Investigation of Induction Motor Performance Fed from PWM Inverter

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Abstract – **Electrical motors are designed on the basis of balanced three-phase sinusoidal input voltage. Non-sinusoidal voltage, which is the common output voltage from PWM inverters, has detrimental effects on induction motors performance characteristics, and derating of machine is required. In this paper the performance of a three-phase induction motor is intensively investigated when it is fed from PWM inverter. The PWM inverter is controlled by two different PWM techniques commonly used, namely Sinusoidal PWM Technique and Selected Harmonic Elimination PWM (SHEPWM) Technique. A complete simulation of a three-phase induction motor fed from PWM inverter was designed using Matlab/Simulink package. The performance of the three-phase induction motor loaded by fan load was compared with the performance of the motor where fed from pure sinusoidal supply voltage. The study confirms that the induction motor under study gives best performance when it is fed from PWM inverter controlled by SHEPWM technique.**

Index Terms – induction motors performance, PWM techniques, inverters, harmonics.

I. Introduction

Energy efficiency is hardly a new theme. In a technologically expanding world, it has become crucial to grip with energy consumption yet still use energy wisely. Electrical motors, particularly in industrial usage, represent a large portion of electrical energy consumption. It is reported that well over 50% of electrical energy generated in the U.S.A. goes to power electrical motors of all sizes [1]. The U.S.A. and North American neighbors have taken the lead to put energy efficiency into legislation. Motor efficiency legislation in the U.S.A. stems from the Energy Policy and Conservation Act (EPCA) of 1975, passed in response to the oil crisis of the early 1970s. Since October 1992, the motor industry has been preparing for implementation of EPACT'92. The driving force behind the EPACT'92 legislation was energy conservation, which included the impact on natural resources and the ecological impact on the environment. New product options are now available to the user and products that do not meet the legislated minimum efficiencies have been obsoleted. The exceptions are motors that are exempt from the law. The motor portion of EPACT'92 only covers three-phase ac integral-horsepower squirrel cage induction motors [2].

The output of an induction motor (I.M.) depends mainly on heating and motor's life is shortened by overheating. The temperature rise resulting from losses is therefore, a major factor in determining the machine performance. The presence of harmonics in the applied voltage output from PWM inverter, can cause excessive heating. The amount of voltage distortion, measured by a "Distortion Factor" (DF), which is defined by IEEE standard 519, is used to establish the harmonic limits. This standard suggests that no derating of the motor would be necessary for a harmonic content of up to 5%, which is the limit of the voltage distortion on industrial power systems. However, no limit is specified in regard to the individual harmonic content [3].

Many automated industrial applications require efficient and fast control of ac motors. This is performed using electronic power PWM inverters. The PWM inverters transfer energy obtained from an electrical source to controlled industrial process using semiconductor switches which are turned on and off at fast repetition rate [4], [5]. The algorithms, which generate the switching functions, PWM techniques are manifold [6]-[8]. They range from simple averaging schemes to involved methods of real time optimization. An important consideration is the quality of the PWM inverter output voltage, the quality is improved by selection of certain PWM techniques. It is well known that PWM techniques will introduce a certain amount of harmonics. The effect of these harmonics on motor's supply will diminish motor overall performance, as it will reduce efficiency, produce excessive heat, noise, torque pulsation, etc... [1] - [12].

II. Induction Motor Performance

The overall I. M. performance is affected by the following factors:

1. Heating;	2. Efficiency;
3. Power Factor PF;	4. Breakdown Torque;
5. Inrush Current;	6. Starting Torque;
7. Acceleration Capabilities;	8. Sound Level·
9. Enclosure Type;	10. Service Factor;
11. Adjustable Frequency.	

The application requirements involving many of these parameters are such that it is normally not possible for the designer to optimize them all at the same time. In some situations, these parameters conflict with each other and the designer is forced to make several compromises. When faced with the decision to choose between maximum efficiency and maximum PF, for example, it is well known that, once the motor is built, the efficiency becomes an inherent part of the machine and is difficult to improve. However, the system PF can be improved by use of power factor improvement equipment [2].

