A Novel Approach to Evaluation of Magnetizing Circuit Parameters in Transformers by Using PSPICE

S. Cundeva, L. Petkovska, M. Cundev
"Sts. Cyril & Methodius" University
Faculty of Electrical Engineering
Skopje, Macedonia

Abstract - **The paper deals with a methodology for determination of the magnetizing circuit parameters of a transformer. The methodology is described in full for a general case of a loaded transformer. Later it is used for determination of the magnetizing circuit parameters of a spot resistance welding transformer. However, the procedure is applicable to any power transformer for parameter evaluation. The steady-state parameters of the spot resistance transformer are determined by using the PSPICE simulation transformer model. The simulated results fit very well with the correspondent derived from the measurements over the actual transformer. The PSPICE transformer model shows non-accuracy during an inrush transient. The time variation of the magnetizing parameters during the fist period of the inrush transient is calculated numerically. Some directions for further investigation are addressed.**

Keywords: Transformer model, Magnetizing circuit parameters, PSPICE, Steady-state, Transient

I. INTRODUCTION

The PSPICE transformer model has been proved to represent accurately the phenomena happening in a single phase power transformer in the case of steady-state [1,2,3]. The model is not restricted to sinusoidal shapes only, but also in the case when the currents are non-sinusoidal and discontinuous the simulation results are very accurate. The model is reliable in transients as long as the core is not driven into saturation [1,2].

The model takes into account the hystersis behaviour of the transformer core. It can predict the following nonlinear effects: initial permeability, saturation of magnetization, hystersis and dynamic core losses [3].

The PSPICE transformer model could serve in the creation of an accurate simulation represent of a real power transformer. Afterwards the model could be used to predict the transformer behaviour over a wide range of working conditions.

In this paper a PSPICE transformer model of a real spot resistance welding transformer is derived. The abilities of the simulation model are used to evaluate the magnetizing circuit parameters of the unloaded transformer in case of steady-state and during inrush transient. In steady-state, the results from the computer simulation are compared with the corresponding from the measurements, while for the case of inrush transient comparison is made between the simulated results and the numerically calculated.

II. TRANSFORMER MODELS

A. *Mathematical model of a loaded transformer*

An ordinary transformer, comprehending a welding transformer, too, is consisted of at least two, or more coils i.e. windings, which are coupled magnetically. The mathematical model of the transformer, assuming to be loaded, is shown in Fig. 1.

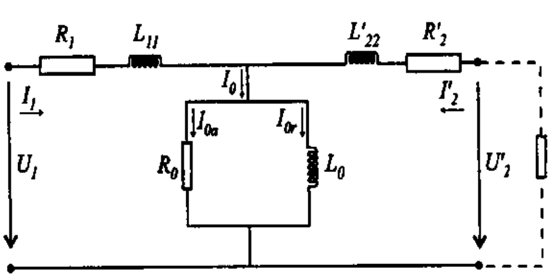

Fig. 1 Equivalent T-circuit of a loaded transformer

The resistance R_1 and R_2 are accounted for the ohmic losses in the windings caused by the finite conductivity of the conductors. L_{11} and L_{22} are the leakage inductances of the primary and the secondary winding, respectively. The voltages u_1 and u_2, are imposed and obtained voltages at the terminals of the transformer, respectively. These quantities are mutually related by the following voltage balance equations:

$$\begin{aligned} u_1 &= R_1 \cdot i_1 + L_{11}\frac{di_1}{dt} + N_1\frac{d\Phi}{dt} \\ u_2 &= R_2 \cdot i_2 + L_{22}\frac{di_2}{dt} + N_2\frac{d\Phi}{dt} \end{aligned} \qquad (1)$$

where Φ is the mutual flux in the core linking the two transformer windings.

The emfs of the two windings are described by:

$$\begin{aligned} e_1 &= -N_1\frac{d\Phi}{dt} \\ e_2 &= -N_2\frac{d\Phi}{dt} \end{aligned} \qquad (2)$$

where N_1 and N_2 are the number of turns of the transformer windings. The magnetizing circuit is presented as a parallel connection of the magnetizing inductance L_o and the magnetizing reactance R_o. The magnetizing current is presented by its component: the active component of the magnetizing current I_{oa} flows through the resistance and the reactive component I_{or} flows through the inductance.

