A NOVEL STRATEGY FOR RAISING THE UNIT OUTPUT OF LARGE SYNCHRONOUS MACHINES

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Abstract
In power systems, the major source of electrical energy is the synchronous generator. However, the increase in the unit size of the conventional synchronous generator has not kept pace with the corresponding increase in the unit output of prime movers driving them, and the demand for electrical energy keeps growing. To this end, a novel strategy for increasing the unit output of synchronous generator is proposed in this paper. The scheme uses circuit theory concepts and composite rotor magnetic structure to amplify X_d/X_q ratio on which the reluctance output power depends without altering the physical geometry of the machine. The analysis of the machine is based on airgap flux density distributions and flux linkages.

Keywords: X_d/X_q *ratio, modified q-axis reactance X_q mmf, permeance and flux density distributions, transposed auxiliary windings*

1.0 INTRODUCTION

The volume of the rotor of an electrical machine is a rough measure of its output. The output is also proportional to the speed. The limit to the diameter of the rotor of a synchronous generator is set by the centrifugal force, which the end bells are capable of withstanding. This is also influenced by the angular velocity of the machine. Two-pole generators have given way to slower four-pole synchronous turbine generators; for in spite of the resulting reduction in speed it has still been possible to improve the unit output. The reduction in speed has enabled greater length of the rotor to be accommodated than was possible at the higher speed. This is because less deflection of the rotor occurs with the larger diameter of the slower machine, and there are therefore fewer tendencies to whirling problem. Consequently, the airgap can be made smaller and the excitation mmf required can thus be lowered. The most dramatic increases in unit output have been accomplished through improved cooling - ranging from air cooling, hydrogen cooling to direct cooling using cold water passed through hollow conductors of both the armature and excitation windings. Improved cooling of the exciting windings means that, the higher excitation currents can be used resulting in larger emfs.

The limit in the excitation flux is, however, set by magnetic saturation. If this can be circumvented, higher emfs can be obtained even with shorter rotors. The super-conducting machine, with no iron in the magnetic circuit is one of the strategies for accomplishing the objective of increasing unit output of the synchronous generator [1] the main constraint to increasing the diameter of a conventional ferromagnetic synchronous generator, as mentioned earlier, is that of containing the centrifugal forces on the rotor end-bells.

Machines without rotating windings therefore offer the possibility of increasing unit output by the use of larger rotor diameters. If for example, the diameter is increased by 25% say, there would be a corresponding increase in output power of $(5/4)^2 - 1 = 9/16$? 50% ($P \alpha D^2L$ product). Given a fixed load torque, if the speed of the machine is doubled, output power will be doubled. The category of the machines that operate without moving conductors includes permanent magnet machines, hysteresis machines and reluctance machines. The permanent magnet synchronous machine cannot be considered for use in large power generation because the excitation level cannot be regulated. The hysteresis machine has found a place in a lower power self-synchronising motor. The conventional synchronous reluctance machine yields an output that is less than 30% of the output of an induction machine of comparable size. The ratio of X_d to X_q on which the reluctance output of the machine depends is usually of the order of 1.5 to 2 in a conventional machine, and contributes only a small proportion of total output of a synchronous machine. A novel type of salient-pole synchronous-reluctance generator is proposed, whose X_d, to X_q, ratio can theoretically be varied, without limit, even though the physical parameters of the machine remain fixed. Tuning the system through the use of capacitors in conjunction with an auxiliary set of stator windings varies the X_d to X_q ratio.

2.0 DESCRIPTION OFTHE MACHINE

The proposed machine has a composite structure, the rotor is half salient-pole and half cylindrical rotor as shown in Fig. l. The stator primary windings span both sections of the machine. Another set of windings, the auxiliary windings also span both sections. In the latter case, however, the coil winding sides are transposed in the passage from one machine section to the other. Rotor excitation windings if required will run straight through like the primary windings.

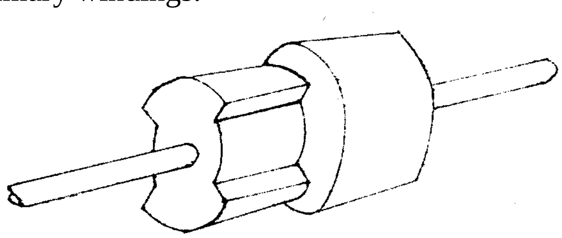

Fig. 1: The composite magnetic rotor structure

2.1 Impedance of a synchronous-reluctance machine as a function of load angle

The impedance of a synchronous reluctance machine expressed as a function of the load angle,δ is given by [2] as:

$$Z = j\left\{\begin{matrix} \frac{1}{2}(X_d + X_q) \\ + \frac{1}{2}(X_d - X_q)(cos2\delta - jsin2\delta) \end{matrix}\right\} \qquad (1)$$

where X_d and X_q are the direct axis and the quadrature axis synchronous reactances respectively. The corresponding distribution of airgap flux density may be expressed as:

$$B = M_o \cos(\theta - \omega_o t)[P_O + P_1 \cos 2(\theta - \omega_o t - \delta)] \qquad (2a)$$

where M_o cos(θ-ω_ot) is the distribution of the primary winding mmf and P_o + P_1 cos2(θ-ω_ot-δ) is the permeance distribution of the salient pole section of the machine.

