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Method of reliability tolerance design based on EDA technology and its application on DC hybrid contactor

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Abstract: Tolerance design, including tolerance analysis and distribution, is an important part of the electronic system's reliability design. The traditional design needs to construct mathematic model of material circuit, which involves large amount of workload and lacks of practicability. This paper discusses the basic theory of electronic system's reliability tolerance design and presents a new design method based on EDA (Electronic Design Automatic) software. This method has been validated through the application research on reliability tolerance design of the DC hybrid contactor's control circuit.

Key words: Reliability, Tolerance analysis, EDA (Electronic Design Automatic)
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INTRODUCTION

The reliability of an electronic product is defined as the probability of its normal operation without failures under the specified conditions for a certain time period. To be brief, the reliability is the probability that an electronic product could work normally. The efforts for having a reliable product should start from the very beginning of its design stage. Taguchi Kuoyiqi proposed a "Thrice Designed" method, by which the product design process is divided into three stages: the system design, the parameter design, and the tolerance design. The tolerance design is important for enhancing the reliability of product. Especially, for a complex system with high precision, the tolerance design plays an important role. However, the common simulation methods in the tolerance design require mathematic model of the circuit, which involves complicated calculations and heavy workload. What is more, the circuit model cannot be used in common. As a consequence, the tolerance design technology has been greatly limited in the engineering application (Adamantios, 2000; Parkinson, 2000).

With the emergence and development of EDA (Electronic Design Automatic), the exploitation of the electronic product and system has been revolutionarily changed. Many EDA based simulation softwares for electronic system are available on the market. With these softwares, the workload of the tolerance design has been significantly alleviated in terms of the circuit and elements modeling, and furthermore, the complex calculation has been avoided and the designing cycle has been largely shortened.

Based on the traditional tolerance design theory and EDA technology, a method for electronic system's reliability tolerance design is given. By using the simulation and analysis function of the EDA software, the modeling and statistic calculating in tolerance design are simplified and adjusted. This method has been validated by the reliability tolerance design and simulation of the DC hybrid contactor's control circuit.

PRINCIPLE AND MEDTHOD OF TOLERANCE DESIGN

The circuit tolerance design is a circuit design technology, which minimizes the circuit output's warp by designing and distributing the tolerance range of each component, when components' parameters in the circuit are given. It is not only a main design method for keeping the parameters of the circuit's function stable, but also an important technique for enhancing production capacity and reducing cost. The primal problems that the reliability tolerance design of the electronic system needs to solve include: (1) Which factors influence the output characteristic seriously; (2) How to set the controllable variables to make the output's tolerance as small as possible; (3) How to design the controllable variables so that the incontrollable variables would influence the output characteristic as small as possible; (4) While the output's tolerance range is given, how to distribute each controllable variable's tolerance to reduce the production cost (Zhai *et al*., 2002). In specific analysis and design, the circuit tolerance design includes tolerance analysis and tolerance distribution. Through tolerance analysis, the influence of each design variable on the output characteristic can be obtained. Then the tolerance distribution scheme can be checked. Through tolerance distribution, the tolerance, which is defined in qualification or obtained by calculating, can be distributed to each correlated design variable, and be the basis for each variable's designing. In fact, the tolerance design is a process in which the tolerance analysis and the tolerance distribution cooperate recurrently again and again, and finally find the optimal cooperation of the parameter tolerance.

Tolerance analysis

The circuit tolerance analysis technology is an estimation technology for the stability of the circuit performance parameter. As any electronic system may be affected by kinds of stochastic disturbance factors inevitably, there is always deviation between component parameter and its nominal value in actual circuit, which is named tolerance. The major factors inducing tolerance include: (1) Parameter deviation: Because of the fabrication technology, there is a small deviation between system component's parameter and its nominal value; (2) Environment influence: The variety of the environment, such as the change of ambient temperature, makes the electronic component's parameter drift; (3) Degradation effect: The component parameters may change as time elapses. In the circuit, the deviation between component's actual parameter and its nominal value cannot be ignored. Sometimes it may be extraordinary serious. Consequently, when designing an electronic system, it is essential to study the influence of each parameter's change on the circuit output characteristic, which is named as the tolerance analysis. When doing the circuit tolerance analysis, one or more situations will be considered according to the environment and actual requirements.

