MENOUFIYA UNIVERSITY
FACULTY OF ENGINEERING
ENG. RESEARCH BULL.
Vol. 17 Part I, 1994

P.P. : 261 : 274
Received at : 6 / 4 / 1994
Accepted at : 27 / 4 / 1994

EFFECT OF UNBALANCE VOLTAGES ON THE PERFORMANCE OF 3-PHASE RELUCTANCE MOTOR

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ABSTRACT

A certain degree of unbalance in the voltages is always expected at the consumers end due to the non-uniform distribution of single-phase loads. This will lead to violation of linear output-input relationship of reluctance motors.

In this paper, an effort has been made to highlight the adverse effect of the unbalanced voltages on the performance of 3-phase reluctance motor. The scope of this paper is to provide a 3-element static balancer, one for each phase , which enables a 3-phase reluctance motor to operate satisfactorily from unbalanced supply .

In order to evaluate the proposed technique, the resulting non-linear differential equations describing the whole system (feeder, balancer and motor) are solved numerically using the Runge-Kutta method of numerical integration. Also, a series of test results are presented to confirm the validity of the theoretical prediction .

LIST OF MAIN SYMBOLS :

C = balancer capacitance
f = frequency
J = moment of inertia
L_d, L_D = stator and rotor d-axis self inductance
L_q, L_Q = stator and rotor q-axis self inductance

L_f = feeder inductance
M_{AD} = mutual coupling coefficient for d-axis
M_{AO} = mutual coupling coefficient for q-axis
N = speed
p,P = number of pair poles , operator $(\frac{d}{d_t})$
R_a = stator resistance
R_D, R_Q = Rotor D & Q axis resistance
R_f = feeder resistance
T_e = electromagnetic torque
T_L = load torque
θ = elect.angle between stator and rotor
ω = angular velocity (rad./sec.)

Suffixes a , b and c denote phases a , b and c
Suffixes d , q denote stator d and q axis
Suffixes D , Q denote rotor d and q axis
Suffixes s , m source and motor respectively

INTRODUCTION

Operation of polyphase reluctance motors from an unbalanced voltages may lead to decrease torque, excessive heating, poor efficiency and unbalanced line currents [1-5] . The adverse effect of this unbalance phenomenon on the performance of a reluctance motor, which is quite commonly used nowadays, is not realised at all.

To compensate unbalanced voltages, a predetermined shunt capacitor banks, for each phase, is suggested and analytical expression is derived to predict the value of the balancer capacitance in terms of machine impedance parameters.

This paper presents a new technique for predicting the behaviour of 3-phase reluctance motors operated from unbalanced supply voltages, using the d-q axis model. The method is shown to be a very powerful tool in comparison with the method of symmetrical components. It is shown that the present model is very convenient for digital simulation. Moreover, experimental results are provided in order to demonstrate the validity of the proposed technique.

THEORETICAL BASES :

The system under consideration consists of a 3-phase reluctane motor fed from unbalanced 3-phase supply through a feeder, and a static balancer elements , one for each phase, as shown in Fig.(1). The motor ratings are given in table (1) , while the motor parameters and balancer capactiances are shown in table(2) .

For any degree of unbalanced voltages , the machine input impedance per phase is determined . Next, the static balancer capacitance for each phase is calculated from :

$$\omega c = \frac{1}{Z_i} \text{Sin } \Phi_L .$$

where z_i = motor input impedance / phase
Φ_L = motor phase angle

The simulation model is adapted to predict the balancer capacitance for any unbalanced degree. The unbalance in supply voltages are taken such that , the voltage of phase (a) is taken as the rated value, while 10 per cent reduction are presented for phases b & c . The feeder impedance is taken about 10% of the motor impedance at full- load ($R_f = 4\ \Omega$, $L_f = 0.07$ H) .

MATHEMATICAL MODEL

A detaild description of the main equations [6] which lead to the simulation are given in the Appindix . Assumptions and idealizations made about reluctance machines are as follows :
1) linear magnetic circuit .
2) identical stator windings .
3) space harmonics are neglicted .

