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SYNCHRONIZATION OF RELUCTANCE MOTORS

Farouk I. Ahmed, S.E. Abo-Shady, Member, IEEE and K.F. Ali

Electrical Power and Machines Department, Cairo University, A.R. EGYPT

Abstract- In most of control and industrial applications, a high degree of rotational stability and uniformity of speed is required. These requirements can be achieved by using reluctance motors. The synchronization process of such motors is of prime importance for these applications. Therefore, a simple and accurate criterion is developed to define this process. The validity of the criterion developed is confirmed through experimental results. The effect of supply voltage variations, the supply frequency and the ratio x_d/x_q on the synchronization process is investigated.

INTRODUCTION

Reluctance motors have been very successfully used in a wide variety of applications which require constant speed operation and high degree of rotational stability.[1]

The motor must pass through an electromechanical transient process,(i.e. synchronization or pulling-into-step process), in order to attain its synchronous speed. The precise determination of the transient behaviour requires a complete solution of the electrical and mechanical non-linear differential equations describing the motor.

In this regard, intensive studies have been made with the help of differential analyzers, analog and digital computers. As such studies are very time consuming, many assumptions, based on observations inferred from these studies, are made to obtain simplified solutions of the problem.[2-4] Some of these assumptions are unsatisfactory with regard to neglecting the effect of specific parameters or choosing the boundary conditions of the synchronization period. Lawrenson et al[5] have introduced a simple and useful criterion for the determination of the maximum value of the inertia that can be synchronized against a certain load torque. However, they have neglected the dependency of the amplitude of the pulsating torque on the slip during synchronization and considered it to be constant equal to its value at the synchronous speed. Further, the pulsating torque variation with slip is found to be greatly affected by the large values of the ratio x_d/x_q and also by the high values of the supply frequency 6.

In view of the above, it is intended to develop a modified criterion which takes into account the variation of the pulsating torque during the synchronization process. The validity of this criterion is verified through experimentation on an actual machine.

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Almost, in all the published literature, no study has been reported regarding the effect of supply voltage variations, the supply frequency and the ratio x_d/x_q on the synchronization process. Lawrenson et al[7] have considered the variations in the supply voltage and its effect on the synchronizing capability of the motor through the use of analog and digital computers. The effect of these parameters is, therefore, investigated and discussed in this paper.

THE SYNCHRONIZATION PROCESS

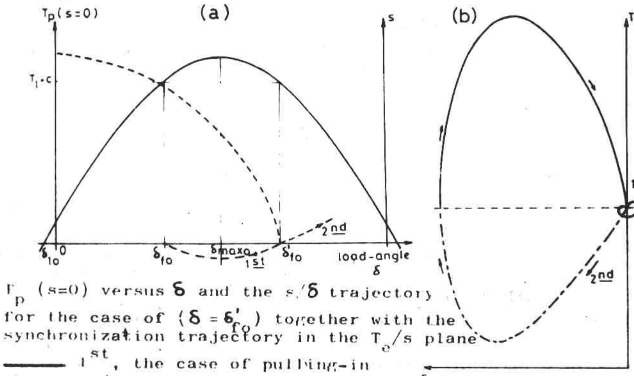
As a result of the construction asymmetries, (i.e. magnetic and electrical asymmetries), provided in the rotor of a reluctance motor, the electromagnetic torque developed by the motor has two components, namely, the asynchronous torque,(time independent), and the pulsating torque,(time dependent). 8 As in the case of induction motors, the asynchronous torque brings the motor up to a speed very close to the synchronous speed. Then, the motor must pass through an electro-mechanical transient in order to change its mode of operation from that of an induction motor to that of a reluctance motor. At such a high speed, the frequency of the pulsating torque is so small that this component tends to act as if it were a steady torque, and this may help the rotor accelerate and go into synchronism.

Instead of studying this phenomenon with the help of analog and digital computers, which is very time consuming, the steady-state asynchronous operation of such motors is considered. In this concern, the pulsations of the speed are neglected, (i.e. the motor is considered to operate asynchronously at a constant speed), and simplified analytical solutions can be obtained[8]. Consequently, a simple analytical expression for the electromagnetic torque developed is obtained which helps in deriving the synchronization criterion. The expressions of the torque components and the different load-angles necessary for the derivation of the criterion are given in Appendix-I.

PULL-IN CRITERION

Logically, the synchronization process is assumed to start when the accelerating torque, existing on the shaft of the machine, starts to increase from a zero value. This accelerating torque helps the rotor accelerate and go into synchronism. The process terminates when the accelerating torque next becomes zero.

The different possibilities which can occur during the synchronization process have been studied in reference [5] to define the various modes of operation. With the consideration of the most critical mode of operation given by Fig.1, the terminal conditions of the synchronization process can be determined. For this case, the slip reaches the zero value at a load-angle lies in the unstable region of the pulsating torque versus load-angle curve. At this load-angle, either pull-in or pole slip occurs depending on system operating conditions. If these conditions tend to reduce the load-angle below this value, then T_p will increase above (T_1+c) and synchronization takes place with further acceleration and termination at the steady-state load-angle corresponding to the applied load torque, T_1. However, if the system conditions tend to increase the load-angle, T_p will be less than (T_1+c) and a pole slip occurs. The two possibilities are illustrated in Fig.1.



T_p (s=0) versus δ and the s/δ trajectory for the case of ($\delta = \delta'_{fo}$) together with the synchronization trajectory in the T_e/s plane
——— 1st, the case of pulling-in
— - — 2nd, the case of pole-slipping

Under such a condition, the inertia that can be synchronized against a certain load torque is the maximum. This is because the net accelerating torque, during the completion of synchronization, has maximum value.

