Performance Analysis of Pole Amplitude Modulation Motors

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Abstract

Induction motor operated with pole amplitude modulation technique is to give two speeds or more. The motor parameters are modified for each speed. These parameters are function of the motor number of poles, number of stator series turns per phase, stator winding factor and type of operation.

The parameters of a tested motor are calculated taking into account the above factors at two speeds 1500 & 3000 r.p.m. The performance characteristics of the motor are calculated based on the equivalent circuit and compared with experimental results.

List of symbols

a_b	area of each rotor bar, m^2
a_e	area of rotor end ring, m^2
CP	constant power.
CT	constant torque.
D_e	mean diameter of rotor end ring ,m.
I	phase current , A.
K_d	distribution factor.
K_p	pitch factor
Kp_L	pitch factor at low speed.

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Kp_h	pitch factor at high speed.
K_{wh}	winding factor at high speed.
K_{wL}	winding factor at low speed.
K_{ws}	stator winding factor .
L_b	length of each rotor bar.
L_m	magnetizing inductance, henery.
m_s	number of stator phases.
MCT	MOS-controlled thyristor.
P	number of poles.
P_h	number of poles for high speed.
P_L	number of poles for low speed.
pf_h	power factor at high speed.
pf_L	power factor at low speed.
q	number of slots per pole per phase.
r'_2	rotor phase resistance referred to stator.
S_r	number of rotor bars.
T_s	number of stator series turns per phase.
V	applied phase voltage, V.
V_{AN}	Line to neutral voltage of phase A.
V_{BN}	Line to neutral voltage of phase B.
V_{CN}	Line to neutral voltage of phase C.
VT	variable torque.
X'_2	rotor phase leakage reactance referred to stator.
X_m	magnetizing reactance, Ω.
ρ	resistivity Ω.m.
ζ_h	efficiency at high speed.
ζ_L	efficiency at low speed.
Φ_h	flux per pole for high speed.
Φ_L	flux per pole for low speed.
σ	The coil span

1- Introduction :

Induction motors are single speed machines . Some forms of control over the speed has been done since the motor was invented. One of this forms is the pole amplitude modulation technique, where each phase consists of two similar groups of coils. This pole amplitude modulation could be done by reversing the current in one half of the coils of each phase. In doing this modulation to increase the speed, the motor current will decrease if the coils of each phase remain in series. Consequently the magnetic field and the developed torque will decrease .

To utilize the motor with high grade, the flux density must be kept constant. To achieve this requirement, the voltage per coil must be changed, either by connecting the two coils of each phase in parallel or delta and star connections. It is noticed that these connections modulate the magnetic field , consequently the motor power. It will also increase the motor efficiency by reducing the applied voltage when the load torque is small. These changes cause the motor parameters to be varied due to :

a) Number of poles.
b) Number of stator series turns per phase.
c) Stator winding factor.
d) Types of operation which are either
   1- Costant torque
   2- Constant power
   3- Variable torque

To study the performance characteristics of pole amplitude modulation motors, the above factors must be taken into account.

2- Tested motor

The tested motor [1] is a double layer, 120^{o} degree phase spread, connected to give 4 poles and 2 poles, i.e. rotates at 1500 r.p.m. and 3000 r.p.m. respectively. The parameters of this motor at 4-pole are indicated in Appendix 1.

3 - Calculation of rotor resistance and leakage reactance:

The total phase resistance of rotor referred to stator is given by :[1]

$$r'_2 = 4\, m_s T_s^2 k_{ws}^2 \rho \left[\frac{L_b}{a_b s_r} + \frac{2}{\pi} \frac{D_e}{P^2 a_e} \right]$$

– putting $k = 4m_s\rho$

$$A = \frac{L_b}{S_r a_b}$$

$$B = \frac{2}{\pi} \frac{D_e}{a_e}$$

$$\therefore r'_2 = T_s^2 K_{ws}^2 \, k(A + B / p^2) \qquad [1]$$

The rotor phase leakage reactance referred to stator is [1] .

$$X`_2 = K_{ws}{}^2\, K`\, T_s^2\, x_2 \qquad [2]$$

where $K` = \frac{4m_s}{s_r}$

The rotor resistance and leakage reactance will be changed by :

1- Changing the number of poles which affects the winding factor (k_w).

2- Changing the connection of stator winding which affects the number of series turns/phase.

4- Calculation of stator winding factor :

a) Calculation of distribution factor :

The distribution factor (k_d) will be calculated from,

$$k_d = \frac{\sin\left(\frac{s}{m_s p} \times \frac{180\,P}{2 \times s}\right)}{(s / m_s p)\sin\left(\frac{180\,P}{2s}\right)} \qquad [3]$$

where s is the number of stator slots

(b) Calculation of pitch factor :

The pitch factor will be calculated from :

$$K_p = \cos(\sigma/2) \qquad [4]$$

At low speed , the winding has full pitch

$K_{PL} = 1$

At high speed connection, the span of the coils is one half of the pole pitch.

