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Effect of Phase-Balancer Capacitance on the Dynamic Behavior of a Three-Phase Induction Motor Operated from a Single Phase Supply

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Abstract. This paper presents an analysis for the transient performance of a three phase induction motor operated from a single-phase supply via phase modifier capacitor inserted with stator phases. The analysis is performed using the instantaneous symmetrical components approach along with sequence operational equivalent circuits of the motor.

It has been shown that the choice of phase balancer condenser should be decided upon by the steady state performance levels as well as steady state double frequency torque pulsations. It was concluded that there exists a value of the capacitor that yields minimum value of torque pulsations, thus adding a new criterion for capacitor selection.

List of Symbols

X_m	Magnetizing reactance of the motor.
T_e	Electromagnetic torque developed by the motor.
J	Intertia of rotating parts.
D	Damping factor.
X_1	Stator leakage reactance.
X_2	Rotor leakage reactance referred to stator.
i_{sr}, i_{rr}	Real part of stator and rotor instantaneous sequence currents.
i_{sg}, i_{rg}	Imaginary part of stator and rotor instantaneous sequence currents.
υ	Rotor speed in p.u.
s	Slip in p.u.
V_m	R.M.S. values of applied single phase motor voltage.
V_p/V_n	R.M.S. values of per phase positive and negative stator voltages.
V_s	Instantaneous value of input supply voltage.

1. Introduction

Operation of three phase induction motors from single phase supply is sometimes dictated by the nature of the available supply. An example of such situation is the electrification of rural areas where three phase farming equipments are to be operated from the usually available single-phase supply. Another example is usually met in electric locomotives where auxiliary pumps and fans are set to operate on the single phase traction supply.

Solution of such problems was conventionally achieved by using single to three phase rotary converters or motor/generator sets. To avoid maintenance problems and added system costs, static phase converter circuiteries have been developed and successfully utilized. One of the simplest phase converter schemes [1,2,3,4] is shown diagrammatically in Fig. 1. An alternative scheme, reported recently, is shown in Fig. 2 [5]. This scheme is based on the synthesis of a second phase of supply from the available source, through an auto-transformer rectifier-filter-inverter arrangement in a way to feed the three phase load.

The first scheme is characterized by simplicity and less expenditure regarding auxiliary equipments (capacitors), but suffers from the fact that efficient operation demands motor derating and capacitor variation to match new load conditions. As for the second scheme, it is suitable for motors of high ratings, since extra cost associated with power electronic devices will be counterbalanced by better running performance figures.

The choice of the phase balancer capacitor in the first scheme is based on maximizing certain output criterion. For example ref. [6] discussed methods of determining suitable capacitor sizes throughout the speed range to ensure:

a) Minimum unbalance;
b) Minimum negative sequence voltage; or
c) Zero negative sequence voltage.

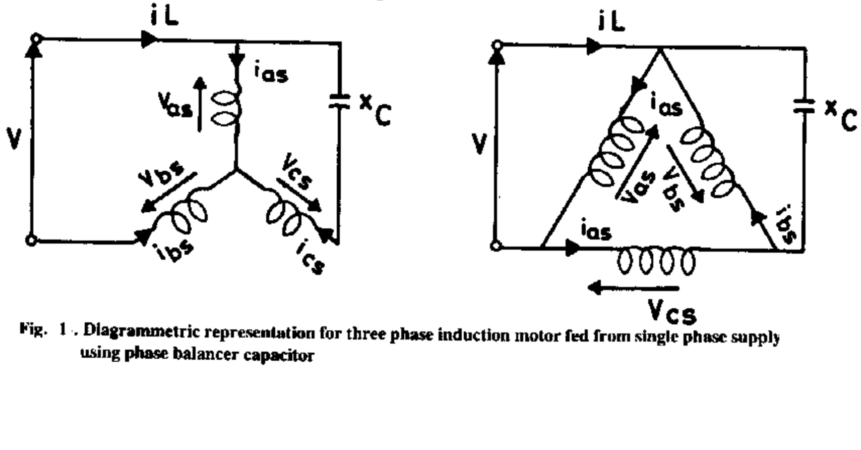


Fig. 1. Diagrammetric representation for three phase induction motor fed from single phase supply using phase balancer capacitor

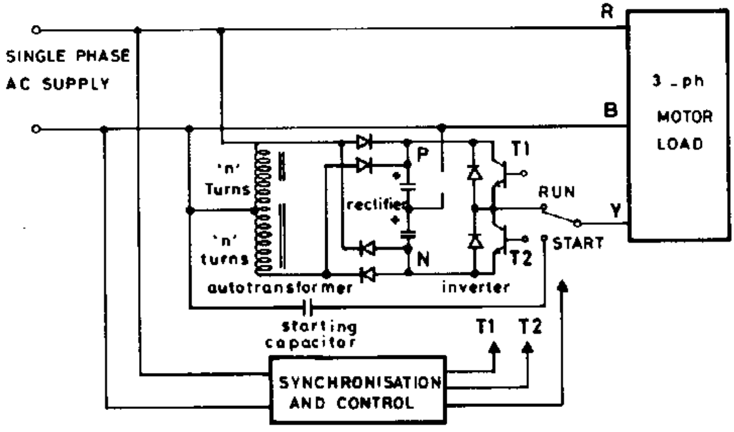


Fig. 2. Schematic representation for operating three phase induction motor from single-phase supply using second phase synthesis

Moreover, ref. [7] extended the scope of capacitor choice by presenting extensive analysis for running performance under the above mentioned criteria and added methods for determining capacitor sizes yielding:

a) Maximum output torque; or
b) Maximum input power factor.

