# OUTPUT ENHANCEMENT IN THE TRANSFER-FIELD MACHINE USING ROTOR CIRCUIT INDUCED CURRENTS

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## ABSTRACT

The output of a plain transfer-field machine would be much less than that of a conventional machine of comparable size and dimensions. The use of short-circuited rotor windings, it is shown, would lead, under certain circumstances, to considerable improvement in its performance. The rotor windings not only give rise to an increase in the induced emf but also augment output by effectively lowering the synchronous reactance of the output winding. The rotor circuit current can be increased by connecting it to a synchronous condenser load, and thereby further increase both the emf and the synchronous reactance thus leading to a higher output and greater synchronous stability. The same effects have their parallel for the asynchronous mode of operation.

## INTRODUCTION

In alternators which have dc fed rotating fields the magnitude of the current that can be passed through the rotating windings is limited by practical consideration imposed by the slip-ring/brush combination. In order to keep the current low and still set up the required magnetic field a large number of turns of coils are used. Much of the turns are buried in the coil, and the rotor heating could therefore set the limit to the available output.

In wound rotor induction motors the provision of slip rings and brush adds considerably to the cost of fabrication. For many applications using high speed motors, or in environments that are potentially explosive, sliding contacts cannot be tolerated.

Various electromagnetic machines have been developed which although completely stator excited, exhibit characteristics similar to that of conventional ac machines that have one of the two windings, excitation and output windings on the rotor. In these machines coupling between the output and excitation windings is either directly through the agency of rotor saliency or indirectly through their mutual coupling with a third passive winding on the rotor.

The earliest example of the saliency effect machine is the inductor alternator [1,2]. Its characteristics are similar to those of the conventional alternator. It has found application mainly as a single phase high frequency alternator; however polyphase types have been built. As a motor it can only run synchronously, it is therefore not self starting. Some self-starting motors in this class have been described in recent literature [3,4,5]. The motors described in reference [31 and [4] like those of references [l] and[2]have basically two independent sets of stator windings of different pole numbers Pi and P2 respectively and a multiple-pole rotor. The Pi poles of mmf due to one set of windings will interact with the 2pr poles of the fundamental component of airgap permeance variation due to the Pr poles of the rotor, to produce airgap flu distribution with 2Pr ± P1 poles. If the second winding has 2pr+P1 or 2Pr - P1 poles energy conversion can be achieved at a suitable frequency. If the secondary current is obtained by induction from the first winding, the mode of operation will be asynchronous and the machine will be self- starting. For normal synchronous operation one of the windings will be excited with direction current.

The transfer- field machine described in reference [5] and[6] differs from these other machines in that both sets of windings have the same number of poles which is the same number of poles as the rotor; thus there is no restriction as to the choice of pole number of one winding in relation to the other winding pole number. The smallest number of pole pairs i.e. unity can thus be used. Higher speeds can therefore be obtained with this machine than with any of the other reluctance effect types, and consequently a relatively high value of goodness factor would be expected. Furthermore, since the two sets of windings have the same number of poles and are thus interchangeable, the possibility exists of operating both windings in series or in parallel and hence double the output.

When the secondary/rotor winding of a conventional would-rotor induction machine is made to supply the primary (rotor) winding of an inverted induction machine to which it is rigidly coupled; and if the secondary (stator) winding of the second, machine is short-circuited, the combination will operate at a synchronous speed different from those of the original machines. If the coupled machines have different pole numbers one machine only may be used to house all four sets of windings; so that the stator has two sets of windings with different pole numbers and the rotor similarly has two different sets of windings corresponding to the two stator windings. This form of brushless operation of a controllable motor is referred to as self-cascading7. The same objective can be achieved using a modified squirrel cage in the rotor; the result is analogous to the inductor alternator.

Another form of brushless operation involving two machines combines effects which are due to saliency and effects due to induced currents flowing *in* asymmetrical rotor circuits. In this case two identical reluctance machines 9 are coupled together and their primaries connected in parallel *in* a manner so that apart from the current which is drawn from the supply, currents of a different frequency are circulated *in* the closed path provided between the two machine windings. The combination will run as a motor with synchronous speed which is half the normal synchronous speed of the normal reluctance machine. The rotor circuit effects are shown to compliment the effects due to saliency.