The total motor losses consist of iron, windings, mechanical, and stray losses; details and expression for each loss can be found in [3]. For typical NEMA standard design B machines operating at full-load, the losses can be distributed as [10]:

- Mechanical losses	9%
- Iron losses	20%
- Stator copper losses	37%
- Rotor copper losses	18%
- Stray losses	16%

Another aspect which should be considered is the duty or demand cycles which can significantly vary with respect to time. A number of studies have indicated that, for most applications, motors are operating at loads significantly below the full-load rated value. The motor's efficiency and PF drop off at very rapid rate, usually below 50% and in this case, a motor that is more properly sized will yield improved efficiency and PF. It should also be pointed out that maximum efficiency does not necessarily occur at full load, in fact in many cases, it occurs around 75% of the load. The caution is the system demand. One effective alternative is to parallel a number of smaller motors and cycle them on or off depending upon the demand or use an adjustable-speed drive to throttle back the load [11]. Little attention has to be given to how motor speed relates to efficiency and PF. Simply stated, large high-speed motors have best efficiency and PF characteristics, and as speed and/or horsepower are reduced, so are the efficiency and PF [2].

AC induction motors will operate successfully under running conditions at rated load with a variation in the voltage plus or minus 10% of rated voltage, with rated frequency, and variation in the frequency plus or minus 5% of rated frequency, with rated voltage. Performance within these voltage and frequency variations will not be necessarily agreed with the standards established for operation at rated voltage and frequency [3]

III. Pulse Width Modulation Techniques

A. Voltage Waveshape

The non-sinusoidal supply voltage output from PWM inverter can be expressed in a general form as:

$$v(t) = \sqrt{2}\left[V_1 \sin \omega t + \sum_{n=2}^{N} V_n \sin(n\omega t + \theta_n)\right] \tag{1}$$

where V_1 is the fundamental supply voltage, V_n represents harmonic voltages of order n, and θ_n is the harmonic phase angle. The fundamental and the [3n+1] for n=1, 2,... order voltage harmonics contribute to a rotating magnetomotive force (MMF) in the direction of motion and hence results in the development of a positive torque. The [3n+2] for n=0, 1, 2,... order voltage harmonics results in a rotating MMF in opposite direction of motion of the rotor and hence contributes to a negative torque. Where the [3n+3] for n=0, 1, 2,... order voltage harmonics produces no rotating MMF and, therefore, no torque. If there are a certain number of pulses per quarter cycle, and it is an odd number, the harmonic order will be even number only [3].

B. Sinusoidal PWM Technique

In the Sinusoidal Pulse Width Modulation SPWM technique, the required switching pattern is generated by comparing an isosceles triangle carrier signals with a modulated sinusoidal reference signal. This technique is commonly used in industrial applications. By controlling the magnitude and frequency of the modulated sinusoidal signal, the output voltage magnitude and frequency of the PWM inverter are controlled accordingly. The harmonic spectrum in the PWM inverter output voltage controlled by this technique at unity modulation index M and for harmonics order up to 41st is shown in Fig.1, [7].

C. Selected Harmonic Elimination PWM Technique

In the selected harmonic elimination (SHEPWM) technique, the orders of harmonics to be eliminated or controlled are equal to the total number of chop angles per quarter cycle K. In order to evaluate the chop angles, a set of K simultaneous equations using Equ. (1), is assembled and solved using any iterative method [6]. For on-line calculations of the required switching pattern a modeling technique can be used [7]. Also the new trends of using expert system in the field of power electronics was led to use the Artificial Neural Network ANN technique for calculating the required switching pattern for on-line applications [8].

The harmonic spectrum of the PWM inverter output voltage controlled by SHEPWM technique at unity modulation index and nine chops per quarter cycle for harmonics order up to 49th is shown in Fig. 2. It is shown in this figure that the trplian harmonic voltages are present, but these harmonics will be canceled in the three-phase star connection.

IV. INDUCTION MOTOR MATLAB/SIMULINK MODEL

Induction machine dynamics are usually modeled by equivalent circuits in the synchronous rotating reference frame, d and q axes [12]. This model is used to build the Matlab/Simulink blocks. By using the built-in power system blocks in Matlab/Simulink, a complete three-phase induction motor fed from PWM inverter model was developed. The induction motor is loaded by a fan load in this study. The PWM inverter is controlled by the two previously mentioned PWM techniques. Also voltage/frequency (V/F) control is considered in this developed model. In this study the performance of induction motor fed from pure sinusoidal supply is used as the reference base for comparison.

Figure 3 shows the complete three-phase PWM inverter Matlab/Simulink model. This model is divided into three main parts as follows:

Part 1 PWM Inverter

This part contains the three-phase PWM inverter utilizing GTO switches. To control these switches another block is used (labeled pulses source), the pulses source block swapped according to each PWM technique used. Also, this block considered the V/F control. The V/F control is used in this study only in the case of the induction motor fed from pure sinusoidal supply, and fed from PWM inverter controlled by SPWM. The results in this case are shown in Fig. 4.