The choice of capacitor, under the previously mentioned conditions, was mainly based on steady state analysis. This is performed by assuming only the steady state equivalent circuits and evaluating average values of power and torques as well as effective values of currents and voltages. Moreoever, it should be born in mind that the motor operates in such a scheme in an unbalanced mode. This means that double frequency pulsating torque exists in the steady state operation. These torque pulsations might reach prohibitive values and affect motor stability especially at low frequencies.

The aim of this paper is to shed light on steady state torque pulsations and to compare motor performance regarding such pulsations when using capacitors satisfying the previously mentioned criteria.

2. Analysis

The motor considered in this investigation is connected as shown in Fig. 1-b *i.e.* delta connected. However, the analysis presented could be applied to star connected motors as well after modifying its parameters.

Steady state analysis for the motor operating under such conditions is achieved by using phasor symmetrical components transformations applied to sequence equivalent circuits of the motor. The analysis has been covered extensively in the literature [7&8]. As for transient analysis, it could be achieved by using equivalent D/Q model of the motor after being modified to suit motor conditions or by using the instantaneous symmetrical components (i.s.c) transformation along with its operational equivalent circuits [8&9].

2.1. Motor Equations in Transient Model

The equations describing motor transient performance when operated as shown in Fig. 1, can be deduced using (i.s.c) approach. Reference [8] gave detailed analysis for such a problem for motors connected either in star or in delta. The analysis was achieved primarily via instantaneous symmetrical components for both sequence voltage and currents. The second step was to reformulate motor dynamic equations in terms of real and imaginary parts of (i.s.c) of currents. Motor equations in this case can be written using constraints equations (1) as follows:

$$V - V_{sa} = 0$$

and

$$V_{sc} + \frac{X_c}{p}(i_{sc} - i_{sb}) = 0 \qquad (1)$$

where

$$p = \frac{1}{\omega}\frac{d}{dt}; \quad \text{and} \quad X_c = \frac{1}{\omega C}$$

Transforming constraint equations into equivalent (i.s.c.) yields:

$$V = \frac{1}{3}(V_s^+ + V_s^-)$$

$$0 = \frac{1}{3}(aV_s^+ + a^2V_s^-) + j\frac{X_c}{p}(i_s^+ - i_s) \qquad (2)$$

Using constraints equations along with sequence voltage balance equation expressed in terms of sequence currents and impedances as shown in Fig. 3; then

$$V = \frac{1}{\sqrt{3}}\{(R_s + X_sp)\,i_s^+ + X_mp\ i_r^+ + (R_s + X_sp)\ i_s^- + X_mpi_r^-\}$$

$$0 = \{\frac{R_r}{(1 - j\frac{v}{p})} + X_r p\}\ i_r^+ + X_m p\, i_s^+ \tag{3}$$

$$0 = \{\frac{R_r}{(1 - j\frac{v}{p})} + X_r p\}\ i_r^- + X_m p i_s^-$$

$$V = \frac{1}{\sqrt{3}}\{a[(R_s + X_s p)\, i_s^+ + X_m p\ i_r^+] + a^2 (R_s + X_s p) i_s^-$$

$$+ X_m p i_r^-]\} + j\frac{x_c}{p}(i_s^+ - i_s^-)$$

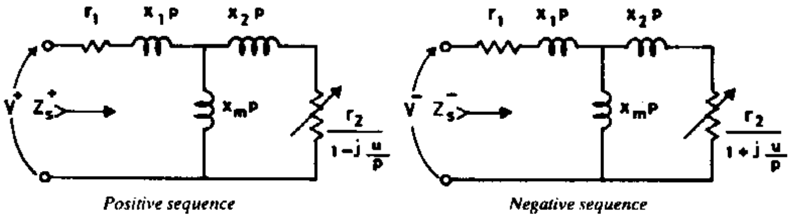


Fig. 3. Positive and Negative sequence operational equivalent circuits of three-phase induction motor

where;

X_s is the self reactance of stator phase winding = $X_1 + X_m$ &
X_r is the referred value of rotor phase self reactance = $X_2 + X_m$

Currents instantaneous symmetrical components i_s^+ and i_s^- will be complex but when transformed into actual phase currents should yield real values. Such a condition is only fulfilled if these quantities are conjugates. The same applied for i_r^+ and i_r^-. Consequently, these currents could be written in terms of its real and imaginary parts as follows:

$$\begin{aligned} i_s^+ &= i_{sr} + j\, i_{sg} \\ i_s^- &= i_{sr} - j\, i_{sg} \\ i_r^+ &= i_{rr} + j\, i_{rg} \\ i_r^- &= i_{rr} - j\, i_{rg} \end{aligned} \tag{4}$$

Substituting from (4) into (3), then

$$\frac{\sqrt{3}}{2} V = (R_s + X_s p)\, i_{sr} + X_m p\, i_{rr}$$

$$0 = (R_r + X_r p)\, i_{rr} + X_m p\, i_{sr} + v(X_r\, i_{rg} + X_m\, i_{sg}) \qquad (5)$$

$$0 = (R_r + X_r p)\, i_{rg} + X_m p\, i_{sg} - v(X_r\, i_{rr} + X_m\, i_{sr})$$

$$0 = (R_s + X_s p)\, i_{sr} + \sqrt{3}(R_s + X_s p)\, i_{sg} + X_m\, p i_{rr} + \sqrt{3}\, X_m\, p i_{rg} + 2\sqrt{3}\, \frac{X_c}{p}\, i_{sg}$$

