A New Hybrid Synchronous Machine Capable of Ultra-High Output Power.

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ABSTRACT

This article presents the steady-state performance analysis of a new hybrid polyphase synchronous machine capable of ultra-high power output. The machine comprises a round rotor and a salient-pole rotor which are mechanically coupled together and housed in their respective stators. Each component machine has two identical stator windings, known as the main and auxiliary windings. The main windings are connected in series and tied to an infinite busbar for generator operation, while the auxiliary windings are transposed in passing from one component machine to the other and feed a variable capacitance load. A DC field winding spanning both sections of the machine is mounted on the combined rotors.

It is shown that the operational value of $x_d^{'} / x_q^{'}$ ratio of the machine is dependent on the variable capacitance load of the auxiliary windings and varies from zero to infinity and hence the output power which is directly proportional to it. Unlike the conventional synchronous machines where the reluctance component of the output power is invariably very small, compared to the excitation component, the converse is the case in the new hybrid synchronous machine.

(Keywords: ultra-high output power, transposed auxiliary windings, variable $x_d^{'} / x_q^{'}$ ratio, capacitance tuning)

INTRODUCTION

The steady-state performance of a hybrid synchronous reluctance machine has been reported in [1-6], each having two stator windings known as the main and auxiliary winding. There are no rotor conductors including damper windings. The machine comprises a round rotor and salient pole rotor that are mechanically coupled together and integrally wound. The main windings are connected in series while the auxiliary windings are connected in anti-series (transposed) between the two sections of the machine. By tuning the load capacitance of the auxiliary winding, it becomes possible to vary the operational q-axis reactance ($x_q^{'}$) of the machine from zero to infinity, while the d-axis reactance ($x_d^{'}$) remains constant. Thus a variable $x_d^{'} / x_q^{'}$ ratio is achieved which varies from zero to infinity and hence the output power which is directly proportional to it.

Figure 1 shows the per phase schematic arrangement of the machine while Figure 2 shows the coupled circuit equivalent.

Analysis of Figure 2 assumes the following:

a) The synchronous reactance x_s of the round rotor section of the machine is matched to the d-axis reactance (x_d) of the salient pole section by design (ie $x_s = x_d$)

b) The main and auxiliary windings of the machine have the same pole number as the rotor poles and occupy the same slot space and, thus perfectly coupled (unity coefficient of coupling) and hence $x_{mr} = x_s = x_d$ and $x_{ms} = x_1$

c) The resistance of the winding is neglected.

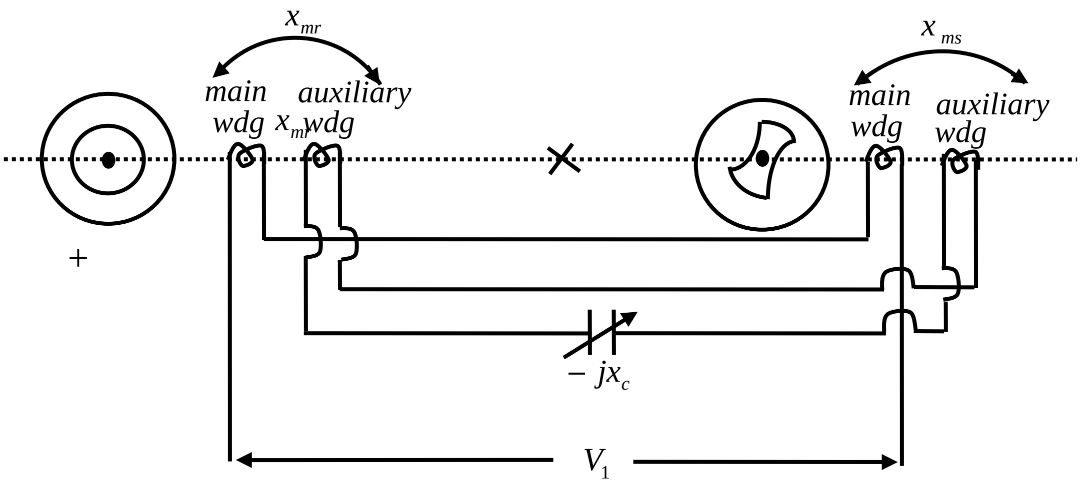

Figure 1: Per Phase Schematic Arrangement of the Hybrid Synchronous Machine.

