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Analysis of reliability based on thermal cycle and aging effect in electron devices

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Abstract. This paper concentrates on the estimation of reliability of an automotive electronic power device using thermal cycle, aging effect and accumulated damage. Thermal model has been developed for analysing the factors of power loss. A look-up table has been constructed to calculate the power loss and finite-element modelling was used to find out the aging effect. Thermal model was developed by using FLOTHERM. It is in the form of either Foster or Cauer network. Comparison of results from the thermal model has been done. Preprocessing of data by filtration and spectrum truncation was also explored. Reliability can also be estimated by calculating the accumulated damage with the help of Pagoda Roof method and Miner's rule. Finally, a method was proposed of using Ga NFET instead of MOSFET to calculate power dissipation.

Keywords. Thermal cycle; reliability; temperature; thermal model.

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1. Introduction

Reliability is the first and foremost concern to be considered while designing an automotive electronic power steering system. Reliability can be affected by various factors such as load cycle, stress–strain damage, thermal cycles, etc. Among these factors, reliability of an electronic power device is affected by thermal cycle. High temperature application in automotive electronics has increased so much. To analyse the device under temperature condition is therefore necessary. The analysis should be done during the design of the converter itself. Failure mechanisms of devices should be examined under harsh and terrible conditions, so that the reliability can be estimated easily. This will allow lifetime prediction and assure safe operations of vital functions of the device.

For the analysis, an accurate thermal model should be constructed. It is used for calculating the thermal cycle and also for simulating energy dissipation. For different manufacturers, the parameters may vary. The parameters may be chosen according to the convenience of the manufacturer. Now, the junction temperature is one of the most important aspects in thermal cycle. Junction temperature is nothing but the maximum temperature the device can withstand. According to the updated thermal model, it is easy to compute the junction temperature of MOSFET [1]. This paper gives an entire view of reliability with complete analysis of thermal cycle and aging effect.

2. Thermal cycle analysis

2.1 *Implementation of the converter model*

Analysis of thermal cycle can be initiated by using an automobile in which an electronic power steering (EPS) converter is fixed. Along with this EPS converter, a Tektronix digital oscilloscope is fitted where the signals of both input and output can be displayed. The DC motor's input current is given and the corresponding output can be obtained. Figure 1a presents the experimental configuration of the automobile steering cycle used to test an EPS controller with a Tektronix digital oscilloscope. Figure 1b presents the steering cycle detected by the oscilloscope. From the current signal, it is easy to obtain information about the load in order to calculate the power loss. The compact model used in the EPS converter is shown in figure 2. R_0 and L_0

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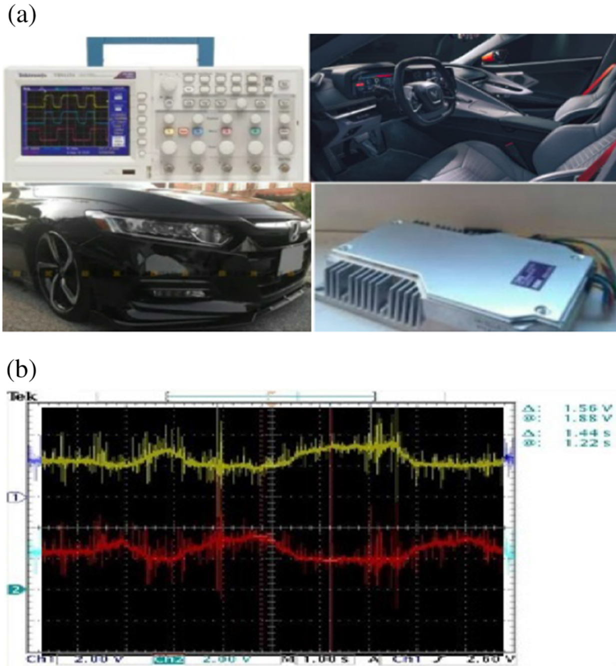

Figure 1. (**a**) Steering cycle experiment and (**b**) oscilloscope detection of signals.