There are many methods for circuit tolerance analysis, such as Monte-Carlo Analysis, Incremental Computation, Interval Analysis, and so on. Monte-Carlo Analysis is mainly introduced in this paper.

Monte-Carlo Analysis (also called Probabilistic Method) is a statistic analysis method, which analyzes the deviation of circuit performance parameter with parameter sampling value of circuit element, when parameter of the circuit element yields to a certain distribution (Shi and Kang, 2001). Its primary principle is that, when the problem under study is the occurring probability of a certain event, we can regard the occurring probability of the event gotten by sampling experiment as the solution of the problem. The analysis result of this method shares the most similarity with the actual situation. The concrete process of Monte-Carlo Analysis is that: firstly, building mathematics model of the material circuit; then, according to the actual situation, determining the probability distribution regularities of the component parameters near their nominal value; thirdly, realizing the random sampling of known probability distribution and establishing estimation of various statistics. Through sampling the component parameter for several times, multiple random output characteristics can be obtained. By statistically analyzing the characteristics, the square diagram can be drawn and the distribution regulation of the output characteristic can be obtained. Combining with the correlated qualification, we can analyze the regulation and then calculate the confidence level. While carrying on the circuit sampling analysis, we must pay attention that the sampling times should meet the required precision. In the actual calculation, Monte-Carlo Analysis needs to build up the mathematic model and carry out the random sampling from the known distribution, which is a very tedious process.

Tolerance distribution

The parameter tolerance distribution of a component is a method that distributes parameter tolerance of the circuit output characteristic to every component's parameter tolerance in the circuit. It is expressed mathematically by the following inequalities:

$$R_s(R_1,R_2,...,R_i,...,R_n) < R_s^*, \quad (1)$$

$$\boldsymbol{g}_s(R_1,R_2,...,R_i,...,R_n) < \boldsymbol{g}_s^*, \quad (2)$$

where R_s^* is the tolerance of the system output characteristic; $\boldsymbol{g}_s^*$ is the comprehensive constraint condition for system design, including: cost, temperature, volume, power consumption, and so on. So it is a vector function relationship; R_i is the tolerance of design variable i.

The tolerance distribution includes three contents. Firstly, according to the product's application environment or the index proposed by customer, the tolerance range of the output characteristic is determined. Then, through the circuit sensitivity analysis and tolerance analysis, utilizing Equalitarian Distribution, Proportion Unit, Weighted Distribution and other reliability distribution methods, the tolerance of the output characteristic is distributed to every component's parameter tolerance in circuit. The result is regarded as the basis for choosing component. Thirdly, there are always several solutions from the inequality above, so there must be a certain method in tolerance design to select the most reasonable optimum solution from all distribution schemes.

An important basis for circuit tolerance distribution is the circuit's sensitivity. The circuit sensitivity is the sensitivity degree of the circuit's output characteristic to each circuit component's parameter. Its definition has two forms, the absolute sensitivity and the relative sensitivity. The absolute sensitivity is defined as the change rate of the circuit output characteristic versus the component parameter (Ling, 1991). The circuit output characteristic is given as $Y=f(X_1,X_2,\ldots,X_n)$, where $X_1,X_2,\ldots,X_n$ are the parameters of n components in circuit. Then the absolute sensitivity can be expressed as

$$D_X^Y = \frac{\partial Y}{\partial X_i}, \quad i \in \{1,...,n\}. \quad (3)$$

The relative sensitivity is also called the normalized sensitivity. It is defined as the ratio between the relative variable of the circuit output parameter and the relative variable of the component parameter. Giving $X_{10},X_{20},\ldots,X_{n0}$ as the center values of n component parameters, the relative sensitivity can be expressed as:

$$S_X^Y = \frac{X_{i0}}{Y_0}\cdot\frac{\partial Y}{\partial X_i} = \frac{X_{i0}}{Y_0}D_{X_i}^Y, \quad i \in \{1,...,n\}. \quad (4)$$

