EVALUATING TOLERANCE AND UNCERTAINTY OF PERFORMANCE IN ELECTRIC MACHINE BY USING STOCHASTIC SIMULATION

Young-Kyoun Kim and Jung-Pyo Hong *Senior Member, IEEE*
Department of Electrical Engineering, Changwon National University, Changwon, 641-773, Korea
ensigma@hitel.net, jphong@sarim.changwon.ac.kr

ABSTRACT

A tolerance analysis is important in electric machine industry for improving product robustness and reducing production costs. Therefore, Stochastic simulation is required to evaluate the uncertainty because the tolerance analysis requires yielding the uncertainty of design variables. This paper presents a new way of tolerance analysis using stochastic response surface methodology, which is one of the stochastic simulation methods, in electric machines.

INTRODUCTION

The design of electric machines needs to consider the proper allowance of dimensional tolerances on manufacturing them. In general, small tolerances in manufacturing processes result in increase of the production cost but large tolerances give less expensive one [1, 2]. On the other hand, dimensional tolerances of electric machines can affect their performances in the electrical point of view. Therefore, finding the proper band of tolerances are interesting to the designer and manufacturer. So, in the design stage of electric machines, the design guide of tolerances of design variables is required.

Such a tolerance is defined as uncertainty of design variables. Stochastic simulation treats usually the uncertainty of design variables as random parameters. The general method for the tolerance analysis is Monte Carlo Simulation. However, the outstanding disadvantage of this method is that it requires a great number of computations to have an acceptable precision of statistically significant results. The number of the samples will be very much, with very high computational costs.

In order to overcome this point, this paper proposes the method of the tolerance analysis by using Stochastic Response Surface Methodology (SRSM). The SRSM, which is one of the techniques of statistical approximation, approximates the output function by using a polynomial fitting and calculates specific statistical quantities of outputs [1, 3]. These quantities of both input and output uncertainty are used to define patterns of their variability and to achieve the tolerance analysis in electric machines. As an Example, Tolerance analysis using SRSM is applied to design for a synchronous generator.

CONCETP OF STOCHASTIC SIMULATION

The SRSM deals with all input parameters in terms of random variables, which has the standard normal distribution, N(0,1) [3]. The uncertainty in the i-th input of the model, x_i, is transposed properly as a function of the i-th standard random variable, ξ_i, by applying an appropriate transformation. The second order polynomial approximation of the uncertainty between the outputs and inputs is addressed by the series expansion of standard random variables in terms of polynomial chaos expansion.

$$y = a_0 + \sum_{i=1}^{n} a_i\xi_i + \sum_{i=1}^{n} a_{ii}(\xi_i^2 - 1) + \sum_{i\neq j}^{n} a_{ij}(\xi_i\xi_j) \tag{1}$$

where n is the number of standard random variables used to represent the uncertainty input in the model and the coefficients a is the unknown coefficients to be estimated.

ELEMENTARY STATISTICS FOR EVALUATING TOLERANCE

In this symmetrical distribution, the tolerance band of design variables is easy to quantify in terms of the percentage of the area that will occur between one, two or more standard deviation from the mean μ as follows [2]:

$$\Delta x = \pm n\sigma \quad (n = 1, 2, 3, \cdots) \tag{2}$$

Modeling variation of outputs according to tolerance of design variables is made by SRSM. From a set of N samples, the basic moments of the distribution of an output y_i can be calculated as follows [2]:

$$\mu_{y_i} = \mathrm{E}\{y_i\} = \frac{1}{N}\sum_{j=1}^{N} y_{i,j} \tag{3}$$

$$\sigma_{y_i}^2 = \mathrm{E}\{(y_i - \mu_{y_i})^2\} = \frac{1}{N-1}\sum_{j=1}^{N} (y_{i,j} - \mu_{y_i})^2 \tag{4}$$

$$f_{y_i y_j}(y_i, y_j) = \frac{\partial^2}{\partial y_i \partial y_j} F_{y_i y_j}(y_i, y_j) \tag{5}$$

where, μ_{yi} is a mean, σ_{yi}^2 is a variance and σ_{yi} is a standard deviation, $f_{yi,yj}(y_i,y_j)$ is a joint probability density function, $F_{yi,yj}(y_i,y_j)$ is a joint cumulative distribution function, respectively.