For this critical specified case, the terminal conditions are as follows;

$$\delta = \delta'_{fo} \qquad s = 0 \tag{1}$$

From these terminal conditions, it is possible to work backwards to a general pull-in criterion.

The equation of motion of a reluctance motor can simply be written as[5] ;

$$T_t = J\, P^2\theta_m = T_a + T_p - T_1 \tag{2}$$

In terms of slip, equation (2) can be written in a form suitable for the derivation of the criterion, (see Appendix-I), as follows;

$$-J\,\frac{W_s^2}{P}\,.\,s\,\frac{ds}{d\delta} = T_a + T_p - T_1 \tag{3}$$

Equation (3) is a non-linear differential equation in the slip and it is very difficult, if not impossible, to obtain a direct analytical solution. However, the variation of the slip during the synchronization process can be represented as a cosine function of the load-angle, which is justified through the study of many complete transient synchronization characteristics by analog and digital computers.[5] With this assumption, a simple analytical solution of equation (3) can be obtained. In order to satisfy the terminal conditions, the slip equation may be written as :

$$s = s_o \cos(\delta - \delta'_{fo} + \pi/2) = s_o \cos(\delta - \delta_o) \tag{4}$$

Where, s_o and δ_o are the initial slip and initial load-angle, respectively.

With the help of Appendix-I, δ_o is given by ;

$$\delta_o = -(\delta_{fo} - 2\,\delta_{1o}) \tag{5}$$

The initial value of the slip can be obtained from equations (3) and (4), under the condition that the accelerating torque equals zero. It follows that ;

$$s_o = \frac{1}{2U}\left(-V + (V^2 - 4\,U\,W)^{1/2}\right) \tag{6}$$

where,

$$U = a + d\,\sin 2\delta_o + g\,\cos 2\delta_o \tag{7}$$

$$V = b + e\,\sin 2\delta_o + h\,\cos 2\delta_o \tag{8}$$

$$W = f\,\sin 2\delta_o + i\,\cos 2\delta_o - (T_1 + c) \tag{9}$$

The constants from a to i are defined in Appendix-I.

Finally, performing the integration of equation (3), using equation (4) and substituting for initial and final conditions, yields the pull-in criterion for the maximum inertia which can be synchronized against a certain load torque as ;

$$J = \frac{P}{W_s^2}\cdot\frac{2}{s_o^2}\Big[-\Big(\frac{g\,s_o^2}{2} + 2/3\,h\,s_o + i\Big)\cdot \sin 2\delta_o + \Big(\frac{d\,s_o^2}{2} + e\,s_o + \frac{h\,s_o}{3} + f\Big)\cdot \cos 2\delta_o - \pi/2\Big(T_1 + c - \frac{a\,s_o^2}{2} + b\,s_o + \frac{d\,s_o^2}{4}\sin 2\delta_o - g\,\frac{s_o^2}{4}\cos 2\delta_o\Big)\Big] \tag{10}$$

However, with the assumption that the amplitude of the pulsating torque remains constant during the synchronization period, the expressions of s_o and J are reduced to those given by Lawrenson et al[5]. Although these expressions are simple, they may lead to erroneous results as will be shown latter.

Effect of Supply Voltage Variations on the Synchronization Process

As the torque developed by a machine is proportional to the square of the supply voltage, a machine which satisfactorily synchronizes a certain load on the full supply voltage may fail to do so when it is run up on a reduced voltage. Thus, it is important that allowance be made at the determination of a motor specification for any possible fall in the voltage. This can be achieved by deriving a criterion for the load torque that can be synchronized against a certain applied voltage for a specific inertia. However, due to the fact that most of the parameters (e.g., initial slip and initial load-angle) which define such a criterion are load dependent, it is very difficult to derive an explicit criterion in this concern. In spite of this difficulty, a family of curves, representing the maximum load torque that can be synchronized against a specific inertia, may be obtained for various values of the applied voltage with the help of the criterion presented in the precending item. These curves are then used to determine the minimum voltage capable of synchronizing a specified load torque and inertia. This minimum voltage will be referred to as "the synchronizing voltage".

Effect of the Supply Frequency on the Synchronization Process

Reluctance motors, used as variable speed drives, are fed from variable frequency power supplies. The effect of the supply frequency on the inertia, that can be synchronized against a certain load torque is to be investigated. This can be achieved by applying the above pull-in criterion for different supply frequencies.

Effect of the Ratio x_d/x_q on the Synchronization Process

Reluctance motors are usually designed with relatively high values of the ratio x_d/x_q resulting in high values of the torque at their synchronous speed, (i.e. pull-out torque). However, the torque components are found to be greatly affected with the large values of this ratio. Therefore, this ratio has a pronounced effect on the initial slip and the maximum inertia that can be synchronized against a certain load torque.

It has been found also that the maximum torque,(pull-in torque), which can be synchronized against a certain inertia is much affected by this ratio. In general, pull-in torque increases with the ratio x_d/x_q up to a certain point after which it falls[1]. The importance of studying such an effect is due to the fact that the value of the maximum pull-in torque is often the limiting feature in the design of such motors.

CALCULATED AND EXPERIMENTAL RESULTS

The calculated results concerning the criterion and the factors affecting the synchronization process are presented for different motors having different sizes, different values of the ratio x_d/x_q and different arrangements of the rotor bars. Experimental verification of the analytical results has been made using an actual machine having the parameters given in Appendix-II.

Comparison between the Criterion Developed and the Criterion Reported by Lawrenson et al[5]

As the value of the initial slip plays an important role in determining the maximum inertia that can be synchronized, Fig.2 shows the variation of s_o and s'_o with the load torque.