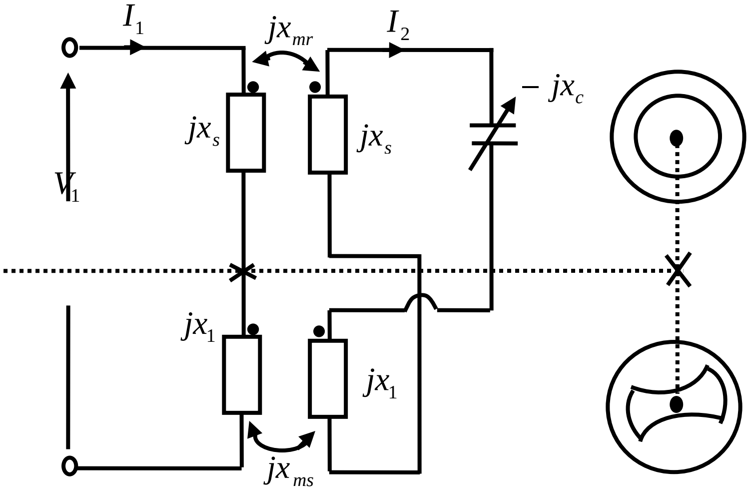

Figure 2: The Coupled Circuit Equivalent of the Hybrid Synchronous Reluctance Machine.

For a sinusoidally distributed stator winding and a salient-pole rotor structure, the winding reactance x_1 is a function of rotor position and well known as [7]:

$$x_1 = \frac{1}{2}(x_d + x_q) + \frac{1}{2}(x_d - x_q)[\cos 2\delta + j\sin 2\delta] \quad \textbf{(1)}$$

The machine is analysed as a magnetically coupled circuit. Applying KVL equation in the two meshes of Figure 2 and noting the positive and negative couplings in the respective halves of the machine, it can readily be deduced that:

$$V_1 = j2x_d I_1 + j(x_1 - x_d)(I_1 + I_2) \quad \textbf{(2)}$$

and

$$0 = j2x_d I_2 + j(x_1 - x_d)(I_1 + I_2) - jx_c I_2 \quad \textbf{(3)}$$

Equations (2) and (3) lead directly to the per-phase steady state equivalent circuit of the machine as shown in Figure 3.

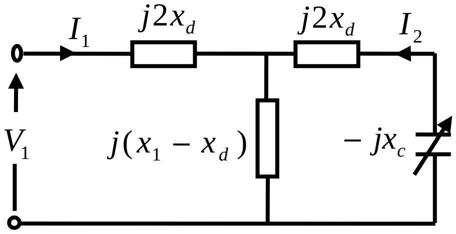

Figure 3: Per Phase Steady State Equivalent Circuit of the Hybrid Synchronous Reluctance Machine.

From Figure 3, it can readily be deduced that the input impedance is given by V_1/I_1 is:

$$Z_{in} = j\left[\frac{(4x_d - x_c)(k-1)\cos 2\delta + (4x_d - x_c)(k+1) - 2kx_c}{3k+1+(k-1)\cos 2\delta - \frac{2kx_c}{x_d} + j(k-1)\sin 2\delta} + \frac{j(k-1)(4x_d - x_c)\sin 2\delta}{3k+1+(k-1)\cos 2\delta - \frac{2kx_c}{x_d} + j(k-1)\sin 2\delta}\right] \quad \textbf{(4)}$$

where $k = \frac{x_d}{x_q}$ **(5)**

Equation 4 can be simplified as:

$$Z_{in} = j\left[\frac{(a+jb)}{(c+jd)}\right] = \left[-\left(\frac{bc-ad}{c^2+d^2}\right) + j\left(\frac{ac+bd}{c^2+d^2}\right)\right] \quad \textbf{(6)}$$

$$= -R_e + jX_e \quad \textbf{(7)}$$

Where:

$$(4x_d - x_c)(k-1)\cos 2\delta + (4x_d - x_c)(k+1) - 2kx_c = a \quad \textbf{(8)}$$

$$(4x_d - x_c)(k-1)\sin 2\delta = b \quad \textbf{(9)}$$

$$3k+1+(k-1)\cos 2\delta - \frac{2kx_c}{x_d} = c \quad \textbf{(10)}$$

$$(k-1)\sin 2\delta = d \quad \textbf{(11)}$$

AXIS REACTANCES OF THE MACHINE

Consideration of the reactive component of Z_{in} (Equation 7) leads directly to the direct and quadrature axes reactance. Thus when $\delta = 0$, the salient pole rotor of the machine is in the direct axis position and hence"

$$x_d^{'} = 2x_d \quad \textbf{(12)}$$

and when the rotor is in the quadrature axis position, $\delta = \pi/2$ radians

$$x_q^{'} = \frac{(4x_d - x_c) - kx_c}{k+1-\frac{kx_c}{x_d}} \quad \textbf{(13)}$$

From Equation 12 and 13, it is apparent that for a fixed value of x_d and k, determined by the geometry of the salient pole section of the machine, the quadrature axis reactance $x_q^{'}$ is dependent on the variable parameter x_c and hence, for appropriate value of x_c, $x_q^{'}$ takes values between 0 and infinity while $x_d^{'}$ remains constant and thus a variable of $x_d^{'}/x_q^{'}$ ratio which varies from zero to infinity is obtained.

The loci of Z_{in} (Equation 7) as δ varies from 0 to π are family of circles of radius $\frac{1}{2}(x_d^{'} - x_q^{'})$ and centre $(\frac{1}{2}(x_d^{'} + x_q^{'}),0)$ for various values of x_c as shown in Figure 4 and all the family of circles are tangential to the straight line passing through $2p.u$ for $x_d = 1p.u$. When $x_d = \left|-x_q\right|$, the machine will draw or supply the same current irrespective of load.

The asynchronous behavior and pull-in characteristics under constant current conditions provide an interesting study. The more interesting loci are probably those for which the quadrature axis current $I_q^{'}$ has a leading power factor. For a given output, the machine when operating on one of such a locus will draw less current than would be the case if the locus was with a lagging $I_q^{'}$.

For a constant applied voltage, the current loci which are the inverse of the impedance loci are family of circles too, tangential to the line 0.5pu as shown in Figure 5. The straight line extending from $\pm\infty$ in the current loci which implies infinite output power corresponds in the impedance loci to $x_q^{'} = 0$ as expected. The power factor is given by:

$$\cos\phi = \frac{R_e}{\sqrt{R_e^2 + X_e^2}} \qquad \textbf{(14)}$$

Plots of the power factor for various values of x_c are shown in Figure 6.

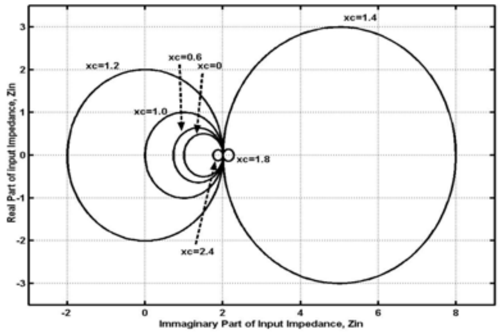

Figure 4: Impedance Loci of the Idealized Hybrid Machine.

