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A DIGITAL SIMULATION OF A CYCLOCONVERTER FED INDUCTION MOTOR

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ABSTRACT

The paper presents a complete digital simulation of a three-phase cycloconverter fed induction motor. The modelling of the motor avoids numerical inversion of the inductance matrix even when the stator currents are interrupted. The simulation program is developed using a unified method for the modelling of system including switching devices. The program facilitates predection of the system behaviour. Simulation results for both starting and steady state operation are reported. Also the computed steady state performance of the motor are developed, and proved to yield good agreement when compared with the relevant test values.

PRINCIPAL NOTATIONS the main notations used in the following are :

In the motor equations

[V] : voltage vector
[i] : current vector
[R] : resistance matrix
[L] : inductance matrix
L_s : stator-phase inductance.
M_s : mutual inductance between two stator phases
L_r : rotor-phase inductance
M_r : mutual inductance between two rotor phases
M_o : maximum mutual inductance between stator-rotor phase

R_1 : stator-phase resistance
R_2 : rotor-phase resistance
P : differential operator (d/dt)
θ : electricql angle between stator and rotor
$\dot{\theta}$: $d\theta$ / dt
T : electromagnetic torque of the motor
T_r : load torque
J : moment of inertia
f : friction coefficient
Ω : motor speed
L_1 : $L_s - M_s$; $M = \frac{3}{2} M_o$, $M_1 = M / \sqrt{\frac{2}{3}}$
L_2 : $L_r - M_r$; $M_2 = M / \sqrt{3}$
L_3 : $L_s + M_s$; $M_3 = \sqrt{2}\, M_s$; $M_4 = M / \sqrt{\frac{3}{2}}$
δ : $1 - (M_2/L_1L_2)$
δ_1 : $1 - (M_2^2/L_2L_3)$; $\delta_2 = 1 - (M_2^2/L_1L_2)$; $\delta_3 = 1 - (M_1^2/L_2L_5)$

For the cycloconverter : indexes $i(i \varepsilon [1,3])$, $j(j \varepsilon [1,6])$ and $k(k\ \varepsilon [1,3])$.

1. *INTRODUCTION*

Static converters are often studied using analytical methods. For circuits with a low number of semiconductors, these methods are justified and lead to good representation of the converter under investigation. In order to investigate both the steady state and transient behaviour of complex circuits with a large number of semiconductors, digital simulation should be used.

The digital simulation of static converter-rotating machine system is a complecated problem concerning many papers [1-7]. For this purpose, a method generally used [1] is to consider the whole system as a network whose topology varies according to the state of conduction of the converters.This method gives a good results for the investigation of machine steady state, but does not suitable for machine transient.

The transient behaviour of a rotating machine is generally to be investigated by solving a set of non-linear differential equations, which are convenient to be dealt with in a separate way. Consequently,it seems interesting to find a suitable model allowing study of the behaviour of the whole system (source, converter, machine and controllers).

Using the digital simulation, the performance of a three phase cycloconverter fed passive load [5], and induction motor [6,7] have been studied. Also, the harmonic analysis of the output voltage has been used for studying the behaviour of the cycloconverter [8]. A study of the problem of quantization which is linked with numerical control voltage of a three phase cyclo-converter controlled by a microprocessor has been presented [9].

The present paper developes a complete digital simulation of the cycloconverter-fed induction motor. The method of simulation used allow the user of such simulation to take easily into account all parts of the whole system [3,4].The model of the cycloconverter has been eastablished using the connection matrices [2], and the model of the motor has been developed such that to reduce large computation time of the digital simulation.

2. *SYSTEM DISCRIPTION AND ASSUMPTIONS*

The system under consideration consists of a three phase induction motor fed by a cycloconverter composed of 18-thyristors divided into six groups, two of them are connected in antiparallel to the same load phase (Fig.1). The stator phases of the motor as well as the source phases are star connected with neutral interconnection.