$K_{Ph} = 0.707$

The winding factor K_{ws} will be :

$K_{ws} = K_d * K_p$

$K_{wL} = 0.96$

$K_{wh} = 0.68$

5- Calculation of magnetizing reactance (x_m) :

The magnetizing inductance is given from the relation [2]:

$$L_m \propto \left[k_{ws} * \frac{T_s}{p}\right]^2$$

$$\therefore x_m \propto k_{ws}^2 \frac{T_s^2}{P^2} . \qquad [5]$$

6- Stator resistance and leakage reactance :

The stator resistance and leakage reactance (r_1& x_1) will be changed according to the connection of the winding , whether they are in series or in parallel.

7- Types of Operations :

The possible star and Δ combinations of the phases themselves are shown in table (2) .These are respectively to give constant-torque, constant-power and variable - torque .

Case 1 : constant-torque operation :

If the same torque from no-load to pull out is to be obtained, refering to table (2) with the same line valtage the torque ratio is given by :

$$\frac{\text{low speed output}}{\text{high speed output}} = \frac{3V * I * \eta_L * pf_L}{\sqrt{3}\ V * 2 * I * \eta_h * pf_h}$$

$$\text{Torque ratio} \frac{\text{low speed torque}}{\text{high speed torque}} = 1.73 \frac{\eta_L * pf_L}{\eta_h * pf_h}$$

The ratio $\frac{\eta_L * pf_L}{\eta_h * pf_h}$ is less than unity, in part because it has been shown from the experimental results on the tested motor [1] that the power factor at low speed is smaller than that at high speed and in part because the efficiency is also affected, as shown in figure (9) & (10).
So the above torque ratio is close enough to unity .

Also the flux per pole at low speed (ϕ_L) and high speed (ϕ_h) are also affected. From the e.m.f. equation the ratio ϕ_L/ϕ_h at constant torque oparation can be calculated as :

$$\frac{\sqrt{3}V}{V} = \frac{kw_L}{kw_h} * \frac{\varphi_L}{\varphi_h} \cdot \frac{T_s}{T_{s/2}}$$

$$\frac{\varphi_L}{\varphi_h} = 0.64$$

Case 2: Constant horse-power operation :

Refering to table (2) .

$$\frac{\text{low speed output}}{\text{high speed output}} = \frac{3\frac{V}{\sqrt{3}} * 2 * I * \eta_L * pf_L}{3V * I * \eta_h * pf_h}$$

$$= 1.15 \frac{\eta_L * pf_L}{\eta_h * pf_h}$$

The above ratio of outputs becomes close enough to unity.

Also from e.m.f. equation we can get $\phi_L/\phi_h = 0.83$ at constant- horse power.

Case 3 : Variable - torque operation :

Refering to table (2).

$$\frac{\text{low speed output}}{\text{high speed output}} = \frac{3\frac{V}{\sqrt{3}} * I * \eta_L * pf_L}{3\frac{V}{\sqrt{3}} * 2 * I * \eta_h * pf_h}$$

$$\frac{\text{low speed torque}}{\text{high speed torque}} = \frac{\eta_L * pf_L}{\eta_h * pf_h}$$

This ratio is relatively so much less than the above ratio of constant - torque connection.

In this case $\phi_L/\phi_h = 0.35$.

These changes in the flux per pole from low to high speed are necessarily accompanied by nearly proportional changes in the flux densities in the stator and rotor cores, behind the teeth.

8- Calculations of the output power and torque :

Control of speed by pole amplitude modulation is to obtain two speeds or more . A switch is used to connect the current in each phase in a certain direction at low speed . At high speed, the switch reverses the current in a half of each phase windings. If the two halfs remain in series at high and low speeds, the flux per pole remains nearly constant according to the e.m.f. equation

$$E = 4.44 \, f \, \phi \, T_S \, k_W$$

Since the pole area in the air gap at high speed is double that at low speed, the flux density will be decreased to about half of the low speed value . Concequently the full load torque obtained at the low speed can not be obtained at the high speed. So the voltage must be increased at the high speed or decreasing the number of series turns of each phase by connecting the two half windings in parallel instead of being in series.

There are three methods to control the speed according to the requirements of different loads. In each method, a switch is used to modulate the connection and the corresponding change of the voltage. The motor is designed to operate with one of these methods to change the speed from low to high values or vice versa.

To compare these methods, it is supposed that the supply voltage is changed as shown in table (1), so the motor gives the rated torque at the high speed. The motor torque at low speed is changed to suit the different loads with efficiency improvement.

