies charge IGBT's input capacitance C_{ies} through the drive resistance, where $C_{ies} = C_{gc} + C_{ge}$.

The duration from t_0 to t_1 is considered as the turn-on delay time and can be expressed in Equation 1

$$t_{\text{don}} = \Delta t_1 = R_{\text{g}}\left(C_{\text{gc}} + C_{\text{ge}}\right)\ln\frac{V_{\text{gon}} - V_{\text{goff}}}{V_{\text{gon}} - V_{\text{geth}}} \tag{1}$$

Phase II (t_1~t_2): The voltage V_{ge} will continue to rise, until the voltage is greater than the turn-on voltage V_{GEth}, and the IGBT become turn-on. In this interval, the current rising time can be extracted.

Phase III (t_2~t_3): At t= t_2, the collector current of IGBT rises to the load current, and the current in the continuation diode becomes reverse. Due to the reverse diode recovery process, the collector current of IGBT will continue to rise, in this interval, miller platform voltage and duration can be extracted.

Phase IV (t_3~t_4): While IGBT works in the active region, the collector current I_C keeps constant value; the gate voltage is maintained at V_{geth}; the collector voltage drop. The duration is shown in Equation 2:

$$t_{fv} = \frac{C_{GC\_AVG}(V_{CE'} - V_{CE\_ON})}{I_{GP}} \tag{2}$$

B. The influence of junction temperature on the turn-off process and the expression of parameters

The turn-off process of IGBT can be divided into three stages for analysis. Parameters such as turn-off delay time, voltage fallen time and turn-off loss can be extracted, as shown in FIG. 3[29].

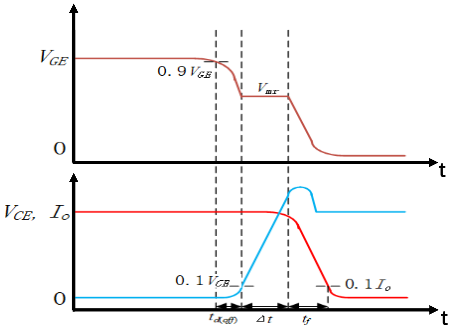

FIGURE 3. **Voltage and current waveform during IGBT turn-off process**

Phase I (t_{doff}): Firstly, the drive voltage changes rapidly when the gate drive sends out a turn-off signal; then, the drive current is established and discharged through the drive resistance, while the gate voltage V_{GE} drops and the collector current I_C keeps I_0 due to the inductive load. Finally, the gate voltage drops to the Miller platform voltage V_{mr}. The duration is recorded as the turn-off delay time t_{doff}.

$$t_{\text{doff}} = R_{\text{g}}\left(C_{\text{ge}} + C_{\text{gc,L}}\right)\ln(\frac{V_{\text{gon}} - V_{\text{goff}}}{V_{\text{gp}} - V_{\text{goff}}}) + \frac{(V_{\text{gp}} - V_{\text{ce(sat)}})R_{\text{g}}C_{\text{gc,L}}}{V_{\text{gp}} - V_{\text{goff}}} \tag{3}$$

Phase II (△t): at this time, the grid voltage has reached miller platform, and the depletion layer begins to be formed in the base region. As the carrier is discharged from the depletion layer, the collector-emitter voltage V_{CE} of IGBT begins to rise. The miller platform voltage and duration can be extracted.

$$\mathrm{t}_{rv} = ((\mathrm{V}_{CE,sat})_{I_L} - \mathrm{V}_{Ge,L}) * \frac{C_{GC,L}}{I_G} \tag{4}$$

Phase III (t_f): when the collector emitter voltage V_{CE} of IGBT is equal to the bus voltage V_{DC}, the continuation diode

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is forward biased. Then the load current IL begins to transfer from IGBT to the diode. Voltage fallen time and voltage change rate can be extracted.

