Induction Machine Efficiency Improvement by Means of Voltage Control

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ABSTRACT

Minimum input power and maximum efficiency occur at a characteristic optimum slip value which can be calculated for any induction motor. Efficiency is independent of output power when a sinusoidal voltage controller reduces the voltage so as to maintain the characteristic slip as load changes. The solutions obtained with a practical solid state controller including saturation effects do not appear to significantly change these results.

INTRODUCTION

Variable voltage operation of an induction machine to improve the part load efficiency is receiving considerable attention as an energy conservation measure [1-4]. Although the concept is limited to applications where the motor duty cycle includes substantial periods of operation at light load, there are numerous industrial and commercial applications which can produce substantial energy savings. While both fixed frequency and variable frequency drives can exploit voltage control to improve performance, this paper is concerned primarily with fixed frequency drives.

The goal of this paper is to outline the basic concepts involved in efficiency improvement by voltage control, to identify the basic limitations of the approach, to examine the influence of the non sinusoidal excitation resulting from use of phase back thyristors to control voltage and to consider some of the effects of the saturation non-linearity of the machine.

BASIC CONCEPT OF VOLTAGE CONTROL FOR EFFICIENCY IMPROVEMENT

In essence, efficiency improvement by voltage control is achieved by reducing the applied voltage when the torque requirement of the load can be met with less than full motor flux. The reduced motor flux results in reduced core loss and reduced stator I^2R loss because the magnetizing component of stator current is reduced. However, the reduced flux also requires a larger slip to produce the required torque compared to operation at full rated flux. The slip dependent rotor loss and load component of the stator I^2R loss are hence increased. With proper regulation of the applied voltage the total losses can be reduced for most part load operating conditions. Clearly, too large a voltage reduction will create unacceptably large values of slip, high rotor and stator I^2R losses and a net increase in total motor losses.

The nature of the improvement which is attainable can be illustrated by considering an idealized situation where motor parameter variations are neglected and the voltage controller is assumed to produce sinusoidal excitation at all voltage levels. Under these assumptions the conventional induction machine equivalent circuit of Fig. 1 applies and optimal voltage control strategies are easily determined.

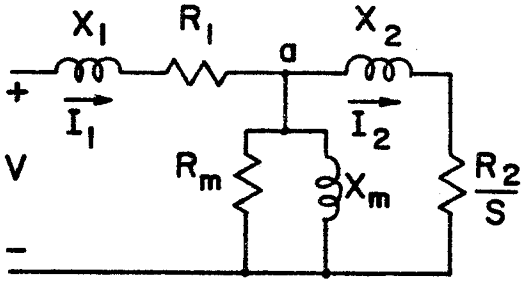

Fig. 1 Per Phase Induction Motor Equivalent Circuit

As is well known, normal constant voltage operation of an induction machine results in the motor slip varying in proportion to the required load torque. Generally, the load torque is considered as the independent variable and slip, power factor, efficiency etc. are considered as the dependendent variables. However, it is clear that the only variable quantity in the circuit of Fig. 1 is the slip and hence, the input impedance, power factor and efficiency may properly be considered as functions of slip. With this point of view it is clear that there is an optimal slip which yields maximum efficiency and that this slip value and the maximum efficiency are independent of torque or voltage. Thus, optimal (maximum efficiency) operation for any attainable torque is at the specific voltage which causes operation at the fixed value of slip which yields maximum efficiency.

The situation is illustrated in Fig. 2 for a typical small induction machine. The solid line represents the efficiency curve for normal constant voltage operation illustrating the typical drop in efficiency as the load is reduced. The dashed line of constant efficiency represents the performance if the voltage is varied to hold the slip constant at the value which yields maximum efficiency. For the machine of Fig. 2 the required slip value is 0.024; slightly below the rated slip of 0.0255. The area to the left of the constant voltage efficiency curve represents a measure of the improvement attainable by controlling the voltage. Clearly, one basic requirement is that a substantial portion of the load cycle must consist of load levels where there is a significant efficiency improvement. For the machine of Fig. 2 this requires load torques below about 30% to attain at least a 5 point efficiency improvement.