For the same power, the low speed torque will be double the high speed torque as shown in Fig. (1) . This case is suitable for workshop machines, since it usually starts at no load, consequently, the load torque is periodically increased. In this case, the motor rated phase voltage is 220 -V at low speed, or the voltage of half of phase winding is 110 volt. Using the switch to reconnect the winding for high speed, the half phase winding voltage is reduced to 95.25 V , as shown table (2)

If the motor is used to operate a constant load torque at the two speeds, the motor torque at the low speed must be decreased to the value of high speed torque to improve the motor efficiency at low speed. In this case the half winding voltage is decreased from 110 volt (CP) to 82.25 volt .

If the motor is used to operate a fan load, it is preferable to decrease the motor torque more, by another voltage reduction in order to improve motor effeciency at low speed. This is achieved by reconnecting the stator winding from the case number (6) to the case number (5) . In which the voltage will be decreased to 47 . 625 volt.

The motor parameters are calculated from equations (1,2,3,4 &5) The values of these parameters are shown also in table (1) . The motor characteristics are calculated at different cases of operation as shown in Figs. (2,3,&4) . The high speed characteristics (2,4) are the same at the different methods (CP, CT & VT) except the phase current in the constant power case is halfed because the phase windings are in series.So there is only one curve for the high speed case .

Fig. (1) shows the motor torque in different cases during the run up. The maximum torque (T_{max}) is 5.67 N.m. at low speed in the constant power case. It decreases to 2.91 N.m. at the high speed for the same case while it is 3.17 N.m. at low speed for constant torque case and 1.06 N.m. for the case of variable torque .

The full load torque in (CT) case for the high and low speeds is 1.78 (N.m.) . In the case of fan load, the (VT) case is used. when the full load torque at the high speed is 1.78 (N.m.) , the low speed torque is .466 (N.m.).

The currents during the Run up are shown in Fig. (2) . The current will be high if the starting is done at the high speed, and that is wrong, since the starting must be with the low speed for different methods (Cp, CT & VT), then changing to the high speed. The starting current will be with suitable value in case of (CP) , decreases in the case of (CT) and decreases more in the case of (VT) .

The input power (P_{in}) and the output power (P_{out}) are shown in Fig.(3). The values are nearly in the same rates as the rates of current in different operations. The power factor will be changed as shown in Fig.(4).

During motor loading, the calculated and experimental characteristics are shown in Figs. (5,6,7,8 ,9 & 10) . Fig. (5) shows the variation of motor speed with load torque in the three cases. The motor current variation with load torque is shown in Fig.(6) . In case of (CT) , the high speed current is (2.58 A) . It decreases to (1A) in the low speed due to the voltage decreasing.The motor current will be (2A) if it operates at (CP) at the same torque . At full load (4 N.m.) the current will be (3.23A) at low speed, while in the high speed is (2.58). In the case of (VT) , the fan load (.466 N.m.) draws (0.5A) in the low speed instead of (0.6 A) if it operates with (CT) case or (1.65 A) in (CP) case .

Input and output powers and their rate of change are shown in Figs (7 & 8) .

In Fig. (9), it is clear that the effect of voltage changes on improving the efficiency. At full load and high speed, the efficiency is (.828) , while in the low speed is (0.76) in (CP) case , (0.76) in (CT) case and (0.75) in (VT) case. The improvement in the efficiency at low speed appears where it is (0.75) in (VT) case instead of being (0.57) in (CT) case, or instead of being (0.41) in (CP) case.

In the same degree, the power factor will be improved as shown in Fig. (10) . It is (0.67) in (VT) case instead of (0.4) in (CT) case and (0.31) in the case of (CP) . Also the power factor will be improved from (0.59) in (CP) case to (0.72) at (CT) case.

9- Conclusion :

To calcultate the motor performance characteristics under pole amplitude modulation, the motor parameters for both stator and rotor should be modified according to the following :

If the current in the half phase winding is reversed with the phase windings remaining in series, the stator phase resistance and leakage reactance remain constant. The rotor phase resistance and leakage reactance are decreased due to the decreasing of the winding factor. The stator phase magnetizing reactance is increased to about the double value due to the variation of both the winding factor and the number of poles.

In reducing the number of poles to the half, and if the phase windings are remained in series, the supply voltage becomes insufficient to obtain the rated output. The supply voltage must be changed. This is achieved by reconnecting the winding either in parallel star or series delta.