In the turn-off stage 1-3, the turn-off loss E_{off} can be expressed by Equation 5. The turn-off loss is obtained by integrating the difference between the input power and the output power according to time. The specific position of the probe will be described in section IV.

$$E_{off} = E_{\mathrm{I}} + E_{\mathrm{II}} + E_{\mathrm{III}} = \int_{t1}^{\mathrm{t}_1 + \mathrm{t}_{\mathrm{d(off)}} + \Delta t + \mathrm{t}_f} I_C \cdot V_{CE} \cdot dt$$

$$= \frac{1}{2} * \int_{t_1}^{\mathrm{t}_1 + \mathrm{t}_{\mathrm{d(off)}} + \Delta t + \mathrm{t}_f} \left[V_{TV_{bus}} * I_{TA_{bus}} - \left(V_{TV_1} - V_{TV_2} \right) I_{TA_1} \right] dt \qquad (5)$$

According to the above formula of switching process parameters, IGBT operating junction temperature will affect the interelectrode capacitance, and then they will change the switching process parameters. However, the design of IGBT will lead to the change of interelectrode capacitance, which leads to the inconsistency of the parameters with the highest precision of each IGBT extraction model, which changes the adaptability of IGBT junction temperature extraction model and is harmful to the high-precision extraction of IGBT junction temperature. In this paper, a high precision online extraction of IGBT junction temperature based on stepwise regression algorithm is proposed, which can effectively avoid large deviation caused by a single parameter, ensuring the simplicity of extraction of temperature sensitive parameters.

III. Establishment of junction temperature model

The definition of multiple linear regression ensures that it is far superior to the previous results of temperature sensitive electrical parameter method in terms of both the information contained in independent variables and the accuracy of fitting results. The model is shown in Equation 6:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_{\mathrm{m}} X_{\mathrm{m}} + e \qquad (6)$$

Where, Y is the dependent variable，X_1，X_2，…，X_m is independent variables, partial regression coefficient β_j (j=1,2，…，n) represents the average change in Y when X_j increases or decreases by one unit while other independent variables remain unchanged. Residual e shows the random error after removing m independent variables.

In this paper, the junction temperature model based on TSEPs is studied. The voltage, current and time parameters are noticed because they are easy to be measured, which do not need to destroy the packaging of semiconductor devices, but also optimize the precision of junction temperature extraction. An IGBT junction temperature extraction method based on stepwise regression algorithm is proposed. Firstly, variables (that the degree of fit and partial regression square are significant) are added one by one; then, the variables in the regression model are tested when a new variable is added. Finally, variables with insignificant test results are deleted. It can be guaranteed that every variable in a subset of all independent variables is significant. This process goes through several steps until new variables can no longer be added. In this case, all variables in the regression model are significant for the dependent variables.

The process of establishing the temperature model in this paper is mainly divided into the following parts. Firstly, the regression algorithm based on stepwise forward is taken as an example for analysis (the backward method is opposite to the forward method, all independent variables are selected into the regression model first, and then the independent variables that make the model worse are gradually removed):

1) Primary selection of TSEPs; 2) Eliminate variables; 3) Stepwise regression;4) Model establishment

A. Primary selection of TSEPs

The internal mechanism can be reacted by different TSEPs, but the accuracy is different in different IGBT structures. In order to avoid the collinearity problem and measurement difficulties, some commonly used TSEPs are selected as the research focus in this paper.

B. Primary selection of TSEPs

It is assumed that each parameter has a certain linear relation with junction temperature, that is, each parameter can fit the relation shown in formula (7) with junction temperature

$$TEMP = \beta_0 + \beta_{\mathrm{n}} X_{\mathrm{n}} + \gamma I_C \qquad (7)$$

When the variable X_i is calculated, the value of the statistic is tested through the corresponding regression coefficient F, recorded as $F_1^{(1)}, \ldots, F_p^{(1)}$, and the maximum value is taken as $F_{i1}^{(1)}$:

$$F_{i_1}^{(1)} = \max\left\{ F_1^{(1)}, \ldots, F_p^{(1)} \right\} \qquad (8)$$

For a given significance level α， the corresponding critical value is $F^{(1)}$, while $F_{i1}^{(1)} > F^{(1)}$, X_{i1} is added to the regression model.

C. Stepwise regression

A binary regression model of dependent variable Y and the subsets of independent variable $\{X_{i1},X_1\},\ldots,\{X_{i1},X_{i1-1}\},\{X_{i1},X_{i1+1}\},\ldots\{X_{i1},X^p\}$ is established, and there are p-1 models in total. The value of the statistic is tested through the corresponding regression coefficient F, recorded as $F_k(^2)(k \not\subset I_1)$, and the maximum value is taken as $F_{i2}^{(2)}$:

$$F_{i_2}^{(2)} = \max\left\{ F_1^{(2)}, \ldots, F_{i_1-1}^{(2)}, F_{i_1+1}^{(2)}, \ldots, F_p^{(2)} \right\} \qquad (9)$$

For a given significance levelα， the corresponding critical value is, while $F_{i2}^{(1)} > F^{(2)}$, X_{i2} is added to the regression model. Otherwise, the variable addition process is terminated. Repeat the following procedure:

1. Check whether the independent variable meets the requirements;
2. Add independent variables to the model;
3. Check whether the model accuracy is improved

D. Model establishment

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The establishment process of junction temperature model is shown in FIG. 4 The specific process is as follows:

Step 1: Input TSEPs and junction temperature data

Step 2: Increase or eliminate variables based on R^2 and significance levelα

Step 3: Carry out regression algorithm based on step forward and step backward respectively.

