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DIVIDED-WINDING-ROTOR SYNCHRONOUS GENERATOR NO-LOAD FIELD CONTROL FACTORS

BY

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ABSTRACT:

The limiting values of the no-load excitation currents in either field winding of a synchronous machine with d.w.r., are examined. To identify the factors affecting these limits a theoretical study of the no-load m.m.f. distributions in the air-gap is first carried out. A laboratory model is then used to obtain and analyze the actual distributions. The study shows that these factors depend on the pole-winding spread and the shift-angle of the resultant field arround the d.w.r. It is also shown that thermal unbalance and higher temperature -rise are expected to occur when the resultant field is shifted away from the d-axis.

0.0. Nomenclature:

b_p : = pole-arc = 2β

C_a : = active-axis no-load field control factor

C_r : = reactive-axis no-load field control factor

F_R : = air-gap resultant field of a d.w.r.

F_a : = active-component of F_R along the actual active-axis

F_r : = reactive-component of F_R along the actual reactive-axis

$(i_f)_a$: = active-axis no-load excitation current

$(i_f)_r$: = reactive-axis no-load excitation current

$(I_f)_{d.w}$: = maximum no-load excitation current in either axes while the excitation current in the other axis is equal to zero.

$(I_f)_c$: = conventional rotor excitation current

$(P_{fo})_{d.w}$: = no-load excitation power of a d.w.r.

$(P_{fo})_c$: = no-load excitation power of a c.w.r.

$(R_f)_{d.w}$: = total resistance of either winding of a d.w.r.

$(R_f)_c$: = total resistance of a c.w.r.

τ : = pole winding spread

α : = $\beta/2$

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θ : = shift-angle of F_R measured from the actual active-axis

θ' : = shif-angle of F_R measured from the 180°- active - axis

c.w.r. = conventional-winding-rotor

d.w.r. = divided-winding-rotor.

1.0. INTRODUCTION:

It has recently shown [1-3] that more stable operation of turbo-generators is ensured by excitation control using divided-winding-rotor (d.w.r.). In a synchronous machine with d.w.r., the conventional pole-winding is divided into two adjacent windings where each of them has its own excitation supply. In this case the resultant field can be made to rotate with respect to the rotor in such a way as to meet the control requirements of the machine. This prevents slipping and reduces hunting between the stator and rotor magnetic fields when the rotor is momentarily oscillating or running out of synchronism [1]. It has also shown [8] that under both steady-state and transient operating conditions, a synchronous generator with d.w.r. has a number of advantages over the conventional-winding rotor (c.w.r.).

Most of the puplished papers[3,8]on the d.w.r. generators are interested only in the control problems. They give little attention to the design aspects of these machines. Some attention must therefore be given to the design aspects and features of the d.w.r. machines which may somewhat differ from those already established for the c.w.r. machines.

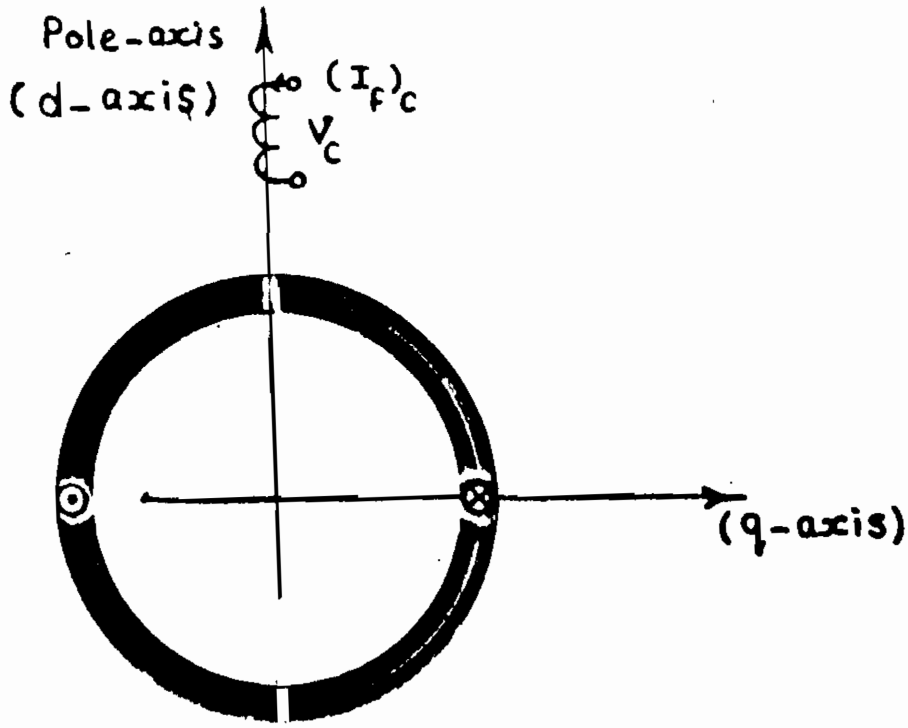
This paper proceeds in this direction. The limiting value of the no-load excitation current in either winding as well as the factors affecting these values are studied. The relations for the no-load excitation power are obtained to help in the prediction of thermal stresses in a d.w.r.