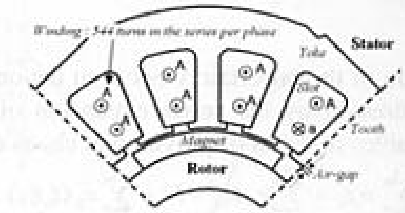
CASE STUDY FOR TOLERANCE ANALYSIS

A. *Model and Defining Design Variables Framework*

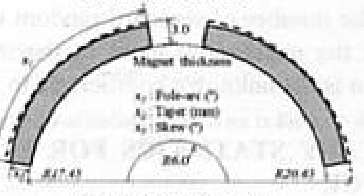
The applied machine is a single phase 200(W) symphonious generator as shown in Fig. 1 (a). The stator has 16 slots, 2 layer and short pitch (3/4) winding, and the rotor is built of 4 title of radial magnets, bonded NdFeB magnets, The no-load EMF waveform of synchronous generators is a criterion of performance assessment and the maximum distortion factor of the output voltage is specified in the literature [4]. In designing a generator, the design guide of its design variables required to evaluate the variation of the distortion factor of the output voltage. In order to apply the tolerance analysis regarding design variables on the generator, three design variables of the generator are defined as shown in Fig. 1 (b).

B. *Field Computation Framework*

The magnet field within the generator is computed using the two-dimensional finite element method (2-D FEM). The analysis domain comprises a fourth model of the whole generator and periodic conditions are used as boundary conditions of analysis model.



(a) Analysis model



(b) Design variables

Fig. 1. Analysis model of the single-phase generator

TABLE I
MOMENTS REGARDING TOLERANCE OF DESIGN VARIABLES

Section	μ_{xi}	σ_{xi} at $\Delta x_{xi} = \pm 10$ %	σ_{xi} at $\Delta x_{xi} = \pm 5$ %
Pole-arc (x_1)	72.68 (*deg.*)	2.423	1.211
Taper (x_2)	2.39 (*mm*)	0.08	0.04
Skew (x_3)	3.07 (*deg.*)	0.102	0.051

C. Framework for Evaluating Tolerance

In order to consider uncertainty of design variables, the mean (μ_{xi}) and standard deviation (σ_{xi}) of them are obtained from (2). The tolerances of design variables are regarded as 3σ and their distribution are assumed as normal distributions, and the fundamental moments of design variables are calculated with assuming uncertainty, which is 10(%) and 5(%), respectively. Table I presents the moments of design variables.

RESULTS FOR EVALUATING TOLERNACE

When the manufacturing process is running at the design variable tolerance of 10 (%) based on the three-sigma level. The joint probability distribution of the induced voltage and distortion factor is shown in Fig. 2. In order to reduce scatter of the outputs from their population, design variables need to run at a tighter tolerance than 10 (%), such as 5(%).