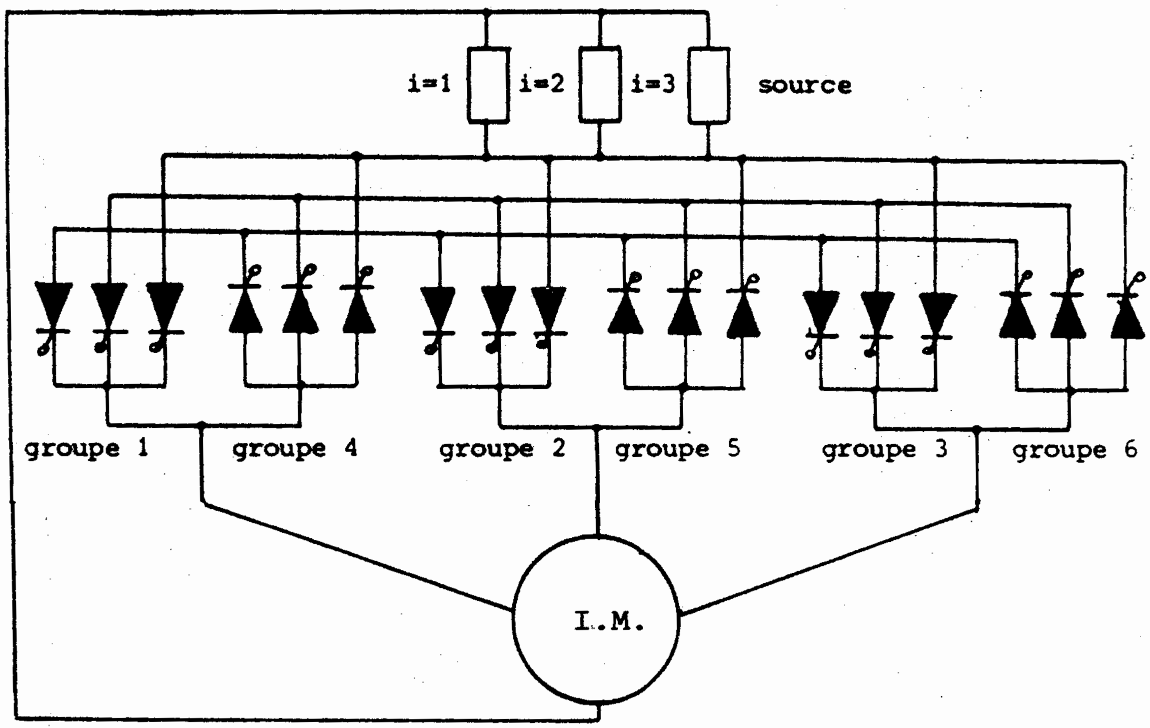

Fig. 1. Induction motor - cycloconverter scheme

2.1. *Firing Devices*

Each thyristor is triggered by a so-called "coincidence pulse generator",i.e. a pulse is generated on Th_{ij} (Th_{ij} is the thyristor of the group number j connected to the source phase number i) when the control voltage denoted FcR_j crosses the firing curve ALM_{ij} synchronized on the i^{th} source voltage (Fig. 2). The real control voltage FcR_j is either equal to a theoritical control voltage denoted FCT_j (when group j is allowed to be fired) or to the inverter limit BO (when the group is not desired to be fired)

2.2. *Control Units*

The two groups of thyristors connected to the same motor phase are not allowed to be fired at the same time. At any time, the groups to be fired are chosen from three control functions (FCI_k), which may be

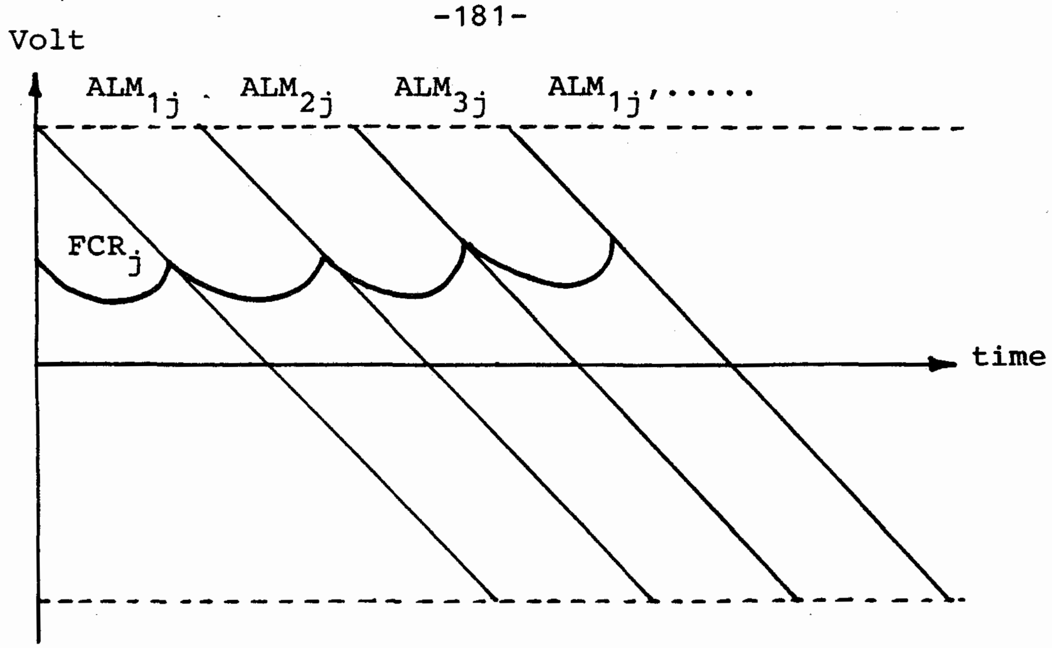

Fig. 2. Principle of the pulse generator

computed in various ways.Furthermore a change of group will be allowed only when the current in the corresponding motor phase is zero for a time greater than a security delay time (τ). This security time must be as small as possible because of its great influence on the current harmonincs [8]; but it cannot be smaller than the recovery time of the thyristors.

2.3. Basic Assumptions

The following main assumptions are taken into consideration :

For the motor; the space harmonic, the saturation and the iron losses are neglected. Also the m.m.f. is sinusoidal distributed.

For the cycloconverter; the thyristors are considered as ideal switches and the commutation phenomenon between the source phases are negligable.