For the motor under test, the maximum inertia that can be synchronized against a certain load torque is determined by the two criteria and given in Fig. 3 as a multiple of the system inertia, (rotor inertia and the

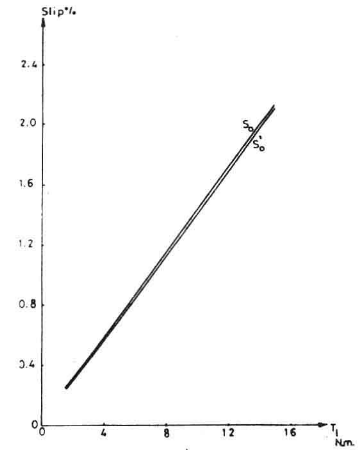


Fig. 2 Variation of S_o and S'_o with the load torque for the motor under test.

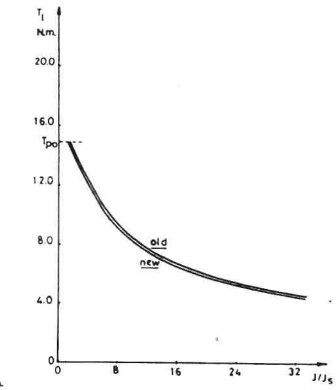


Fig. 3 Load torque versus maximum inertia calculated by old and new critera for a 2 hp motor having $X_d/X_q = 2.172$, $r_a = 1.13\ \Omega$.

load inertia). As initial slips s_o and s'_o are small at light loads, the maximum inertia that can be synchronized at such loads will be large. On the other hand, increasing the load torque results in an increase of s_o and s'_o. Hence, the maximum inertia that can be synchronized will be smaller.

The variation of the amplitude of the pulsating torque with slip, as shown in Fig.4 (case:1), makes the initial slip s_o larger than s'_o. Therefore, the maximum inertia that can be synchronized against a certain load torque will be less than that calculated by the old criterion. The difference between the values of the maximum inertia calculated by

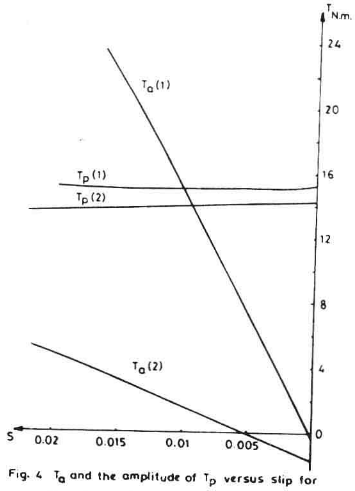


Fig. 4 T_a and the amplitude of T_p versus slip for
(1) motor under test,
(2) motor having $X_d/X_q = 4.266$, $r_a = 1.14\ \Omega$.

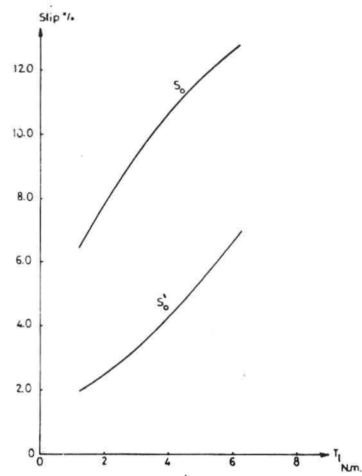


Fig. 5 Variation of S_o and S'_o with the load torque for a motor having $X_d/X_q = 4.266$ $r_a = 1.14\ \Omega$.

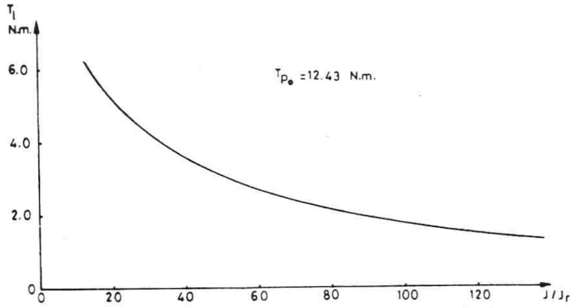


Fig. 6 Load torque versus maximum inertia calculated by old criterion for a 2 hp motor having $X_d/X_q = 4.266$, $r_a = 1.14\ \Omega$.

the two criteria for this specific case is small due to :

(i) The ratio x_d/x_q of the motor under consideration is small.

(ii) The uniform distribution of the rotor bars of such a motor results in a steep slope of the average torque/slip curve near synchronous speed, as shown in Fig.4 (case:1).

Accordingly the difference between s_o and s_o' is reduced.

However, with high values of x_d/x_q and a nonuiform distribution of the rotor bars, as shown in Fig.4. (case: 2), the variation of the amplitude of the pulsating torque with slip is much higher and the difference between s_o and s_o' is much larger as shown in Fig. 5. Then, the maximum inertia will be greatly reduced. For a reluctance motor, (case : 2), having x_d/x_q of about twice that of the motor under test and r_{kd}/r_{kq} = 0.109, the variation of the maximum inertia with the load torque is calculated for each criterion and drawn in Fig.6 and 7.

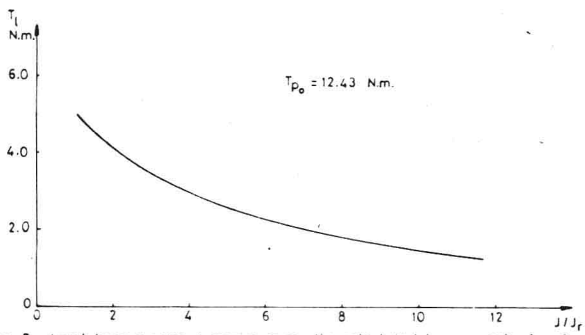


Fig 7 Load torque versus maximum inertia calculated by new criterion for a 2hp motor having x_d/x_q = 4.256, r_a = 1.14 Ω.