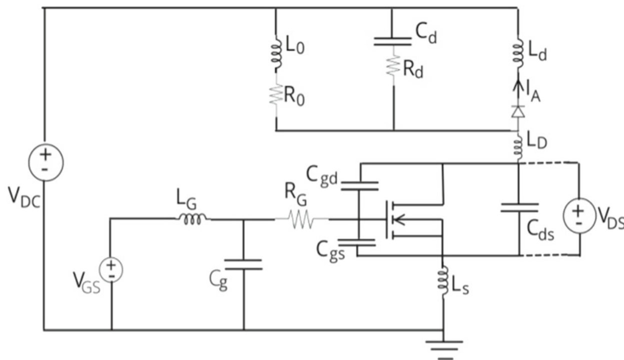

Figure 2. Compact model of the device.

denote load components. Series combination of R_{d} and C_{d} is called a snubber. L_{c} denotes source inductance. L_{d} and L_{D} denote stray and diode inductances respectively. R_{G} and L_{G} denote gate resistance and gate inductance respectively.

Some of the conditions involved in the look-up table are

1. Metal oxide semiconductor field effect transistors (MOSFETs), diode and triode conduction power losses which depend on resistance, current and temperature.
2. MOSFET, diode and triode switching power losses which depend on load current and junction temperature.

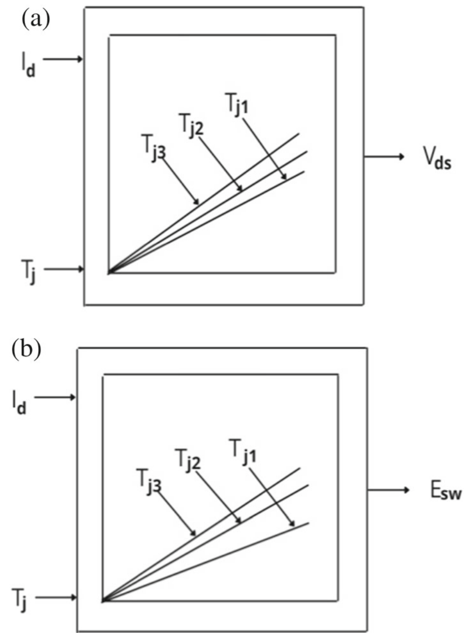

Figure 3. Look-up table for (**a**) V_{ds} characteristics and (**b**) power losses.

2.2 *Construction of look-up table and power loss calculation*

The temperature of the device usually varies with fluctuation of the load and also some external conditions. Compact or behavioural model is used for the simulation of electrothermal model. Power losses of switching are obtained by the look-up table which is displayed in figure 3. The main parameters involved in conduction and switching losses (i.e. turn ON and turn OFF) are the device parameter, DC motor current and control duty ratio.

Relationship between V_{ds} and i_{d} can be given by

$$V_{\mathrm{ds}}(t) = f_{\mathrm{cont}}(i_{\mathrm{d}}(t), T_j(t)), \tag{1}$$

where T_j is the junction temperature.

In this equation, voltage varies when resistance is affected by junction temperature. Power loss can be calculated using the equation

$$E_{sw}(k) = f_{sw}(i_c(k), T_j(k)). \tag{2}$$

Most important parameters for transient switching device losses are controller voltage duty cycle, overload current (I_{c}) and device junction temperature.

3. Aging effect analysis

Thermomechanical properties are mostly affected by high-temperature aging. Exploration of aging effects

can be done by the construction analysis. Oxidation is one of the major factors that influences degradation of the material properties [2,3]. The temperature-dependent properties of the materials are characterised by dynamic model analysis (DMA). Glass transition temperature (T_g) and coefficient of thermal expansion (CTE) were measured by thermal mechanical analysis (TMA). Thermal stability and moisture absorption properties were characterised by thermal gravitational analysis (TGA).

