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A. Echarri and G. Pasotti: ON THE OPTIMIZATION OF
SUPERCONDUCTING TURBOALTERNATORS. -

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LIST OF PRINCIPAL SYMBOLS. -

- R = load resistance per phase.
 L = load inductance per phase.
 R_a = per phase resistance of armature winding.
 L_a = per phase self-inductance of armature winding.
 L_f = self-inductance of field winding.
 n = number of pairs of poles.
 θ = mechanical angle measuring displacement of rotor relative to stator.
 $n\theta$ = electrical angle.
 ω = $n d\theta/dt$ = constant electrical radian frequency.
 M = maximum value of mutual inductance between the field winding and one phase of the armature winding.
 J_f = current density on the field winding.
 J_a = current density on the armature.

(x) - Universidad de Granada (Spain).

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N_f = number of turns on the field winding.

N_a = number of turns per phase on the armature.

R_1 = internal radius of the field winding.

R_2 = external radius of the field winding.

R_i = internal radius of the armature.

R_e = external radius of the armature.

$y = R_1/R_2$, $x = R_i/R_0$, $s = \rho/R_2$ where ρ = radial position of a point
(see Fig. 1).

$R_2/R_0 = xR_2/(R_2 + \text{air gap}) = \frac{x}{\beta_0}$, where air gap = $R_i - R_2$ for machines
with external armature and $\beta_0 = \frac{R_2 + \text{air gap}}{R_2}$.

$R_0/R_2 = yR_0/(R_0 + \text{air gap}) = \frac{y}{\beta_i}$, where air gap = $R_1 - R_0$ for machines
with internal armature and $\beta_i = \frac{R_0 + \text{air gap}}{R_0}$.

l = effective electrical length of the machine.

$\mu_0 = 4\pi \times 10^{-7}$ henry/metre.

$\alpha = R_a/R$.

$Q_m = 3\omega L_a/2R$, $Q_L = \omega L/R$, power factor = $(1 + Q_L^2)^{-1/2}$.

K^2 = square of the maximum coefficient of coupling between the
field winding and the stator winding.

M. K. S. units are always used in this paper.

1. - INTRODUCTION. -

Increasing demands for electrical power have to be met by generating plants of increasing size in order to reduce capital costs for generation and plant construction for a given power.

Alternating two- and four pole turboalternators are now being delivered in some countries with ratings approaching 1000 and 1400 MVA respectively. Rotational speeds of these machines are then 3000 - 3600 or 1500 - 1800 revolutions per minute respectively, for the common industrial frequencies of 50 - 60 cycles.

It is well known that for a given frequency the power of an elec-trical machine depends, amongst other things, of the square of the ro-tor diameter D , the length l , the magnetic induction B and the current density J_a on the armature conductors allowed by the cooling conditions on the armature.

In the last twenty years the product D^2l has been increased about 4 times, the progress having due mainly to progress in the technology of special steels. It does not seem that further increasements will be as spectacular in the next twenty years. During the same time the magne-tic induction has been increased by perhaps 15 - 20 %, progress being hampered now by iron saturation problems. On the other hand the ar-mature current density J_a is limited for traditional turboalternators by Joule-heating effects and the related cooling problems.

The development during the 1960's of superconducting materials carrying high current densities J_f at quite high magnetic fields, ($J_f \approx \approx 10^8$ Amps/m² at $B \approx 6 - 10$ Tesla for Nb-Ti and Nb₃Sn alloys respec-tively), with minimal energy dissipation, besides the normal to be ex-pected from thermal leaks of the dewar where they need to be cooled at liquid helium temperatures, has opened the possibility of increasing the maximum power and the efficiency of alternators.

Some studies⁽¹⁻¹¹⁾ and small experimental realizations⁽¹²⁻¹⁴⁾

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have been undertaken to explore the possibility of use of superconductors in this type of machinery. More recently, the construction of the 1 MVA turbine generator and feasibility studies of 1000 and 10000 MVA turbine generators using superconducting field windings has been undertaken at M. I. T. (14).

It is worth noting that nearly all of these machines were designed with a superconducting field winding at 4.2°K and a copper armature at 300°K. The only exception(13), have both, field winding and armature winding, made in superconducting Nb₃Sn. It presented serious cooling problems during running trials. The reason for this choice of room-temperature copper armature lies in the fact that actual commercial superconducting materials present prohibitive losses under alternating current at industrial frequencies in the presence of magnetic fields as low as 0.1 Tesla.

The purpose of this article is to analyze a three-phase alternator with a constant current supplied to the field windings or with the field winding terminals shortcircuited and operating with constant flux linkage, the mathematical model is that developed by Stekly and Woodson(2).

The alternator is analyzed under four possible versions (see Fig. 1):

- a) superconducting dipolar winding with outside armature ;
- b) superconducting dipolar winding with inside armature ;
- c) superconducting quadripolar winding with outside armature ;
- d) superconducting quadripolar winding with inside armature.

2. - GENERAL RELATIONS. -

Through the paper the following general relations(2) have been widely used :

$$(1) \quad L_a = \mu_0 N_a^2 l L_{A, 2n}$$

$$(2) \quad N_f I_f = \pi(R_2^2 - R_1^2)J_f/2 = \pi R_2^2 J_f(1 - y^2)/2$$

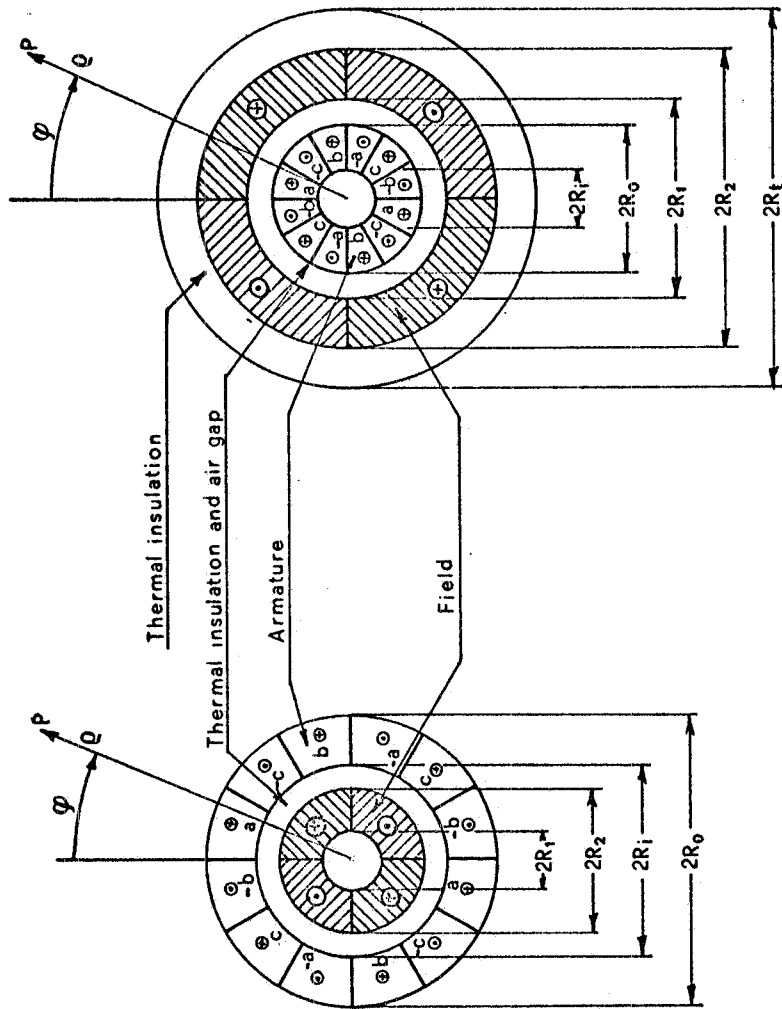


FIG. 1 - Alternator configurations for four-pole machines with armatures on the outside and on the inside.