Part 2 Induction Motor

This part contains the induction motor block with its load. The three-phase induction motor under this study has the following data:

Supply voltage 220 V, Rated output 20 HP,
Frequency 60 Hz, Number of poles 4-pole
Magnetizing Reactance $X_m = 5.83\ \Omega$
Stator winding: $R_s = 0.11\ \Omega$, $X_s = 0.22\ \Omega$
Rotor winding: $R_r = 0.08\ \Omega$, $X_r = 0.22\ \Omega$
Total inertia: $J = 0.5$ Kg/m^2
Friction Factor: $F = 0.015$ N.m.s
Inverter input d.c. voltage $E = 400$ V

The motor is loaded by fan load defined as $C_L\ \omega_r^2$

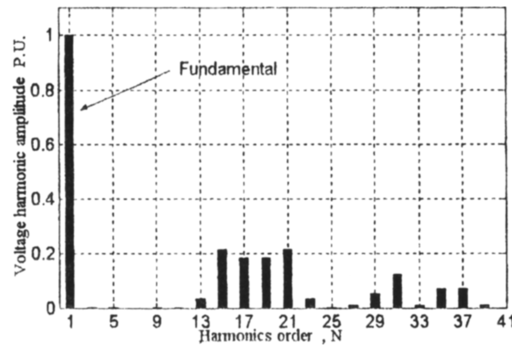

Fig.1. Harmonic spectrum for SPWM technique.

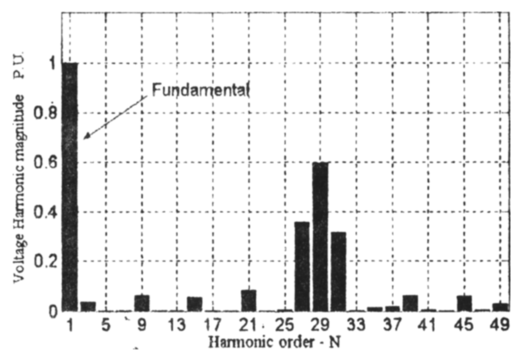

Fig.2. Harmonic spectrum for SHEPWM technique.

where C_L is the load constant, and is equal to 0.0022, and ω_r is the motor speed in rad/s.

Part 3 Recording Results

This part is using the built-in blocks in Matlab/Simulink for the resulting data from simulation recording, storing, and drawings shown in the next article.

V. RESULTS AND DISCUSSION

The performance of the induction motor under study was achieved by considering the designed model shown in Fig 3. Considering the different PWM techniques mentioned in article III. The block labeled "pulses source" shown in Fig.3. is used to apply the different PWM techniques, while when studying the performance of the three-phase induction motor fed from pure sinusoidal supply, this block is replaced by sinusoidal generator.

The figures in this part are presented in a fashion to be easy for comparison between the three supply cases defined as follows;

Case 1: the induction motor is supplied from pure sinusoidal voltage, the corresponding figures in this case will be shown in the sub-graphs labeled (a) and (d).

Case 2: the induction motor is supplied from PWM inverter controlled by SPWM technique, for carrier frequency F_c of 360 Hz and modulation index M of 0.9, the corresponding figures in this case will be shown in the sub-graphs labeled (b) and (e).

Case 3: the induction motor is supplied from PWM inverter controlled by SHEPWM technique, for number of chops per quarter cycle K equal to 9 and modulation index M equal to 0.9, the corresponding figures in this case will be shown in the sub-graphs labeled (c) and (f).

Also, in all figures x-axis represents rotor speed,. except Fig.4 and Fig.7 x-axis represents time.