One of the methods for analysing the aging effect is finite-element modelling. With the help of this modelling, half of the package is simulated. Oxidation effect on the epoxy molding compound at high temperature can be reduced. Stress induced by the oxidation effect and shrinkage of the layer can be minimised.

The calculation of electron transport in MOSFETs with biaxially tensile strained silicon channel was formulated using two-dimensional drift diffusion model (DDM) including strain effects. The carrier mobility dependence on the lateral and vertical electric field model was especially considered in the formulation. By using this model, numerical method based on finite-difference modelling is performed [4].

4. Construction of thermal model network

One of the most crucial factors for designing an automotive electronic power device is its junction temperature.

Hence, an accurate thermal model will be beneficial in junction temperature estimation and will be helpful in predicting lifetime. Therefore, by using the software called FLOTHERM, the thermal model will be constructed.

Thermal resistance network is usually in the form of either a Cauer network or a Foster network (displayed in figure 4). This module and heat sink model are established to estimate the instantaneous temperature.

5. Computation of junction temperature

Thermal model is used for the approximation of simulated junction temperature and base-plate temperature. Using this method, simulation can be accomplished. In automobile steering systems, single and common impacts are the typical items. Usually, transient power losses rapidly increase the junction temperature. The graph showing the simulated and base-plate temperature is shown in figure 5. It is possible to understand from eq. (1) that the junction temperature can be computed by knowing drain-to-source voltage and drain current.

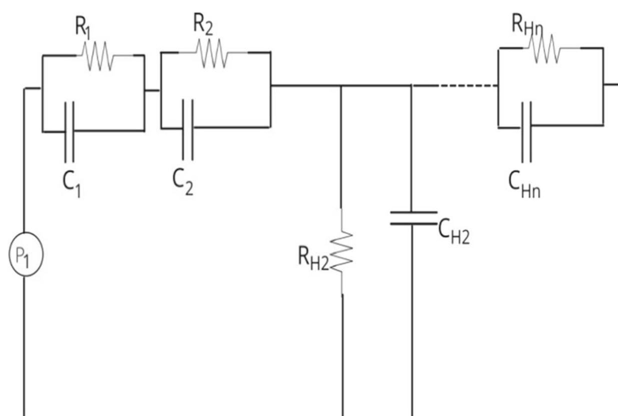

Figure 4. Thermal resistance network.

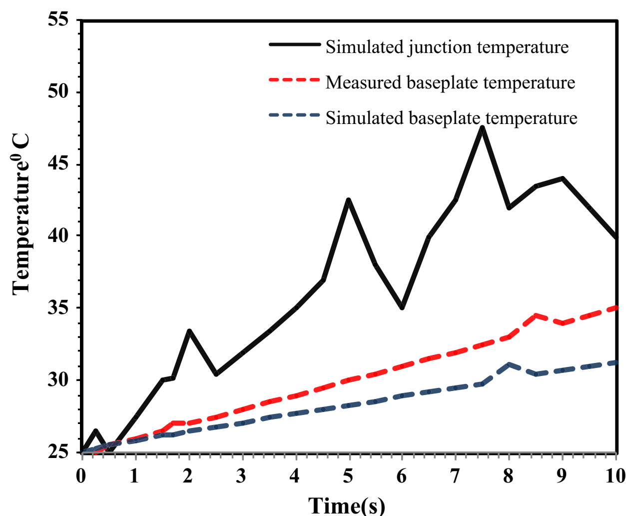

Figure 5. Simulated and base plate temperatures.

6. Processing of data

Some procedures are introduced to rectify the impact created by thermal cycles [5]. They are data filtration and spectrum truncation.

6.1 *Data filtration*

Data filtration is applied directly on the machine in which the reliability is to be tested, where the thermal excursion takes place [5].

Thermal cycle defined as the interval between two subsequent relative minima should not exceed 20°C. Junction temperature curves are smoothed out as shown in figure 6.