The nonlinear effect is the nonlinear relation between the circuit's output characteristic and the parameter. By using the nonlinear effect in tolerance distribution, the operating point or the center point can be chosen reasonably on nonlinear curve in order to minimize the parameter's sensitivity to the output characteristic (Chen, 1999). With every parameter's sensitivity, we can distribute lesser tolerance to the component, whose sensitivity is higher, and distribute more tolerance to the component, whose sensitivity is lower. So the resource of the circuit component can be collocated efficiently and the product's performance to price ratio could be enhanced.

RELIABILITY TOLERANCE DESIGN OF ELECTRONIC PRODUCT BASED ON EDA TECHNOLOGY

As described above, the traditional tolerance design method needs to build the circuit's mathematic model and to carry on statistic calculation for many times, which involves large workload and lacks of practicability. With the development of the EDA technology, many complicated works, such as modeling and calculating, can be handled by computer. Therefore, the workload of the tolerance design can be lightened significantly. The traditional tolerance design method is simplified and adjusted with EDA simulation analysis software in this paper. The specific steps are:

(1) A suitable EDA simulation analysis software is selected, according to the characteristic of the specific electronic system design and the circuit's feature, such as a system design or a module design, an analog circuit or a digital circuit, etc.

(2) According to the application environment of the electronic product or the requirements given by customer, the confidence level, the product's correlated characteristic, the qualification of target parameters and the correlated technical requirements are

determined.

(3) The major factor affecting the target output characteristic is analyzed. According to the given constraint condition and influencing factor, the center values of the target output characteristics and correlated design variables are determined by the circuit's optimum design.

(4) By using the EDA software, the circuit schematic diagram of the electronic system is drawn and simulated. Then the simulation result is compared with the actual experiment's result to ensure the accuracy of the software's simulation. Then the sensitivity analysis to each design variable is carried on.

(5) According to the sensitivity of each design variable and the present technological level, the parameter tolerance is distributed to each design variable in circuit. Using the simulation and analysis function in EDA software, the tolerance distributed regulation of the circuit output characteristic is obtained by Monte-Carlo Analysis.

(6) The target output characteristic of the circuit is compared with other correlated product's characteristic or qualification, and the product's confidence level is calculated and judged whether it meets the technical requirements.

(7) According to the producing difficulty of correlated component, the technology's dispersivity, the price and so on, the most reasonable tolerance distribution scheme is chosen to achieve the balance between the electronic product's cost and reliability. If all feasible tolerance distribution schemes are not qualified, returning to Step (3) and the center value of the target characteristic is re-selected.

EXAMPLE ANALYSIS

Primary principle of DC hybrid contactor

The tolerance design of the DC hybrid contactor's control circuit is given as an example (Fig.1). The DC hybrid contactor's operating circumstance is the same as the contactor CZO-40 used in the locomotive. By using the power electronic device controlled by a logic controlling circuit, it is possible to achieve the switching without arc in certain conditions. The contactor's pick-up characteristic and releasing characteristic indicate a certain delay time (pick-up time and releasing time) from the controlling coil electrifying to the contact finger acting (the same as the case of power-failure of the coil) (Evans *et al*., 1999; Su *et al*., 1999). However, an arc occurs when the contact finger picks up and releases. An appropriate power electronic device (the break-over and shut-off time of power electronic device is usually microseconds or even nanoseconds) is connected in parallel with mechanical contactor. While the contactor is picking up or releasing, the power electronic device breaks over rapidly and most current flows through the power electronic device. When the contactor has picked up or released completely after its delay time, the power electronic device shuts off. This is the integrated design principle of the DC hybrid contactor (Atmadji and Sloot, 1998; Stephan and Manpred, 1985; Chen *et al*., 2005). The equipment consists of electronic control system and execution system. The former checks action time sequence and

