INFLUENCE OF RANDOM VARIABLES ON TRANSFORMER INRUSH CURRENT

L. PIERRAT,*, T. TRAN-QUOC*,****

* Laboratoire d'Electrotechnique de Grenoble
BP. 46, 38402 Saint Martin d'Hères Cedex - FRANCE

** Electricité de France, Division Technique Générale
37 Rue Diderot, 38040 Grenoble Cedex - FRANCE

ABSTRACT- This paper studies influences of random variables such as switching angle and remanent flux on transformer inrush current. In order to study this problem, a model for determination of instantaneous magnetization characteristics of transformers (saturation and hysteresis loop) by taking into account only the measured rms voltages, rms currents and power losses is presented. A uniform probability distribution function is assumed for the switching angle and the remanent flux. By using Monte-Carlo simulation techniques, the influence of these random variables on inrush current is investigated.

I. INTRODUCTION

Industrial and public power systems necessary include a great number of transformers. The switching of these transformers can produce highly distorted inrush currents in the network. Computation of transformer inrush current offers important data for power systems operation, protection and internal transformer phenomena. Since inrush currents result from transient phenomena, it is difficult to accurately observe and analyze.

Inrush current is determined, on the one hand, by the transformer characteristics, on the other hand, by initial electric and magnetic conditions before connection of transformer to the network. These conditions are linked to magnetic nonlinearity of transformer, i.e. to saturation and hysteresis. Several methods have been developed to predict inrush current by using analytical formulation and numerical simulation [1-7].

The switching angle (α) and the remanent flux (λ_T) have an impact on the transformer inrush current. Since the angle of the applied voltage and remanent flux are not known at the instant the transformer is energized, the switching angle and remanent flux are considered random variables. Influence of random variables such as occurrent moment of short-circuit and remanent flux on transient performance of protective current transformer has been presented in [8].

This paper studies influences of random variables on transformer inrush current. In order to study this problem, a model for determination of instantaneous magnetization characteristics of transformers (saturation and hysteresis loop) by taking into account only the measured rms voltages, rms currents and power losses is presented. A uniform probability distribution function is assumed for the switching angle and the remanent flux. By using Monte-Carlo simulation techniques [9], the influence of these random variables on inrush current is investigated.

II. PROPOSED MODEL

A single phase equivalent circuit of a transformer can be shown in Fig. 1. The magnetizing part of transformer can be represented by a nonlinear inductance in parallel with a nonlinear resistance. The nonlinear inductance represents saturation part, and the nonlinear resistance represents hysteresis part.

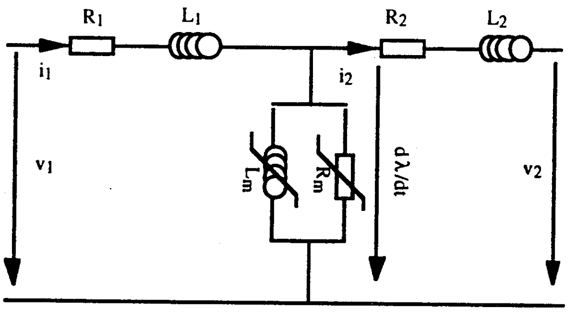

Fig. 1. Single-phase equivalent circuit of a transformer.

From measured rms voltages, rms currents and power losses, the main saturation curve and the equivalent hysteresis loops are obtained. The required data for the present method are easily available from the final test in the manufacturer's report [1, 8, 10-14].