B. *Transformer model in PSPICE*

The transformer simulation model is carried out by using the PSPICE package [4]. The Jiles-Atherton hysteresis core model [5] is a part of this package. This model accounts for the following nonlinear effects: initial permeability, saturation of magnetization, hystersis and dynamic core losses [3].

The equivalent circuit of the PSPICE transformer model is presented in Fig. 2.

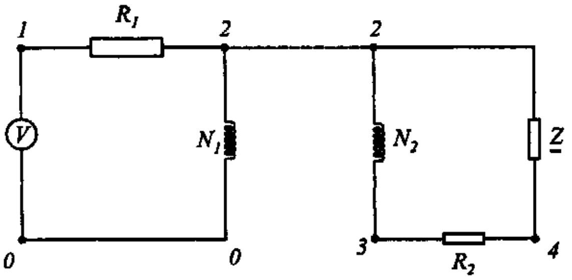

Fig. 2 PSPICE model of a loaded transformer

The magnetizing circuit is shown in different form, as in Fig. 1. It is defined through the "CORE" PSPICE statement. The coils are becoming *"windings"*, so the inductances are specified with the number of turns [3]. The Jiles-Atherton hysteresis model [5] is used for generation and analyses of the B-H curve of the magnetic core in the transformer, calculating the inductance and the flux for each winding.

III. METHODOLOGY EVALUATION

The procedure which follows is concerned with the most general case of evaluation of the magnetizing circuit parameters. It describes the methodology for a loaded transformer being the most general case of different working conditions. The case of an unloaded transformer is just a special case where there is no secondary current.

The methodology is described for the mathematical model of a transformer and for the PSPICE model, too.

The following assumptions were made:

- the instantaneous iron losses are defined through the relation:

$$p_{Fe} = e_1 \cdot i_o \qquad (3)$$

- the current in the magnetizing circuit is defined as:

$$i_o = i_1 + i_2^{'} = i_1 + \frac{i_2}{K_T} \qquad (4)$$

where K_T is the transformer ratio

$$K_T = \frac{e_1}{e_2} = \frac{N_1}{N_2} \qquad (5)$$

From the comparison of the two models, the equivalent circuit in Fig. 1 and the PSPICE model in Fig. 2, the following relations are valid respectively:

- the instantaneous power in the transformer core is:

$$\begin{aligned} p_{Fe} &= e_1 \cdot i_1 - e_2 \cdot i_2 \\ p_{Fe} &= v(0,2) * i(r1) - v(3,2) * i(r2) \end{aligned} \qquad (6)$$

- the average power i.e. the core losses is:

$$\begin{aligned} P_{Fe} &= \frac{1}{T}\int_0^T p_{Fe}(t)dt = avg(p_{Fe}(t)) \\ P_{Fe} &= avg(v(0,2) * i(r1) - v(3,2) * i(r2)) \end{aligned} \qquad (7)$$

- the apparent power is:

$$\begin{aligned} S_{Fe} &= U_1 \cdot I_1 - U_2 \cdot I_2 \\ S_{Fe} &= rms(v(0,2)) * rms(I(r1)) - \\ &\quad - rms(v(3,2)) * rms(i(r2)) \end{aligned} \qquad (8)$$

- the reactive power is:

$$Q_{Fe} = \sqrt{S_{Fe}^2 - P_{Fe}^2} \qquad (9)$$

- the current in the magnetizing circuit is:
- the active component

$$I_{oa} = I_o cos\varphi_o = I_o \cdot \frac{P_{Fe}}{S_{Fe}} \qquad (10)$$

- the reactive component, i.e. the transformer magnetizing current

$$I_{or} = I_o \sin\varphi_o = I_o \cdot \frac{Q_{Fe}}{S_{Fe}} = I_\mu , \qquad (11)$$

- parameters of the magnetizing circuit
- the resistance

$$R_o = \frac{E_o^2}{P_{Fe}} = \frac{E_o}{I_{oa}} = \frac{E_1}{I_{oa}} \qquad (12)$$

- the reactance

$$X_o = \frac{E_o^2}{Q_{Fe}} = \frac{E_o}{I_{or}} = \frac{E_1}{I_{or}} \qquad (13)$$

The equations from (1) through (11) determine the magnetizing circuit parameters accounted in serial connection, as well. Signing the serial resistance as R_m and the serial reactance as X_m, they are determined by the relations (14) and (16) respectively:

$$R_m = \frac{P_{Fe}}{I_0^2} \tag{14}$$

$$Z_m = \frac{E_0}{I_0} \tag{15}$$

$$X_m = \sqrt{Z_m^2 - R_m^2} \tag{16}$$

Note that the PSPICE program has options to calculate accurately rms, average and instantaneous values of the time varying functions.

