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Modeling of IGBT Using Temperature Prediction Method

Amit Thakur **Y S Thakur**

***Abstract* — A temperature prediction method of Insulated Gate Bipolar Transistor (IGBT) module based on autoregressive moving average model is proposed. Historical and current temperature datum of IGBT module is indispensable to the ARMA method, temperature time series is obtained by uniform sampling, and autoregressive (AR) model is constructed. Temperature time series prediction of IGBT module is realized by employing optimal prediction theory of autoregressive moving average (ARMA) module. Experiments results show the effectiveness and the satisfactory precision of the prediction method.**

Keywords- Autoregressive Model; Insulated Gate Bipolar Transistor; Optimal Prediction; Time Series Analysis

Introduction

I. INTRODUCTION

Power electronics equipments are widely used because of the fast development of economy and the policies implementation of energy saving and emission reduction in China. Consequently, power semiconductors, as key parts of converter, become more important than before. Insulated gate bipolar transistor (IGBT), full controlled power electronic devices, has been widely applied for industrial and traction inverter applications, because of the advantage of combine the facile drive of metallic oxide semiconductor field effect transistor (MOSFET) with the low conduction loss of bipolar junction transistor (BJT) [1]. Nevertheless, all kinds of power electronics equipments are extensively employed, so the reliability of IGBT must be high. IGBT frequently come into being failures due to its rigor working conditions and the important component of commutation current, and it is very difficult that find the reasons of IGBT failures because of its various. In order to exactly discover reasons of IGBT failures, it is indispensable to deeply research interior failure mechanism of IGBT. Correlative technological literatures [2-4] show that junction temperature of IGBT is one of the most important reasons. It may result in bond line breaking; solder failure and substrate damage, etc. . . . Although fault features is not obvious, and is difficultly detected, its value become large along with time. So future temperature of IGBT module can be estimated by prediction technique based on past and present status, which is vital to improve reliability of IGBT module.

Temperature prediction of IGBT module is main research content of this paper. Usually, interior temperature of IGBT module can be measured or estimate, on which module temperature can be predicted. Health status of IGBT module can be diagnosed and system fault can be forecasted by analyzing predicted temperature. Therefore, auto-regressive (AR) model is constructed by employing time series analysis method, and future temperature of IGBT module can be predicted based on past and present temperature and AR model in this paper.

II. PREDICTION METHOD AND ITS MODELING PROCESS

A. Optimal Prediction Method of ARMA

A stationary time series $\{x_t\}$ always can be expressed with linear combination of a series of white noise, and the weight function of this linear combination is defined as Green function G_j of ARMA model. The expression is as follows:

$$x_t = \sum_{j=0}^{\infty} G_j a_{t-j} \tag{1}$$

(1) also may be modified because t only is a subscript variable of (1), so (2) is obtained from (1).

$$x_{t+l} = \sum_{j=0}^{\infty} G_j a_{t+l-j} \tag{2}$$

Furthermore, the form of the expansion of (2) is given by

$$x_{t+l} = (G_0 a_{t+l} + G_1 a_{t+l-1} + \ldots + G_{l-1} a_{t+1}) + (G_l a_t + G_{l+1} a_{t-1} + \ldots) \tag{3}$$

If the value x_{t+l} of future l steps is predicted when time is, and the prediction value is signed as x (,), the terms of the first bracket on the right-hand side of (3) cannot predict future time parameters a_{t+1}, a_t+_2, a_{t+l} on condition that known parameters a_t, a_{t-l}, a_1 when time is t because $\{ a \}$ is white noise. Therefore, the terms in the right first bracket of (3) is impossible to be predicted. (4) can be obtained by modifying (3).

$$x_{t+l} = e_t(l) + x_t(l) \tag{4}$$

In (4),

$$e_t(l) = G_0 a_{t+l} + G_1 a_{t+l-1} + \ldots + G_{l-1} a_{t+1} = \sum_{j=0}^{l-1} G_j a_{t+l-j} \tag{5}$$

$$\hat{x}_t(l) = G_l a_t + G_{l+1} a_{t-1} + \ldots = \sum_{j=l}^{\infty} G_j a_{t+l-j} \tag{6}$$

Here, $e_t(,)$ is prediction error of forward , steps in (4), X_t (,) is prediction value of forward l steps in (4). The meanings of (5) and (6) is obvious and profound, and is fundament theories and methods [9].

B. Temperature Prediction Model of IGBT Module

1) Temperature Datum Preprocess of IGBT Module

Constructing ARMA model must satisfy the conditions that times series is stationary datum, normal distribution and zero mean, so $\{ x_t \}$ need be checked in order to accord

with the above conditions behind of being sampled from temperature analog signals or directly measured by temperature sensors. If temperature series doesn't satisfy the above conditions, it must be preprocessed.