In a no-load test transformer, the rms voltages, currents, and core losses are measured in low voltage winding (ex: in secondary winding). In this case, the magnetizing current i_0 is equal to the secondary current i_2. The total current i_0 comprises two parts: the main saturation current i_s and the hysteresis current i_h (current of loss part). The main saturation flux-current curve $i_s = f(\lambda)$ can be represented by a pth odd order polynomial:

$$i_s = A_1 \lambda + A_p \lambda^p \qquad p = 3, 5, 7 \ldots \tag{1}$$

The hysteresis current $i_h = f(\lambda, d\lambda/dt)$ is determined by a qth even order polynomial:

$$i_h = \left\{ D_0 + D_q \left(\frac{d\lambda}{dt} \right)^q \right\} \frac{d\lambda}{dt} \qquad q = 2, 4, 6 \ldots \tag{2}$$

From (1) and (2) the magnetizing current can be determined by:

$$i_0 = A_1 \lambda + A_p \lambda^p + \left\{ D_0 + D_q \left(\frac{d\lambda}{dt} \right)^q \right\} \frac{d\lambda}{dt} \tag{3}$$

Where λ is flux linkage; A and D are sets of constants and these constants will be determined from the measured data by using the least squares curve fitting method [8, 14, 15].

This method allows to obtain a complete magnetization characteristic (saturation and hysteresis) for any voltage level. A set of experimental data leads to a unique solution that respects energy constraints imposed by the model.

By using the method suggested, the saturation characteristics and hysteresis loops of a 2 kVA, 150/150 V, single phase 50 Hz transformer [14], are computed. From measured rms voltage-current and power losses-voltage, the v - i_h curve is calculated. This curve represents the current through in the branch (R_m) in function of the maximal applied voltage.

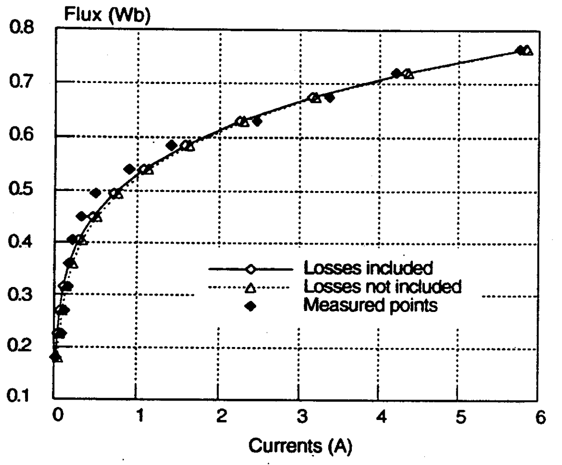

Fig. 2. λ - i_s main instantaneous saturation curves.

From the rms total current (i_0) and the rms hysteresis current (i_h), the rms saturation current (i_s) is obtained. From the rms saturation current and the measured voltages, the main instantaneous saturation λ- i_s curve is obtained (Fig. 2). Fig. 3 shows static hysteresis loops of the transformer at six different applied rms voltages: 0.46, 0.6, 0.73, 0.86, 1.0, 1.13 pu.

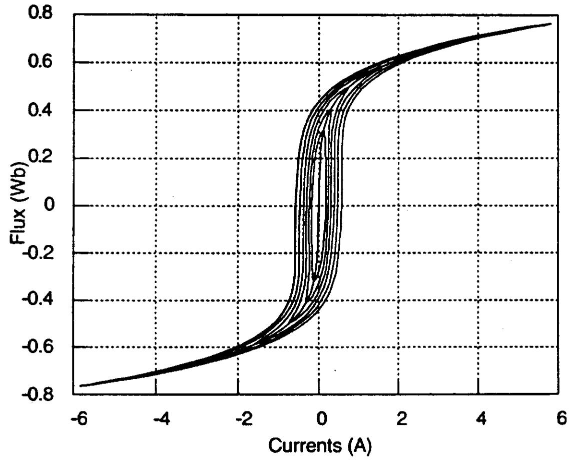

Fig. 3. Static hysteresis loops of transformer.

III. INFLUENCE OF RANDOM VARIABLES ON INRUSH CURRENT

III.1. Simulation conditions

The inrush current of the single-phase transformer is shown in Fig. 4 with a particular values of switching angle and remanent flux (α=36.4°, λ_r=0.87 pu).

