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Improved Control Strategy for Three-Phase AC Choppers under Induction Motor Load

طريقة تحكم محسنه لمقطع التيار المتردد ثلاثى الطور مع محرك حثى ثلاثى الأطوار

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الملخص : هذا البحث يقدم طريقة تحكم محسنه للتحكم فى مقطع التيار المتردد ثلاثى الطور مع محرك حثى ثلاثى الأطوار. و هذه الطريقة المحسنه تعرف بطريقة التحكم فى زاوية الإطفاء. و هذه الطريقة تم مقارنتها مع طريقة التحكم فى زاوية الوجه و طريقة زاوية التحكم المتماثلة لتوضيح مدى تحصن سلوك النظام. و كل هذه الطرق تعتمد على تغيير جهد العضو الثابت للمحرك للتحكم فى سرعته. وتتميز هذه الطريقة المقترحة بمعامل قدرة عالى و معامل توافقيات أفضل من الطريقتين الأخرتين خلال منطقة التشغيل الطبيعية. تم عرض سلوك المحرك مع طرق التحكم المختلفة. و تم عمل نظام المحاكاة باستخدام برنامج المحاكاة PSIM. و تم مقارنة نتائج المحاكاة مع النتائج المعملية المستخلصة من نموذج معملى. و تم عرض التوافقيات فى تيار الخط و تيار المحرك و معامل القدرة لكل طرق لاالتحكم المختلفة.

Abstract — This paper presents a modified control strategy for controlling three-phase ac chopper under induction motor load. This modified strategy is known as Extinction Angle Control (EAC). This new strategy is compared with the Modified Phase Angle Control (MPAC) and Symmetrical Angle Control (SAC) to demonstrate its superior performance. These strategies are based on varying the stator ac voltage to control the speed of three-phase induction motor. The proposed strategy is characterized by a higher power factor and a better total harmonic distortion compared with the other two strategies over the normal operating arrange. Performance evaluation of the motor under the different switching strategies is demonstrated. The simulation of the system is carried out using PSIM computer program. The simulation results are compared with the experimental results obtained from a laboratory prototype. The levels of harmonics in the supply currents and power factor are evaluated for different control strategies.

***Index Terms* — AC chopper, Induction motor, parallel port, speed control**

I. INTRODUCTION

There are intensive works on starting and speed control of three-phase induction motor using ac voltage regulator [1]. Most of these researches use thyristors to control the output voltage using phase angle control technique [2, 3]. Thyristors limit the operation of the controller due to their commutation characteristics in addition to generation of the low order harmonics which will be injected into the electrical supply and the machine. Invention of modem switches like MOSFET and IGBT starts a new revolution in controlling electric machines in general and induction motor in particular [4,5].

AC choppers have been used to control both static and dynamic loads [6-11]. Three-phase ac chopper has been used to control the speed of three-phase induction motor [4,5]. Single-phase and three-phase ac choppers are characterized by cost reduction and effective control strategy.

The drawback associated with the ac choppers that using thyristors are high harmonic contents in the supply and machine currents, very poor power factor especially at light loads, narrow speed control range, and low efficiency.

The essence of this paper is to evaluate the performance of an ac chopper loaded by an induction motor under Extinction Angle Control (EAC) strategy. The performance under EAC will be compared with that obtained under the Modified Phase Angle Control (MPAC) and Symmetrical Angle Control (SAC).

II. SYSTEM UNDER STUDY

The system under study consists of six bidirectional switches as shown in Fig. 1. Three switches are connected in series with stator terminals of the motor and the other three are used to provide freewheeling path across stator windings.

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III. MATHEMATICAL MODELS FOR DIFFERENT SWITCHING STRATEGIES

In any control strategy, the relation between the machine phase voltage and input voltage can be expressed as:

$$v_r(\omega t) = S_x(\omega t) * v_s(\omega t) \qquad (1)$$

where, $S_x(\omega t)$ is the switching function and $v_r(\omega t)$, $v_s(\omega t)$ are the motor terminal and supply phase voltages, respectively.