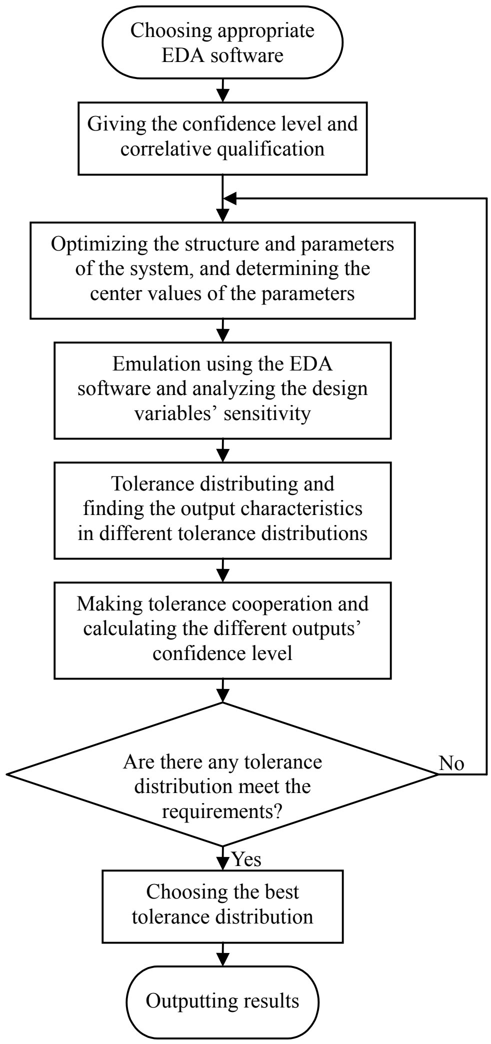

Fig.1 The flow chart of the tolerance design

gives trigger control pulse. The latter accepts trigger control and responses rapidly. The execution system is made of power electronic device and contactor connected in parallel. The primary function of the electronic control system is to time and control the power electronic device in execution system (Pter and Slobodan, 1986). Fig.2 is the principle block diagram.

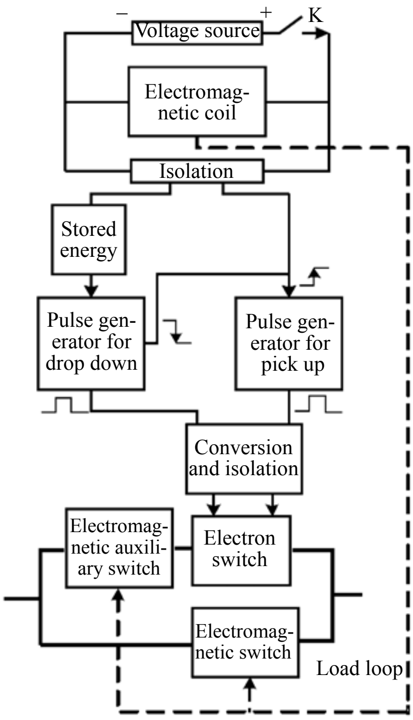

Fig.2 The principle block diagram of the DC hybrid contactor

The cooperation action between power electronic device and contactor is strictly according to the cooperation time sequence of every logic segment. Fig.3 is the time sequence controlling logic model of every segment. Taking contactor coil break-over as the acting signal, the control circuit gives a high level signal and the power electronic device conducts. The device's break-over starting time T_1 must be between the coil's electrifying time T_{on} and the contactor's pick-up time T_{cl}. After the contactor picked up, the control system outputs a low level signal and the power electronic device shuts off. The break-over end time T_2 must be longer than the pick-up time T_{cl}. Similarly, when the contactor's coil powerfails, the break-over ending time T_3 of the power electronic device must be longer than the releasing time T_{cu}. Through an optimum design of circuit parameters, the target output characteristic's center values are determined as T_1=45 ms, T_2=160 ms, T_3=110 ms.