The previous equation can be put in state space form maintaining that an extra equation is added to account for the integration of i_{sg} present in the last term in equation (5). Hence;

$$p\, Q_{sg} = i_{sg}$$

Therefore, the previous equations can be put as

$$p\, [i]^{s,r} = [X]^{-1} . [V]$$

where

$$[i]^{s,r} = [i_{sr}\; i_{sg}\; i_{rr}\; i_{rg}\; Q_{sg}]^t$$

$$[X] = \begin{bmatrix} X_s & 0 & X_m & 0 & 0 \\ X_m & 0 & X_r & 0 & 0 \\ 0 & X_m & 0 & X_r & 0 \\ X_s & \sqrt{3}X_s & X_m & \sqrt{3}X_m & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

and

$$[V] = \begin{bmatrix} \frac{\sqrt{3}}{2}V_s - R_s i_{sr} \\ - R_r i_{rr} - v(X_r i_{rg} + X_m i_{sg}) \\ - R_r i_{rg} + v(X_r i_{rr} + X_m i_{sr}) \\ - R_s i_{sr} - \sqrt{3} R_s i_{sg} - 2\sqrt{3} X_c Q_{sg} \\ i_{sg} \end{bmatrix}$$

Moreover, electromagnetic torque equation when put in p.u. notation using real and imaginary parts of motor currents is then written in the following form:

$$T_e = \frac{2}{3} X_m (i_{rr} i_{sg} - i_{sr} i_{rg})$$

The previous equation along with mechanical system equation yields

$$p\,v = (T_e - Dv - T_L)/2\omega H$$

H is the interia constant of the machine.

2.2. Steady State Equations

Input supply voltage (V_s) can be expressed in the time domain as

$$V_s = \sqrt{2}\, V_m \sin(\omega t)\ ; \ \ \omega = 2\pi f$$

It follows then that steady state equations can be obtained by substituting "j" for "p" and (1-s) for (v) in transient analysis equation (5).

$$\begin{aligned} \frac{\sqrt{6}}{2} V_m &= Z_s I_{sr} + j X_m I_{rr} \\ 0 &= Z_r I_{rr} + j X_m I_{rr} + (1 - s) \,.\, (X_r I_{rg} + X_m I_{sg}) \\ 0 &= Z_r I_{rg} + j X_m I_{sg} - (1 - s) \,.\, (X_r I_{rg} + X_m I_{sr}) \end{aligned} \quad (6)$$

$$0 = Z_s I_{sr} + \sqrt{3} Z_s I_{sg} + j X_m I_{rr} + j\sqrt{3} X_m I_{rg} - j 2 \sqrt{3} X_c I_{sg}$$

Equation (6) can be rewritten as

$$[V] = [Z] \cdot [I] \tag{7}$$

where

$$[V] = [\frac{\sqrt{6}}{2}V_m \quad 0 \quad 0 \quad 0]^t,$$

$$[I] = [I_{sr} \quad I_{sg} \quad I_{rr} \quad I_{rg}]^t$$

and

$$[Z] = \begin{bmatrix} Z_s & 0 & jX_m & 0 \\ jX_m & (1\text{-}s)X_m & Z_r & (1\text{-}s)X_r \\ -(1\text{-}s)X_m & jX_m & -(1\text{-}s)X_r & Z_r \\ Z_s & (\sqrt{3}\, Z_s - j2\sqrt{3}\, X_c) & jX_m & j\sqrt{3}X_m \end{bmatrix}$$

Solution of equation (7) for steady state values of motor i.s.c.'s real and imaginary parts of currents yields phasor values of I_{sr}, I_{sg}, I_{rr} & I_{rg} which when transformed to the time domain gives:

$$i_{sr} = I_{sr} \sin(\omega t - \phi_1),$$

$$i_{sg} = I_{sg} \sin(\omega t - \phi_2),$$

$$i_{rr} = I_{rr} \sin(\omega t - \phi_3),$$

and

$$i_{rg} = I_{rg} \sin(\omega t - \phi_4),$$

The instantaneous value of electro-magnetic torque developed is then given by:

$$T_e = \frac{2}{3} X_m [I_{rr} I_{sg} \sin(\omega t - \phi_3) \,.\, \sin(\omega t - \phi_2) - I_{sr} I_{rg} \sin(\omega t - \phi_1) \,.\, \sin(\omega t - \phi_4)]$$

$$= \frac{1}{3} X_m [I_{rr} I_{sg} \{\cos(\phi_2 - \phi_3) - \cos(2\omega t - \phi_3 - \phi_2)\} - I_{sr} I_{sg} . \{\cos(\phi_4 - \phi_1) - \cos(2\omega t - \phi_1 - \phi_4)\}] \quad (8)$$

Equation (8) shows two distinct torque components:

1) ***Average value given by:***

$$T_{av} = \frac{X_m}{3} \{I_{rr} I_{sg} \cos(\phi_2 - \phi_3) - I_{sr} I_{rg} \cos(\phi_4 - \phi_1)\} \quad (9)$$

2) ***Double supply frequency oscillatory component given by:***

$$T_{osc} = \frac{X_m}{3} [I_{sr} I_{rg} \cos(2\omega t - \phi_1 - \phi_4) - I_{rr} I_{sg} . \cos(2\omega t - \phi_2 - \phi_3)] \quad (10)$$

It follows then that the amplitude of torque oscillations is given by:

$$T_{osc} = \frac{X_m}{3} \{ [I_{sr} I_{sg} \cos(\phi_1 + \phi_4) - I_{rr} I_{sg} \cos(\phi_2 + \phi_3)]^2 + [I_{sr} I_{rg} . \cos(\phi_1 + \phi_4) - I_{rr} I_{sg} \sin(\phi_2 + \phi_3)]^2\}^{1/2} \quad (11)$$

3. Simulation

The main objective of the present paper is to shed light on the effect of phase balancer condenser on motor dynamic performance. Therefore, two computer programs were written to evaluate motor behavior in the transient as well as steady state modes based on the i.s.c. approach listed earlier.