2.0. Conventional Winding Rotor [4]

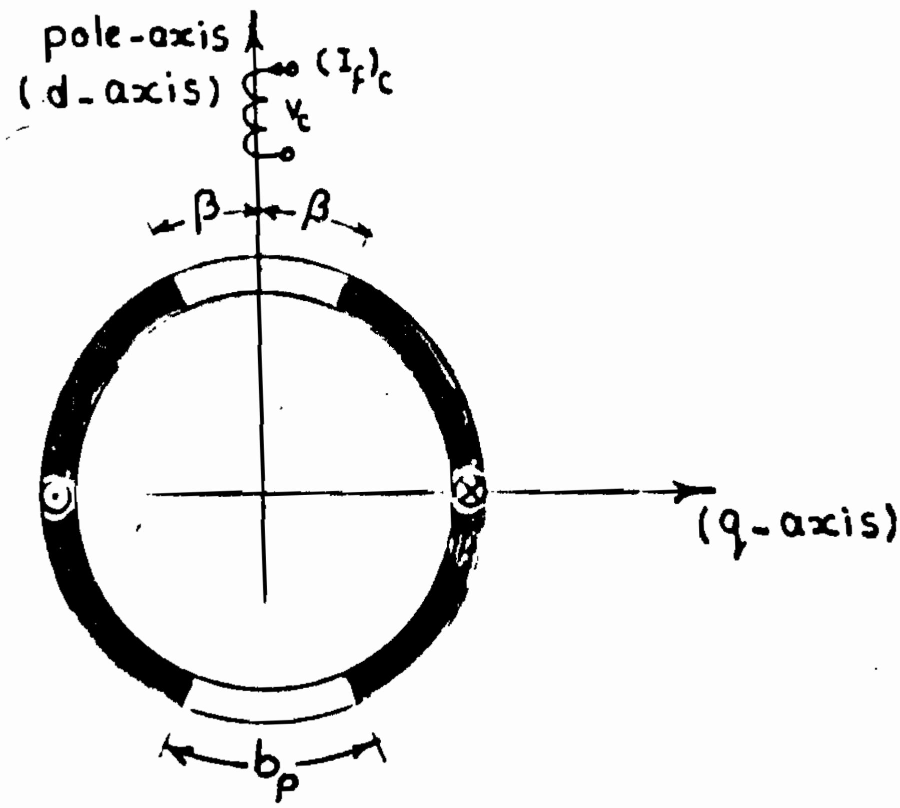
Fig.(1-a) gives a 2-pole conventional rotor with pole winding spread "τ" equal to 180°. Here the pole-are "b_p" is equal to zero. Conventional rotor with τ less than 180° is usually built in actual turbo-generators which allows enough place to accumulate the damper winding in the empty pole-arc:

$$b_p = \pi - \tau = 2\beta \qquad \text{..........(1)}$$

Fig.(1-b) shows a sketch of a c.w.r. with a pole winding spread less than π by an angle 2β which forms the pole-arc.



(a) pole winding spread = 180°



(b) pole winding spread $\angle$ 180°

Fig.(1). Schematic layout of c.w.r., 2-pole.

The pole winding of Fig.(1) can be represented, for purposes of advanced machine analysis, by a single coil with magnetic-axis coincides with the pole-axis (direct-axis). This coil is excited by the conventional excitation current $(I_f)_c$ under the excitation supply voltage $(V_f)_c$.

Neglecting rotor slotting, a stepped m.m.f. distribution curve will approach a perfect triangle or a trapezoid for rotors having τ equal to or less than π respectivily. Naturally, the established air-gap m.m.f. distribution wave is stationary with respect to the rotor and is quite different from the sinusoidal distribution which is usually assumed in the analysis of synchronous machines. This difference stands behind the air-gap space harmonics and its influence on the induced e.m.f. and the machine performance generally [7].

3.0. Divided Winding Rotor:

In this type of field windings, each pole winding is divided into two identical and electrically separate half-pole windings taking into account that the whole-pole winding may be spread over a given pole winding spread $\tau \leq 180°$. Each of the two half-pole windings will be excited from its own excitation supply.

For a d.w.r. with a given number of poles, all half-pole windings which belong to the same axis are connected together in alternative manner and excited from the corresponding supply. Thus each resultant pole consists of two adjacent half-poles on two-axes.

A resultant field will be produced by the separate and simultaneous excitation along these two axes. The schematic of 2-pole conventional rotor discussed before, Fig.(1), can now be modified to conform with this type of excitation just mentioned. These two axes may be designated by active-and reactive-axes. This designation is related directly to the machine control problem. Sketches of d.w.r. with pole winding spread equal to or less than 180° are given in Fig.(2) and will be discussed in following.

3.1. Divided winding rotor with τ = 180°.

Although the 180°-pole winding spread, Fig.(2-a), is not practical; it will be discussed for purpose of comparison. The divided pole winding can be replaced by two equivalent concentrated coils with magnetic axes along the active-and reactive-axis. Both axes are equally shifted about the d-axis and are in perpendicular to each other ($\tau/2$ = 90°).

The excitation of these two-axes results into two individual field distributions forming a resultant field F_R. F_R can be shifted from the active-axis by an angle θ in clockwise direction. Under no saturation conditions the shift-angle depends on the individual m.m.fs. components F_a and F_r. The resultant field F_R could be made to rotate with respect to the rotor itself according to the proper axcitation in the two-axes. The resultant field F_R arround the rotor is constant only under the assumption that either F_a or F_r has a sinusoidal distribution. It is convenient, here, to assume that both fields are components of the resultant field along the corresponding active-or reactive-axis. The two components can be expressed as a function of the shift-angle θ, by

$$F_a = F_R \cos \theta \qquad \text{...........(2-a)}$$

and

$$F_r = F_R \sin \theta \qquad \text{...........(2-b)}$$

This relation states that the active-or reactive-component is maximum and equal to F_R, when the other compoent is zero and the resultant field-axis coincides with the corresponding active-or reactive axis.