A. Modified Phase Angle Control (MPAC)

MPAC strategy is carried out by switching ON the series switch of phase a of Fig. 1 (S_a) at delay angle α with respect to phase voltage of phase a. The series switch S_a is in OFF state when $0<\omega t<\alpha$, in the same time the shunt switch of phase a, ($\overline{S_a}$) is ON. The switching state will reversed when $\alpha<\omega t<\pi$. The switching state in the negative half cycle of supply voltage is same as in positive half cycle. So, the frequency of the switching function is double the supply frequency as the case of switching functions of all strategies under study. The switching signals of the other two phases are shifted from the switching signal of phase a by 120°. The switching signal of series switch S_a is shown in Fig. 2. Continuous time varying for the motor voltage can be obtained by using Fourier transform in the switching function then substituting the results into (1). The rms of the fundamental component of motor voltage is:

$$V_{r1} = \frac{V_m}{\sqrt{2}\,\pi}\sqrt{\sin^2(\alpha)+(\pi-\alpha)^2+(\pi-\alpha)\sin(2\alpha)} \qquad (2)$$

The fundamental component of the motor voltage, V_{r1} is inversely proportional with the value of α. The angle of V_{r1} with respect to supply voltage, (ψ_1) where:

$$\Psi_1 = \tan^{-1}\left[\frac{\alpha}{2} + \tan\left(\frac{\alpha}{2}\right) * \left(\frac{\pi-\alpha+\sin\alpha}{\pi-\alpha-\sin\alpha}\right)\right] \qquad (3)$$

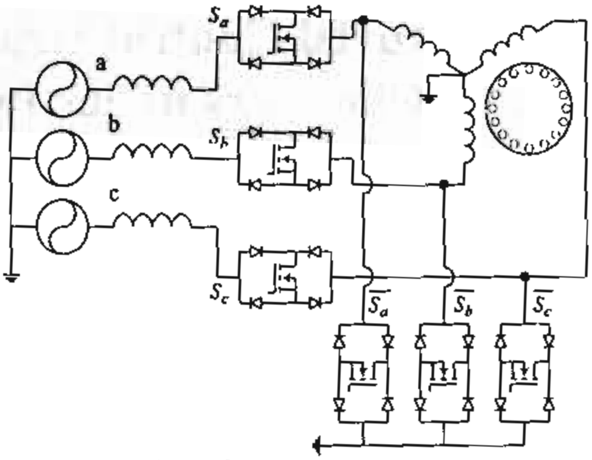

Fig. 1. System under study.

B. Symmetrical Angle Control (SAC)

SAC is carried out by varying the conduction angle γ as shown in Fig. 3. The series switch of phase a (S_a) is in OFF state in the following periods $0<\omega t<\alpha/2$ and $\pi-\alpha/2<\omega t<\pi$, in the same time the shunt switch of phase a ($\overline{S_a}$) is ON. The series switch is in ON state in the period $\alpha/2<\omega t<\pi-\alpha/2$ in the same time the shunt switch is OFF. The switching state in the negative half cycle of supply voltage is same as in positive half cycle. So the frequency of the switching function is twice the supply frequency. The switching signals of the other two phases are shifted from the switching signal of phase a by 120°. The fundamental component of phase voltage at the terminal of the machine, V_{r1} is inversely proportional with the value of angle α.

The continuous time varying of phase a voltage of SAC can be obtained by using Fourier transform of switching function and using the results in (1). The rms component of the fundamental phase voltage at motor terminal is:

$$V_{r1} = \frac{V_m}{\sqrt{2}\,\pi}\left[(\pi-\alpha)+\sin(\alpha)\right] \qquad (4)$$

The angle of V_{r1} with respect to supply voltage is zero.