Step 4: Output the optimized T-TSEPs model according to the comparison results of Step 3

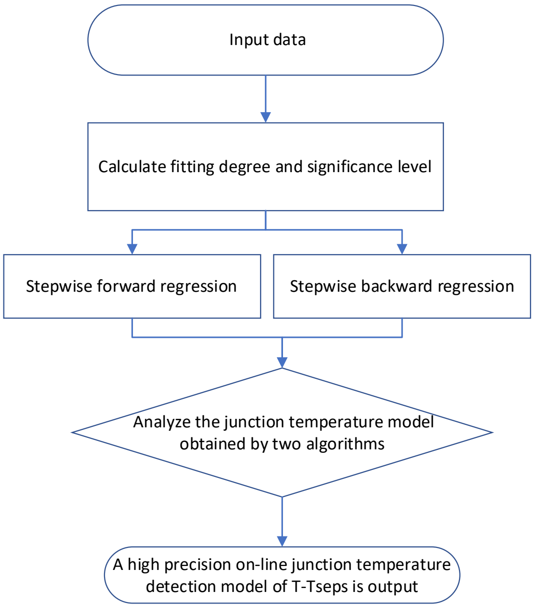


FIGURE 4. IGBT junction temperature modeling based on stepwise regression algorithm

It can be seen that the junction temperature model based on stepwise regression can not only avoid the measurement of useless variables, but also ensure the on-line high precision measurement of junction temperature. Its advantages are as follows:

1) More perfect information collection. Under the condition of large sample size and multiple parameters, the linear deviation of T-TSEPs caused by parameter selection can be avoided.

2) Rapid extraction. The irrelevant variables and the sensor layout can be effectively reduced in the established model, but ensure the accuracy.

IV. Experiment and Simulation

A. Improved experimental circuit platform

In this paper, on the basis of voltage type inverter circuit (full-bridge inverter circuit), current sensors and voltage sensors are added together to form a test platform. The laboratory test platform is shown in Fig 5, and the improved experimental circuit l is shown in Fig 6.

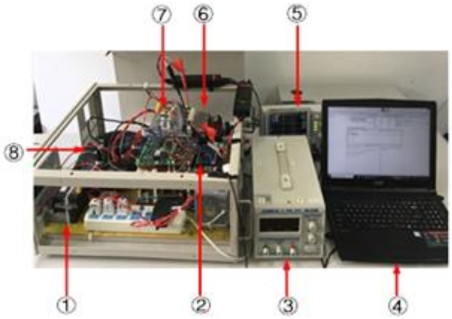


FIGURE 5. Physical diagram of test platform

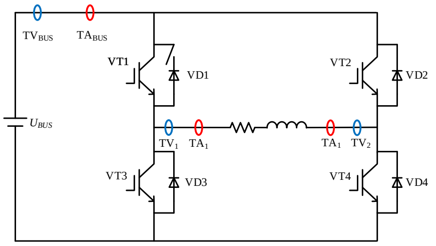


FIGURE 6. Schematic diagram of main circuit of test platform

The experimental equipment in the Figure 5 are: (1) PTC (plate of temperature controller); (2)control board provides control signal for driver; (3) high power DC power supply (4) upper computer; (5) mixed signal oscilloscope; (6) high voltage differential probe and high precision current probe; (7) cooling fan; (8) IGBT module to be tested; (9) inductive load.

The placement of sensors in the experimental circuit is shown in FIG 6. During IGBT reliability state detection, there are 5 state information to be collected, including: bus voltage (U_{BUS}), bus current (I_{BUS}), half-bridge midpoint voltage (U_1,U_2) and load current (I_{OUT}). IGBT switching state can be determined by detecting changes in voltage and current.