The resultant field F_R can be defined as "the maximum active or reactive field, $\hat{F}_a$ or $\hat{F}_r$, when either is acting alone to produce the rated no-load voltage", thus

$$\hat{F}_a = \hat{F}_r = F_R \qquad \text{...........(3)}$$

and equations (2) can be rewritten as

$$F_a = \hat{F}_a \cos \theta \qquad \text{...........(4-a)}$$

and

$$F_r = \hat{F}_r \sin \theta \qquad \text{...........(4-b)}$$

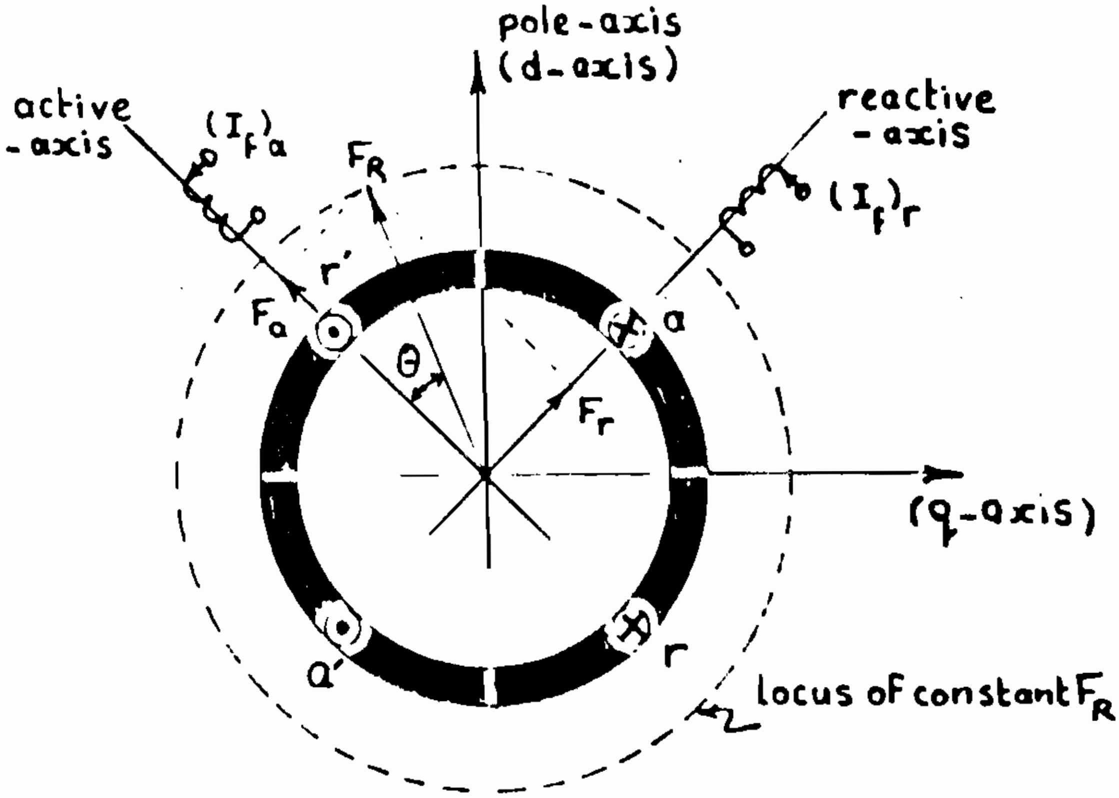
Neglecting saturation equations (4) can be written as:

$$(i_f)_a = (I_f)_a \cdot \cos \theta \qquad \text{...........(5-a)}$$

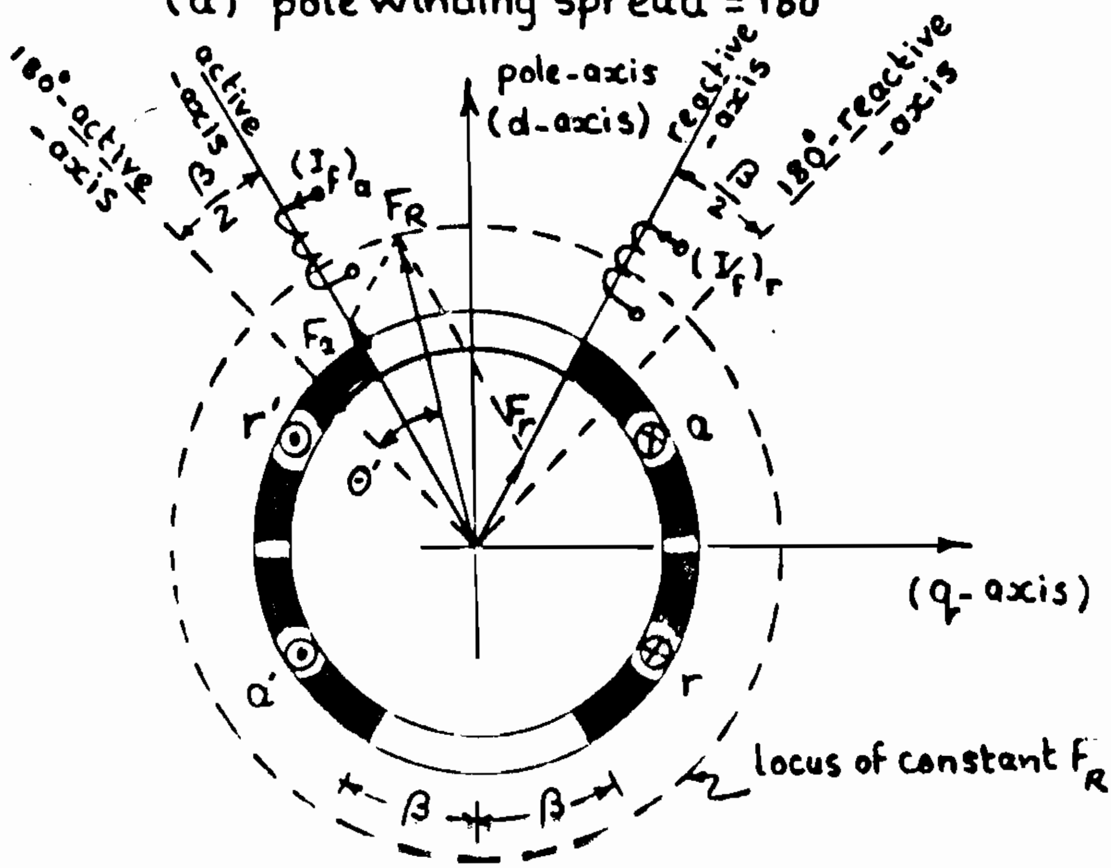
and

$$(i_f)_r = (I_f)_r \cdot \sin \theta \qquad \text{...........(5-b)}$$

Where $(I_f)_a$ and $(I_f)_r$ are the maximum excitation currents in both axes respectivily.