C. Proposed Strategy, Extinction Angle Control (EAC)

EAC strategy is carried out by switching on the series switch of phase a, (S_a) at zero crossing point of supply voltage, then switching it OFF at angle $(\pi-\alpha)$ as shown in Fig. 4. The series switch of phase a (S_a) is in ON state when $0<\omega t<\pi-\alpha$, in the same time the shunt switch is of phase a, $(\overline{S_a})$ is OFF. The switching state will reversed when $\pi-\alpha<\omega t<\pi$. The switching state in the negative half cycle of supply voltage is same as in positive one. So, the frequency of the switching function is double the supply frequency. The switching signals of the other two phases are shifted from the switching signal of phase a by 120°. The rms component of the fundamental phase voltage at motor terminal is:

$$V_{r1}=\frac{V_m}{\sqrt{2}\,\pi}\sqrt{\sin^2(\alpha)+(\pi-\alpha)^2+(\pi-\alpha)\sin(2\alpha)} \qquad (5)$$

It is clear from Fig. 5 that the fundamental component of the voltage at the terminal of the motor, V_{r1}, is inversely proportional to the value of angle α. The angle between V_{r1} and the supply voltage, Ψ_1 is given by:

$$\Psi'_1=\tan^{-1}\left[-\frac{\alpha}{2}-\tan\left(\frac{\alpha}{2}\right)*\left(\frac{\pi-\alpha+\sin\alpha}{\pi-\alpha-\sin\alpha}\right)\right] \qquad (6)$$

The variations of the motor voltage with the firing angle α under the three switching strategies are shown in Fig. 5. It is clear that the fundamental component of the motor voltage in MPAC and EAC are the same for any value of α. But the fundamental component of the motor voltage in SAC is differ than the values of MPAC and EAC for values of α.

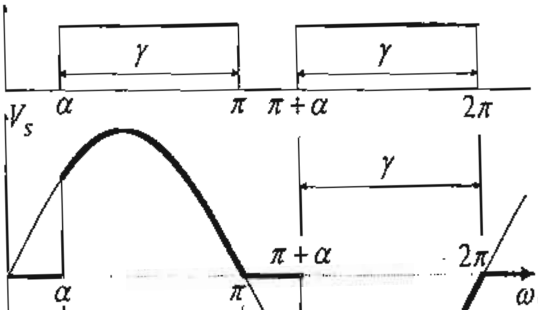

Fig. 2. Switching function and motor-terminal voltage of one of series switches in case of MPAC.

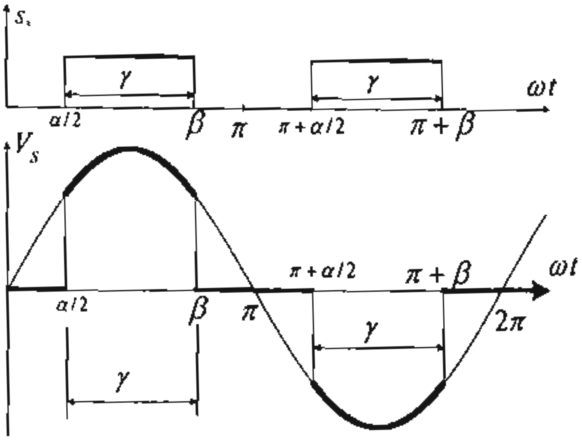

Fig. 3. Switching function and motor-terminal voltage of one of series switches in case of SAC.

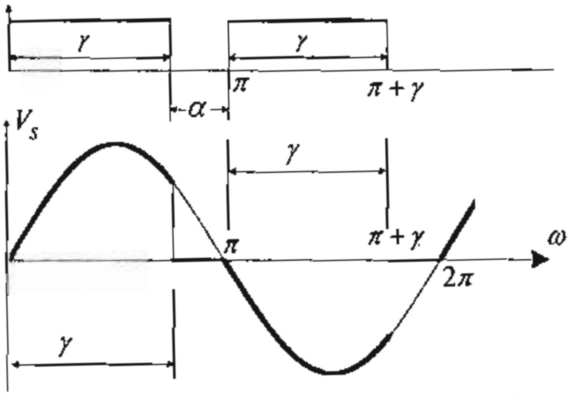

Fig. 4. Switching function and motor-terminal voltage of one of series switches in case of EAC.

IV. SIMULATION AND EXPERIMENTAL WORK

The simulation of the system under study for different strategies has been carried out by using PSIM computer program [12]. The induction motor used in the simulation and experimental study is a 380V, 3.81 A, 1.0 kW, 60 Hz and 4 poles. Its parameters are shown in Table(1).