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Appendix I

(A) Data of the tested motor:

The data of 3-phase induction motor used in the laboratory measurements are ;0.75 HP., 380/220 V, 1.6/2.77 A, 50 HZ , 1425 r.p.m., 0.71 effeciency , 0.74 power factor, 36 stator slots, 28 rotor slots. The motor parameters are ;

Stator phase resistance = 14.2 Ω

Stator phase leakage reactance = 25 Ω

Stator phase magnetising reactance = 250 Ω

Equivalent iron loss phase resistance = 1700 Ω

T_S = Number of series turns / phase = 456

Conductor diameter = 0.55 mm

(B) Dimentions of Rotor Bars :

L_b = length of each bar = 45 mm

a_b = area of each bar = 24.6 mm^2

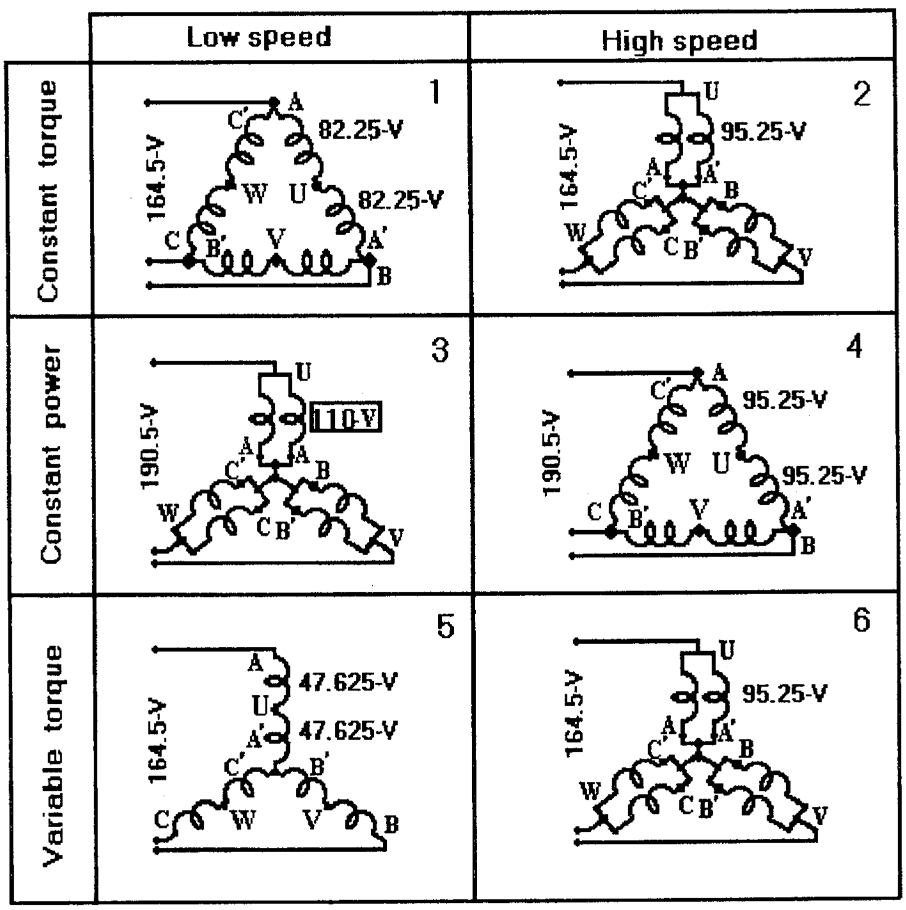
D_e = mean diameter of end ring = 60 mm

a_e = area of the end ring = 150 mm^2

Table (1).Voltage& parameters at different operation

No.	Constant torque: low speed 1	Constant torque: high speed 2	Constant power: low speed 3	Constant power: high speed 4	Variable torque: low speed 5	Variable torque: high speed 6
V	164.5	95.25	110	190.5	95.25	95.25
R1	14.2	3.55	3.55	14.2	14.2	3.55
X1	25	6.17	6.17	25	25	6.17
R2	6	1.2	1.2	2.4	6	1.2
X2	30	3.7	7.5	7.5	30	3.7
R_M	1700	850	425	3400	1700	850
X_M	250	125	62.5	500	250	125

Table (2).Connections of different operations& the voltages.



