THE ROLE OF SYNCHRONOUS GENERATOR PARAMETERS ON EVALUATING MINIMUM EXCITATION POWER REQUIREMENTS

BY

Hassan Ali Abou-Tabl, B.Sc., Ph.D.,*

SYNOPSIS:

The paper derives, first, a general relation of the ecitation power in terms of the synchrououus generator parameters. The condition for minimum requirements on excitation power is tested for extended range of both type of machines, namelly, the salient-pole type and the cylindrical-rotor type. The saliency effect (x_q) has an appreciable influence on the minimum excitation power. The possibility of building salient-pole generator which can operate with minimum excitation power at all power factors is proved. For turbo-generators it is also shown that a wide range of such machines can be built to operate with minimum excitation power at 0.8 lagging power factor which is the most usual operating load power factor.

0.0. Nomenclature:

- E_f : = internal or excitation voltage, per phase;
- E_q : = r.m.s. value of voltage behind transient reactance;
- I : = rated current;
- I_f : = field current;
- I_{fo} : = steady-state field current;
- K : = variable factor;
- L_{ff} : = self-inductance of field winding;
- M_f : = equivalent stator to rotor mutual inductance;
- P_f : = total field-or excitation power;
- P_{fo} : = steady-state excitation power;
- P_{ft} : = transient excitation power;

---

* Lecturer, Faculty of Engineering, Mansoura University,
Mansoura Bulletin, December 1977.

$(P_{fo})_{min}$:= minimum steady-state excitation power;
$(P_{ft})_{min}$:= minimum transient excitation power;
R_f := field circuit resistance;
T'_{do} := open circuit field time-constant;
V := stator terminal voltage, per phase;
V_f := field circuit terminal voltage;
X_d := direct reactance;
X'_d := transient reactance;
X_q := quadrature reactance;
ω := rotor angular velocity;
ϕ := power factor angle;
λ_f := flux linkage of field circuit.

note : lower case lettere designate the corresponding per-unit values.

1.0. INTRODUCTION:

From the analytical viewpoint a 3-phase synchronous machine can be regarded as a stator consists of 3-distributed phase windings a,b, and c, Fig.(1), and a rotor carriee the d.c. field winding f. In order to have an ideal synchronous machine the possibility of other electrical circuits on the rotor formed by the damper bars in practical machine is ignored, as well as the saturation hystersis and eddy currents.

The resulting voltage-current relations of the machine based on the above assumptions are functions of the stator-to-rotor displacement angle Θ. Therefore, the resulting equations are algebraically very complicated. If the concept of dividing m.m.fs into direct and quadrature axis components is formed and by make use of the d-q-o transformation method, the analysis of the voltage-current relations will be greatly simplified [6], [7].

The analysis leads to the excitation (internal) voltage relation which can be obtained directly from the phasor diagram of a salient-rotor machine operating at rated (VA).

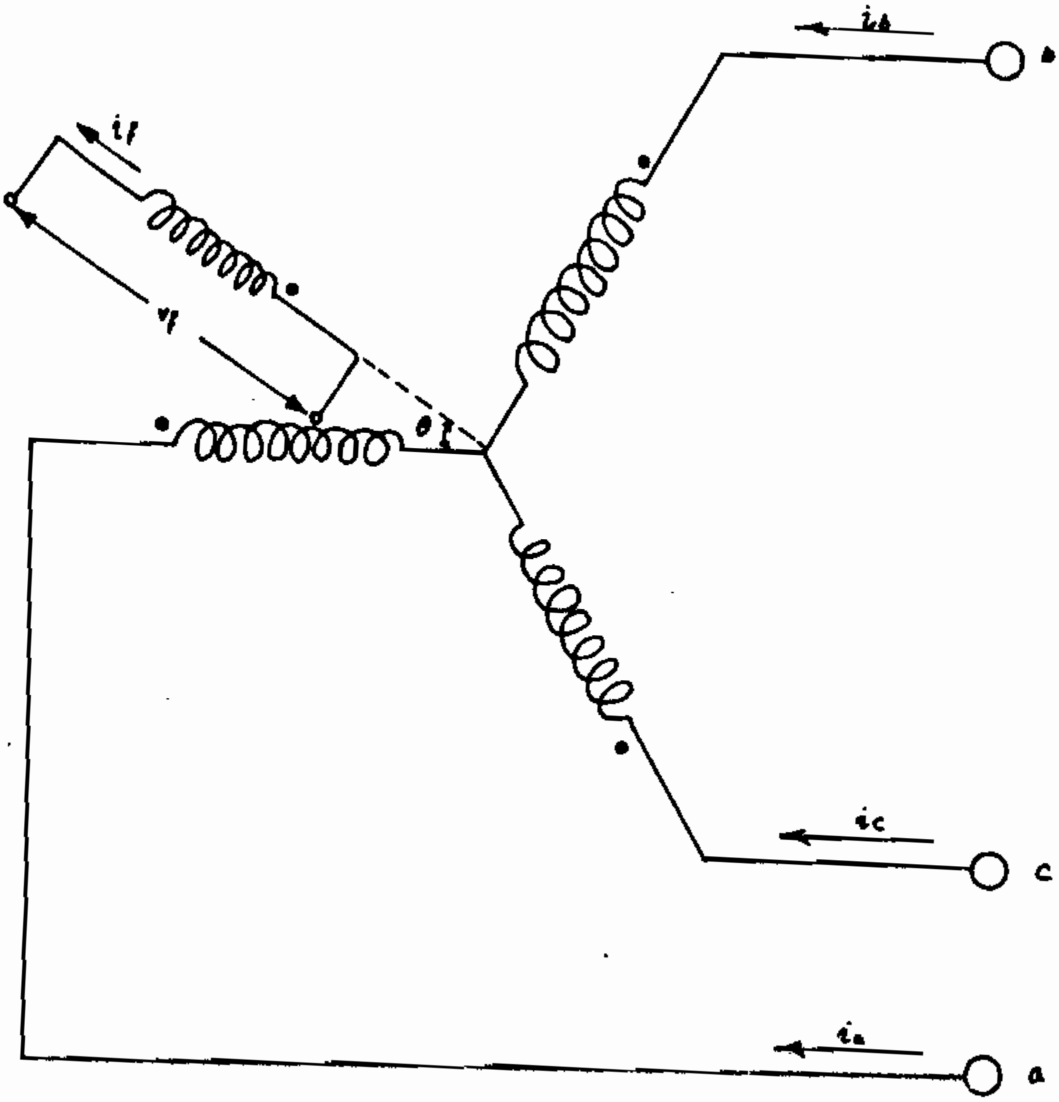

FIG. C.1) COUPLED CIRCUIT MODEL OF THE IDEALIZED SYNCHRONOUS MACHINE.

It has the form:

$$E_f^2 = V^2 + (IX_d)^2 \pm 2V(IX_d)\sin\phi - \frac{(x_d - x_q)^2 (VI)^2 \cos^2\phi}{V^2 + (IX_q)^2 \pm 2V(IX_q)\sin\phi} \qquad \text{......(1-a)}$$

where

+ ve sign for lagging power factor,

− ve sign for leading power factor.

Rewritting the above equation in per-unit values, it becomes:

$$e_f^2 = 1 + x_d^2 \pm 2x_d \sin\phi - \frac{(x_d - x_q)^2 \cos^2\phi}{1 + x_q^2 \pm 2x_q \sin\phi} \qquad \text{.....(1-b)}$$

This relation is required for the following derivation of general excitation-power relation.

2.0. General Form of Excitation Power

Excitation power supplied to the field circuit at rated load of the machine is

$$P_f = I_f V_f \qquad \text{.....(2)}$$

From the basic machine analysis the field voltage V_f can be described as

$$V_f = I_f R_f + \frac{d}{dt}(\lambda_f)$$

Substituting this relation in Eq. (2), the excitation power can be rewritten in the following form

$$P_f = I_f^2 R_f + I_f \frac{d}{dt}(\lambda_f) \qquad \text{......(3)}$$

Steady-state rated load excitation power, P_{fo}, that is required for normal operation condition can be defined as

$$P_{fo} = I_{fo}^2 R_f \qquad \text{......(4)}$$

This leads to a general form of excitation power, which can be suggested to suite the machine requirements on excitation power

$$P_f = P_{fo} + \left[\left(\frac{I_f}{I_{fo}}\right)^2 - 1\right] P_{fo} + I_f \frac{d}{dt}(\lambda_f) \quad ....(5)$$

In addition to the steady-state excitation power P_{fo}, the above relation gives the additional excitation power required under transient conditions (instabilities). The latter two terms define the transient component of excitation power

$$P_{ft} = \left[\left(\frac{I_f}{I_{fo}}\right)^2 - 1\right] P_{fo} + I_f \frac{d}{dt}(\lambda_f) \quad ....(6)$$

The first term of Eq.(6) represents the excess I^2R dissipation in the field circuit when the field current I_f is other value than the steady-state rated value I_{fo}, while the second term represents the rate of change of stored magnetic energy in the field circuit. Thus the total excitation power, P_f, can be experessed as the sum of the rated load steady-state excitation power P_{fo} and the transient component P_{ft} [1].

$$P_f = P_{fo} + P_{ft} \quad ....(7)$$

3.0. Effect of Machine Parameters on Excitation Power:

The effect of the machine parameters on the required excitation power can be best explained when a relation exists between them. This relation can be found with help of the basic analysis of the machine, which gives that [4]

$$I_f = \frac{\sqrt{3}\, E_f}{\omega M_f} \quad \text{and} \quad \omega \frac{M_f^2}{L_{ff}} = X_d - X_d' \quad ...(8)$$

Applying this relations, Eq.(8), to both component of the excitation power, Eqs. (4) and (6), gives that

$$P_{fo} = \frac{3\, E_{fo}^2}{\omega_o T_{do}'(X_d - X_d')} \quad ....(9)$$

and

$$P_{ft} = \left[\left(\frac{I_f}{I_{fo}}\right)^2 - 1\right] P_{fo} + \frac{3\, E_f}{\omega_o(X_d - X_d')} \cdot \frac{d}{dt}(E_q') \quad ....(10)$$

The observed relation between the excitation power and the machine parameters, Eqs. (9) and (10), will be now discussed in more details for each component.