Table (1) The induction motor parameters.

R_s Ω	R_r Ω	$L_s=L_r$ H	L_m H	n, rpm
3.13	1.74	0.008334	0.136873	1770

In the system under study the standard parallel port of the PC is used to generate switching signals for each strategy. PC parallel port is a D-shaped female connector and has 25 pins as shown in Fig. 6. It provides eight output pins (2-9), five input pins (10-13,15), four bidirectional pins (1,14,16,17) and pins (18-25) are all ground pins. High level programming languages such as Visual Basic is used to driving the parallel port of PC. Due to slow timers supplied with Visual Basic programming language a high resolution timer must be developed by using the API (Abdication Programming Interface) functions which are available in the Windows system.

It is necessary to synchronize the output parallel port pulses with the supply voltage. So, zero-crossing detector should be used to send a pulse to the program in the beginning of each cycle via the input pins of the parallel port. Zero crossing detector is designed using op-am as shown in Fig. 7. Opto-coupler isolator has been used to isolate the parallel port pins from the power circuit. The opto-coupler used in the circuit is 4n32. Six opto-couplers are used between the output pins of parallel port and the gate of each switch. Also a suitable resistor between the output pin and the opto-isolator to limit the current to value less than 5mA to protect the parallel port of PC from high output current. A different dc power supplies are designed for biasing different control circuits.

The experimental results are obtained from the laboratory prototype shown in Fig. 8. Fig. 9 shows the signal of s_a along with phase a voltage for MPAC (as an example) at α =30°. Fig. 10 shows the switching signals S_a, S_b and S_c at the output of opto-coupler in case of α =30° as an example.

Figs.10 to 12 show the phase voltages at the motor terminals, the supply current and the motor current with respect to its phase voltages at α =30° for MPAC, SAC, and EAC, respectively.

Fig. 13 shows the variation of fundamental component of motor terminal voltage with motor speed for different control strategies. It is clear from this Fig. that the motor speed variation with motor voltage is the same for all control strategies. Fig. 14 shows the efficiency with motor speed. It is clear that the MAC and EAC have better efficiency compared with SAC technique. This high efficiency is due to the low harmonic distortion in the supply and motor currents in these two techniques. Fig. 15 and Fig. 16 show the simulation and experimental results of the THD of supply current and motor current with motor speed for different control strategies. It is clear that the THD of supply current in case of using MPAC is better than the two other techniques. It is also clear from that the THD of motor current of MPAC and EAC better than the SAC. Fig. 17 shows the simulation and experimental results of the power factor with motor speed. The power factor of EAC is lagging only in high speeds and become leading in lower speeds.

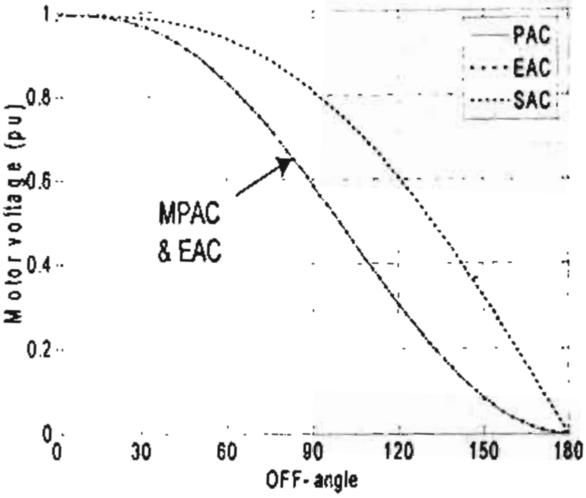

Fig. 5. Variation of motor terminal voltage with the OFF angle α for MPAC, SAC, and EAC.

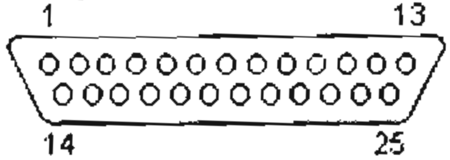

Fig. 6. PC parallel port, D-shaped female connector.