To avoid inversion of the machine inductance matrix for reducing the computation time , equation (A-1) is arranged in a state form as given below :

$$P\begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{bmatrix} = \begin{bmatrix} L_D/K_1 & 0 & -M_{AD}/K_1 & 0 \\ 0 & L_Q/K_2 & 0 & -M_{AQ}/K_2 \\ -M_{AD}/K_1 & 0 & L_d/K_1 & 0 \\ 0 & -M_{AQ}/K_2 & 0 & L_q/K_2 \end{bmatrix} \left[\begin{bmatrix} v_d \\ v_q \\ v_D \\ v_Q \end{bmatrix} - \begin{bmatrix} R_a & -L_q\dot{\theta} & 0 & -M_{AQ}\dot{\theta} \\ L_d\dot{\theta} & R_a & M_{AD}\dot{\theta} & 0 \\ 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & R_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{bmatrix} \right] \qquad (1)$$

where : $K_1 = L_d L_D - M^2{}_{AD}$

$K_2 = L_q L_Q - M^2{}_{AQ}$

Without Static Balancers : The unbalanced d-q axis voltages are given by :

$$v_d = v_{ds} - R_f i_{ds} - L_f P i_{ds} + L_f \dot{\theta} i_q \qquad (2)$$

$$v_q = v_{qs} - R_f i_{qs} - L_f P i_{qs} - L_f \dot{\theta} i_d \qquad (3)$$

where v_{ds} and v_{qs} are the supply d & q axes voltages,
i_{ds} and i_{qs} are the supply d & q axes currents .

The axis variables may related to the phase variables by :

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\Pi}{3}) & \sin(\theta + \frac{2\Pi}{3}) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (4)$$

$$= [G] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

where G is the transformation matrix
The supply voltages are given by :

$$\left.\begin{aligned} v_a &= V_a \ \text{Sin} \ (\omega t) \\ v_b &= V_b \ \text{Sin} \ (\omega t - \frac{2\Pi}{3}) \\ v_c &= V_c \ \text{Sin} \ (\omega t - \frac{4\Pi}{3}) \end{aligned}\right\} \qquad (5)$$

With Static Balancers : The machine voltages may be evaluated from :

$$Pv_{ma} = \frac{1}{C_a}(i_{sa} - i_{ma}) \qquad (6)$$

$$Pv_{mb} = \frac{1}{C_b}(i_{sb} - i_{mb}) \qquad (7)$$

$$Pv_{mc} = \frac{1}{C_c}(i_{sc} - i_{mc}) \qquad (8)$$

The d and q axes supply surrents are calculated from :

$$P i_{ds} = (v_{ds} - v_d - R_f i_{ds}) / L_f - \dot{\theta} \, i_q \qquad (9)$$

$$P \, i_{qs} = (v_{qs} - v_q - R_f i_{qs}) / L_f - \dot{\theta} \, i_d \qquad (10)$$

where :

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = [G] \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = [G] \begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix}$$

The above equations are used for constructing the computer program . The simulation results are reported for transient and steady state condition .

EXPERIMENTAL VERIFICATION

In order to verify the validity of the simulation results , a series of tests are carried out on an available laboratory 3-phase reluctance motor , having the following ratings :

TABEL (1) : MOTOR DATA

rated voltage ,	V	220 / 380
rated current ,	A	1.9 / 1.1
rated power ,	W	300
rated speed	rpm	1500
frequency	Hz	50

The balancer capacitances are determined for a certain value of load torque and used with the simulation as well as experimental results. Table (2) contains the motor parameters and balancer capacitance values .

TABLE (2) MOTOR PARAMETERS

R_a	X_d	X_q	X_{md}	X_{mq}	X_D	X_Q
27	258	102	236	80	337	190
R_D	R_Q	p	J	C_a	C_b	C_c
78.3	89	2	0.00092	6.6	10.6	2.8

All resistances and reactances in ohms , J in kg.m^2 and C in μF .

SIMULATION AND TEST RESULTS

In order to obtain the motor behaviour either in transient or running condition, the forgoing developed differential equations were solved numerically using a digital computer and the Runge-Kutta numerical integration technique . Simulated and experimental results for the system with and without static balancers have been made and compared. Unless otherwise stated in what follows, the unbalances are performed such that , the voltage of phases b , c are reduced by about 10% from its rated values , while the voltage of phase (a) is left without any changing .