3. MODELLING OF THE SYSTEM

In order to carryout the simulation, the various devices involved in the system are modelled as follows:

3.1. Model of the Cycloconverter

As previously established [2], the cycloconverter may be represented by a connection matrix [c] which can be deduced as :

$\sum_i C_{ik} = 0$ if the motor phase k is not connected to the source and $I_k = 0$

$\sum_i C_{ik} = 1$ if the motor phase k is connected to the source

This modelling allow a simple computation of the voltages of the motor phases when they are fed by the cycloconverter :

$$[V]_m = [C]^t \; [V]_s \qquad (1)$$

where $[V]_m$ and $[V]_s$ are respectively the motor and the source voltages. Furthermore, the source currents are given by : $[i]_s = [C]\,[i]_m$ (2)

where $[i]_s$ & $[i]_m$ are respectively the source and the motor phase currents.

3.2. Model of the Firing Devices (Pulse Generators)

It may be consider that, each pulse generator has two models depending on the value of the control voltage (FCR_j). The generators can be modelled by a "firing function" $FAL_{ij} = ALM_{ij} - FCR_j$. AS FCR_j has two values (FCT_j or BO), therefore, the models of the generators can be deduced as :

$$\begin{aligned} &\text{First model : } FAL_{ij} = ALM_{ij} - FCT_j \\ &\text{Second model : } FAL_{ij} = ALM_{ij} - BO \end{aligned} \qquad (3)$$

3.3. Model of the Control Units

The control units may be modelled by clock counters C_k, which are initialized when the corresponding currents are zeros. Thus, each of them has two models and can be represented by the following logical variables :

ICLOCK = 1 when the clock counter is running, and
$C_k = t - t_{ok}$ where t_{ok} is the extinction time of the current in the k^{th} motor phase.

ICLOCK = 0 when the clock counter is not running, and
$C_k = 0$

3.4. Model of the Motor

The general electrical equation of induction machines may be written in the following matricial form :

$$[V] = [L] \frac{d}{dt} [i] + ([R] + \dot{\theta} \frac{d}{d\theta} [L]) [i] \qquad (4)$$

The inductance matrix[L] is of order six which varies according to θ, and consequently to the time when the motor is rotating. The main problem encountered when dealing with numerical solution of equation (4) is caused by the inversion of [L], which has to be made in a repetitive way(for instance three times for each step when a fourth order Rung Kutta algorithm is used). The inversion of a matrix is a long calculation and will leads to increase the time taken by the program of simulation. Also the accuracy of the inversion of matrix[L] depends on the values of the matrix elements.

The usual method used to avoid the matrix inversion is the d.q. transformation, which leads to a constant matrix. However, it is not always possible to use this method; when an induction machine is fed by a static converter and especially by a cycloconverter,the three phases are not always supplied(one phase or two phases disconnected).

In order to solve this problem, a new transformation has been used[6,7] leading to constant inductance matrices even when one or two stator phases are switched off.

Let us denote 1,2 and 3 to the stator phases, phase 1 being the "dissymetric one" (when one phase is not supplied it denoted by "1" and when two phases are switched off, "1" in this case denoted the third phase). The rotor phases, are short-circuited, and it is always possible to use the d.q. transformation, then, the transformed rotor currents are then denoted by $\bar{I}_d$ and $\bar{I}_q$.

The stator phases are connected in star, its neutral is connected to the supply neutral, and it can be consider that, the motor has four different models depending on the number of stator phases which supplied by the cycloconverter. These models are easily deduced from the connection matrix as given below :

1. <u>Model 1 (three stator phases are supplied)</u>

This model corresponding to presence of three elements equal one in the connection matrix [C]. The conventional d.q. transformation is used with axes linked to the stator, the transformed stator voltages and currents are respectively denoted (V_α, V_β) and (i_α , i_β). The equations are then as follows :

$$\frac{d}{dt}\begin{bmatrix} i_\alpha \\ i_\beta \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} = \begin{bmatrix} \frac{1}{\delta L_1} & 0 & -\frac{M}{\delta L_1 L_2} & 0 \\ 0 & \frac{1}{\delta L_1} & 0 & -\frac{M}{\delta L_1 L_2} \\ -\frac{M}{\delta L_1 L_2} & 0 & \frac{1}{\delta L_2} & 0 \\ 0 & -\frac{M}{\delta L_1 L_2} & 0 & \frac{1}{\delta L_2} \end{bmatrix} \left\{ \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_1 & 0 & 0 & 0 \\ 0 & R_1 & 0 & 0 \\ 0 & M\dot{\theta} & R_2 & L_2\dot{\theta} \\ -M\dot{\theta} & 0 & -L_2\dot{\theta} & R_2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} \right\} \quad (5)$$

and the homopolar equation $V_h = R_1 i_h + L_h \frac{d}{dt} i_h$ (6)

The motor torque is given by $T = PM(\bar{I}_d i_\beta - \bar{I}_q i_\alpha)$ (7)