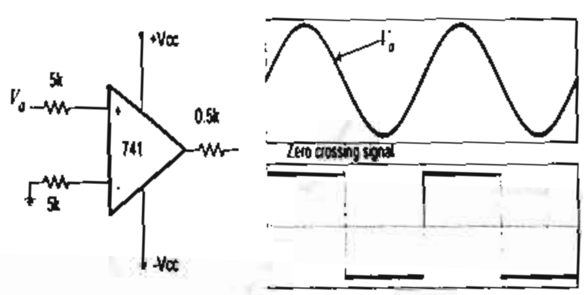

Fig. 7. Zero crossing circuit and its output signal along with phase a voltage.

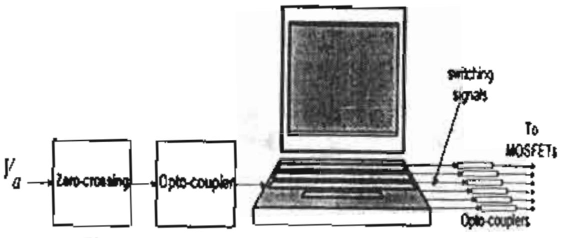

Fig. 8. The proposed control system.

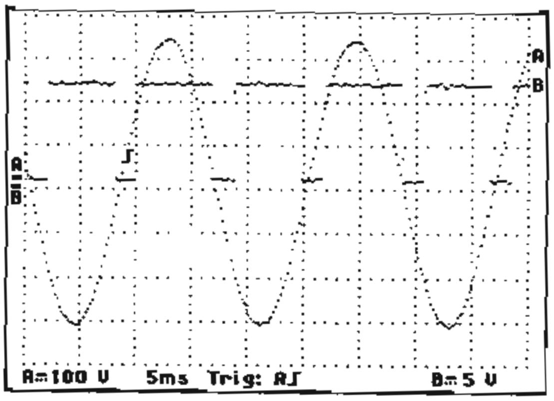

Fig. 9. The signal of Sa along with phase a voltage for MPAC $\alpha=30°$.

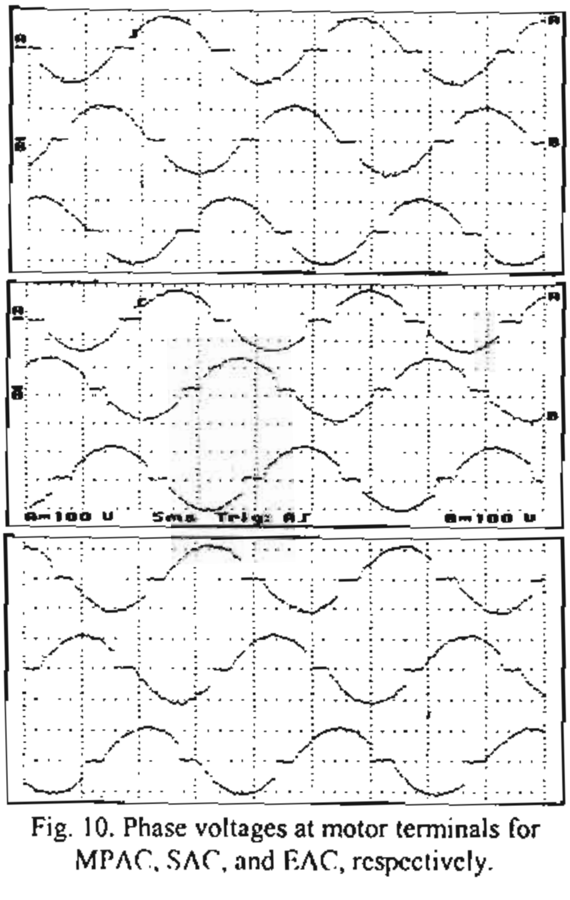

Fig. 10. Phase voltages at motor terminals for MPAC, SAC, and EAC, respectively.