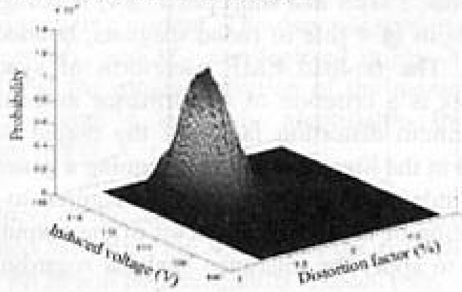


Fig. 2. Predicted joint probability distributions at the 10% tolerance

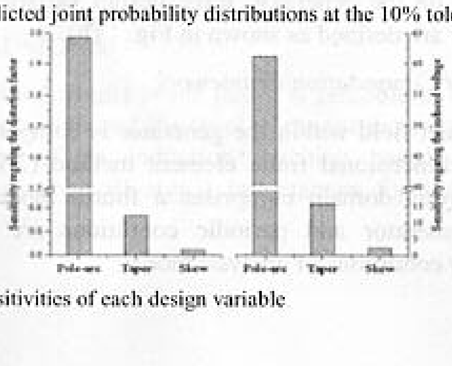


Fig. 3. Sensitivities of each design variable

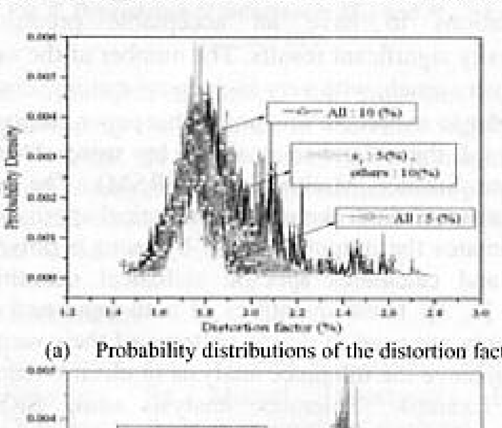
The scatter of population of outputs at the design variable tolerance of 5(%) gravitates toward the means of the outputs. However, if all design variables are regulated with tight tolerance, the manufacturing cost is increased. The sensitivity, which is obtained from variance analysis, of each effect for three design variables, is shown in Fig. 3. From the results of variance analysis, the pole-arc (x_1) needs to be controlled with a tighter tolerance than the others. The results according to running tolerances are compared with each case and then they are shown in Fig 4. These results show, when the pole-arc (x_1) is controlled with a proper tight tolerance and the tolerance of the others are is regulated with loose tolerance, the scatter of population of outputs extremely centralizes in the means of the outputs, compared that all design variables are regulated with tight tolerance.

CONCLUSION

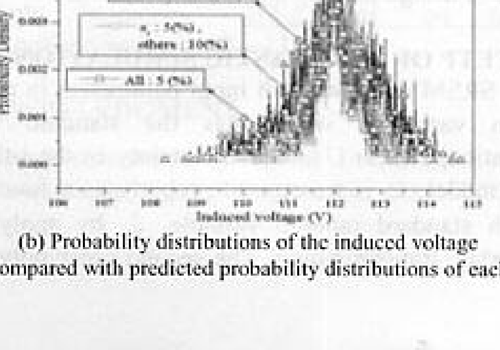
At design stage of electric machines, the design guide of tolerances is required to guarantee the robustness of the performance and to reduce the manufacturing costs on electric machines. This paper proposed the new method for the tolerance analysis and this method is applied to estimate the variation of the performance of the no-load EMF according to dimensional tolerances of design variables. The proposed technique for the tolerance design will effectively assist in predicting the variations of their performances and production quality.

REFERENCES

1. Y. K. Kim et al., 2002, Digests of CEFC'02, 64
2. C. M. Creveling, 1995, "Tolerance Design", Addison-Wesley
3. S. S. Isukapalli, et al., 1998, Risk Analysis, 18(3), 351-363
4. D. H. Im, J. P. Hong, C.E. Kim, Y. B. Jung, 1996, Nonlinear Electromagnetic Systems, *IOS Press*, 108-111