Results and Observations

Without static balancers, the starting behaviour can be summarised as follows; Figures (2,3) show the computed and experimental variation of motor phase currents and speed with time . It may be observed that the 10 per cent unbalances in line voltages cause much larger unbalance in line currents (Fig. 2). It is well known that the unbalanced currents produce an unbalanced spatial distribution of heating in the stator, and this increasingly injurious to successful motor operation . Fig.(3) illustrates that unstable operation prevail in which the machine is not able to synchronise at all .

With staic balancers, similar starting behaviour are recorded in Figures (4,5). Fig. (4) shows the variation of motor current with time. Comparison between Fig. 4 and 2, reveals that the unbalance degree in motor phase currents are impvoved, and smooth motor currents are prevail. Correcting the unbalanced current assess in creating better circular rotating field and in turn increasing the motor developed torque as illustrated from the speed trace of Fig. (5) .

Finally, the predicted and experimental steady state performance of motor voltages and currents are illustrated in Figures (6,7) , respectively. The effect of employing phase balancers on increasing and balancing motor voltages and reducing the supply current are evidently observable from these Figures. .

CONCLUSIONS

Three element capacitive balancers provide an alternative means for balanced operation of a 3-phase synchronous reluctance motor from unbalanced supply. Analytical expressions have been derived to predict the values of the balancer elements in terms of machine impedance parameters .

The paper has presented a mathematical model for predicting the machine behaviour when operated from unbalanced supply. The proposed technique has its outstanding advantages of simplicity, accuracy and flexibility in comparison to other techniques. The validity of the proposed method has been verified by the close agreement between simulated and experimental results .

The study has skimmed the surface of a common problem, but it should be emphasised that , the static balancer elements have to be varied with the degree of unbalance. This can be achieved by using switched capacitor technique .

APPENDIX

The transformed voltage equations are given by [6] .

$$\begin{bmatrix} v_d \\ v_q \\ v_D \\ v_Q \end{bmatrix} = \begin{bmatrix} R_a + PL_d & -L_q\dot{\theta} & PM_{AD} & -M_{AQ}\dot{\theta} \\ L_d\dot{\theta} & R_a + PL_q & M_{AD}\dot{\theta} & PM_{AQ} \\ PM_{AD} & O & R_D + PL_D & O \\ O & PM_{AQ} & O & R_Q + PL_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{bmatrix} \quad (A-1)$$

Electromagnetic torque in the transformed system is given by :

$$T_e = \tfrac{2}{3}p \ (L_d i_d + M_{AD} \ i_D) i_q - (L_q i_q + M_{AQ} i_Q) i_d) \qquad (A\text{-}2)$$

The mechanical equation is given by :