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$$(3) \quad N_a I_a = \pi(R_0^2 - R_i^2)J_a/6 = \pi R_0^2 J_a (1 - x^2)/6$$

from which it is obtained :

$$(4) \quad N_a I_a / N_f I_f = (J_a/J_f) (R_0^2/R_2^2) \left[(1-x^2)/(1-y^2) \right] / 3 .$$

For the sake of convenience we use the notation $\gamma = J_a/J_f$

$$(5) \quad L_f = \mu_0 N_f^2 l L_{F, 2n}$$

$$(6) \quad W_f = (1/2) L_f I_f^2 = \mu_0 l L_{F, 2n} R_2^4 J_f^2 \pi^2 (1-y^2)^2 / 8$$

where W_f is the magnetic energy stored by the superconducting magnet.

$$(7) \quad M = \mu_0 l N_a N_f (R_2/R_0)^n m_{0, 2n}$$

for the case of external armature.

$$(8) \quad M = \mu_0 l N_a N_f (R_0/R_2)^n m_{i, 2n}$$

for the case of internal armature.

$$(9) \quad K_0^2 = M^2 / L_a L_f = k_{0, 2n}^2 (R_2/R_0)^{2n}$$

for the case of external armature.

$$(10) \quad K_i^2 = M^2 / L_a L_f = k_{i, 2n}^2 (R_0/R_2)^{2n}$$

for the case of internal armature.

The mathematical expressions for $L_{A, 2n}$, $L_{F, 2n}$, $m_{0, 2n}$, $m_{i, 2n}$, $k_{0, 2n}^2$, $k_{i, 2n}^2$ can be found in Table I.

TABLE I - Self-inductances, mutual inductances, coupling coefficients and power coefficients as a function of design parameters (end effects neglected)(2).

Number of poles Parameter	n = 1 (Dipole)	n = 2 (Quadrupole)
L _F	$L_{F_2} = 16(1+3y^4 - 4y^3)/3\pi^3(1-y^2)^2$	$L_{F_4} = 2 \left[1-y^4 - 4y^4 \ln(1/y) \right] / \pi^3(1-y^2)^2$
L _A	$L_{A_2} = 12(1+3x^4 - 4x^3)/\pi^3(1-x^2)^2$	$L_{A_4} = 9 \left[1-x^4 - 4x^4 \ln(1/x) \right] / 2\pi^3(1-x^2)^2$
Armature on the outside	$m_{02} = 16(1-y^3)/\pi^3(1+x)(1-y^2)$ $k_{02}^2 = 4(1-x)^2(1-y^3)^2 / (1+3x^4 - 4x^3)(1+3y^4 - 4y^3)$ $P_{02} = \pi^2(1-y^2)^2 m_{02}^2 / 4L_{A_2}$	$m_{04} = 6(1+y^2) \ln(1/x) / \pi^3(1-x^2)$ $k_{04}^2 = 4(1-y^4)^2 \left[\ln(1/x) \right]^2 / \left[1-x^4 - 4x^4 \ln(1/x) \right] \left[1-y^4 - 4y^4 \ln(1/y) \right]$ $P_{04} = \pi^2(1-y^2)^2 m_{04}^2 / 4L_{A_4}$
Armature on the inside	$m_{i2} = 16(1-x^3)/\pi^3(1+y)(1-x^2)$ $k_{i2}^2 = 4(1-y)^2(1-x^3)^2 / (1+3y^4 - 4y^3)(1+3x^4 - 4x^3)$ $P_{i2} = \pi^2(1-y^2)^2 m_{i2}^2 / 4L_{A_2}$	$m_{i4} = 6(1+x^2) \ln(1/y) / \pi^3(1-y^2)$ $k_{i4}^2 = 4(1-x^4)^2 \left[\ln(1/y) \right]^2 / \left[1-y^4 - 4y^4 \ln(1/y) \right] \left[1-x^4 - 4x^4 \ln(1/x) \right]$ $P_{i4} = \pi^2(1-y^2)^2 m_{i4}^2 / 4L_{A_4}$

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3. - MAGNETIC FIELD DISTRIBUTION AND ARMATURE REACTION EFFECTS. -

Figs. 2a) and 2b) show the distribution of the radial field as a function of s in the position corresponding to $\theta = 0$. From these figures it would seem convenient, at least in the case of a dipolar winding, an internal armature rather than an external one, because the field is higher. It is easy to see however that for a same value of the parameter x and a given magnet, the flux cut by the external armature is about the same than the flux cut by an internal armature.

Figs. 3a) and 3b) show the maximum values of the D.C. field seen by the superconducting winding for an average current density $J_f = 10^8$ Amps/m², as a function of the superconducting magnet external radius R_2 . No account is taken of the magnetic field which will be produced by the armature alternating current and will then influence further the magnetic field seen by the superconducting windings. Of course, the armature effect will depend on the chosen dipolar or quadripolar winding pattern, on the relative position of armature and field winding (internal or external), and of the allowed current density on the armature conductors.

Calculations of armature fields are quite straightforward from Figs. 2a) and 2b), by simple substitution of R_2 by R_0 , and J_f by J_a while the magnet thickness parameter y is substituted by x . If J_a is not much smaller than J_f then armature effects can be very important indeed. Thus for a two-pole machine with $y = 0.8$, $R_2 = 0.25$ metres, $J_f = 10^8$ Amps/m², the D.C. field seen by the windings is 4 Tesla. For an internal armature with $x = 0.8$ and an external radius R_0 20% smaller the internal radius R_1 of the field winding and $J_a = 10^8$ Amps/m² also (perhaps possible, in principle, for a superconducting armature), the armature see not only the full 4 Tesla D.C. field but also a 2.6 Tesla rapidly alternating magnetic field. The D.C. magnet

