AC-AC Voltage Regulator Conditioning Converter with Three Control Schemes

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Abstract – In this paper, a comparative study of modified phase-angle, extinction-angle, and pulse width modulation control techniques for the purpose of power factor improvement of single-phase AC-AC voltage regulators have been illustrated as applied to a single-phase ac voltage converter by an example of the widely used single-phase induction motor as a dynamic load. Observations on power factor, displacement factor and total harmonic distortion factor are described and discussed on the basis of the simulated and measured results of this work.

I. INTRODUCTION

AC voltage converters have been widely used in induction motor drive systems. These drive systems are normally negatively viewed as they contribute to the deterioration of the supply power factor and to the high line current harmonic contents. Phase-angle control line commutated voltage controllers and integral-cycle control of thyristors have been extensively employed in this type of converters for many applications. Such techniques offer some advantages as simplicity and the ability of controlling large amount of power economically. However, it suffers from inherent disadvantages such as; retardation of the firing angle causes lagging power factor at the input side especially at large firing angles, high low order harmonic content in both of load and supply sides. Moreover, a discontinuity of power flow appears at both input and output sides [1]-[5]. Also in the conventional phase angle control technique, the input power factor is poor and decreased with increasing the firing angle [6]-[8].

On the other hand, the efficiency of a squirrel cage induction motor reaches its maximum at rated load. At light loads, the machine becomes quite inefficient; since the phase of the stator current is lagging, this results in a poor power factor. Such a behavior can be explained by the fact that a constant supply voltage is usually applied to the machine and under decreasing load conditions; the internal impedance of machine becomes mainly reactive [9]. Therefore, it is very difficult to make a clear choice for the best method of the ac voltage control technique. Efficiency is a prime factor, but more and more attention is given today, by the utilities, to the power factor. Probably some compromise, taking into account both the efficiency and the power factor, should lead to the realization of what could be called an electronic variable transformer.

Trying to resolve this dilemma with simple ac voltage converters is an almost impossible task. On the other hand, adding a complex controller costing several times the price of the motor is in itself an objectionable solution.

Studies have been made to propose different methods of varying the operating stator voltage of an induction machine under light load. One of these recent studies shows that for any load condition, some applied voltages yield minimum input power and maximum efficiency. Furthermore, trying to optimize the input power factor results in a performance that falls notably short of maximum efficiency [10].

The main objective of this paper is to present simple scheme to generate a variable ac voltage directly from the line employing power factor improvement techniques with comparative study between these techniques. Secondary objective is applying these control techniques for the speed control of the widely used single-phase induction motor and also to give comparative results on motor speed, power, power factor, displacement factor and overall system efficiency.

This paper is aimed at using the modified phase-angle control (PAC), extinction-angle control (EAC), and pulse width modulation (PWM) techniques to control both the firing and extinction angles by the make use of forced commutations of switches and to introduce a freewheeling path in parallel with the load terminals. The proposed ac voltage converter employs only two controlled switches with the aid of two diode bridge rectifier. Reducing the number of controlled switches is essential for the control simplicity, cost, reliability, decreasing the switching losses and therefore enhances the converter efficiency.

The modified PAC [11], [12] is a special case of symmetrical PWM where there is only one pulse per half-cycle. In the conventional phase-angle control the conduction is started at $\omega t = \alpha$ and continued until the current reaches zero value naturally, while in the modified phase-angle control the conduction is forced commutated at the zero crossing of the supply voltage and a freewheeling path is provided for the load current to discharge the stored energy of the load inductance. The switching frequency used is double the supply frequency.

The extinction-angle control (EAC) is similar to that with phase-angle control where there is only one pulse per half-cycle. In the phase-angle control the conduction is started at $\omega t = \alpha$ and continued until the current reaches zero value naturally, while in the EAC control the conduction is started at zero crossing of the supply voltage, forced commutated at the $\omega t = \pi - \beta$ and also a freewheeling path is provided for the load current to discharge the stored energy of the load inductance. The output voltage is controlled by varying the extinction angle β. The fundamental component of input current leads the input voltage, and the displacement factor (and power factor) is leading. In some applications, this feature may be desirable to simulate a capacitive load and to compensate for line voltage drops [8].