3.1. Dynamic Performance Program

This program is written to solve for motor currents and torque during transient run-up period. In this case equations (5) are solved simultaneously after being put in state-space form and applying the Runge-Kutta method for numerical integration. The program is also designed to monitor the value of motor speed and switch over capacitor value from starting to running value upon attaining 75% of the synchronous speed.

3.2. Steady State Program

The steady state performance is predicted by simply solving algebraic equation (7) to determine steady state i.s.c. currents in the phasor domain. This is followed by evaluating average value and amplitude of the oscillatory torque components in the electro-magnetic torque.

4. Results and Discussion

The investigation was carried out on a delta connected three-phase, 3 phase, 415 V, 3.7 KW, 7.6 A, Δ connected induction motor whose parameters are as follows:

$$R_s = 0.0533 \text{ p.u} \quad , \quad X_1 = X_2 = 0.087 \text{ p.u}$$
$$R_r = 0.061 \text{ p.u} \quad \& \quad X_m = 2.77 \text{ p.u}$$

Therefore

$$X_s = X_r = 2.857 \text{ p.u.}$$

Inertia constant (H) = 0.065 sec.

No-load frictional torque may be considered to be (0.028 + 0.19 v) p.u.

Using above mentioned parameters along with transient state program, motor dynamic performance was predicted under different conditions. Firstly, the effect of the value of the phase balancer capacitor was investigated. Moreover, loading effect was then studied.

Selection of capacitor values was based on evaluating relevant capacitor ratings yielding optimum performance criterion [7], as shown in Fig. 4.

Variation of torque and speed versus time during transients following direct switching to the supply with the motor unloaded are illustrated in Fig. 5, assuming a capacitor value of 0.118 p.u. to be connected during starting and running. Such a capacitor value yields maximum (V_p/V_n) at starting. Keeping this capacitance connected even during running led to excessive double frequency torque pulsations amounting to 5.8 p.u. during steady running conditions. On the other hand using a capacitances of 0.10261 and 0.1174 p.u. yield torque and speed variations shown in Figs. 6 & 7 for unloaded case. The first capacitor yields maximum torque while the second gives maximum power factor both at starting.

In the previous cases torque oscillations during steady running conditions are approximately of the same order and have reached values of such an order that produced pronounced speed oscillations. Severe torque pulsations will contribute to high noise level and might be even harmful at low frequencies. Therefore, it is customary to change phase balancer capacitors according to motor speed.

Results related to cases of having a specific capacitor at start and another at run are shown in Figs. 8, 9 and 10. The case shown in Fig. 8 employs a starting capacitor of 0.11847 p.u. (yielding maximum V_p/V_n at starting) and a running one of 1.5137 p.u. (corresponding to maximum V_p/V_n during unloaded running). Torque pulsa-

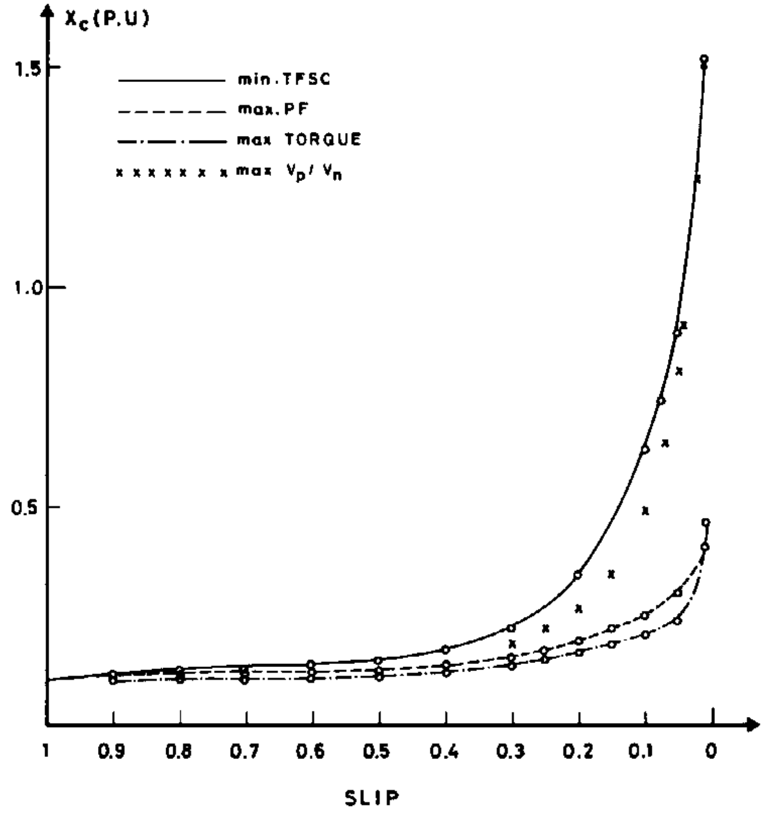


Fig. 4. Variation of phase balancer capacitance versus slip to satisfy different opeating criteria

tions in the steady state are of negligible order. As for the second case shown in Fig. 9, starting capacitor was chosen to be equal to 0.1174 p.u. (related to maximum power factor at starting) while the running capacitor was set to 0.4083 p.u. (maximum torque at running). Torque oscillations in the steady state have reached an order of 2.0 p.u. The third case shown in Fig. 10 is related to starting the motor with a capacitor of 0.10261 p.u. (maximum torque at starting), while running capacitor equals to 0.4602 p.u. (maximum power factor at running). Again torque oscillations amounted to 1.28 p.u.