The influence of machine size on performance is illustrated in Fig. 3 which is drawn for a relatively large induction motor. Note that in this case the area available for efficiency improvement is much smaller since the voltage efficiency curve is flatter. The improvement in efficiency is thus smaller at all loads and hence significant improvement in efficiency requires operation at even lighter loads than the smaller machine of Fig. 2. However, even though the efficiency improvement is small, the energy savings can be large because of the higher power level of this larger machine.

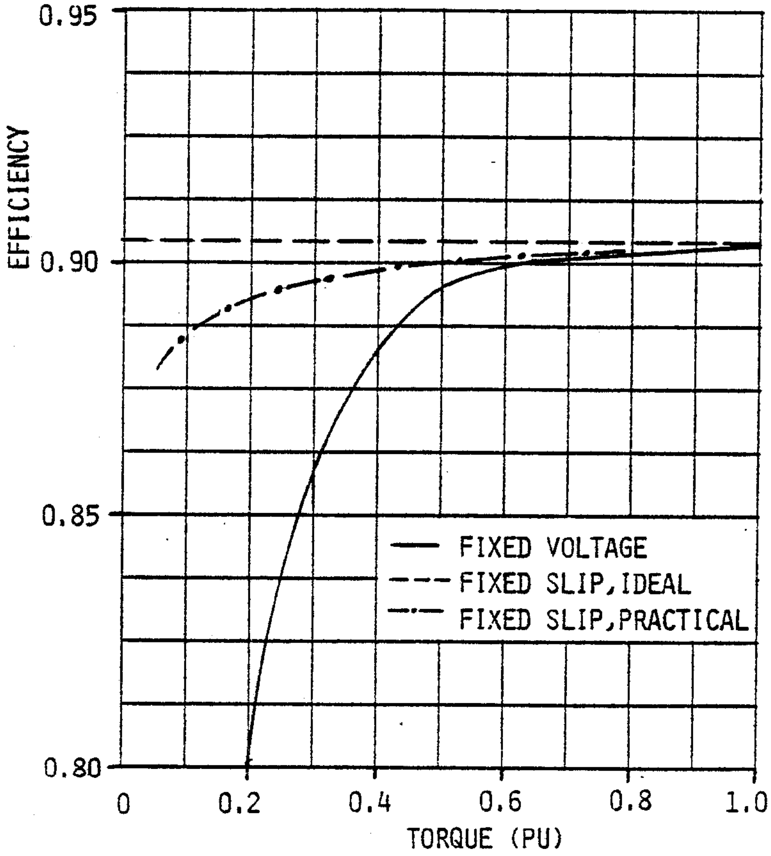

Fig. 2 Efficiency vs. Torque for 7 1/2 HP Machine Operating at Fixed Voltage and with Fixed Slip.

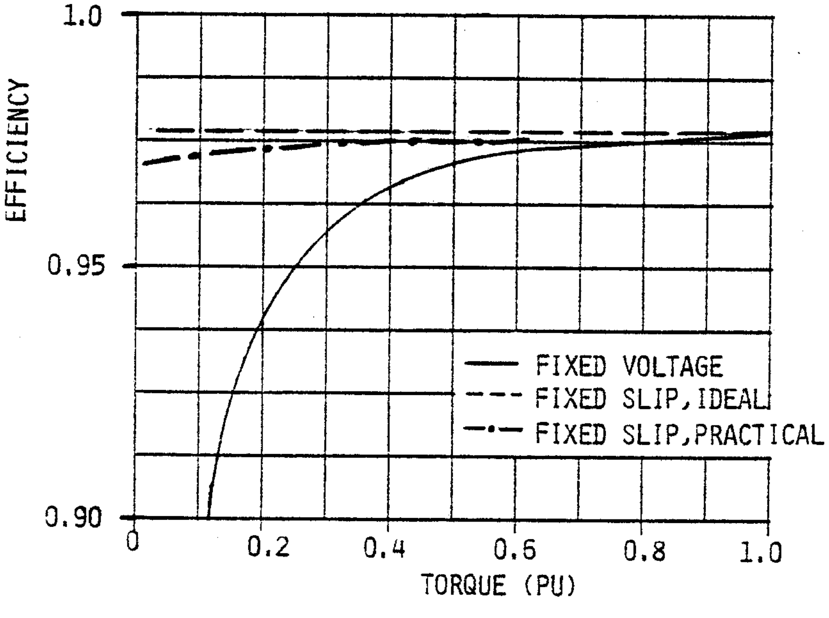

Fig. 3 Efficiency vs. Torque for 1000 HP Machine Operating at Fixed Voltage and with Fixed Slip.