The PWM technique is similar to the modified PAC except that it can be operated at a high switching frequency operation instead of the low switching frequency (double supply frequency).

II. CIRCUIT DESCRIPTION and PRINCIPLE of OPERATION

Fig. 1 shows the schematic representation of the power circuit configuration, which consists of a single-phase induction motor connected to an ac source through an ac voltage converter. The forward switch S_1 is used periodically to connect and disconnect the load to the supply, i.e. regulates the power delivered to the load. The parallel switch S_2 provides a freewheeling path for the load current to discharge the stored energy of the load inductance when the forward switch S_1 is turned off.

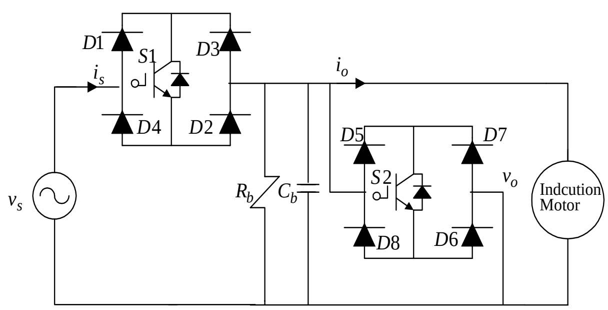

Fig. 1 Configuration of ac voltage converter fed single-phase induction motor.

Due to non-ideality of the switching devices, a dead time is introduced to avoid commutation problem and a by-pass capacitor C_b is added parallel to the load in order to provide a path for the current during the dead time when both switches are opened. When the forward switch S_1 is turned on, the by-pass C_b is charged by the supply voltage and to bleed this accumulating charge, a bleeding resistance R_b is added parallel to the by-pass capacitor C_b. Both the capacitor C_b and the resistance R_b constitute the by-pass circuit.

The operation modes are divided into three modes: active, dead time and freewheeling modes. The current conducts through the input and output sides, providing energy to the load during the active mode, freewheels through the freewheeling path during the freewheeling mode and bypasses during the dead time mode. Detailed description of these modes is found in [11].

III. PERFORMANCE of TESTED CONVERTER

This section presents a comparative performance evaluation of the ac voltage converter with the different control techniques by simulation using MATLAB Simulink package and experimentally by using a prototype model rating 1.1 kVA, 220 V, 5A where the used power electronic switches are MG50J2YS1 (600V, 50A) IGBT'S and PSB 35/14 (1400V, 35A) diode bridge rectifier.

Test Motor

The proposed power factor improvement control techniques have been applied to a dynamic load represented by a 1/6 Hp, 180 V, 1.8 A, 50 Hz split-phase squirrel cage induction motor coupled to a fan as a mechanical load to obtain variable speed operation. The test motor parameters are:

R_m =7.25 Ω	X_M = 7.81Ω
M = 101.81 Ω	P = 2
R_r = 7.08 Ω	X_r = 3.9Ω
R_a = 15.6 Ω	X_a = 11.2Ω

Detailed analysis of the motor performance equations is found in [13]. The obtained simulated and experimental results will be discussed in the following; for all figures the solid line refers to simulated results while circles represent the measured results:

Fig. 2 shows the variation of the simulated and measured rms values of the motor applied voltage with the firing angle for both conventional and modified PAC.

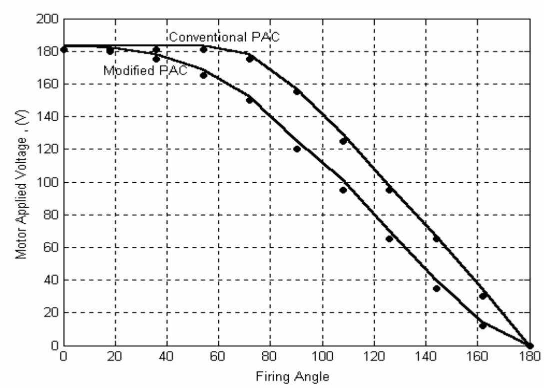

Fig. 2 Motor applied voltage versus the firing angle.