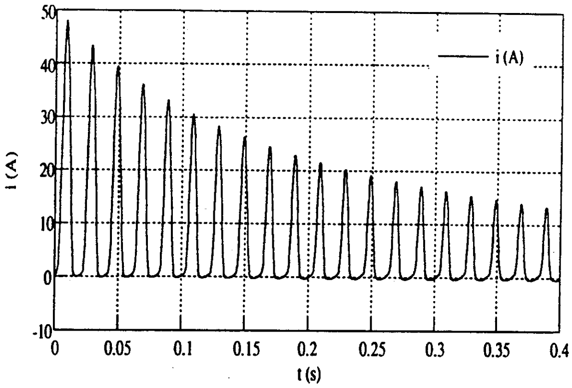

Fig. 4. Inrush current at a particular value of switching angle and remanent flux.

Due to damping, the highest inrush current magnitude corresponds to the first peak current in Fig. 4. Since switching angle and remanent flux are random variables, this maximum inrush current magnitude is also a random variable. In order to study protective coordination of transformer, it is necessary to know random distribution of this magnitude.

A uniform probability distribution function (pdf) is assumed for the switching angle (α) and the remanent flux (λ_r). The remanent flux varies between -1.0 and +1.0 pu, the switching angle varies in the range ±180°. pdfs of switching angle and remanent flux are generated by using the Monte-Carlo simulation technique [9]. With the help of two independent random generators, simultaneous influences of the switching angle and residual flux on inrush current are studied.

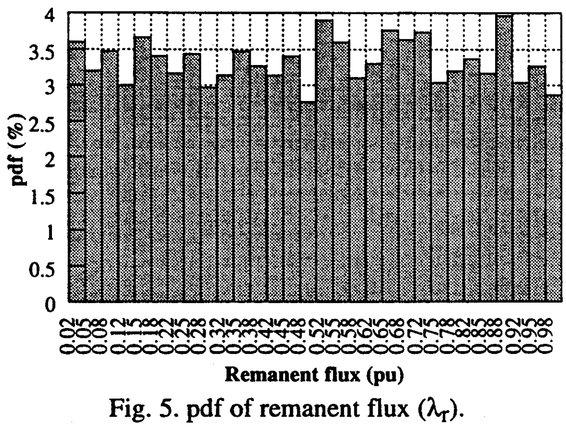

Fig. 5. pdf of remanent flux (λ_r).

Fig. 5 shows a uniform probability distribution of remanent flux obtained by random generator (about 3000 samples). It is the same for a uniform probability distribution of switching angle.

The Monte-Carlo simulation has a general characteristic; it permits to obtain at the same time pdf of α and λ_r, as well as deterministic relation between 4 variables (i, λ, α and λ_r).

III.2. Influence of switching angle (α)

With the help of the random generator for α, the influence of switching angle on maximum inrush current magnitude is shown in Fig. 6. In addition, Fig. 7 shows the influence of switching angle on flux; this internal variable characterizes saturation level in the magnetic core. This shows that the inrush current and the flux reach maximum values at $\alpha = k\pi$ ($k = 0, 1, 2...$).

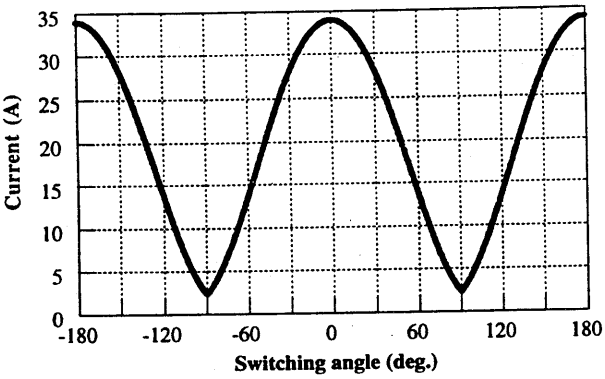

Fig. 6. Inrush current according to switching angle.