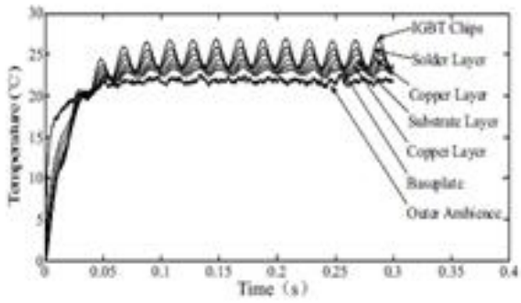

Figure 1. Interior layers temperature of IGBT modules

Interior temperature curves of IGBT module are given by fig.1, and they are measured on condition that converter employs hysteresis pulse width modulation (HPWM) strategy. Temperature time series can be obtained by sampling analog temperature curve. It is not difficult to reach a conclusion that sampled time series is not accord with above conditions by calculating and analyzing Statistic parameters of these time series.

The mathematics expressions of temperature times series are given by (7) by analyzing temperature datum and curves, and (7) is consist of three terms

$$x_t = m_t + s_t + a_t \qquad (7)$$

Here, m_t is trend term, it denotes variational temperature trend. s_t is repetition term, it shows variational temperature periods that is subject to modulation strategy. a_t is random noise term, it implies the influence of random factors. Above temperature time series should be preprocessed in order to construct ARMA model based on known datum, sequentially, a time series that character of stationary datum, zero mean and normal is obtained. Preprocessing steps and methods is as follows. Firstly, trend extraction, m_t is eliminated from (7). Secondly, zero processing. Mean of $\{x_t\}$ is estimated, and subtracted from former time series. Finally, standardization processing. Former time series is standardized for improving calculation precision, reducing rounding error and avoiding overflow. A feasible time series is obtained by above processing.

Temperature time series that only has random noise term is predicted by utilizing ARMA model and time series that has been processed. And then, prediction value of primal temperature time series can be calculated by combining trend value and repetition value

2) Modeling Process of Temperature Prediction

Step1: Model Identification

Determining AR, MA or ARMA model is main task of model identification. The optimal model that fits time series datum is chose by utilizing autocorrelation function (ACF) and partial autocorrelation function (PACF). If ACF is truncated and PACF is trailed, MA model meets the requirements. Contrarily, AR model is adopted. If two functions are all trailing, choosing ARMA model is the best. Unbiased Estimation can be calculated by using estimation formula of ACF [9] based on finite length sample value $\{x_t\}$ (t=1, 2, .., *N)*. According to the definition of PACF [9], all coefficients and PCF of model is obtained by solving equations with Levinson recursive algorithms. Figure 2 and Figure 3 give ACF and PACF value of IGBT chip temperature time series. In addition, latter analysis all adopts the example of IGBT chip temperature time series in order to avoid expatiating.

With respect to IGBT chip temperature time series, ACF is trailed and PACF is truncated. The conclusions are drawn by analyzing ACF and PACF curves in Figure 2 and Figure 3 and criterions of ACF and PACF in [10]. Hence, AR model is optimal temperature prediction method, and its order is not less than five.

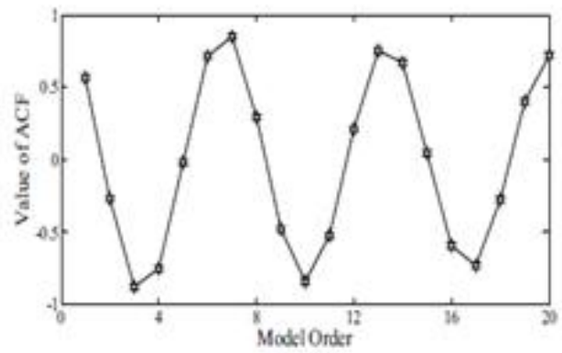

Figure 2. Relationship between ACF and model order

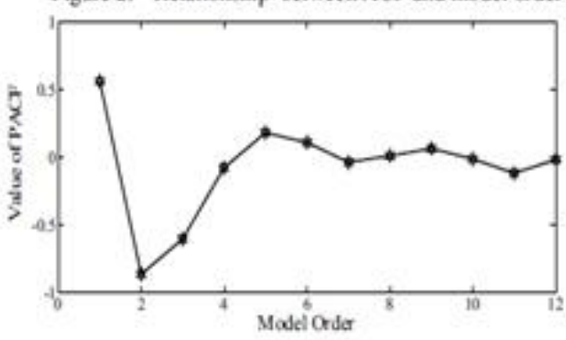

Figure 3. Relationship between PACF and model order

Step2: Model Order Selection

The method of model order selection is AIC rule. The value of AIC rule function decides that different order AR model is ideal and non-ideal in modeling process. As a rule, optimal AR model is chose when AIC rule function is minimum value. The definition of AIC function is as follows.