2. Model 2 (one phase disconnected)

This model corresponding to presence of two elements equal one in the connection matrix [C]. When one motor phase is disconnected from the cycloconverter, the following transformation on the stator variables are made :

$$\begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} = [D] \begin{bmatrix} g_1 \\ g_\gamma \\ g_\beta \end{bmatrix} \text{ where } [D] = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & -1 \end{bmatrix} = [D]^{-1} \quad (8)$$

this transformation leads to the following equation; which will gives the currents in the other phases :

$$\frac{d}{dt} \begin{bmatrix} i_\gamma \\ i_\beta \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} = \begin{bmatrix} \frac{1}{\delta_1 L_3} & 0 & \frac{M_2}{\delta_1 L_2 L_3} & 0 \\ 0 & \frac{1}{\delta L_1} & 0 & \frac{-M}{\delta L_1 L_2} \\ \frac{M_2}{\delta_3 L_2 L_3} & 0 & \frac{1}{\delta_1 L_2} & 0 \\ 0 & \frac{-M}{\delta L_1 L_2} & 0 & \frac{1}{L_2} \end{bmatrix} \left\{ \begin{bmatrix} V_\gamma \\ V_\beta \\ 0 \\ 0 \end{bmatrix} \right.$$

$$\left. \begin{bmatrix} R_1 & 0 & 0 & 0 \\ 0 & R_1 & 0 & 0 \\ 0 & M\dot{\theta} & R_2 & L_2\dot{\theta} \\ M_2\dot{\theta} & 0 & -L_2\dot{\theta} & R_2 \end{bmatrix} \begin{bmatrix} i \\ i_\beta \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} \right\} \quad (9)$$

and the voltage of the disconnected phase is given by :

$$V_1 = (M_3 \ , \ M_1) \frac{d}{dt} \begin{bmatrix} i_\gamma \\ \bar{I}_d \end{bmatrix} \quad (10)$$

The motor torque is $T = P(M\, \bar{I}_d i_\beta + M_2\, \bar{I}_q\, i_\gamma)$ (11)

3. Model 3 (Two phases disconnected)

For this model, only one element equal one is presence in the connection matrix [C]. Using the above transformation (eq. 8), the currents in the machine are computed by the following equation :

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} = \begin{bmatrix} \frac{1}{\delta_3 L_5} & -\frac{M_1}{\delta_3 L_2 L_s} & 0 \\ -\frac{1}{\delta_3 L_2 L_s} & \frac{1}{\delta_3 L_2} & 0 \\ 0 & 0 & \frac{1}{L_2} \end{bmatrix} \left\{ \begin{bmatrix} v_1 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_2 & L_2\dot{\theta} \\ -M_1\dot{\theta} & -L_2\dot{\theta} & R_2 \end{bmatrix} \begin{bmatrix} i_1 \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} \right\} \quad (12)$$

and the voltage of the disconnected phases are given by :

$$\begin{bmatrix} V_\gamma \\ V_\beta \end{bmatrix} = \begin{bmatrix} M_3 & -M_2 & 0 \\ 0 & 0 & M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ \bar{I}_d \\ \bar{I}_q \end{bmatrix} \quad (13)$$

The motor torque is given by $T = -P\sqrt{\frac{2}{3}}\, M\, i_1\, \bar{I}_q$ (14)

4. Model 4 (Three-phases disconnected)

This model correspond to a connection matrix having its elements equal zero, the electrical equations are reduced to :

$$\frac{d}{dt}\begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} = -\begin{bmatrix} \frac{R_2}{L_2} & \dot{\theta} \\ -\dot{\theta} & \frac{R_2}{L_2} \end{bmatrix} \begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} \quad (15)$$

and the voltage of the stator phases are computed by :

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = -\frac{M}{L_2}\sqrt{\frac{2}{3}} \begin{bmatrix} R_2 & L_2\dot{\theta} \\ -\frac{R_2}{2} + \frac{\sqrt{3}}{2} L_2\dot{\theta} & -\frac{L_2}{2}\dot{\theta} + \frac{\sqrt{3}}{2} R_2 \\ -\frac{R_2}{2} - \frac{\sqrt{3}}{2} L_2\dot{\theta} & -\frac{L_2}{2}\dot{\theta} - \frac{\sqrt{3}}{2} R_2 \end{bmatrix} \begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} \quad (16)$$

4. METHOD OF SIMULATION

The method of simulation for this system is developed according to a general modelling proposed by the authors in previous works (3-7). To simulate it, the whole system is divided into two subsystems : a "completed analogical subsystem" which is the whole set of models of each different parts of the system, and a "finite state automata" whose part is to choose the right models at any moment.The analogical subsystem and the automata are linked by an "interface", which associates the logical inputs of the automata to analogical variable.

The global flow-chart of the simulation is shown in Fig.3.
The step 0, in which all the constants, the analogical and logical variables are initialzed, is in the main program.
The step 1, is achieved with independent subroutines so that a change in the load or in the controller should lead to modify only one subroutine. A fourth order Runge-Kutta algorithm is used to integrate the differential equation.
A single subroutine named "CYCLOP" deals with steps from 2 to 7. In fact, this subroutine represents the characteristic of the cycloconverter, and helps to choose the suitable model for the simulation.