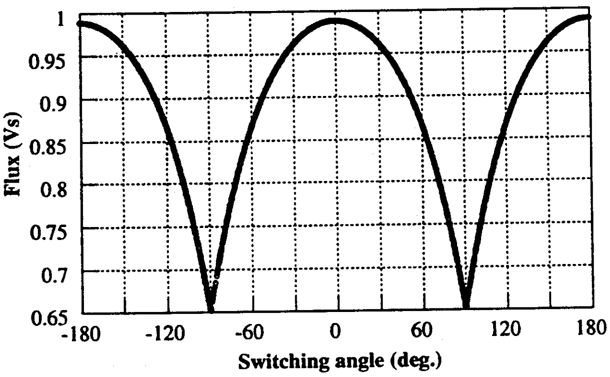

Fig. 7. Flux magnitude according to switching angle.

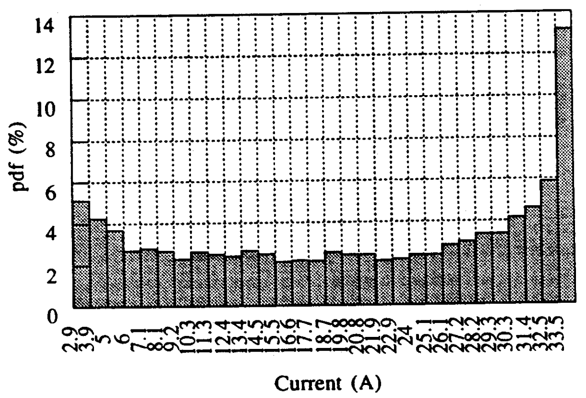

Fig. 8. pdf of inrush current.

Figs. 8 and 9 show the probability distribution functions of inrush current and flux magnitudes according to random switching angle.

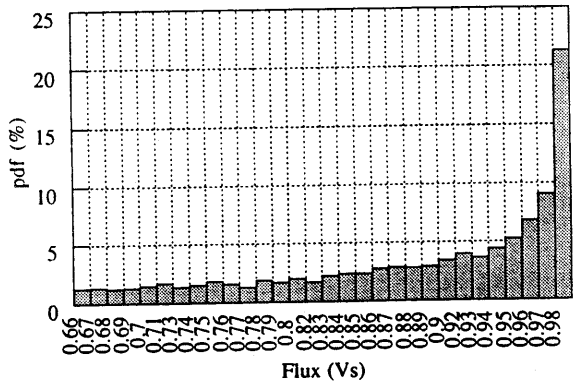

Fig. 9. pdf of flux magnitude.

III.3. Influence of remanent flux (λ_r)

The residual flux λ_r of transformer will either improve or worsen the inrush current.

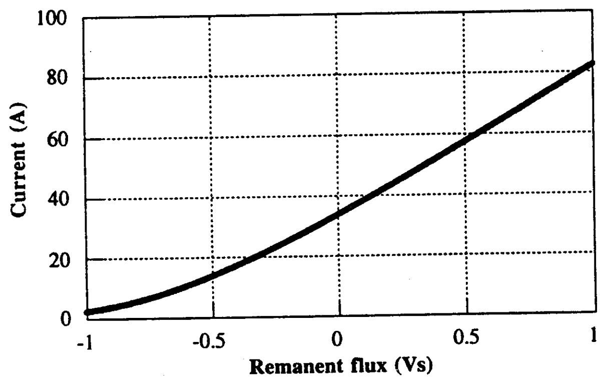

Fig. 10. Inrush current according to remanent flux.

