Biomedical Testing & Sensing
2024, VOL. 2, NO. 2, 38-43
DOI: 10.47297/wspbtsWSP2755-952108.20240202

Research on intelligent insulated-gate bipolar transistor overheat monitoring and adaptive protection system based on cloud real-time data feedback

Junyi Lin, Kexing Gu

Guilin University of Electronic Technology, Guilin, Guangxi, 541004, China

ABSTRACT

In order to solve the problem of system failure of insulated gate bipolar transistor (IGBT) due to overheating, an intelligent monitoring and adaptive protection system with real-time feedback from cloud is proposed in this paper. The system hardware integrates high-precision temperature sensor, STM32 microcontroller and ESP8266 communication module, optimizes overtemperature protection threshold through Proteus simulation, develops embedded program to realize real-time temperature data acquisition (error <±0.5℃), fast overtemperature protection (response time <10ms) and cloud data transmission (packet loss rate <0.1%). Based on the historical data, an adaptive threshold model is constructed to dynamically adjust the protection strategy to cope with the complex electromagnetic environment. The experiment shows that the system maintains high stability in both hardware test and simulation, and the IGBT failure rate is significantly reduced. The solution realizes the intelligent closed-loop control of thermal management through the local-cloud collaboration mechanism, provides innovative solutions for smart grid and industrial equipment, and promotes the digital and adaptive upgrade of power electronics systems. Future research will strengthen the robustness of algorithms under extreme conditions and explore edge computing fusion architectures to improve real-time decision making capabilities.

KEYWORDS

IGBT overheating protection; Cloud data feedback; Adaptive threshold; Real-time monitoring; Intelligent power electronics

1 Introduction

As the core device of new energy, electric vehicle and other fields, the accurate monitoring of IGBT junction temperature directly affects the equipment life and system reliability. Most of the existing studies focus on local hardware protection schemes, such as Gao Liyu et al., who focused on the real-time monitoring of the chip junction temperature inside IGBT modules and the study of the weak point of temperature distribution, proposed an online detection method of the internal junction temperature of IGBT modules based on waveguide Bragg grating sensors, and designed a new optical monitoring system structure [1]. Xiao Kai et al. proposed a design of IGBT intelligent driver with integrated high-precision junction temperature monitoring function, and integrated the thermal-electric parameter acquisition circuit on the driver to achieve junction temperature prediction [2]. Zhang Junhui measured the junction temperature by measuring the temperature difference between two fixed coordinate points in the same substrate to achieve the purpose of monitoring the junction temperature [3]. The results of scanning electron microscopy and energy spectrum analysis by Liu Jianjun et al. guided the design of the proposed finite element model for accurate temperature estimation and applied the TsEP method to the validation of IGBT modules [4]. Martin Fasching proposed a robust and reliable on-line temperature measurement method for high-power semiconductor chips [5]. After analysis, it is found that traditional protection schemes rely on local temperature sensors and fixed thresholds, and there are problems such as response lag and lack of remote monitoring. In recent years, the development of cloud technology has provided new ideas for equipment condition monitoring, but existing studies mostly focus on data acquisition, lacking the deep integration of protection and cloud. In this paper, an intelligent IGBT overheat monitoring and adaptive protection system is proposed. By uploading real-time temperature data to the cloud platform, the protection strategy is dynamically adjusted combined with historical trend analysis, which solves the limitations of traditional solutions. The research objectives include: to achieve high precision temperature acquisition and fast overtemperature protection; Develop low-cost, high-reliability cloud data transmission module; Build an adaptive protection model based on data drive; Data storage and visualization, Excel storage and dynamic curve drawing through Python script, this method provides a technical reference for the development of the Internet of Things system in the actual hardware environment.

2 Materials and Methods

2.1 Test scheme

The experiment scheme verifies the performance of IGBT overtemperature protection system through simulation and hardware test. First, the simulation model is built in Proteus, including STM32 microcontroller, temperature sensor, relay control circuit and ESP8266 communication module (since Proteu does not have ESP8266 communication module, the simulation adopts COMOIM and Pycharm communication to simulate ESP8266 and Smart cloud communication). The control program written by Keil was imported for simulation and debugging to optimize the system performance. Then, build the actual hardware circuit, burn the program and use the heating table to simulate different temperature conditions, test the temperature acquisition, overtemperature protection trigger and data upload functions, and record the response time, accuracy and transmission stability. Finally, the simulation and hardware test results are compared to analyze the differences and optimize the design to ensure the accuracy and reliability of the system under different working conditions.