In this paper the effects of rotor windings on the Transfer-field machine is examined, it is shown that *in* addition to modifying the synchronous inductance of the windings, the rotor winding also directly affects the mutual coupling between the primary stator winding and the secondary or output stator winding.

## Basic Principles of the TF machine

The Transfer-field (TF) machine is structurally basically a reluctance machine. It differs however from the simple reluctance machine *in* two import- ant respects+: (i) it has two sets of windings instead of one *(ii)* each winding has a synchronous reactance which is *in*- dependent of rotor position, whereas the winding reactance of a simple reluctance machine varies cyclically. The manner in which this is achieved will be explained with reference to an idealized machine: Consider a reluctance machine with two sets of windings one skewed through $180^0$ in a right-handed spiral and the other skewed $180^0$ in a left-handed spiral. The inductance of each set of windings will be constant and independent of rotor position but the mutual coupling between them will vary cyclically with rotor position. The machine can be used as an energy converter. If the winding conductors are to be housed in slots then in order to achieve simultaneously for both sets of windings, the machine must be divided or broken up into a number of identical' longitudinal cylindrical sections. Separated by non-magnetic barriers: The conductors are shifted appropriately from section to section.

The flux produced in the airgap of each of the sections of a TF machine by sinusoidal distributed stationary primary winding mmf has two components. The first which is independent of rotor position; it is the relevant component for the determination of the self-inductance of the winding; its axis coincides with the axis of the exciting winding in all section of the machine. The second component of the flux rotates at twice the speed of the rotor and has zero linkage with the primary winding but has the same space relationship with the axes of the secondary winding in each of the machine sections; this is the mutual flux and induces the out- put emf in the secondary.

The self flux is proportional to the average value of the inductance taken over a complete cycle for the original reluctance machine from which the TF machine was derived. If $L_d$ and Lq are the axis reactance of the original machine then the self-inductance of the TF machine is $(L_d + L_q)/2$. The mutual inductance between the primary and secondary windings is proportional to the mean of the difference between $L_d$ and $L_q$.

## 2. ASYNCHRONOUS MODE.

### A Simple Equivalent Circuit

Let us assume that the primary and secondary windings have equal number of turns which are similarly distributed. The equivalent circuit for asynchronous operation of the TF machine with the secondary short circuited will be as shown in Fig. 1. Slip is with respect to the asynchronous' speed of the applied field which is twice the actual 'asynchronous' speed of the rotor. Considering the equivalent circuit, the reactance between the points A and D when the secondary is open circuited is $X_{q+\frac{xd-x_q}{2}} = \frac{x_d-x_q}{2}$

Which gives the air gap magnetizing reactance as expected. The reactance between the points C and D is the coupling reactance between primary and secondary. The total primary leakage reactance $X_1$ is the sum of the reactance $X_q$ between A and C plus the conventional leakage reactance $X_1$.

### Torque Output

The ratio of coupling reactance to the magnetizing reactance is

$$C = \left(\frac{x_d - x_q}{2}\right) / \left(\frac{x_d + x_q}{2}\right) + x_1$$

$$= \frac{k-1}{k+1+2\sigma} \text{ where k}$$

$$= x_d/X_q \text{ and } \sigma = x_{1/}x_q$$

This ratio would compare very unfavorably with the equivalent ratio for a conventional induction motor which is given by

$$c^1 = \frac{x_a}{x_a + x_1} = \frac{1}{1+b\sigma}$$

where $X_a$ = air gap reactance of the induction motor and $b = X_q / X_a$

In a typical reluctance machine K will be of order 3; and $b < \frac{1}{k}$, let it be say 0.25. the ratio $x_{1/}x_a$ is of the order of 0.1 therefore $\sigma = \frac{x_1/x_a}{b} = \frac{0.1}{0.25} = 0.4$

$$\text{hence } c = \frac{3-1}{3+1+0.8} = \frac{2}{4.8} = 0.427$$

$$C^1 = \frac{1}{1 + 0.25 \text{ x } 0.1} = \frac{1}{1 + 0.025}$$

The ratio C or $c^1$ fixes the magnitude of the emf induced in the secondary winding and hence determines the current and torque. The value of C will be improved by increasing K. In practice the value of K is limited by the magnitude of the magnetizing current that can be tolerated.

