Field Weakening in Buried Permanent Magnet AC Motor Drives

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Abstract—**The usual uncoupled $d - q$ model of salient pole synchronous machines (Park's model) may be insufficient for accurate modeling of buried magnet permanent magnet machines. The addition of a nonbilateral coupling between the direct and quadrature axis equivalent circuits is shown to improve the steady-state model greatly. The cross coupling reactance has important implications in improving operation in the constant horsepower mode. In particular, it is demonstrated that the cross coupling term acts to reduce the effective internal voltage so that some field weakening can be achieved. The results should be useful in permanent magnet machine design for variable speed drive applications.**

INTRODUCTION

INDUCTION and synchronous motor static drives are presently in an advanced stage of development. In contrast, permanent magnetic motor drives have only recently begun active development. A primary motivating factor for this development is the interest in high-performance high-efficiency servomotor drives particularly for the machine tool industry. One of the primary limiting features of permanent magnet motor drives is the lack of excitation control. As a result, the internal EMF of the motor rises in proportion to the motor speed. Such behavior is desirable in the so-called constant torque range, since it is consistent with the constant volts per hertz control which is normally used during this mode of operation. However, when the speed continues to rise, the voltage limit of the associated frequency converter is reached. The motor is then said to enter the field weakening or constant horsepower model of operation. The internal voltage must now be adjusted to be compatible with the applied converter voltage. However, since the permanent magnets inherently provide the equivalent of a constant field excitation, the internal EMF of the machine continues to increase as speed increases. As a result, the motor power factor becomes leading and the current to be commutated by the inverter continues to increase as speed increases. In the case of a permanent magnet machine fed by a current source inverter, voltage stresses on the converter semiconductors also continue to rise, since the commutation spike increases with both motor internal voltage and dc link current.

It has recently been reported [1] that the expected performance in the high-speed region is not always observed. In the case of machines of the so-called "buried magnet" type, the variations of the current and power factor are much smaller than expected on the basis of the conventional two-axis synchronous machine theory. The speed range above base speed for constant power operation is larger than the anticipated speed range before the torque decreases excessively. These special features are analyzed in this paper.

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NEW MODEL FOR BURIED PERMANENT MAGNET MOTORS

Recently, it has been suggested that the usual uncoupled $d - q$ model of salient pole synchronous machines (Park's model) may be insufficient for accurate modeling of buried magnet permanent magnet machines [1]. In particular, if the conventional model is used, the direct axis synchronous reactance X_d varies in an erratic manner. For certain values of load, the value of X_d must even be negative if the equivalent circuit is expected to predict the observed values of direct and quadrature axes current. The presence of permanent magnets in the motor prevents use of most of the conventional parameter measurement methods. A simple way to approach the problem is to measure and identify the curves, $V_d = f(I_q)$ and $V_q = f(I_d)$. The results for the q axis are shown in Fig. 1 for fixed speed. Since the equation of the equivalent circuit of the q axis is $V_q = E + X_d I_d$, all curves should cross at the same point for $I_d = 0$. The particular curve pattern of Fig. 1 seems to be a characteristic of buried permanent magnet machines [1]. It was observed that the distance between two curves for $I_d = 0$ is proportional to I_q. The addition of a coupling term between the direct and quadrature axis is an obvious remedy, and the mathematical model of the permanent magnet machine is then rewritten as

$$V_d = X_q I_q$$

$$V_q = E + X_d I_d + X_{qd} I_q.$$

If P is the number of poles and ω is the operating frequency used to define the $d - q$ reactances, then the torque equation becomes

$$T = \frac{3P}{4\omega}\left[\frac{VE}{X_d}\sin\delta + \frac{V^2(X_d - X_q)}{2X_d X_q}\sin 2\delta + \frac{V^2 X_{qd}}{X_d X_q}\sin^2\delta\right].$$

The first two terms can readily be recognized as the magnet torque term and the reluctance torque term. The third term represents the contribution of the cross coupling, which

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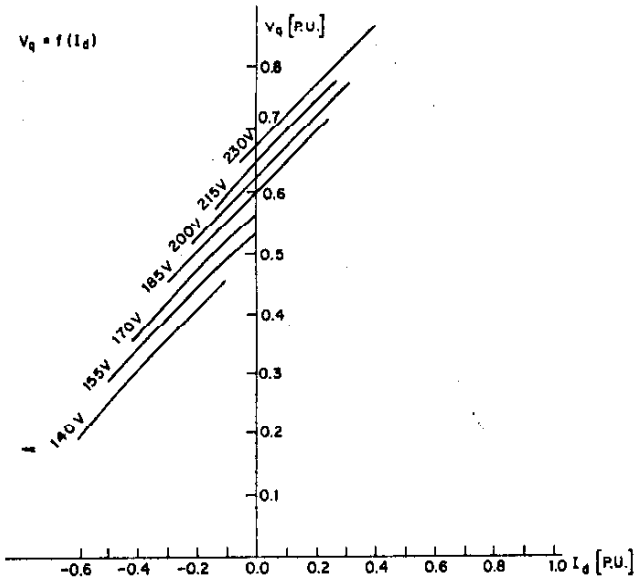

Fig. 1. q axis measurements: $V_q = f(I_d)$.