It is inferred, that neglecting the variation of the amplitude of the pulsating torque may lead to false results especially at high degrees of motor asymmetries.

Effect of the Supply Voltage Variation

For the motor under consideration, the criterion developed is applied for different loads with different supply voltages and the results are illustrated in Fig.8.

The load torque, which can be synchronized against a certain value of the supply voltage, is plotted in Fig.9. The variation of the pull-out torque with the supply voltage is also shown in Fig.9. From the two curves, it is inferred as expected that the motor capability of synchronizing a certain load torque is much reduced for a certain reduction in the supply voltage. This agrees with the observations recommended by Lawrenson et al throughout the study of such a problem on analog and digital computers.[7]

Experimental Verification

In order to verify the calculated results of Fig.9 experimentally, the motor is fed with its rated voltage and synchronized while driving a certain load torque. Then the voltage is reduced gradually until the motor loses its ability to synchronize this load and the rotor slips behind the air-gap field. This can be noticed with the help of a stroboscope. The test is repeated for different values of the load torque and the synchronizing voltage is measured each time. The points obtained by this test are shown in Fig.9.

The analytical results are in a good agreement with the test results. This confirms the validity and accuracy of the criterion developed.

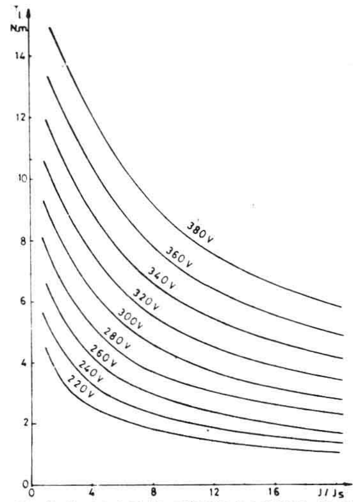


Fig. 8 T_l versus maximum inertia for different values of the supply voltage.

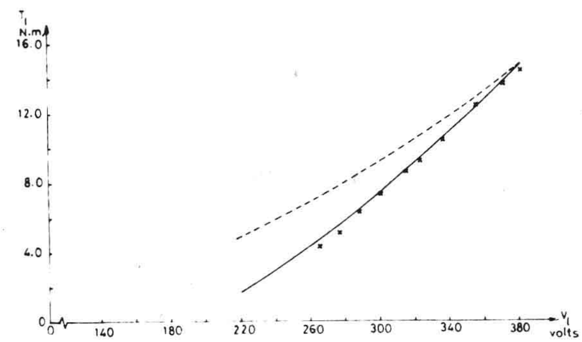


Fig 9 Load torque versus synchronizing voltage, (line value), for the motor under consideration. --- pull-out torque x x x experimental points — calculated using the developed criterion.

Effect of the Supply Frequency

With the help of the criterion developed, the maximum inertia that can be synchronized against a certain load torque is calculated for different values of the supply frequency. The ratio of the supply voltage to the supply frequency is maintained constant for all operating frequencies to keep the flux in the air-gap approximately constant. The calculated results of the motor under test are shown in Fig.10.

As the slope of the average torque/slip curve increases with an increase in the supply frequency, the initial slip s_o will have smaller values and hence the maximum inertia increases. However, the variation of the slope of the average torque/slip curve and hence the initial slip s_o is much reduced at high values of the supply frequency as shown in Fig.11. This illustrates why the increase of the maximum inertia is much smaller at higher frequencies.

Applying light loads on the shaft of the motor leads to an increased acceleration during the synchronization process. Consequently, the curves representing the maximum inertia versus the supply frequency will be shifted upwards for the small values of the load torque.

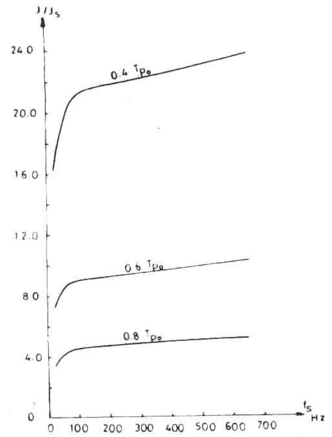


Fig 10 Variation of J/J_s with the supply frequency for different load values (p.u. of T_{po} at 50 Hz) for the motor under test

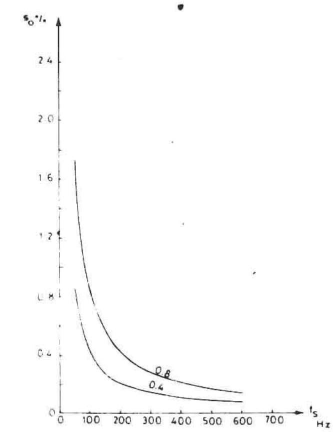


Fig 11 Initial slip versus f_s for different load values, for the motor under test

Effect of the Ratio x_d/x_q

The effect of the ratio x_d/x_q on the variation of the amplitude of the pulsating torque and the negative value of the average torque at zero slip can be deduced from Fig.4. It follows that :

(i) increasing this ratio leads to higher negative values of the average torque at zero slip.

(ii) The variation of the amplitude of the pulsating torque becomes larger as this ratio increases.