During the experiment on the above platform, the temperature of IGBT can be changed through PTC (PTC can be used for temperature control of IGBT), and then the dynamic TSEPs in the switching process under different junction temperatures can be extracted, such as: turn-on delay time t_{don}, collector current rising time tri, turn-off delay time t_{doff}, collector - emitter voltage rising time t_{fv}, collector current falling time t_{fi}, etc. FF50R12RT4 was selected as IGBT module in the experiment. The module parameters are shown in Table I.

TABLE I
MODULE PARAMETERS OF IGBT

IGBT MODEL	*FF50R12RT4*
Configuration	*Dual*
Dimensions (length)	*94.0 mm*
Dimensions (width)	*34.0 mm*
Housing	*34 mm*
$I_{C(nom)}$ / $I_{F(nom)}$	*50.0 A*
I_{Cmax}	*100.0 A*
Qualification	*Industrial*

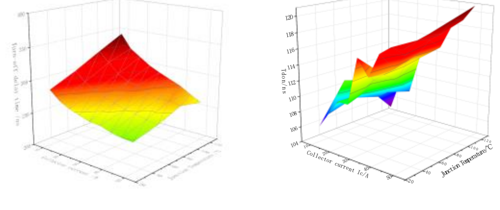
Technology	*IGBT4 - T4*
$V_{CE(sat)}$ (T_{vj}=25°C typ)	*1.85 V*
VF (T_{vj}=25°C typ)	*1.75 V*
Voltage Class	*1200.0 V*

B. Simulation

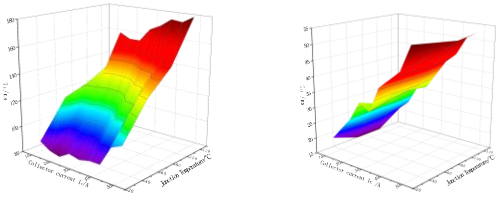
The simulation experiment is based on Windows10, Matlab2016a and ORIGIN2018. The optimal junction temperature model was established with the boundary conditions, as shown follows: T（20℃~120℃）, I_{bus} (10A~50A), U_{bus} (1200V), F ≥ 0.1. The IGBT junction temperature model is improved and compared with the existing research methods, showing better fitting degree.

The three-dimensional linear fitting diagram of TSEPs-I_C-T is shown in FIG 7. A-FIG 7.F. The fitting degree and linearity of the TSEPs-I_C-T are shown in Table II.

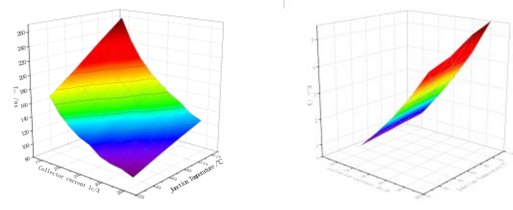
The partial regression coefficient of TSEPs-IC-T is shown in Table III. TABLE IV and TABLE V shows the IGBT junction temperature model based on stepwise forward regression (F≤0.1). TABLE VI and TABLE VII shows the IGBT junction temperature model based on stepwise backward regression (F≥0.1).



A. t_{doff}-I_C-TEMP B. t_{don}-I_C-TEMP



C. t_{fi}-I_C-TEMP D. t_{ri}-I_C-TEMP



E. t_{rv}-I_C-TEMP F. E_{off}-I_C-TEMP

FIGURE 7. Traditional model of TSEPs-IC-T

TABLE II
THE FITTING DEGREE AND LINEARITY OF TSEPS-IC-T

Parameter	*R^2*	*Adjusted R^2*	*Significance*
t_{doff}-I_C-TEMP	*0.823*	*0.812*	*0*
t_{don}-I_C-TEMP	*0.21*	*-0.39*	*0.71*
t_{fi}-I_C-TEMP	*0.668*	*0.647*	*0*
t_{ri}-I_C-TEMP	*0.1998*	*0.150*	*0.26*
t_{rv}-I_C-TEMP	*0.816*	*0.805*	*0*
E_{off}-I_C-TEMP	*0.771*	*0.774*	*0*

TABLE III
PARTIAL REGRESSION COEFFICIENTS BASED ON STEPWISE REGRESSION

Parameter	*t_{doff}*	*t_{don}*	*t_{fi}*	*t_{ri}*	*t_{rv}*	*E_{off}*	*I_C*	*Constant*
t_{doff}-I_C-TEMP	1.89						2.435	-525.528
t_{don}-I_C-TEMP		3.7					-1.156	-309.943
t_{fi}-I_C-TEMP			0.88				-0.308	-22.149
t_{ri}-I_C-TEMP				9.91			-8.159	-38.638
t_{rv}-I_C-TEMP					1.23		2.989	-199.741
E_{off}-I_C-TEMP						85.44	-8.241	83.625