$$AIC(p) = N \ln \sigma_a^2 + 2p \qquad (8)$$

Step3: Model Parameters Estimation

The solving method of AR model parameters utilizes estimation of Yule-Walker equations. Model parameters are easy to be calculated because the rank of Toeplitz matrix is full. Solving method is given by (9).

$$\varphi = T^{-1}\rho \qquad (9)$$

Here,

$$\rho = (\rho_1 \ \rho_2 \ \cdots \ \rho_n)^T, T = \begin{bmatrix} \rho_0 & \rho_1 & \cdots & \rho_{n-1} \\ \rho_1 & \rho_0 & \cdots & \rho_{n-2} \\ \cdots & \cdots & \cdots & \cdots \\ \rho_{n-1} & \rho_{n-2} & \cdots & \rho_0 \end{bmatrix}$$

Is a Toeplitz matrix.

Step4: Applicability Analysis of AR model

Applicability of AR model is checked by using information rule. In conclusion, with respect to IGBT chips temperature time series, AIC rule value of different order model on basis of the definition of (8). AIC values are in TABLE I.

TABLE I. AR MODEL ORDER AND THE VALUE OF AIC

Model Order	5	6	7	8	9	10
AIC	-27.55	-21.22	-19.57	-18.38	-15.84	-17.55

AIC value of AR (9) is minimum in TABLE I, so AR model order is chose as 9.

III. TEMPERATURE PREDICTION OF IGBT MODULE

Three-phase bridge type converter of adopting Hysteresis PWM is as a practical case in this paper. Its power devices utilize SEMIKRON SKM 75GB123D, *VCES*=1200*V*, *IC*= 75*A*, *Eon*=8*mJ*, *Eoff*=5*mJ*. The purpose and approach of this paper is to construct temperature prediction model by ARMA model on basis of known temperature of IGBT modules, and sequentially realize precision temperature prediction.

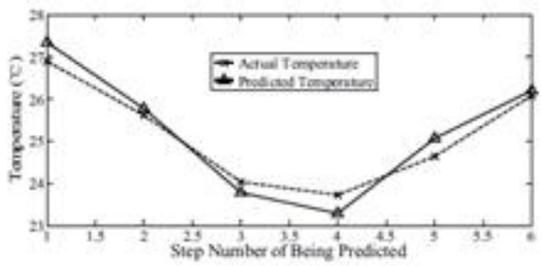

Figure 4. The Comparison Between Predicted Teperature and Actual Temperature of IGBT Chips in Different Step

TABLE II. ONE STEP AHEAD ERRORS OF AR MODEL

Step Number	1	2	3	4	5	6
Relative Errors	1.676	0.624	1.079	1.835	1.741	0.462

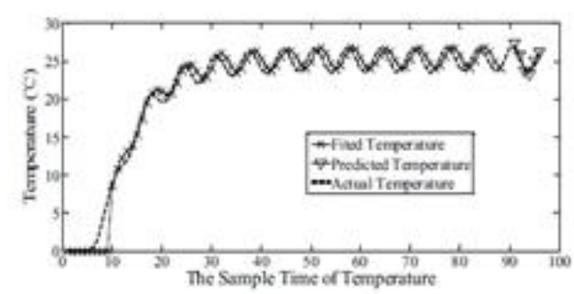

Figure 5. The Whole Curves of Predicted Teperature, Actual Temperature and Fited temperature of IGBT Chips

One-step-ahead chips temperature predictive curves and errors of IGBT modules are given by Figure 4 and TABLE II respectively. The prediction method completes temperature prediction, and its error less than 2%. Whole raw chips temperature and its prediction value of IGBT modules show in Figure 5; furthermore the validity of AR model is verified.

IV. CONCLUSIONS

AR model is constructed for temperature time series on the basis of known historical and current temperature, and it realizes precise prediction about IGBT chips temperature in terms of optimal prediction method of ARMA model. With regard to research results in this paper, there are several explanatory problems are as follows:

- The purpose of IGBT modules temperature prediction is to know real-time running status of IGBT modules, and provide a necessary datum information basis for evaluating health status of IGBT modules, so it is theoretical foundation of fault prediction.
- Enough historical and current datum, analog temperature are uniformly sampled, are indispensable to predict accurately temperature of IGBT modules, and sampling period complies with Shannon sampling theorem.
- Applicable range of AR model for temperature prediction accords with linear time series. Usually, time series in this paper is linear, and meets the requirement of AR model.
- The paper merely studies chips temperature prediction of IGBT modules. Temperature prediction methods of interior other layers in IGBT modules is about the same with IGBT chips. Their dissimilarity is calculation of AIC value again. Furthermore optimal order of AR model is obtained.

Many methods of temperature prediction in IGBT modules can be used. This paper only emphasize on time series analysis, so we will spend a lot of effort in the question

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