EFFICIENCY CONTROL OF INVERTER FED INDUCTION MOTOR DRIVES

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ABSTRACT

Induction motor losses at partial loads can be significantly reduced by operating an adjustable frequency drive at the optimum slip which yields maximum efficiency. The present investigation quantifies the potential improvement in induction motor efficiency for both standard and energy efficient motors operating on a six-step voltage-source inverter supply. The analysis employs a comprehensive model of the induction motor which incorporates the frequency - dependent nature of the motor parameters and effects of stray load loss. Efficiency contours are plotted on a torque- speed plane for constant volts/hertz operation and for optimum slip frequency control plotted as a contour map.

1 INTRODUCTION

Adjustable-speed induction motor drives are finding wide acceptance in process control industries because of the resulting improvement in process efficiency. Attention must also focus on improving the efficiency of the drive system itself, since operating cost savings accrued by efficiency optimized-

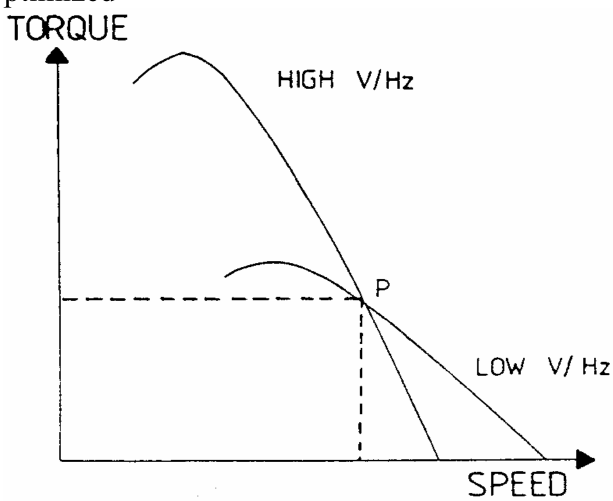

Fig. 1: *Torque- Speed Characteristics for operation at point P*

operation may be substantial over the life cycle of the drive system. Induction motor efficiency can be for example improved by means of reduced voltage operation at light loads. This energy-saving measure has received considerable publicity recently. Particularly in the case of fixed-frequency induction motor drives. The control is also appropriate for adjustable-frequency drives, since many practical drive systems operate at light load for substantial periods of time. However, little quantitative information is available on the magnitude of the efficiency improvement which can be realized in practice. In an adjustable-frequency induction motor drive, the voltage and frequency applied to the motor are independently variable and a specific torque-speed operating point can be achieved with a variety of different voltage-frequency combinations. Each voltage-frequency pairing defines a particular motor torque-speed characteristic passing, through the specified operating point P, as in fig. 1, but motor efficiency may vary widely. If the voltage is high then magnetizing current and core losses are large. If the voltage is reduced excessively then motor currents and copper losses may rise unduly. Consequently, there is an optimum voltage and frequency which gives the specified torque and speed with maximum efficiency.

At light loads maximum efficiency will be achieved with a reduced voltage and increased slip, as-

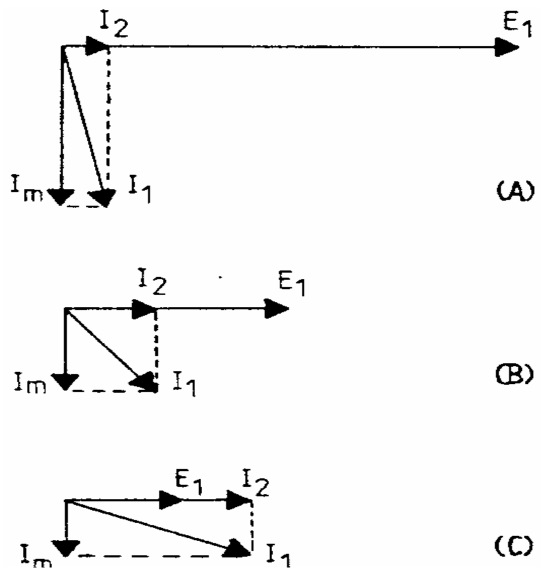

Fig. 2: *Phase diagrams for reduced voltage operation*

compared with the usual constant volts/hertz mode of operation. The latter approach maintains the air gap flux at or near its nominal value, thus achieving a high utilization of the motor iron and permitting the development of high motor torque at all supply frequencies. For these reasons the constant volts/ hertz and constant flux modes of control have been regarded as optimum control strategies for the drives with high dynamic· However at light load motor flux is greater than necessary for the development of the required torque and losses are high resulting in a motor efficiency which is less than optimum.