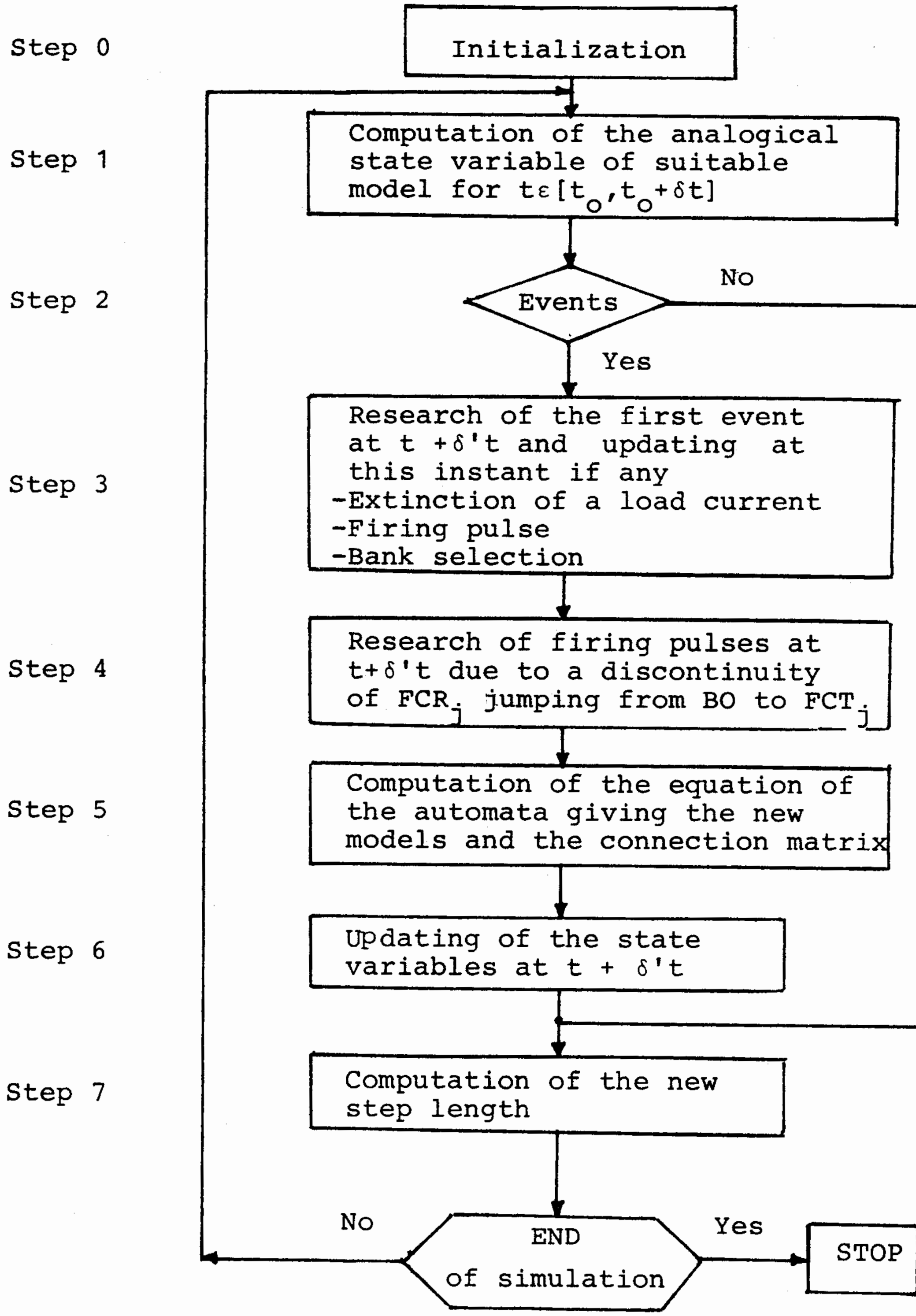

Fig. 3 Global flow-chart of the simulation

5. *RESULTS*

The following results of the simulation have been recorded on a display unit. Some transient and steady state behaviours of the cycloconverter-induction motor drive are selected in order to show the accuracy and flexibility of the simulation used. The parameters of the motor as well as the system conditions are given in the appendix.

The results concerning the starting-up period with a motor frequency of 10 Hz and load torque of T_L = 2 + 0.01 x speed. Fig. 4 shows the current and voltage for one phase of the motor at the first cycle of starting. Fig. 5 indicates the current of the same phase of the motor during the whole starting-up period, from which the subtransient and transient period can be evaluated. The currents of the stator phases at the first cycle of starting are shown in Fig.6. Fig. 7 gives the torque and speed during the starting-up period.These characteristics are approximately the same such that obtained when using the three-phase source with the induction motor and it can be noted clearly the pulsating torque at the beginning of this interval. Fig. 8 illustrate the phase current and the output of the band-pass filter for the same starting as in Fig.4. Concerning Fig.8, it should be noted that, during the first half cycle, the filter is not able to follow the phase current, due to the quick change of the phase shift between the phase current and voltage.

Fig. 9 gives the steady state phase currents of the motor.

In order to show the accuracy of the simulation program, the experimental set-up [7] is used to determine the speed-torque and current-torque characteristics of the motor. These results are compared with the simulation results as shown in Figs. 10 and 11.

