Performance Maximization of Variable Frequency Synchronous Motor Drive Based on Power Loss Control

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Abstract

This paper presents a novel approach to the establishment of the operational boundary for synchronous motors in variable speed drives. This is based on the strategy of keeping the motor total power loss constant at its rated value with rated output power. Subject to hot spot risks, this is likely to ensure the thermal robustness of the motor at any operating point, independent of motor current and power limits. The proposed strategy of control adjusts the net air-gap flux to achieve the desired speed and maintain the motor total loss within the rated value. The motor operational boundary for a typical motor, under the proposed control strategy, is established and compared with the corresponding boundary under conventional V/F control. Higher torques, output powers and efficiencies are achieved. Furthermore the operational speed range can be extended above base speed, compared with the more limited range with conventional V/F control. Efficiency maximization at different values of part load is also investigated by controlling the net air-gap flux. A significant reduction in power loss is obtained, achieving worthwhile significant energy savings. The theoretical analysis is derived based on an equivalent circuit model. Saturation, armature reaction and variation of iron losses are taken into consideration. Experimental verification at some of the theoretical results is obtained.

1. Introduction

Recently attention has been given to synchronous motors in variable speed drive schemes [1-7]. In the constant torque operating region (below base frequency region), control schemes based on constant air-gap-flux and unity power factor [1], or constant torque angle[2] or maximum efficiency[3,4] have been reported. The maximum torque versus speed capability is commonly found by limiting the armature current magnitude to the rated value. In the flux weakening region (above base frequency region), voltage control strategies [5,6] are utilized for torque control. At speeds higher than base speed, operation is commonly limited to rated output power value. Current limiting obviously

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reduces copper losses, but not necessarily the iron losses. Similarly, limiting the shaft power does not limit the power losses directly. The operational performance of inverter driven permanent magnet synchronous motors with current and power constrained rated values has also been investigated [7]. The control and dynamics of the permanent magnet synchronous motor drive operating with a maximum power loss versus speed profile are modelled and analysed in [8 and 9]. Power loss control has also been applied to variable frequency induction motor drives [10]. With this, it is found that above base frequency region, the voltage can be increased linearly against speed, reaching 130% at double base frequency [10].

In this paper, a power loss control strategy is applied to variable frequency synchronous motor drives. The proposed control is achieved by adjusting V/F at any speed to keep the power loss constant at the rated value. This is essential to maintain the thermal robustness of the motor over a wide speed range. It also allows increases in current, torque and output power beyond full load values, especially below base speed operation. Hence the motor operation is not limited by rated current and shaft power. The motor characteristics of voltage, torque, current, output power, power loss (copper and iron losses), power factor and efficiency are obtained experimentally and theoretically. These characteristics are compared to those obtained by conventional control of V/F (constant V/F below base frequency and constant voltage above base frequency). Improvements in efficiency, a wider range of speeds and torques higher than the rated value are the advantages of the proposed power loss control. This paper also presents the results of efficiency maximization at different part load values (¼ , ½ and ¾ full load torque). The reductions in losses and the consequent increases in efficiency are observed, which achieves significant energy savings. The computer programme based on the proposed equivalent circuit model and flow chart is developed to compute the performance characteristics. Experimental verification is also provided.

2. Performance analysis

The steady state performance of a synchronous motor fed from a variable frequency supply is obtained using the proposed equivalent circuit model of Fig.1, where R_a is the stator resistance per phase. The variation of iron losses is taken into account and represented by an equivalent resistance R_m, where:

$$R_m = R_{mb} \left(F_b / F \right)^{1.1} \qquad (1)$$

R_{mb} is a resistance giving the estimated iron loss at base frequency (F_b). Equation (1) is an empirical formula obtained from the experimental results. Leakage and armature reaction reactances vary with supply frequency (F) and are given by:

$$X_L = X_{Lb} \left(F / F_b \right) \qquad (2)$$

$$X_a = X_{ab} \left(F / F_b \right) \qquad (3)$$

Where X_{Lb} and X_{ab} are the base leakage and armature reaction reactances respectively. The induced e.m.f. (E_F) is proportional to frequency and is given by:

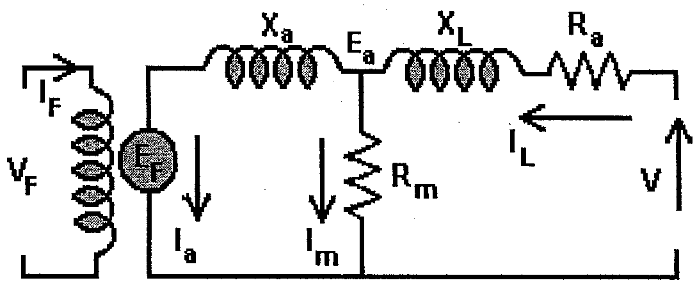


Fig.1 The proposed equivalent circuit model

$$E_F = E_{Fb}\ (F / F_b) \tag{4}$$

Where E_{Fb} is the induced e.m.f. at base frequency. The effect of saturation on E_F and X_a is taken into account from the measured results of the magnetising and armature reaction curves which, for particular machine investigated, are fitted and represented by the following equations :

$$E_{Fb} = 9.457 + 132.691\, I_F - 17.175\, I_F^2 + 0.295\, I_F^3 \tag{5}$$

$$X_{ab} = 220.321 + 24.678\, I_F - 29.557\, I_F^2 + 0.632\, I_F^3 \tag{6}$$

At any supply voltage (V), frequency (F) and load angle (δ), the load current can be derived as ;