(a) pole winding spread = 180°



(b) pole winding spread ∠ 180°

Fig.(2). Schematic layout of d.w.r., 2-pole.

Depending on assumption given in eq.(3) it can be deduced that

$$(I_f)_a = (I_f)_r = (I_f)_{d.w.} \qquad \text{..........(6)}$$

where "$(I_f)_{d.w.}$ is the maximum excitation current in one axis to have rated no-load voltage, while the excitation current in the other axis is equal to zero". Equations (5) of the individual excitation currents can now rewritten as

$$(i_f)_a = (I_f)_{d.w.} \cdot \text{Cos}\ \theta \qquad \text{...........(7-a)}$$

and

$$(i_f)_r = (I_f)_{d.w.} \cdot \text{Sin}\ \theta \qquad \text{...........(7-b)}$$

According to equations (7) the proper excitation componets can be selected to obtain a constant no-load resultant field F_R shifted by an angle θ. Reversed polarity of one or both excitation sources is necessary to ensure shift-angles $\theta > (\pi/2)$.

3.2. Divided winding rotor with $\tau < 180°$

Figure (2-b) shows a sketch of a 2-pole d.w.r. with $\tau < 180°$. It is seen that each half-pole winding has moved back from the pole-axis (d-axis) by an angle β. The quadrature-axis is still having the same orientation as before. Accordingly, each of the active-and reactive-axis advances towards the d-axis by (β/2). The net angle between them is

$$\tau/2 = (\pi/2) - \beta.$$

Thus both axes are no-more perpendicular to each other as in case of $\tau = \pi$.

Generally, the active-and reactive-axis are equally displaced about the d-axis and inturn about the q-axis:

Total displacement about d-axis $=(\pi/2)-\beta = \tau/2$ ....(8-a)

or

Total displacement about q-axis $=(\pi/2)+\beta = \pi-(\tau/2)$ (8-b)

These relations show that the angle between the active-and reactive-axis depends directly on the pole winding spread.

Assuming that each of the two components, F_a and F_r, has a sinusoidal distribution, the resultant field F_R can be held constant by having the proper values as well as the proper shift.

It would be mentioned that both active-and reactive axis, have a space position corresponds to the pole winding spread. To have a unified measure of θ the referance is taken as the 180°-active axis. The 180°-active axis is in quadrature with the corresponding 180°-reactive axis, Fig. (2-b), and both relate to a factitious pole winding spread of 180°.

Assuming that $\theta' = \theta + (\beta/2)$, the shift-angle measured from 180°-active axis, then referring to Fig.(2-b) the following relation can be written

$$\begin{bmatrix} (F_R)_a \\ (F_R)_r \end{bmatrix} = \begin{bmatrix} \text{Cos } (\beta/2) & \text{Sin } (\beta/2) \\ \text{Sin } (\beta/2) & \text{Cos } (\beta/2) \end{bmatrix} \cdot \begin{bmatrix} F_a \\ F_r \end{bmatrix} \quad .....(9)$$

where

$(F_R)_a$: = resultant field component along the 180°-active axis;
= F_R Cos θ', and

$(F_R)_r$: = resultant field component along the 180°-reactive axis;
= F_R Sin θ'.

The above matrix equation, eq.(9), can be solved to obtain the resultant field components

$$F_a = F_R \cdot \frac{\text{Cos } (\theta' + \alpha)}{\text{Cos } 2\alpha} \quad ....(10\text{-a})$$

and

$$F_r = F_R \cdot \frac{\text{Sin } (\theta' - \alpha)}{\text{Cos } 2\alpha} \quad ....(10\text{-b})$$

where $\alpha = (\beta/2)$.

Equations (10) give the two components F_a and F_r, along the corresponding axes, in terms of the resultant field F_R and shift-angle θ'. Effect of the pole winding spread is present through α. For a pole winding spread $\tau = \pi$; $\theta' = \theta$ and 2β is equal zero, relations (10) turn to be (2). As defined before, maximum active-and reactive-field, F_a and F_r, are obtained according to eq.(10) at $\theta' = \alpha$ and $\theta' = (\tau/2) + \alpha$ or when the resultant field axis coincides with the active-and reactive-axis. While either field component is maximum it is found that the other is zero, and the definition of F_a or F_r is satisfied to give $F_a = F_r = F_R$.

For linear field conditions, it can be assumed that F_a or F_r is proportional to the corresponding excitation currents $(i_f)_a$ or $(i_f)_r$ respectivily. The following relations would be written in accordance with equations (10).

$$(i_f)_a = (I_f)_{d.w.} \cdot \frac{\cos\,(\theta' + \alpha)}{\cos\,2\alpha} \qquad \text{..........(11-a)}$$

and

$$(i_f)_r = (I_f)_{d.W.} \cdot \frac{\sin\,(\theta' - \alpha)}{\cos\,2\alpha} \qquad \text{..........(11-b)}$$

Equations (11) are the general relations of the individual no-load excitation currents which give the proper axcitation along the two axes in order to shift the constant resultant field F_R by an angle θ'.

.0. No-Load Field Control Factors:

The two terms $\cos(\theta' + \alpha)/\cos 2\alpha$ and $\sin(\theta' - \alpha)/\cos 2\alpha$ can be defined as the no-load field control factors. Equations (11) are therefore,

$$(i_f)_a = C_a \cdot (I_f)_{d.w.} \qquad \text{..........(12-a)}$$

and

$$(i_f)_r = C_r \cdot (I_f)_{d.w.} \qquad \text{..........(12-b)}$$

where

$$C_a = \cos\,(\theta' + \alpha)/\cos\,2\alpha \qquad \text{..........(13-a)}$$

and

$$C_r = \sin\,(\theta' - \alpha)/\cos\,2\alpha\ . \qquad \text{..........(13-b)}$$

C_a and C_r are the no-load field control factors.