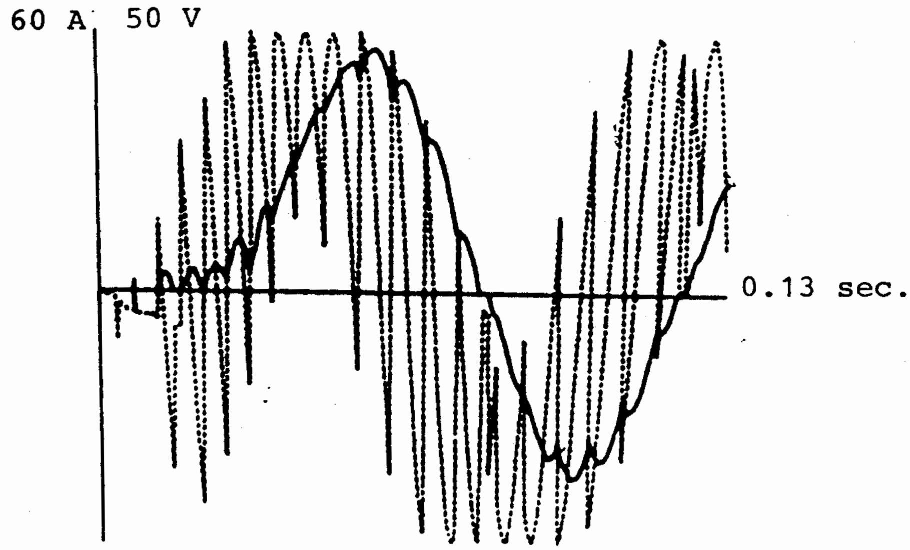

Fig. 4. Phase current and voltage during the first cycle of starting

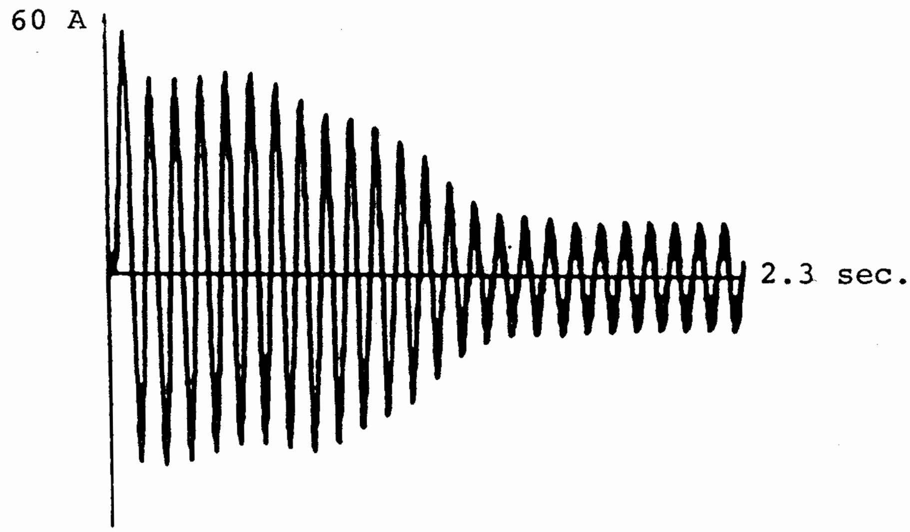

Fig. 5. Phase current during the whole starting-up period

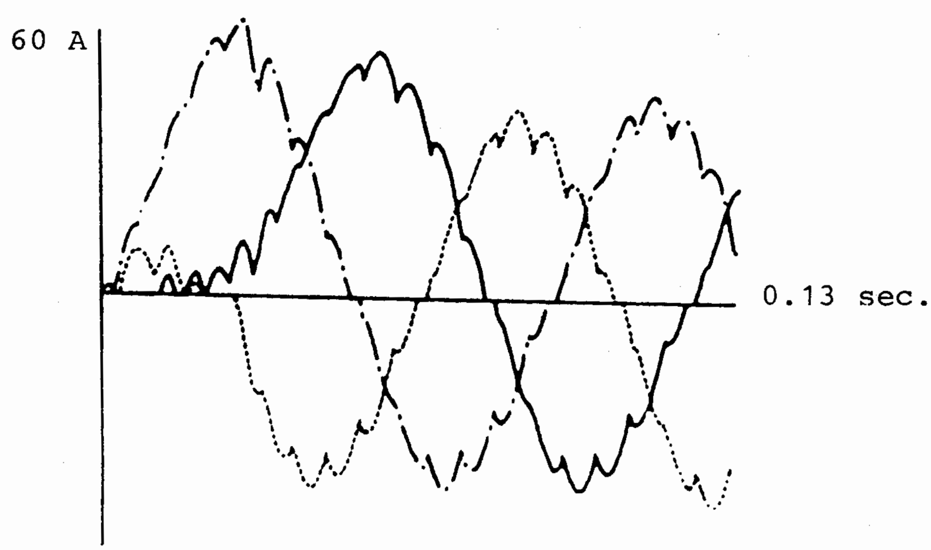

Fig. 6. Phases current at the first cycle of starting

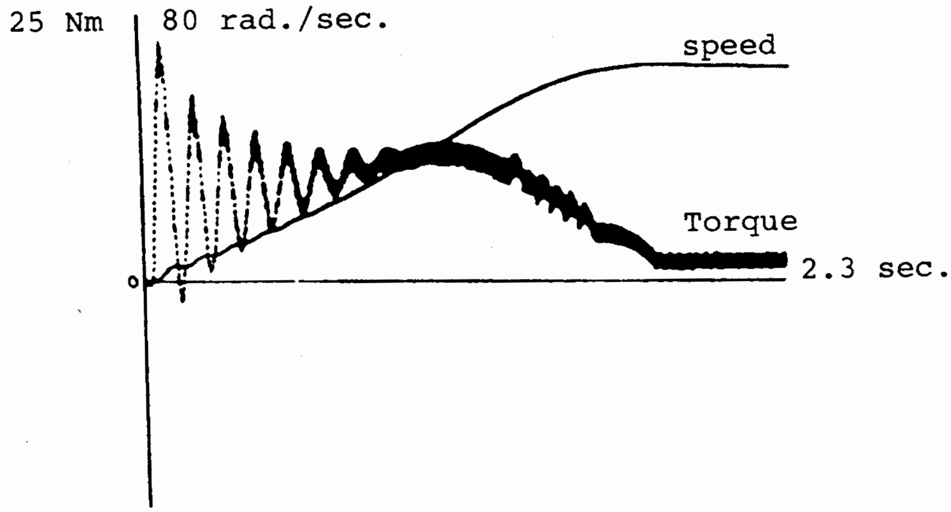

Fig.7. Torque and speed during the starting-up

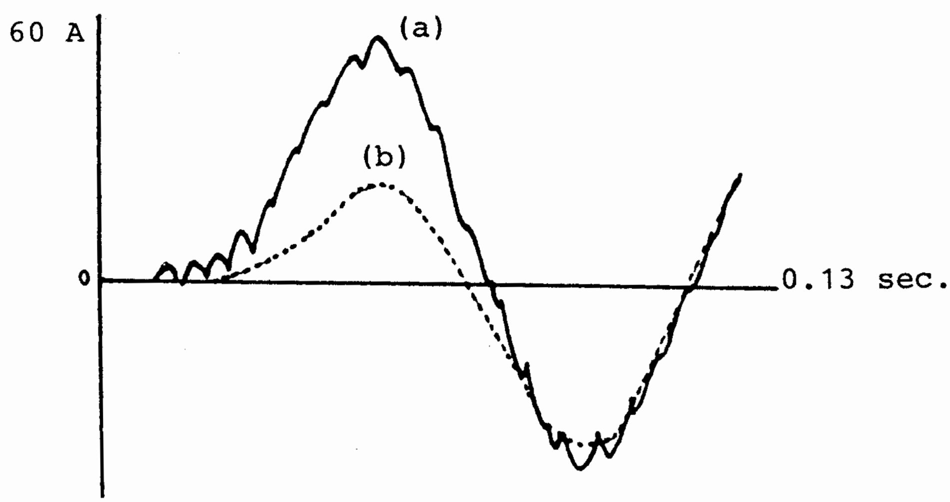

Fig. 8. (a) Phase current and
(b) Output of the filter

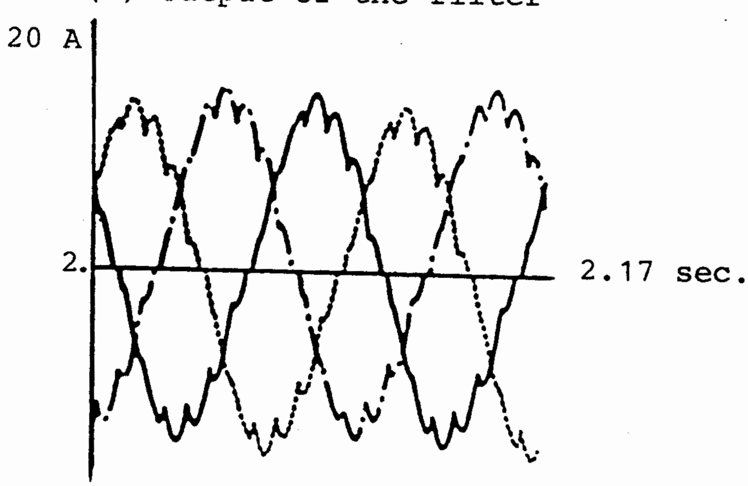

Fig. 9. Stead state phase currents

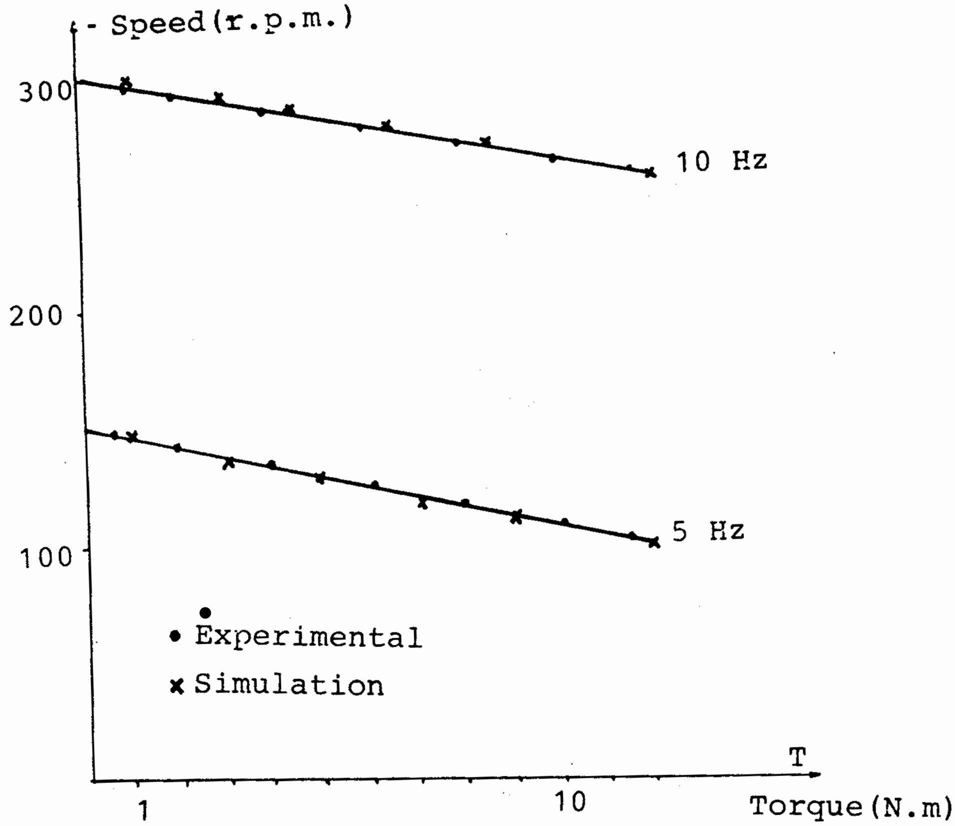

Fig.10. Speed-Torque characteristics.