$$I_L = \frac{(R_m + j\, X_a)\ V}{Z_L(R_m + j\, X_a) + j\, R_m X_a} - \frac{E_F\, R_m}{Z_L(R_m + j\, X_a) + j\, R_m X_a} \tag{7}$$

where, $Z_L = R_a + j\ X_L$

The air-gap voltage and input power are calculated as;

$$E_a = V - I_L Z_L \tag{8}$$

$$P_{in} = 3\ V\, I_L \cos(\phi) \tag{9}$$

where $\cos(\phi)$ is the motor power factor and ϕ is the angle of the current I_L. The total losses are the summation of field copper loss, stator copper loss and iron loss (neglecting friction and windage losses). The total losses are given by:

$$P_{Loss} = I_F^2 R_F + 3\, I_L^2 R_a + 3\, E_a^2 / R_m \tag{10}$$

The output power, torque and efficiency are given respectively as;

$$P_{out} = P_{in} - P_{Loss} \tag{11}$$

$$T = P_{out}\ P / 4\pi F \tag{12}$$

where P is the number of poles.

$$\eta = P_{out} / P_{in} \tag{13}$$

A computer programme was built to solve the above performance equations at any given speed and for any conditions. The corresponding flow chart is given in Fig. 2.

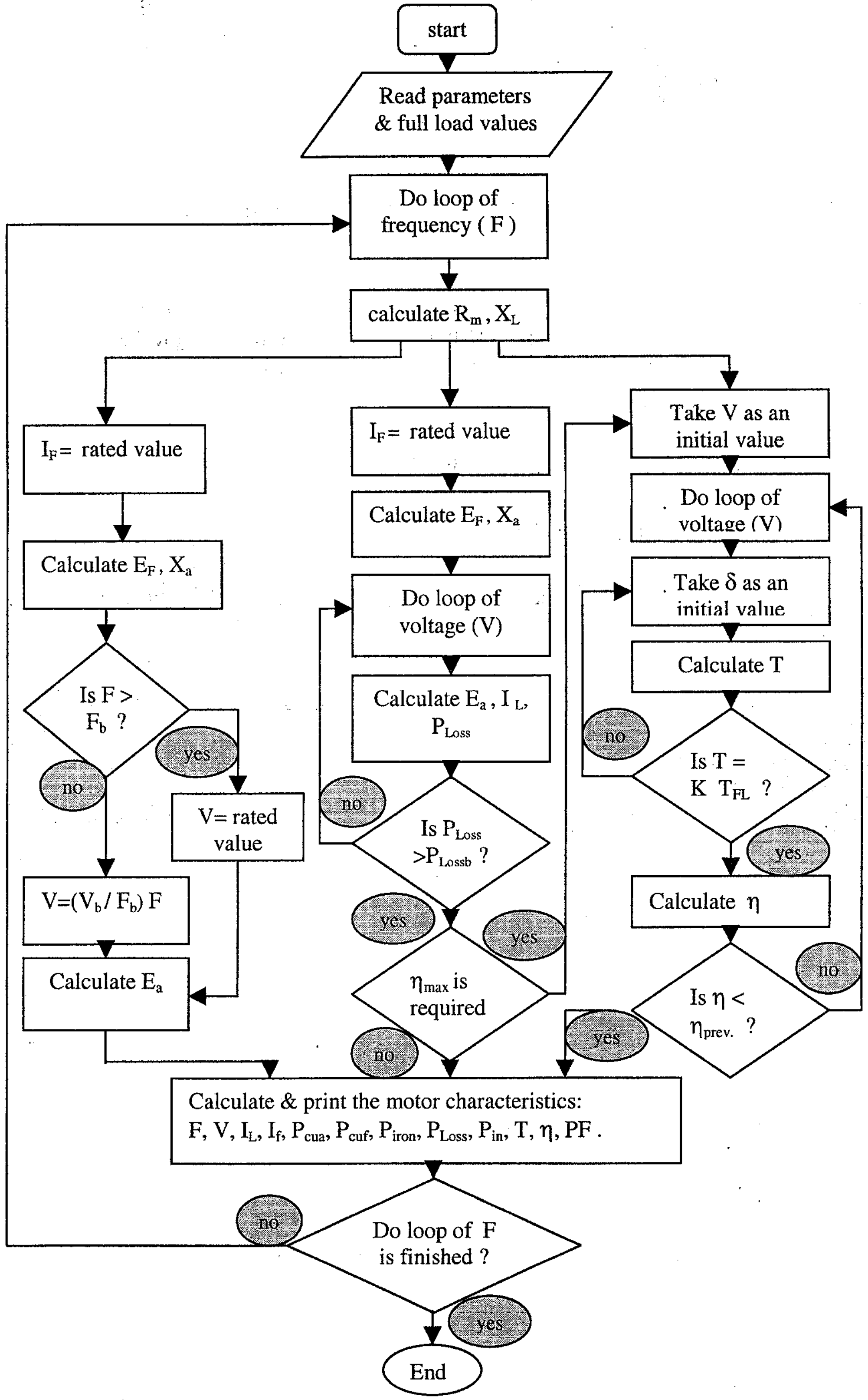


Fig. 2 Flow chart of the computer programmes .