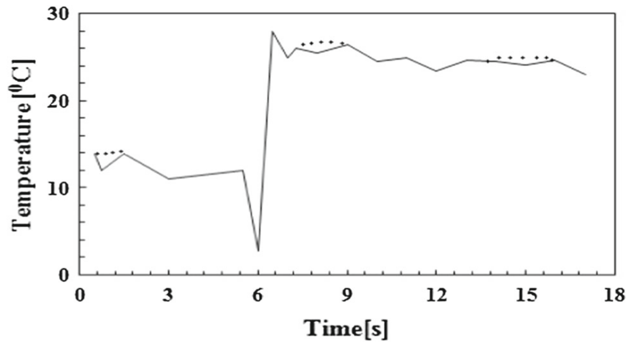

Figure 6. Junction temperature profile.

6.2 *Spectrum truncation*

It is also applied to correct the thermal cycles in such a way that the thermal cycles whose excursion is smaller than 20°C are not considered in statistics.

7. Implementation of the pagoda roof method

There are many methods to capture the characteristics required for obtaining the statistic random transient thermal cycling of material fatigue [6,7]. But an efficient method to calculate the stress cycle is the pagoda roof method which is usually called the rain flow counting method. This is called the pagoda roof method because of the plotting, when the time axis is vertical and the load stress represents a series of roofs on which water falls.

Load stress needs to be modified before rainflow counting method is applied. Only the extreme points are needed for this method. Therefore, other points in the stress load profile need to be discarded. This method is used to gather information about the distribution of the number of cycles that can be related to the device failure rate using the reliability theory. Some methods are used to evaluate the reliability of the power device through an accelerated thermal cycling test in manufacturing, typically either measures device heat by itself or uses an external load. Failure inducing cycling during the test can be specified by temperature range and mean temperature. But these methods have a common limitation that the variations of failure mechanisms with different cycling temperatures are unknown. An algorithm for this method is shown in figure 7.

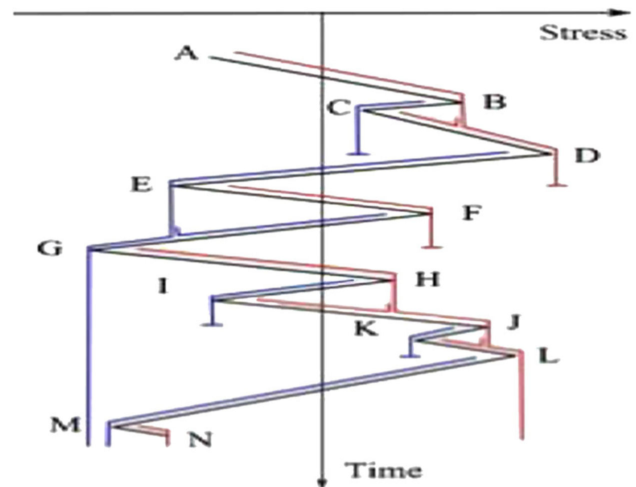

Figure 7. An algorithm of rainflow counting method.

8. Miner's rule for damage calculation

Some procedures are adapted to extract the statistical distribution of thermal cycles. Some models are designed on the basis of principle of linear accumulation damage related to the cyclic fatigue. Cumulated fatigue can be assumed to be linear in Miner's rule. This rule is the simplest cumulative damage model which states that if the average number of cycles at the ith stress is N_i and the average number of cycles to failure at the ith stress is N_{fi} then the damage fraction C is given by

$$C = \sum \frac{N_i}{N_{fi}}. \tag{3}$$

When $C = 1$, the device tends to fail. It is possible to understand mathematically from eq. (3) that the temperature cycle with large junction temperature mainly contributes to the damage even though the number of cycles is less.

9. Reliability of automotive electronic power device

Thus, using rainflow counting method and with the help of Miner's rule, reliability of an automotive electronic power device was estimated. Thermal cycles are in large number in low-temperature region. When the switching cycles are low, the service life of the automotive electronic power device will be high. The reliability estimated using the rainflow method is shown in figure 8.