TABLE IV
MODEL SUNMMARY BASED ON STEPWISE FORWARD REGESSION

Model	R	R²	Adjusted R²	Error of standard estimate
1	.706[a]	.499	.470	24.50052
2	.809[b]	.655	.612	20.95599
3	.948[c]	.898	.877	11.77864
4	.961[d]	.923	.901	10.60588
5	.970[e]	.942	.919	9.56403

a. predictive variable: (constant), t_{fi}
b. predictive variable: (constant), t_{fi}, t_{doff}
c. predictive variable: (constant), t_{fi}, t_{doff}, E_{off}
d. predictive variable: (constant), t_{fi}, t_{doff}, E_{off}, I_c
e. predictive variable: (constant), t_{fi}, t_{doff}, E_{off}, I_c,t_{rv}

TABLE V
COEFFICIENT[a] BASED ON STEPWISE FORWARD REGESSION

Model		Unstandardized cofficient		Standardized coefficient	t	Significance level
		B	Standar error	Beta		
1	(constant)	-13.805	21.745		-.635	.534
	t_{fi}	.751	.182	.706	4.115	.001
2	(constant)	-146.261	52.632		-2.779	.013
	t_{fi}	.556	.172	.523	3.227	.005
	t_{doff}	.551	.205	.436	2.690	.016
3	(constant)	-352.770	45.514		-7.751	.000
	t_{fi}	.297	.106	.279	2.797	.014
	t_{doff}	1.228	.162	.970	7.599	.000
	E_{off}	17.469	2.926	.691	5.970	.000
4	(constant)	-191.302	86.443		-2.213	.044
	t_{fi}	.303	.096	.285	3.171	.007
	t_{doff}	.730	.276	.576	2.641	.019
	E_{off}	48.104	14.679	1.903	3.277	.006
	I_C	-3.573	1.684	-1.498	-2.121	.052
5	(constant)	-600.588	214.025		-2.806	.015
	t_{fi}	.381	.094	.359	4.046	.001
	t_{doff}	3.091	1.177	2.442	2.627	.021
	E_{off}	41.550	13.616	1.644	3.051	.009
	I_C	-3.772	1.522	-1.581	-2.479	.028
	t_{rv}	-1.567	.763	-2.140	-2.053	.061

a. dependent variable: TEMP

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TABLE VI
MODEL SUNMMARY BASED ON STEPWISE BACKWARD REGESSION

Model	R	R^2	Adjusted R^2	Error of standard estimate
1	.970[a]	.942	.905	10.37738
2	.970[b]	.942	.913	9.94322
3	.970[c]	.942	.919	9.56403

a. predictive variable: (constant), t_{ri}, t_{fi}, t_{doff}, t_{don}, E_{off}, t_{rv}, I_C
b. predictive variable: (constant), t_{ri}, t_{doff}, t_{don}, E_{off}, t_{rv}, I_C
c. predictive variable: (constant), t_{ri}, t_{doff}, E_{off}, t_{rv}, I_C

TABLE VII
COEFFICIENT[a] BASED ON STEPWISE FORWARD REGESSION

Model		Unstandardized cofficient		Standardized coefficient	t	Significance level
		B	Standar error	Beta		
1	(constant)	-489.209	667.654		-.733	.479
	I_C	-3.237	4.341	-1.357	-.746	.472
	t_{don}	-.800	4.525	-.108	-.177	.863
	E_{off}	43.554	18.660	1.723	2.334	.040
	t_{doff}	2.981	1.399	2.356	2.131	.056
	t_{fi}	.388	.119	.365	3.271	.007
	t_{rv}	-1.510	.882	-2.062	-1.711	.115
	t_{ri}	-.584	4.488	-.204	-.130	.899
2	(constant)	-565.290	308.216		-1.834	.092
	I_C	-3.759	1.584	-1.576	-2.373	.035
	t_{don}	-.248	1.496	-.033	-.166	.871
	E_{off}	42.158	14.625	1.668	2.883	.014
	t_{doff}	3.046	1.253	2.407	2.431	.032
	t_{fi}	.380	.098	.358	3.882	.002
	t_{rv}	-1.545	.805	-2.110	-1.920	.079
3	(constant)	-600.588	214.025		-2.806	.015
	I_C	-3.772	.094	.359	4.046	.001
	E_{off}	41.550	1.177	2.442	2.627	.021
	t_{doff}	3.091	13.616	1.644	3.051	.009
	t_{fi}	.381	1.522	-1.581	-2.479	.028
	t_{fv}	-1.567	.763	-2.140	-2.053	.061

a. dependent variable: TEMP

As can be seen from FIG 6.A, many researchers believe that the junction temperature presents a very good linear relationship with the turn-off delay time when the collector current is small.