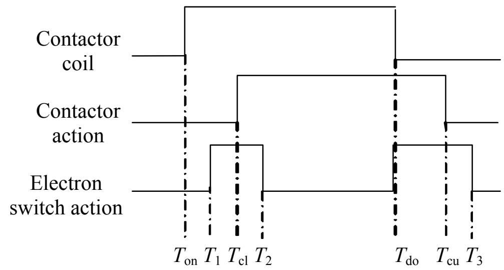

Fig.3 The action logic chart of the DC hybrid contactor

The confidence level of the system is required to be 0.9980. Because the pick-up time and releasing time of the electromagnetic switch are affected by many external environment parameters and changes of internal parameters, their dispersivity is obvious. Therefore, the fluctuation range in time sequence is obvious and the control cooperation may fail easily. As a result, every design component must be designed by tolerance method.

Circuit tolerance design

According to the workflow of electronic system's reliability tolerance design described in the third section, the tolerance design procedure is given as follows:

(1) Many EDA tool softwares with different functions are available on the market at present. Since this paper studies the electronic circuit design as an example and the trigger control circuit is D/A circuit, a software of OrCAD/PSpice, which supports D/A circuit's simulation and analysis is chosen for the tolerance design.

(2) The incontrollable variables that affect contactor action's delay time characteristic mainly are temperature, abrasion, aging, voltage fluctuation in electric network, and so on. According to the incontrollable variables above, the delay characteristic experiment of the contactor CZO-40 is done under different temperatures and different voltages. The pick-up time and releasing time of the contactors with different action times are recorded through the experiment. By curve fitting the experiment data, the distribution curves of the contactor's pick-up time T_{cl} and releasing time T_{cu} affected by every incontrollable variable are obtained (Fig.4). Both contactor characteristic distributions yield Gaussian distribution. The

mean value of pick-up time μ_{cl} is 89.8689, the standard deviation σ_{cl} is 23.2364; the mean value of releasing time μ_{cu} is 39.2687, and the standard deviation σ_{cu} is 20.8973 ms.

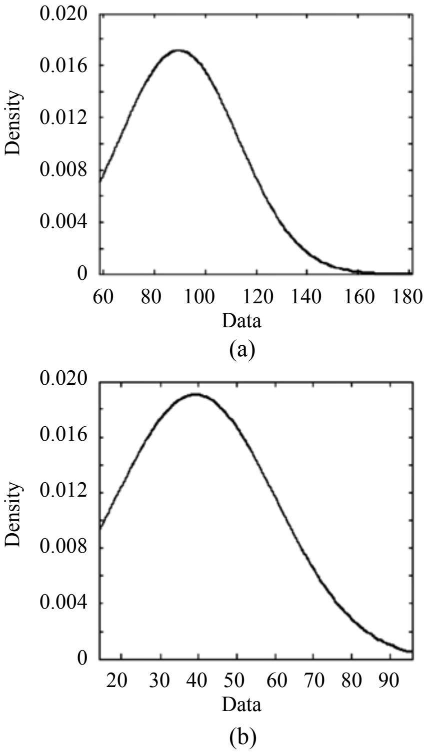

Fig.4 Distribution curve of the CZO-40 Contactor's pick-up time (a) and releasing time (b)

(3) Correlated the design variables affecting every characteristic of target, the output are determined through circuit analysis. For example, there is a "pick-up break-over" (it means the power electronic device breakovers when the contactor picks up) time T_2, and its correlated design variables are obtained that C_4=1 μF, R_{11}=300 kΩ through circuit analysis.

(4) The control circuit's schematic diagram is plotted in OrCAD/PSpice 9.2. Fig.5 is the sketch map of the power electronic device's "pick-up break-over" pulse-generating circuit. V (OUTPUT) is the output port of "pick-up break-over" impulse, which controls the break-over starting time T_1 and ending time T_2 of the power electronic device when contactor picks up. Through simulating, the output impulse's ending time is obtained as T_2=160.61 ms, which is similar to the calculated center value (T_2=160 ms).