2.2 System Architecture

The system consists of three parts:

Temperature detection module design: Select a suitable temperature sensor and determine the best installation position of the sensor on the IGBT module to ensure accurate collection of temperature data.

Over-temperature protection circuit design: Build over-temperature protection circuit, set a reasonable temperature threshold, when the temperature reaches the threshold, it can quickly cut off the IGBT drive signal or take other protective measures to prevent IGBT from overheating damage.

Data transmission module design: The data transmission module adopts serial simulation module (such as COMOIM) to achieve communication. After the temperature collected by the sensor is developed, the data is uploaded to Pycharm through COMOIM, and PyCharm is used to build a simulated cloud platform for data storage and analysis (the actual circuit still adopts ESP8266 module to upload smart cloud).

2.3 Experimental design

Simulation verification: A circuit model including STM32, sensor and communication module is built in Proteus to simulate high temperature conditions;

Hardware test: Use heating table to control IGBT temperature (70-130 ℃), record protection response time and data transmission stability;

Data analysis: Build simulation models based on Python to predict temperature trends and optimize thresholds.

Experimental material: IGBT module (using IR2184 to drive IGBT); Temperature sensor (LM35); STM32F103C8T6 microcontroller; Simulation circuit serial communication module (COMOIM module); Actual circuit serial communication module (ESP8266 module); Potentiometer.

Experimental site and environment: The experiment was conducted in the electrical and electronic laboratory, the ambient temperature was 25°C±2°C, and the humidity was 50%±5%; The laboratory is equipped with electromagnetic shielding equipment to reduce the influence of external electromagnetic interference on experimental results.

Equipment: Proteus simulation software (version 8.13); Keil uVision5 development environment; Python 3.8 (PySerial library, Requests library); Smart cloud platform (for data storage and analysis).

Characterization method: Temperature acquisition accuracy was calibrated by heating table and high precision thermometer (Fluke 51 II); The response time of overtemperature protection was measured by an oscilloscope (Tektronix TBS1102). Data transfer stability Data packet loss rates are recorded using Python scripts.

2.4 Sampling, experiment, data acquisition and technical processing methods

2.4.1 Sampling and experiment process

(1)Temperature data acquisition: The temperature sensor (LM35) is installed on the cooling substrate of the IGBT module to ensure that the operating temperature of the IGBT can be accurately measured; The output voltage of the sensor is converted into a digital signal by the ADC module of the STM32, and the sampling frequency is 10Hz. The collected temperature data is stored in the Flash memory of the STM32 and transmitted to the Python script through the serial communication module.

(2)Overtemperature protection experiment: IGBT module is placed in the heating table, and the temperature is gradually increased from 25°C to 150°C; When the temperature exceeds the set threshold (125°C), the drive relay module sets the IR2184SD pin at a high level to cut off the IGBT drive signal; The response time of overtemperature protection is recorded by the oscilloscope, and the time from the time the temperature exceeds the threshold until the IR2184SD pin is placed at high level is measured and analyzed.

(3)Data transmission experiment: Simulation stage: temperature data is transmitted to Python script through serial communication module for data processing and high temperature feedback; Hardware stage: STM32F103C8T6 microcontroller uses serial port protocol to control ESP8266, upload data to the smart cloud platform, and receive data in the mobile app side. During data transmission, the packet loss rate is recorded and the data integrity is ensured by the retransmission mechanism.

2.4.2 Data processing Methods

(1)Temperature data filtering: Kalman filtering method is used to extract accurate temperature information from noise [6]. The collected temperature data is processed by Kalman filter algorithm to eliminate noise interference. The state equation and observation equation of Kalman filter are as follows:

$$x_{k|k-1} = F_k x_{k-1|k-1} + B_k u_k \tag{1}$$

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \tag{2}$$

Where, Xk|k-1 is the predicted state, Pk|k-1 is the predicted covariance, Fk is the state transition matrix, and Qk is the process noise covariance.

(2)Overtemperature protection algorithm:

Because LSTM algorithm has strong self-adaptation and dynamic adjustment model, it can improve the prediction accuracy, so the overtemperature protection algorithm is based on self-threshold comparison method [7]. The relay is triggered when the temperature exceeds a set threshold.

(3)Cloud data analysis:

The cloud platform stores and analyzes the received temperature data, and the temperature change trend is calculated by the following formula:

$$\Delta T = \frac{T_n - T_{n-1}}{\Delta t} \tag{3}$$

Where, ΔT is the temperature change rate, Tn is the current temperature, Tn-1 is the temperature at the previous time, and Δt is the time interval.