For the motor under consideration and another motor of the same rating but having x_d/x_q of about twice the value of the original motor, the maximum pull-in torque is calculated and plotted versus the maximum inertia, (expressed as a multiple of the rotor inertia), in Fig.12. The parameters of the other motor are presented in reference [9]. As shown in this figure, the maximum pull-in torque of the motor under consideration equals the pull-out torque for a total inertia of about twice the rotor inertia. However, for the other motor, with the same total inertia, the pull-in torque is only about one third of its pull-out torque. Although the difference in the ratio x_d/x_q is not large for the two motors, the value of the pull-in torque is highly reduced. This results from the electrical asymmetry provided in the rotor of the second motor which has $r_{kd}/r_{kq} = 0.109$.

For two motors, having the parameters presented in reference [10], the maximum pull-in torque is calculated and plotted versus the maximum inertia, (expressed as a multiple of the rotor inertia), in Fig.13. For the two motors the maximum pull-in torque is relatively small compared with the pull-out torque. Moreover, the maximum pull-in torque decreases with the increase of the ratio x_d/x_q.

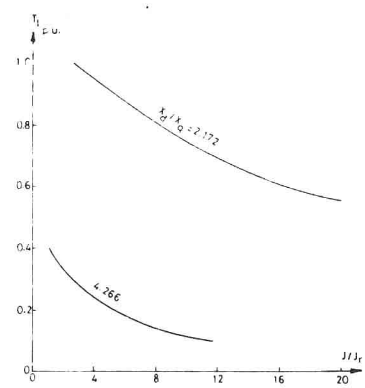


Fig 12 Load torque versus maximum inertia for two motors of the same rating (2 hp), with different values of the ratio x_d/x_q

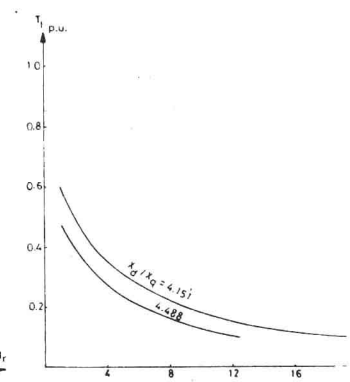


Fig 13 Load torque versus maximum inertia for two motors of the same rating (4.4 hp), with different values of the ratio x_d/x_q

CONCLUSIONS

The important features of the criterion developed emanate from the following considerations :

(i) The critical modes of operation,

(ii) The variation of the amplitude of the pulsating torque with slip, and

(iii) The simplifying assumptions based on the physical understanding of the problem to obtain the maximum inertia which can be synchronized against a certain load torque.

The validity and accuracy of the criterion developed have been confirmed through suitable experiments on an actual machine.

In light of the study of the synchronization process and the different factors affecting it, the following conclusions have been inferred.

(1) The maximum inertia which can be synchronized by a motor is greatly reduced for higher load torques.

(2) The motor capability of synchronizing a certain load torque is much reduced when the supply voltage is decreased. Thus, during the determination of motor specifications, it is important that an allowance should be made for a possible fall in the applied voltage.

(3) For the small and moderate ranges of the operating frequency, the maximum inertia that can be synchronized against a specific load torque increases with the frequency. For high operating frequencies such an increase is quite small as the initial slip becomes nearly constant.

(4) The ratio x_d/x_q has a considerable influence on the synchronization process in the following manner.

i) The maximum pull-in torque is much reduced with high values of the ratio x_d/x_q especially with a nonuniform distribution of the rotor bars. This result is very important as it represents the limiting feature in the design of such motors.

ii) For a machine having a high value of the ratio x_d/x_q, the amplitude of the pulsating torque varies greatly with slip and thence the initial slip during the synchronization process becomes larger.

iii) The maximum inertia that can be synchronized against a certain load torque by a machine having large value of the ratio x_d/x_q is quite small.

(5) Neglecting the variation of the amplitude of the pulsating torque may lead to false results especially at high degrees of motor asymmetries.

The method presented can be extended to investigate the synchronization process of synchronous motors having field windings in their rotors.

NOMENCLATURE

- j — $\sqrt{-1}$
- J — moment of inertia
- J_r — moment of inertia of the rotor
- J_s — moment of inertia of the rotor and load
- p — operator d/dt
- P — number of pole pairs
- r_a — armature resistance
- r_{kd}, r_{kq} — equivalent d- and q-axis damper winding resistance, respectively
- s — per unit slip
- s_a — average value of s
- s_o — value of s at the beginning of synchronization process with the consideration of variable amplitude of the pulsating torque
- s'_o — value of s at the beginning of synchronization process with the assumption of constant amplitude of the pulsating torque
- t — time
- T_e — electromagnetic torque developed
- T_a — average torque component
- T_p — pulsating torque component
- T_t — accelerating torque
- T_l — load torque
- x_d, x_q — d-and q- axis synchronous inductance, respectively
- $x_d(j\,s_a w_s), x_q(j\,s_a w_s)$ — operational inductance at frequency $s_a w_s$
- x_{kd}, x_{kq} — equivalent d- and q-axis damper winding inductance, respectively
- x_{kdl}, x_{kql} — equivalent d-and q-axis damper winding leakage inductance, respectively
- x_{md}, x_{mq} — d-and q-axis magnetizing inductance, respectively
- x_{sl} — armature leakage inductance
- $\hat{V}$ — amplitude of the applied voltage
- δ — load-angle in electrical radians
- δ_o — value of δ at the beginning of synchronization process
- $\dot{\theta}$ — angular rotor speed in electrical rad/sec
- θ_m — angular rotor position in mechanical radians
- w_s — angular frequency of the supply