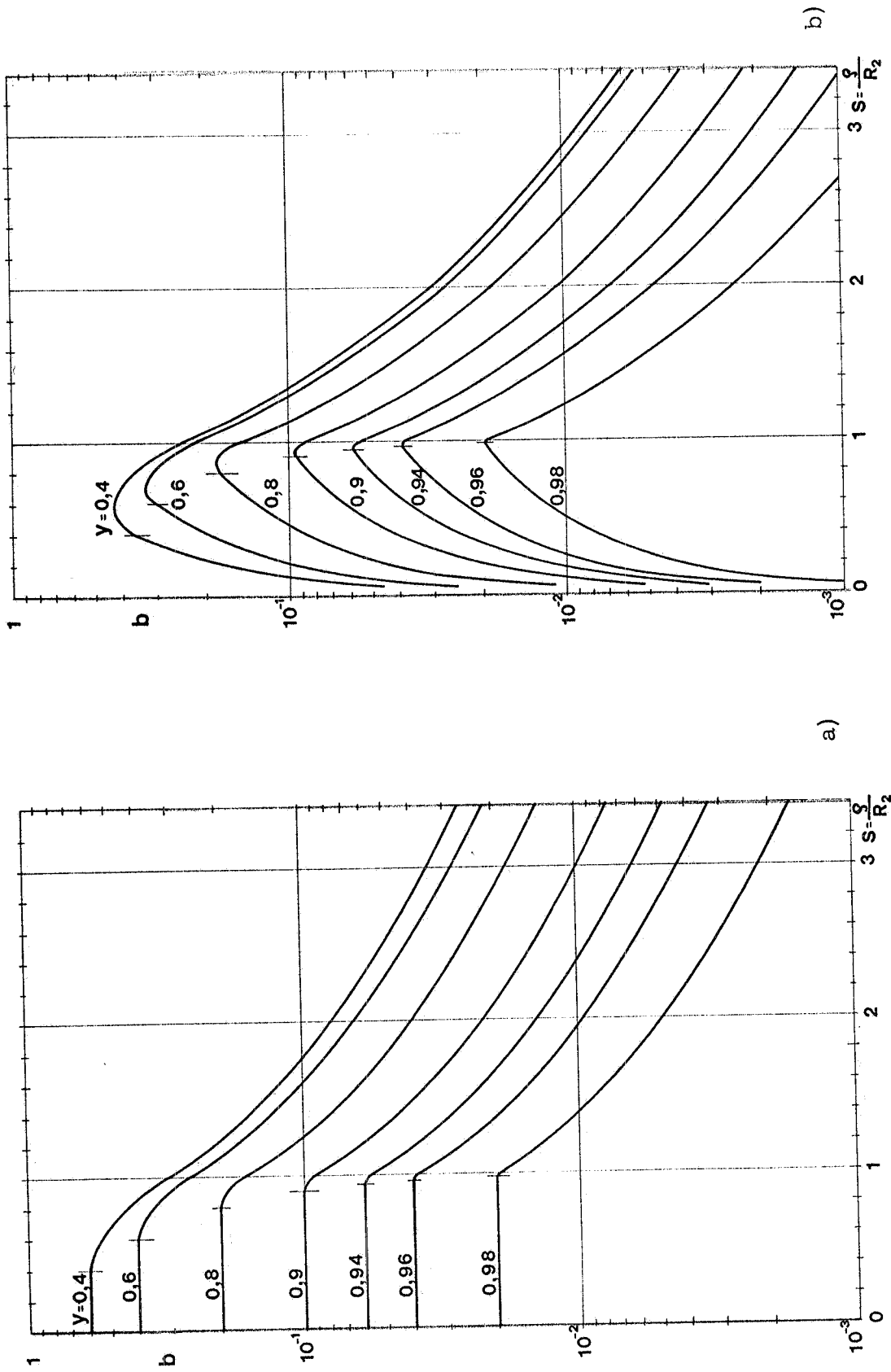


FIG. 2 - a) Radial flux density distribution $b(s)$, where $s = \rho/R_2$, as a function of the radial position ρ per dipolar windings of internal radius R_1 , external radius R_2 , thickness parameter $y = R_1/R_2$, for $\theta = 0$. The total radial field in tesla is obtained multiplying $b(s)$ by $2\mu_0 R_2 J_f / \pi$ (MKS units). - b) ibidem for quadrupolar windings.

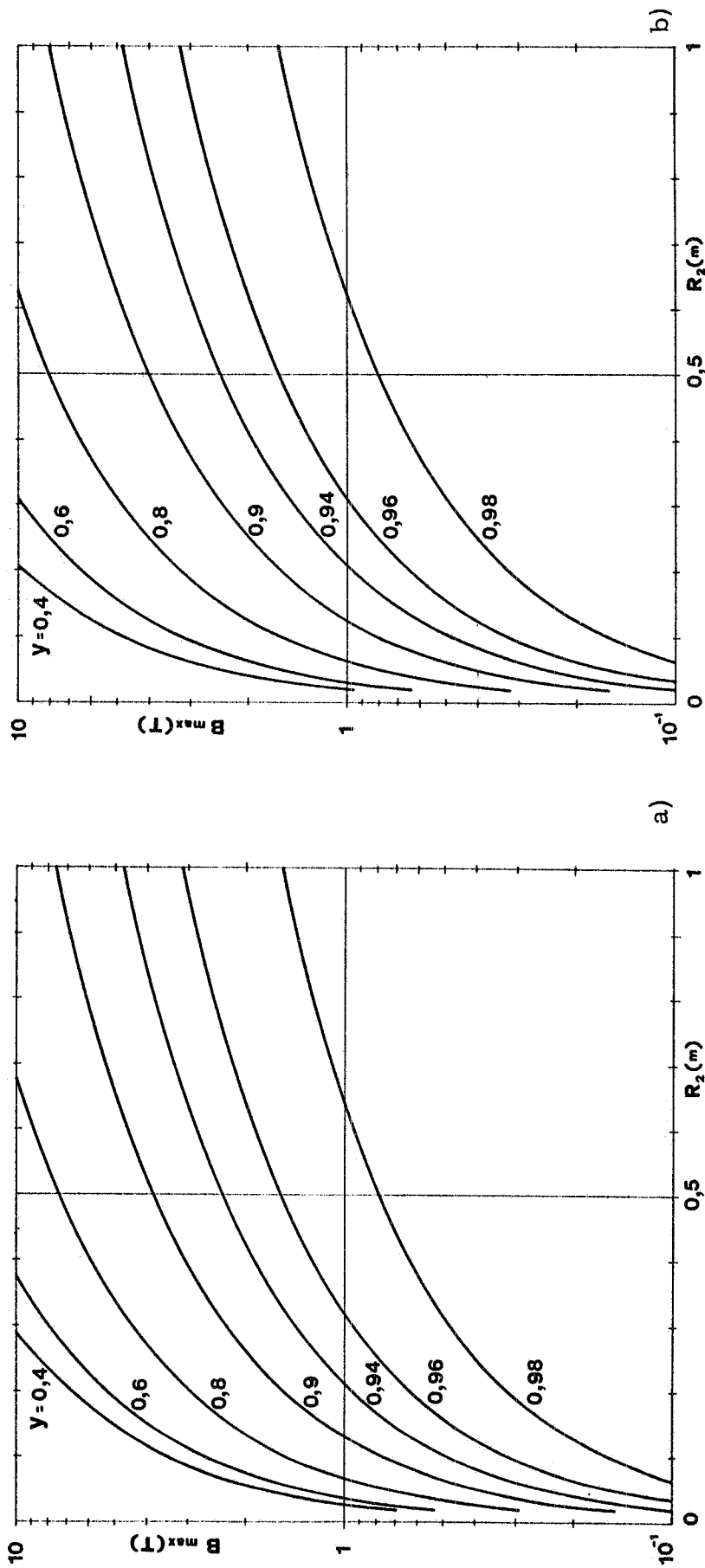


FIG. 3 - a) Outside radius of field winding necessary to produce a given field on the inside of a dipole with an overall current density of 10^8 A/m², without considering armature reaction (see text). -
 b) Maximum field seen by the quadrupolar windings with identical assumptions than in fig. a).

himself suffers the action of an 1.43 Tesla field synchronous with the superconducting field winding. There are however superimposed harmonics whose frequency and intensity depends of the type of winding configuration chosen for the armature. These harmonics can be reduced with a copper shield, coaxial with the armature and solidary to the magnet. The copper shield present however a certain amount of heating due to eddy-currents.

If $J_a = 10^7$ Amps/m² (which is perhaps the case of a cryogenically cooled aluminum armature), the alternating fields seen by armature is 0.26 Tesla, and the field seen by exciting magnet is 0.143 Tesla. These fields are much lower than in the preceding case. The picture brightens further if the armature is in copper at room temperature with $J_a = 10^6$ Amps/m², a rather conservative value for copper at 300°K, when account is taken that the r. m. s. value will be 0.707 this value.

If the dipolar winding has the armature outside, then the field on the superconducting magnet windings due to armature reaction is then 6 Tesla when $J_a = 10^8$ Amps/m².

It is felt however that when the windings are made quadripolar, the fields seen by the D.C. windings can be reasonably small with proper choice of parameters.

Whether or not a superconducting armature with an alternating self-field on the armature of a few Tesla, is a reasonable proposition, remains to be seen. Although several hundred papers have been published so far in A.C. losses in superconductors very few papers have been published on the effects of A.C. currents and superimposed D.C. fields having industrial significance⁽¹⁵⁾. It is clear that more work in this field of research is necessary to fill the gaps of our knowledge.