$$P\omega_m = \tfrac{1}{J}(T_e - T_L) \qquad (A-3)$$

$$\text{where} \quad \omega_m = P_\theta \qquad (A-4)$$

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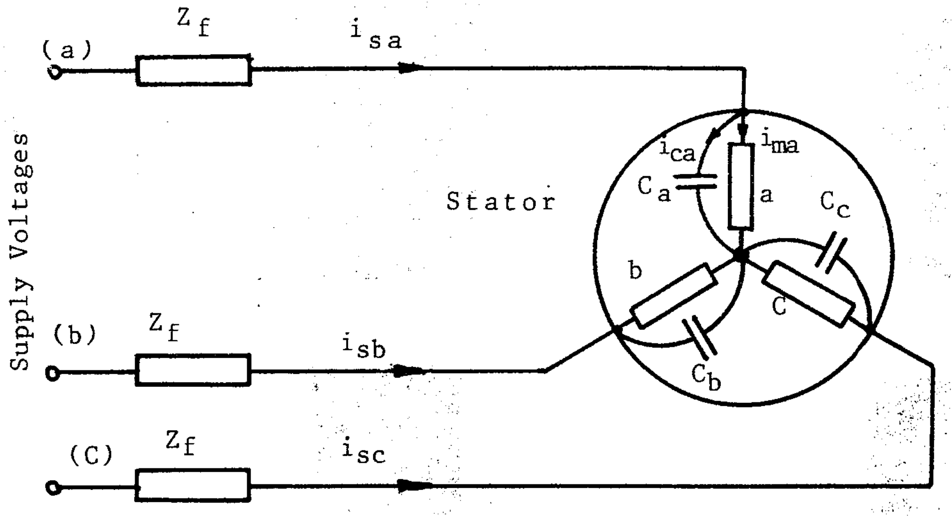
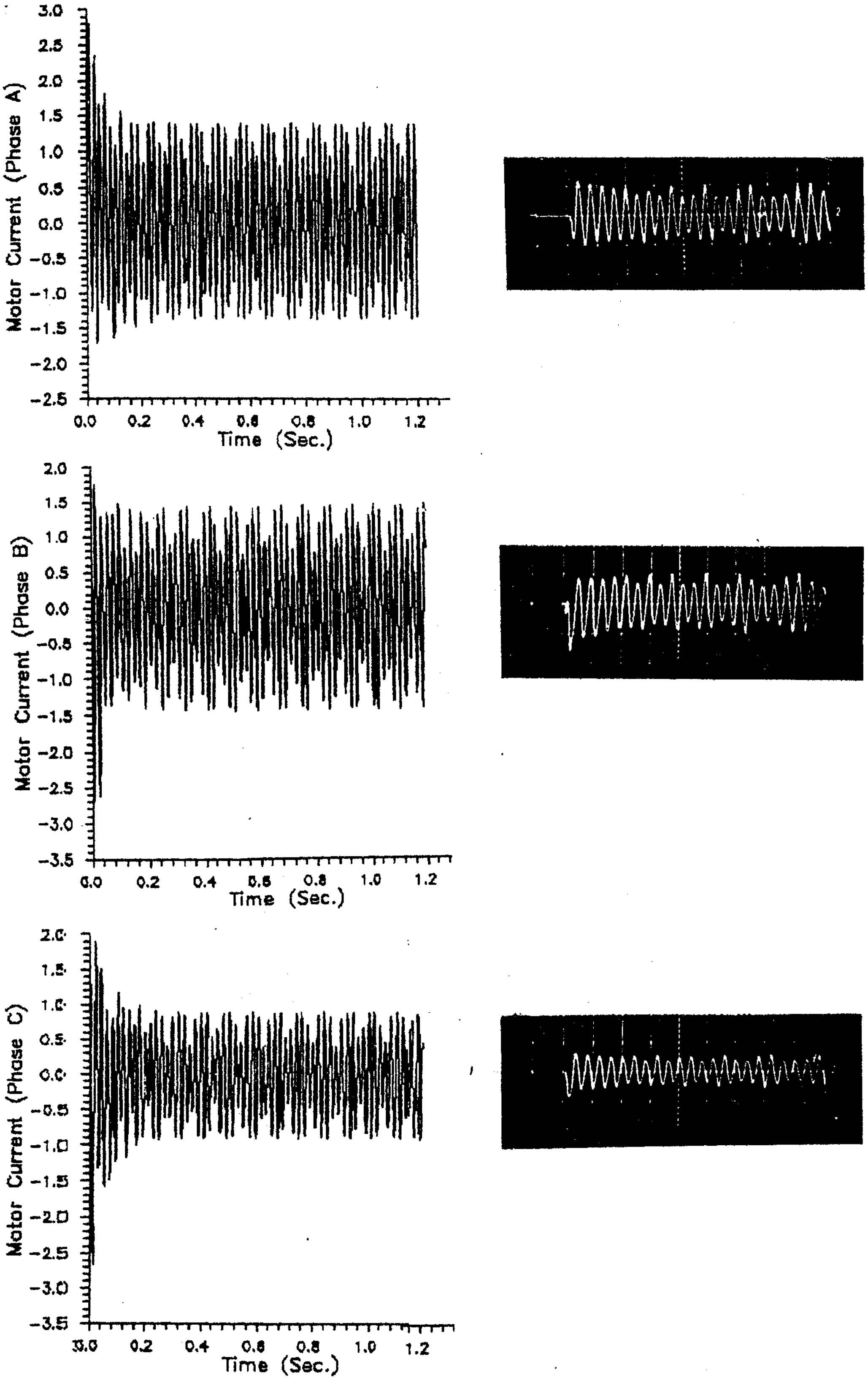
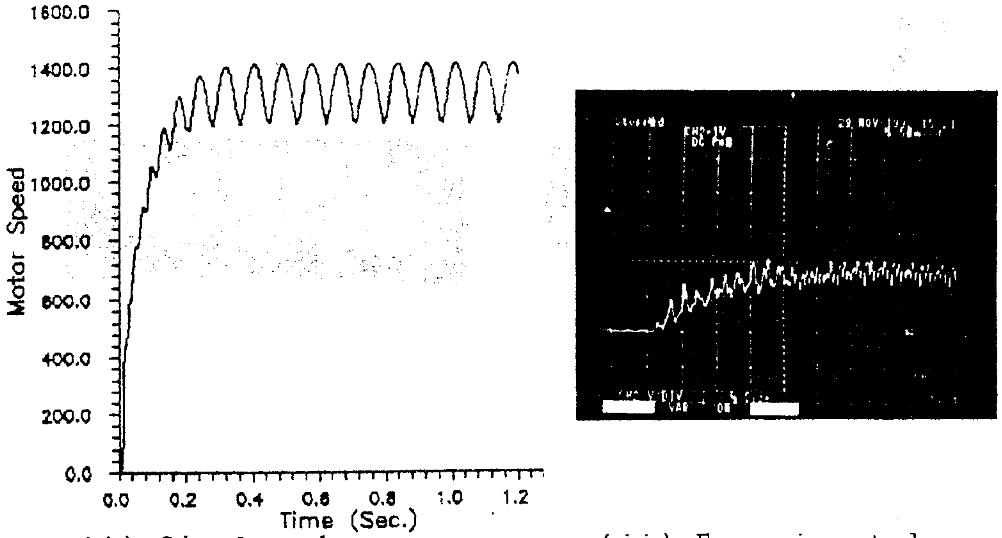