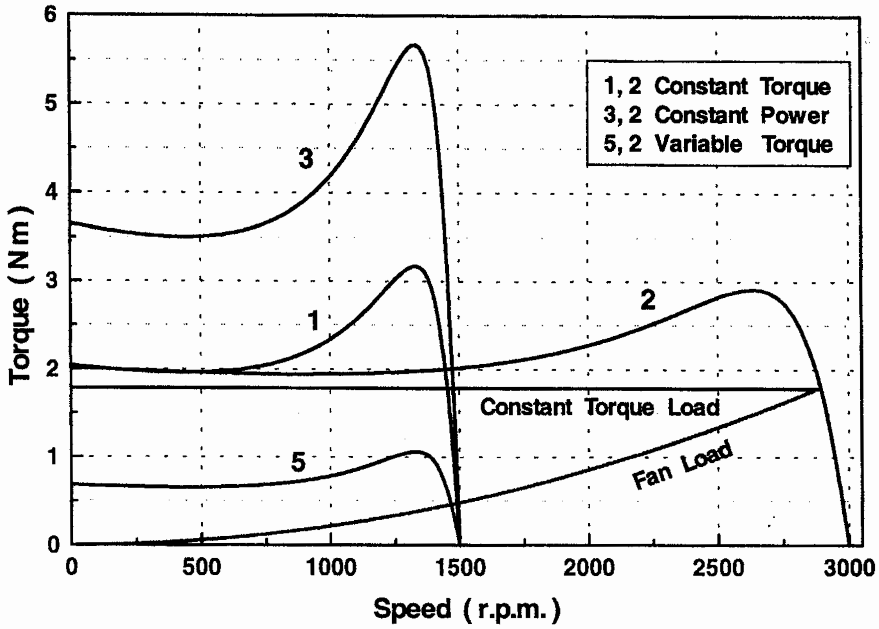


Fig.(1).Torque versus speed at different operations.

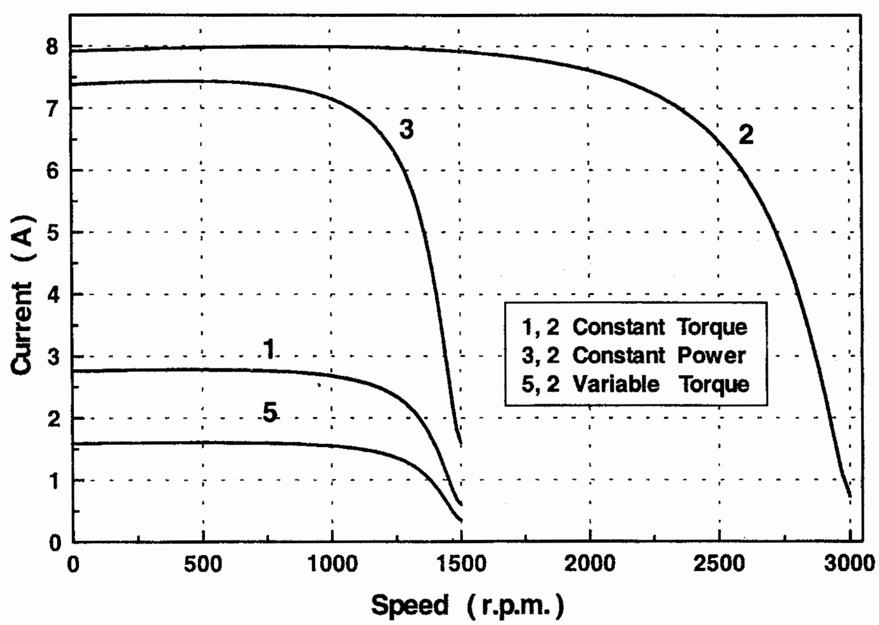


Fig. (2).Input current versus speed at different operations.

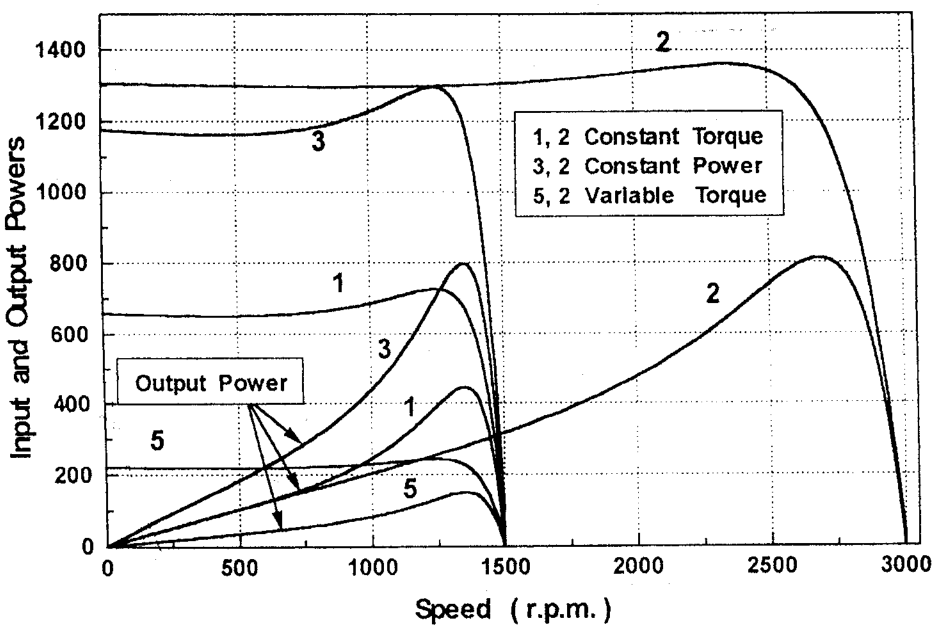


Fig.(3).Input &output powers versus speed at different operations.