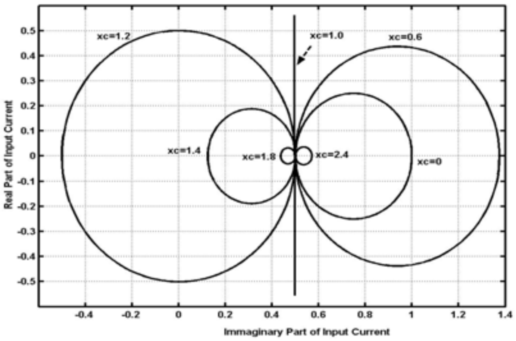

Figure 5: Current Loci of the Idealized Hybrid Machine.

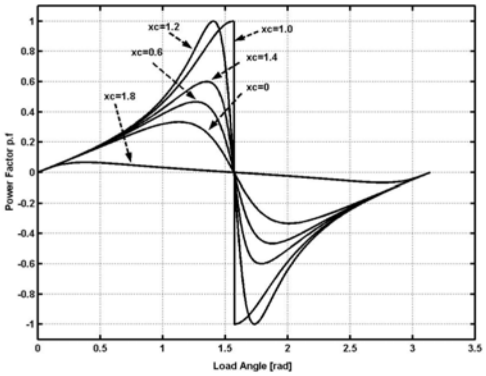

Figure 6: Power Factor Load Angle Plots of the Idealized Hybrid Machine.

DEMERITS OF THE HYBRID SYNCHRONOUS RELUCTANCE MACHINE

One of the major demerits of the hybrid synchronous reluctance machine is that the round rotor half of the machine does not contribute to torque production, since there are no windings in the rotor. Its function is essentially for impedance matching of the direct axis reactance of the salient pole section of the machine to equal the synchronous reactance x_s of the round rotor half (i.e $x_s = x_d$). More importantly, the machine cannot operate as a standalone machine as it must be connected to an existing mains supply for the purpose of deriving its magnetizing current in a manner akin to induction generators.

Obe and Senjyu [8] suggested the exploration of the possibility of embedding some permanent magnets in the round rotor half of the machine with a view to making it contribute to the output power and thus reduce the load angle δ for maximum power output of the machine.

This paper is an extension of the hybrid synchronous reluctance machine reported in [1-6] to operate in the pure synchronous mode by introducing a DC field winding spanning both sections of the machine and mounted on the combined rotors.

This technique enables the salient pole half of the machine to produce excitation cum reluctance power while the round rotor section contributes excitation power only. The new hybrid synchronous machine will thus have superior output characteristics to the hybrid synchronous reluctance machine [1-6] and the conventional DC field excited synchronous machines.

DESCRIPTION OF THE HYBRID SYNCHRONOUS MACHINE UNDER STUDY

The machine under study comprises a round rotor and a salient pole rotor that are mechanically coupled together and housed in their respective stators. There are two identical windings on the stator side known as the main and auxiliary windings as described in [1-6] that are appropriately interconnected and wound for the same pole numbers as the rotor poles.

The only difference between the machine under study and [1-6] is that a DC excitation field winding spanning both sections of the machine is now mounted on the combined rotor as shown in Figure 7.

ANALYSIS OF THE HYBRID SYNCHRONOUS MACHINE

The magnitude of EMF (E_f) induced in both halves of the machine by the rotor field winding flux ϕ_f is assumed equal. The total EMF induced in the main winding is thus the sum of the EMFs (E_f) in both halves of the machine and equals $2E_f$.

Similarly, the EMFs induced in the both halves of the auxiliary winding are equal and add up to zero due to the transposition (anti series connection) of the auxiliary windings. The equivalent circuit of the machine is thus represented as shown in Figure 8 assuming motoring convention.

Applying the KVL equation for the two meshes of Figure 8, it can readily be shown that

$$V_1 = 2E_f + j2x_d I_1 + j(x_1 - x_d)(I_1 + I_2) \quad \textbf{(15)}$$

$$0 = j2x_d I_2 + j(x_1 - x_d)(I_1 + I_2) - jI_2 x_c \quad \textbf{(16)}$$

Equations (15) and (16) lead directly to the equivalent circuit shown in Figure 9.