From the previous Figures, it could be concluded that:

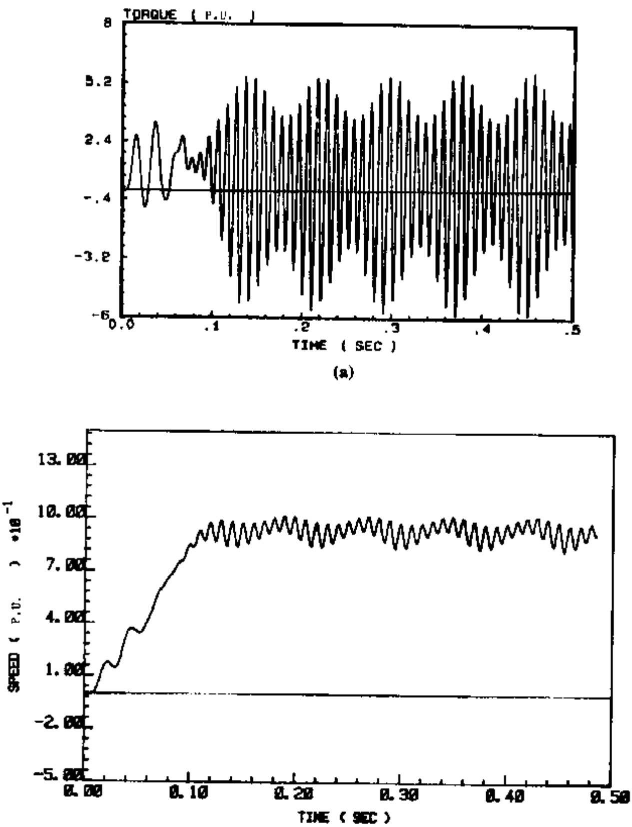
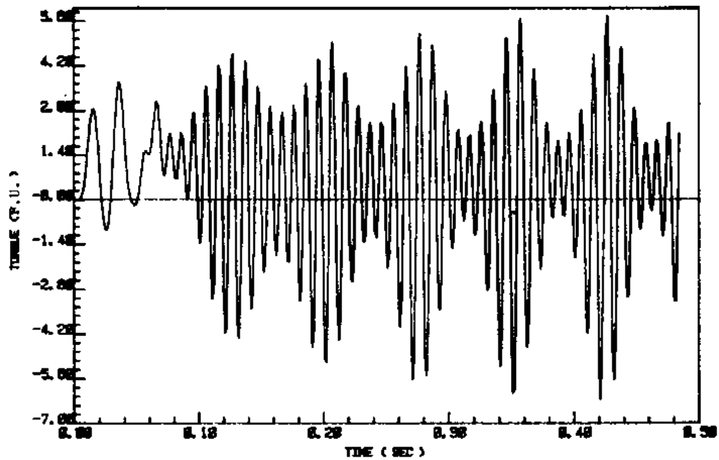


Fig. 5. Variation of torque and speed versus time upon switching on to an AC supply of 1.0 p.u. $X_{c_{st}}$ = 0.118 p.u. and $X_{c_{run}}$ = 0.118 p.u.

– Starting torque patterns have not been affected by choosing a capacitor related to one of the three criteria, namely; maximum V_p/V_n, maximum power factor or maximum torque. This resulted from the fact that deviation in capacitor rating for the three cases is so small.

– Steady state torque pulsations are of negligible order when maximum V_p/V_n capacitor is used, while using either maximum torque or power factor capacitors yielded high values of torque oscillations.



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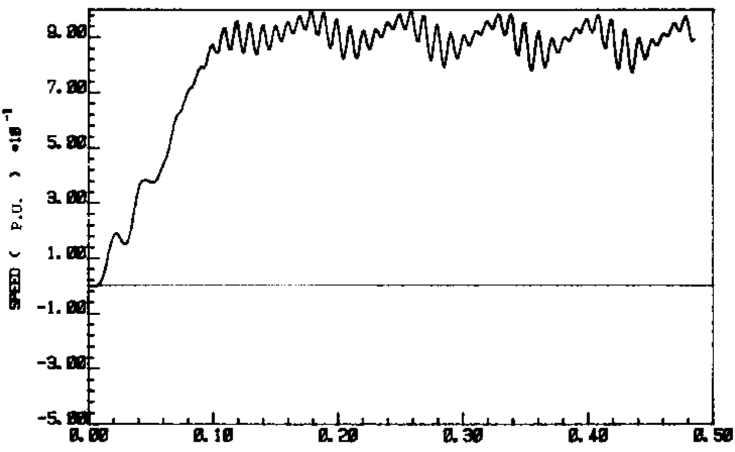
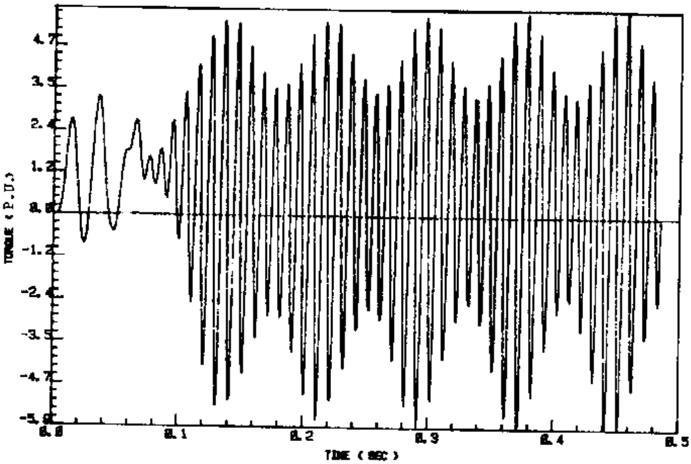


(b)

Fig. 6. Torque and speed variations upon switching on to an AC supply of 1.0 p.u. (Unloaded case) $X_{c_{st.}}$ = 0.10261 p.u. and $X_{c_{run}}$ = 0.10261 p.u.