3.1. Steady-state Excitation Power

It is evident, from Eq. (9), that the steady-state excitation power has further relation to the machine parameters, namelly, through the excitation voltage (internal voltage) E_f. To achieve more simplification, per-unit values may be used for steady-state excitation power which can defined as

$$P_{fo} = \frac{p_{fo}}{(IV)_{base}}$$

Rewritting equation (9) in per-unit values, and substituting for e_{fo}^2 with help of Eq. (1-b) give the following general form of the steady-state excitation power

$$P_{fo} = \frac{1}{\omega_o \, T_{do}(x_d - x_d')} \cdot \left[1 + x_d^2 \pm 2x_d \sin \phi - K(x_d - x_q)^2 \right] \quad ..(11)$$

where

$$K = \frac{\cos^2 \phi}{1 + x_q^2 \pm 2x_q \sin \phi} \quad ......(12)$$

This general relation of steady-state excitation power at rated load is applicable for both type of synchronous machine, namelly, the salient pole type and the cylindrical rotor type. In cylindrical rotor machine, it can be assumed that $x_d = x_q$ and the term $K(x_d - x_q)^2$ in Eq.(11) becomes zero. This term will be defined as the saliency effect. The factor K, Eq. (12), is a function of the quadratere reactance x_q and the power factor $\cos \phi$.

For machines with $0 < x_q \leqslant 1$, the factor K increases in volue from zero at 0.0 lagging p.f., having its maximum K = 1 at a leading power factor under the condition that $\sin \phi = x_q$, then decreases to zero at 0.0 leading power factor, Fig. (2).

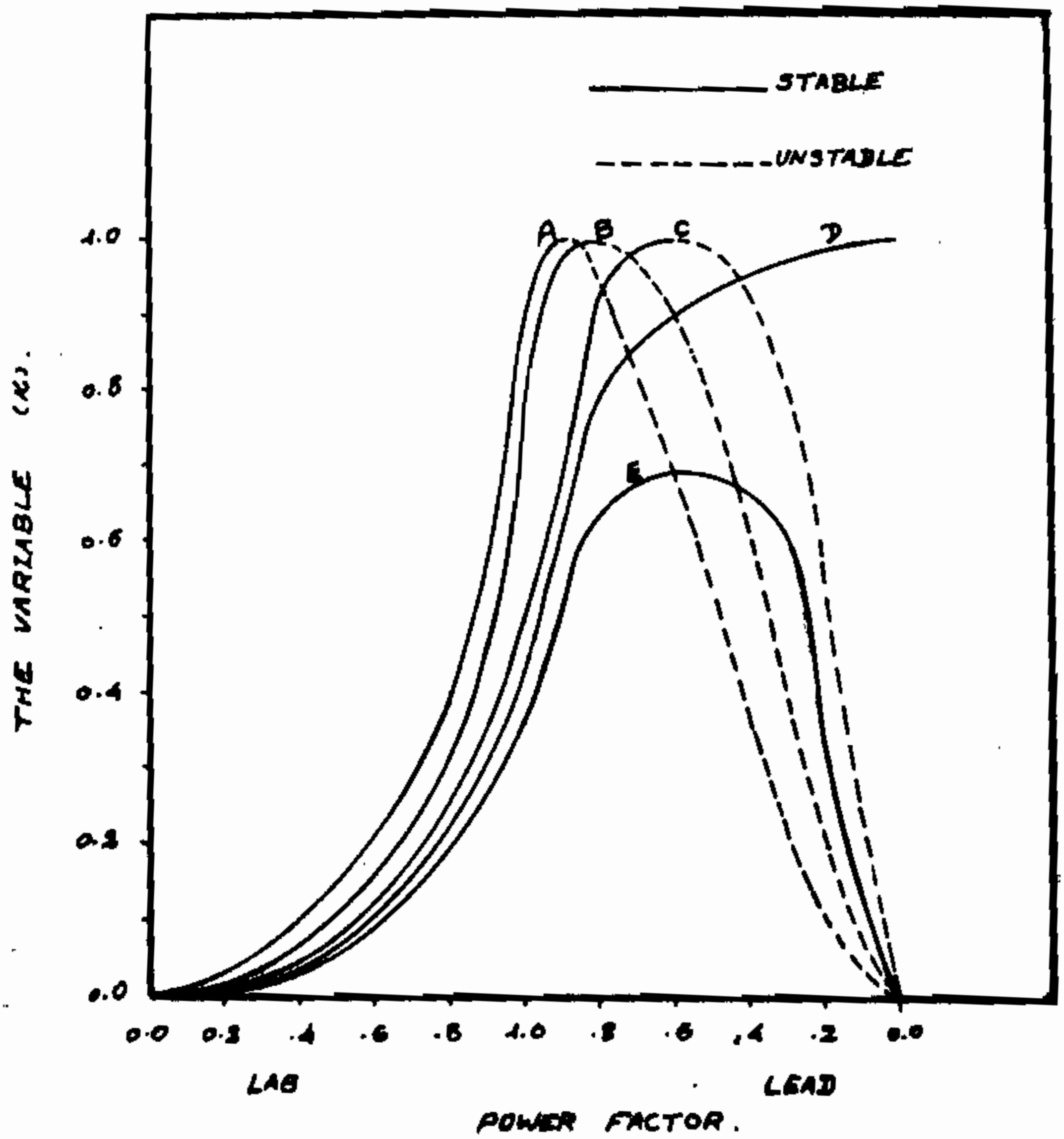

FIG.(2): REPRESNT THE EFFECT VARIABLE K BY THE POWER FACTOR FOR DIFFERENT VALUES OF x_q.

A x_q = 0.4 P.U.
B x_q = 0.6 "
C x_q = 0.8 "
D x_q = 1.0 "
E x_q = 1.2 "

For machines with $x_q > 1$, the factor K varies in such a manner as before but has a maximum less than one. Curves of factor K are helpfull for further calculations.

Beside the machine parameters, it is seen from Eqs. (11 and 12) that the power factor has an effect on the steady-state excitation power as an operational variable. This effect is shown in Figs. (3) and (4) in which p_{fo} is plotted against x_d for different power factors. The time constant and the transient reactance are assumed to be constant [1]. Both type, salient and cylindrical rotor machines, are considered by taking different values of x_q, differ between 0.6 and 1.0 per-unit, while $x_d = x_q$ for cylindrical machines.

The curves presented for a given power factor in Fig. (3) or (4) show the tendency of the steady-state excitation power p_{fo} to pass through a minimum value and then continue to increase with increasing direct reactance x_d. The increase of p_{fo} after having a minimum is remerkable for cylindrical machines. For zero lagging or leading power factor, the quadrature reactance x_q has no effect on p_{fo}.

It is noticed also that the steady-state excitation power at zero leading power factor can be equal zero in a machine having the corresponding direct reactance. In this case, the machine can be considered as a selfexcited machine which needs no external excitation.

3.2. Transient Excitation Power

Transient excitation power is a part of the total excitation power p_f, and it is required mainly to ensure the rate of change in the stored magnetic energy in the field winding to force or weaken the field flux. This interpretation can be easily obtained by looking into the pe -unit relation of p_{ft}

$$p_{ft} = \left[\left(\frac{i_f}{i_{fo}}\right)^2 - 1\right] p_{fo} + \left(\frac{i_f}{i_{fo}}\right) \frac{e_{fo}}{\omega_o(x_d - x_d')} \cdot \frac{d}{dt}(e'_q) \quad .....(13)$$