APPENDIX -I

Electromagnetic Torque Developed

The electromagnetic torque developed by a 3 -phase maching having P pole-pairs is given by 4 ;

$$T_e = T_a + T_p \qquad (A-1)$$

where

$$T_a = \frac{1}{2}\hat{V}^2 K_1, \qquad (A-2)$$

$$T_p = \frac{1}{2}\hat{V}^2 (K_2 \sin 2\delta + K_3 \cos 2\delta), \qquad (A-3)$$

$$K_1 = \frac{3}{2} P((C-A)(K_{1d}K_{1q}+K_{2d}K_{2q}) - (B+D).(K_{1d}K_{2q}-K_{2d}K_{1q})), \qquad (A-4)$$

$$K_2 = \frac{3}{2} P((A-C)(K_{1d}K_{2q}+K_{2d}K_{1q})+(B-D).(K_{1d}K_{1q}-K_{2d}K_{2q})), \qquad (A-5)$$

$$K_3 = \frac{3}{2} P\left[(C-A)(K_{1d}K_{1q}-K_{2d}K_{2q})+(B-D).(K_{1d}K_{2q}+K_{2d}K_{1q})\right], \qquad (A-6)$$

$$K_{1d}=((1-2s_a)w_s((1-2s_a)w_s^2-w_s r_a D+r_a^2(AC-BD) -s_a w_s r_a(B+D)) +r_a^3 B(C^2+D^2)+ s_a w_s r_a^2 . (C^2+D^2+AC+BD))\cdot 1/\Delta_1, \qquad (A-7)$$

$$K_{2d}=\frac{1}{\Delta_1}((1-2s_a)w_s(w_s r_a C-r_a^2(BC+AD)-s_a w_s r_a.(A+C)) +r_a^3 A(C^2+D^2)+s_a w_s r_a^2(AD-BC)), \qquad (A-8)$$

$$K_{1q}=\frac{1}{\Delta_1}((1-2s_a)w_s(w_s r_a A-r_a^2(BC+AD)-s_a w_s r_a.(A+C)) +r_a^3 C(A^2+B^2)+s_a w_s r_a^2(BC-AD)), \qquad (A-9)$$

$$K_{2q}=((1-2s_a)w_s(-(1-2s_a)w_s^2+w_s r_a B-r_a^2(AC-BD) +s_a w_s r_a(B+D)-r_a^2 D(A^2+B^2)-s_a w_s r_a^2(A^2+B^2+AC+BD))\cdot 1/\Delta_1, \qquad (A-10)$$

$$A+jB = \frac{1}{x_d(js_a w_s)}, \qquad (A-11)$$

$$C+jD = \frac{1}{x_q(j\,s_a w_s)}, \qquad (A-12)$$

$$x_d(j\,s_a w_s)= x_d - \frac{j\,s_a w_s .\,x_{md}^2}{r_{kd}+j\,s_a w_s x_{kd}} \qquad (A-13)$$

$$x_q(j\,s_a w_s)= x_q - \frac{j\,s_a w_s x_{mq}^2}{r_{kq}+j\,s_a w_s x_{kq}} \qquad (A-14)$$

$$\Delta_1=((1-2s_a)w_s^2+r_a^2(AC-BD)-s_a w_s r_a(B+D))^2+$$

$$(r_a(BC+AD)+s_a w_s r_a(A+C))^2 \qquad (A-15)$$

Equations (A-1) to (A-3) are written in the following forms in order to simplify the analysis presented,

$$T_a = a\,s^2 + b\,s - c \qquad (A-16)$$

$$T_p = (d\,s^2+es+f)\sin 2\delta+(gs^2+hs+i)\cos 2\delta \qquad (A-17)$$

The constants from a to i appearing in equations (A-16) and (A-17) can be determined for a specific machine with the help of equations (A-2) to (A-6), by using a suitable numerical method of curve fitting.

Load-Angle

The load-angle is the angle in electrical degrees which exists between the axis of the resultant magnetic field and the d-axis of the rotor.

Then,

$$\delta = w_s t - \int \dot{\theta}\, dt \qquad (A-18)$$

where, δ is considered positive or leading angle, for motor action.

Hence,

$$p^2\delta = -\ddot{\theta} \qquad (A-19)$$

For constant speed operation, corresponding to average slip s_a

$$\dot{\theta} = (1-s_a)\,w_s \qquad (A-20)$$

For any value of the slip s, equation (A-19) can be written in the following form :

$$p^2\delta = w_s^2\; s\,\frac{ds}{d\delta} \qquad (A-21)$$

Let:

δ_1 be the angle at which T_p, for a slip s, equals zero. Then,

$$\delta_1 = -\frac{1}{2}\tan^{-1}\frac{gs^2+hs+i}{ds^2+es+f}, \qquad (A-22)$$

δ_{max} be the load-angle which makes T_p at its maximum value. For any slip s, δ_{max} is given by :

$$\delta_{max} = \frac{1}{2}\tan^{-1}\frac{ds^2+es+f}{gs^2+hs+i} \qquad (A-23)$$

The relation between δ_1 and δ_{max} is then given by :

$$\delta_1 = \delta_{max} - \pi/4 \qquad (A-24)$$

For the two values of which make the accelerating torque equal to zero at zero slip, as shown in Fig.1, let δ_{fo} be the stable load point given by :

$$\delta_{fo} = \delta_{max_o} - \frac{1}{2}\tan^{-1}\frac{\sqrt{i^2+f^2-(T_1+c)^2}}{T_1+c} \qquad (A-25)$$

δ_{max_o} is determined from equation (A-23) after putting s = o.

The unstable load point defined by δ'_{fo} is then given by :

$$\delta'_{fo} = \frac{\pi}{2} - \delta_{fo} + 2\delta_{10} \qquad (A-26)$$

where δ_{10} is the value of δ_1 at s = 0.