Fig. 3 depicts the variation of the simulated and measured rms value of the motor applied voltage with the extinction angle for EAC technique.

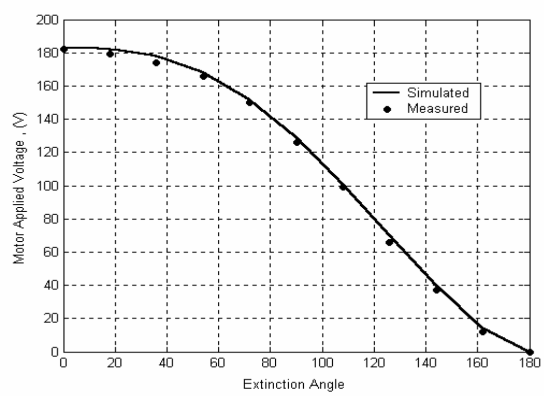

Fig. 3 Motor applied voltage versus the extinction angle.

Fig. 4 demonstrates the variation of the simulated and measured rms value of the motor applied voltage with the duty cycle for PWM technique.

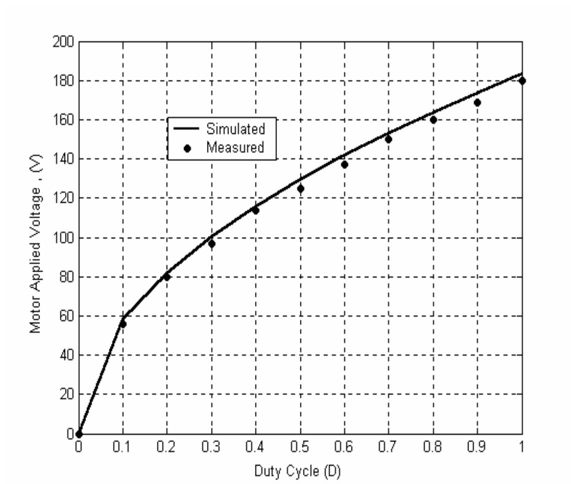

Fig. 4 Motor applied voltage versus the duty cycle.

Fig. 5 demonstrates the variation of the displacement factor versus the rms output controller voltage; the positive sign refers to lagging displacement factor while negative sign refers to leading displacement factor. It must be mentioned that the PWM technique is superior from the displacement factor point of view. However, the displacement factor in the EAC technique gets improved from the load power factor and becomes leading as the extinction angle β exceeds the load angle Φ, which is the reason for the leading nature of the power factor in EAC.

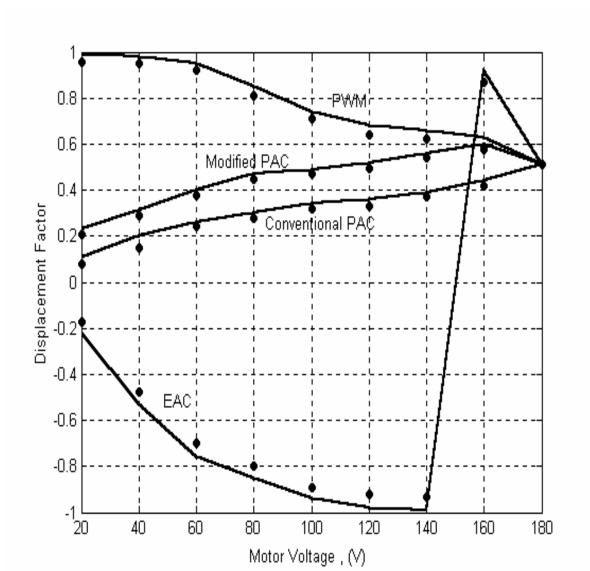

Fig. 5 Variation of the displacement factor versus motor voltage with different control techniques.

Fig. 6 shows the variation of the input supply power factor for the three control techniques, compared with the conventional PAC, versus the rms output controller voltage where positive values refer to lagging power factor while negative refer to leading power factor. It is evident that the EAC technique is superior from the input supply power factor improvement point of view as the input supply power factor not only improves but it gets improved from the load power factor and becomes leading as the extinction angle β exceeds the load angle Φ. However, the PWM technique is better than the modified PAC for improving the input supply power factor without using any input filters. Also, if input supply power factor is required to be more improved with PWM, a small input filter can be used, as the filter size is inversely proportional to the switching frequency.