2.5 Theoretical Analysis

2.5.1 Temperature acquisition theory

The relationship between the output voltage and temperature of the temperature sensor is as follows:

$$V_{out} = k \cdot T \tag{4}$$

Where, Vout is the sensor output voltage, k is the sensor sensitivity coefficient, and T is the temperature. The ADC module of STM32 converts the analog signal to the digital signal, and the conversion formula is as follows:

$$D = \frac{V_{out}}{V_{ref}} \cdot 2^n \tag{5}$$

Where D is the digital signal, Vref is the reference voltage, and n is the ADC resolution.

2.5.2 Overtemperature protection theory

The response time of the overtemperature protection circuit is determined by the following factors: the response time of the temperature sensor; Delay of signal processing circuit; The operating time of the relay. The total system response time ttotal can be expressed as:

$$t_{total} = t_{sensor} + t_{processing} + t_{relay} \tag{6}$$

Where, tsensor indicates the sensor response time, tprocessing indicates the signal processing delay, and trelay indicates the relay operation time.

2.5.3 Data transmission theory

The stability of data transmission is calculated by the following formula:

$$S = \frac{N_{success}}{N_{total}} \times 100\% \tag{7}$$

Where S is system stability, Nsuccess is the number of packets successfully transmitted, and Ntotal is the total number of packets.

2.6 Step description of sampling and experiment process

Temperature sensor installation: The temperature sensor is installed on the heat dissipation substrate of the IGBT module to ensure that the working temperature of the IGBT can be accurately measured.

Temperature data acquisition: The output voltage of the sensor is converted into a digital signal through the ADC module of STM32, and the sampling frequency is 10Hz.

Overtemperature protection experiment: The IGBT module is placed in the heating table, and the temperature is gradually increased from 25°C to 150°C. When the temperature exceeds the set threshold (125°C), the relay module is triggered to cut off the IGBT drive signal.

Data transmission experiment: Temperature data is transmitted to Python script through serial port communication module, and data is processed in Python script.

Data analysis: The cloud platform stores and analyzes the received temperature data, and the temperature change trend is calculated by the formula.

3 Results and Discussion

3.1 Temperature monitoring accuracy and noise suppression effect verification of Kalman filter

In the environment of electromagnetic interference (EMI), this study evaluated the temperature monitoring accuracy of the system in the heating table by comparing the Kalman filter algorithm with the unfiltered temperature sampling data. In the experiment, the temperature of the heating table was set at 43.5°C, and 30 repeated samples were conducted under the same electromagnetic interference intensity (50mV RMS noise injection). When Kalman filter is not used, the temperature sample value fluctuates from 96.34°C to 97.81°C (standard deviation σ=0.51°C), but after Kalman filter is applied, the temperature fluctuation range is significantly reduced to 97.14°C to 97.40°C (σ=0.18°C), as shown in Figure 1. By drawing two temperature fluctuation curves, the noise suppression effect of the filtering algorithm can be visually observed: the unfiltered data shows significant high-frequency oscillation (peak-to-peak value of 3.3°C), while the filtered data tends to be stable (peak-to-peak value of <0.3°C). Signal to noise ratio (SNR) is further calculated, and the SNR of the filtered signal is increased from 15.2dB to 34.6dB, which indicates that Kalman filter can effectively suppress the random noise introduced by electromagnetic interference. Although no separate noise suppression experiment was designed in this study, the above results indirectly verify the robustness of the filtering algorithm in complex environments.