To shift the resultant sinusoidal field of a d.w.r. by an angle θ', the field components F_a and F_r must have the suitable magnitudes and polarity along thoir corresponding axes. Having $(I_f)_{d.w.}$ then the required excitation can be established by simultaneous adjusting of both excitation currents, $(i_f)_a$ and $(i_f)_r$, according to the proper value and sign of the no-load field control factors C_a and C_r.

The variation of both factors with the shift-angle θ' for different pole winding spreads is given in Fig. (3). The pole

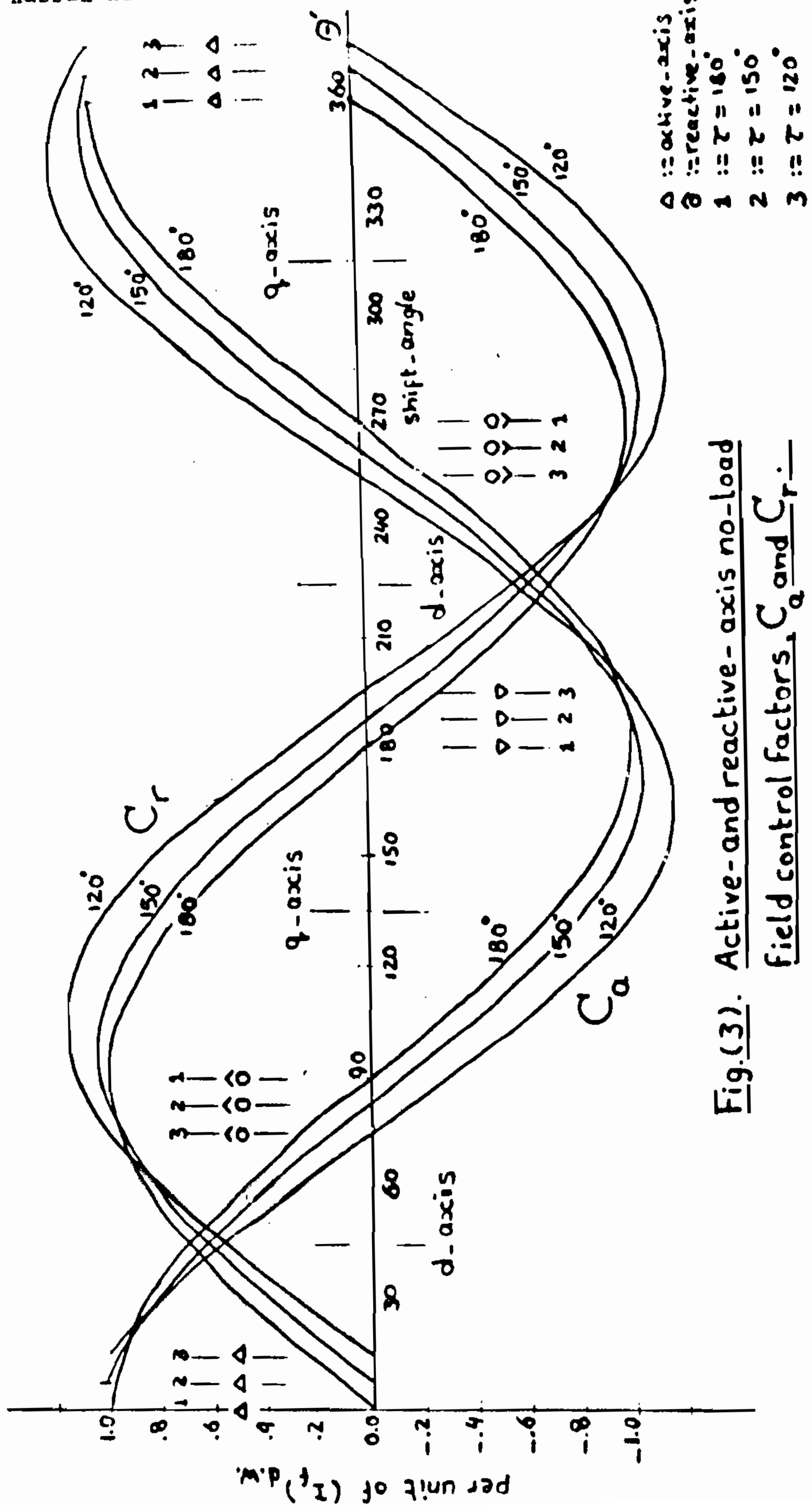


Fig.(3). Active-and reactive- axis no-load field control factors, C_a and C_r.

winding spread has its effect on the two factors through the presence of the angle $\alpha = (\beta/2)$ in equations (13). For a given τ, each factor has a sinusoidal variation shifted from the other by $(\pi/2 + 2\alpha)$. For $\tau = 180°$, the absolute maximum of both factors, C_a or C_r, is equal to unity while for $\tau < 180°$ the absolute maximum is greater than unity (1.035 for $\tau = 150°$ and 1.155 for $\tau = 120°$).

A factor with negative sign means reversed polarity of the corresponding field component. This can be ensured by having the individual excitation sources with reversable polarity. The polarity change of a field component F_a or F_r goes smoothly through null value according to the change of the corresponding field control factor C_a or C_r respectivily. In Fig.(3) C_a or C_r is equal to unity, for all pole winding spreads, if it is required to shift the resultant field-axis to be along the corresponding active-or reactive-axis. To shift the resultant field axis to coincide with the d-axis, both field control factors C_a and C_r will be equal and of similar sign. To shift it to be along the q-axis, both factors will be equal too but of opposite polarity.