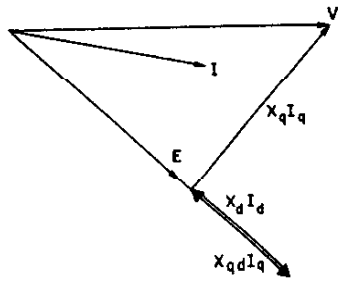

Fig. 2. Phasor diagram for new model.

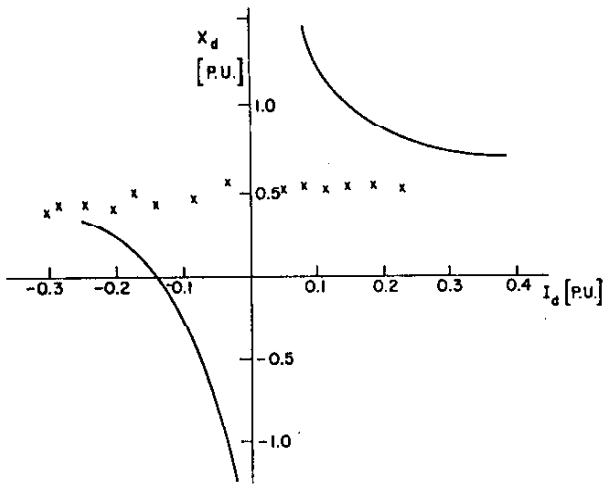

Fig. 3. Measured values for X_d. Solid lines are for conventional model, crosses are for new model.

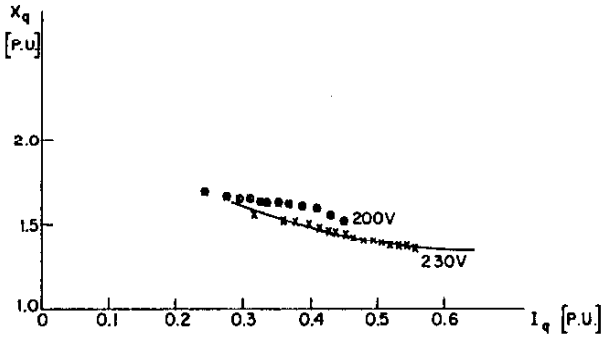

Fig. 4. Measured values of X_d.

depends on $\sin^2 \delta$ and reaches a maximum for the same value of δ as the magnet torque term.

The phasor diagram including the cross coupling term is shown in Fig. 2. Notice that the additional term modifies the internal voltage with respect to I_q in the same manner as a change in field current. In the case of buried magnet machines, the path for the q axis flux usually presents a lower reluctance than the d axis path where the magnets placed in the d axis have nearly the same reluctance as air. Consequently, the value of the reactance X_q will be larger than the value of the reactance X_d. The reluctance torque term will be negative, and the no-load operating point may occur at a value of δ different than $\delta = 0$.

Using the new model and the measured values of V_q, V_d, I_q, and I_d, values of X_d, X_q, and X_{qd} can be calculated. The results of such measurements are shown in Fig. 3. The continuous line shows the values of X_d needed to represent the characteristics of the machine with the classical $d - q$ model. The crosses show the computed values of X_d using the new model. There is almost no variation for these new values, which is consistent with the fact that the magnets form most of the flux path in the d axis. However, saturation can be observed in the q axis as shown in Fig. 4. The cross coupling reactance X_{qd} was observed to have almost no dependence on I_q or I_d. There is, however, some dependence on flux levels as will be explained later.

General Characteristics of the Machine

When considering the characteristics of a drive, two main operating speed ranges are distinguished—the constant torque region below base speed and the constant horsepower region above base speed. Figs. 5–8 illustrate the influence of the additional term in both cases for a simple machine without saliency. Above base speed, the voltage is usually kept constant at its rate value, limited by the rating of the converter. The current is limited by the rating of the machine. However, for the sake of comparison with dc machines, this mode of operation is often considered as a constant power region or field weakening region.

Operation Above Base Speed

For constant power operation, Fig. 5 shows a comparison between two permanent magnet machines—one incorporating the cross coupling effect and one without the effect. Parameters are chosen so that, at base speed and rated torque, both machines have identical characteristics. The two conditions in Fig. 5 represent operation at speeds of 1.0 pu and 2.0 pu. E_1 is the inner voltage for the conventional machine model for 1.0-pu speed. E_1' is the inner voltage for the machine with a cross coupling term. The difference is produced by the cross coupling term.

At 2.0 pu speed, E_1 is doubled to E_2. The voltage and power

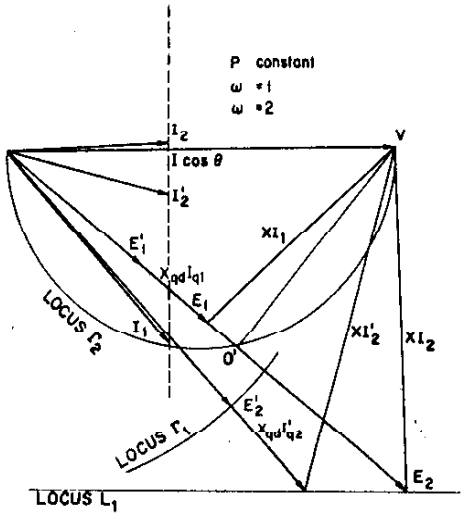

Fig. 5. Operation above base speed. P = constant.