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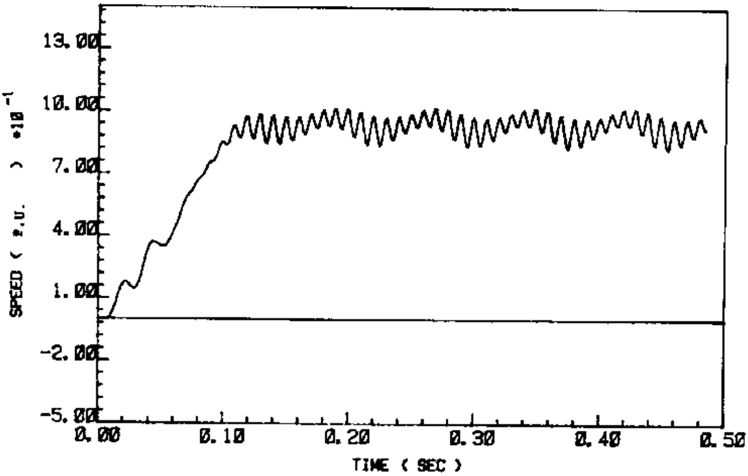

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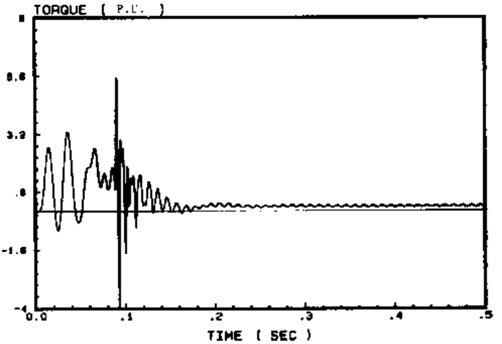
Fig. 7. Torque and speed variation upon switching on to an AC supply of 1.0 p.u. (Unloaded case) $X_{c_{st}}$ = 0.1174 p.u. and $X_{c_{run}}$ = 0.1174 p.u.



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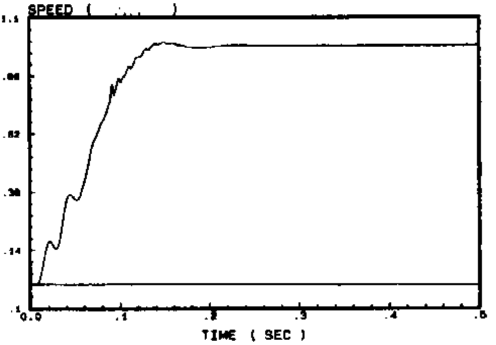


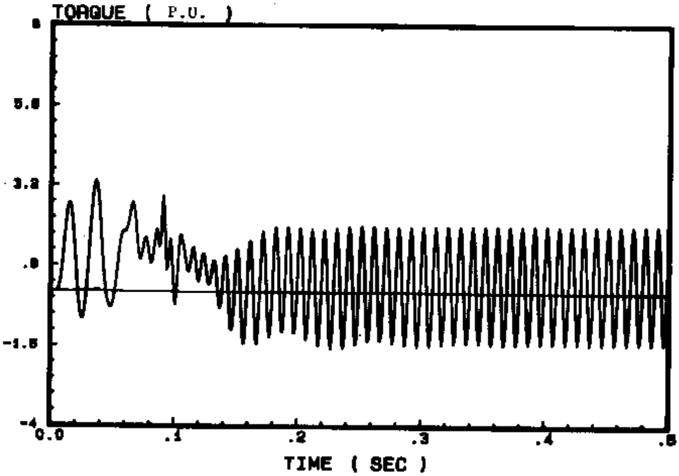
(b)

Fig. 8. Torque and speed variations upon switching on to an AC supply of 1.0 p.u. (Unloaded case) $X_{c_{st}}$ = 0.1185 p.u. and $X_{c_{run}}$ = 1.5137 p.u.

Effect of loading the motor can be well demonstrated by torque and speed/time variations shown in Figs. 11 & 12. In Fig. 11, transient patterns are shown for X_c = 0.10261 p.u. (maximum torque) and X_c = 0.8061 p.u. (maximum V_p/V_n at slip 0.05) and load torque of 0.458 p.u. On the other hand, Fig. 12 shows transient torque and speed for $X_{c_{st}}$ = 0.10261 p.u. and $X_{c_{run}}$ = 0.237 p.u. (maximum torque at slip of 0.05) and load torque of 0.871 p.u. It could be observed that using maximum torque capacitor at running resulted in excessive double frequency torque oscillations.