It is interesting to note that operation at a fixed slip also corresponds to operation with constant power factor. This characteristic is the basis of the Nola controller of reference 1. Each machine clearly has a specific power factor corresponding to maximum efficiency, however, this power factor also occurs for some larger values of slip, usually somewhat beyond rated load. Thus, using power factor to locate the optimal efficiency has the disadvantage of yielding two values of slip and care must be exercised to assure that operation is confined to the proper value.

The use of a controller which minimizes the stator current has also been considered as a means of controlling voltage to improve efficiency. It can be shown [5], however, that this type of control results in too small a value of slip and does not yield optimal performance. The slip values corresponding to minimum current (S_I) and to maximum efficiency (S_{EF}) are given by

$$S_I = \frac{R_2}{X_m+X_2} \qquad S_{EF} = \frac{R_2}{X_m+X_2}\sqrt{\frac{1+A}{1+R_2/R_1}}$$

where

$$A = X_m^2/(R_1 R_m)$$

It is easily shown that $S_I < S_{EF}$ for typical machines.

INFLUENCE OF PHASE BACK VOLTAGE CONTROL

Thusfar, it has been assumed that voltage reduction has been obtained by an ideal adjustable amplitude sine wave supply such as an autotransformer. In practice, cost considerations dictate the use of a solid state voltage controller such as that shown in Fig. 4 in which inverse-parallel thyristors are connected in series with motor lines. Voltage control can now be implemented by delaying the conduction of the thyristors with respect to the uncontrolled current zero crossing point and hence interrupting the flow of current in the motor lines. Although the motor phase voltages are progressively reduced as the delay in the firing point of thyristors increases, the voltages also become increasingly distorted. The harmonics contained in the motor voltage waveform produce additional losses which are not present in simple sine wave control. These losses offset somewhat the gain in efficiency achieved by reducing the fundamental component of voltage.

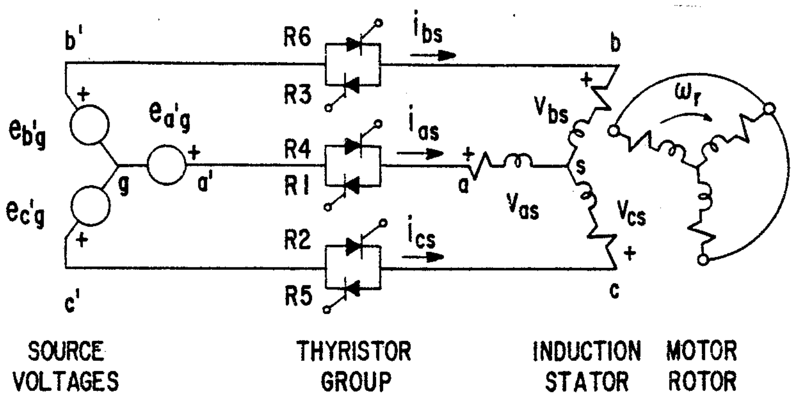

Fig. 4 Practical Voltage Controller Using Inverse-Parallel Connected Thyristors.

In general, the presence of the solid state controller considerably complicates the solution of the motor currents since the problem to be solved involves mixed constraints. In this case the state variable approach has been found to be the most convenient means for obtaining a solution [6]. The dot-dash lines in Figs.2 and 3 show the motor efficiency resulting from the use of a practical phase back controller computed by the state variable technique of reference 6. Note the deterioration in the efficiency for both the low and high horsepower cases. It is interesting to mention that even though the machine currents and voltages depart significantly from sine waves, maximum efficiency for all load conditions is still realized at one value of motor slip.