IV. APPLICATION OF THE METHODOLOGY

The described methodology in section III is given in its most general case. It could be applied for parameter evaluation of a loaded transformer, and for unloaded as well. The methodology is valid for steady-state operation of a transformer, and for transient operation with some assumptions described later in the paper.

However in this paper the methodology has been applied for a less general case i.e. for unloaded transformer. Note that in such case there is no secondary current and the primary current is equal to the unloaded current.

A spot resistance welding power transformer has been used for application of the proposed methodology.

The tested transformer has the following rated data:

primary voltage: 380 V
secondary voltage: 2.53 V
full rated power : 20.4 kVA
rated frequency: 50 Hz
number of primary turns: 150
number of secondary turns: 1

The magnetizing circuit parameters of the unloaded transformer have been determined in the case of steady-state and during inrush transient. Only the first period of an inrush transient occurring for the most unfavorable instant of switching has been investigated. The parameters have been evaluated by the PSPICE program and for the cases where the first shows inaccuracy a numerical approach has been applied.

The section V is devoted to the PSPICE results and section VI to the numerical results.

V. PSPICE EVALUATION OF PARAMETERS

A. *Derivation of the PSPICE transformer model*

The methodology for derivation of an accurate PSPICE simulation model of an actual transformer, is described in [2,6,7].

The procedure of deriving the transformer simulation model presented in Fig. 2, requests a set of initial measurements to be done over the welding transformer.

The following transformer resistances have been found:

resistance of the primary circuit: 0.309 Ω
resistance of the secondary circuit: 465 μΩ
load reactive impedance: 1.27 μΩ

It should be emphasized hereby that all the transformer resistances in the simulation model are included as concentrated.

The following geometrical parameters that the PSPICE core model requires, have been found:

mean magnetic cross section AREA = 110 cm^2
mean magnetic path length PATH = 45 cm
effective air-gap length GAP = 0.0015 cm
pack factor PACK = 0.99

The theoretical CORE parameters have been determined from the measured hysteresis loop through a significant number of iterations. The iteration process is over when the simulated loop, described with the above defined measured geometrical and adjusted theoretical parameters, is as close to the measured loop.

The following theoretical parameters have been found:

magnetization saturation MS = 2.05E6 [amp/meter]
thermal energy parameter A = 220 [amp/meter]
domain flexing parameter C = 0.4
domain anisotropy parameter K = 330 [amp/meter]
interdomain coupling parameter ALPHA = 2.6E-4

B. *Assessment of the accuracy*

At the beginning, the results from the measurements and the PSPICE simulation of the hysteresis loop have been compared for the case of unloaded transformer. On the basis of the hysteresis shape similarities obtained both by measurements and simulation, the core model has been preliminary proved as accurate.

A selection of the measured and the simulated results is presented in Table 1. The simulated hysteresis magnetic properties and magnetizing current show a very good agreement with the measurements. Thus the reliability of the model is proved once more.

Afterwards, the model has been assessed in case when the welding transformer is under load. The results from the simulation have been compared with the corresponding from the measurements. Some of the more interesting electrical quantities and characteristics are presented in Table 2. The results and the calculated errors, show reasonable accuracy of the proposed model.

All the results obtained by the assessment of the transformer PSPICE simulation model fit excellent with the measurements.

This fact proves the exactness of the simulation model.

From that point on, the model is seen as an accurate represent of the real transformer under consideration and can be further used to analyze the behaviour of the real one operating over a wide range of load and working conditions.