The influence of voltage reduction on motor losses can be appreciated by considering the Phasor diagrams of fig.2, which refer to the conventional equivalent circuit of fig. 3. Motor torque is proportional to the power dissipated in rotor resistance R_2 / s and consequently, is proportional to the product $E_1 I_2$. Assuming that influence of rotor leakage reactance is small. Fig. 2(A) shows the phasor diagram for light-load operation at normal voltage and emphasizes the large magnetizing current and low power factor inherently associated with this operating condition. If the voltage E_1 is halved as in fig. 2 (B), rotor current I_2 must double in order to develop the same motor torque as before. Air gap flux and magnetizing current I_m are also halved $if X_m = const$, and the total stator current I_1 is reduced. The resulting reduction in stator copper loss and stator core loss (associated with voltage E_1) more than offsets the increase in rotor copper loss, so that overall motor losses are reduced. However, a further halving of voltage E_1,as in fig. 2(C), results in an increased stator current and increased motor losses. Evidently, there is an optimum value of E_1, and rotor slip s, which develops the required torque with maximum motor efficiency.

2 OPERATION AT MAXIMUM TORQUE PER AMPERE

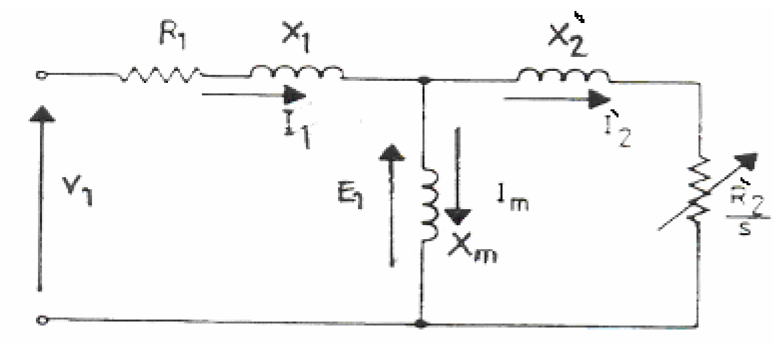

Fig. 3: *Conventional induction motor equivalent circuit at fundamental frequency*

Consider again the fundamental equivalent circuit of fig. 3. For conventional motor operation at a particular supply frequency f_1, the terminal voltage V_1 is constant and motor current and torque increase with rotor slip s. For a three-phase machine the air gap power is given by

$$P_{ag} = 3I_2^{'2}(R_2^{'} / s) = Tw_1 \qquad (1)$$

where T is the mechanical torque in Newton - meters, (including windage and friction) and w_1 is the synchronous angular velocity in mechanical radians per second. In order to maximize torque per ampere the induction motor is operated at the particular slip which develops the required torque with minimum stator current. Rotor current $I_2^{'}$ can be expressed in terms of stator current I_1 as

$$I_2^{'2} = I_1^2 X_m^2 / [R_2^{'} / s)^2 + X_2^{'2} + X_m^2 + 2X_2^{'} X_m] \qquad (2)$$

By substituting in equation (1) gives

$$Tw_1 = 3I_1^2 X_m^2 (R_2^{'} / s) / [(R_2^{'} / s)^2 + X_2^{'2} + X_m^2 + 2X_2^{'} X_m] \qquad (3)$$