INFLUENCE OF MACHINE NON-LINEARITY

The results presented in the previous sections have assumed the set of fixed parameters given in the Appendix. These results will be modified by parameter changes associated with operation at the different flux levels created by changing the motor voltage. The major changes are in excitation parameters X_m and R_m. To evaluate the influence of these parameter changes, a series of parameter and performance tests were run on a 7.5 HP machine similar to that of the Appendix. Figure 5 illustrates the variation of the parameters X_m and R_m. Although the curve of X_m vs. voltage is typical, the curve for R_m is somewhat unexpected since the measurements indicate a peaking in this quantity near 80% rated voltage. However, the decrease in R_m for large values of voltage has been observed in the past [7] and is probably caused by the increased eddy currents resulting from the flux wave tending to become flat-topped at higher saturation levels.

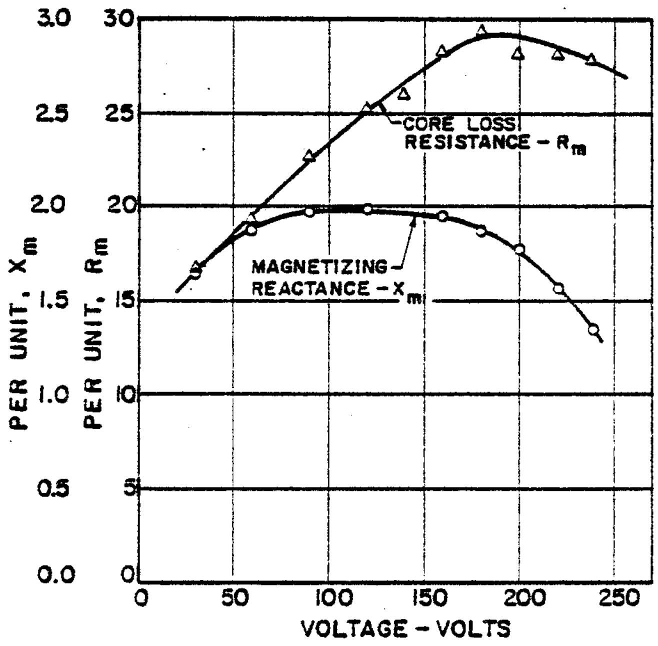

Fig. 5 Variation in X_m and R_m with Changes in Line-to-Line Voltage

The parameter variations caused by saturation result in a machine input impedance which depends on voltage as well as on the slip. As a result, constant slip operation no longer results in constant efficiency and power factor. Figure 6 illustrates the non-linear behavior for the same machine as in Fig. 2. The modified (calculated) curves of Fig. 6 were obtained by using the measured curves of Fig. 5 to describe the per unit variation of R_m and X_m for the induction machine of Fig. 2. Since parameters are assumed to change, maximum efficiency cannot now be achieved by operation at a single value of slip. In this case the optimum value of slip for each load condition is also plotted in Fig. 6. For the particular machine illustrated in Figs. 2 and 6 the change in optimal slip caused by saturation is small and operation at a fixed value of slip yields almost the same performance as the optimal case.

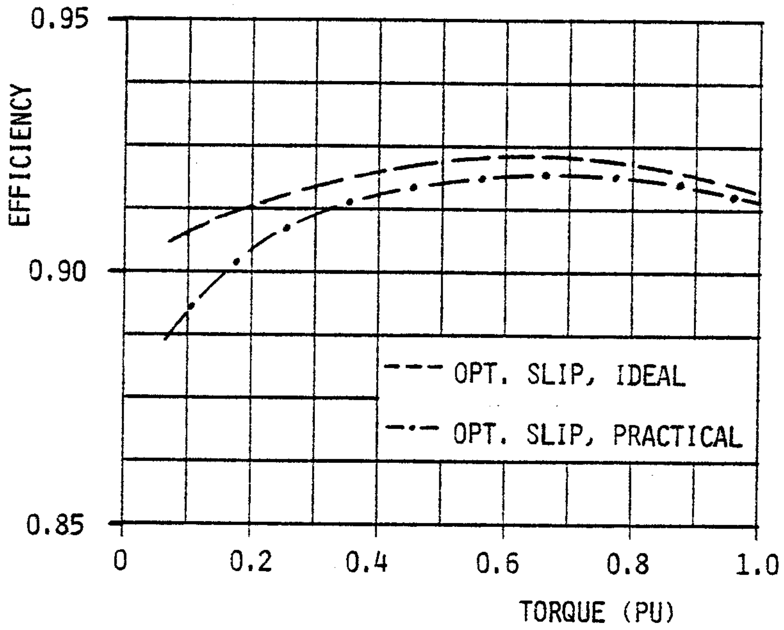

Fig. 6 Optimal Efficiency vs. Torque for Ideal and Practical Voltage Controller Including Effects of R_m and X_m Variation.