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4. - POWER CALCULATIONS. -

For balanced three-phase operation with constant current supplied to the field windings the peak current I_a is given by Stekly and Woodson⁽²⁾ as :

$$(11) \quad I_a = \omega M I_f / R \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right]^{1/2}$$

the peak terminal voltage is :

$$(12) \quad V_a = \omega M I_f (1 + Q_L^2)^{1/2} / \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right]^{1/2}$$

and the generated apparent power (r. m. s. value) :

$$(13) \quad \begin{aligned} P_{g \text{ constant current}} &= \frac{3}{2} V_a I_a = \\ &= 2 K^2 \omega W_f Q_m (1 + Q_L^2)^{1/2} / \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right]. \end{aligned}$$

If the field winding terminals are shortcircuited, the machine is operating with constant flux linkage λ_0 and the current of amplitude I_a is :

$$(14) \quad \begin{aligned} I_a &= 2 Q_m K^2 \lambda_0 \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right]^{1/2} / 3 M \left\{ (\alpha + 1)^2 + \right. \\ &\quad \left. + (Q_m + Q_L) \left[Q_m (1 - K^2) + Q_L \right] \right\} \end{aligned}$$

the terminal voltage :

$$(15) \quad \begin{aligned} V_a &= \omega M \lambda_0 \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right]^{1/2} \left[1 + Q_L^2 \right]^{1/2} / L_f \left\{ (\alpha + 1)^2 + \right. \\ &\quad \left. + (Q_m + Q_L) \left[Q_m (1 - K^2) + Q_L \right] \right\} \end{aligned}$$

the generated power:

$$(16) \quad P_{\text{gconstant flux}} = \frac{\omega \lambda_0^2}{L_f} Q_m K^2 \left[(\alpha + 1)^2 + (Q_m + Q_L)^2 \right] (1 + Q_L^2)^{1/2} / \left\{ (\alpha + 1)^2 + (Q_m + Q_L) \left[Q_m (1 - K^2) + Q_L \right] \right\}^2$$

with the constant flux linkage given by $\lambda_0 = (1 - K^2)L_f I_{fc}$. Under armature short-circuit conditions, and for R_a small, the circuit becomes mainly inductive and the field current increases when the current armature increases: this is a result of armature reaction. It is for this reason that the flux linkage is limited by the critical current I_{fc} .

Now, assuming that $Q_L = 0$ and $\alpha = 0$, the generated power $P_{g.c.c.}$ for constant current supplied to the field windings is:

$$(17) \quad P_{g.c.c.} = \left[2 Q_m / (1 + Q_m^2) \right] \omega K^2 W_f$$

with W_f , the energy stored by the self-inductance of the winding, limited by field and critical current characteristics to a value $W_{fc} = (1/2)L_f I_{fc}^2$.

It is not difficult to see then that the generated power with the constant flux constraint $P_{g_{f.c.}}$ is given by:

$$(18) \quad P_{g_{f.c.}} = P_{g.c.c.} \left\{ (1 + Q_m^2)(1 - K^2) / \left[1 + Q_m^2(1 - K^2) \right] \right\}^2.$$

Thus, since K^2 is always less than unity it can be seen from (18) that for any value of Q_m , the constant flux constraint yields a lower generated power than the constant current constraint.

Fig. 4 is a plot of the coupling coefficient K^2 for dipolar and quadrupolar machines having internal or external armatures of thickness parameter x , for five selected values of the field winding thickness parameter y and assuming the air-gap parameters to be $\beta_0 = \beta_i = 1, 2$.

In what follows, the choice of the gap parameters β_0 and β_i is dictated by the conflicting requirements of putting armature conductors and field windings as close as possible to get a good coupling coef

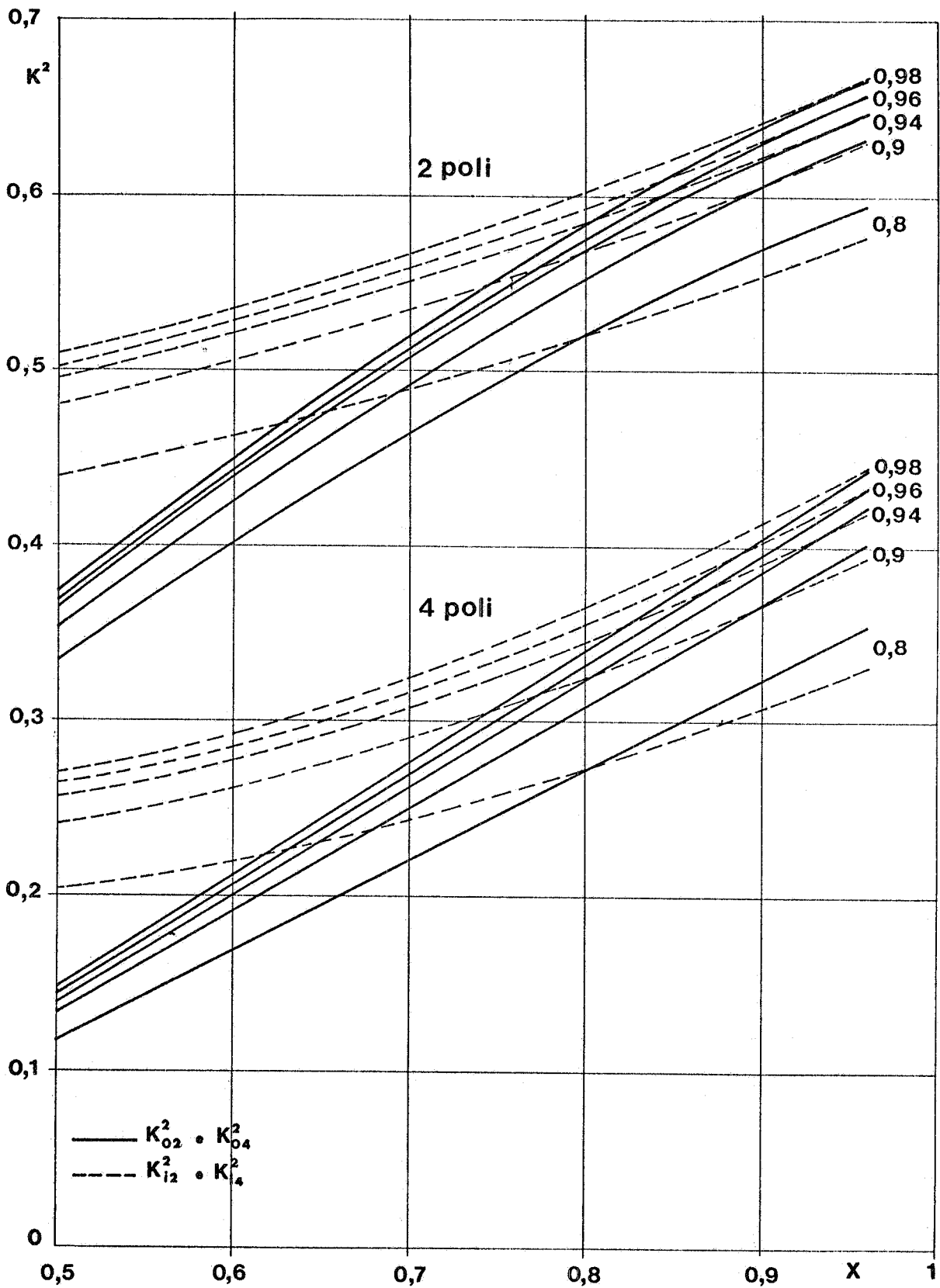


FIG. 4 - Square of the coupling coefficients for dipolar and quadripolar windings for a gap parameter $\beta_0 = \beta_i = 1, 2$. K_{i2}^2, K_{i4}^2 : machines with armature on the inside. K_{02}^2, K_{04}^2 : machines with armature on the outside.

ficient and in the same time allowing for engineering requirements such as vacuum shields, reinforcing rings, etc.