Figure 4 shows the voltage/frequency V/F control results, as Fig. 4 (a) shows the pure sinusoidal supply voltage, Fig. 4 (b) shows the PWM inverter output voltage when it is controlled by SPWM technique and Fig. 4 (c) and (d) show the rotor speed versus time in pure sinusoidal and SPWM supplies generated considering V/F control. Figure 5 (a), (b), and (c) show the motor supply voltage in the three cases mentioned before, respectively. The rotor speed in the previous three cases are shown in Fig. 5 (d), (e), and (f), respectively. The rotor reaches its rated speed, 1755 rpm, in 0.8 sec. for the three cases. Figure 6 (a), (b), and (c) show the stator phase-current in the three cases of supply mentioned before, respectively, it is noticed that the current in the case of SPWM supply is higher than that compared to the two other supplies. Figure 6 (d), (e), and (f) show the motor efficiency. The efficiency with pure sinusoidal supply is 87%, and with SPWM supply is 70% and with SHEPWM supply is 77%, all at rated speed. Figure 7 (a), (b), and (c) show the stator current in the three cases of supply mentioned before, respectively for three-second interval, this is to show there steady state values. While, figure 7 (d), (e), and (f) show the same stator currents, but in short period interval, to show the quality of the current waveforms. Figure 8 (a), (b), and (c) show the motor PF in the three cases of supply mentioned before, respectively. The PF values at rated speed are 86%, 80%, and 77%, respectively. Figure 8 (d), (e), and (f) show the current total harmonic distortion THD, there values are 0%, 35%, and 25%, respectively. Figure 9 (a), (b), and (c) show the torque in the three cases of supply mentioned before, respectively. Figure 9 (d), (e), and (f) show the developed power, respectively. Figure 10 (a), (b), and (c) show the stator copper losses in the three cases of supply mentioned before, respectively. There values at rated speed are 840 W, 1050 W, and 870 W, respectively. Figure 10 (d), (e), and (f) show the rotor copper losses. There values at rated speed are 388 W, 570 W, and 400 W respectively.

It can concluded from the pervious figures, that the induction motor under this study gives its worst performance when supplied from PWM inverter controlled by SPWM techniques compared to when the PWM inverter controlled by SHEPWM technique is adopted.

VI. CONCLUSION

The paper presents an extensive study of the performance of a three-phase induction motor fed from a PWM inverter. The performance of the three-phase induction motor under study is demonstrated in a fashion to be easy for comparison, as shown in Figure 4 through Figure 10.

The best performance occurred in the case of the three-phase induction motor fed from PWM inverter controlled by SHEPWM technique. This study may be extended to investigate the performance of induction motor fed from PWM inverter controlled by the latest PWM technique published named Random Pulse Width modulation RPWM Technique.

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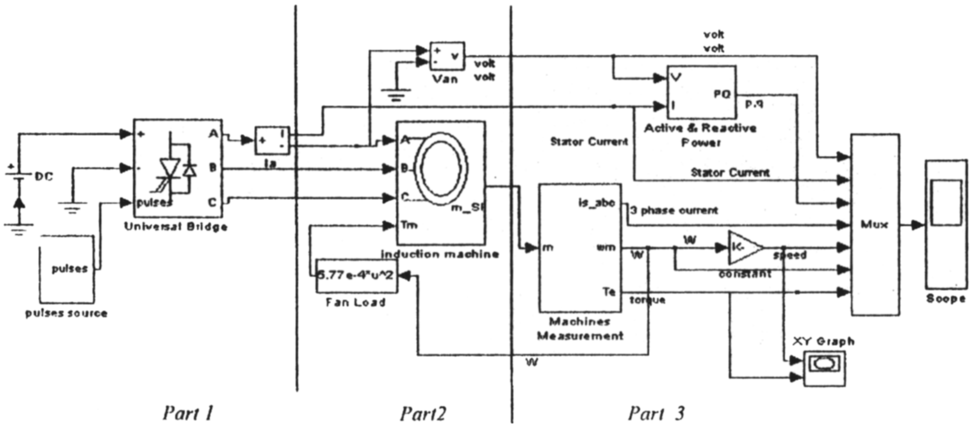