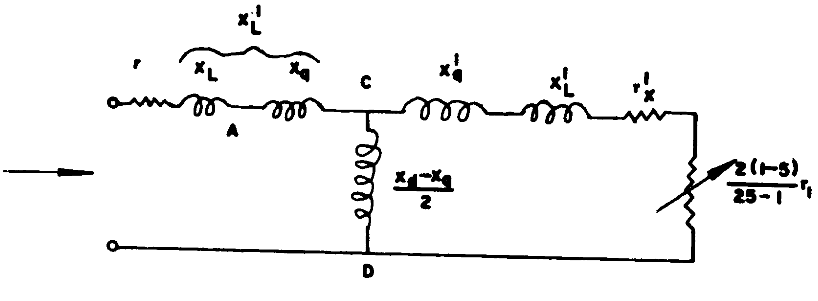

Fig.1. equivalent circuit of transfer field machine $\times_q^1$ $n^2\times_q$ etc where n is the effective turns ratio.

Given that the secondary circuit impedance of the TF machine is the same as that of the conventional 'induction machine with which it is being compared, its secondary current will be less than ½ secondary current of the induction machine, and the torque less than ¼ . The effective leakage reactance of the secondary circuit of the TF machine will be much greater than that of the induction machine, since it is the sum of the conventional leakage reactance xl plus the quadrature axis reactance $X_q$. Consequently the secondary current will be considerably less than that of the conventional machine even for the magnitude of induced emf. The output is therefore further reduced compared to the conventional machine.

**Synchronous Operation - Consideration of Output**

In the synchronous mode of operation, with dc excited primary windings the induced emf in the output or secondary winding is roughly $\frac{\times_d - \times_q}{2\times_a} \approx \frac{K-1}{2K}$

Times that induced in the output winding of a comparable round rotor conventional synchronous machine which has the same number and distribution of winding conductors, and whose synchronous reactance is $X_a$. The effective synchronous reactance of the TF machine is approximately

$$(\times_d + \times_q)/2 = \frac{(K+1)\times a}{2K}$$

Thus the maximum output of the TF machine will be (K-1)/ (K + 1) times the output of the conventional synchronous machine. When K tends to infinity the output ratio tends to unity but the induced emf ratio does not exceed 0.5. The output current of the conventional machine and hence the conductor cross sectional area will be at least twice that of the conventional machine. A value of K of 3 would be readily obtained in practice; and for this figure the output compared to that of the conventional machine is only 0.5 Even when this figure is doubled the output is raised only to 0.7.

There is need therefore to seek to raise the output of the plain TF machine; and the only possible way would be by the use of circuits on the rotor structure to augment the effect of saliency.

Approach to Optimization

The most important factor limiting the output of the TF machine is relatively low coupling between the primary and secondary windings. This coupling depend entirely on the ratio of $X_d$ to $X_q$ The larger this ratio is the higher the output. For a fixed effective ratio pole are the direct axis reactance $X_q$ is relatively independent of alterations of the air gap length in the quadrature axis, but this will produce substantial changes in the quadrature axis reactance. $X_q$. If $X_q$

can be made zero the maximum output will be obtained. A very high value of xd/xq ration is theoretically possible, but this would be obtained at the expense of mechanical rigidity; and also the machine will draw excessive magnetizing current.

In its normal running condition the operation of the TF machine is asynchronous, i.e. the rotor speed is different from that of the field. It follows therefore that the winding impedances will be influenced by closed electric circuits in the rotor.

A short circuited full rotor cage or ploy phase winding will reduce the effective reactance 'of the primary winding in the same way that it would in a conventional induction machine operating at slip. The rotor winding being almost wholly inductive; the rotor currents produce a field which is nearly totally demagnetizing with respect to the applied primary field; additional primary current is drawn from the supply to balance the rotor current. In terms of the supply therefore, the primary reactance is effectively reduced. If the rotor is connected to a capacitive load such that the rotor current is leading, the rotor field will act in the direction of the applied field, and the total current drawn from the supply will be reduced So, in supply terms this will amount to an increase in primary reactance.