3. The operational Performance

To observe the improvement in the motor performance using power loss control strategy, the characteristics are shown alongside those obtained with conventional V/F control. For both power loss control and conventional control, the field current is maintained constant at the rated value for the two regions of operation. Since the field current is kept constant, the giving analysis may be applied on permanent magnet synchronous motors.

3.1 The motor voltage

With conventional control, the voltage is increased linearly with frequency until base frequency is reached, giving constant torque . This means that the V/F is constant at the rated value (base value),which maintains the net air-gap flux density constant. In the flux weakening region, the voltage is maintained constant at its rated value as shown in Fig.3. Applying power loss control instead of the conventional V/F, it is found that the voltage can be increased nonlinearly with frequency. The amount of increase is limited by the maximum power loss. For the investigated machine, at F=20 Hz, it can be shown that the motor voltage can be increased from 87.5 V under the conventional V/F control to 162.5 V under power loss control. This leads to an increase in the motor torque, output power, load current and armature copper loss. The decrease in the iron loss is compensated for by the increase in the armature copper loss. So that the total losses remain constant at the base value .

At frequencies higher than base frequency, the voltage is reduced with frequency as shown in Fig.3, to reduce the net air-gap flux density and consequently the total power loss do not exceed the permissible maximum value. This however decreases the motor torque and output power below the full load values.

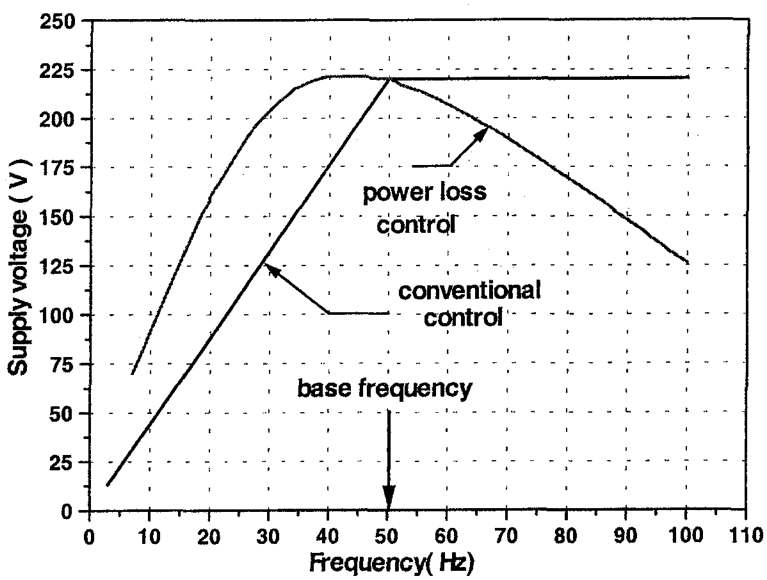


Fig. 3 The motor voltage variation with frequency

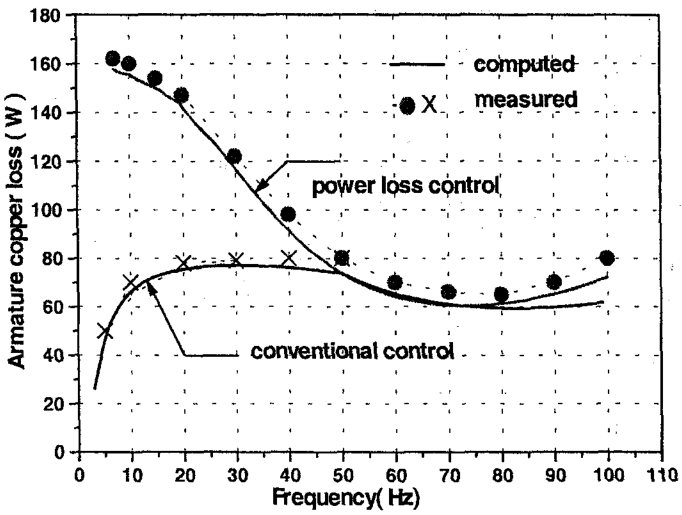
3.2 The motor losses

Under the power loss control strategy, the operating conditions are adjusted so that the total loss is maintained a constant figure, which for the motor studied is 250 W, this being the total loss under rated full load conditions. The motor losses are classified as; field copper loss, armature copper loss iron loss and friction and windage loss. In this study the friction and widage loss is neglected. The field copper loss is maintained constant at 94 W, since the field current is kept constant at the rated value (3.5 A). Figure 4 shows that for frequencies lower than base frequency, the armature copper loss under conventional control is nearly constant at the rated value (74 W). At very low frequency (below 15 Hz), a sharp reduction in armature copper loss occurs because of the voltage drop of the armature leakage reactance decreases by reducing the frequency, while the voltage drop of the armature resistance remains constant. This leads to a reduction in the armature e.m.f and net air-gap flux density as well as the armature current and copper loss. Under power loss control, the armature copper loss is greatly increased (two times the rated value at F=20 Hz). This is due to the increasing in the motor current. Above the base frequency region, the armature copper loss is within the rated value under conventional control power loss control.