Considering only those components, which are involved in the induction of mains frequency emf and neglecting the others, we will have that:

$$B = M_o P_o \cos(\theta - \omega_o t) + \frac{1}{2} M_o P_1 \cos(\theta - \omega_o t - 2\delta)$$

$$= M_o P_o \cos(\theta - \omega_o t) + \frac{1}{2} M_o P_1) [\cos(\theta(\theta - \omega_o t)\cos 2\delta) + \sin(\theta - \omega_o t)\sin 2\delta]$$

$$= M_o P_o \cos(\theta - \omega_o t) + \frac{1}{2} M_o P_1) [\cos(\theta - \omega_o t)\cos 2\delta + \cos(\theta - \omega_o t - \pi/2)\sin 2\delta]$$

$$= [M_o P_o + \frac{1}{2} M_o P_1(\cos 2\delta - j\sin 2\delta)]\cos(\theta - \omega_o t) \qquad (2b)$$

Comparing equations (1) and (2b), it can be deduced that Po relates to

$\frac{1}{2}(X_d + X_q) and\ \frac{1}{2} P_1$

$relates\ to\ \frac{1}{2}(X_d - X_q)$

$hence, P_o + \frac{1}{2} P_1 is\ to\ X_d\ as\ P_o - \frac{1}{2} P_1 is\ to\ X_q$

Suppose this reluctance machine is coupled to a cylindrical rotor synchronous machine whose synchronous reactance has a value X_d; and if the windings of the two machines are connected in series, the gross impedance will be:

$$Z_c = j\{X_d + \frac{1}{2}(X_d + X_q) + \frac{1}{2}(X_d - X_q)(\cos 2\delta - j\sin 2\delta)\}$$

$$= j\{2X_d - \frac{1}{2}(X_d - X_q) + \frac{1}{2}(X_d - X_q)(\cos 2\delta - j\sin 2\delta)\} \qquad (3)$$

Each half of the machine has an auxiliary winding identical with the first or primary winding. The two sets of auxiliary windings are connected in series phase by phase. Unlike the primary windings, the terminals of one set of the windings are transposed. When this auxiliary winding is short-circuited, a modification of the machine impedance will result. Modification of the impedance over a wide range can be obtained if the short-circuit is replaced by a variable balanced capacitance load.

3.0 Analysis of airgap flux density and flux linkages

Let the distribution of the primary winding mmf in both halves of the machine be given by:

$m = M_o\cos(\theta - \omega_o t)$ .... (4)

The flux density distribution in the cylindrical rotor and salient pole halves of the machine will be respectively be:

$$B_c = M_o P\cos(\theta - \omega_o t) \quad (5a)$$

and

$$B_s = M_o\{P_o + P_1\cos 2(\theta - \omega_o t - \delta)\}\cos(\theta - \omega_o t) \quad (5b)$$

where P is the permeance of the airgap of the cylindrical rotor half of the machine and Po+P,cos2(8-wot-6) is the airgap permeance distribution of the salient-pole half

The mean flux distribution as seen by the primary winding is:

$$B_{11} = {}^1/_2(B_c + B_s) = {}^1/_2 M_o\{(P + P_0)\cos(\theta - \omega_o t) + {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta) \quad (6a)$$

and the mean flux distribution as seen by the auxiliary winding is:

$$B_{12} = {}^1/_2(B_c - B_s) = {}^1/_2 M_o\{(P - P_o)\cos(\theta - \omega_o t)\} \quad (6b)$$

Let $P=P_o+½P_1$ which is the necessary condition that the synchronous reactance X_s of the cylindrical section of the machine equals the direct axis reactance of the salient pole section i.e. $X_s = X_d$ [3],then at no-load, i.e $\delta=0$, the primary winding flux linking the auxiliary winding will be zero. Substituting *1/2P*, for P-P_o, the flux linking the auxiliary winding for any δ may be expressed as:

$$B_{12} = M_O P_1 \text{Sin}\delta \sin(\theta - \omega_o t - \delta) \quad (7)$$

Thus an emf of magnitude proportional to the sine of the load angle will be induced in the auxiliary winding. In this form, the output of the auxiliary winding could be used to indicate the load angle of larger synchronous machine to which it is coupled [4].