Table 1: Comparison of measured and simulated magnetic properties

value	measurement	simulation	relative error %
magnetizing current magnitude [A]	1.04	0.99	-4.8
saturation induction [T]	1.064	1.04	-2.2
field at loop tip [A/m]	346.4	332.2	-4.1
remanence [T]	0.688	0.67	-2.6
coercivity [A/m]	120.2	90.7	-24.5

Table 2: Comparison of simulated and measured electrical characteristics of a loaded transformer

value	I_1 [A]	$U_{2,0}$ [V]	I_2 [A]	P_1 [W]	P_2 [W]	S_1 [VA]	S_2 [VA]
simulation	27	2.51	3998	7445	7345	10103	10076
measurements	28.44	2.62	4279	8596	8523	11602	11225
relative error %	-5.0	-4.2	-6.6	-13.4	-13.8	-12.9	-10.2

C. *Evaluation of the steady state circuit parameters*

Following the described methodology in III the magnetizing circuit parameters have been evaluated. The circuit parameters considered in parallel connection R_o and X_o have been determined by the relations (12) and (13) respectively, while the parameters considered in serial connection R_m and X_m have been determined by the relations (14) and (16). The results from the measurements and the simulation are presented in Table 3.

Table 3: Comparison of simulated and measured magnetizing circuit parameters

value	simulation	measurements	relative error %
R_o [Ω]	1489	1445	3.0
X_o [Ω]	707	763	-7.3
R_m [Ω]	294	315	-6.6
X_m [Ω]	585	597	-2.0

The calculated errors in % given in Table 3 prove the accuracy of the approach for evaluation of the magnetizing circuit parameters in transformers. Thus the proposed methodology is proved as accurate for steady state conditions. The results show that despite the fact that the PSPICE model does not include the magnetizing circuit of the transformer in the explicit form, its parameters could be evaluated. The parameters could be considered in parallel connection, as well as in serial.

D. *Evaluation of the parameters during inrush transient*

The derived transformer model and the proposed methodology for parameters evaluation have been applied in the case of inrush transient. Applying to the unloaded simulation transformer model a sinusoidal voltage wave which starts at zero point has performed the inrush transient. In the model no remanence stored in the core has been taken into account.

The real inrush-transient current has been measured by a digital storage oscilloscope for random switching instants of the actual transformer i.e. for random initial feeding voltages and random remanences, too. This has been done in order to observe the shape and the variation of the peak value of the inrush current. The measured inrush currents being almost entirely unidirectional, have shown a rise up to 120 A in the first half-cycle. In the following cycles the current decayed until the normal steady-state magnetizing conditions in the transformer were reached.

Afterwards, the inrush current has been calculated numerically. For the less favorable instants of switching and no remanence stored in the core the calculated inrush have shown the correct shape and a peak value of 90 A. The numerically derived shape and the peak value of the inrush-current, has been assumed as the exact.

The comparison of the simulated results with those calculated numerically for the first peak of the inrush current have shown a significant inaccuracy of the PSPICE model in the prediction of this specific working condition. Where the calculations give an inrush current peak 90 times the current magnitude at no load (see Tab. 1), the PSPICE shows an increase of 4 times, only. The measured and the numerically calculated inrush current have shown that the actual transformer works on the flat slope of the magnetic characteristics i.e. the saturation part. At the same time the simulated flux is far from saturation.

Adding a remanent flux in the simulation model, one can obtain the desired core saturation with the exact values for the residential induction and field and thus simulate the numerically calculated inrush current peak. This approach, being uncertain, is not very convenient for further application because the correct peak value is no guarantee for the accuracy of the full inrush transient. That means that the PSPICE could be capable of simulating the right shapes of the time varying magnetizing parameters, but not the right values.

These results show that the PSPICE transformer model as described above, is not suitable for the inrush transient study. The PSPICE is not capable to reproduce the inrush transient despite the fact that it takes into account the nonlinear core effect. The origin of the inaccuracy is due to the fact that the model can not follow the fast changes happening in the core during saturation. Also a core parameter that is ill-defined by the 50Hz curve and which gives good results in steady-state conditions could have a significant influence on the magnitude of the inrush current [1].

It could be emphasized hereby that the PSPICE results coupled with the numerical results, previously confirmed by measurements, give satisfactory results in the wide range of operating conditions of a transformer.

VI. NUMERICAL EVALUATION

A. *Numerical approach*

The fact that the PSPICE transformer model has shown an inaccuracy in the prediction of the inrush transient, calls for an alternative approach for the evaluation of the magnetizing parameters.