If the motor is required to develop a particular torque at a specific frequency a variety of torque-slip pairings is possible. The particular slip, at which stator current with a given current is a maximum, can be obtained by partial differentiation of the right-hand side of equation (3) with respect to slip and equating to zero. This gives

$$s_{mt} = R_2^{'} /(X_m + X_2^{'}) \tag{4}$$

Motor operation at this constant slip implies that the equivalent circuit has no variable impedances and hence motor input impedance and power factor are constant. Motor terminal voltage V_1 is controlled to deliver the current required for a particular torque. Since the equivalent circuit is linear, torque is proportional to V_1^2. For adjustable-frequency operation, it is useful to define the rotor frequency f corresponding to slip $s_{mt.}$ thus

$$f_{2mt} = f_{1mt} = R_2^{'} /(L_m + L_2) \tag{5}$$

It is independent on supply frequency, assuming constant parameter values.

3 OPERATION AT MAXIMUM EFFICIENCY

The gross mechanical power output, including windage and friction losses, is

$$P_{out} = 3I_2^{'2} R_2^{'} (1-s)/s \tag{6}$$

The corresponding electrical motor power input is

$$P_{in} = 3I_1^2 R_{in} \tag{7}$$

Where R_{in} is the resistive part of the input impedance?

Hence, electrical efficiency is given by

$$\eta = \frac{I_2^{'2} R_2^{'2} (1-s)/s}{I_1^2 R_{in}} \tag{8}$$

If the rotor current $I_2^{'}$ is again expressed in terms of I_1, the current terms cancel, and motor Efficiency is expressed exclusively in terms of equivalent circuit parameters, with fractional slip S, as the only variable. On differentiating with Respect to s, and equating to zero, an expression is obtained for the slip, which yields maximum efficiency. In this case, the approximate equation (2) relating I_1 and I_2 is not permissible, since core loss effects cannot be neglected. A core loss resistance R_m is placed in parallel with the magnetizing reactance X_m in fig. 3, and a more precise current relationship is derived. After some approximation, this analysis yields the optimum slip,

$$s_{op} = \frac{R_2^{'}}{X_m + X_2^{'}} \sqrt{\frac{1+A}{1+(R_2^{'}/R_1)}} \tag{9}$$

Where $A = X_m^2 /(R_1 R_m)$ .Operation at this optimum slip again means that the equivalent circuit has no variable impedances, and a controllable supply voltage V_1 is necessary. Circuit linearity implies that P_{out} / P_{in}. Is constant, and electrical efficiency is independent on motor voltage and torque. The optimum slip s_{op} determines the optimum rotor frequency $f_{2op,}$ where

$$f_{2op} = f_{1op} = \frac{R_2^{'}}{L_m + L_2}\sqrt{\frac{1+A}{1+(R_2^{'}/R_1}} \qquad (10)$$

Since A is proportional to X_m^2,, f_{2op} is a function of the supply frequency. At rated motor Frequency, f_{2op} is greater than f_{2mt}, but f_{2op} decreases with frequency and becomes less than f_{2mt} consequently, the condition for maximum torque per ampere does not correspond to optimum efficiency operation.

4 CONCLUSIONS

The investigation has shown that there is considerable potential for loss reduction in adjustable- frequency ac motor drives. Inverter losses and saturation parameter changes if the motor will moderate the predicted efficiency improvement, but will not alter this general conclusion when a six step inverter is employed. The efficiency improvement is enhanced and undesirable harmonic effects are reduced in an adjustable frequency drive. It is usual to employ an induction motor with a low- slip characteristic. Such motors also offer the greatest potential for improvement in part-load efficiency because of the proximity of the optimum slip to the full-load slip of the motor.

REFERENCES

[1] Lazar, J., Halasz, S., Hunyar, M., Csorgits, F.: Converter controlled induction motor drives,Vol. II_III

[2] Leonhared, W.: control of electrical drives, completely and enlarged edition

[3] Saving in the VSI fed induction motor drive. TUB, Dep>EL>Budapest, Hungary

[4] Kirschen, D. S., Novotny, D. W., Lipo, T. A.: (on line Efficiency optimization of variable Frequency induction motor drives, IEEE Trans