4.0 Auxiliary winding connected to a reactive load.

The major thrust of this paper is to show how the impedance of the machine is modified when a balanced reactive load is connected to the auxiliary winding.

Suppose the machine is operating as a motor, having a load angle δ. This angle is assumed to be maintained when the balanced reactive load is connected to the auxiliary winding. The auxiliary winding current will cause the primary winding to draw a compensating current. Let M_2 and M_1, be the magnitudes of the mmfs due respectively to the auxiliary windings current and the additional/compensating current. The fluxes due to the mmfs must balance, thus

$$M_1\{(P + P_1)cos(\theta - \omega_o t) + {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta)\} = -M_2\{(P - P_0)\cos(\theta - \omega_o t) - {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta)\} \quad (8)$$

The flux due to the gross primary winding mmf M_o, + M_1, will be given by:

$$B_{1T} = (M_o + M_1)\{(P + P_O) + P_i\cos 2(\theta - \omega_O t - \delta)\}\cos(\theta - \omega_O t)$$
$$= (M_O + M_I)\{(P + P_O)\cos(\theta - \omega_O t) + 1/2P_I\cos(\theta - \omega_O t - 2\delta)\} \quad (9)$$

Substitute for$M_I(P + P_O)\cos(\theta - \omega_O t) + 1/2M_I P_I\cos(\theta - \omega_O t - 2\delta)$

$$= M_2\{(p - p_o)\cos(\theta - \omega_o t) - {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta)\}$$ from equation (8), then

$$B_{1T} = M_o\{(P + P_o)\cos(\theta - \omega_o t) + {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta)\} - M_2\{(P - P_o)\cos(\theta - \omega_o t) + {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta)\}.$$

$$= M_o\{(P + P_o)\cos(\theta - \omega_o t) + {}^1/_2 P_1\cos(\theta - \omega_o t - 2\delta) - M_2\{{}^1/_2 P_1\cos(\theta - \omega_o t)$$

$$- {}^{1}\!/_{2}\, P_1 \cos(\theta - \omega_o t - 2\delta)\} \quad (10)$$

Adding and subtracting ${}^{1}\!/_{2}\, M_o P_1 \cos(\theta - \omega_o t)$, and then reorganising, gives

$$B_{1T} = M_o\{P + P_o + {}^{1}\!/_{2}\, P_1) \cos(\theta - \omega_o t)$$
$$- {}^{1}\!/_{2}\, M_o P_1 \cos(\theta - \omega_o t) - {}^{1}\!/_{2}\, M_2 P_1 \cos(\theta - \omega_o t)$$
$$+ {}^{1}\!/_{2}\, M_o P_1 \cos(\theta - \omega_o t - 2\delta)\}.$$
$$+ {}^{1}\!/_{2}\, M_2 P_1 \cos(\theta - \omega_o t - 2\delta)$$
$$= M_O(P + P_o + {}^{1}\!/_{2}\, P_1) \cos(\theta - \omega_o t)$$
$$- {}^{1}\!/_{2}\, (M_o + M_2) P_1 \cos(\theta - \omega_o t)$$
$$+ {}^{1}\!/_{2}\, (M_o + M_2) P_1 \cos(\theta - \omega_o t - 2\delta)$$
$$= 2M_o(P_o + {}^{1}\!/_{2}\, P_1) \cos(\theta - \omega_o t)$$
$$- {}^{1}\!/_{2}\, (M_o + M_2) P_1 \cos(\theta - \omega_o t)$$
$$+ {}^{1}\!/_{2}\, (M_o + M_2) P_1 \cos(\theta - \omega_o t - 2\delta)$$
$$= M_o\{2(P_o + {}^{1}\!/_{2}\, P_1) \cos(\theta - \omega_o t)$$
$$- {}^{1}\!/_{2}\, \{(M_o + M_2) P_1 / M_o\} \cos(\theta - \omega_o t)$$
$$+ {}^{1}\!/_{2}\, \{(M_o + M_2) P_1 / M_o\} \cos(\theta - \omega_o t - 2\delta) \quad (11)$$

A flux density distribution such as this would be associated with a machine with impedance given by:

$$Z_c' - j\{2X_d - {}^{1}\!/_{2}\, (\times_d - \times_q)'$$
$$+ {}^{1}\!/_{2}\, (\times_d - \times_q)'(\cos 2\delta - j sin 2\delta)\} \quad (12a)$$

$$where\ (\times_d - \times_q)' = (\times_d - \times_q).(M_o + M_2)/M_o$$

The direct axis reactance will remain $2X_d$ irrespective of the value of the load connected to the auxiliary winding, and so X_q, may be considered modified and not (X_d-X_q), and hence the impedance of the machine may be expressed in terms of a modified quadrature axis reactance viz, X_q'. Thus the impedance may be written as:

$$Z_C' = j\{2X_d - {}^{1}\!/_{2}\, (X_d - X_q') + {}^{1}\!/_{2}\, (\times_d - \times_q)(\cos 2\delta - j sin 2\delta)\} \quad (12b)$$