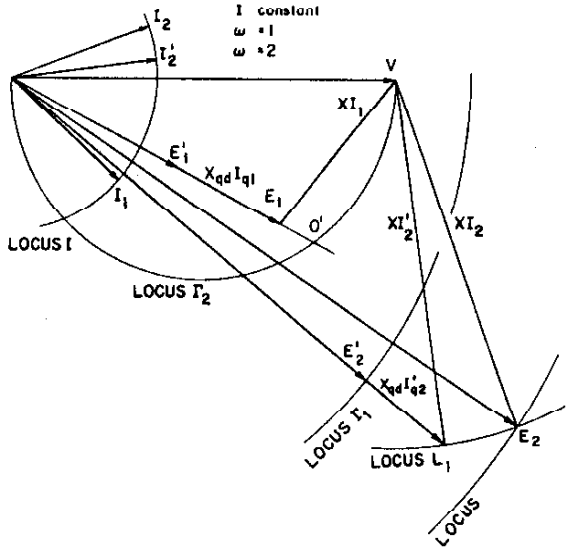

Fig. 6. Operation above base speed. I = constant.

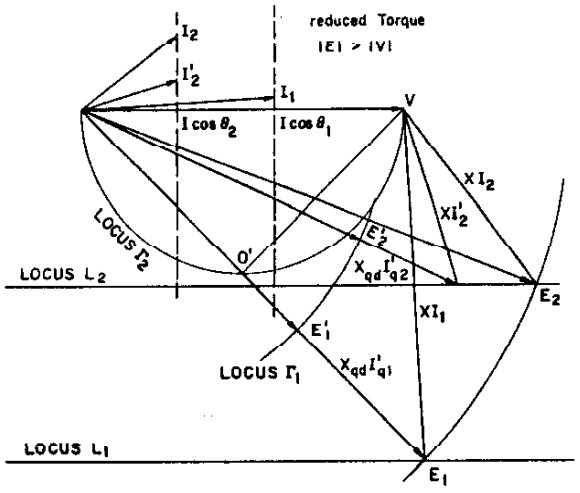

Fig. 7. Operation below base speed, overexcited operation.

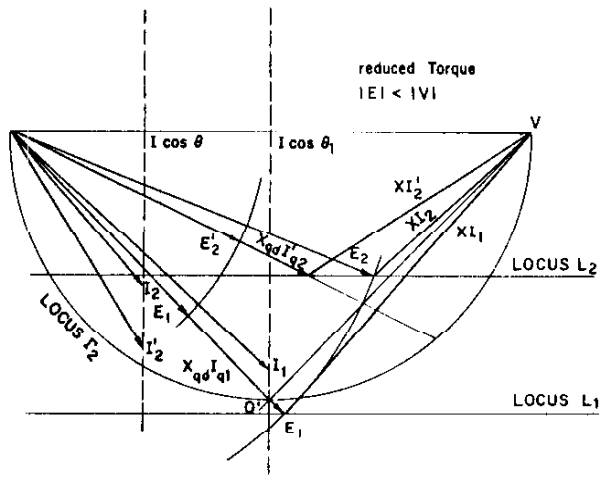

Fig. 8. Operation below base speed, underexcited operation.

are kept constant, so that $I \cos \theta$ and $XI \cos \theta$ are also constant. This last value gives the locus L_1, the locus of the inner voltage of the machine for 2.0-pu speed. From E_2 and V, the vector XI_2 is deduced and also the vector I_2 which is the current of the machine without cross coupling effect at 2.0-pu speed. The solution of the machine with the cross coupling term is established as follows: the distance VO' is equal to XI_q, the distance $E_1'E_1$ is equal to $X_{qd}I_q$. The ratio of these two distances will be a constant depending on the machine. Notice that for every load condition, the point O' will be on the circle Γ_2. The locus Γ_1 is the locus of the inner voltage at 2.0-pu speed (caused by the magnets). The difference between Γ_1 and L_1 will be provided by the cross coupling term.

The ratio defined earlier allows us to find the solution presented in Fig. 5, which locates XI_2' and finally I_2', the current of the machine with cross coupling effect at 2.0-pu speed. The solution I_2' lags the solution I_2, and this will always be the case. Depending on the respective values of E, V, and of the parameters and operating point, I_2' will be larger or smaller than I_2. If speed increases, both currents will become leading, and I' will be smaller than I.

A similar case is shown in Fig. 6, but in this case, the voltage and current are kept constant. The same construction leads to the solution for I_2 (machine without cross coupling) and I_2 (machine with cross coupling). The only differences are due to the fact that in this case the current is kept constant (locus I) so that locus L_1 becomes a circle centered at V ($|XI|$ constant). The phasor diagram shows both machines with leading power factor. The power delivered by the machine with cross coupling will be, in this case, larger.

The influence of cross coupling in the speed range above base speed can easily be understood by considering the power equation. For smooth air gap machines $P = EI_q$ is, in this case, the complete power expression. With rising speed, the counterelectromotive force (CEMF) E rises. The power P is kept constant which means that I_q decreases proportionally. Since the inner voltage of the machine with cross coupling is partly due to the magnets and partly proportional to I_q, it will not rise as much as if it were entirely due to the magnets. The effect will be field weakening, just as if the field had been modified.