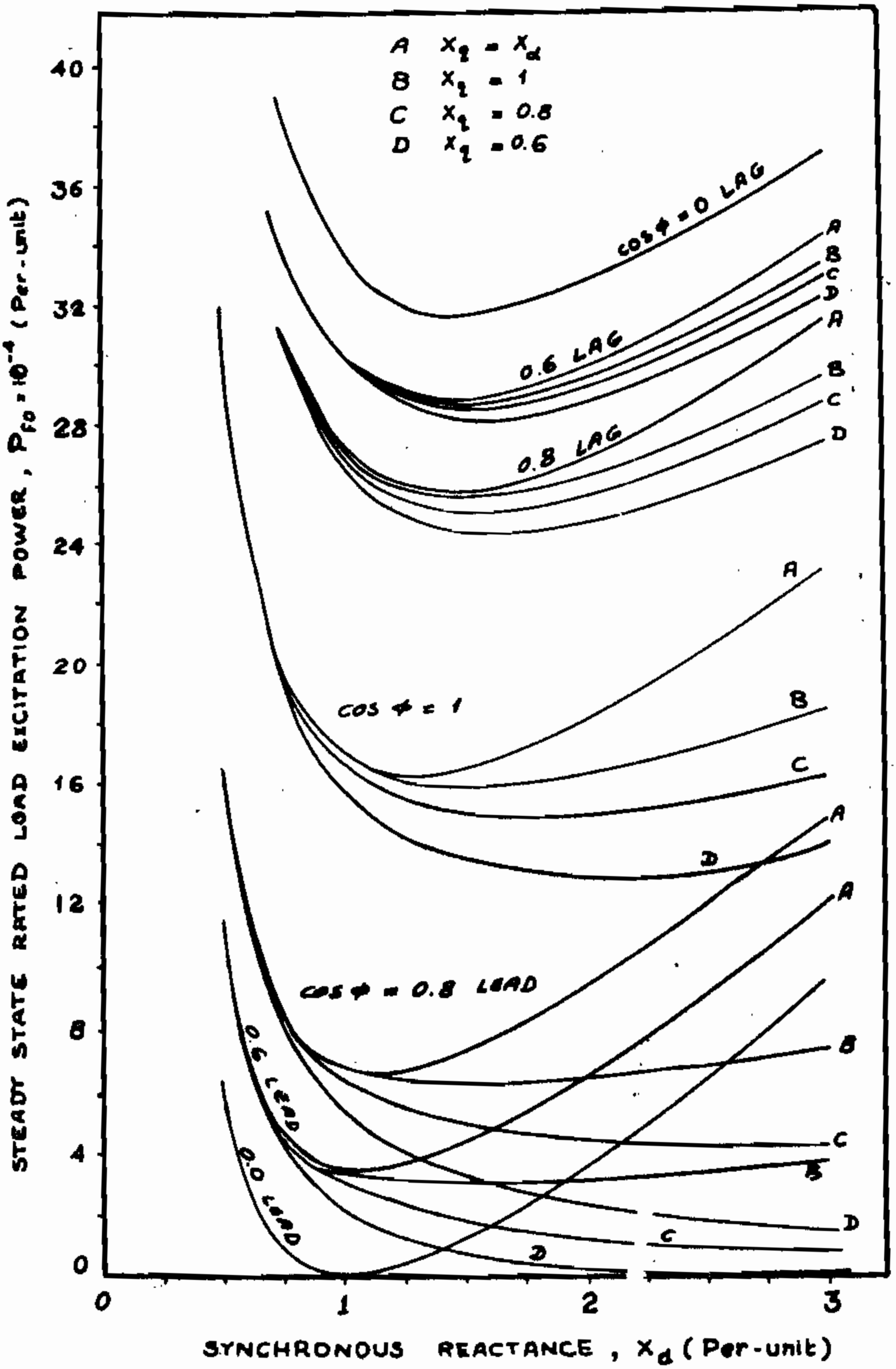

FIG. (3): STEADY STATE EXCITATION POWER REQUIREMENTS FOR SYNCHRONOUS MACHINES AT RATED MVA LOAD; $X'_d = 0.25$ p.u., $T'_{do} = 5$ sec.

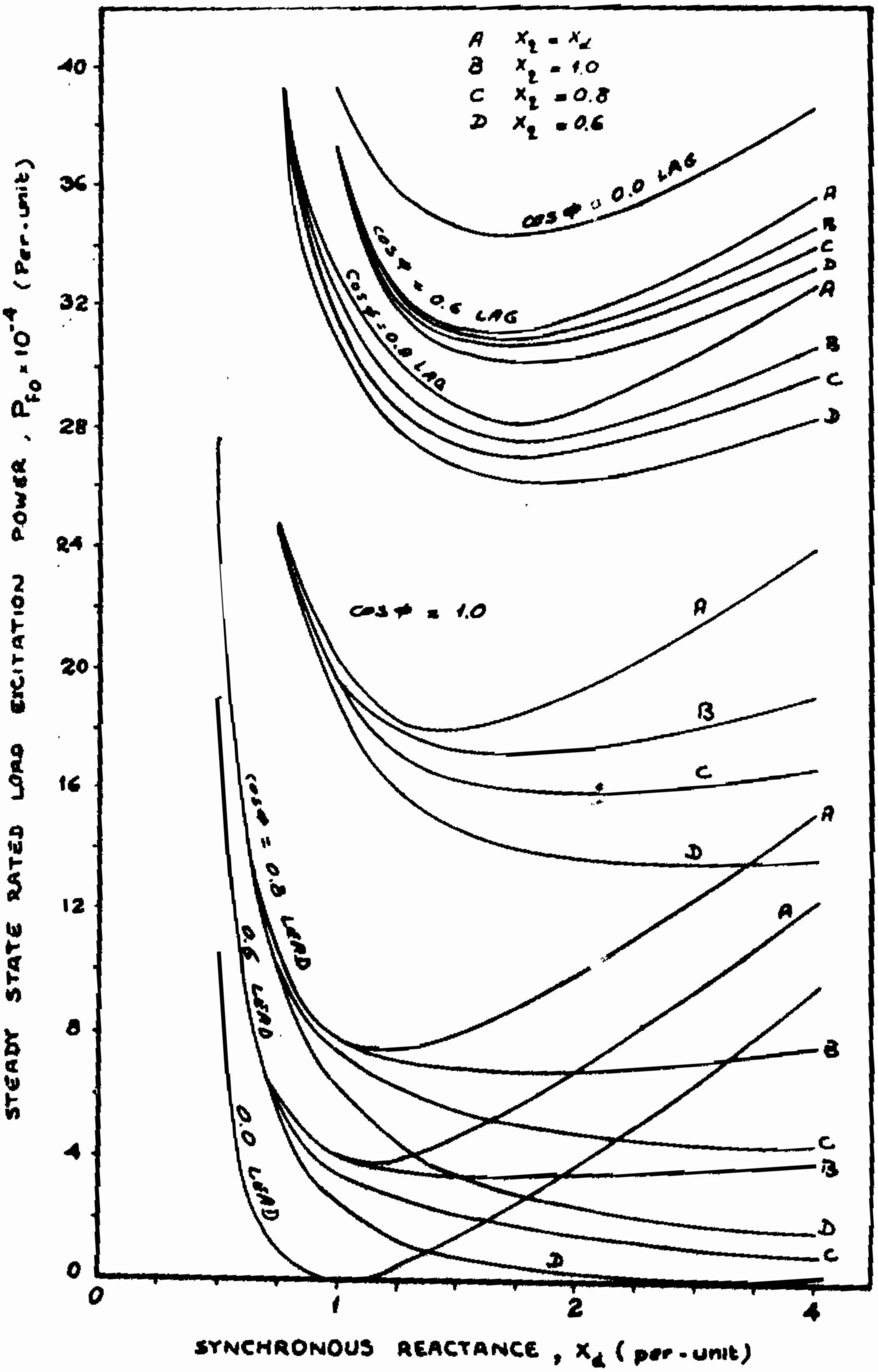

FIG.(4): STEADY-STATE EXCITATION POWER REQUIREMENTS FOR SYNCHRONOUS MACHINES AT RATED MVA LOAD; $x_d' = 0.35$ p.u., $T_{do}' = 5$.

The first term in this equation represents, as mentioned before in section (2.0), the additional power dissipated in the field circuit resistance under transient conditions, when the instantaneous field current, i_f, is other value than the rated load value i_{fo}.

The second term represents the power required to increase the field flux at a per-unit rate $\frac{d}{dt}(e'_q)$, and is equal to the per-unit rate of change in the magnetic energy storage of the generator field winding.

Of special interest is the case where the change in field flux associated with a given control action is accomplished at essentially constant field current, for example: control to effect a small change in terminal voltage or reactive output. In such situtions, the desired change in e_q, and thus i_f, is often rather small, but is to be accomplished rapidly (fast response control action), consequently, the value of $\frac{d}{dt}(e'_q)$ required to obtain the desired control response may be appreciable [4], [5].

The assumption of a small change in i_f leads to the approximation, $(i_f/i_{fo}) \simeq 1.0$ per-unit, so that Eq. (13) reduces to

$$P_{ft} = \frac{e_{fo}}{\omega_o(x_d - x_d)} \cdot \frac{d}{dt}(e'_q) \quad .....(14)$$

Equation (14) is valid when the change in power dissipation, due to the change in i_f, is small in comparison with the rate of change of stored magnetic-energy in field winding.

To show the effect of the machine parameters on the transient-excitation power, Eq. (14) is plotted as a function of x_d, Fig. (5). Also here, the power factor is taken as an operational variable, while other variables in the equation are assumed to be constant. Salient-pole machines are considered by taking different x_q, and for cylindrical rotor machines x_d is equal to x_q.