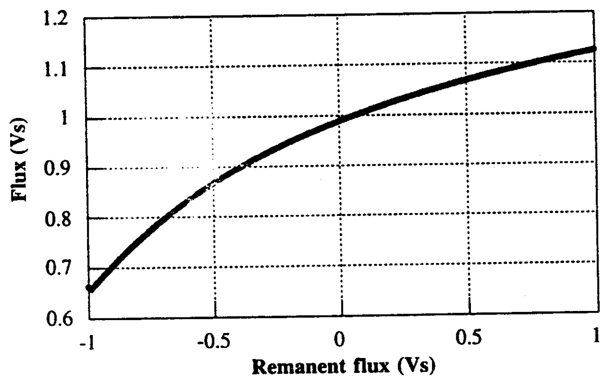

Fig. 11. Flux magnitude according to remanent flux.

With the help of the random generator, influence of residual flux on inrush current and flux magnitudes is shown in Figs. 10 and 11, respectively. This shows that when the remanent flux increases, the inrush current magnitude and the flux magnitude increase.

Figs. 12 and 13 show the probability distribution function of inrush current and flux magnitudes, respectively.

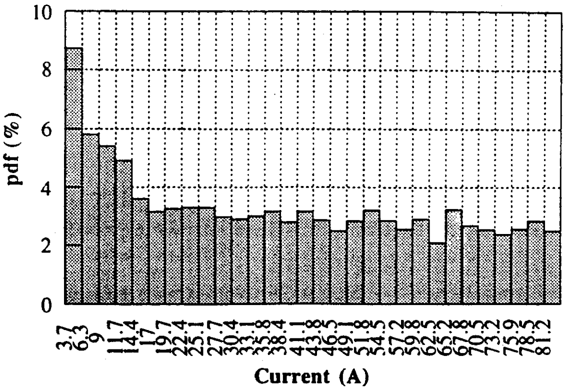

Fig. 12. pdf of inrush current.

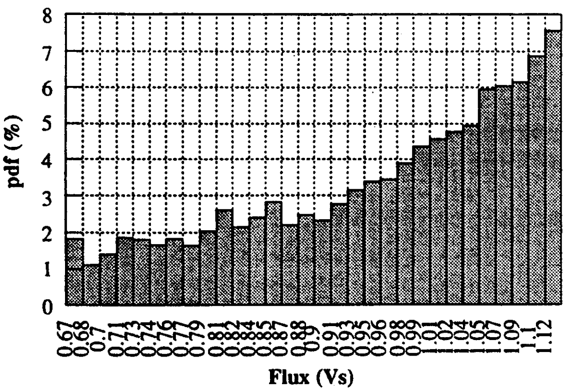

Fig. 13. pdf of flux magnitude.

III.4. Simultaneous influence of switching angle (α) and remanent flux (λ_r)

With the help of two independent random generators, influences of the switching angle and residual flux on inrush current and flux magnitudes are shown in Figs. 14- 17, respectively. Density of points in Figs. 14-17 corresponds to occurrence probabilities. Deterministic envelope curves of Figs. 14- 17 correspond to Figs. 6, 7 and 10, 11. This inllustration permits to explain the simultaneous influence of two random variables (α, λ_r).

Figs. 18 and 19 shows the pdfs of magnetizing current and flux magnitudes.

The results show that when the occurrence moment of short-circuit varies between -180° and +180° and the residual flux varies between -1 and +1 pu, the probability of magnetizing current being higher than 2.6 pu is negligible.

We can observe that, due to simultaneous random variation of α and λ_r, the flux magnitude is near an uniform distribution, the maximum inrush current magnitude is near an asymmetrical exponential distribution. These distributions are strictly bounded.

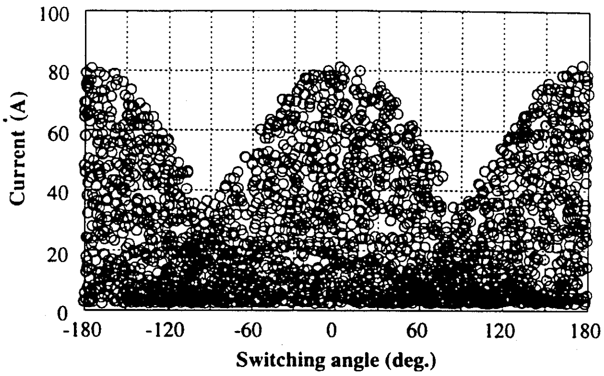

Fig. 14. Inrush current according to switching angle.