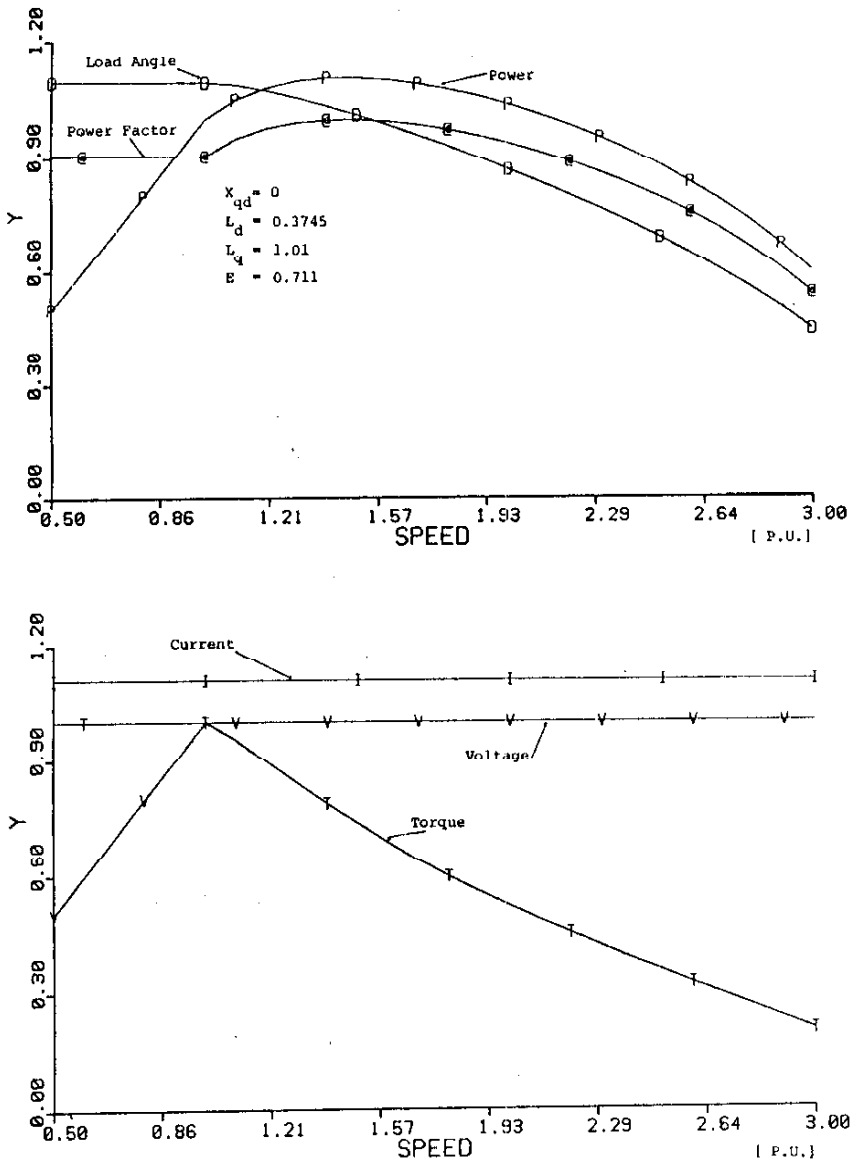

Fig. 9. Salient pole machine characteristics as function of speed. Machine without cross coupling, constant current operation.

Operation Below Base Speed

If the speed is kept constant and the torque reduced, the effect of the cross coupling will depend on the relative values of V and E. Fig. 7 shows the behavior at half-rated torque for the same two machines as in the previous section in the case of overexcited operation, $|E| > |V|$. Locus L_2 is the locus of E for reduced torque where $IX \cos \theta$ is reduced by a factor of two. The currents in this case will be leading, and the cross coupling will have an advantageous effect. Fig. 8 shows the same characteristics but for the case of two underexcited machines in which $|E| < |V|$. In this case, the current I_2', lagging the current I_2, will be larger.

These factors can also be explained by the power equation $P = EI_q$. For a fixed speed, E remains constant, and as the torque and hence the power is reduced, I_q is reduced. As a consequence, the total inner voltage of the machine with cross coupling will be reduced, and I_q will be larger than for the machine without cross coupling. I' will lag I and, depending on parameters and operating conditions, can be larger or smaller in amplitude than for a machine without cross coupling.

The phasor diagrams clearly show that for a smooth air gap machine, the current I' of a machine with cross coupling will always lag the current I of a machine without cross coupling with advantageous consequences above base speed and some disadvantages below base speed.

Performance Curves—Advantages of Cross Coupling

In general, machines have different reactances in the d and q axes. The diagrams and equations become more complex and computer calculation becomes a necessity. Figs. 9–12 show salient pole machine characteristics as a function of the speed. In Fig. 9, the current is kept constant and the machine has no cross coupling. Fig. 10 shows the same characteristics for a machine with cross coupling. These curves have been calculated using the measured parameters of a 2-hp buried permanent magnet machine (Appendix). It is important to