Comparing the dashed curve of Fig. 2 to the dashed efficiency curve of Fig. 6 reveals that efficiency is somewhat better in the non-linear case for torques between 0.9 and 0.4 but becomes poorer below 0.4 per unit torque. The initial increase in efficiency as the torque decreases is a result of the greater than linear decrease in magnetizing current caused by the increase in X_m which is associated with the lower stator voltage. At lower values of torque, the decrease in both X_m and R_m at low voltages overcomes this effect and both efficiency and power factor drop off to values below the constant values of the linear case. Comparing the dot-dash efficiency curve of Fig. 7 to the corresponding dot-dash curve of Fig. 2 shows the effect of the same parameter variation for the case of a practical solid state controller. It can be noted that the effect is again similar with the efficiency first increasing and then decreasing as torque and hence stator voltage are reduced.

Although this study has indicated that optimum efficiency is best obtained by operating at a constant slip or rotor speed, feedback control of these variables to the proper degree of accuracy is difficult and expensive. Figure 7 shows the variation of two other useful parameters corresponding to the optimum efficiency curve for the practical solid state controller of Fig. 6 (dot-dash line). The angle ϕ is the delay angle or phase delay in degrees that the current in a given phase is held at zero before triggering the next successive thyristor.

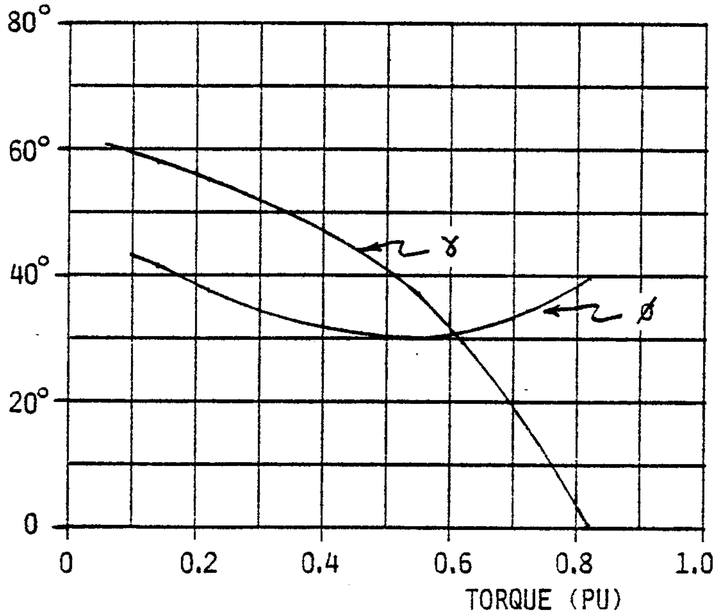

Fig. 7 Delay Angle ϕ and Holdoff Angle γ for Operation at Optimal Efficiency Using Practical Voltage Controller.

CONCLUSIONS

Part load efficiency improvement by controlling stator voltage can be effectively examined by considering slip as the controlled quantity. The linear machine serves as an important initial case and verifies that best efficiency is maintained by keeping slip constant. Although saturation of the machine causes a reduction in efficiency, the slip frequency for the best efficiency at each load torque does not change appreciably to warrant altering the constant slip condition. In addition, use of a thyristor voltage controller in place of an ideal sine wave supply also reduces the efficiency gain but again does not substantially affect the constant slip algorithm.

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APPENDIX

Per Unit Parameters of 7 1/2 and 1000 HP Machines

7 1/2 HP Machine	$R_1 = 0.02$	$X_1 = 0.1$
	$R_2 = 0.020$	$X_2 = 0.1$
	$R_m = 28$	$X_m = 1.5$
1000 HP Machine	$R_1 = 0.005$	$X_1 = 0.1$
	$R_2 = 0.005$	$X_2 = 0.1$
	$R_m = 80$	$X_m = 4$

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