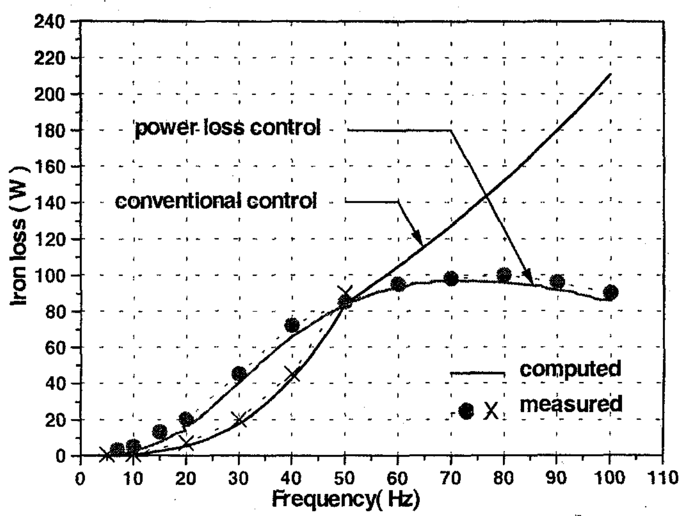
Figure 4(b) shows the variation of iron loss against frequency. Below base frequency, the iron loss is lower than the rated value and reaches the rated value of 82 W at base frequency. Above the base frequency, the iron loss is maintained within the rated value under power loss control, but is greately increased under the conventional V/F control. It reaches approximately 2.7 times the rated value at double base frequency. The total loss variation is shown in Fig.4(c). Under power loss control, the motor can be operated over a wider range of speeds. Under the conventional control, the total losses are lower than the rated value below base frequency. Above base frequency, the total losses are greater than the rated value. The motor hence can not practically operate in this region for extended periods.

3.3 The motor torque and output power

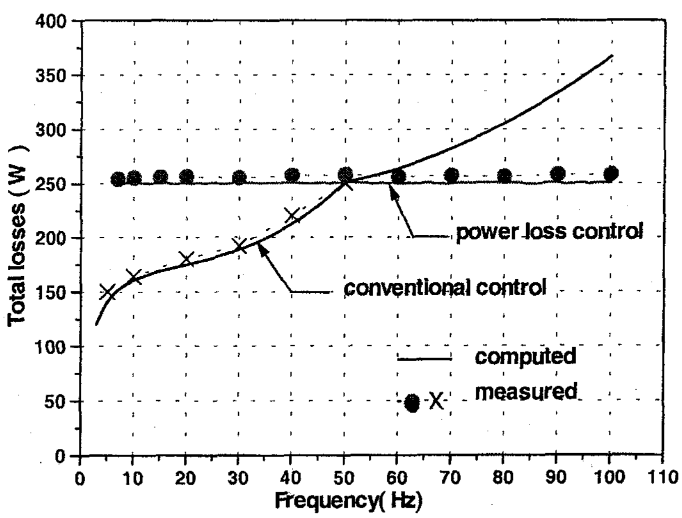
Below base frequency, the developed torque is nearly constant at the rated value (11. 3 N.m), as shown in Fig. 5. The corresponding output power varies linearly with frequency until the rated value (about 1780 Watts) is achieved at base frequency. Under power loss control, the motor can develop torques and output powers higher than the rated value as shown in Figs. 5 and 6 respectively. Above base speed, the developed torque and output power reduce with frequency to maintain the motor losses within the permissible maximum value.



a) Armature copper loss.



b) Iron loss.



c) Total losses

Fig. 4 The motor losses variation with frequency.

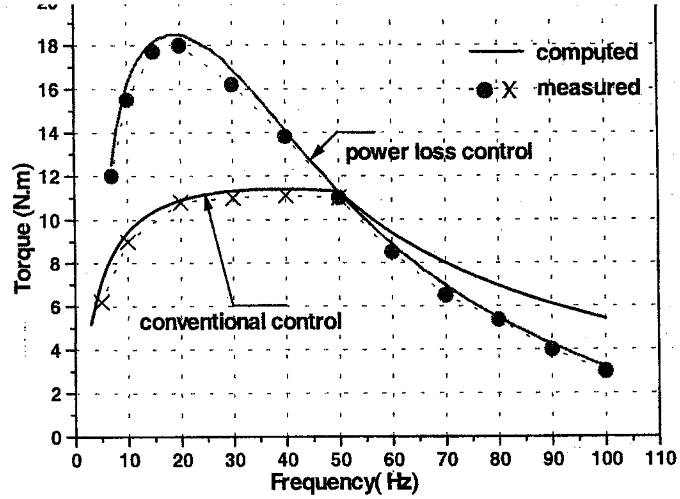


Fig. 5 The developed torque with frequency.

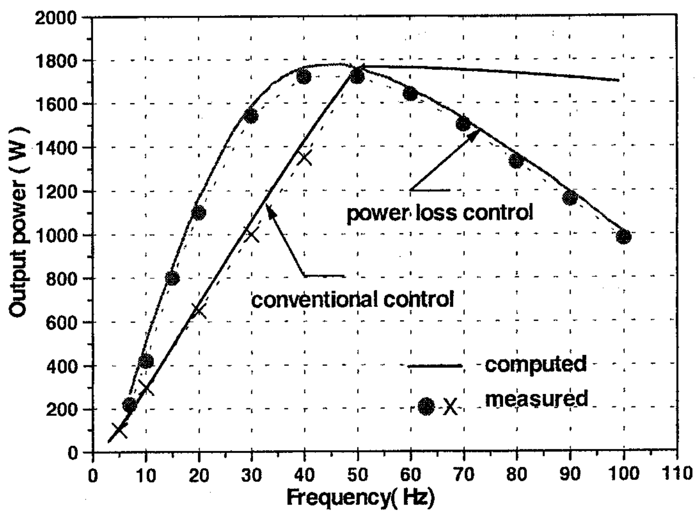


Fig. 6 The output power with frequency.