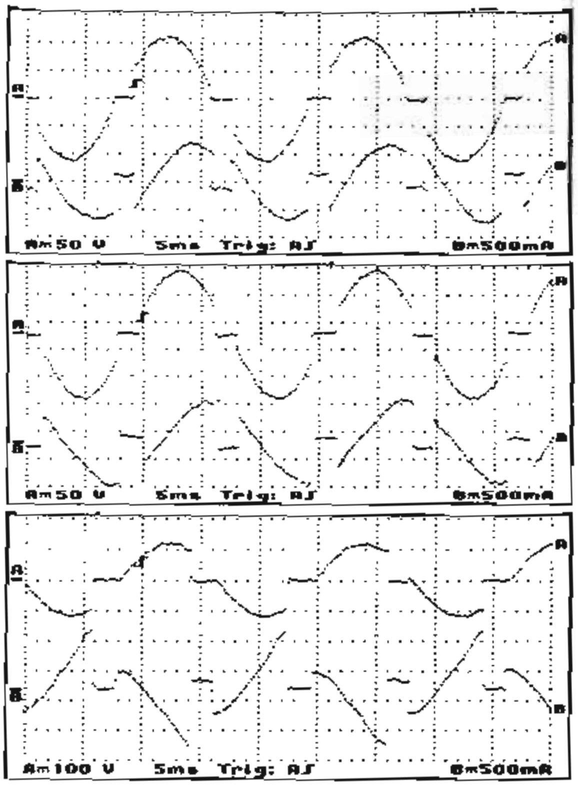

Fig. 11. Motor voltages and supply current of phase *a* for MPAC, SAC, and EAC, respectively at $\alpha=30°$.

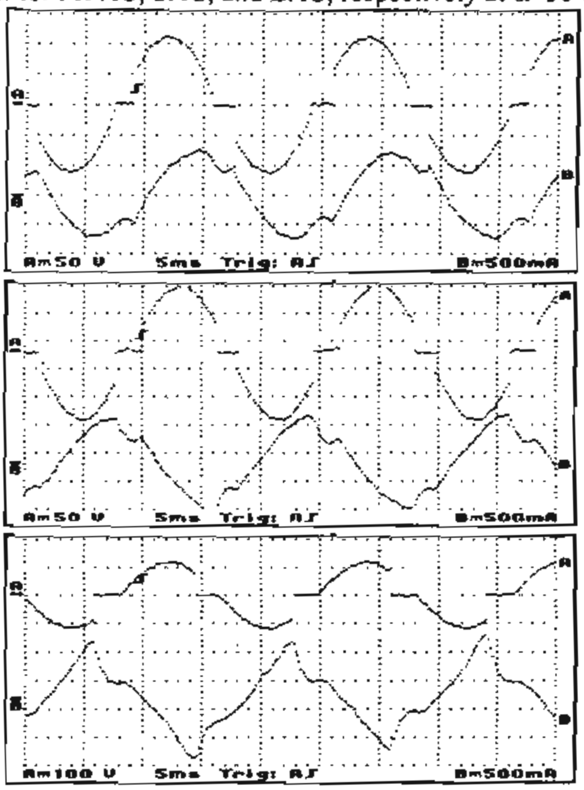

Fig. 12. The voltage at the motor terminals and motor current for MPAC, SAC, and EAC, respectively at $\alpha=30°$.

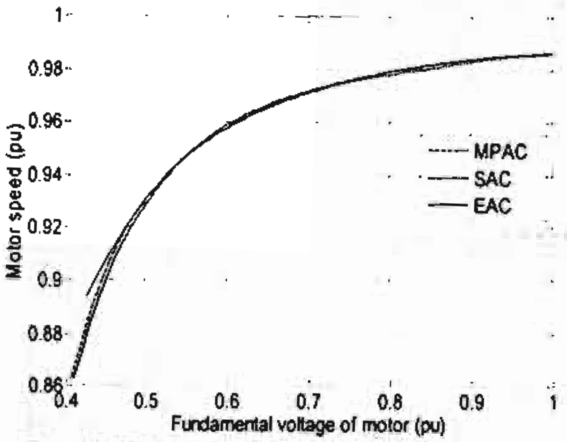

Fig. 13. The fundamental component of motor terminal voltage with motor speed for different control strategies.