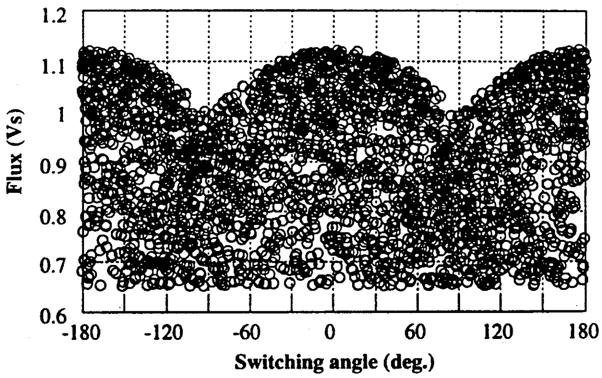

Fig. 15. Flux magnitude according to switching angle.

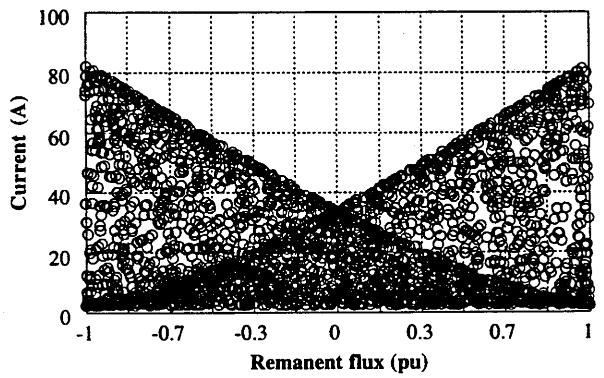

Fig. 16. Inrush current according to remanent flux.

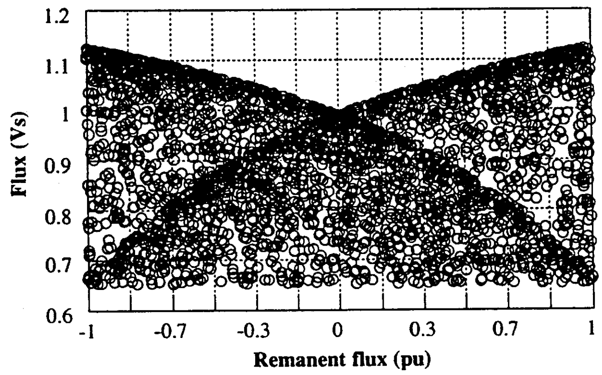

Fig. 17. Flux magnitude according to remanent flux.

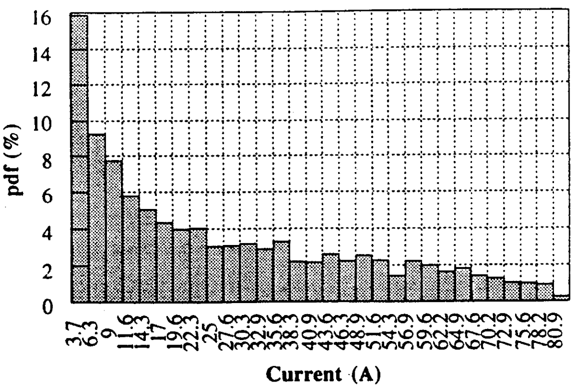

Fig. 18. pdf of inrush current.