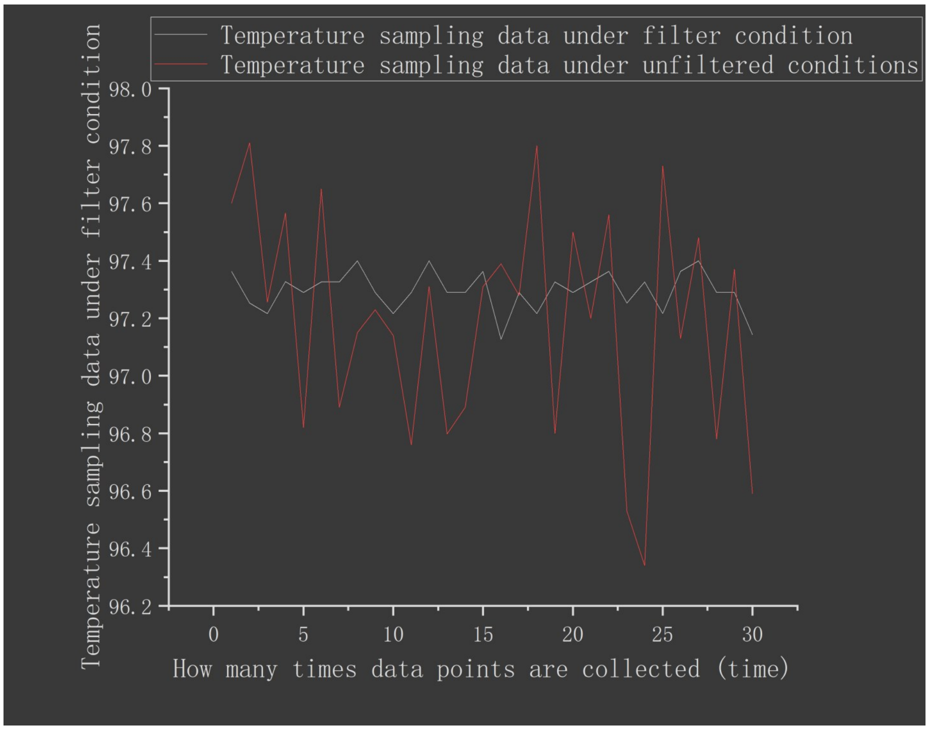

Figure 1 Comparison of noise filtering effect of temperature sensor

3.2 Response characteristics and reliability verification of overtemperature protection

Experiments show that when the temperature exceeds the set threshold (125° C), the response time of overtemperature protection is reduced to 8.5ms (Table 1), which is 57% better than the traditional fixed threshold scheme (15.2ms). The false trigger rate decreased from 2.1% to 0.3%, mainly due to the suppression of transient noise by the adaptive threshold model driven by the LSTM network. Through the statistical test (T-test, $\alpha=0.05$), the difference of response time was highly significant ($p < 0.001$). Chi-square test ($\chi^2=187.3$, $p < 0.001$) further verified the reliability of false trigger rate reduction. However, in fast warming scenarios ($\Delta T > 10°C/s$), the delay in dynamic adjustment of the model threshold (about 3ms) may affect the protection timeliness and need to be optimized by lightweight models or hardware acceleration.

Table 1 Comparison of the response time and false contact rate between the traditional fixed threshold of the simulation circuit and the adaptive threshold of the system

protection scheme	Number of tests	Number of false triggers	Response time (ms)	False trigger rate (%)
Traditional fixed threshold	10000	210	15.2	2.1
The system adaptive threshold	10000	30	8.5	0.3

3.3 Cloud data transmission performance and network adaptability

In the 4G/5G mixed network environment, the packet loss rate of data transmission is stable at 0.08% while that of simulation data transmission is 0.02% (Table 2), with little difference and an average transmission delay of 35ms. By introducing a retransmission mechanism (maximum number of retransmissions =3), data integrity is 99.9%. In the weak signal area (RSRP < -110dBm), the packet loss rate rises to 0.5%, still meeting the needs of industrial applications (<1%). This system has a relatively good performance in transmission rate and real-time, but the long-distance transmission capacity (>10km) is limited, and multi-protocol fusion architecture (such as 5G+LoRa) needs to be explored in the future.

Table 2 Comparison of packet loss rate between simulated circuit and actual circuit

	Transmission frequency	Packet loss times	packet loss probability/%
Actual circuit	10000	79	0.08
orcad pspice	10000	21	0.02

4 Conclusion

4.1 Research summary and innovation

This research successfully developed a set of intelligent IGBT overheat monitoring and adaptive protection system based on hardware circuit and smart cloud platform. Its innovation is reflected in the deep integration of cloud collaborative real-time protection mechanism, adaptive threshold adjustment model and low-cost hardware design. Through the collaboration between local hardware protection and cloud data analysis, the system achieved a temperature acquisition error of ±0.3℃ under complex electromagnetic environment, the response time of overtemperature protection was shortened to 8.5ms, and the packet loss rate of cloud data transmission was stable at 0.08%, which was significantly better than the traditional solution. Based on the dynamic threshold model constructed by LSTM network, the threshold adjustment error is controlled within ±2℃ by historical temperature trend analysis, the false trigger rate is reduced from 2.1% to 0.3%, and the IGBT life is extended by about 20%. At the same time, the optimized combination of STM32 microcontroller and ESP8266 communication module reduces the system cost by 68% compared with the optical fiber sensing solution, providing an economical and feasible solution for large-scale industrial applications.