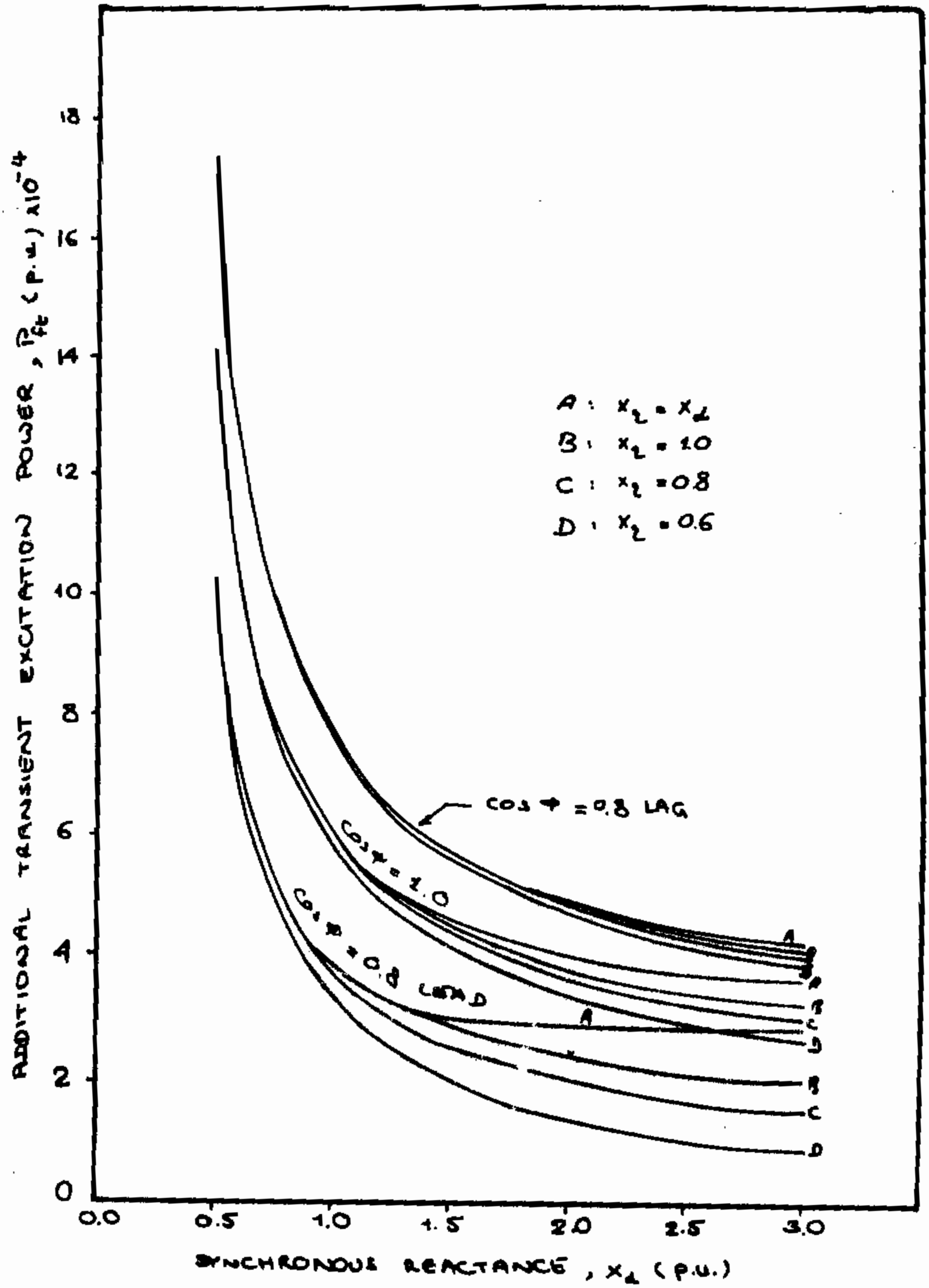

FIG. (5) : ADDITIONAL TRANSIENT EXCITATION POWER REQUIRED TO INCREASE e'_q AT A RATE OF 0.1 p.u./sec. AT RATED LOAD FIELD CURRENT, SALIENT AND CYLINDRICAL ROTOR MACHINE AT RATED MVA LOAD, $X'_d = 0.25$.

It is clear from Eq. (14), that the transient power excitation p_{ft} decreases with increasing x_d, as shown in Fig.(5) for constant e_{fo}.

As a common conclusion on the variation of both p_{fo} and p_{ft}, Figs. (3) to (5), is that the saliency effect can be ignored for small direct reactances x_d. Also for given power factor, the excitation power required according to Eq. (7) decreases with increasing saliency (decreasing x_q). This latter result coinsides naturally with the known effect of the quadrature-axis reluctance on the cross-magnetising component of the armature reaction.

4.0. Minimum Excitation Power:

It is seen in the foregoing sections that the excitation power, represented by its two component, tends to pass through a minimum value when the machine possesses the relevant parameters. It is, also, found that the power factor has the main effect on the level at which the machine will be excited. Of course, not all machines can ensure the conditions of operating at minimum excitation power.

To find a range of machines, either salientor clylindrical type, that each of them has a set of proportional parameters which enable the machine to operate at minimum excitation power, the condition under which the proposed machine can fulfil this requirement will first be obtained.

4.1. Minimum Steady-State Excitation Power:

Steady-state excitation power given by Eq. (11) is a function of the machine parameters x_d, x_d' and x_q. It is well known that x_d' and x_q can be expressed as a ratio of x_d. Therefore the condition for minimum steady-state excitation power will be obtained by equating the first differentiation of p_{fo} in x_d, with zero

$$(1-k)x_d^2 - 2x_d'(1-k)x_d - 2x_d'(kx_q \pm \sin \emptyset) + kx_q^2 - 1 = 0 \quad ......(15)$$

This relation is a second order linerar algebraic equation in x_d, from which

$$x_d = x_d' + \sqrt{x_d'^2 + \frac{1 + k x_q(2x_d' - x_q) \pm 2x_d' \sin \phi}{(1-k)}} \qquad \ldots.(16)$$

Equation (16) gives the condition for minimum steady-state excitation power $(p_{fo})_{min}$, which can be obtained by substituting this condition in Eq. (11).

$$(p_{fo})_{min} = \frac{2}{\omega_o T_{do}'}(1-k)x_d + (kx_q \pm \sin \phi) \qquad \ldots\ldots(17)$$

where k is given by Eq. (12).

The effect of both the machine parameters and power factor on the minimum steady-state excitation power is discussed below.

4.1.1. Effect of power factor on $(p_{fo})_{min}$

Equation (16) and (17) are valid for salient-pole machines, and under the assumption that $x_q = x_d$ are also valid for cylindrical rotor machines. The following study of the effect of power factor on $(P_{fo})_{min}$ takes both type of machines into consideration.

(i) Salient pole machine:

A salient pole machine, which may be built to operate at $(p_{fo})_{min}$, must have its parameters x_d, x_q and x_d' in proportion to each other. These proposed parameters must fulfil the condition given in Eq.(16) for a particular power factor.

According to actual design values of x_q and x_d', they can be related to the direct reactance x_d as follows:

$$x_q = (0.6 - 0.7)\ x_d \qquad \ldots\ldots(18\text{-}a)$$

and

$$x_d' = (0.1 - 0.22)x_d. \qquad \ldots\ldots(18\text{-}b)$$

While x_d and x_q can be assumed and defined to a great assumption with help of machine dimensions, the complementary parameter x'_d must ensure the following condition

$$x'_d = 0.5\ x_d - \frac{0.5(1 \pm x_q \sin \phi)}{x_q \pm \sin \phi}, \qquad \ldots\ldots(19)$$

that the machine may operate at $(p_{fo})_{min}$. The condition (19) is obtained from Eq. (16) by substituting for k and solving for x'_d.

Now, the minimum steady-state excitation power $(p_{fo})_{min}$, Eq.(17), has been calculated for a widerange of salient pole machines with proportional parameters. Actually not all these machines can operate at $(p_{fo})_{min}$. The power factor plays here an important role to find out x'_d, at which the machine may perform its full-load at $(p_{fo})_{min}$, Eq. (19).

For each machine, it has been found the range of power factor in which the machine can operate at minimum steady-state excitation power. The results are tabulated in Table (1) and plotted in Figs. (6) and (7). In Fig. (6) the curves are drawn only for those ranges of power factor, in which the machine can be excited with $(p_{fo})_{min}$. The complete curves may vary having the same shape of that curve for $x_q = 1$ per-unit; to intersect with the positive axis of $(p_{fo})_{min}$, for $x_q > 1$, and with the negative axis, for $x_q < 1$.

For $x_q = 1.0$ per-unit, the transient reactance x'_d is independent on the power factor, and Eq. (19) turns into:

$$x'_d = 0.5\ x_d - 0.5 \qquad \ldots\ldots\ldots(20)$$

It is an advantage for salient generators those having $x_q = 1.0$ per-unit that they can operate with minimum steady-state excitation power at all power factors.

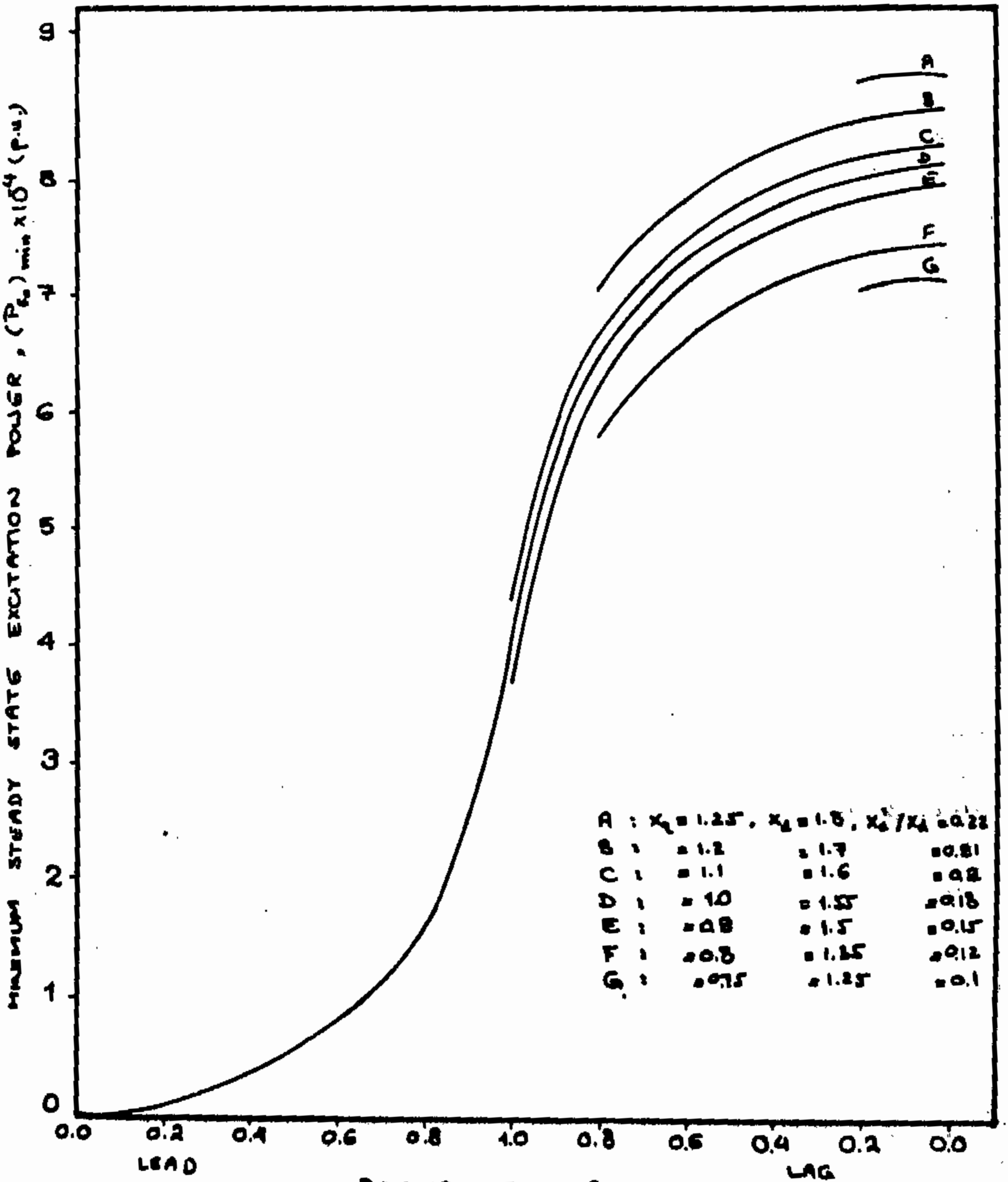

FIG. (6) : MINIMUM STEADY-STATE EXCITATION POWER REQUIREMENTS WITH POWER FACTOR FOR SALIENT TYPE SYNCHRONOUS GENERATORS AT RATED LOAD FOR X_q = 0.75 - 1.25 p.u. , T'_{do} = 23 .