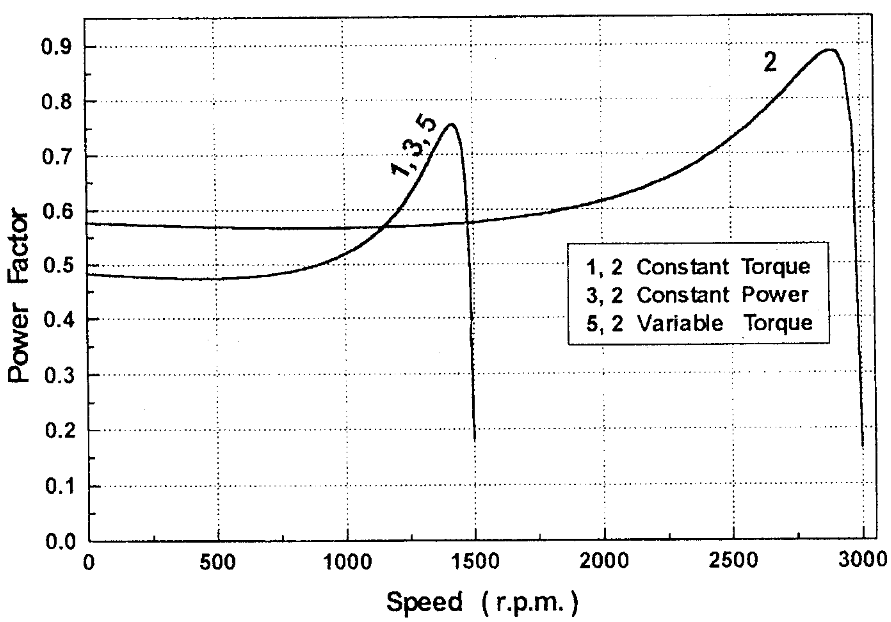


Fig.(4).Power factor versus speed at differnt operations.

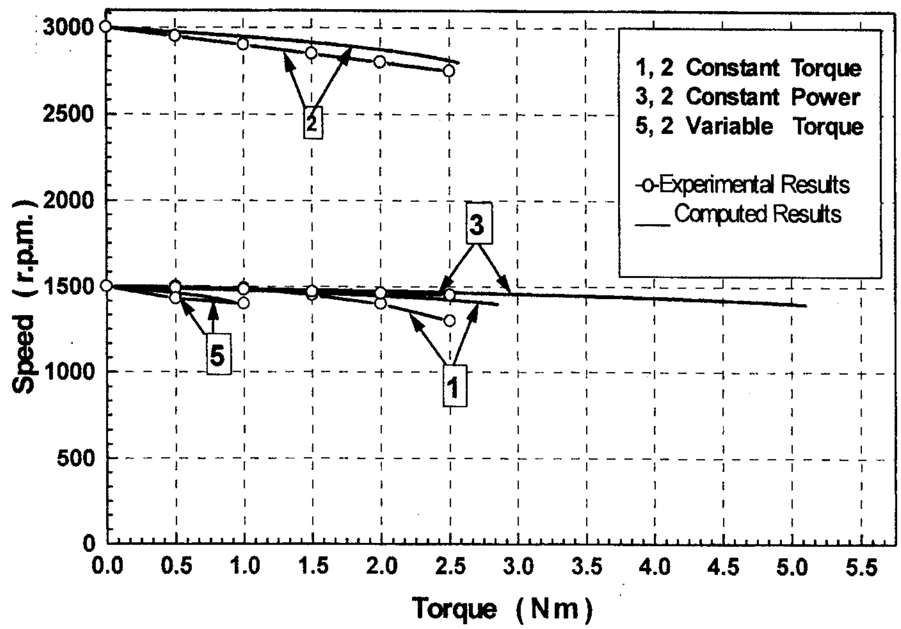


Fig.(5).Speed versus torque at different operations.