(5) The sensitivity of the design variables C_4 and R_{11}, which affect the target output characteristic, is

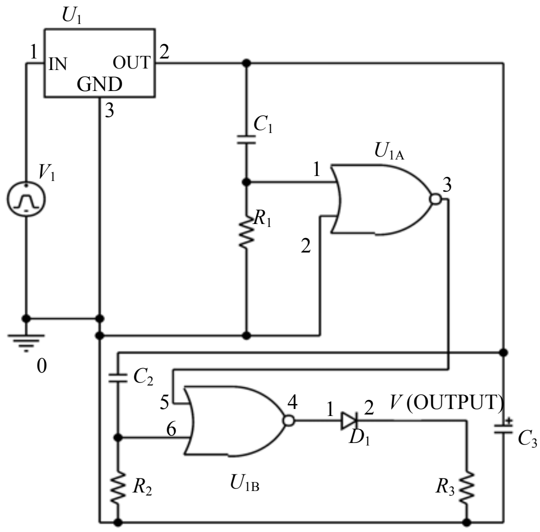

Fig.5 The schematic diagram of "pick-up break-over" pulse-generating circuit

calculated. The sensitivities of two variables are obtained by Eqs.(1) and (2), and both are S=1.027. It reveals that the two variables have the same influence on the output characteristic in this example. Since only two above variables affect the target output characteristic T_2, we can make use of the software to simulate and analyze all possible tolerance distribution schemes, and obtain the tolerance distribution of the target output characteristic rapidly and conveniently. The precisions of resistor and capacitor commonly used are: resistor 5%, 2%, 1% and 0.1%; capacitor 20%, 10%, 5%, 2% and 1%. Taking 5% for both capacitor and resistor as an example and applying Monte-Carlo Analysis of the software, the simulating and analyzing results are produced and shown in Fig.6. Fig.6a is the wave shape when contactor coil electrifies, and Fig.6b is the wave of "pick-up break-over" impulse.

Starting-up the circuit function analysis module, and statistically analyzing the target output characteristic T_2, the statistical histogram of the output characteristic is obtained (Fig.7). The statistic histogram shows the proportion of the "pick-up conducting" time T_2 in different numerical ranges. By the histogram, the target output characteristic yields to Gaussian distribution on the whole. Correlated information is given from the results of statistic analysis below the histogram: mean (μ)=161.261, sigma (σ) =7.60789, maximum (maximum in sample)=177.706, minimum (minimum in sample)=143.862 ms.

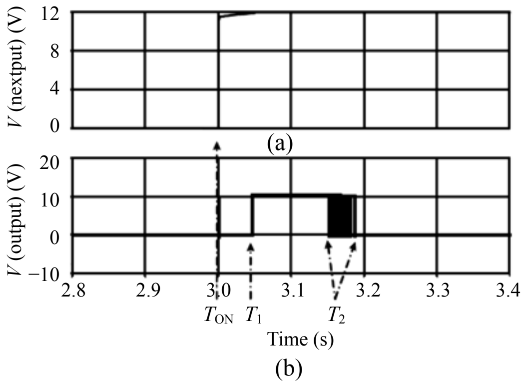

Fig.6 The impulse shape when electron switch picks up. (a) The wave shape when contactor coil electrifies; (b) The wave of "pick-up break-over" impulse

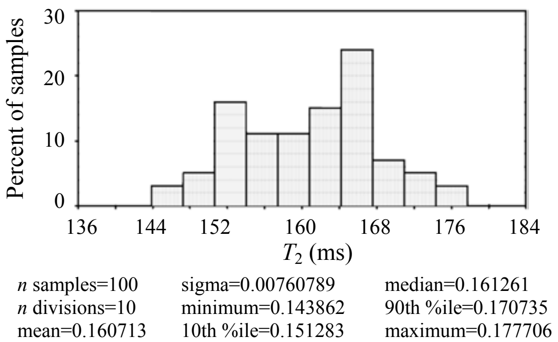

Fig.7 Statistical histogram of impulse's end-time when contactor picks up

(6) Tolerance regularity of the target output characteristic obtained by the distribution is adapted to contactor's releasing time T_{cl}, and the confidence level is calculated. The calculating method is as follows:

In Fig.8, T_{cl} and T_2 show the regularity of contactor's pick-up time and power electronic device's break-over end-time when contactor picks up. It requires that T_2 must be longer than T_{cl}. T_2 and T_{cl} both yield to Gaussian distribution, which is T_2~$N(\mu_2, \sigma_2^2)$ and Y_{cl}~$N(\mu_{cl}, \sigma_{cl}^2)$, μ_2 and μ_{cl} are mean values, and σ_2^2 and σ_{cl}^2 are standard deviations. So the $T(T_{cl}-T_2)$ also yields to Gaussian distribution, which is Y~$N(\mu, \sigma^2)$, the mean μ and the standard deviation σ are obtained as follows:

$$\mu=\mu_{cl}-\mu_2, \tag{5}$$

$$\sigma=\sqrt{\sigma_{cl}^2+\sigma_2^2}. \tag{6}$$

The reliability of the output characteristic is calculated, which is also the probability that T_2 is longer than T_{cl}. The calculating method is:

$$\begin{aligned}P(T_2>T_{cl}) &= P(T_{cl}<T_2)=P(T<0)=\int_{-\infty}^{0} t(x)\mathrm{d}x \\ &= \int_{-\infty}^{0}\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]\mathrm{d}x.\end{aligned} \tag{7}$$

Therefore, the confidence level of the target output characteristic T_2 for pick-up time T_{cl} is obtained (Forouraghi, 2000; Zhai *et al*., 2004).

According to Eqs.(5), (6) and (7), the confidence level of the power electronic device's "pick-up break-over" time is obtained: α_2=0.9983. The confidence level has met the target's requirement (confidence arm: 0.9980). The tolerance distributing method of other two target output characteristics T_1 and T_3 are the same in the above process.

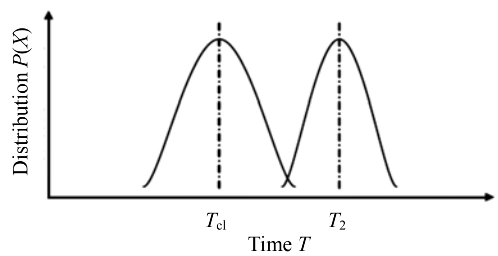

Fig.8 The distribution map of the "pick-up break-over" time and pick-up time

(7) Through Steps (5) and (6), the confidence levels in different tolerance distribution schemes are obtained. Table 1 is the confidence level of "pick-up break-over" time T_2 in every tolerance distribution scheme. All tolerance distribution schemes that reach the aim of the confidence level are given in the table. Different schemes can be chosen in the table according to the actual conditions or users' requirements. The optimal distribution scheme is chosen according to the product cost in this example. The higher the precision is, the more the component costs. So it is better to choose the components with a comparatively lower precision, which could also reach the target confidence level at the same time. From Table 1, it can be seen that both schemes, one with the precision C_4 of 5% and the precision R_{11} of 2% and another with the precision C_4 of 2% and the precision R_{11} of 5%, can reach the target confidence level. However, the resistor's prices of the two precision grades described

above are similar, while the capacitor with high precision is more expensive. Considering the product cost, the resistor with higher precision and the capacitor with lower precision should be selected. So the scheme should be the one in which the precision of C_4 is 5% and the precision of R_{11} is 2%. The choosing for other two tolerance distribution schemes of target output characteristic are the same as the process described above.