For the purposes of this paper a numerical approach has been used in order to find the exact inrush current and to compare it with the measurements and the PSPICE results. This approach and the described methodology have been further used to calculate the time varying magnetizing resistance and reactance over the first inrush period. The methodology applied numerically could be successfully used for determination of the steady-state parameters as well. The results will also agree with those derived by PSPICE and by measurements presented in Tab. 3.

For the actual spot resistance transformer, the inrush current has been calculated numerically from the flux and the measured magnetizing B-H characteristic of the steel sheets. The first period of the flux has been calculated numerically from the flux differential equation, for a switching instant zero and neglected remanence. Then the inrush current has been determined at every instant by the measured magnetic characteristics of the steels. The time variation of the inrush current is presented in Fig. 3.

Following the methodology described in section III the induced emf e_o has been calculated from the flux variation derived in the previous step. Then from the instantaneous core losses the average core losses have been calculated by equation (7) for limited number of time sequences. The core losses during the first period, are presented in Fig.4. The apparent power has been determined by (8) during the first period, too.

The previously calculated quantities and the calculated rms values for the inrush current and for the induced emf at the same time sequences are sufficient data for the determination of the magnetizing circuit parameters.

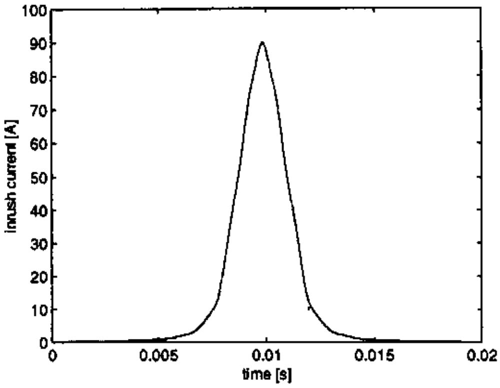

Fig. 3 First period of the inrush current

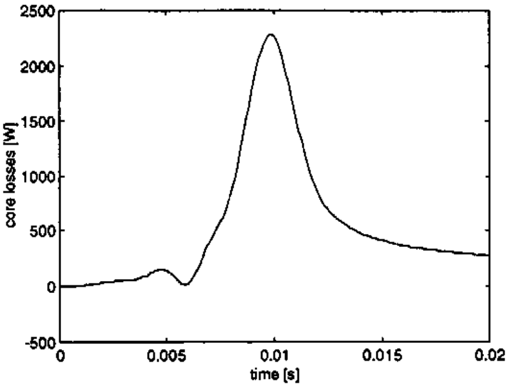

Fig. 4 Core losses in the first period

B. *Magnetizing circuit parameters during inrush transient*

The time variation of the parallel and the serial resistances over the first period have been determined by applying the equations (12) and (14), respectively. The time variation of the parallel resistance is presented in Fig. 5.

The term "reactance" defined as a product of the inductance and the angular frequency ω is becoming meaningless because of the high harmonics occurring during the inrush transient.

Assuming that the parallel reactance in case of transient is defined in terms of the rms of the current at no load being mainly reactive, the reactance has been calculated as $X_o = \frac{E_o}{I_{or}} \approx \frac{E_o}{I_o}$. The time variation of the reactance X_o during the first period is presented in Fig. 6. Consequently, the reactance in case of serial connection of the magnetizing parameters has been calculated as $X_m = \frac{X_o \cdot R_o^2}{R_o^2 + X_o^2}$.

From Fig.5 and Fig.6 the non-linear character of the transient resistance and the transient reactance could be realized.