5.0. Laboratory Simulation of D.W.R.

It is difficult to convert an already built conventional rotor to a divided winding rotor, specially for test purposes where the rotor may be connected alternativily to have some comparative results. This difficulty had been overcome by use the B.K.B. universal laboratory machine, to have a synchronous machine model with d.w.r.

The B.K.B. Universal Laboratory Machine Set [6] consists of a uniform air-gap universal machine and a d.c. dynamometer. As a 3-phase synchronaous gensrator the universal machine rotor acts to form the 3-phase armature where the stator windings represent the field circuit. The 24-slot stator is wound with twelve coils which are short pitched by one slot. These stator coils are brought out, also all other winding connections, to the linear array of terminals 1, 1′ to 12, 12′ on the terminal panel, Fig.(4), which enable it to form a conventional field winding or a divided field winding by making the appropriate coil to coil connections. The leading coil-sides, 1, 2,...12, are located in alternate slots so that the twelve coils are distributed over 360° of the stator periphery. This arrangement gives a single-layer winding with 6 slots/pole to have 180°-pole winding spread or 4 slots/pole to have 120°-pole winding spread.

Fig.(5-a) and (5-b) show the stator connections to have 180° and 120° pole winding spreads respectivily. The two-way switch makes it possible within each τ to have a conventional or divided field winding.

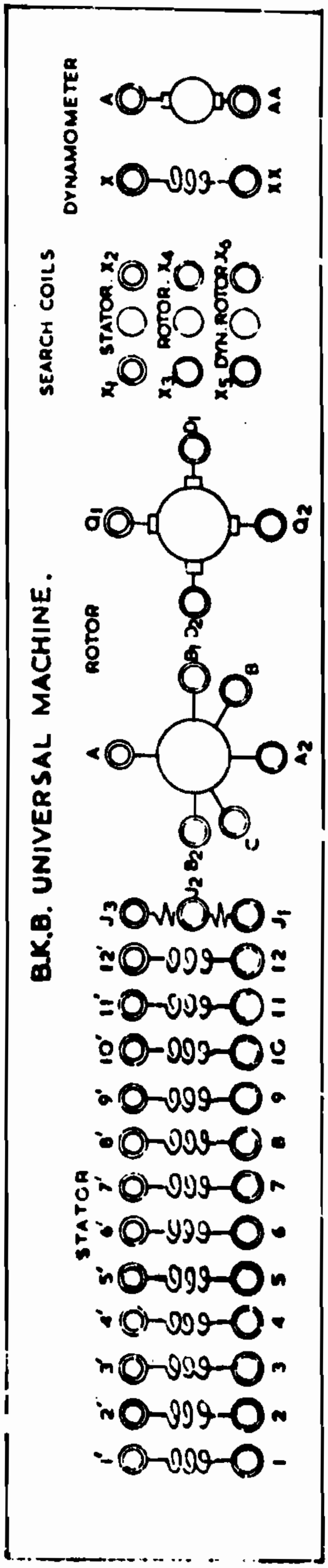
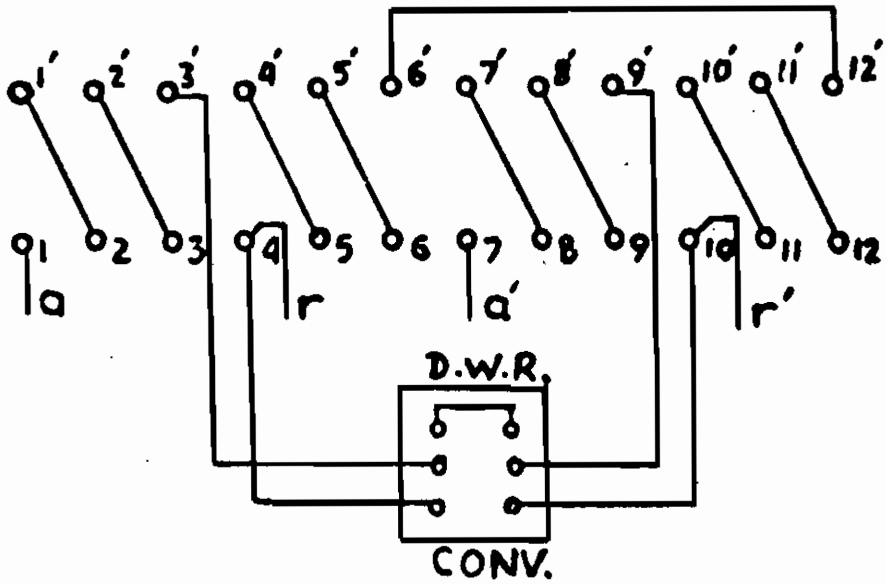
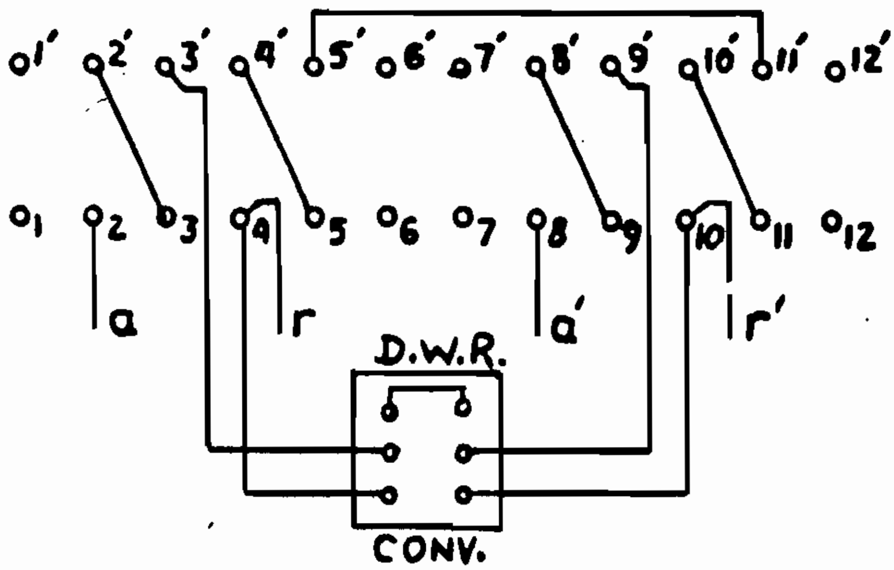


FIG.4. TERMINAL PANEL OF THE UNIVERSAL MACHINE SET.