3.4 The current, power factor and efficiency

The characteristics of load current, power factor and efficiency are shown in Figs. 7,8 and 9 respectively. Increasing the load current, in the higher than base frequency region, leads to a reduction in the motor power factor. This is because of the increased air-gap flux density. Improvement in the power factor occurs at high speed. It reaches nearly unity power factor at approximately 80 Hz. Under power loss control, a small improvement in the motor efficiency is occurred. An efficiency of about 88% is achieved at base frequency, for the investigated machin.

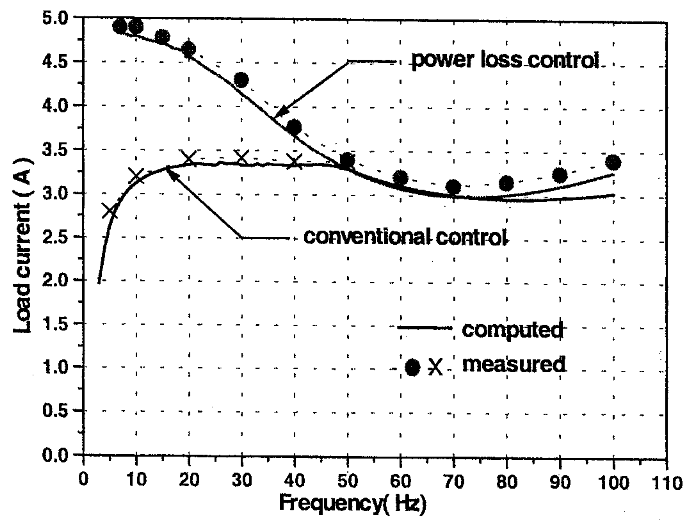


Fig.7 Variation of load current versus frequency.

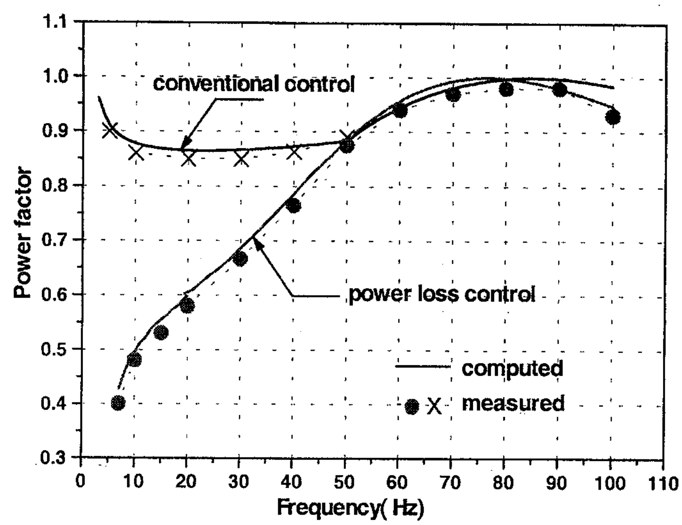


Fig. 8 Variation of power factor versus frequency.

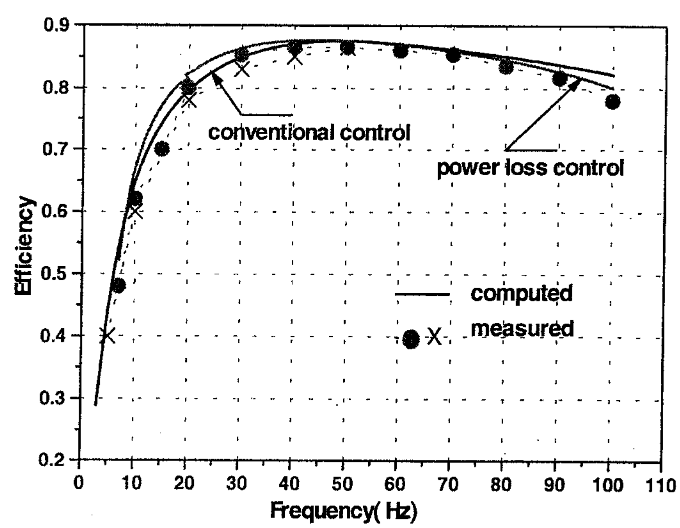


Fig.9 The efficiency versus frequency

4. Part Load Performance

For many applications, such as fans and pumps, the load is proportional with speed. Under the proposed control the synchronous motor can be used to drive that types of load at different levels of load torque.

The developed characteristics under the proposed control are considered as a new rated values of the motor at the corresponding frequency or speed. The available torque developed from the motor is restricted by the permissible boundary curve shown in Fig. 10. It can be shown that the motor can develop constant full load torque (11.3 N.m) only in the region below base frequency. The operating frequency region can be increased above base frequency at torques lower than full load torque. It reaches more than the double base frequency at ¼ full load torque. Operating the motor under part load conditions ,the efficiency can be reduced if the net air-gap flux is maintained at the rated value. Figure 11 shows that the motor efficiency against frequency at ¼ , ½ , ¾ and full load torque, keeping the voltage and then the net air-gap flux at the rated value.