The impedance of the circuit looking through the terminals of V_1 is given by:

$$Z_{in} = j[2x_d + \frac{(x_1 - x_d)(2x_d - x_c)}{x_1 - x_d + 2x_d - x_c}] \quad \textbf{(17)}$$

Hence,

$$V_1 = 2E_f + jI_1[2x_d + \frac{(x_1 - x_d)(2x_d - x_c)}{x_1 + x_d - x_c}] \quad \textbf{(18)}$$

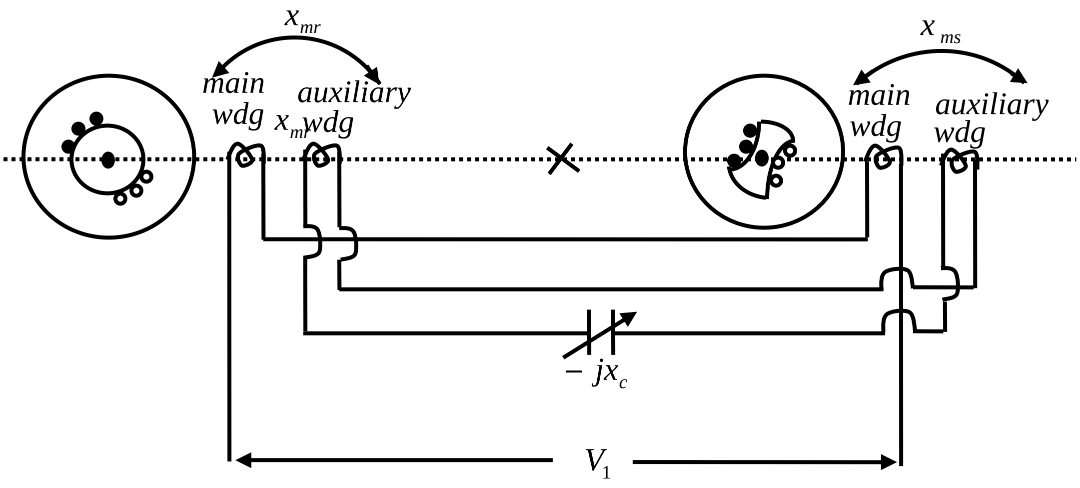

Figure 7: Per Phase Schematic Arrangement of the Hybrid Synchronous Machine with Rotor Field Winding.

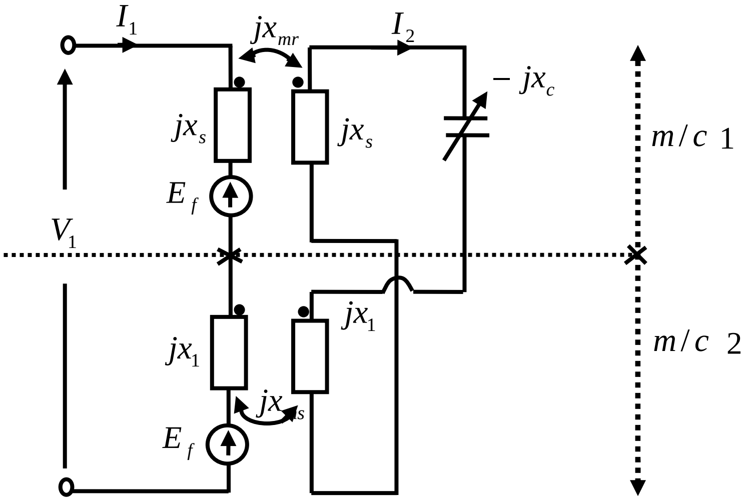

Figure 8: Coupled Circuit Equivalent of the Machine including the Effect of Induced EMF.

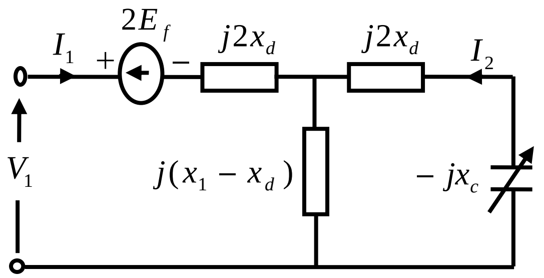

Figure 9: Per Phase Steady State Equivalent Circuit of the Hybrid Synchronous Machine including the Effect of the Induced EMF.