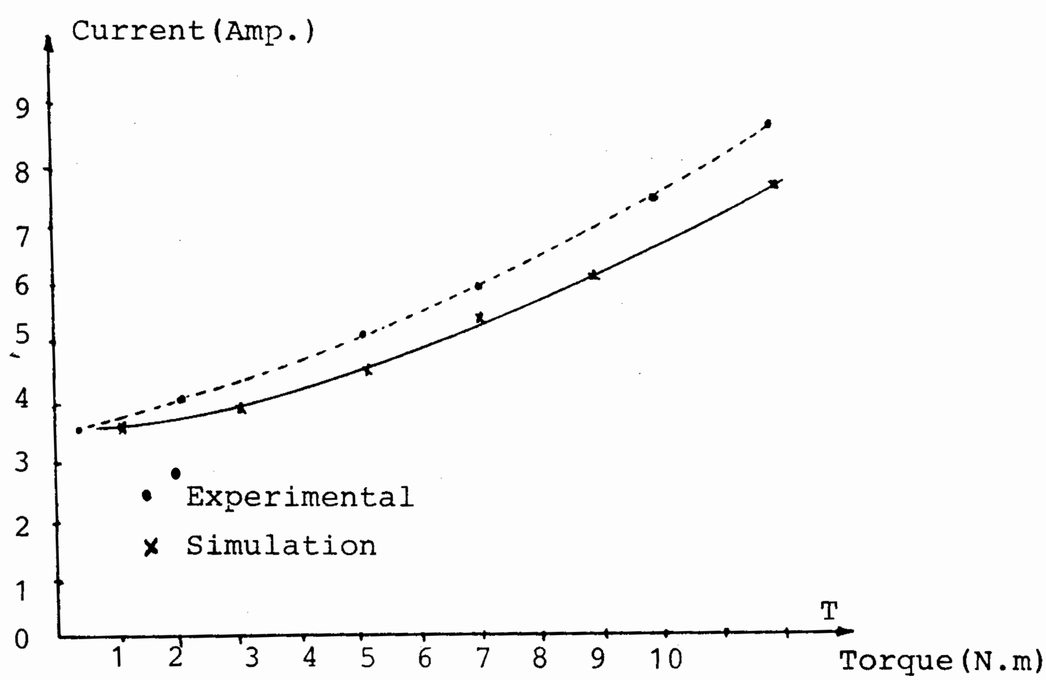

Fig.11. Phase current-Torque characteristics for $f_2 = 7$ Hz.

6. *CONCLUSION*

The present paper developes an attractive complete simulation of a three phase cycloconverter fed induction motor. The new modelling approach of the motor, yield to avoid the numerical inversion of the inductance, and exhibit a large saving in computation time. Also, the method of simulation leads to a modular structure of the program, which make it well suited to study; dynamic behaviour; disturbances occuring in the source and optimal control of all devices used in the system.

The theoritical results which are obtained from the simulation are proved to yield good agreement when compared with the experimental results.

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8. APPENDIX

The motor parameters are :

R_s = 0.27 Ohms, L_s = 0.05 H , M_s = -0.0225 H,
M_o = 0.0307 H , R_r = 0.141 Ohms, L_r = 0.0244 H,
M_r = -0.0122 H , J = 0.2 kg.m² and p = 1.

The source conditions are :

E = 50 volts (e.m.f.), frequency f_1 = 50 Hz.

For all previous results, the theoretical control functions (FCT_j) have a saw-booth waveform, and the current control functions (FCI_k) are the outputs of band-pass filters fed by the motor phase currents.