(a) Probability distributions of the distortion factor



(b) Probability distributions of the induced voltage

Fig. 4. Compared with predicted probability distributions of each cases

The IEE

Engineering the future

Fifth IEE International Conference on

COMPUTATION IN ELECTROMAGNETICS

CEM 2004

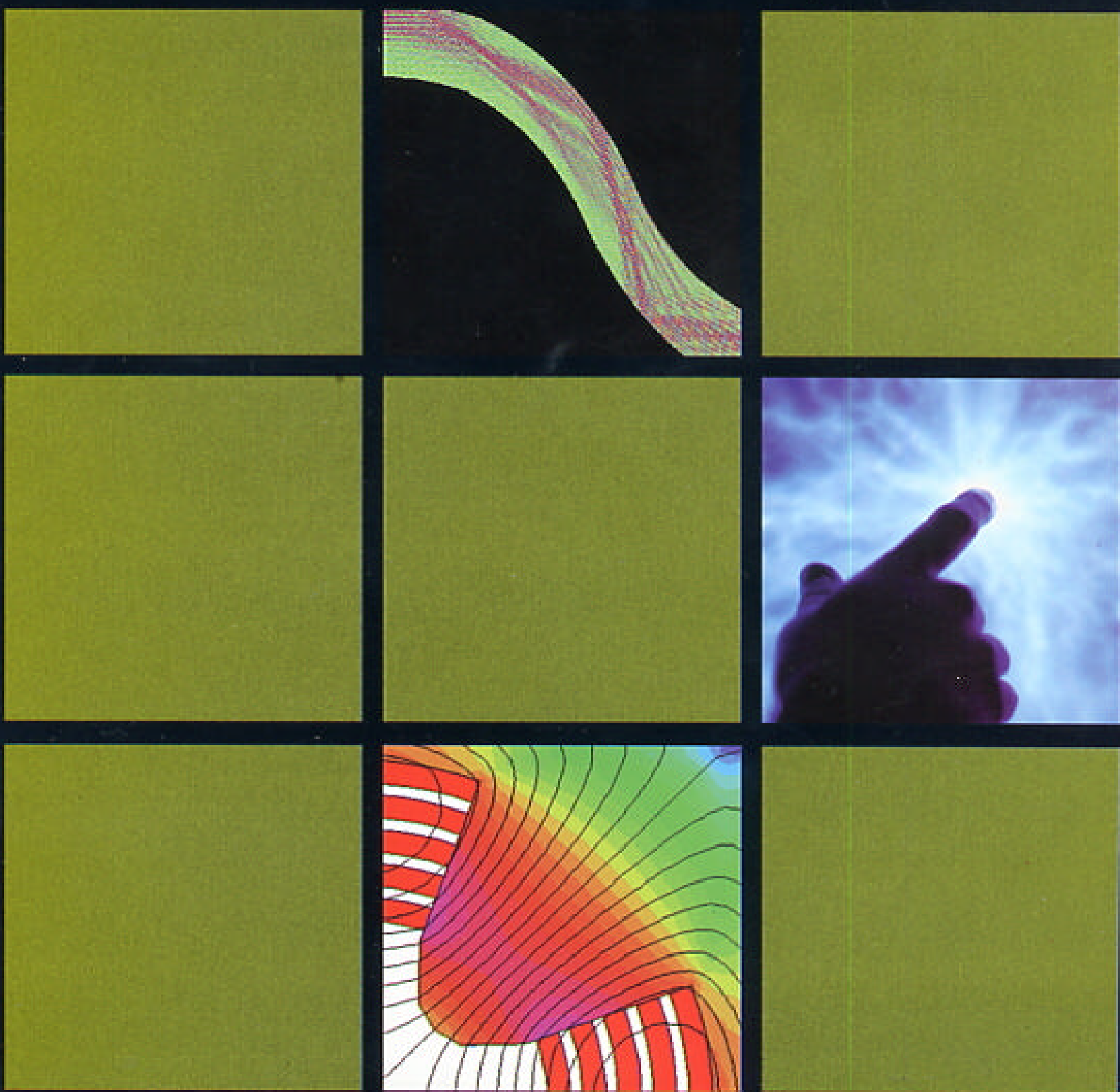
19-22 April 2004

The Alveston Manor Hotel, Stratford-upon-Avon, UK

Organised by the IEE Electromagnetics Professional Network jointly with the IEE Antennas & Propagation Professional Network and the IEE EMC Professional Network

In association with:

The International Compumag Society
ACES UK



51 **Treatment of boundary conditions in the analysis of PBG structures**
K S Thomas, M Molinari and S J Cox
University of Southampton, UK

53 **An improved method for fast frequency-sweep analysis in electromagnetics**
M Condon and C Brennan
Dublin City University, Ireland

55 **Combined analytical and numerical computation approach for design and optimization of 6-phase claw-pole alternators**
S Schulte, C Kaehler, C Schlensok and G Henneberger
Aachen University (RWTH), Germany

57 **Analysis of inductances in saturated induction machine**
M Chomat, J Necesany and I Dolezel
Institute of Electrical Engineering ASCR, Czech Republic

59 **Evaluating tolerance and uncertainty of performance in electric machine by using stochastic simulation**
Y-K Kim and J-P Hong
Changwon National University, Korea

61 **Study of inductance calculation in permanent magnet type transverse flux linear motor**
J Y Lee and J-P Hong
Changwon National University, Korea
D H Kang
Korea Electrotechnology Research Institute, Korea

63 **Low-power and high-efficiency DC brushless motor**
Z Goryca
Technical University of Radom, Poland
B Ślusarek
Tele & Radio Research Institute, Poland

65 **Physical phase variable model of PM synchronous machines for integrated motor drive applications**
O A Mohammed, Z Liu and S Liu
Florida International University, USA

67 **Design and dynamic characteristics analysis of moving magnet linear actuator considering the magnetic nonlinear phenomena**
K-H Hwang and Y-H Cho
Dong-A University, Korea
G-R Jeon and C-H Kim
Busan National University, Korea

71 **Analysis of the electric field distribution in an electrooptic sensor for pulsed high-voltage measurements**
J Rubini Jr, N M Abe and A Passaro
Centro Técnico Aeroespacial (CTA), Brazil
J C Santos
Escola Politécnica da USP - PEA, Brazil

73 **Design and performance of magnetic torque couplers and gears**
M H Nagrial and J Rizk
University of Western Sydney, Australia