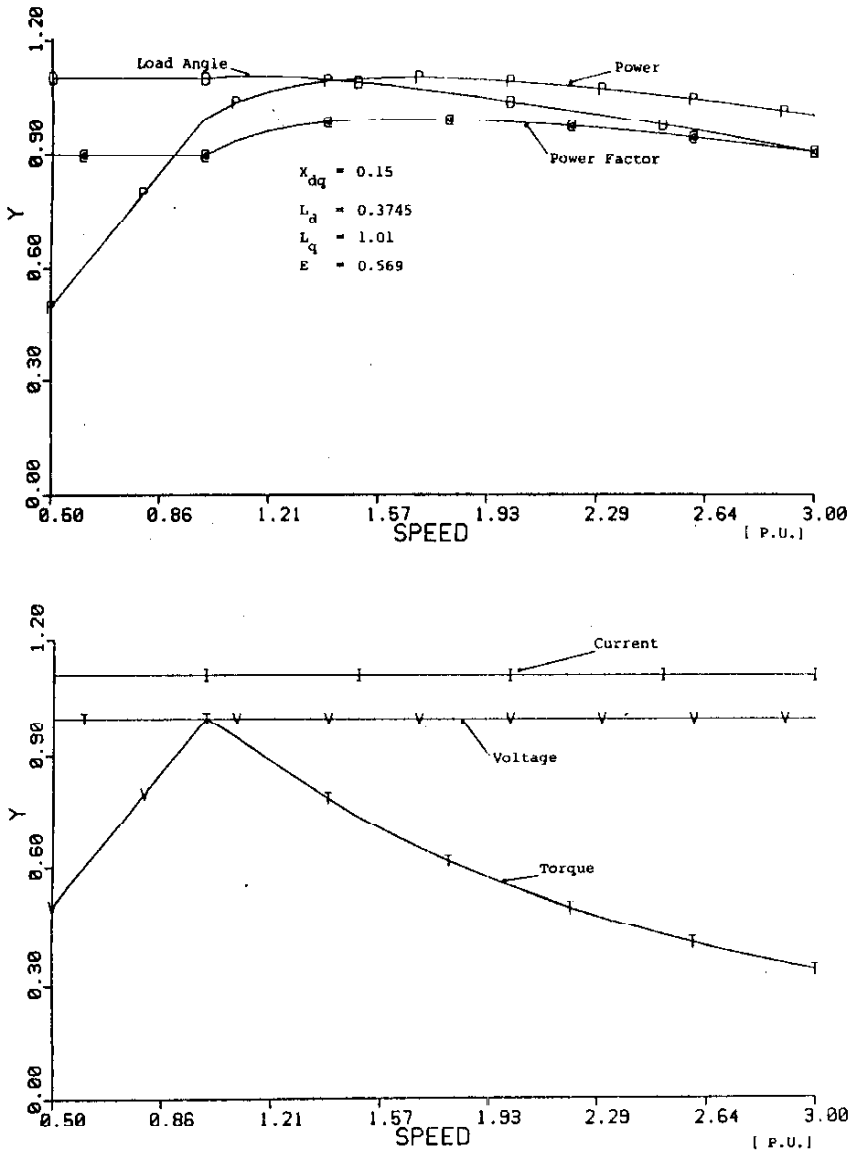

Fig. 10. Salient pole machine characteristics as function of speed. Machine with cross coupling, constant current operation.