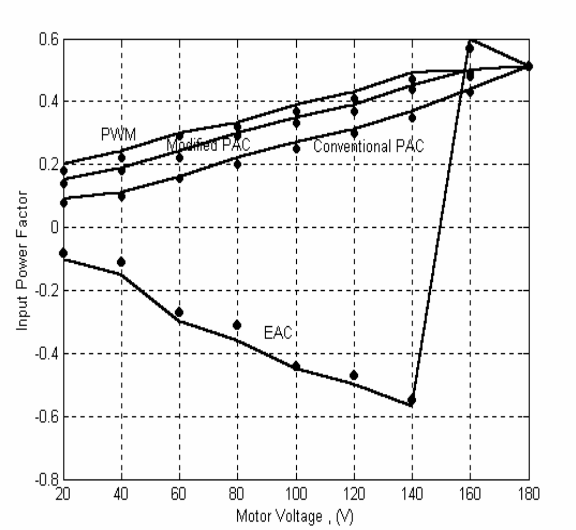

Fig. 6 Variation of the input power factor versus motor voltage with different control techniques.

Figs. 7, 8 and 9 give the variation of the input power factor with the motor slip with different control techniques.

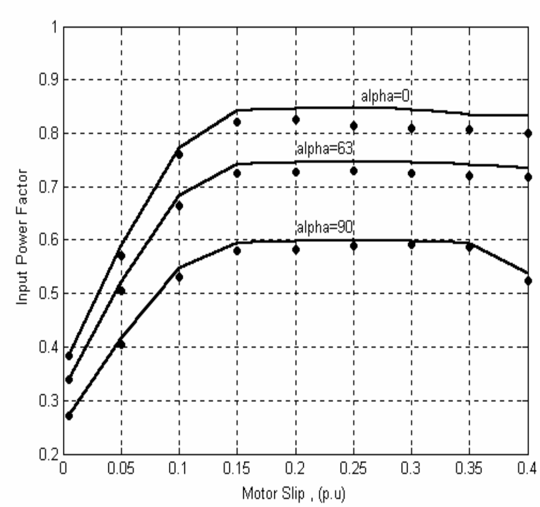

Fig. 7 Variation of the input power factor with the slip for modified PAC technique.

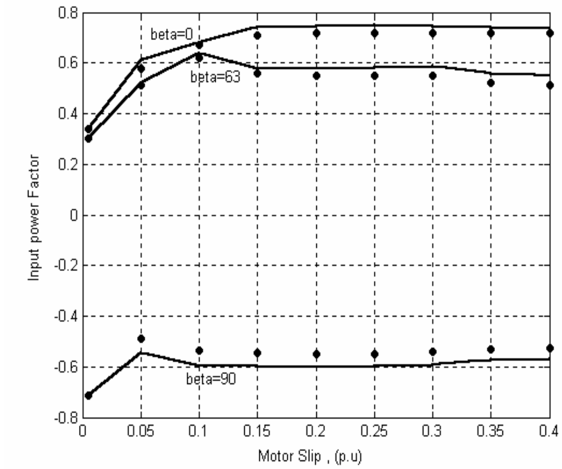

Fig. 8 Variation of the input power factor with the slip for EAC technique.

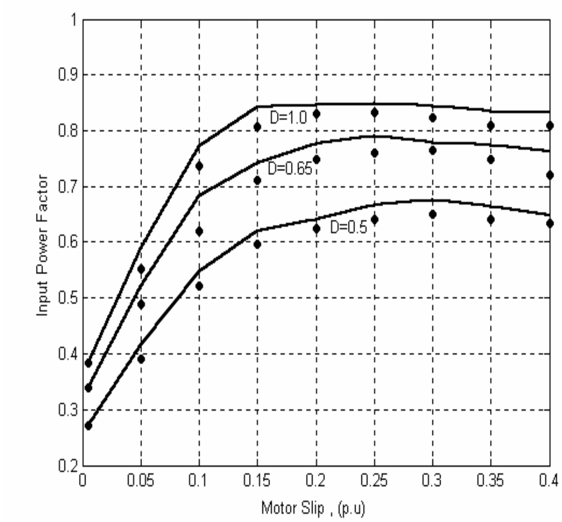

Fig. 9 Variation of the input power factor with the slip for PWM technique.