(a). 180°- pole winding spread.



(b). 120°-pole winding spread.

Fig.(5). Field connections.

The excitation circuits are built as in Fig.(6) from two separate potential dividers: one to excite the active winding, a-a', and the other to excite the reactive winding, r-r'. Each circuit is provided with reversable switch to have reversable polarity, when it is needed, according to the sign of the no-load field control factors. Conventional excitation is obtained from the active excitation circuit, a-a', while the reactive excitation circuit, r-r', is totally disconnected.

6.0. Laboratory Demonstration of No-Load M.M.F.Distribution;

In order to get an idea about the effect of the shifting-angle θ' on the m.m.f. distribution established in the uniform air-gap of a synchronous generator with divided field winding having a given τ , the universal machine set described above has been used. The dynamometer is connected to operate as a motor at 3000 r.p.m. and drive the rotor of the universal machine which will be operate as a synchronous generator. The field system can be connected as in Fig.(5-a) or (5-b) to have a pole winding spread of 180° or 120° respectivily. By switching the two way switch on the side marked "D.W.R.", the corresponding field system divides into two separate circuits and represents a d.w.r.

Adjusting one of the active-or reactive-excitation to have rated no-load voltage, while the other is zero, the one-per unit excitation current $(I_f)_{d.w.}$ can be obtained. The stationary m.m.f. distribution established in the air-gap can be examined and recorded by connecting an oscilloscope to the rotor search-coil X_3X_4.

Waveforms of m.m.f. distributions for given τ and different θ' are obtained by adjusting the proper excitation currents $(i_f)_a$ and $(i_f)_r$, each time, according to equations (12). C_a and C_r are precalculated by equations (13) and then multiplied by $(I_f)_{d.w.}$

7.0. Discussion of Results:

The resultant no-load m.m.f. distribution in the air-gap of a synchronous generator with d.w.r. is the superposition of two individual distributions: the distribution due to the active field winding and the distribution due to the reactive field winding. The resultant field assumes an axis which can be forced to rotate a complete revolation arround the rotor (the stator in machine model) by having the proper value and polarity of excitation currents in accordance with the required shift-angle θ'. For different shifting angles, beginning by $\theta' = \alpha$ in steps of 15° until $\theta' = \alpha + 2\pi$, the air-gap resultant distributions at no-load are given with the conventional distribution in Figs.(7) and (8) for the two different pole winding spreads mentioned before.

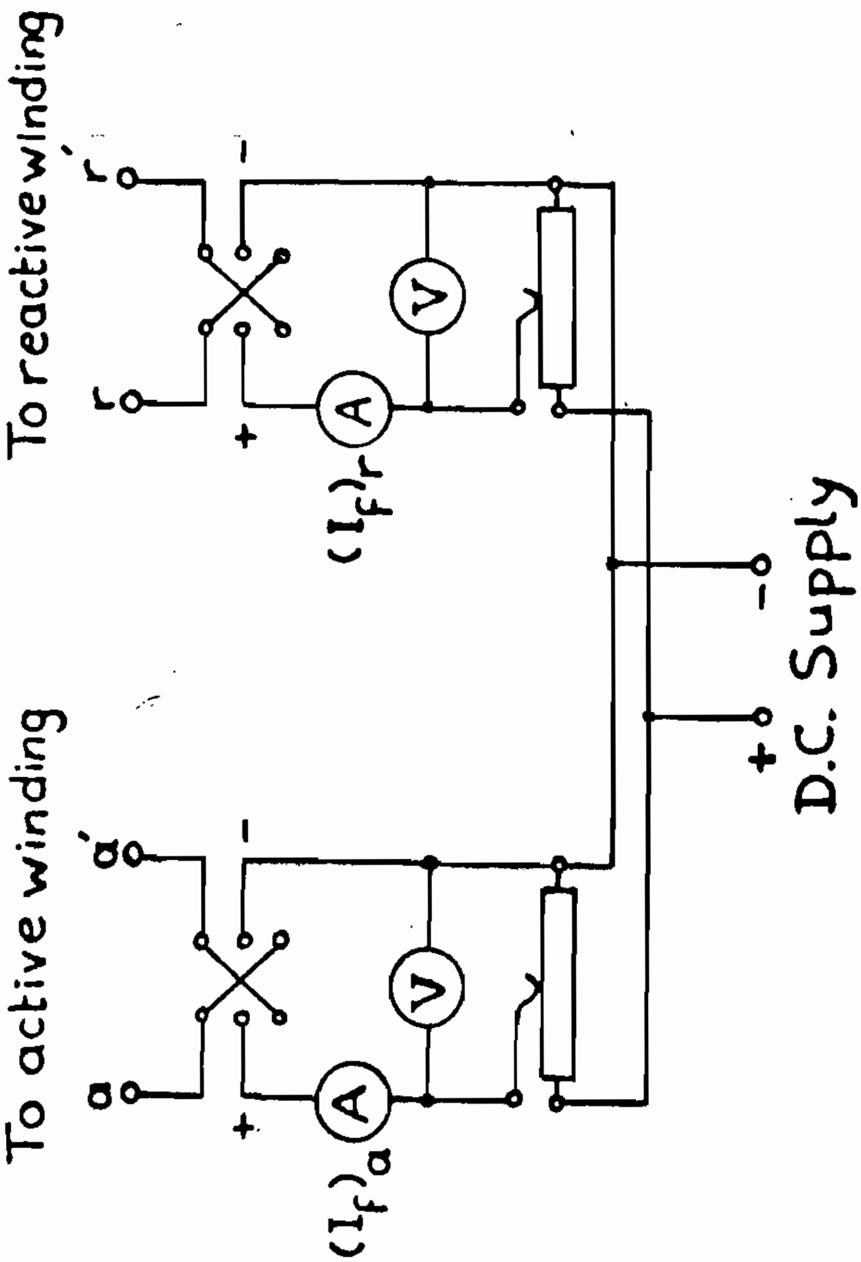


Fig.(6). Excitation Sources for both field windings.