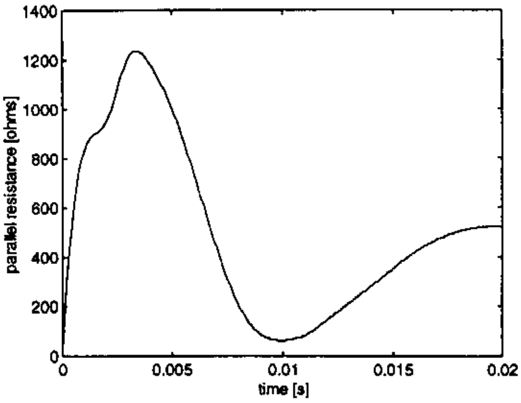

Fig. 5 Time variation of the magnetizing resistance

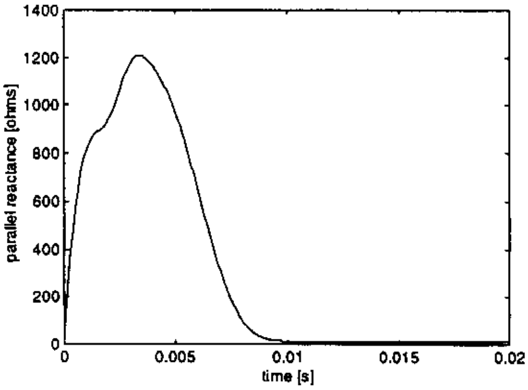

Fig.6 Time variation of the magnetizing reactance

Note that in case of transients the equation $X_o = E_o^2 / Q_{Fe}$ can not be applied when the reactive power is calculated by (9). A possible approach for determination of the reactive power is in terms of the energy returned in the net.

VII. CONCLUSIONS

One of the most interesting application of the PSPICE transformer simulation model is for evaluation of the magnetizing circuit parameters, even though they do not appear in their usual form. A general methodology for determination of the magnetizing circuit parameters numerically and by using PSPICE transformer model has been developed. The development and an application of the PSPICE transformer simulation model presented in this paper has been implemented on a spot resistance welding power transformer. However the proposed methodology is not strictly restricted to the transformer being the object of simulation in this paper. The methodology has been applied in steady-state and in case of inrush transient.

The practical application of the magnetizing circuit parameters evaluation is seen to be interesting in:

(i) The case of a transformer at no load, when the influence of the magnetizing circuit is dominant. These parameters determine:

- the power losses, which have to be paid. They are significant if the transformer works mainly unloaded, being the case of the arc welding transformers;
- the power factor which in such case is very low.

(ii) The case of a transformer at load, working close to saturation point, in particular:

- when the transformer is working at maximum full load;
- if the magnetizing current is asymmetrical. In such case the no load current and its components increase significantly (inrush current).

In the case of steady-state conditions, the methodology applied in PSPICE has been proved as accurate, both for the evaluation of the magnetizing circuit parameters considered in parallel as well as in serial connection.

In case of inrush-transients the application of the proposed methodology by PSPICE does not provide satisfactory results. The PSPICE transformer model is not capable to predict the right inrush-transient. This could be explained by the fact that after all the PSPICE is a quasi DC model, valid for slow variations only. Also a CORE parameter that is ill-defined by the 50Hz curve and which gives good results in steady-state conditions, could have a significant influence on the magnitude of the inrush current.

Additionally for the purposes of the paper, by using the same methodology, the time variation of the resistances during the first period have been calculated numerically. The numerical calculation of the reactances by the proposed methodology is made with some assumptions.

The time variation of the magnetizing circuit parameters during the entire transient will be a subject of further investigation. For that reason the entire inrush transient should be recorded and analyzed. An effort will be made to explain the transient behavior of the parameters in case of unloaded and loaded transformer. The reactance will be determined more accurately in terms of the energy returned in the net.

VIII. REFERENCES

[1] Cundeva S., Bollen M., "PSPICE Modelling and Experimental Results of the Magnetic Behavior of a Primary Side Phase Controlled Transformer", *Proceedings of the IPST'97 Conference*, p.99-104, June, Seattle.

[2] Cundeva S., Petkovska L., Cundev M., "Modelling and simulation of a welding transformer for parameters evaluation", *Proceedings of the ICEM'98 Conference*, p.524-528, September, Istanbul.

[3] Tuinenga P.W., "*SPICE: A Guide to Simulation and Analysis Using PSPICE*", Third ed., Prentice-Hall, New York:, 1995.

[4] "*The Design Center, Circuit Analysis Reference Manual*", MicroSim Corporation, 1993, p.134-140.

[5] Jiles D.C., Atherton D.L., "Theory of ferromagnetic hysteresis", *Journal of Magnetism and Magnetic Materials*, vol. 61, 1986, p. 48-60.

[6] Jiles D.C., Thoelke J.B., "Theory of ferromagnetic hysteresis: Determination of model parameters from experimental hysteresis loops", *IEEE Trans. on Magnetics*, vol. 25, No 5, 1989, p.3928-3930.

[7] Prigozy, S. "PSPICE Computer Modelling of Hysteresis Effects", *IEEE Trans. on Education*, vol. 36, No 1, 1993, p.2-5.