Fig.(1) : Relutance motor with capacitive balancers .



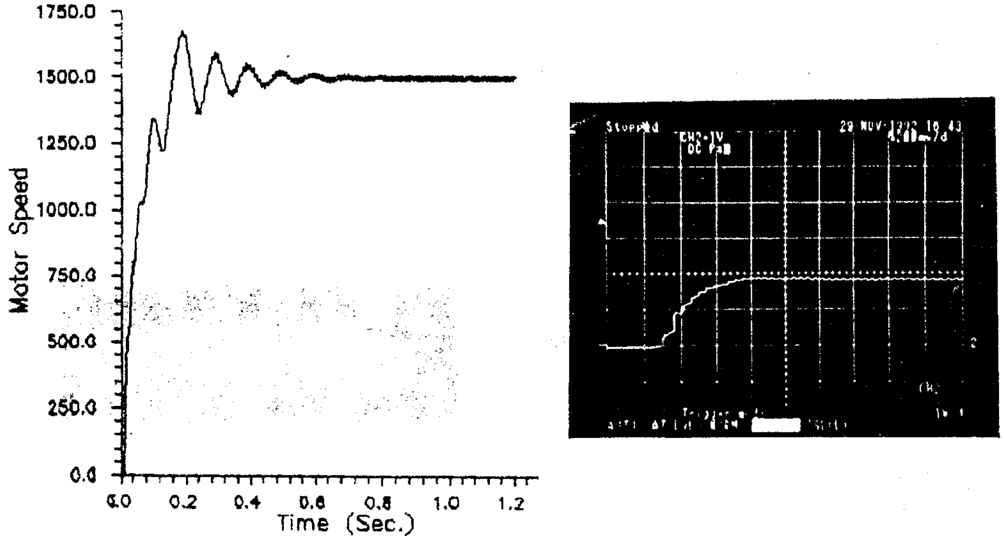
(i) Simulated. (ii) Experimental.

Fig.(2) : Motor phase currents during free acceleration (Without balancers)