Equation 18 may be represented as shown in Figure 10 for generator operation.

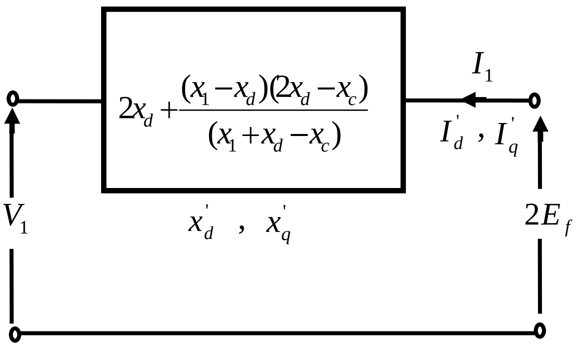

Figure 10: Equivalent Circuit of the Hybrid Synchronous Machine Operating as a Generator.

Where $x_d^{'}$ is the d-axis reactance of the machine impedance $Z_{in} = j[2x_d + \frac{(x_1 - x_d)(2x_d - x_c)}{x_1 + x_d - x_c}]$ for $\delta = 0^\circ$ and given by:

$$x_d^{'} = 2x_d \qquad \textbf{(19)}$$

Similarly, $x_q^{'}$ is the q-axis reactance of the machine impedance:

$$Z_{in} = j[2x_d + \frac{(x_1 - x_d)(2x_d - x_c)}{x_1 + x_d - x_c}]$$

for $\delta = \frac{\pi}{2}$ rads and given by:

$$x_q^{'} = \frac{(4x_d - x_c) - kx_c}{k + 1 - \frac{kx_c}{x_d}} \qquad \textbf{(20)}$$

The d-q components of the load current I_1, $I_d^{'}$ and $I_q^{'}$ will produce component voltage drops $jI_d^{'}x_d^{'}$ and $jI_q^{'}x_q^{'}$. The phasor relations of Figure 10 using V_1 as the reference phasor and neglecting resistance is given by:

$$2E_f = V_1 + jI'_d x'_d + jI'_q x'_q \quad \textbf{(21)}$$

The phasor diagram corresponding to Equation 21 is as shown in Figure 11.

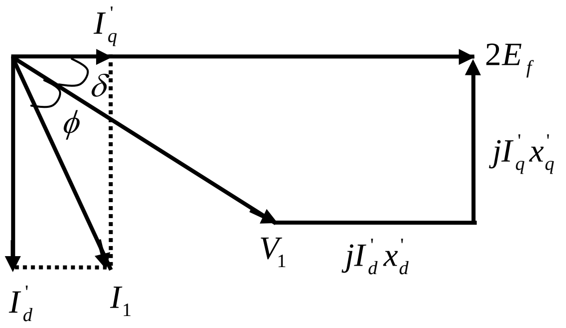

Figure 11: Phasor Diagram of Generator Mode of the Hybrid Machine.

OUTPUT POWER OF THE NEW HYBRID MACHINE

The output power of the machine is given by:

$$S = 3V_1 I_1^* \quad \textbf{(22)}$$

$$S = 3|V_1|\angle -\delta(|I'_q| + j|I'_d|)^* \quad \textbf{(23)}$$

From the phasor diagram (Figure 11):

$$|I'_d| = \frac{|2E_f| - |V_1|\cos\delta}{x'_d} \quad \textbf{(24)}$$

$$|I'_q| = \frac{|V_1|\sin\delta}{x'_q} \quad \textbf{(25)}$$

Substituting Equations (24) and (25) into Equation (23) gives:

$$P = \frac{3|V_1||2E_f|}{x'_d}\sin\delta + \frac{3|V_1|^2\left(\frac{x'_d}{x'_q} - 1\right)}{2x'_d}\sin 2\delta \quad \textbf{(26)}$$

$$= P_f + P_r \quad \textbf{(27)}$$

where P_f is the excitation power and P_r is the reluctance power.