5. Effect of Capacitor Values on Torque Oscillations

The value of the amplitude of double frequency oscillations can be predicted in a straightforward manner by solving steady state equations (sec. 2.2) and substituting in equation (11). The validity of such an approach was ascertained by comparing



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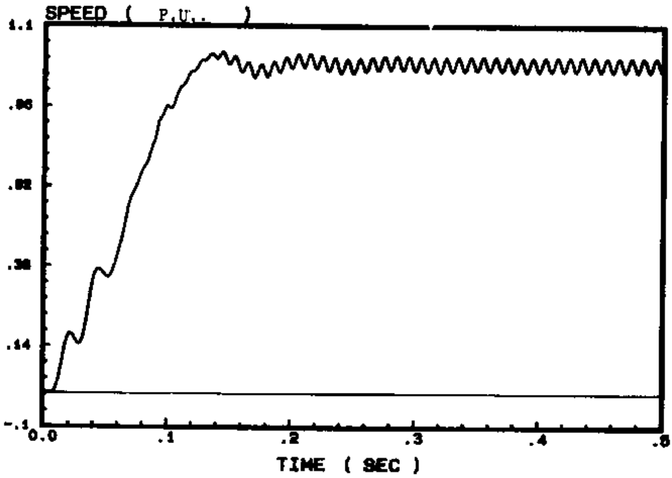
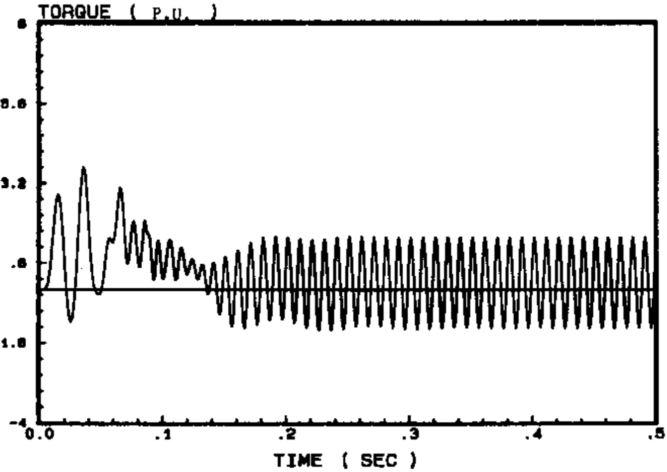


(b)

Fig. 9. Torque and speed variations upon switching to an AC supply of 1.0 p.u. (Unloaded case) $X_{c_{st.}}$ = 0.1174 p.u. and $X_{c_{run}}$ = 0.4063 p.u.



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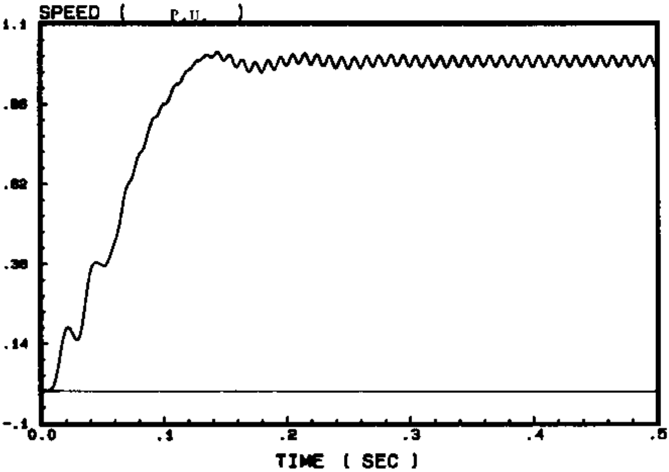

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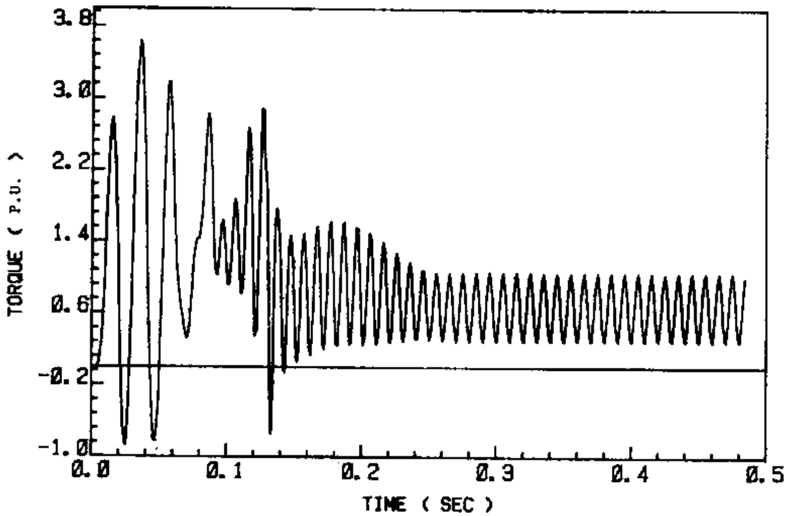
Fig. 10. Torque and speed variations upon switching on to an AC supply of 1.0 p.u. (Unloaded case) $X_{c_{st}}$ = 0.10261 p.u. and $X_{c_{run}}$ = 0.4602 p.u.