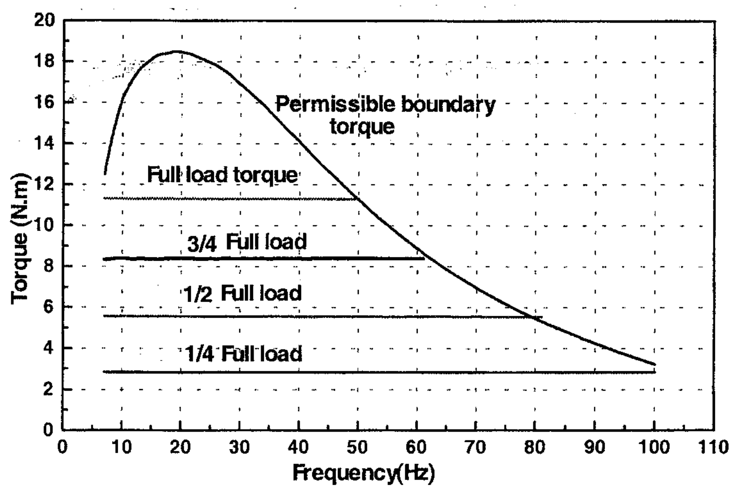


Fig.10 The permissible boundary torque versus frequency under power loss control strategy

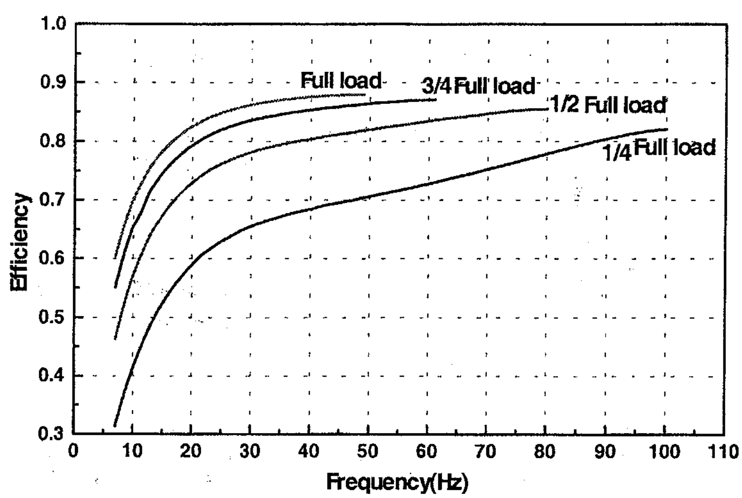


Fig. 11 Efficiency versus frequency without voltage control.

5. Efficiency Maximization

Efficiency is a very important factor in any motor drive, especially at part load operation. The efficiency can be substantially improved by reducing the net air-gap flux. It can be controlled by adjusting the inverter output voltage. At any operating frequency, the stator voltage is reduced to a value which gives minimum losses, achieving maximum efficiency. The controlled voltage at ¼, ½, ¾ and full load torque is shown in Fig. 12. It can be noticed that the stator voltage can be reduced to about 45% from the full load value at base frequency and ¼ full load torque. This improves the efficiency from approximately 70% to 78%. The efficiency curves are illustrated in Fig. 13 at different part load values. Operation at lower load increases the speed range, but decreases the efficiency. At ¼ full load torque, the speed range reaches double base speed and the maximum efficiency is approximately 83%. If the load torque is increased to ½ full load torque, the speed range is limited to 1.6 times base speed and the corresponding efficiency increases to approximately 86%.

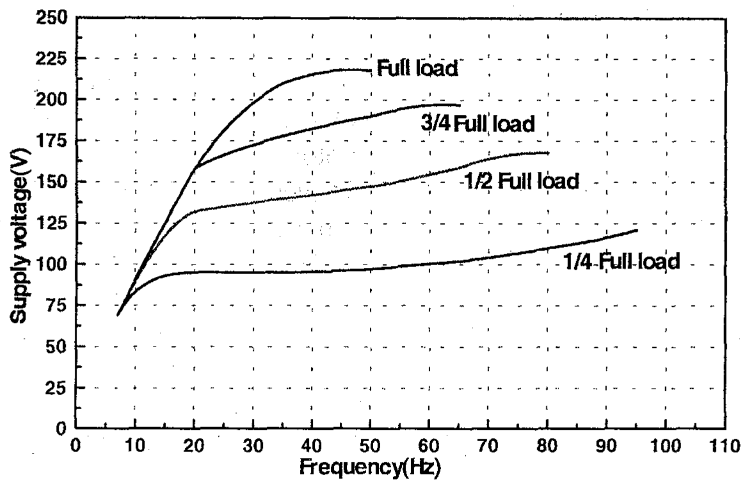


Fig.12 The controlled voltage versus frequency for efficiency maximization.