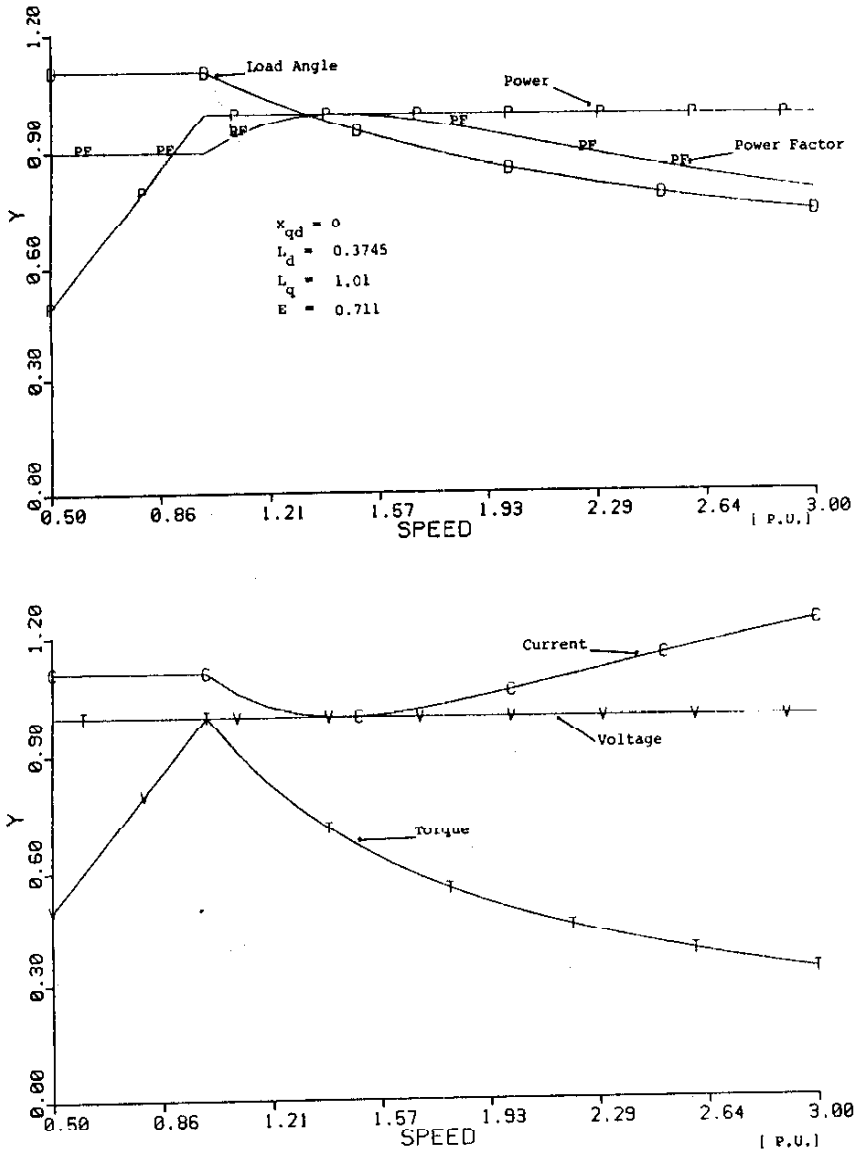

Fig. 11. Salient pole machine characteristics as function of speed. Machine without cross coupling, constant power operation.

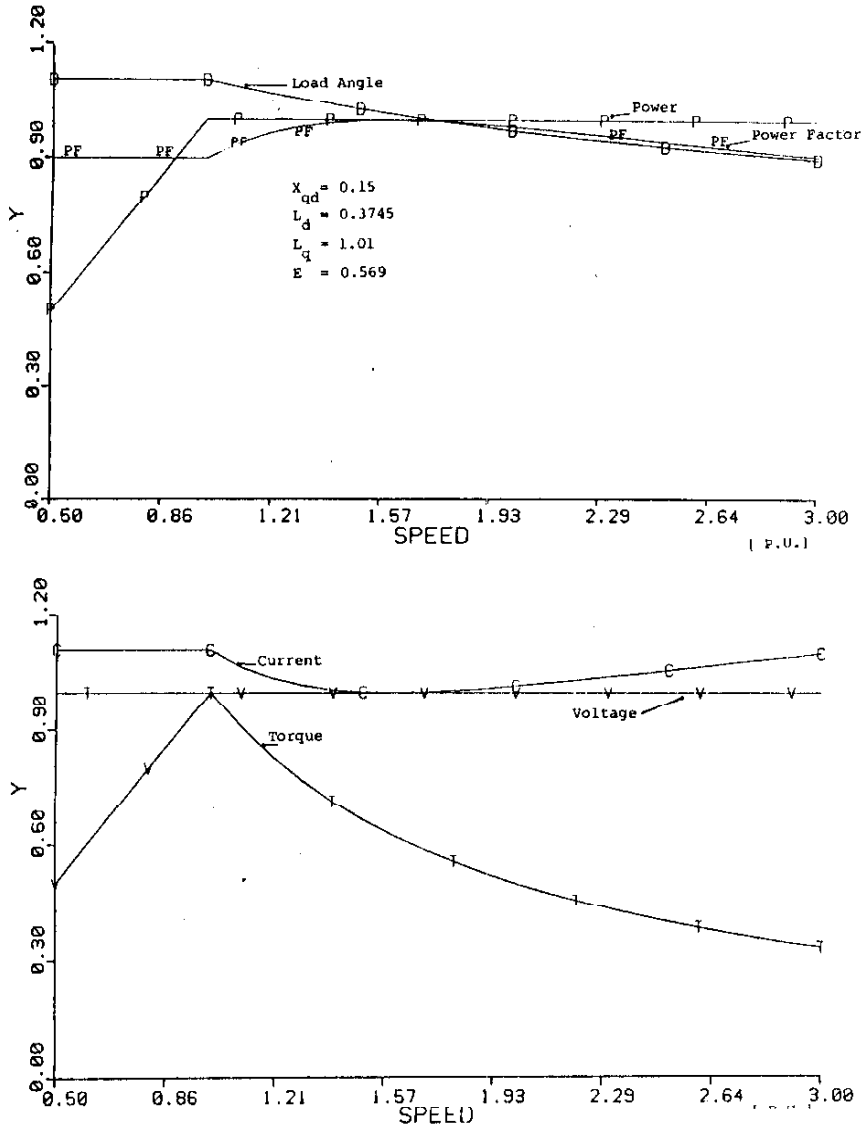

Fig. 12. Salient pole machine characteristics as function of speed. Machine with cross coupling, constant power operation.