Table 1 The reliability levels in different accuracy distributions of the design variables

C	Reliability levels			
	R=5%	2%	1%	0.1%
20%	0.9927	0.9927	0.9927	0.9927
10%	0.9972	0.9993	0.9993	0.9993
5%	0.9997	0.9997	0.9997	0.9997
2%	0.9997	0.9998	0.9998	0.9998
1%	0.9998	0.9999	0.9999	0.9999

(8) Through the tolerance designing described above, the tolerance distribution schemes with the least cost have been chosen. Table 2 is the tolerance ranges and confidence levels of target output characteristics obtained through simulation. From the table, we can see that all of the center values and confidence levels of target output characteristics have met the target requirements.

Table 2 The tolerance design's result of the DC hybrid contactor's control circuit

Aid parameters	T_1	T_2	T_3
C precision	5%	5%	10%
R precision	5%	2%	5%
Center valuation μ (ms)	48.1828	161.516	115.261
Tolerance σ (ms)	3.11116	7.64489	12.3094
Qualification (ms)	<89.8689	>89.8689	>39.2987
Confidence level α	0.9999	0.9983	0.9992
Target confidence level	0.9980	0.9980	0.9980

CONCLUSION

(1) Simulating and analyzing circuit by EDA softwares, not only the workload for modeling the circuit can be obviously lightened, but also much complex calculation can be avoided.

(2) The tolerance design method based on EDA technology has led this technology into the tolerance design. Using simulation and analysis function in EDA software, the modeling and statistic calculation is simplified and adjusted, which provides a new approach for reliability tolerance design of electronic system.

(3) Using the tolerance design method described above, the tolerance design of the DC hybrid contactor's control circuit is accomplished. The simulation and analysis have validated the method for electronic product's reliability tolerance design based on EDA technology.

References

Adamantios, M., 2000. Reliability Allocation and Optimization for Complex Systems. 2000 Proceedings Annual Reliability and Maintainability Symposium, p.216-221.

Atmadji, A.M.S., Sloot, J.G.J., 1998. Hybrid switching: A review of current literature. *IEEE*, **2**:683-688.

Chen, L.Z., 1999. Robust Design. China Machine Press, Beijing (in Chinese).

Chen, L., Wang, Y.Y., Zhai, G.F., 2005. Research on technology of DC hybrid switch apparatus. *Low Voltage Apparatus*, **6**:9-13 (in Chinese).

Evans, S.A., Smith, I.R., Kettleborough, J.G., 1999. Static and dynamic analysis of a permanent magnet rectilinear Laws' relay actuator. *IEE Proc.-Electr. Power Appl.*, **146**(1):11-16. [doi:10.1049/ip-epa:19990216]

Forouraghi, B., 2000. A genetic algorithm for multiobjective robust design. *Applied Intelligence*, **12**(3):151-161. [doi:10.1023/A:1008356321921]

Ling, X.T., 1991. Tolerance Analysis and Design for Circuit Parameter. Fudan University Press, Shanghai (in Chinese).

Parkinson, D.B., 2000. The application of reliability method to tolerancing. *Journal of Mechenical Engineering*, **122**:149-154.

Pter, J.T., Slobodan, K., 1986. 270-V DC hybrid switch. *IEEE*, **9**:97-100.

Shi, J.Y., Kang, R., 2001. Research on method of circuit tolerance analysis based on EDA technology. *Journal of Beijing University of Aeronautics and Astronautics*, **27**(1):121-124 (in Chinese).

Stephan, G., Manpred, L., 1985. Commutation and erosion in hybrid contactor systems. *IEEE*, **8**:34-39.

Su, X.P., Li, Z.G., Lu, J.G., 1999. Study on the Reliability Optimization Design of Electromagnetic System in Miniature Relays. Proceedings 47th Relay Conference, **18**:2-7.

Zhai, G.F., Liang, H.M., Xu, F., Hao, Y.L., 2002. Comprehensive analysis and discussion for reliability tolerance design method of electromagnetic relay. *Low Voltage Apparatus*, **6**:12-16 (in Chinese).

Zhai, G.F., Liang, H.M., Xu, F., Liu, M.K., 2004. New method of tolerance design of electromagnetic relay reliability. *Journal of Engineering Design*, **15**(5):12-16.