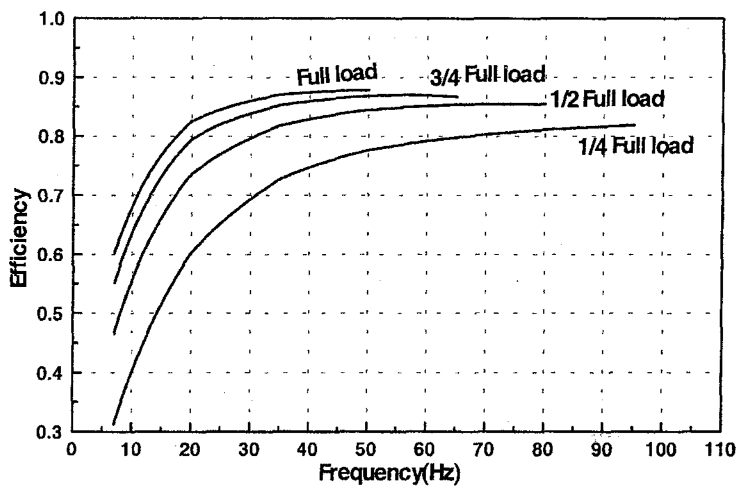


Fig . 13 Efficiency versus frequency under voltage control.

6. Reduction in Losses

As a result of reducing the air-gap flux at part load operation , the losses can be reduced depending on the amount of reduction in the air-gap flux . Significant reduction in losses is occurred at a quarter of full load torque as illustrated in Fig.14. The shaded area between the two curves (losses with and without voltage control) represents the reduction in losses over the operating frequency range. Increasing the part load level decreases the reduction in losses. A small reduction in losses is shown in Fig. 15 at half-full load torque.

The percentage increase in efficiency is shown in Fig. 16. About ten percent improvement in efficiency is obtained at a quarter of full load torque. But three percent improvement is obtained at half of full load torque. This is due to the small reduction in losses at ½ full load torque.

7. Experimental Verification

The experimental results are obtained using 3-phase wound rotor induction machine operated as a synchronous motor. The motor has the following data : 2 kW , 50 Hz, 4-pole, 6.2/3.4 A, rotor current 3.5 A. The motor has been fed from frequency converter; type (Reliance Electric, A.C V*S Drives, GP-2000). A mechanically coupled DC machine is utilised as a dynamometer for loading purpose .The characteristics have been investigated through a wide range of frequency (5-100 Hz). The measured results are plotted in a comparative form with the computed results, where good agreement has been achieved.

8. Conclusions

The strategy of maximum power loss control is proposed and applied on variable frequency synchronous motor drive. The philosophy of the proposed control is maintaining the power loss constant at the permissible maximum value at any desired speed, independent of the motor current and power limits. This is achieved by controlling the stator voltage and consequently the net air-gap flux density. The optimum operational boundary is defined over a wide rang of speed (below and above base speed). The motor can develop torques and output powers higher than the full load values. Torque of about 1.6 times the full load is obtained at frequency of 20 Hz. The motor characteristics are obtained and compared with those obtained under the conventional V/F control. An improvement in efficiency is occurred. The operating speed range can be extended above base speed, but it is limited to base speed under the conventional V/F control.

Loss minimization is also investigated for part load drives. The controlled voltage for maximum efficiency is obtained at different levels of part load. The reduction in losses and then the increasing in efficiency are illustrated against frequency. An increasing of approximately 10% in efficiency is achieved at ¼ full load torque.