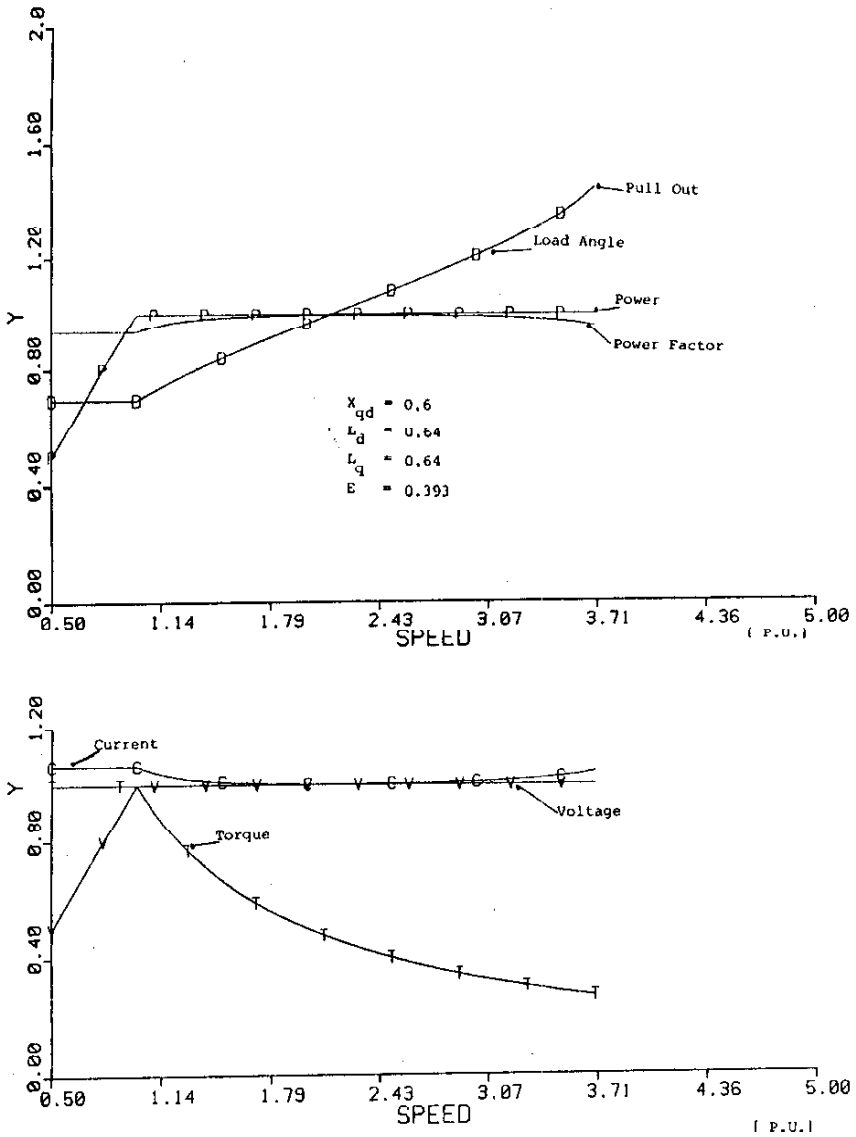

Fig. 13. Characteristics of machine with very large X_{qd}/X_q ratio.

observe that the machine with cross coupling delivers an almost constant power, for constant current, while the power delivered by the machine without cross coupling decreases rapidly. The useful speed range is in this case noticeably larger than expected from a permanent magnet machine. The same comparison is done in Figs. 11 and 12, but in this case the power is kept constant above base speed. Again, this cross coupling effect is seen to be advantageous with a much slower rise of the current as speed increases.

Disadvantages of Cross Coupling

It is important to note that the cross coupling effect is not always advantageous. As shown earlier, such coupling can cause higher currents at low torque and also shorten the overall useable speed range. Fig. 13 shows the computed characteristics of a hypothetical machine with very large X_{qd}/X_q ratio. Such a machine will behave fairly well with constant power until 4-pu speed, where pullout occurs. The same problem occurs for machines with usual values of X_{qd} but at much higher speeds.

INFLUENCE OF CROSS COUPLING AS VIEWED FROM THE AIR GAP VOLTAGE—ORIGIN OF THE PHENOMENON

In order to understand the mechanism behind the cross coupling phenomenon, a full pitch search coil was placed in the stator slots of the machine described in the Appendix. The coil was used to provide a picture of the flux density along the air gap. Waveforms of the voltage at the terminals of the coil are shown in Fig. 14; trace A represents the waveform when the machine is driven as a generator on open circuit. Traces B and C show the waveforms when the machine is run with almost no q axis current or no d axis current, respectively. Trace A shows a square wave representing the flux due to the magnets only. The tilt in the waveform is apparently due to eddy currents and disappears at low speeds. Traces B and C

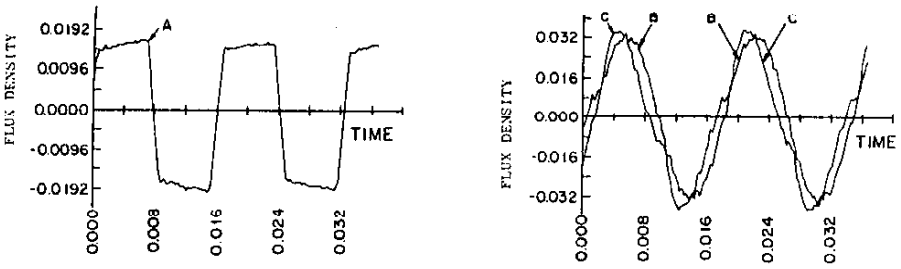

Fig. 14. Measured air gap voltage waveforms. Trace A: open circuit operation. Trace B: No q axis current. Trace C: no d axis current.