Now we enquire about the value of Q_m as a function of design parameters. From the definition in the text it is not difficult to see that for a dipole with external armature :

$$(19. a) \quad \begin{aligned} Q_m/(1+Q_m^2) &= \left[L_{A_2}(1-x^2)/2m_{02}(1-y^2) \right] (J_a/J_f) (R_0/R_2)^3 \cdot \\ &\cdot \left\{ 1 - \left[L_{A_2}(1-x^2)/2m_{02}(1-y^2) \right]^2 \left(\frac{J_a}{J_f} \right)^2 (R_0/R_2)^6 \right\}^{1/2} \end{aligned}$$

for a dipole with internal armature :

$$(19. b) \quad \begin{aligned} Q_m/(1+Q_m^2) &= \left[L_{A_2}(1-x^2)/2m_{i2}(1-y^2) \right] (J_a/J_f) (R_0/R_2) \cdot \\ &\cdot \left\{ 1 - \left[L_{A_2}(1-x^2)/2m_{i2}(1-y^2) \right]^2 \left(\frac{J_a}{J_f} \right)^2 (R_0/R_2)^2 \right\}^{1/2} \end{aligned}$$

for a quadrupole with external armature :

$$(19. c) \quad \begin{aligned} Q_m/(1+Q_m^2) &= \left[L_{A_4}(1-x^2)/2m_{04}(1-y^2) \right] (J_a/J_f) (R_0/R_2)^4 \cdot \\ &\cdot \left\{ 1 - \left[L_{A_4}(1-x^2)/2m_{04}(1-y^2) \right]^2 \left(\frac{J_a}{J_f} \right)^2 (R_0/R_2)^8 \right\}^{1/2} \end{aligned}$$

for a quadrupole with internal armature :

$$(19. d) \quad \begin{aligned} Q_m/(1+Q_m^2) &= \left[L_{A_4}(1-x^2)/2m_{i4}(1-y^2) \right] (J_a/J_f) \cdot \\ &\cdot \left\{ 1 - \left[L_{A_4}(1-x^2)/2m_{i4}(1-y^2) \right]^2 \left(\frac{J_a}{J_f} \right)^2 \right\}^{1/2} \end{aligned}$$

Now, from $\omega K^2 L_f I_f^2 = \omega M^2 I_f^2 / L_a$ we have for a dipole with external armature :

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$$(20. a) \quad I_f^2 M_{02}/L_{a2} = \mu_o l J_f^2 R_2^4 \left(\frac{R_2}{R_0}\right)^2 P_{02}$$

for a dipole with internal armature.:

$$(20. b) \quad I_f^2 M_{i2}/L_{a2} = \mu_o l J_f^2 R_2^4 \left(\frac{R_0}{R_2}\right)^2 P_{i2}$$

for a quadrupole with external armature :

$$(20. c) \quad I_f^2 M_{04}/L_{A4} = \mu_o l J_f^2 R_2^4 \left(\frac{R_2}{R_0}\right)^4 P_{04}$$

for a quadrupole with internal armature :

$$(20. d) \quad I_f^2 M_{i4}/L_{A4} = \mu_o l J_f^2 R_2^4 \left(\frac{R_0}{R_2}\right)^4 P_{i4}$$

where P_{02} , P_{i2} , P_{04} , P_{i4} are given in Table I.

For a frequency of 50 cycles ($\omega = 314$), a length of 1 metre, two possible gap parameters $\beta_0 = \beta_i = 1.1$ and 1.2 , and peak armature current densities having respective values of 10^8 , 10^7 and 10^6 Amps/m², values of $P_g/R_2^4 J_f^2$ for the case of constant current supply have been calculated from formulae (19) and (20). The results can be seen in Figs. 5 to 8.

From these figures it seems that in the case of a dipole with external armature, the power is greater when the air-gap increases. It must however be remembered that for a same x , when the air-gap increases, increases also the external radius of the armature and consequently the volume. For a fixed magnet, a same value of J_a/J_f and $\beta_0 = \beta_i$ a machine with external armature has a $P_g/R_2^4 J_f^2$ much greater than the machine with internal armature. But also the volume of the external armature is greater by a factor $\beta^4/x^2 y^2$ than that of the internal armature. Table II shows the volume ratios compared with the power ratios for the case of dipolar and quadrupolar machines for some values of the armature thickness parameter x , the field windings thickness parameter y , $\beta = 1, 2$ and $\gamma = 10^{-2}$. It is clear from the table

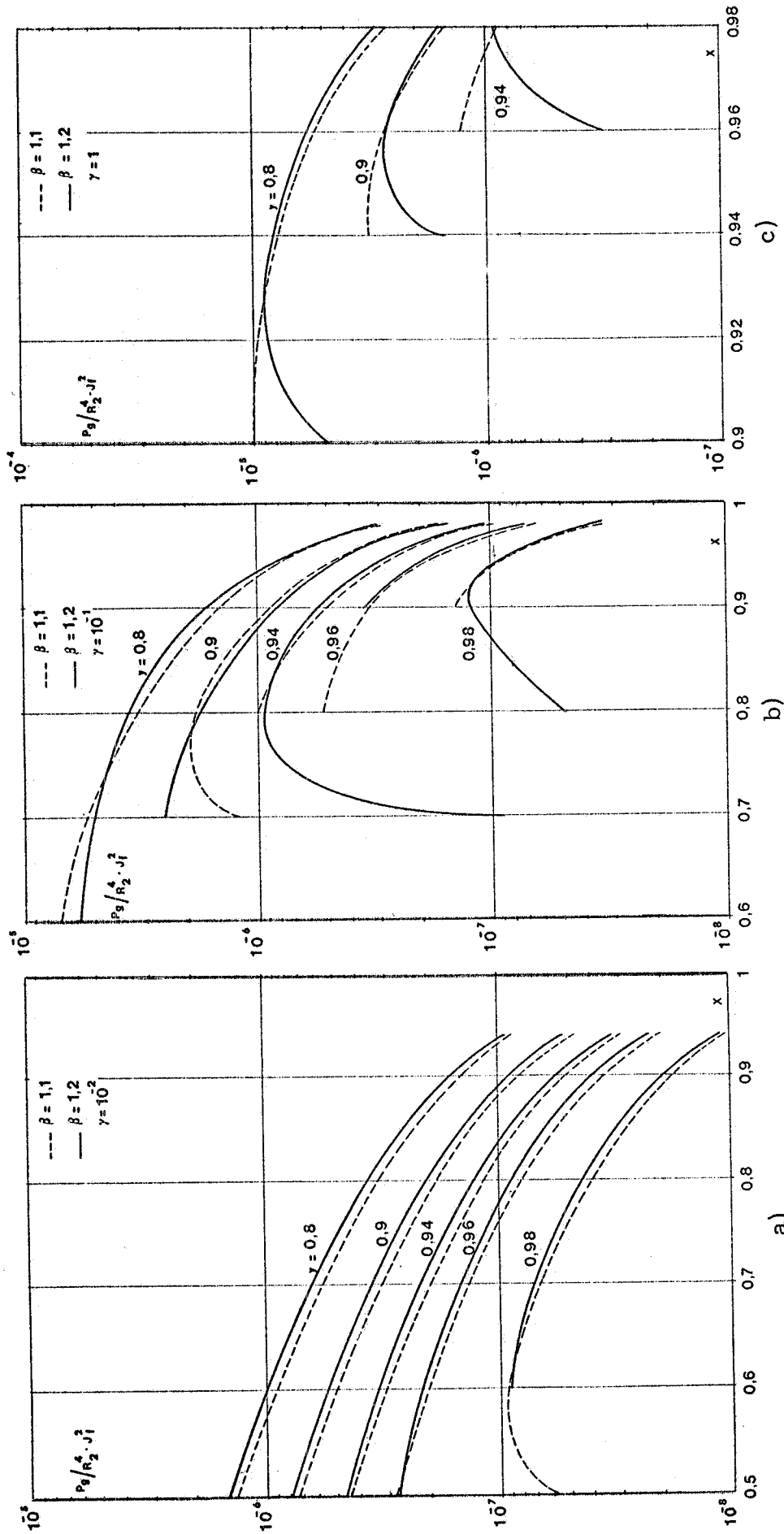


FIG. 5 - Values of $P_g/R_2^4 J_f^2$ as a function of x and y , for an air-gap parameter $\beta_0 = 1.1$ or 1.2 .

a) $\gamma = J_a/J_f = 10^{-2}$; b) $\gamma = 10^{-1}$; c) $\gamma = 1$

dipolar machine, outside armature.