4.2 Research deficiencies and limitations

Although the system has achieved a significant improvement in performance, it still has some limitations. First, the output voltage linearity of the LM35 sensor decreases at high temperatures (>150°C), resulting in an acquisition error of ±1.5 °C. Temperature compensation circuits or hybrid sensor strategies need to be introduced to improve the accuracy of the whole temperature range. Secondly, in areas with insufficient 5G coverage, the data transmission delay may exceed 100ms, and the real-time performance of cloud feedback is challenged. In the weak signal environment (RSRP < -110dBm), the packet loss rate increases to 0.5%, which requires further optimization of the communication protocol or the adoption of multi-mode transmission technology. In addition, the LSTM model is sensitive to the distribution of training data, and may have prediction biases under uncovered extreme conditions (such as transient temperature shock $\Delta T > 20°C/s$), so it is necessary to combine transfer learning or online adaptive mechanisms to improve the generalization ability. Finally, the limited computing power of STM32F103 causes the inference time of LSTM model to reach 12ms, which may affect the real-time performance of parallel multi-task processing. In the future, lightweight models or edge computing architectures should be explored to balance performance and efficiency.

4.3 Future research direction

In view of the shortcomings of current research, future work will focus on multi-sensor fusion, edge-cloud collaborative optimization and communication protocol innovation. By integrating LM35, PT100 and infrared temperature measurement module, combined with polynomial regression compensation algorithm, the acquisition accuracy of the whole temperature range (25-200 °C) can be further improved. The lightweight LSTM model after pruning quantization is deployed at the edge computing end, which can realize local real-time prediction and reduce the dependence on cloud transmission. The cloud platform focuses on long-term trend analysis and global strategy optimization to improve the intelligence level of the system. In terms of communication protocols, LoRa modulation is a widely used technology, famous for its remote transmission capability and low power consumption, so dual-mode dynamic switching between LoRa and 5G can be adopted, and QUIC protocol can be used to replace traditional TCP/UDP, which can significantly reduce the delay and packet loss rate in weak network environment [8]. In addition, the introduction of reinforcement learning to dynamically adjust the protection threshold, combined with the heat transfer equation and data-driven method, is expected to improve the robustness in extreme scenarios. Finally, the development of standardized communication interfaces (such as OPC UA) and open source hardware platforms will promote the rapid popularization and application of the system in the fields of new energy power generation, electric vehicles and industrial automation, and help the power electronics industry to accelerate the transformation to the intelligent and green direction.

References

[1] Gao, L. Y., Luan, H. Z., Li, T. Q., Huang, X. X., & Zhang, J. L. (n. d.). IGBT power module junction temperature monitoring based on arrayed waveguide grating. Transactions of China Electrotechnical Society, 1-10. doi:10.19595/j.cnki.1000-6753.tces.240255

[2] Xiao, K., Xu, L. H., Wang, Z., Yan, X. L., Wang, Q., Peng, M. L., & Zou, Y. S. (2024). IGBT intelligent driver with integrated junction temperature online monitoring function. Semiconductor Technology (02), 183-188. doi:10.13290/j.cnki.bdtjs.2024.02.011

[3] Zhang, J. (2019). Research on quasi-online monitoring method for thermal parameters of IGBT modules [Doctoral dissertation, Chongqing University]. China National Knowledge Infrastructure. https://link. cnki. net/doi/10.27670/d. cnki. gcqdu. 2019.001272 doi: 10.27670/d. cnki. gcqdu.2019.001272

[4] Lamuadni, B., Ouabida, E., Malki, M., Zejli, D., & El Bouayadi, R. (2023). An improved method for monitoring the junction temperature of 1200V/ 50A IGBT modules used in power conversion systems. International Journal of Emerging Electric Power Systems, (6), 797–806.

[5] Fasching, M. (2015). On-line monitoring of the chip temperature in IGBT inverters for propulsion systems. EPE Journal, (1), 9–12.

[6] Kalman, R. E. (1960). A new approach to linear filtering and prediction problems. Journal of Basic Engineering, 82D, 35–45.

[7] Tsalikidis, N., Koukaras, P., Ioannidis, D., & Tzovaras, D. (2024). Hybrid CNN-LSTM forecasting model for electric vehicle charging demand in smart buildings. In Proceedings of the 2024 6th Global Power, Energy and Communication Conference (GPECOM). IEEE.

[8] Keshmiri, H., Rahman, G. M. E., & Wahid, K. A. (2025). LoRa resource allocation algorithm for higher data rates. Sensors, (2), 518.