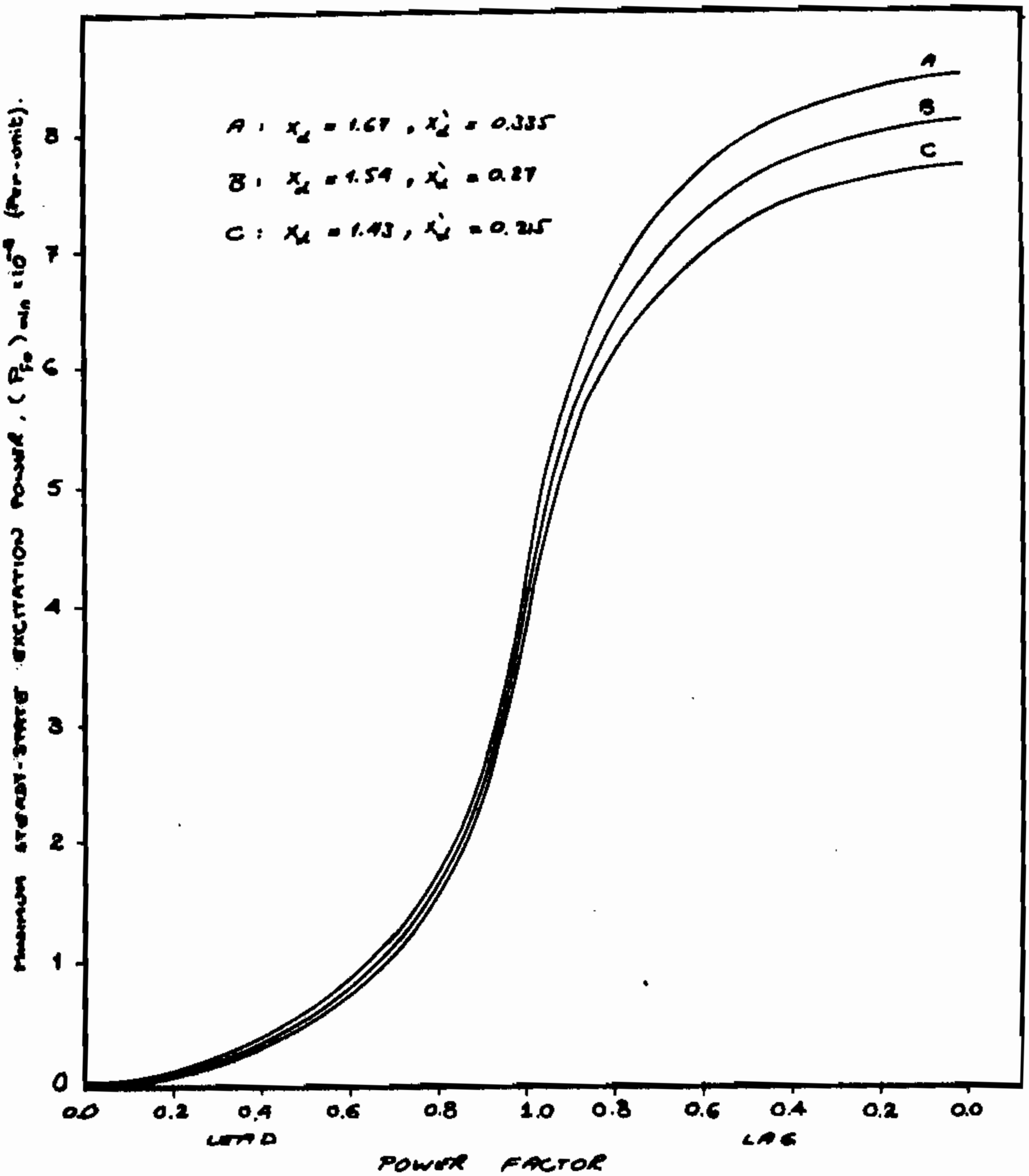

FIG. (7): EFFECT OF THE X_d LIMITS ON THE MINIMUM STEADY-STATE EXCITATION POWER REQUIREMENTS FOR SYNCHRONOUS GENERATORS SALIENT TYPE AT RATED LOAD (X_q = 1.0 , T_{do}' = 20).

P.F. / REACTANCES	0.0 LAG	0.2	0.4	0.6	0.8	U. P.F.	0.8	0.6	0.4	0.2	0.0 LEAD
$X_d = 1.25$, $X_q = 0.75$	X	X									
1.35 , 0.8	X	X	X	X	X						
1.4 , 0.85	X	X	X	X	X						
1.5 , 0.9	X	X	X	X	X	X					
1.6 , 0.95	X	X	X	X	X	X	X				
1.55, 1.0	X	X	X	X	X	X	X	X	X	X	X
1.5 , 1.05	X	X	X	X	X	X	X				
1.6 , 1.1	X	X	X	X	X	X					
1.65 , 1.15	X	X	X	X	X						
1.7 , 1.2	X	X	X	X							
1.8 , 1.25	X	X									

TABLE (1) : RANGE OF POWER FACTOR AT WHICH AN ACTUAL SALIENT POLE GENERATOR CAN BE OPERATE WITH MINIMUM P_{Fo} .

(ii) Cylindrical rotor machines

For cylindrical-rotor machines, it can be assumed that $x_q = x_d$, further that practical designs give

$$x'_d = (0.1 - 0.25)\ x_d \qquad \text{.......(21)}$$

Thus the condition to get minimum steady-state excitation power is

$$x'_d = \frac{0.5\ (x_d^2 - 1)}{x_d \pm \sin \phi} \qquad \text{.......(22)}$$

Substituting in the p_{fo} relation, Eq. (11), with the condition (22); the minimum steady-state excitation power for cylindrical machines can obtained

$$(p_{fo})_{min} = \frac{2}{\omega_o T_{do}}\ (x_d \pm \sin \phi). \qquad \text{.......(23)}$$

The above relation for $(p_{fo})_{min}$ has been calculated for a wide range of cylindrical generators. The check for proportionality between the parameters of a given machine is done with help of Eqs. (22) and (21) to have the power factor range, in which the machine can operate at minimum steady-state excitation power.

The results are tabulated in Table (2) to give the range of power factor, in which the corresponding cylindrical machine can be excited with $(p_{fo})_{min}$. The choosen machines have a direct reactance x_d lies between 1.05 and 2.0 per-unit. Some of these cylindrical generators are given in Fig. (8) with its power factor rangee.

Further inspection of Table (2) shows that a wide range of real cylindrical rotor machines can operate with minimum steady-state excitation power at 0.8 lagging power factor which is the more usual operating load power factor. It is meant by real machine that machine which has proportional parameters x_d, x_q and x'_d.

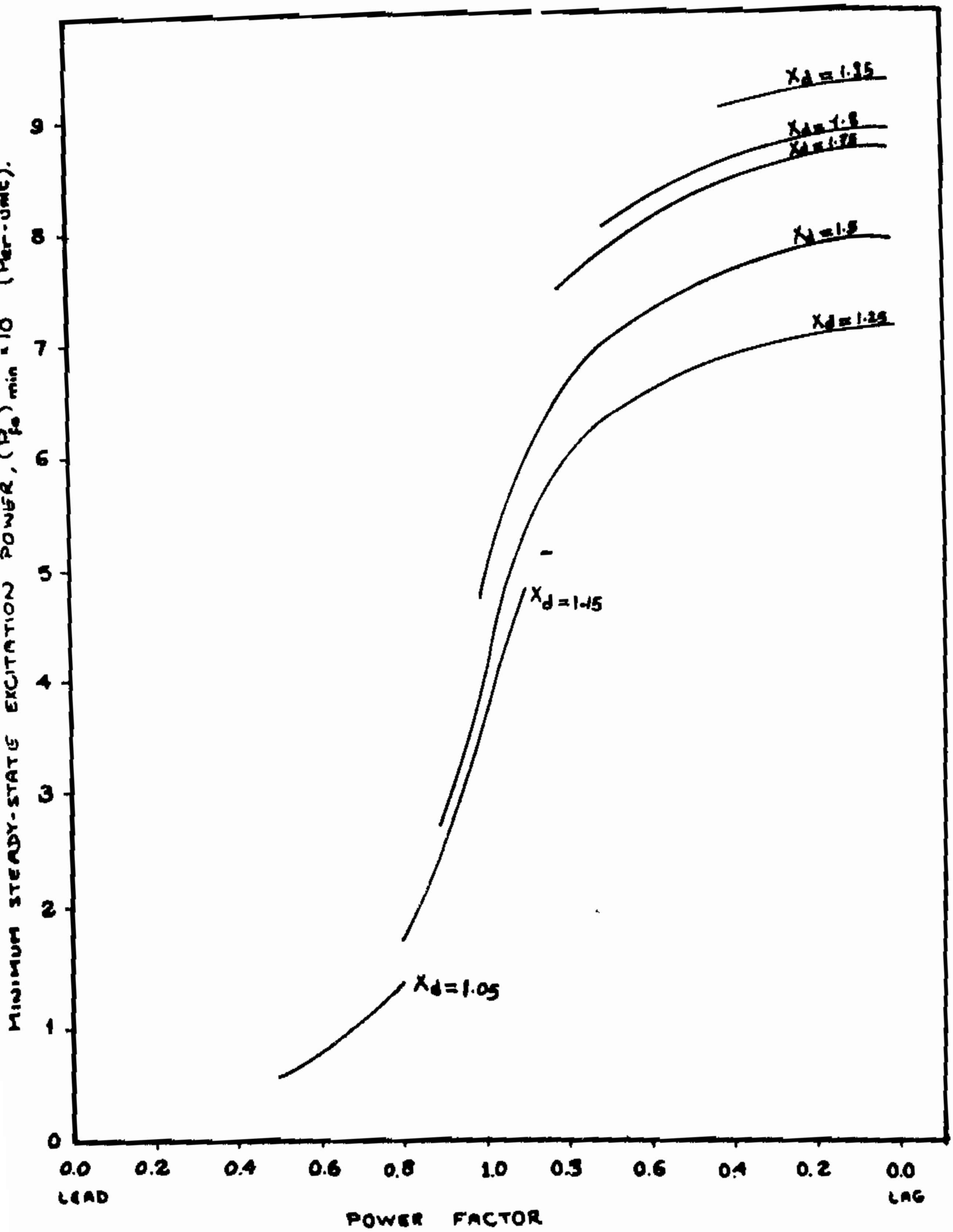

FIG. (8) : MINIMUM STEADY-STATE EXCITATION POWER REQUIRMENTS WITH POWER FACTOR FOR CYLINDRICAL TYPE SYNCHRONOUS GENERATOR AT RATED-LOAD, $T'_{do} = 20$.