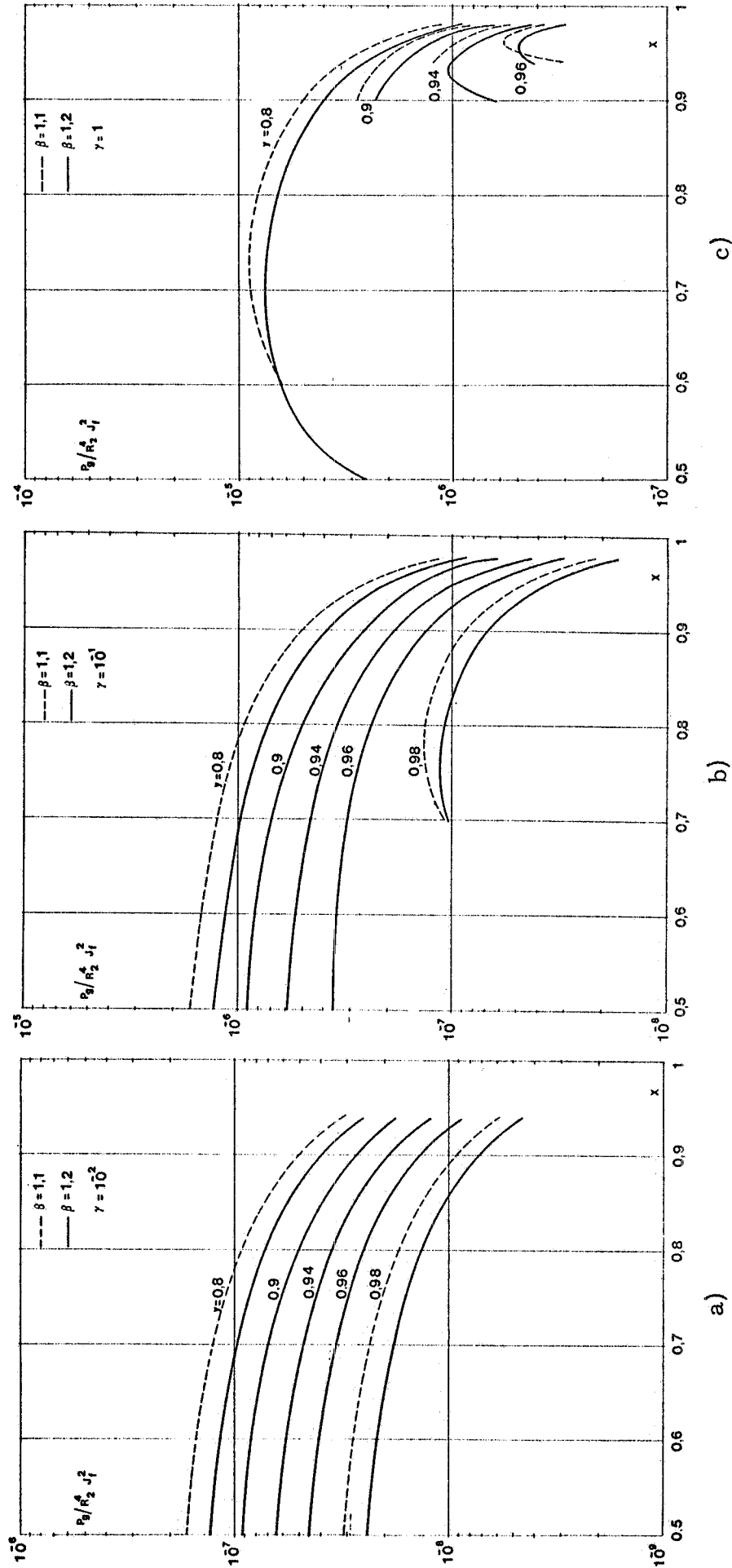


FIG. 6 - a), b), c) ibid. for dipolar machine, inside armature. For $x \geq 0.5$, $y \leq 0.96$, $\gamma = 10^{-2}$ or 10^{-1} is : $P_g(\beta_i = 1.1) = 1.3 P_g(\beta_i = 1.2)$.

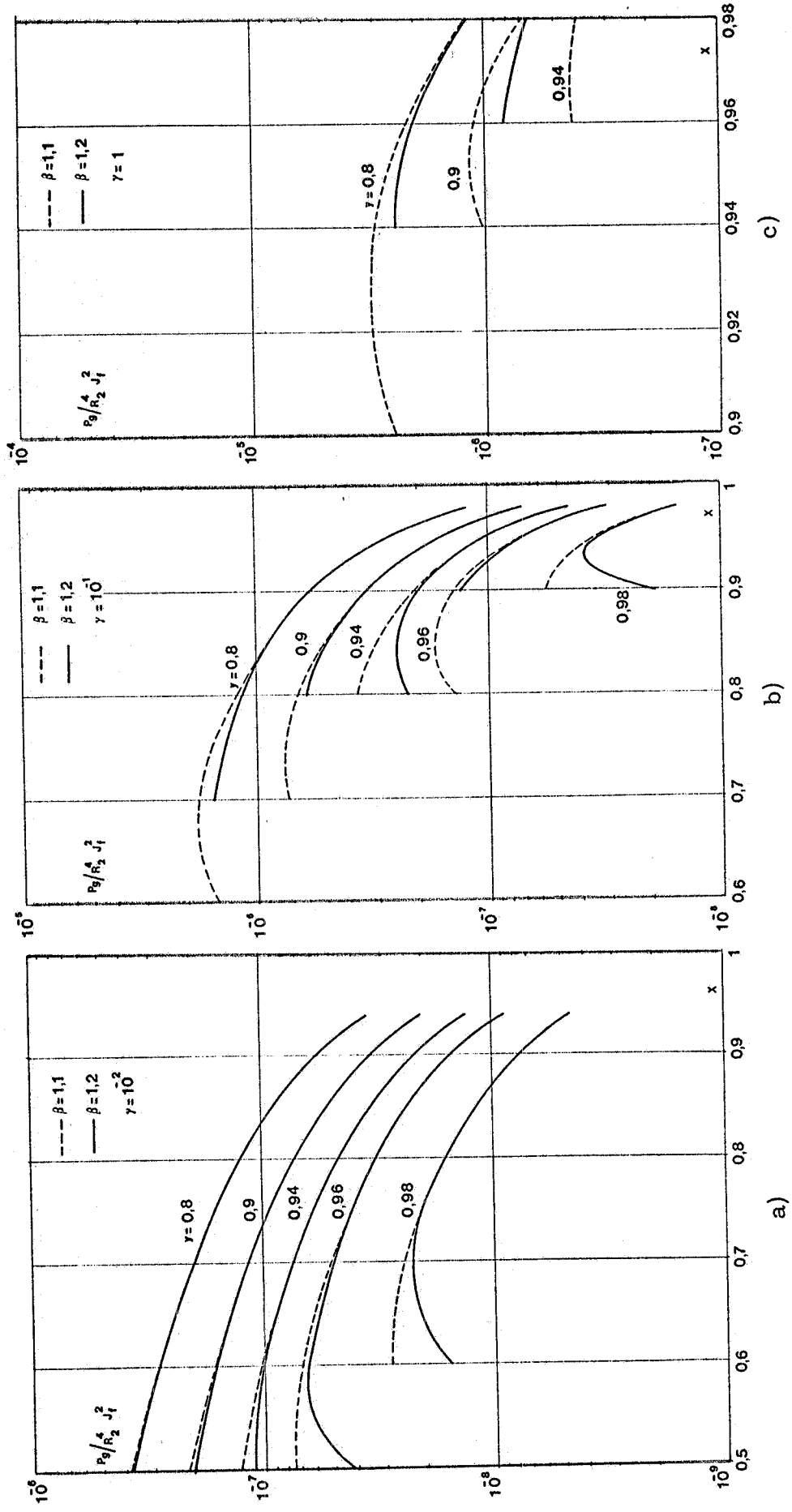


FIG. 7 - a), b), c) ibid. for quadrupolar machine, outside armature.