Fig. 3 PWM Inverter-Fed Induction Motor Matlab/Simulink Model

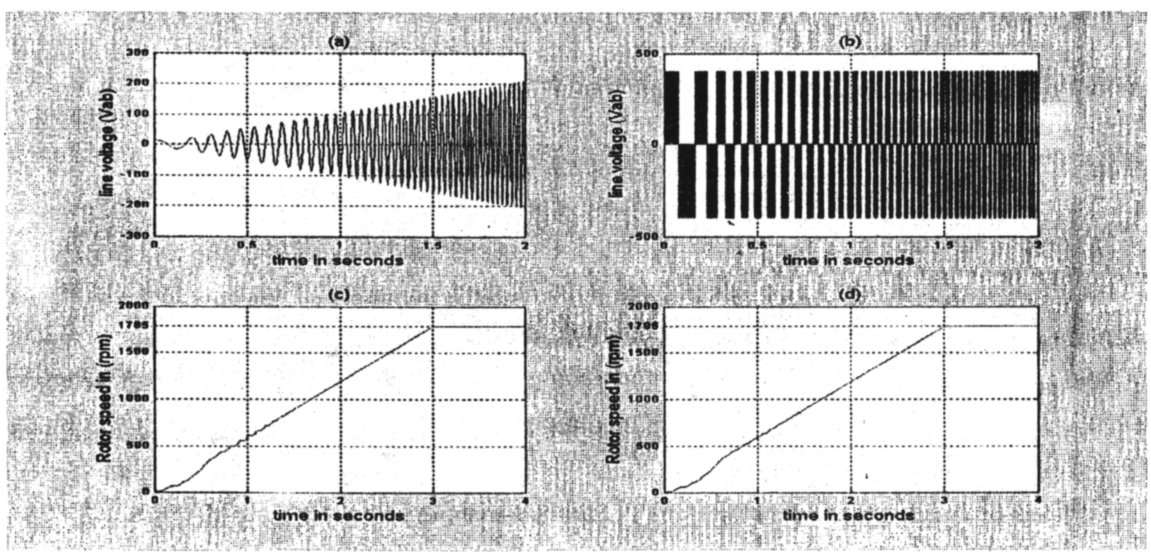

Fig. 4 Voltage / Frequency control
(a) & (c) pure sinusoidal supply voltage and rotor speed versus time
(b) & (d) SPWM supply voltage rotor speed versus time

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Dr. Gamal is listed in *Who's Who in science and engineering*, in the 9th edition. He authored or coauthored numerous technical papers published in leading journals and conference proceedings.

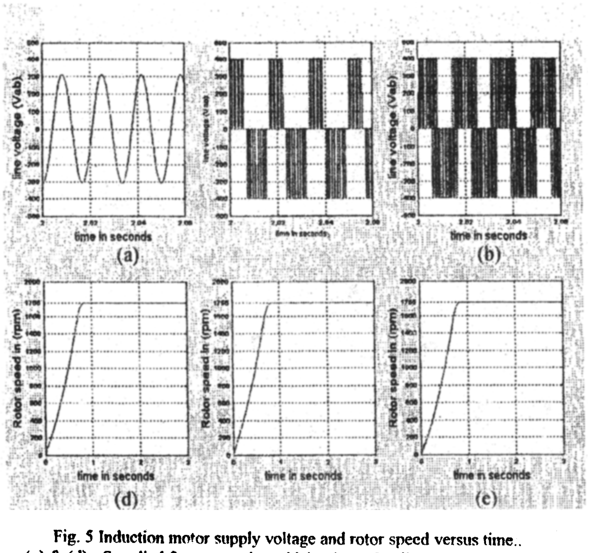

Fig. 5 Induction motor supply voltage and rotor speed versus time..
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9, M=0.9)

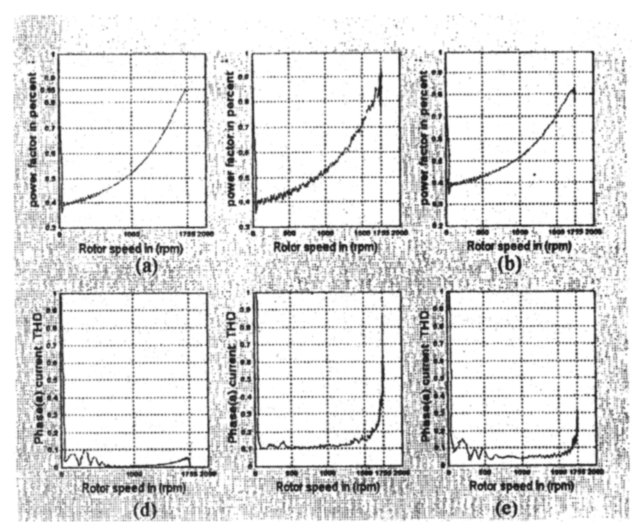

Fig. 8 Power factor and current total harmonic distortion versus speed.
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9, M=0.9)