APPENDIX -II

Parameters of the 3-phase Reluctance Motor under Consideration

Rated voltage	=	380	volt.
Frequency	=	50	Hz
r_a	=	1.133	ohm
$w_s x_{sl}$	=	1.275	ohm
$w_s x_d$	=	53	ohm
$w_s x_q$	=	24.4	ohm
$w_s x_{kd}$	=	55.212	ohm
r_{kd}	=	0.837	ohm
$w_s x_{kdl}$	=	3.488	ohm
$w_s x_{kq}$	=	28.21	ohm
r_{kq}	=	0.837	ohm
$w_s x_{kql}$	=	5.048	ohm

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ELECTRICITY GENERATION PLANNING IN SOUTH AFRICA

- G.Z. Ben-Yaacov* -
Electricity Supply Commission
Johannesburg, South Africa

ABSTRACT

The paper discusses the problems of establishing an adequate long-range power generation development plan for the South African system. The discussion covers energy resources, energy policy planning procedures, computer modeling techniques, economics of generating plant selection and reserve margin. Details of the existing generation system in South Africa, the possible interconnection with other Southern African countries and guidelines on future generating plant in South Africa are also given.

INTRODUCTION

Electricity consumption in South Africa is increasing at an average rate of about 7% per annum and in 1980 it will be about 15 000 MW and 100 000 Gwh generated. (Table 1). Of the 1980 consumption about 92% of the units will be generated by the Electricity Supply Commission (Escom) and 6% by the five large municipal undertakings in Johannesburg, Pretoria, Cape Town, Port Elizabeth and Bloemfontein. Plans are on hand for Escom to supply the further load growth of all five of these large municipalities so that, when their existing plant is retired, Escom will supply over 98% of the electricity consumed in South Africa.

YEAR	SYSTEM MAXIMUM DEMAND, MW	ELECTRICAL ENERGY MWH X 10^6	GROWTH RATE % PER YEAR
1950	1 500	10,5	7,5
1960	3 600	22,8	8,5
1970	8 000	47,6	8,0
1975	11 000	70,8	8,5
1978	13 600	83,3	7,2
1980	15 600	96,0	7,1
1985	22 000	135,0	6,9
1990	30 000	185,0	6,6
2000	56 000	345,0	6,2
2010	100 000	620,0	5,8
2020	175 000	1 100,0	5,5
2030	300 000	1 800,0	5,3

TABLE 1 : ELECTRICITY REQUIREMENTS FOR SOUTH AFRICA

Escom is a non-profit making organisation which was established in 1923 in terms of the Electricity Act of 1922 to "establish, acquire and operate and maintain electricity undertakings to provide an efficient, cheap and abundant supply of electricity" in South Africa. At present Escom owns and operates six electricity regions. The price of electricity varies from region to region but the overall average per unit sold is less than 2,2 cents (USA) per kWh.

* presently with Systems Control, Inc.
Palo Alto, California

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In general, power is supplied in bulk (at voltages from 6,6 to 275 kV) to towns and other large consumers who distribute this bulk. Escom does, however, supply some 100 000 urban and rural consumers at 380/220 volts from supply lines operating at 11 or 22 kV.

As South Africa covers an area of about 1 200 000 km^2, the average load density is only about 12 kW per km^2, but in Johannesburg the maximum load density is about 150 MW per km^2 and, with the increasing construction of high rise buildings, it is expected to rise ultimately to about three times this figure. In 1980 the population will be about 25 million bringing about an average consumption of 4 000 kWh per capita. This figure is expected to rise to over 8 000 kWh per capita by the year 2000.

The power system, as shown in Figure 1, is a country-wide network of transmission lines for transmitting power generated at power stations to consumers. The present installed capacity is over 16 000 MW with an additional 11 000 MW currently under construction - incorporating fossil, nuclear, hydro-electric and pumped storage plant. The national and regional transmission network has approximately 110 000 kilometers of overhead power lines and cables of all voltages varying between 22 and 400 kV AC and 533 kV DC, and using some 120 000 MVA of installed transformer capacity.

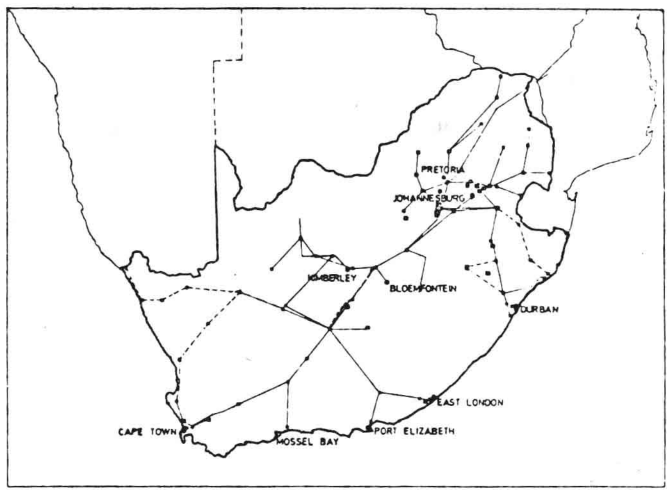

FIG. 1 : NATIONAL INTERCONNECTED POWER SYSTEM

This paper discusses the electricity requirements of South Africa, as well as the economically optimum mix of conventional generating plant needed to meet these requirements. The effects of national energy policy and limited energy resources are discussed, and details of the application of computer analysis techniques for the planning of the power generation system are also given. The contents of the paper include different reports by various authors in a number of energy conferences and publications. The selection of topics, the analysis of techniques and the results presented here reflect the author's view and are not necessarily supported by official policy in South Africa.