P.F. / REACTANCE	0.0 LAG	0.2	0.4	0.6	0.8	U.P.F.	0.8	0.6	0.4	0.2	0.0 LEAD
X_d = 1.05							X	X			
1.1							X				
1.15						X	X				
1.2					X	X					
1.25	X	X	X	X	X	X					
1.3	X	X	X	X	X	X					
1.35	X	X	X	X	X	X					
1.4	X	X	X	X	X	X					
1.45	X	X	X	X	X						
1.5	X	X	X	X	X						
1.55	X	X	X	X	X						
1.6	X	X	X	X	X						
1.65	X	X	X	X	X						
1.7	X	X	X	X	X						
1.75	X	X	X	X	X						
1.8	X	X	X	X							
1.85	X	X	X	X							
1.9	X	X	X	X							
1.95	X	X	X								
2.0	X										

TABLE (2): RANGE OF POWER FACTOR AT WHICH A CYLINDRICAL ROTOR GENERATOR CAN OPERATE WITH MINIMUM P_{fo}.

4.1.2. Effect of the Direct Reactance on $(p_{fo})_{min}$:

The relation between the minimum steady-state excitation power $(p_{fo})_{min}$ and the direct synchronous reactance x_d is a straight line as shown in Fig. (9) and (10) for both type of generators the salient-pole and cylindrical rotor respectively. These figures are drawn with the help of Tables (1) and (2).

(i) Salient-pole machines

In the curves representing the salient-pole generators, Fig. (9), it can not be said that each point represents a real machine.

At zero lagging power factor, the quadrature reactance x_q has no effect. A range of real machines exsists on the line corresponding to 0.0 lagging power factor and is limited by two dotted lines.

For other power factors only one real generator exsists for each relevant quadrature reactance x_q. All these real generators can operate with minimum steady-state excitation power at a definite power factor, and they lie between the two dotted lines.

For leading power factors, there are not so many real machines which can operate with minimum steady-state excitation power. It is evident that each of all these real machines has a direct reactance which lies within a range of 1.25 to 1.75 per-unit.

(ii) Cylindrical-rotor machines

Fig. (10) shows the curves obtained for the cylindrical rotor synchronoue generators to give the relation between $(p_{fo})_{min}$ and x_d. Here the quadrature reactance x_q has naturally no effect and the only variable is the power factor.

Each point on a straight line represents a real generator, which can operate with minimum steady-state excitation power at the corrsponding power factor.

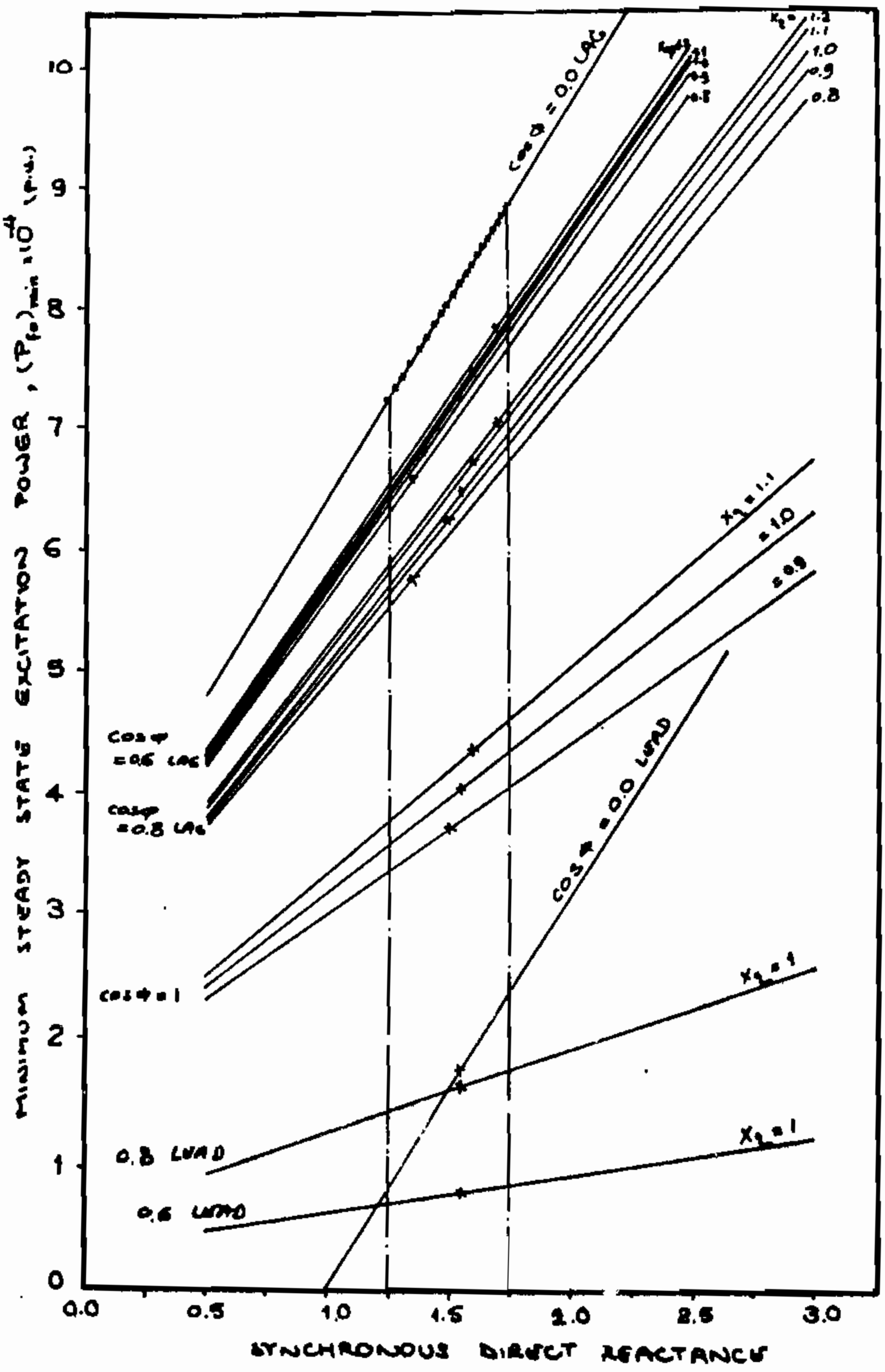

FIG. (9): ACTUAL RANGE OF X_d IN WHICH REAL MACHINES SALIENT TYPE CAN BE BUILT TO OPERATE WITH MINIMUM P_{fo} AT CORRESPONDING POWER FACTOR.