10. Ga NFET instead of MOSFET

In this paper, the junction temperature is calculated in an electronic power device using MOSFET. MOSFET has a disadvantage that heat can be conducted away from both sides of the MOSFET chip.

Hence, the calculated values are inaccurate. Therefore, instead of MOSFET, gallium nitride field effect

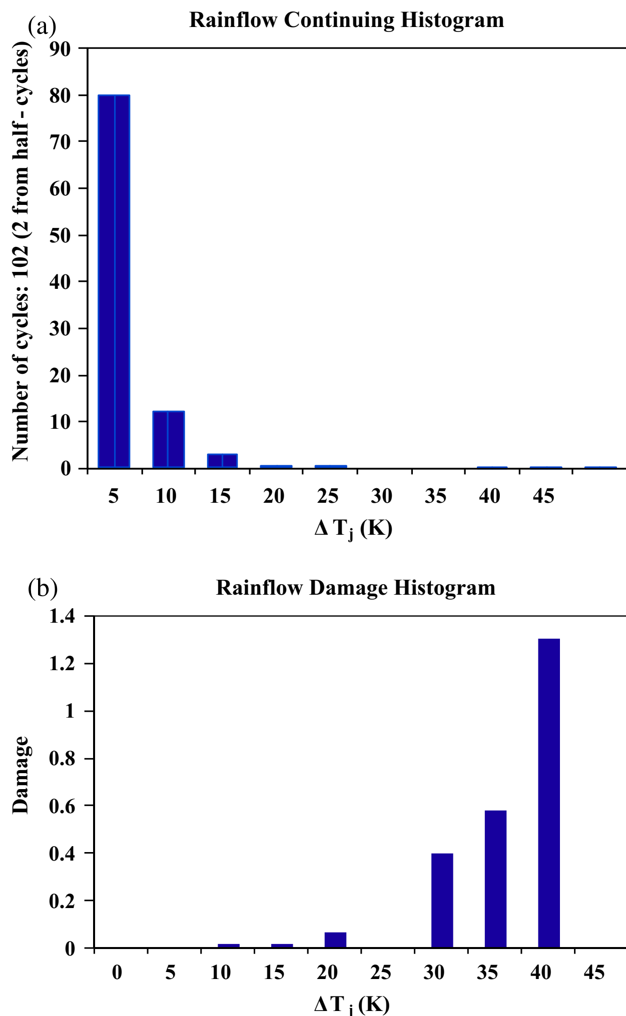

Figure 8. (**a**) Rain flow cycle counting histogram and (**b**) damage histogram.

transistor (Ga NFET) can be used because of its improved thermal performance [8]. Ga NFET can be implemented by developing a compact and accurate electrothermal model using lumped thermal impedances.

The electrothermal model provides a means to calculate the junction temperature in response to power dissipation transients in power devices. It can provide a valuable tool to estimate the junction temperature. Equation (2) makes it clear that the power loss can be calculated with the help of overload current (I_c) and device junction temperature.

11. Conclusion

Thus, this paper has covered different factors that affect the reliability of an automotive electronic power device. The paper gives the overall view of the analysis of thermal cycle. Look-up table was constructed and power loss calculation was accomplished. All parameters were estimated to analyse the thermal cycle. Moreover, analysis of aging effect on the automotive electronic power device was also presented. Finite-element modelling technique was employed. Thermal model was developed by FLOTHERM. The results are compared with values from the thermal model. The data was preprocessed using data filtration and spectrum truncation. The cycle counting method was used to obtain the statistics for thermal cycle. This method has provided the distribution of the number of cycles using reliability theory. Eventually, Miner's rule was applied to calculate the accumulated damage in the given automotive electronic power device. Finally, a method was proposed where MOSFET was replaced with another device named Ga NFET and finite difference modelling was replaced by another numerical method called finite-element modelling. Thus, this paper gives the overall view of the factors involved in the estimation of reliability of an automotive electronic power device.

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