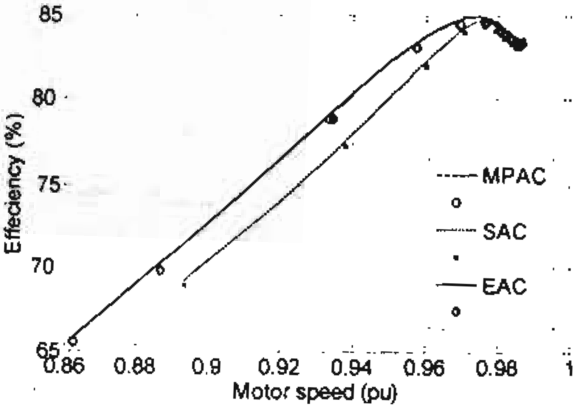

Fig. 14. The efficiency with motor speed for different control strategies.

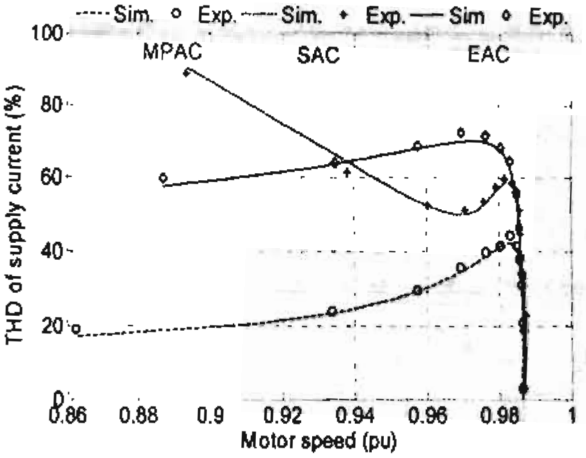

Fig. 15. THD of supply current with motor speed for different control strategies.

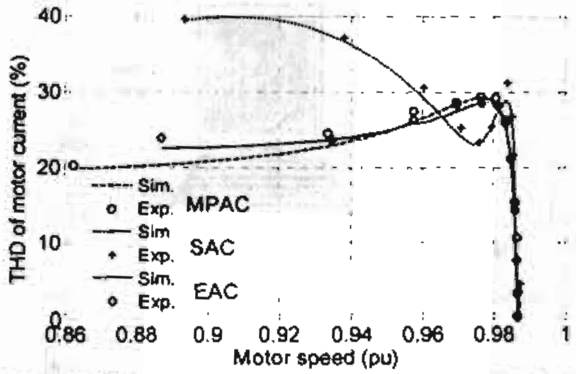

Fig. 16. THD of machine current with motor speed for different control strategies.

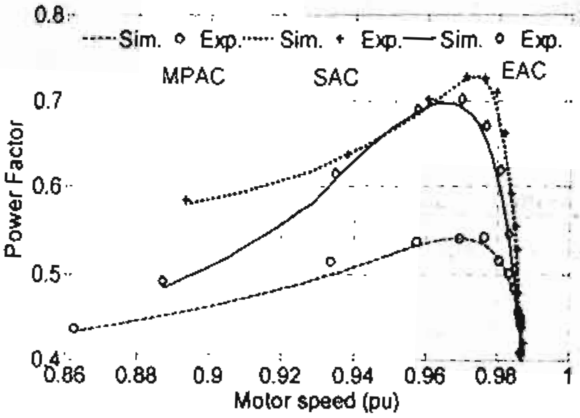

Fig. 17. Power factor with motor speed for different control strategies.

V. CONCLUSIONS

Three-phase ac choppers provide a simple and low cost option for speed control and starting of three-phase induction motor. Invention of modern fast switches as IGBT and MOSFET improves the performance of ac voltage regulators. Three control strategies have been analyzed for speed control of thee-phase induction motors. The simulation using PSIM computer program and experimental results from a laboratory prototype reveal that all switching strategies give high level of harmonics in supply and motor currents. Because of these high harmonic levels, it is recommended to use input filter. EAC has a high power factor and they goes to be leading at low speeds. EAC strategy has a better performance compared with the other two techniques. So, it is recommended to use EAC in three-phase ac choppers for induction motor control.

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