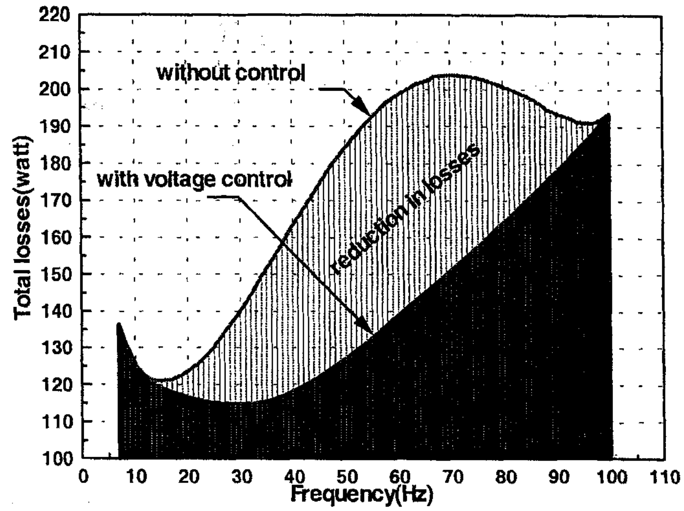


Fig .14 The losses variation with frequency at ¼ full load torque

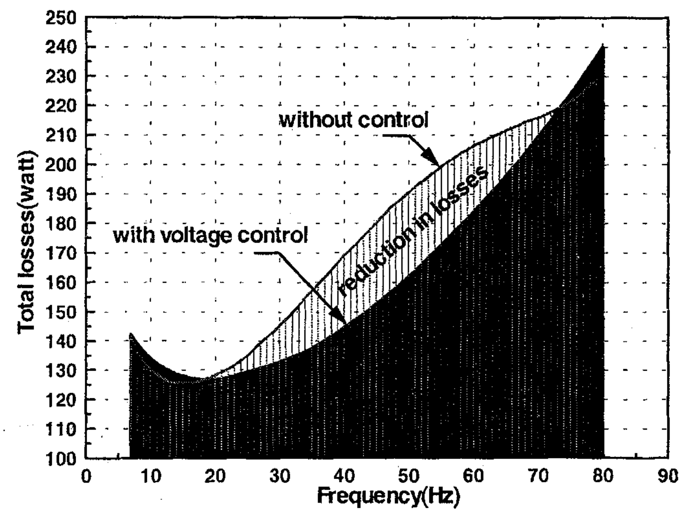


Fig. 15 The losses variation with frequency at ½ full load torque

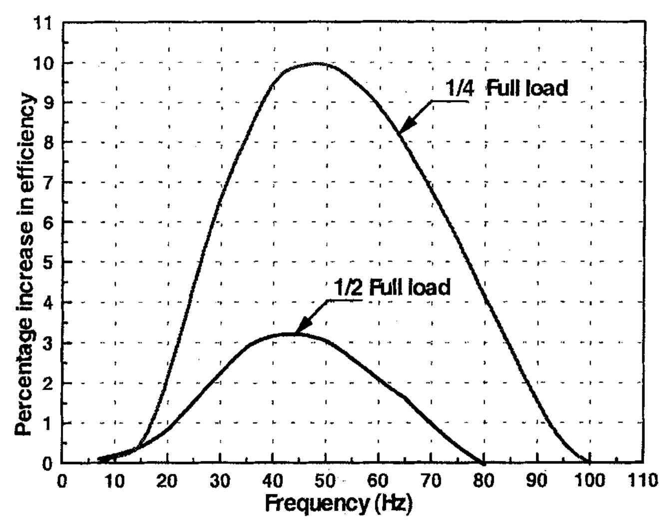


Fig 16 The percentage increase in efficiency.

This however leads to a significant energy saving. The steady state analysis is developed, based on the equivalent circuit model. Saturation, armature reaction and variation of the iron loss with frequency are considered. Good agreement between the computed and measured results has been achieved, confirming the accuracy of the proposed model.

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تعظيم أداء تشغيل المحرك التزامني ذو التردد المتغير في التسيير علي أساس التحكم في مفاقيد القدرة

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ملخص البحث

نظراً للتقدم الكبير في مجال الكترونيات القوي والتحكم في الآلات الكهربية، أصبح من السهل إستخدام المحركات التزامنية في التسيير الكهربي عند تغذيتها من منبع جهد متغير التردد. ذلك سوف يؤدي الي تغيير في خواص آداء المحرك عند سرعات التشغيل المختلفة. لذا يقدم هذا البحث دراسة مستفيضة لتحديد خواص آداء التشغيل العظمى للمحرك التزامنى عند تغذيته من منبع جهد متغير التردد. وتم إقتراح إستراتيجية للتحكم في تثبيت مفاقيد قدرة المحرك عند أقصى قيمة مسموح بها وبذلك نضمن الأمان الحرارى للتشغيل مادامت المفاقيد لاتتعدى القيمة المسموح بها عند أى سرعة. وعليه فإنه يمكن تشغيل المحرك بغض النظر عن القيم المقننه للتيار أو العزم أو قدرة الخرج. وبناءاً على ذلك أمكن تحديد حدود آداء التشغيل الجديدة للمحرك متمثلة فى التيار والعزم وقدرة الخرج و مفاقيد النحاس و مفاقيد الحديد و معامل القدرة والكفاءة عند أى تردد أو سرعة. وتم تنفيذ ذلك بالتحكم في قيمة كثافة الفيض المغناطيسى فى الثغرة الهوائية بواسطة التحكم فى قيمة V/F عند أى سرعة تشغيل بحيث تعطى أقصى مفاقيد قدرة مسموح بها. كما تمت مقارنة الخواص المبنية علي أساس التحكم فى تثبيت مفاقيد القدرة بالخواص المأخوذة علي أساس التحكم الشائع لقيمة V/F (V/F ثابتة خلال منطقة التشغيل قبل سرعة التزامن، V ثابتة خلال منطقة التشغيل بعد سرعة التزامن). وبالمقارنة نتجت بعض المزايا مثل الحصول على عزم وقدرة خرج أكبر (حوالي ١,٦ من عزم الحمل الكامل) وتحسين فى كفاءة المحرك بالاضافة إلي إمكانية تشغيل المحرك خلال مدى أكبر من سرعة التزامن.

كما انتقل البحث إلى دراسة تعظيم كفاءة المحرك عندما يعمل بأحمال جزئية (ربع، نصف، ثلاث أرباع الحمل الكامل). حيث انه من المعلوم أن كفاءة التشغيل تقل كثيراً عندما يعمل المحرك عند جزء من الحمل. وبالتحكم فى قيمة V/F بحيث نحصل على أقصى كفاءة وبالتالى أقل مفاقيد قدرة عند أى سرعة تشغيل و بمقارنة ذلك بالمفاقيد والكفاءة بدون التحكم فى V/F ، إتضح مقدار النقص فى المفاقيد و كذلك النسبة المئوية للزيادة فى الكفاءة التى وصلت فى حدود ١٠% فى حالة ربع الحمل و ٣% فى حالة نصف الحمل. تم أيضاً إقتراح النموذج الرياضى المبنى على أساس الدائرة المكافئة آخذاً فى الاعتبار تأثير التشبع المغناطيسى ورد فعل عضو الاستنتاج وكذلك تغيير مفاقيد الحديد مع السرعة. وتم إعداد برنامج الكمبيوتر المناسب لحساب خواص المحرك نظرياً عند أى سرعة وعند أى نسبة للحمل و بأى طريقة للتحكم فى V/F. كما تم الحصول على النتائج المعملية التى أظهرت تقارب كبير مع النتائج النظرية.