The rotor winding can be split into two separate D-axis and Q-axis windings. The D-axis winding has its axis along the direct axis of the rotor, and the Q-axis winding has its axis along the quadrature axis of the rotor. 'are effect of the separate windings In relation to the TF machine will be considered presently.

A single phase d-axis rotor winding will have no influence on the reactance of the primary winding the latter's axis coincides with the q- axis of the rotor, but will have the most effect when the winding axis coincides with the rotor d-axis. Similarly a q-axis rotor winding will have the most effect on the quadrature axis reactance of the primary winding and non on the direct· axis reactance. If the current induced by the primary winding in the d-axis rotor magnetic field will assist the primary field; and so, for given applied voltage the *primary* current will be less than it would be if the rotor coils were absent. The primary winding d-axis rotor winding. 'Lagging pf currents in the d-axis rotor windings will reduce the primary d-axis reactance. The primary q-axis reactance is lowered by induced reactive currents in the q-axis rotor windings.

It can be deduced therefore that a combination of d-axis rotor winding with leading pf currents and q-axis rotor windings with lagging pf current will raise the effective $X_d$ to $X_q$ ratio of the TF machine. Analysis of Airgap Fluxes. A qualitative analysis of the mechanism of the effect of rotor circuits on the TF machine will be approached by considering a simple 2-pole reluctance motor which has a single-phase wound rotor, rotating at speed w. Let a field be established in the airgap by dc currents flowing in the primary winding. The flux density distribution due to the primary mmf can be broken into two components: (i) a steady component A Cos x and (ii) a rotating component A'Cos(x - 2wt) . The axes of the two fields are thus coincident at time t = 0 or nπ/w where n is any integer.

Consider the plane of the

single phase rotor winding to be retarded an angle rom the d - - axis of the rotor so that the axis, of the winding at time t = 0 is at the position x = -(α+π/2). The emf induced in it by the components of the primary field may be written respectively

+ cA Cos (wt, -α) and -cA' Cos (wt +α). The difference in sign is because the relative motion between the rotor conductors and the rotating component of the applied field is in the opposite sense to the relative motion of the conductors to the stationary component of the applied field. If the rotor circuit is preponderantly reactive (as would be expected) the net rotor current would be expressible in the form

$$i_{r=-C'A\cos(wt-\propto\mp{}^{\pi}/_{2})-A'\cos(wt+\propto\mp{}^{\pi}/_{2})}$$

$$= \mp 2c'A'\sin\ \propto\ \cos wt + C'(A-A')\cos\left(wt-\propto\mp{}^{\pi}/_{2}\right)\ \ldots\ldots(1)$$

Where - 2 signifies zero lagging power factor and /2 signifies zero leading power factor with respect to the induced emf.

The rotor current has two components, one whose amplitude is proportional to Sinα and the other whose amplitude is proportional to A-A' and also has a phase angle which depends upon the angle α.

Rotor mmfs and fluxes

Two cases will be considered i, e, When α= 0 and when α = π/2. These represent the situation for the rotor winding axis coinciding with the q-axis of the rotor respectively.

The general expression for rotor mmf distribution, assuming a Sinusoidal distribution is

$$F = i_r\sin(\times+\propto-wt)\ldots\ldots\ldots\ldots\ldots(2)$$

$$when\ \propto=0$$

$$F_1 = \mp C'^{(A-A')}\sin wt\sin(x-wt)$$

$$= \mp\frac{C'}{2}(A-A')\{\cos\times-\cos(\times-2wt)\}\ \ldots\ldots\ldots(3)$$

The airgap permeance distribution may be written

$$\Delta = P_0 + P_1 cos2(\times-wt)\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

if harmonce are neglected

Hence from the product $f_1\Delta$ the flux density distribution is given as

$$B = \mp\frac{C'}{2}(A-A')\left(\frac{p_o}{2}-\frac{p_1}{4}\right)\cos\times-\left(\frac{p_0}{2}-\frac{p_1}{4}\right)\cos(\times-2wt)\ldots\ldots\ldots(5)$$