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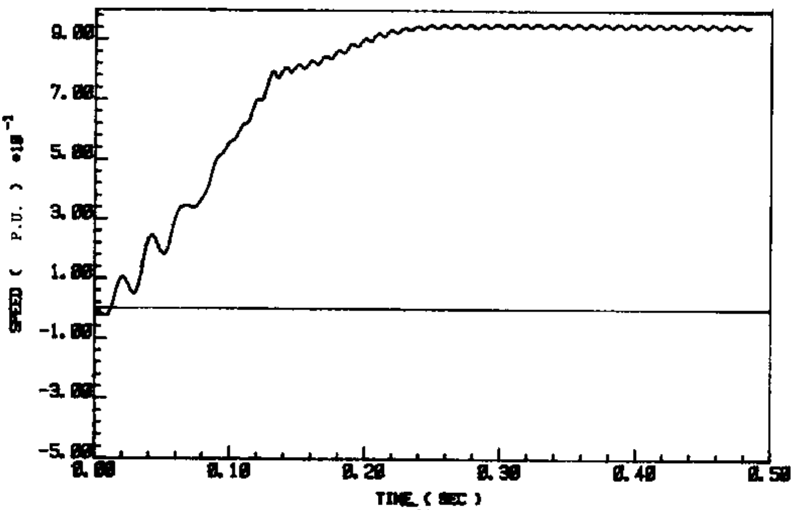
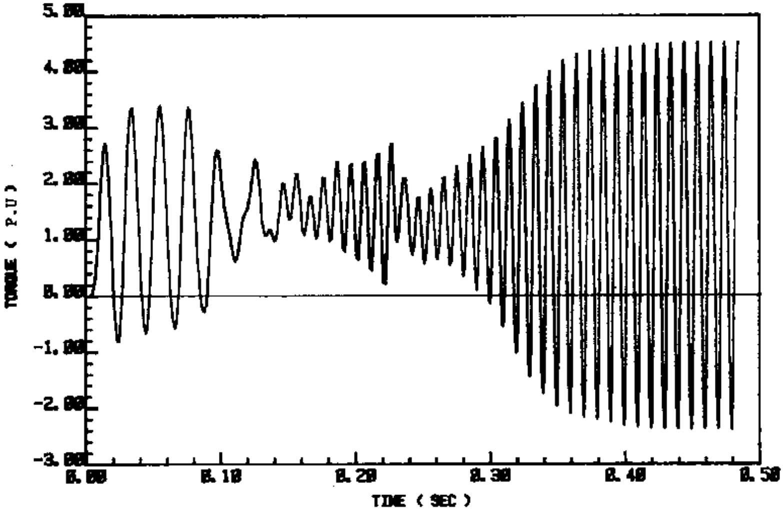


(b)

Fig. 11. Torque and speed variation upon switching on to an AC supply of 1.0 p.u. (motor loaded with 0.458 p.u.) $X_{c_{st.}} = 0.10261$ p.u. and $X_{c_{run}} = 0.8061$ p.u.



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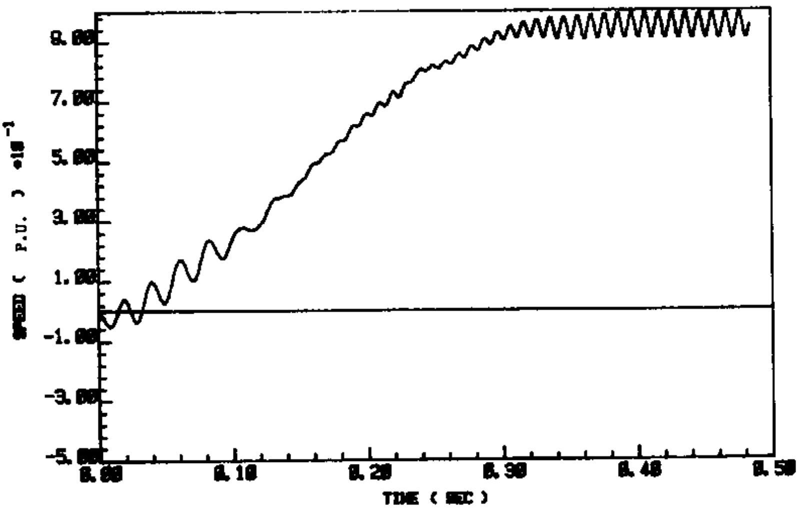

(b)

Fig. 12. Torque and speed variation upon switching on to an AC supply of 1.0 p.u. (motor loaded with 0.871) p.u. $X_{c_{st}}$ = 0.10261 p.u. and $X_{c_{run}}$ = 0.237 p.u.

observed that it is close to capacitor values yielding maximum V_p/V_n. The difference may be attributed to stator impedance drops. On the other hand, variation of minimum torque oscillations versus slip is shown in Fig. 13. Again, values of such minimum torque oscillations are very close to those resulted from using maximum V_p/V_n capacitors.

6. Conclusions

From the foregoing analysis the following conclusions can be drawn:

- Choice of phase balancer capacitor is governed by steady state as well as dynamic performances of the motor.
- In steady state running conditions there exist double frequency torque oscillations due to the existence of unbalance in motor currents.
- Double frequency torque oscillations are of high amplitudes when maximum torque capacitor is employed. Moreover, using maximum power factor capacitors yielded less torque oscillations followed by maximum V_p/V_n capacitors.
- Capacitor value could be chosen in order to yield minimum torque oscillations. These values are close to maximum V_p/V_n capacitor values.
- Choosing running capacitor to yield maximum V_p/V_n is favoured in the light of the steady state as well as transient performances.

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تأثير موازنات الطور السعوية على الأداء الديناميكي لمحرك الحث ثلاثي الأطوار عند تشغيله من منبع أحادي الطور

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ملخص البحث: يقدم هذا البحث تحليلا للأداء الانتقالي لمحرك الحث ثلاثي الأطوار عند تغذيته من منبع أحادي الطور عن طريق معدل طور سعوي موصل مع ملفات أوجه الثابت. وتم تطبيق مدخل المركبات المتماثلة اللحظية على دوائر المحرك المكافئة الانتقالية والتتابعية لإيجاد معدلات الأداء الديناميكي.

ولقد تبين أن اختيار سعة موازن الطور يجب أن تتحدد عن طريق اعتبار معدلات أداء المحرك في حالتي الاستقرار ووضع مركبات العزم المتنابضة بضعف تردد المنبع في الحسبان. ولقد استنتج من التحليل وجود قيمة للمكثف تعطي أقل قدر ممكن من مركبة العزم المتنابضة. وبالتالي يضيف هذا البحث عاملاً آخرًا ينبغي مراعاته عند تحديد قيمة موازن الطور.