ENERGY RESOURCES

The growth in the demand for energy in South Africa is shown in Figure 2. Unlike most other countries, South Africa uses coal for a large proportion of its energy. (Table 2). This is largely due to the large and relatively cheap local deposits of coal which provide approximately three-quarters of the total energy requirements (i.e. more than double the world average for domestic resources). As a result, the electrical, the metallurgical and mining industries are almost exclusively dependent on coal as a primary energy source. The usage of various energy sources by different consumer sectors is given in Table 3. It is very interesting to note that only China and Poland, among the developed countries, rely on coal to an extent equalling the position in South Africa.

	SOLID FUELS	LIQUID FUELS	GAS	OTHER	TOTAL
U.S.A.	19,6	42,7	36,0	1,7	100
Canada	10,8	48,9	30,9	9,4	100
Western Europe	26,2	57,9	12,3	3,7	100
West Germany	35,4	52,1	11,2	1,3	100
United Kingdom	40,3	46,2	12,1	1,4	100
France	20,5	66,3	9,9	3,3	100
Italy	7,3	75,1	13,5	4,0	100
Netherlands	5,5	35,9	58,6	-	100
Japan	22,2	72,6	1,6	3,6	100
Eastern Europe and Russia	48,4	28,9	21,6	1,1	100
Russia	39,2	33,8	25,7	1,3	100
Poland	85,0	8,4	6,5	0,1	100
China	89,8	9,1	-	1,1	100
Australia	47,2	45,2	5,7	1,9	100
South Africa	76,1	23,3	-	0,6	100
Rest of the world	21,7	59,0	15,6	3,8	100
World	32,5	43,5	21,6	2,4	100

TABLE 2 : PERCENTAGE OF PRIMARY FORMS OF ENERGY TO TOTAL CONSUMPTION, ACCORDING TO COUNTRY (1972)

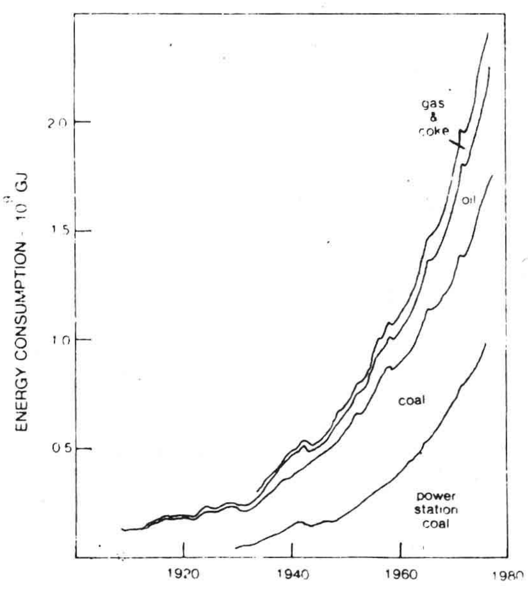

FIG. 2 : SOUTH AFRICAN ENERGY CONSUMPTION - 10^9 GJ PER ANNUM

When coal is discussed it is important to differentiate between two components of coal classifications - (a) coal reserves, or that coal which is fairly well surveyed and which is extractable by current technology at current prices and (b) unknown coal reserves or coal which has either not yet been discovered or which is at present not commercially available. This is, of course, a simplification since the boundary between these two groups is tenuous. In addition, the boundary moves because of changes in economics and technology. A number of estimates of our coal reserves have been made over the last thirty years and according to the latest estimates, South Africa has a probable total minable reserve of some 81 000 million tons of coal of which about 25 000 million tons are extractable under prevailing economic conditions. The total reserves of coal are further affected by two factors - the technology of coal-mining and the technology of coal utilization. Most of South Africa's coal is still obtained by the wasteful bord-and-pillar method. The average extraction rate is further affected by the Government pricing policy which makes it necessary to mine the good areas of a mine only. The effect of coal utilization technology can be judged by the fact that coal is defined in the above estimate as a carbonaceous substance with not more than 35% ash. The reason for using a figure of 35% is that it is not possible at present to use coal with a higher ash content. However, new technology is showing us that we can use such coal. For instance, combustion of coal in a fluidised bed is now a viable proposition. Since the amount of coal present in a fluidised bed at any instant is only 2%, the remainder being sand, it does not matter what the ash content of the coal is. The only criterion for the coal is that its total calorific value must be such that it can maintain the incoming air temperature above the flame extinction temperature. In practice, an ash content of 80% has been shown to be feasible. Such developments are currently being implemented commercially.

SECTOR	ELEC-TRICITY	COAL	PETROL	GAS/ COKE	TOTAL
Household and Agriculture	3,9	7,1	4,9	0	15,9
Industry	7,7	15,3	5,7	18,0	46,7
Transport	1,0	6,6	21,9	0	29,5
Mining	5,1	2,2	0,6	0	7,9
TOTAL	17,7	31,2	33,1	18,0	100,0

TABLE 3 : PERCENTAGE OF NET SECONDARY ENERGY USAGE BY SECTOR AND SOURCE (1974 DATA)

It is difficult to estimate how long the supply of coal will last. The total production of coal rose from 27 million tons in 1952 to about 66 million tons in 1976. The expected maximum production, which could be obtained by the year 2020, is about 250 million tons. However, assuming that the coal recovery will increase to 60% by the end of the century and that we can use coal with up to 60% ash content, then the likely pattern of coal consumption will be as shown in Figure 3.

With the commissioning of the Koeberg Power Station, in 1982, South Africa will receive nuclear power. If this power proves economical in the coastal areas then a large proportion of future power generation in these areas could become nuclear. The latest estimate of South Africa's uranium reserves is 350 000 tons (190 000 tons at 15$/lb U_3O_8 and 160 000 tons at 15-30$/lb U_3O_8). The future use of uranium within