As can be seen from FIG 6.B, the linearity between t_{don} and temperature is not good. As can be seen from FIG 6.C, while the collector current is small, there is a great linearity between t_{fi} and temperature. From FIG 6.D, it can be found that the linearity between Tri and junction temperature is not obvious. FIG 6.E shows the relationship between voltage rising time t_{rv} and junction temperature at the turn-off time. It can be found that it has a good linearity, but it is easily affected. FIG 6.F shows the relationship between the turn-off loss and junction temperature, which has a good linearity but is easily affected by other IGBTs.

Moreover, there are different interelectrode capacitance in different IGBTs due to different interior structure, which will cause the accuracy of TSEPs-T model worse under different conditions. But IGBT junction temperature model based on multiple stepwise regression can be widely used in industrial applications.

It can be seen from table IV to VII that (the boundary condition is set to F⩾0.1) the junction temperature model based on stepwise forward regression is consistent with the model based on stepwise backward regression.

The model takes the following temperature sensitive electrical parameters as the data source, including collector current I_C, turn-off loss E_{off}, turn-off delay time t_{doff}, collector current fall time t_{fi}, and collector - emitter voltage rising time t_{rv}. The model is set up as shown in Formula 10 (For IGBT: FF50R12RT4).

$$\begin{aligned} TEMP = -600.588 - 3.772 * I_c + 41.550 * E_{off} \\ +3.091 * T_{doff} + 0.381 * T_{fi} - 1.567 * T_{rv} \end{aligned} \tag{10}$$

According to the above formula, it can be found that in the actual working conditions, even if the parameter measurement is inaccurate, the temperature deviation will not be too large, because more TSEPs can effectively restrict the error caused by inaccurate measurement of a parameter.

It can be seen from Table II and VI that the fitting degree and adjusted R^2 of this model are much higher than the traditional junction temperature model based on a single TSEP. In terms of accuracy, the model established by this algorithm is 18.7% higher than the junction temperature model based on the turn-off loss, 13.1% higher than the junction temperature model based on the turn-off delay time, and 14.2% higher than the junction temperature model based on the voltage rising time. This shows the superiority of this algorithm in improving IGBT online junction temperature detection. In engineering practice, IGBT can be calibrated before operation. Different IGBTs choose different models before they leave the factory, which is beneficial to the on-line high-precision junction temperature detection of IGBTs in the future

The above results and analysis fully demonstrate that the modeling method based on stepwise regression algorithm for IGBT junction temperature extraction is feasible and effective.

V. Conclusion

In this paper, a high accuracy IGBT junction temperature extraction method based on stepwise regression algorithm is proposed. The optimized junction temperature extraction model for IGBT is established by stepwise regression algorithm, and then applied to the actual on-line monitoring, which can effectively improve the stability and reliability of power electronic devices. The traditional single TSEP method is easily affected by the interelectrode capacitance of IGBT, and the replacement of IGBT will result in the failure of the previous junction temperature model.

In this algorithm, more thermal sensitive parameters are added to the traditional temperature sensitive electrical parameter model, while the accuracy of temperature extraction remains unchanged. Simulation results show that this algorithm is suitable for high precision IGBT on - line junction temperature extraction. This method has the following advantages:

1) Convenient application. The IGBT junction temperature model is modeled before leave factory. This method can realize IGBT junction temperature extraction by measuring the parameters contained in the model. The parameters of the selected voltage and current are readily available and do not destroy the package.

2) Higher accuracy. Through big data analysis, the measurement error of single parameter is avoided. At same time the model established by this algorithm is 18.7% higher than the junction temperature model based on the turn-off loss, 13.1% higher than the junction temperature model based on the turn-off delay time, and 14.2% higher than the junction temperature model based on the voltage rising time.

3) Wide applicability. The junction temperature model of IGBT with different structures is established, in order to be widely used

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