The locus of this impedance is a circle of radius ½(X_d-X_q) and centre at the point

$$(0, j\, {}^{1}\!/_{2}\, (3 \times_d + \times_q{}'))$$

Fig. 2 shows the impedance loci of the machine. As the auxiliary mmf'M_2 increases thus increasing (X_d-X_q') and hence the diameter ½(X_d-X_q') of the impedance circle, the effective machine quadrature axis reactance X_q,' decreases. This effective quadrature axis reactance can therefore be made so small as to make the ratio X_d/X_q' very large.

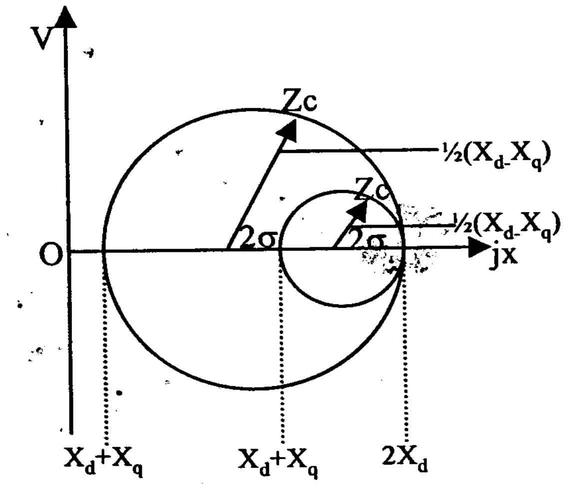

Fig.2: The impedance loci of the machine showing the effects of the modified quadrature axis reactance X_q'.

The modified quadrature axis reactance X_q' can be negative, depending upon the capacitance loading of the auxiliary winding [5]. The ratio of the direct axis reactance to the quadrature axis reactance of the machine can be made very large; a value of infinity is possible when the effective quadrature axis reactance is reduced to zero. For a given power output in the working range, the higher the ratio becomes, the less the current i.e the power factor is better. This ratio increase is effected by increasing the current loading of the auxiliary windings.

When dc excited rotor windings are provided, producing a field which is co-phasal in space in both sections, the machine can operate as a salient pole synchronous generator in which it is possible to make the reluctance output the major component of the total output. In conventional synchronous generators, the X_d to X_q ratio, on which the reluctance power depends, is small, usually less than 2. If this ratio were increased to 5, the reluctance power for a machine with 1.2 p.u. excitation could rise from 37% to the nearly 90% of the total output, at a load angle of 45°. Using the technique described in this paper X_d to X_q ratios tending to infinity can be obtained, resulting in machines in which the greater proportion of the output will be provided by reluctance effect.

5.0 CONCLUSIONS

An analysis of a novel synchronous machine, which is a combination of cylindrical rotor machine and a salient-pole machine coupled together and having their windings interconnected, has been presented. It was shown that the effective X_d to X_q ratio for the combination can be varied, and that at least in theory can have infinite value. The technique involved can be used to boost the unit output of synchronous generators.

In addition to the very high potential output of the machine resulting from the high X_d to X_q ratio, the unit output can be further raised if the rotor diameter is increased and further raised by doubling the rotor speed, adopting a 2-pole design instead of the standard 4-pole design.

The provision of a squirrel cage will make the machine self-starting as a motor. When the motor has run up to speed, the auxiliary winding with a suitable, connected capacitance load, is brought in and the rotor synchronised. The capacitance load may subsequently be changed so that a higher X_d, to X_q ratio is obtained in order to provide greater stability when the machine is mechanically loaded.

In the analysis above, a linear magnetic circuit is assumed. The combination of primary and auxiliary winding mmfs, which add up in the salient pole end of the machine, will ensure that saturation occurs. Saturation effects will increase as the mechanical load on the machine increases and may in fact lead to an output higher than what is calculated on the basis of an unsaturated system.

It is felt that when fully developed, the machine will have a superior performance in run-up and synchronizing qualities by comparison with conventional forms of the synchronous reluctance motors and also have a higher rating than an induction motor of the same size. Reluctance motors in use are rated about a third of an induction motor of the same size. With its potential rating and likely high pull-in capacity, this novel reluctance machine would be able to compete with the induction motor as a general industrial drive.

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