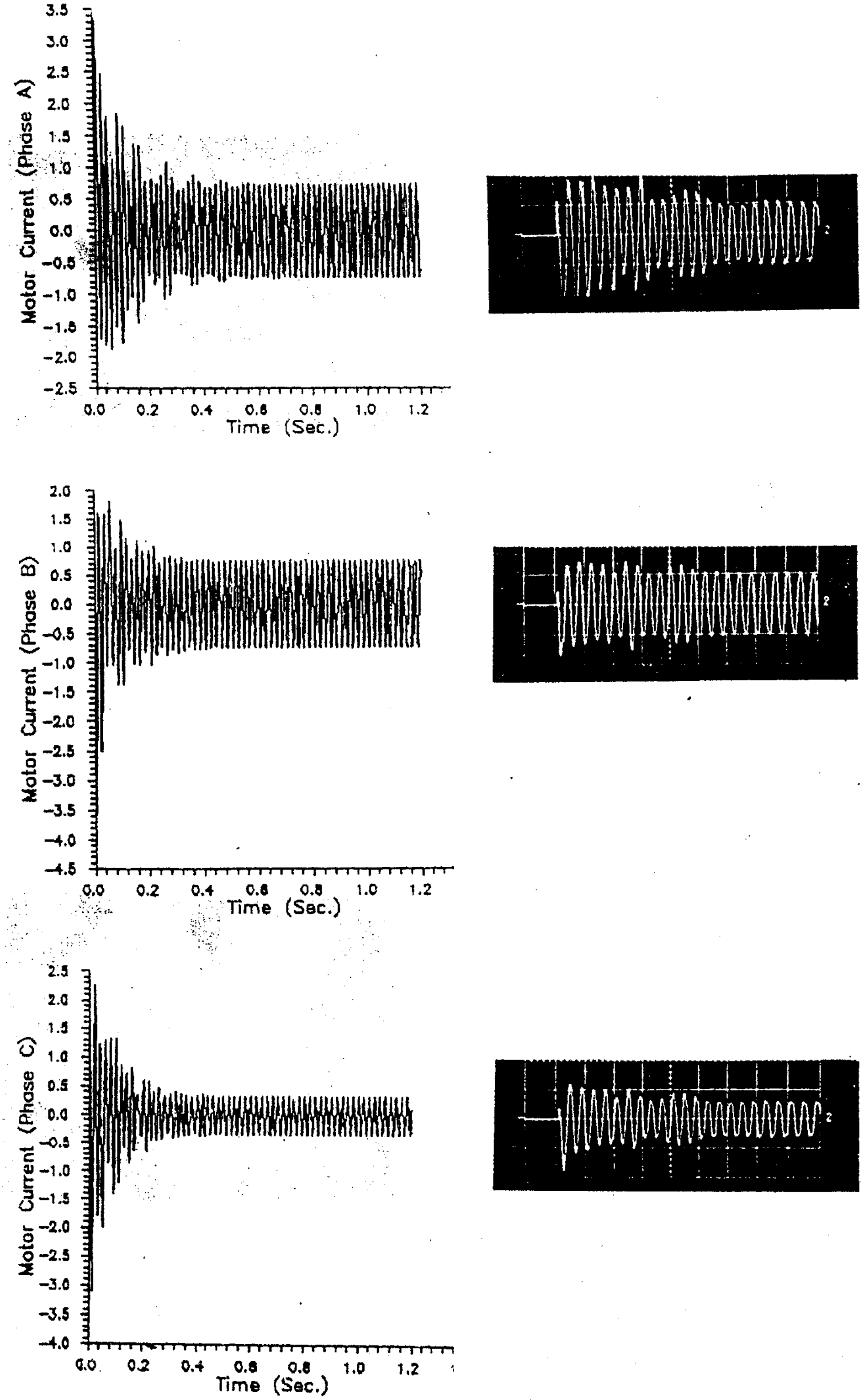
(i) Simulated . (ii) Experimental .

Fig.(3) : Motor speed during free acceleration (Without balancers) .



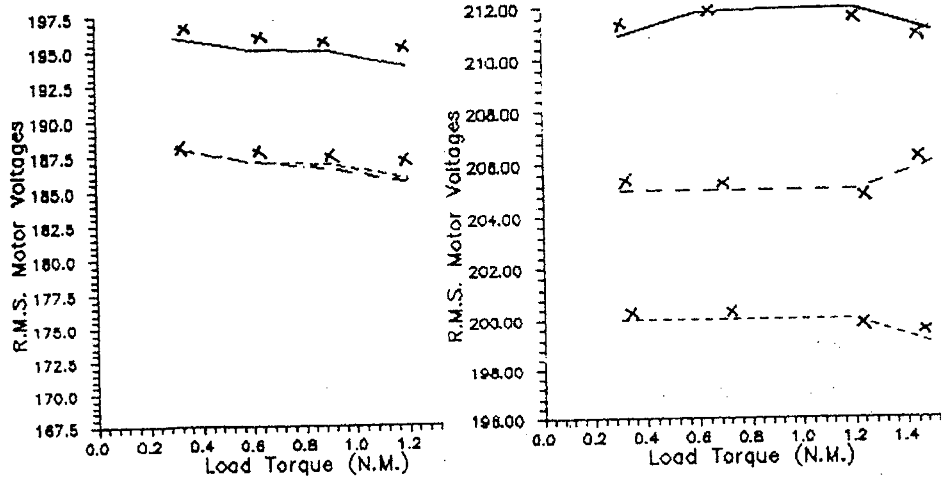
(i) Simulated . (ii) Experimental .