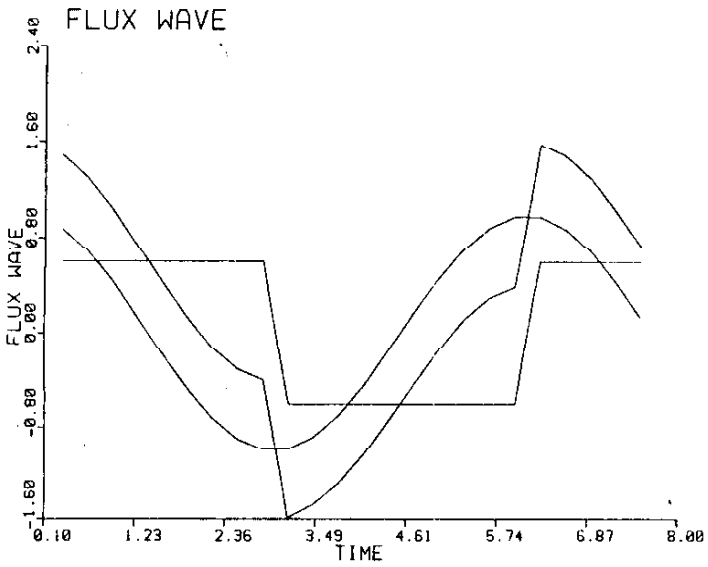

Fig. 15. How superposition of square wave and sine wave approximates results of Fig. 14, trace C.

show the additional influences of the sinusoidal stator MMF. These curves can be approached theoretically by the superposition of the square wave and a sine wave phase shifted by the proper angle. This theoretical result is shown in Fig. 15.

The influence of the cross coupling factor on the amplitude of the air-gap flux can be shown as follows. Knowing the values of the parameters X_d, X_q, and X_{qd} and having measured I, V, δ, and PF, it is possible to carry out the following calculations, using the values of the fundamental components.

Classical Model:

a) $X_dI_d = 0.809$
$V_q = E + X_dI_d = 2.090$
$X_qI_q = 0.8816$
$V = 3.04 \cos(\omega t - 16.8°)$.

b) $X_dI_d = 0.1037$
$V_q = E + X_dI_d = 2.2037$
$X_qI_q = 1.811$
$V = 2.85 \cos(\omega t - 39.4°)$.

New Model:

a) $X_dI_d = 0.809$
$X_{qd}I_q = 0.131$
$V_q = E + X_dI_d + X_{qd}I_q = 3.04$
$X_qI_q = 0.8816$
$V = 3.16 \cos(\omega t - 16.2°)$.

b) $X_dI_d = 0.1037$
$X_{qd}I_q = 0.269$
$V_q - E + X_dI_d + X_{qd}I_q = 2.472$
$X_qI_q = 1.811$
$V = 3.06 \cos(\omega t - 36°)$.

The numerical values shown are scaled values obtained from the measurements and are for purposes of comparison only. The applied voltage being the same in both cases (230 V line to line), the fundamentals of the two waveforms should be equal. In the case where X_{qd} is not used (classical model), it can be noted that a substantial difference exists between the values calculated in the two cases. This difference is significantly reduced when the complete model is used. The calculated results are consistent with the value provided by the measured waveforms.

It is reasonable to think of the cross coupling effects as a result of the redistribution of the flux in the air gap. This redistribution occurs because the magnets are buried in the rotor, behind a certain mass of iron which the flux has to cross before reaching the air gap. Saturation of the iron in this pole piece above the magnet is the cause of the redistribution of flux. As might be anticipated, the cross coupling factor varies with the flux density. Fig. 16 presents the measured variation as a function of the air gap voltage.

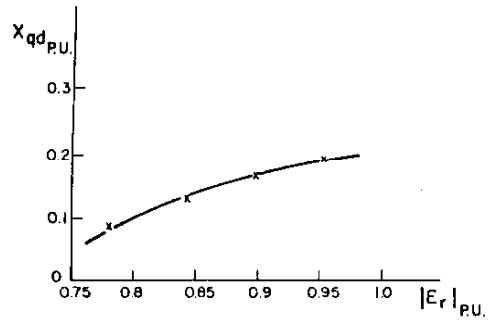

Fig. 16. Cross coupling factor as function of air gap voltage.

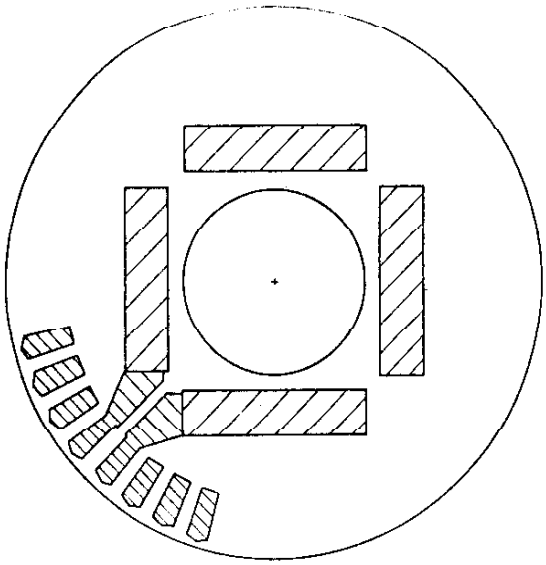

Fig. 17. Schematic of magnet arrangement in rotor of machine.

CONCLUSION

A new machine model involving a cross coupling $X_{qd}I_q$ voltage drop in the q axis is presented. This effect is shown to have an important field weakening action in the constant horsepower region. This term in the $d - q$ model has been shown to be related to a redistribution of the rotor (magnet) flux, resulting from q axis saturation.

APPENDIX

The test motor has the following nameplate data: Reliance Electric Company, 2 hp, 115/230 V, 10.6/5.13 A, 60 Hz, 1800 r/min. Fig. 17 shows a schematic of the magnet arrangement in the rotor of the machine.

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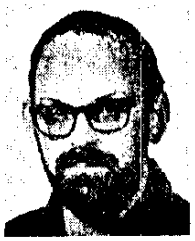

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