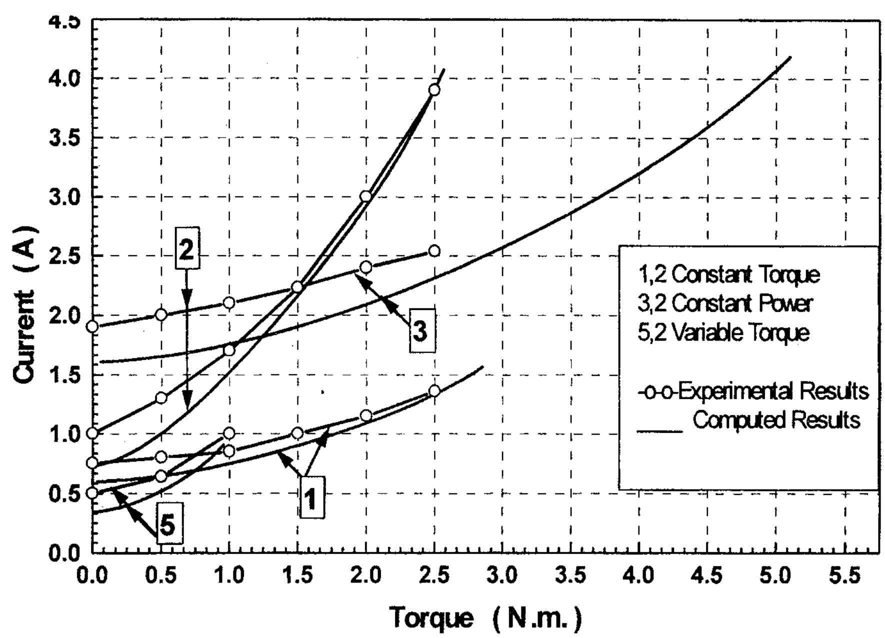


Fig.(6).Current versus torque at different operations.

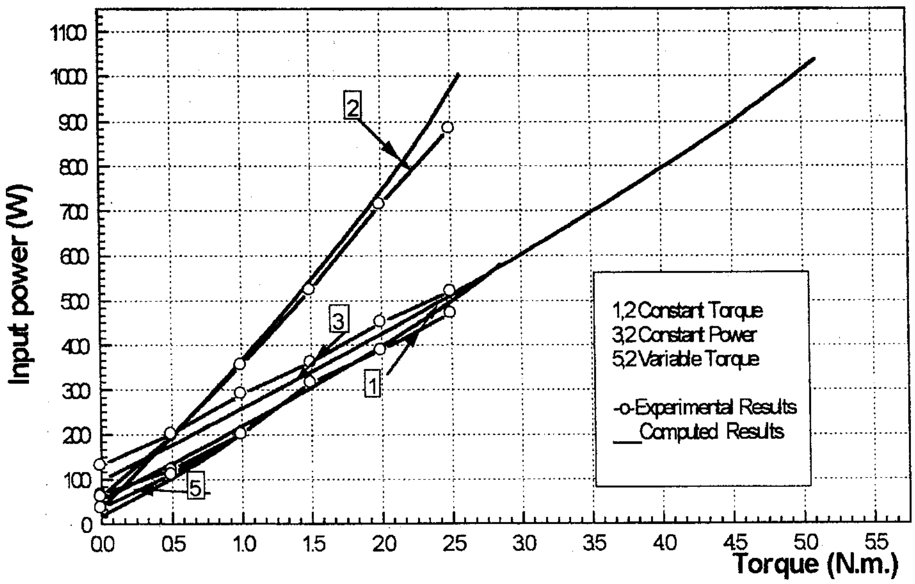


Fig.(7).Input power versus torque at different operations.

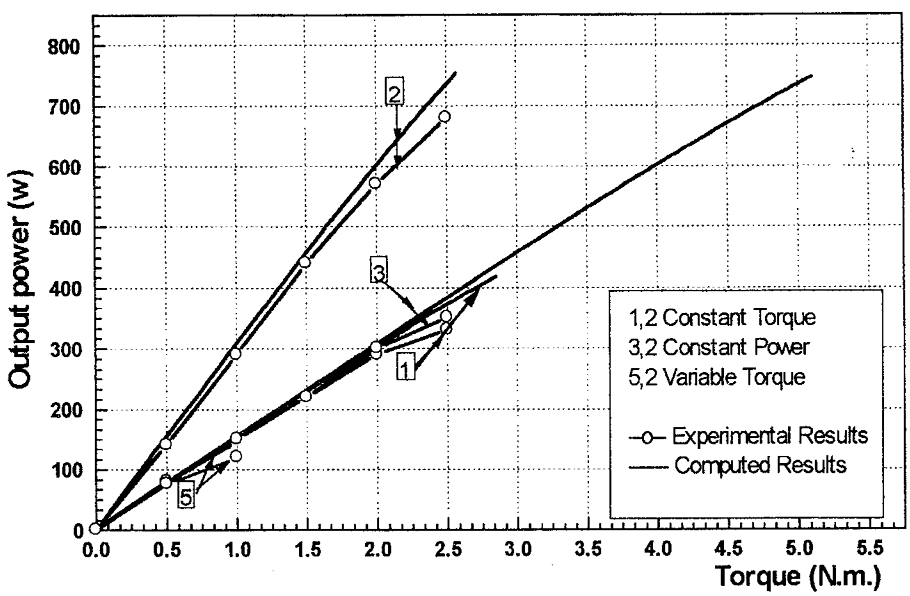


Fig.(8). Output power versus torque at different operations.