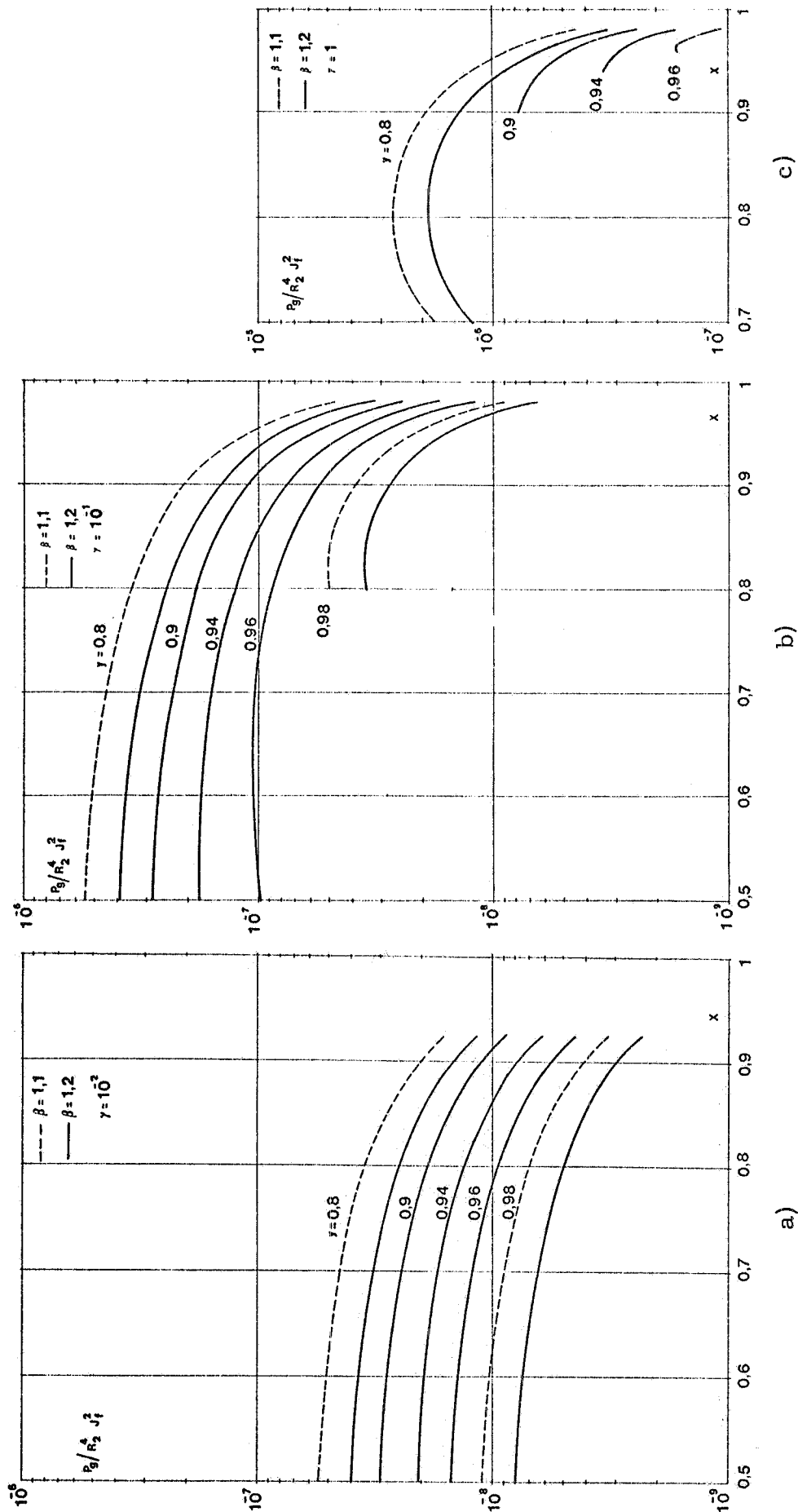


FIG. 8 - a), b), c) ibid. for quadrupolar machine, inside armature.

$$P_g(\beta_i = 1.1) = 1.42 P_g(\beta_i = 1.2).$$

TABLE II

x	y	external armature volume internal armature volume	$\frac{P_{g.c.} \text{ external armature}}{P_{g.c.} \text{ internal armature}}$	
			dipolar machine	quadripolar machine
0.5	0.8	12.9	11.2	9.6
0.9	0.9	3.15	3.4	3.1
0.94	0.98	2.25	2.65	2.5

that the increased power with the outside armature configuration is due mainly to the proportional increase in volume.

As seen from the formulae (19), there are selected values of x , y , β and γ giving an imaginary value of Q_m , and no power is delivered. This is more frequent when γ approaches unity. From the physical point of view this means that the internal voltage drop is greater than the generated tension.

The delivered power with the constant flux constraint is then easily calculated from formula (18) and use of the pertinent graphs.

The values of $\omega L_a/R = (2/3)Q_m$ have been calculated from the equations (19) with the assumption of gap parameters $\beta_0 = \beta_1 = 1, 2$ and possible values of the armature current density of 10^8 , 10^7 and 10^6 Amps/m². The results can be seen in Fig. 9. Thus the internal voltage drop can be easily calculated as a function of the generated voltage. The maximum generated power for the case of the field winding fed by constant current is obtained for $\omega L_a/R = 2/3$.

CONCLUDING REMARKS. -

To finish this paper and as a small help to those interested in studying the possibility of financial competition between a turboalternator