Fig.(5) : Motor speed during free acceleration (With balancers).



(i) Simulated . (ii) Expermental .

Fig.(4) : Motor phase currents during free acceleration (With balancers).



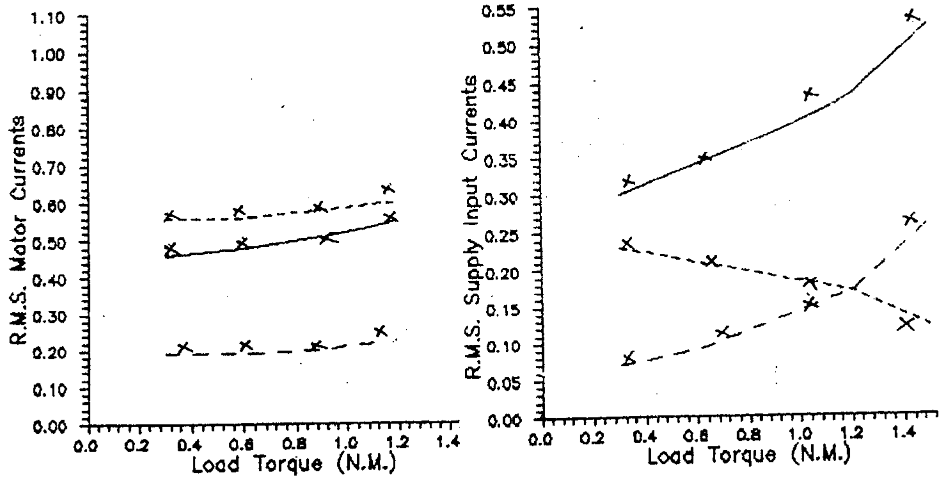
(i) Without balancers. (ii) With balancers .

Fig.(6) : Simulated and Experimental results of motor voltages

———————— Phase (a)

------------ Phase (b) x x x Experimental

— — — — — Phase (c)



(i) Without balancers. (ii) With balancers.

Fig.(7) : Simulated and Experimental results of supply currents.

" تأثير الجهد الغير متزن على أداء محركات الممانعة المغناطيسية ذات الثلاثة أوجه "

ملخص البحث

من المعتاذ أن يكون الجهد عند أطراف المستهلك غير متزن – ويرجع هذا الى عدم التحميل المنتظم للاحمال على أوجه الشبكة الكهربية – وهذا بدورة يفسد استقامة علامة الخرج والدخل لمحركات الممانعة المغناطيسية مما يفقدها أهم خاصية لها وهى الدوران بسرعة التزامن •

يقدم هذا البحث طريقة مبسطة للتغلب على عدم أتزان الشبكة الكهربية باستخدام موازن استاتيكى لكل وجه من اوجه المحرك • ولتقييم التقنية المقترحة ، فقد تم حل المعادلات التفاضلية اللاخطية الممثلة للنظام (المغذى – الموازن الاستاتيكى – المحرك) ، وقد تم اشتقاق المعادله التى تحدد سعة الموازن الاستاتيكى بدلاله بارامترات المحرك ووضعت ضمن برنامج الحاسب الآلى لحساب سعة الموازن الاستاتيكى المناسبة لأى درجة من درجات عدم أتزان الأوجه الثلاثيه •

ولاثبات صحة الحسابات النظرية فقد تم بناء التجربة المعملية الممثلة للنظام واخذت النتائج المعملية عند البدء والاستقرار ووجد تقارب ملحوظ بين النتائج المعملية والنظرية ، وقد أوضحت النتائج عجز المحرك عن التزامن مع المنبع عند عدم استخدام الموازن الاستاتيكى وكيف أمكن التغلب على هذة الظاهرة وتشغيل المحرك بصورة مرضية من منبع غير متزن الجهد •