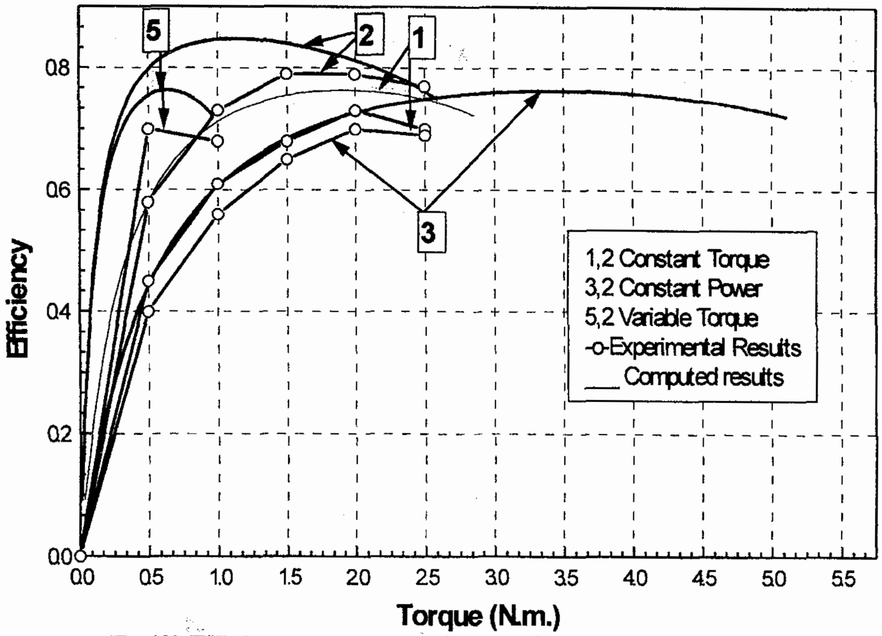


Fig.(9).Efficiency versus torque at different operations.

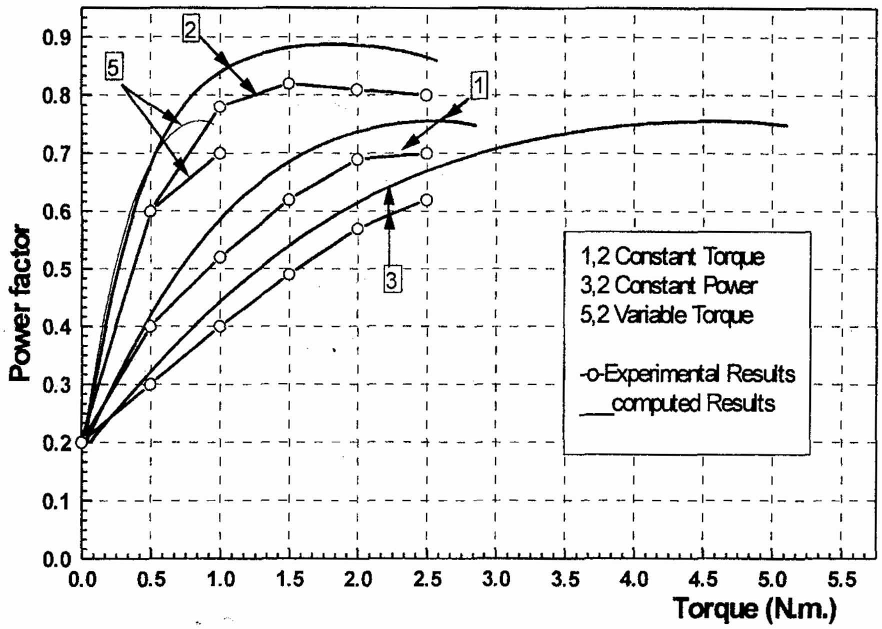


Fig.(10).Power factor versus torque at different operations.

تعيين خصائص المحرك الذى يعمل بطريقة تعديل قيمة القطب

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ملخص البحث

فى هذا البحث تم تعيين خصائص المحركات التأثيرية التى تعمل بطريقة تعديل قيمة القطب " **Pole Amplitude Modulation** " عند السرعتين ١٥٠٠و٣٠٠٠ لفة فى الدقيقة فى الحالات التالية:

١-ثبوت العزم.   ٢- ثبوت القدرة   ٣- تغير العزم.

تم الأخذ فى الاعتبار تأثير تغيير عدد الأقطاب وطريقة توصيل ملفات كل وجه ونوع الحمل على متغيرات المحرك (**motor parameters**).

أجريت التجارب العملية على المحرك عند السرعتين ١٥٠٠و٣٠٠٠ لفة فى الدقيقة فى الحالات الثلاث ومقارنة النتائج العملية بالنتائج النظرية.