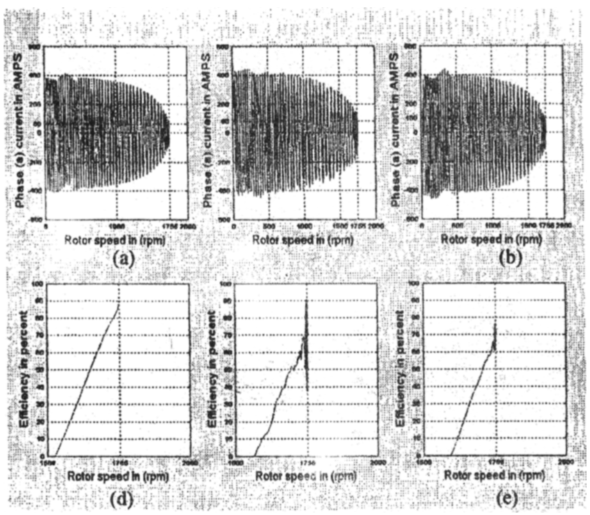

Fig. 6 Stator phase current and motor efficiency versus speed.
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9; M=0.9)

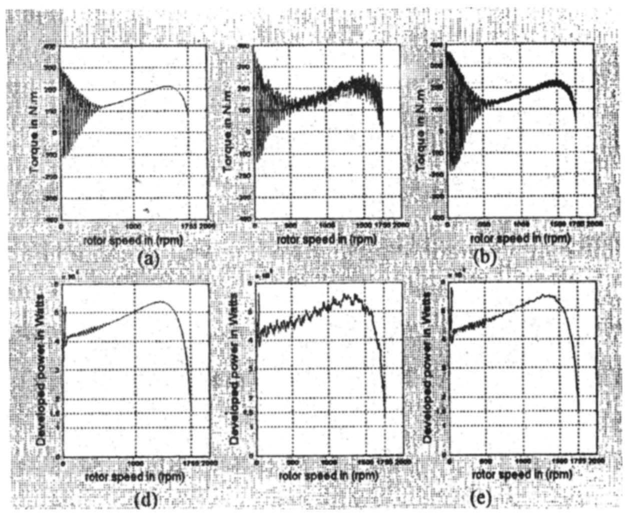

Fig. 9 Torque and developed power versus speed.
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9, M=0.9)

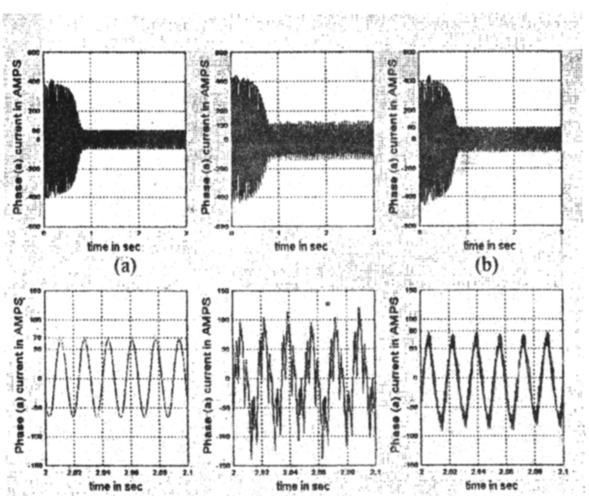

Fig. 7 Stator phase current versus time.
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9, M=0.9)

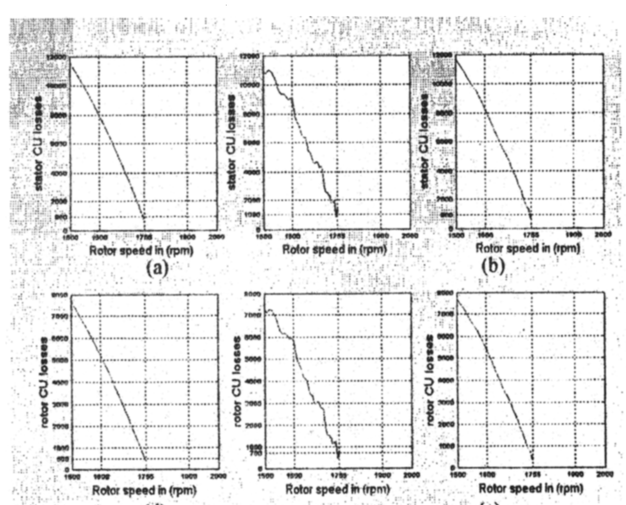

Fig.10 Stator copper losses and rotor copper losses versus speed.
(a) & (d) - Supplied from pure sinusoidal voltage for direct on-line starting.
(b) & (e) - Supplied from PWM inverter controlled by SPWM (F_C=360, M=0.9)
(c) & (f) - Supplied from PWM inverter controlled by SHEPWM (K=9, M=0.9)