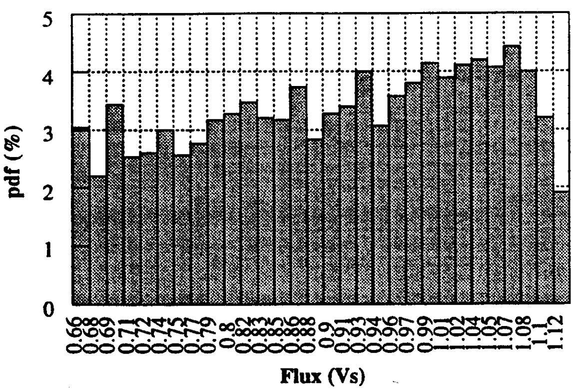

Fig. 19. pdf of flux magnitude.

IV. CONCLUSION

The proposed method permits to simulate accurately transient characteristics of inrush current. By using Monte-Carlo simulation techniques, the influence of random variables on inrush current has been studied. The results have a practical value because uniform variation of random variables (remanent flux and switching angle) covers a wide range of influence factors.

V. REFERENCES

[1] H.W. Dommel, Electromagnetic Transient Program Reference Manual, Section 6, *Department of Electrical Engineering - The University of British Columbia*, Vancouver, 1986.

[2] R. Yacamini, A. Abu-Nasser, "The Calculation of Inrush Current in Three-phase Transformers," *IEE Proc.*, Vol.133, Pt.B, No. 1, Jan. 1986, pp. 809-811.

[3] H.L. Nakra, T.H. Barton, "Three Phase Transformer Transients," *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-93, No. 6, November /December 1974, pp. 1810-1819.

[4] J.G. Frame, N.Mohan, T.Liu, "Hysteresis Modelling in an Electromagnetic Transient Program," *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-101, No. 9, September 1982, pp. 3403-3412.

[5] E.P. Dick, W. Watson, "Transformer Models for Transient Studies Based on Fiel Measurements," *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-100, No. 5, September 1980, pp. 809-811.

[6] D.N. Ewart, "Digital Computer Simulation Model of a Steel-Core Transformer," *IEEE Trans. on Power Delivery* Vol. 1, No. 3, July 1986, pp. 174-183.

[7] D. Dolinar, J. Pihler, B. Grocar, "Dynamic Model of a Three-Phase Power Transformer," *IEEE Trans. on Power Delivery* Vol. 8, No. 4, October 1993, pp. 1811-1819.

[8] T. Tran-Quoc, L. Pierrat, "Influence of Random variables on Protective Current Transformer Transient Performance," *IEEE/ICDS'95*, Texas, USA, April 1995.

[9] R.Y. Rubinstein, Simulation and the Monte Carlo Method, *Jonh Wiley & Sons*, 1981.

[10] W.L.A. Neves, H.W. Dommel, "On Modelling Iron Core Nonlinearities," *IEEE Trans. on Power Systems*, Vol. PWRS-8, May 1993, pp. 417-425.

[11] W.L.A. Neves, H.W. Dommel, "Saturation Curves of Delta-Connected Transformers from Measurements," *IEEE/PES 1994 Summer Meeting*, San Francisco, CA, July 24-28, 1994.

[12] S. Prusty, M.V.S. Rao, "A Direct Piecewise Linearized Approach to Convert rms Saturation Characteristic to Instantaneous Saturation Curve," *IEEE Trans. on Mag.*, Vol. Mag-16, No. 1, January 1980, pp. 156-160.

[13] C.E. Lin, C.L. Cheng, C.L. Huang, J.C. Yeh, "Investigation of Magnetizing Inrush Current in Transformers," *IEEE/PES, 1992 Winter Meeting*, New York, January 26-30, 1992, Paper 92 WM 246-9 PWRD.

[14] L. Pierrat, T. Tran-Quoc, "New Method for Modelling Magnetization Characteristics of Transformers by Including Hysteresis," ICEM'94, Paris, France, Sept. 1994.

[15] T. Tran-Quoc, L. Pierrat, "An Efficient Non Linear Transformer Model and Its Application to Ferroresonance Study," *IEEE/CEFC'94*, Aix Les Bains, France, July 1994, to be published in IEEE Trans. on Magnetics, May 1995.