A plot of the real output power P of the machine with δ for typical values of $V_1 = 1 p.u$, $E_f = 1.2 p.u$ and δ from zero to π for some values of x_c is as shown in Figure 12.

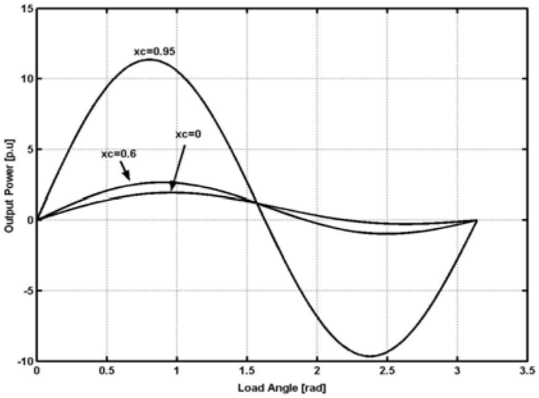

Figure 12: Output Power of the Hybrid Machine for δ from zero to π.

Figure 13 shows the plot of the real output power P of the machine with δ for $x_c = 0.9999999999\ p.u$ which is chosen as an approximation to $1.0 p.u$.

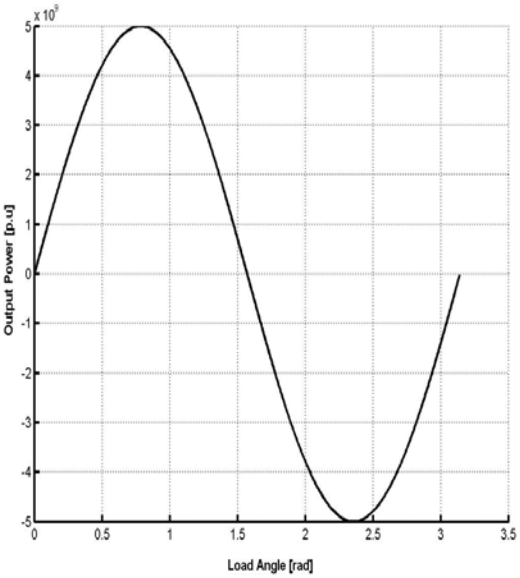

Figure 13: Output Power of the Hybrid Machine for δ from zero to π at $x_c = 0.9999999999\ p.u$

For a typical value of $\delta = 30^\circ = \frac{\pi}{6} rad$, the excitation power P_f is constant at 0.6pu, whereas the reluctance power P_r for some values of x_c is as shown in Table 1.

A cursory glance at Table 1 shows that when the auxiliary winding is on open circuit ($x_c = \infty$) that the operational x_d' / x_q' ratio is low and consequently the output power. When the auxiliary winding is short circuited ($x_c = 0$) there is a small decrement of the operational q-axis reactance (x_q') and a consequent increase in x_d' / x_q' as (x_d') is always constant and hence an increased output power. When a variable capacitance load is introduced into the auxiliary winding, there is a marked decrement of the q-axis reactance (x_q') and a corresponding increase in the output power due to the neutralization of the inductive reactance of the machine by the capacitive load. At $x_c = 1.0 p.u$, the inductive quadrature reactance (x_q') of the machine is completely neutralized by the capacitive reactance leading to infinite x_d' / x_q' ratio and a corresponding infinite output power. If, however, the capacitive reactance exceeds the inductive reactance, the machine operates at leading power factor.