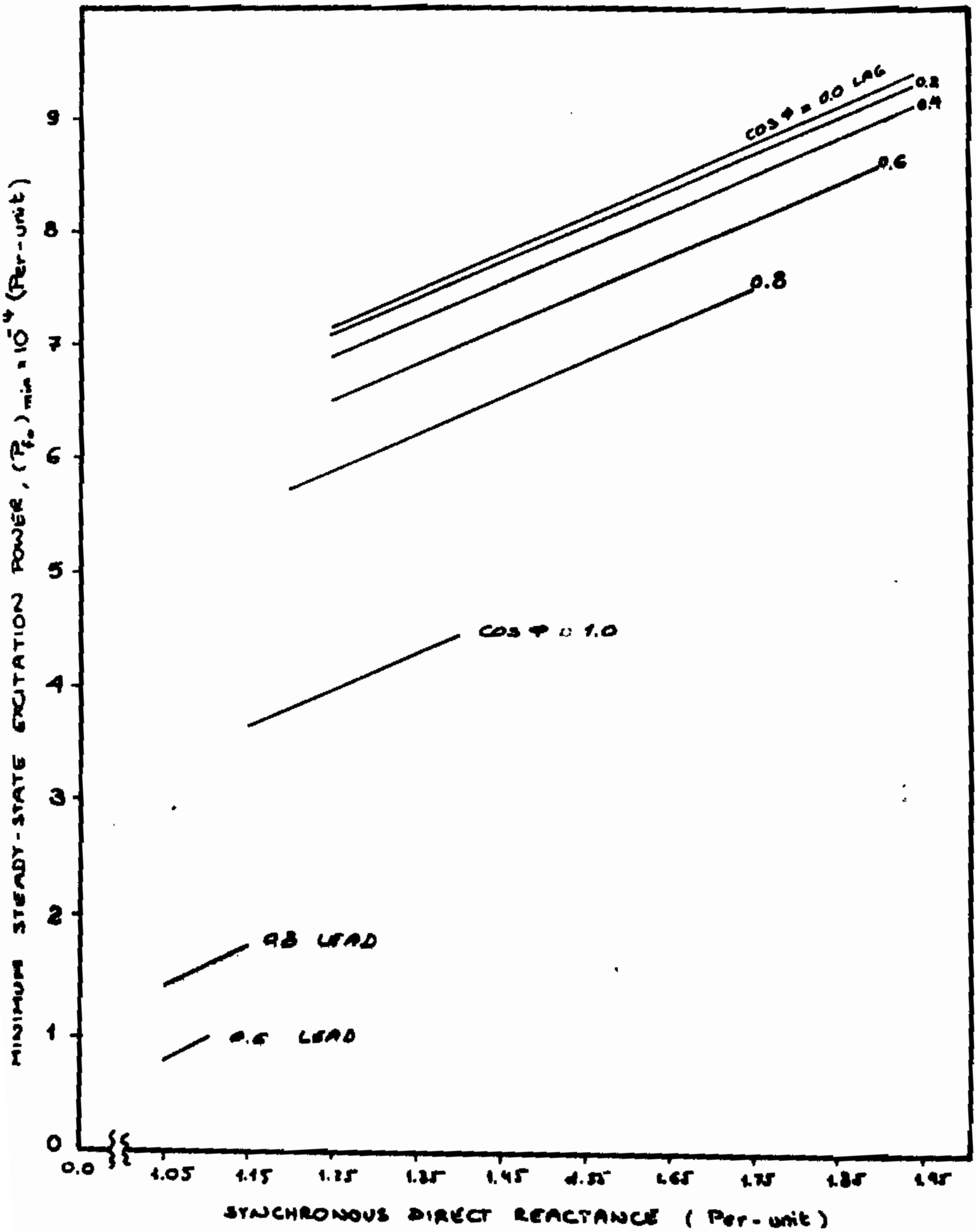

FIG. (10) : ACTUAL RANGE OF X_d IN WHICH REAL MACHINES, CYLINDRICAL TYPE, CAN BE BUILT TO OPERATE WITH MINIMUM P_{fo} AT THE CORRESPONDING P.F.

It is obvious in Fig.(10) that the range of real cylindrical machines relative to a particular power factor is wider. While for salient pole generators extents the vange of real machines to correspond a range of x_d lies between 1.25 per-unit and 1.75 per-unit; extents the range of real cylindrical generators to correspond a direct reactance range from 1.1 per-unit to 1.95 per-unit.

4.2. Minimum Transient Excitation Power $(p_{ft})_{min}$:

Transient excitation power is the complementary part of the total excitation power, p_f, required at any instant. The condition stated before to have the minimum steady-state excitation power will be also used here to define the corresponding minimum of the transient excitation power $(p_{ft})_{min}$.

Substituting Eq. (19) or (22) in Eq. (14) for transient excitation power; the two following relations of the minimum transient-excitation power can be obtained

$$(p_{ft})_{min} = \frac{2}{\omega_o} \cdot \frac{d}{dt}(e'_q) \frac{x_q \pm \sin \phi}{(1 \pm 2x_q \sin \phi + x_q^2)^{1/2}} \quad \text{......(24)}$$

for salient-pole generator, and

$$(p_{ft})_{min} = \frac{2}{\omega_o} \cdot \frac{d}{dt}(e'_q) \frac{x_d \pm \sin \phi}{(1 \pm 2x_d \sin \phi + x_d^2)^{1/2}} \quad \text{.....(25)}$$

for cylindrical-rotor generator.

It is seen from Eq. (24) that the minimum transient excitation power for a salient generator is independent on the direct reactance x_d and depends on the quadrature reactance x_q, while Eq. (25) shows that $(p_{ft})_{min}$ for a cylindrical rotor generator depends on the direct reactance x_d. It is also seen that both relations are function in the power factor.

4.2.1. Effect of Power Factor on $(p_{ft})_{min}$:

The relation between the minimum transient excitation power and the power factor is given in Fig(11) for salient-pole generator, and in Fig. (12) for cylindrical rotor generator.

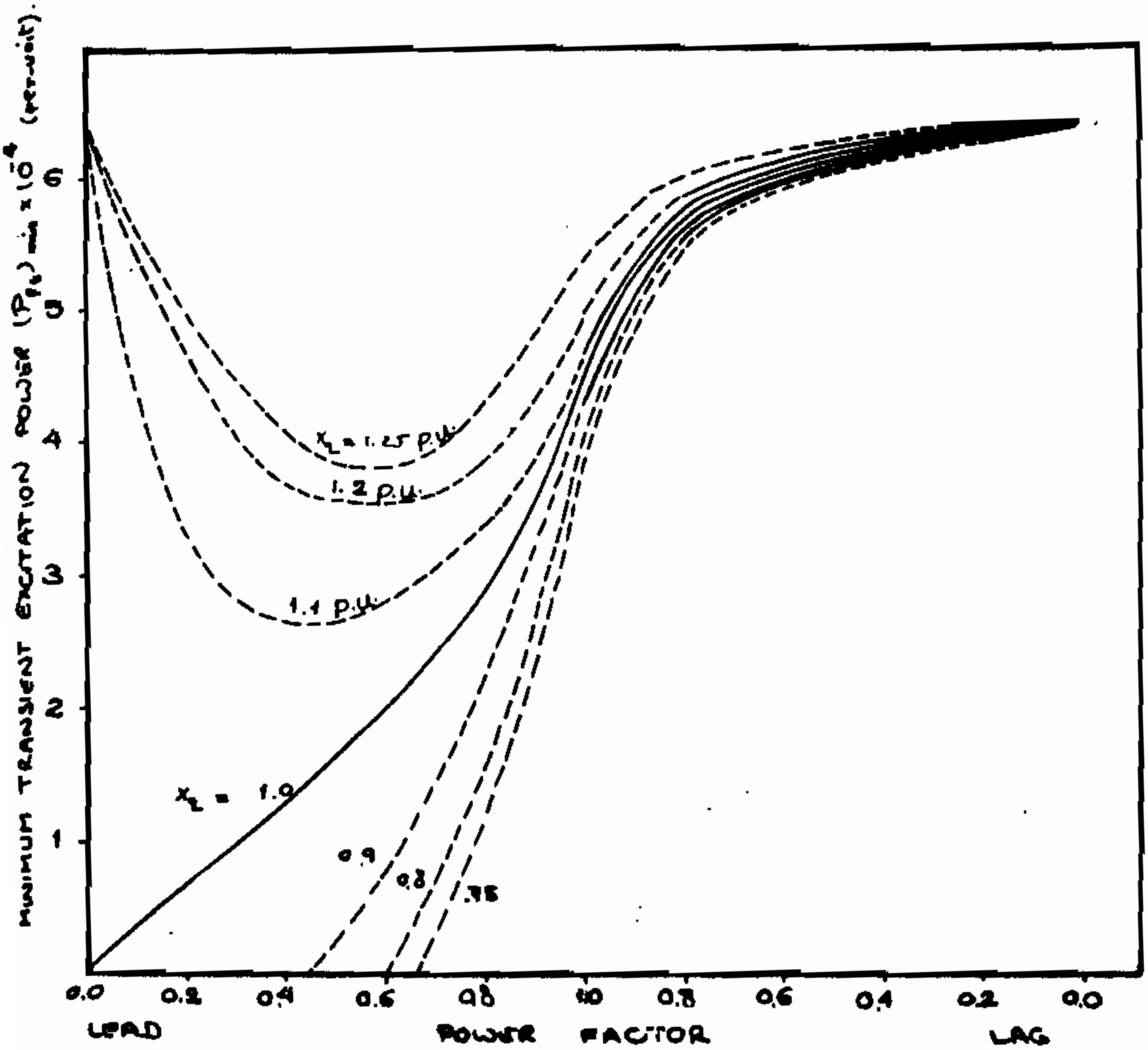

FIG. (11): MINIMUM TRANSIENT EXCITATION POWER REQUIRMENTS AGAINST POWER FACTOR FOR SALIENT ROTOR SYNCHRONOUS GENERATOR AT RATED LOAD, T'_{do} = 20 SEC AND de'_q/dt = 0.1 .