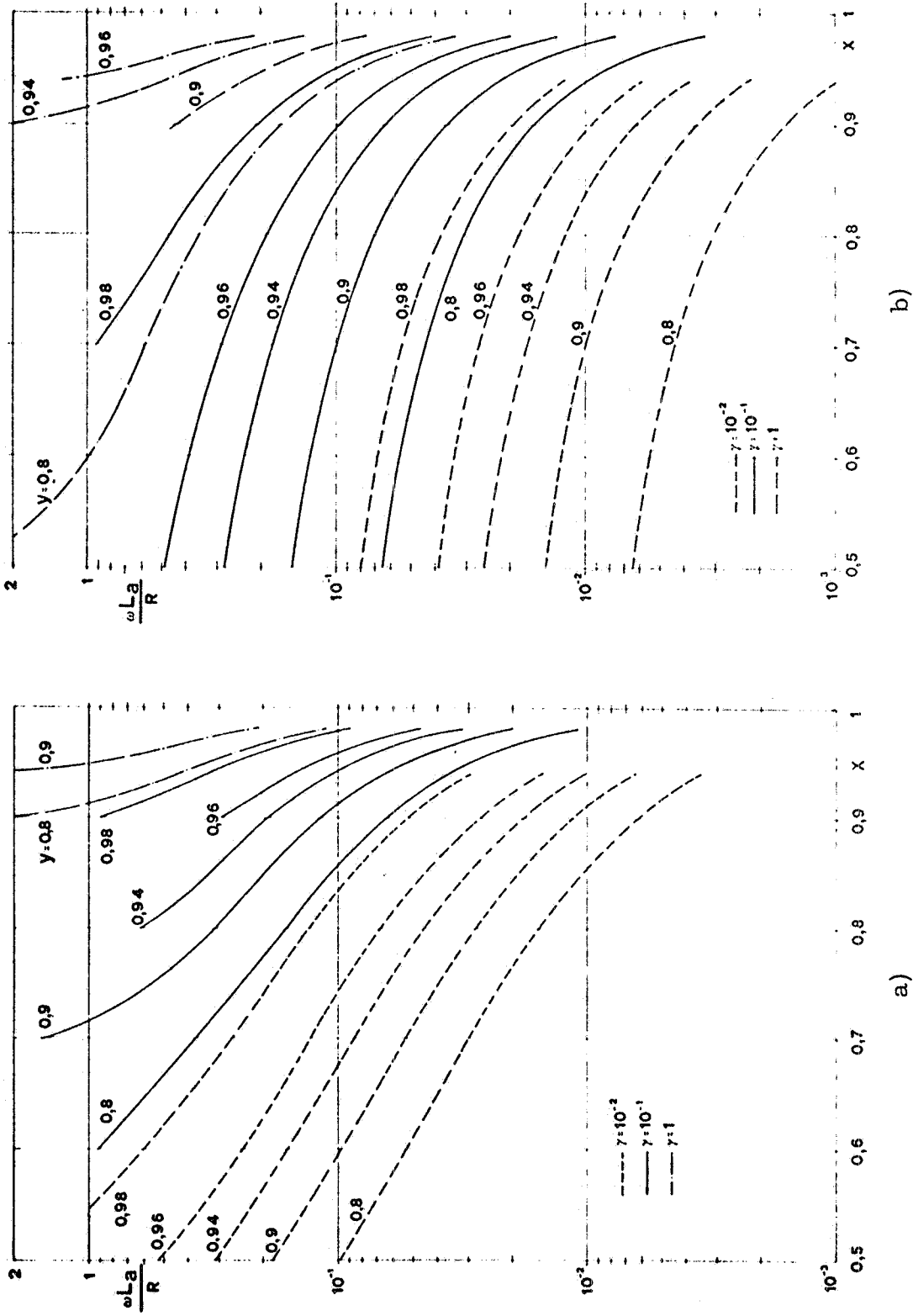


FIG. 9 - The ratio $\omega L_a/R$ as a function of the armature thickness parameter x and the magnet thickness parameter γ for an air-gap machine $\beta_0 = \beta_i = 1, 2$ and three possible current densities ratio : a) two-pole machine with outside armature; b) two-pole machine with inside armature.

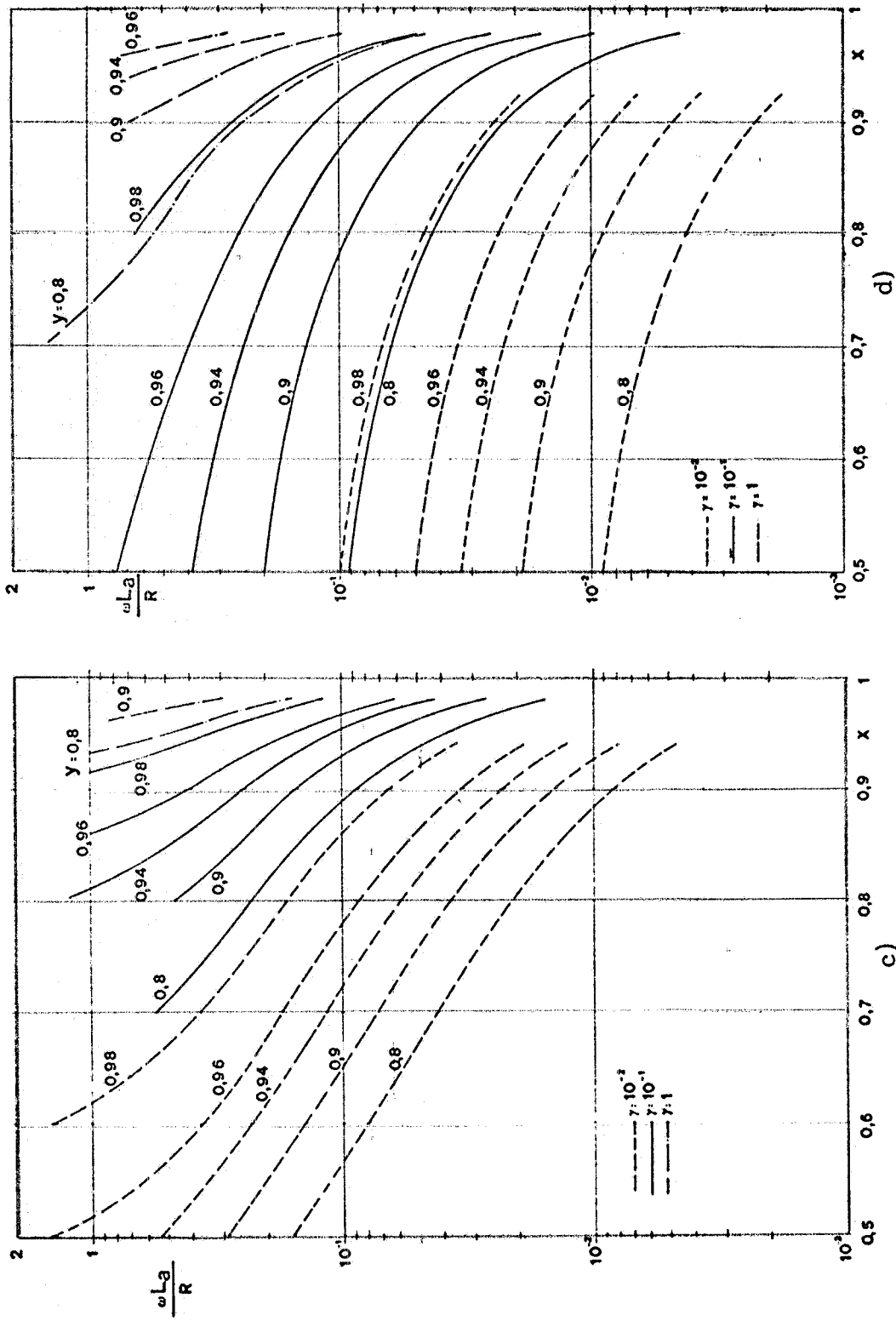


FIG. 9 - The ratio $\omega L_a/R$ as a function of the armature thickness parameter x and the magnet thickness parameter y for an air-gap parameter $\beta_0 = \beta_i = 1.2$ and three possible current density ratios: c) four pole machine with outside armature; d) four-pole machine with inside armature.

with superconducting windings and a traditional machine we would like to note that a semi-superconducting alternator of 600 MVA, with a flux density three times greater than a conventional machine, has, with a rotor of diameter 30% smaller than the conventional, a power per metre of length three times greater. The weight, excluding helium liquefier, is three times smaller.

The capital cost C for a big liquefier is given in American U. S. dollars by an equation of the type :

$$C = C_0 Q^n$$

here Q is the amount of heat in kilowatts having to be removed at low temperature, while the constant C_0 for machines removing dissipated heat at 4.5°K, 20°K and 77°K is 290000, 70000 and 6000 respectively, the exponent n being then 0.52, 0.63 and 0.68. The electrical power in kilowatts necessary to run a liquefier who removes kilowatts of heat at low temperatures is respectively 500, 33 and 6 kilowatts per kilowatt of heat to be removed⁽¹⁶⁾.

The mechanical problems and engineering considerations associated with a rotating dewar of a turboalternator is being actively pursued in some Laboratories. Thullen and Smith^(9, 10) have considered these problems for the particular case of a 1000 MVA semisuperconducting turboalternator.

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