7.1. 180°-pole winding spread:

In this case the active-and reactive axes differ by an angle equal to $\tau/2 = 90°$; thus they are in perpendicular to each other. It is seen in Fig.(7) that the group of distributions obtained in range of the d-axis, $\theta' = 0$ to $90°$ are obtained again in range of the q-axis, $\theta' = 90°$ to $180°$. They are generally repetitive every 90°. Having F_R towards the active-axis, $\theta' = 0$, in this case the active-winding is working alone and the field distribution is a stepped trapezoid. The same distribution is obtained by having F_R along the reactive-axis, $\theta' = 90°$,. In this case the reactive winding is working alone.

Beginning at the active-or reactive-axis and shifting F_R in clockwise direction towards the other axis, the trapezoidal waveform converts in an observed manner with advanced θ' to be a stepped triangle exactly when F_R coincides with the d-axis or q-axis, respectivily.

It is seen that the actual field distribution is not sinusoidal. Accordingly the resultant field maximum is not constant and varies between 1.0-perunit, at the active-or reactive -axis, and $\sqrt{2}$ - per unit, at the direct-or quadrature-axis as θ' advanced.

When the resultant field-axis coincides with the direct.or quadrature-axis; the resultant field distribution is the dual case of the conventional distribution (the stepped triangle waveform given in Fig.(7) above). The field current measurements, for $\tau = 180°$, also agree with this result. In such case;

$$(i_f)_a = (i_f)_r = 0.707\ (I_f)_{d.w.} \simeq (I_f)_c \quad ....(14)$$

where $C_a = C_r = 0.707$, and the induced e.m.f. in both cases are naturally the same.

In accordance with the induced e.m.f. in proportional with different θ', the measurements show that the no-load line voltage is approximately constant for all angle shifts. Assuming constant permeability, the above observation means that the area under the flux-density distribution curve, which may behave similar to that of the m.m.f., or the flux per pole is not groatly affected by the angle shifts.

7.2. 120°-pole winding spread:

Here the active-and reactive axes are not perpendicular. They differ from each other by $\tau/2 = 60°$ about the d-axis, and by $(\pi - \tau/2) = 120°$ about the q-axis. There-fore the field distribution-waveforms, as θ' increases, in the sharp-angle $(\tau/2)$ region are not identical to that occurring in the wide-

Although the excitation power is constant it can happen that one winding, the active or reactive one, is thermally more stressed than the other winding, specially when the resultant field axis is so far away from the direct-or quadrature-axis and coincides with one of the winding magnetic axes. In the last case the current capacity of the corresponding winding winding can rise to about $\sqrt{2}$ of its conventional value.

For 120°-pole winding spread, the excitation power can be obtained by equation (16) which can be rewritten as

$$(P_{fo})_{120} = [\, C_a^2 + C_r^2 \,] \cdot K \qquad \text{..........(18)}$$

where

$$K = [\,(R_f)_{d.w.} \cdot (I_f)^2_{d.w.}\,]_{120} \qquad \text{.....(19)}$$

$$= \text{Constant.}$$

Equation (18) relates the no-load excitation power of 120°-divided winding rotor to the no-load field control factors C_a and C_r. This relation is plotted in Fig.(9) in p.u. for different values of θ'. It is seen that the minimum excitation power (0.666 p.u.) delivered to field system accurs at $\theta' = 45°$. This occurs when the resultant field axis coincides with the d-axis or in other wards when a dual-conventional excitation is established by the divided winding excitation; in this case

$$C_a = C_r = C,$$

$$(I_f)_c = C\,(I_f)_{d.w.}, \text{ and if}$$

$$(R_f)_c = 2(R_f)_{d.w.}$$

then it can found from equation (16), that

$$(P_{fo})_{d.w.} = (P_{fo})_c \qquad \text{..........(20)}$$

In order to shift the resultant field axis to coincides with the q-axis (τ = 120°); maximum no-load excitation power of 2.0 per unit is required. Naturally, excitation power of 1.0 per unit is required when one winding, the active-or reactive-winding, is acting alone to obtain the rated no-load voltage.

It is then advisable to have the resultant field-axis in direction of the d-axis to work withminimum no-load excitation power. Shifting the resultant field-axis towards the active-or reactive-axis is still acceptable but further shifting towards the q-axis enlarges the required excitation power to be, at the q-axis, three times of that required at the d-axis. The field current capacity is now so high and thermal stresses are expected to happen when the machine is operating in this region.

9.0. Conclusion:

The study shows that for proper analysis of a d.w.r. turbogenerator, the two magnetic axis of the rotor should be equally displaced about the d-axis by an angle equal to half a pole winding spread τ .

The study shows, also, that the values of no-load field control factors are required in adjusting the two corresponding excitation sources in order to shift the no-load resultant field F_R by a given angle shift θ.

It has been show that under no-load conditions and τ other than 180° minimum no-load excitation power requires the resultant F_R to be as mear as possible to the d-axis. Shifting the resultant F_R towards the q-axis roquires larger values of excitation power, 3 times of that required at the d-axis for τ=120°, with the result that heat stresses are amainable to occur.

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