In comparison, the excitation power component is negligibly small (in the operational range $x_c \le 1.0 p.u$) compared to the reluctance power component and hence the overall output power of the machine which is the sum of P_f and P_r is P_r dominant. For $x_c = 1.0 p.u$ the reluctance power P_r (and by implication the total output power, P) will tend to infinity. The steady state limit of the hybrid machine is about $\delta = 45^\circ$ unlike the conventional salient pole synchronous machine. It is seen from the table that for $x_c = 0.99 p.u$ that the reluctance power P_r is 72 times the contribution due to DC excitation P_f. DC excitation would nevertheless have to be required in order that the machine could operate as a standalone generator.

Table 1: Output Power Components of the Hybrid Machine for various values of x_c at Operational Value of $\delta = 30^\circ$ and the percentage contributions of P_r and P_f to the total output power P

Capacitive Reactance x_c **(p.u)**	**Operational** x_d' / x_q' **Ratio for** $k = 3$	**Excitation Power** P_f **(p.u)**	**Reluctance Power** $\lvert P_r \rvert$ **(p.u)**	**Total Output Power** $\lvert P \rvert$ **(p.u)**	% P_f	% P_r
∞	1.50	0.60	0.43	1.03	58.25	41.75
0.00	2.00	0.60	0.87	1.47	40.82	59.18
0.60	2.75	0.60	1.52	2.12	28.30	77.70
0.95	11.50	0.60	9.09	9.69	6.19	93.81
0.99	51.50	0.60	43.73	44.33	1.35	98.65
1.00	∞ (infinity)	0.60	∞ (infinity)	∞ (infinity)	≈ 0.00	≈ 100.00
1.20	-1.00	0.60	1.73	2.33	25.75	74.25
1.40	0.25	0.60	0.65	1.25	48.00	52.00
1.80	0.88	0.60	0.11	0.71	84.51	15.49
2.00	1.00	0.60	0.00	0.60	100.00	0.00

CONCLUSION

In this paper, it is shown that when a cylindrical rotor machine is mechanically coupled to a salient pole machine, with the synchronous reactance x_s of the round rotor machine made equal to the direct axis reactance x_d of the salient pole section (i.e $x_s = x_d$); on the d-axis, the effective d-axis reactance of the machine is $x_d^{'} = 2x_d$ and the effective q-axis reactance is $x_q^{'} = x_d + x_q$, giving a ratio $k^{'} = \frac{x_d^{'}}{x_q^{'}} = \frac{2x_d}{x_d + x_q} = \frac{2k}{k+1}$ where $k = \frac{x_d}{x_q}$.

For a fixed machine geometry ($k = \frac{x_d}{x_q}$), the effective saliency factor, $k^{'}$, can be raised if a second set of stator (auxiliary) windings whose coil sides are displaced 180º electrical (transposed) between the two sections of the machine are installed and feed a balanced variable capacitance load. By varying the capacitance loading, $x_q^{'}$ will vary from zero to infinity while $x_d^{'}$ remains unaffected and a variable $\frac{x_d^{'}}{x_q^{'}}$ ratio which is directly proportional to the reluctance power component is achieved at good power factors and normal currents.

The new hybrid synchronous machine will have a higher output power to size ratio compared to the conventional salient pole synchronous machine, because the excitation power has a factor of 2 which compensates for coupling two machines. Furthermore, the reluctance component is very large and far exceeds the excitation component.

Constructionally, the stator of the new hybrid synchronous machine will have deeper slots in order to accommodate the two sets of windings (main and auxiliary). The output voltage of the auxiliary winding could be sensed and used in the control of the mechanical governing or adjustment of the field excitation when there is need to improve stability of operation.

The machine is expected to have a relatively better asynchronous run-up characteristic than a conventional salient pole synchronous machine because the capacitance of the auxiliary winding can be tuned such that the difference between the effective rotor d-axis reactance $x_d^{'}$ and the effective quadrature axis reactance $x_q^{'}$ will not be so pronounced. The pull-in torque, as a ratio of the pull-out torque will therefore be greater. The stability of the machine on load can be raised by increasing the auxiliary winding capacitance load after the machine has been brought to synchronism.

The new hybrid synchronous machine is being studied for bulk power supply in view of its ultra-high power output potential.

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