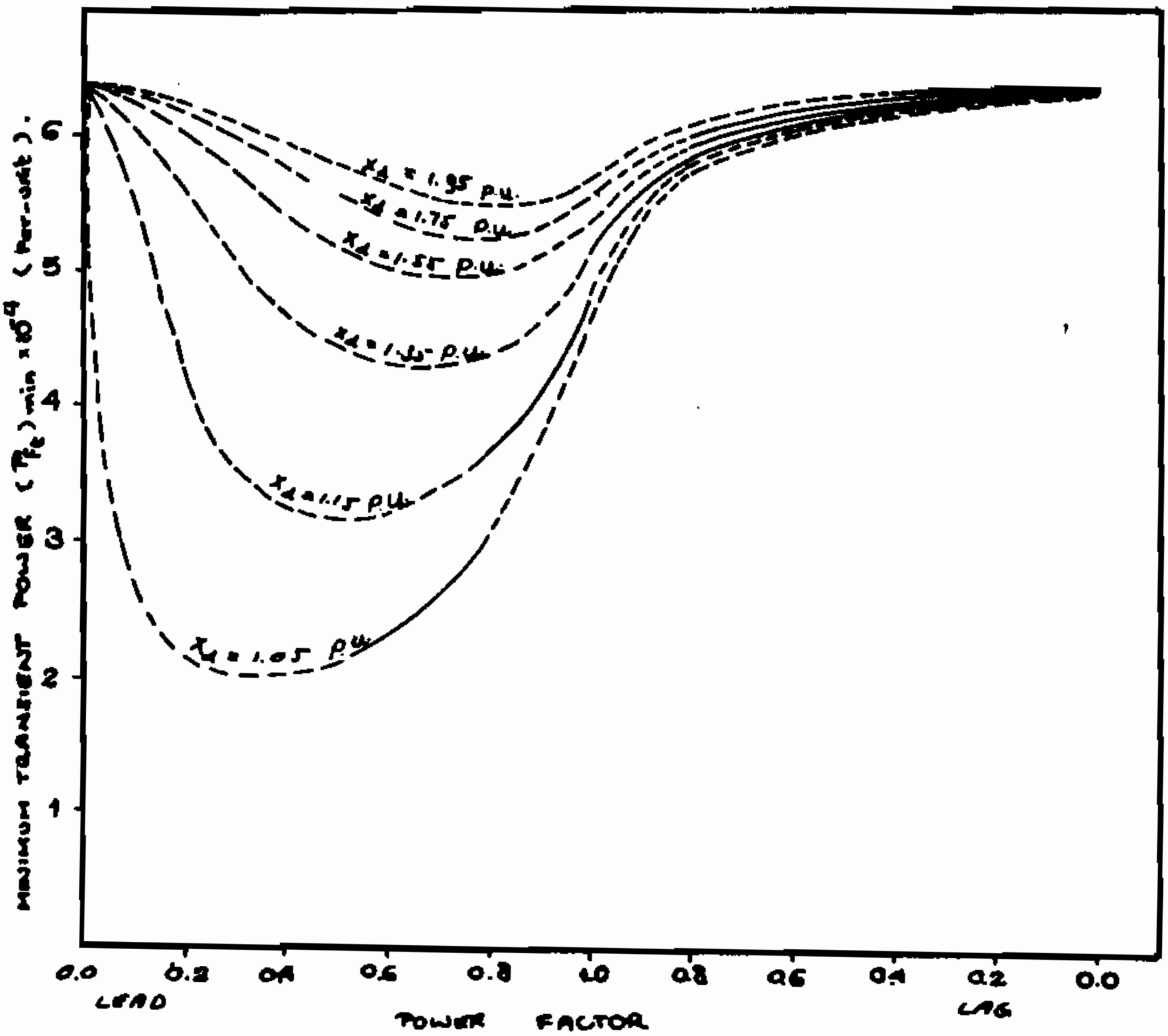

FIG.(12): MINIMUM TRANSIENT EXCITATION POWER REQUIREMENTS AGAINST POWER FACTOR FOR CYLINDRICAL ROTOR SYNCHRONOUS GENERATOR AT RATED LOAD, T'_{do} = 20 SECOND AND de'_{q}/dt = 0.1 .

The curves had been checked for real machines, which are represented by the continuous portion of each curve. Dotted portions on the curves give the total variation of $(p_{ft})_{min}$ against power factor.

For salient-pole generators the considerations govern the variation of the steady-state excitation power with the power factor are also valid here; but with the exception that for $x_q > 1.0$ per-unit the corresponding curves gather itself to the same value of $(p_{ft})_{min}$ at both zero power factor. The same range of generators taken in Fig. (6) is also treated here in Fig.(11). It is obvious that the minimum transient excitation power required by real machines takes the same power factor limits as the steady-state excitation power.

For cylindrical rotor generators, Fig. (12), it is seen that the relation between the minimum transient excitation power and power factor takes such a variation that the corresponding curves gather itself to the same positive value of $(p_{ft})_{min}$ at both zero power factor. The same range of generators choosed in Fig. (8) is also treated here to show that the required $(p_{ft})_{min}$ for real cylindrical-rotor generators extends over the same ranges of power factor that found for $(p_{fo})_{min}$.

4.2.2. Effect of the Direct Reactance x_d on $(p_{ft})_{min}$:

It is seen from Eq. (24) for the salient type of generators, that the minimum transient excitation power does not depend on the direct reactance x_d, thus a corresponding relation between $(p_{ft})_{min}$ and x_d does not exist.

For cylindrical type of generators Fig. (13) give the relation betwsen $(p_{ft})_{min}$ and x_d for the same range of machines selected in Fig. (10). It is evident that for power factors lie between 0.0 lagging and about 0.8 lagging, the transient excitation power seems to be constant. Further inspection of Fig. (13), shows that real cylindrical machines, represented by continuous portions of the curves, extend over the same ranges of x_d that

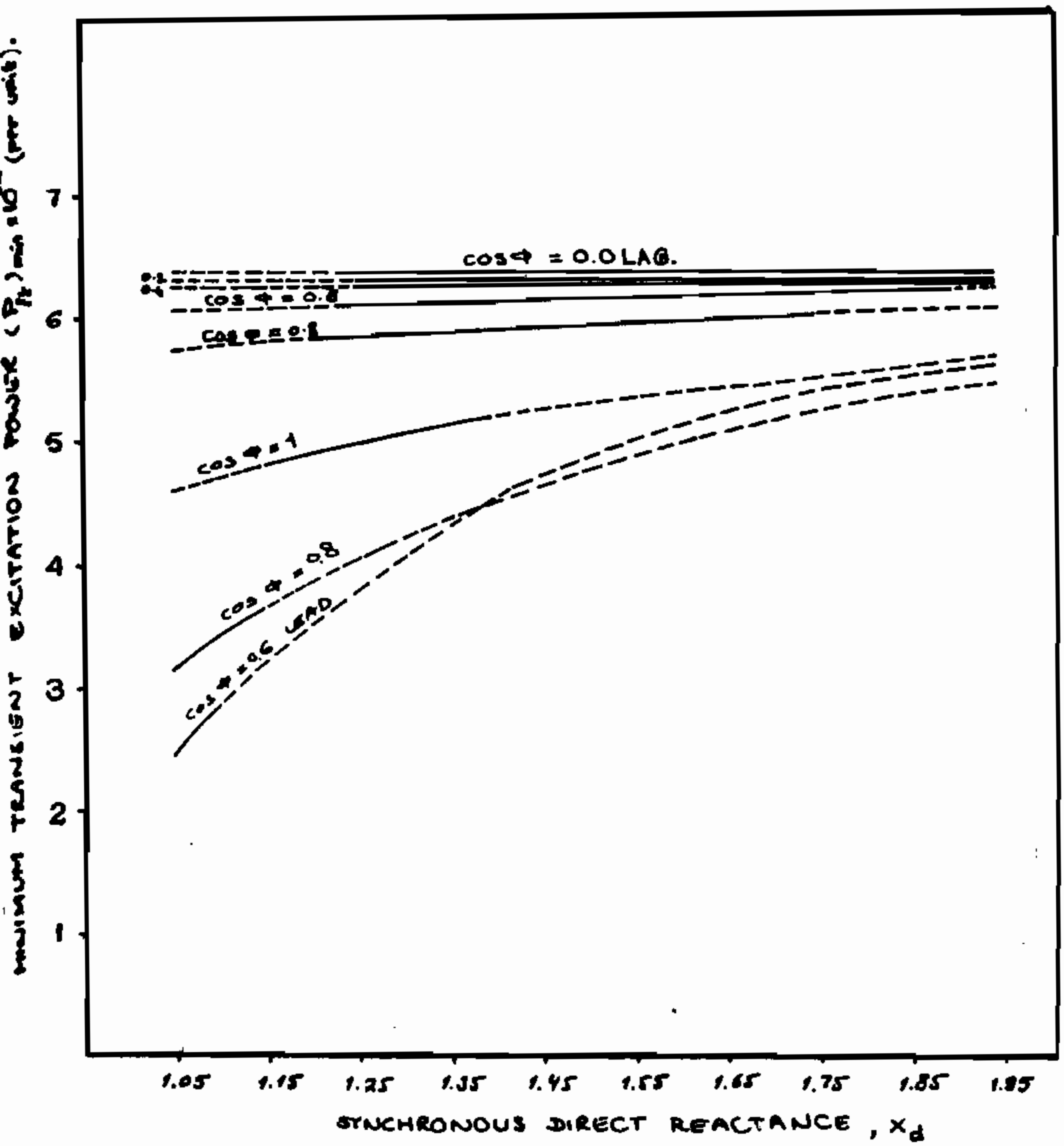

FIG. (13): MINIMUM TRANSIENT EXCITATION POWER REQUIREMENTS AGAINST DIRECT REACTANCE FOR CYLINDRICAL-ROTOR SYNCHRONOUS GENERATOR AT RATED LOAD, T'_{do} = 20 sec, AND $de'_q / dt = 0.1$.

have been found in Fig. (10) for $(p_{fo})_{min}$.

5.0. CONCLUSION:

It is seen from the above study that the synchronous generator parameters, in addition to load power factor, play an important role in limiting the excitation power to a minimum value. It can be emphasised that the saliency effect (x_q) has an appreciable influence on the minimum excitation power. For example, a salient-pole generator with a quadrature reactance $x_q = 1.0$ per-unit is able to operate at minimum excitation power at all power factors. Salient-pole generators having x_q values different from 1.0 per unit are able to operate at minimum excitation power within different smaller power factor ranges.

On the other hand cylindrical rotor generators can operate at minimum excitation power within more extended ranges of power factor than that found for salient-pole generators.

It may also be concluded that a wide range of real cylindrical-rotor synchronous generators can be built to operate with minimum excitation power at a power factor of 0.8 lagging which is considered to be the most usual operating load power factor.

REFERENCES:

1. Amin, A.R.: "Excitation of a.c. generator using rectfiers and their effect on synchronous machine performance", M.Sc. Thesis at Cairo Higher Institute of Technology, 1974.

2. Barret, Ph.: "Reliability of Excitation Systems and their Components", CIGRE Report of Study Committee No.(11), WG(04), ELEKTRA No. (43) December 1975, pp. 15-32.

3. Easton, V.: "Excitation of Large. Turbo Generatore", PROC. IEE, Vol. III, No. 5, May 1964 pp. 1040-1048.

4. Einstein, T.H.: "Generalized Representation of Generator Excitation Power Requirements", IEEE Trans., Vol. PAS-91, No. 5, September/Oktober 1972. pp. 1840-1847.

5. Einstein, T.H.: "Magnetic Energy Storage in Synchronous Machines", IEEE Trans., Vol. PAS-92, No. (1), January/February 1973, pp. 346-351.

6. Lewis, W.A.: "A Basic Analysis of Synchronous Machines Part I", AIEE Trans., Part III, Vol. 77, 1958, pp. 436-451.

7. Park, R.H.: "Two-Reaction Theory of Synchronous Machines Part I, Generalized Method of Analysis", AIEE Trans., Vol. 48 (July, 1929), pp. 716-730.