When $\propto={}^{\pi}/_{2}$

$$f_2 = \mp\{2C'A'coswt + K'^{(A-A')}\cos wt\}\sin\left(\times+{}^{\pi}/_{2}-wt\right)$$

$$= \mp C'(A+A')\cos\ wt\cos\ (\times-wt)$$

$$= \mp\frac{C'}{2}(A+A'\{\cos\times+\cos(\times-2wt)\}\ldots(6)$$

The product $F_2\Delta$ gives the flux density distribution as

$$B = \mp C'(A + A)\left(\frac{P_0}{2} + \frac{P_1}{44}\right)\{\cos \times \cos(\times - 2wt)\}. \ldots\ldots (7)$$

Equations (5) and (6) show that neglecting harID0nics, the flux density distribution due to rotor currents has *(i)* a stationary component and *(ii)* a rotating component, both similar to the corresponding components of the distribution of the applied primary field.

Consider the flux of the q-axis rotor winding given by (5). When the rotor power factor is zero lagging the stationary component of rotor flux opposes the stationary component of the applied field; and the rotating component augments the rotating component of the applied field, when the rotor power factor is zero leading the situation is reversed, the stationary component of the applied field is increased and the active or rotating component reduced. A lagging power factor in the q-axis winding is therefore necessary.

Consider the flux of the d-axis rotor winding given by (7). When the power factor angle of the rotor circuit is zero lagging the rotor fluxes oppose both components of the applied field. Reduction in the effective rotating field means reduced coupling, which is unacceptable. Although the asynchronous reactance is also reduced because the stationary component of flux is reduced, this could not offset the deleterious effect of reduced coupling between primary and secondary on the other hand if the rotor circuit pf angle is leading both components of primary field are strengthened. Although the synchronous reactance is increased and leads to a reduced maximum output in the synchronous mode, the increase in coupling due to the increase in the active component of primary field would have a greater effect.

The best all-round effect is obtained with a q-axis rotor winding with a zero lagging power factor angle. If this is combined with having a d-axis rotor winding with zero leading power factor angle the effect will be an increase in the coupling due to the combined contribution of both d -and q - axis rotor winding fluxes in strengthening the rotating component of the primary field. The d-axis and q-axis windings have opposite effects on the synchronous reactance; there would altogether be a net increase in synchronous reactance.

## 3. CONCLUSION

It has been shown that self-cascading can be used to enhance the output of a TF machine. This is consistent with the effect of rotor circuits in brushless stator-controlled synchronous induction machines as demonstrated by Broadway et al.

In small TF machines where space limitations preclude the use of wound rotors, a cage would normally be used. The cage can be resolved into d-axis and q-axis elements. The former must be kept down as much as practicable, since, unless the impedance of its circuit is capacitive it will tend to have a detrimental effect on output. In large machines with would rotors, both d-axis and q-axis windings can be utilized. The effect of the rotor windings increases with increase in the magnitude of their currents which can be readily controlled by connecting these windings to suitable reactive loads.

Even in large machines the d-axis rotor windings are not likely to be employed because their effect would tend to increase the level of saturation in the magnetic circuit since the rotor current field strengthens both the stationary and the rotating components of the applied field. Utilization of the q-axis rotor winding only will reduce the complexity of the machine and will tend to maintain saturation at the level determined by the primary excitation since, the action of the q-axis rotor winding is, in effect, to convert part of the stationary flux into rotating flux.

The synchronous reactance can be reduced to a very low value by connecting suitable capacitance in the q-axis winding circuit. In doing this the effective reactance of the rotor must be large enough to maintain near zero power factor impedance angle. A low reactance will lead to large rotor currents which will lead to increased output emf. The combination of a high secondary emf and low synchronous reactance will result in increased stability in the synchronous mode of operation.

The transfer-field machine has the advantage when compared with other related reluctance-effect synchronous machines that the two component groups of stator windings are isolated and so the machine can be used in situations-Where widely different boltage levels obtain between the excitation windings on one hand and the output windings on the other or where the impedance characteristics of the two circuits are different: for instance in high voltage alternators with low voltage dc excitation windings or low voltage battery charging alternators with usually high resistance field windings.

The possibility of internally modifying the effective synchronous impedance of the TF machine and thereby realising output and increasing stability has important implications for the application of the TF machine for large scale power production.

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