Fig. 10 illustrates the variation of the total harmonic distortion *THD* factor of the input supply current versus the rms controller output voltage. Although EAC technique offers the best results for input supply power factor, it offers the worst results for *THD* in input supply current, especially at high extinction angles due to the forced commutation of switches. Also, the modified PAC gives *THD* nearly similar to PWM in its value but the high frequency operation with PWM technique shifts the input supply current harmonic contents towards the high frequency values which facilitate the filtering requirements. However, the lower order harmonics are cancelled in the load and supply sides while the harmonics near the switching frequency and its multiples are easily filtered by a filter tuned with the switching frequency.

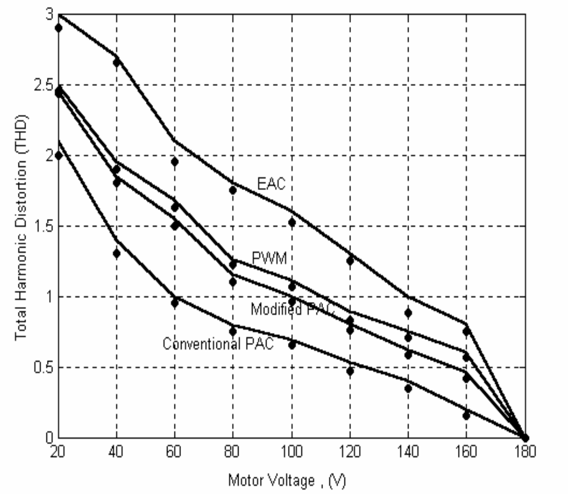

Fig. 10 Variation of the *THD* of input current versus motor voltage with different control techniques.

Figs. 11, 12 and 13 give the variation of the motor speed with different control techniques.

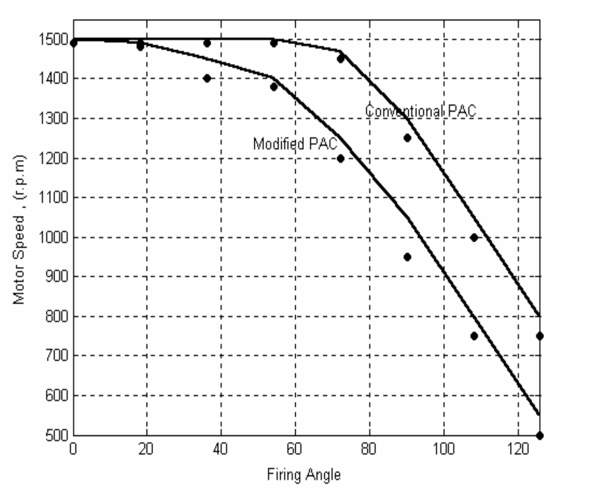

Fig. 11 Variation of the motor speed with the firing angle for modified PAC technique.

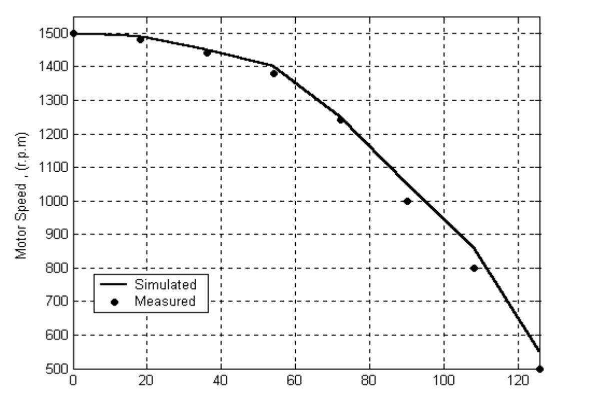

Fig. 12 Variation of the motor speed with the extinction angle for EAC technique.

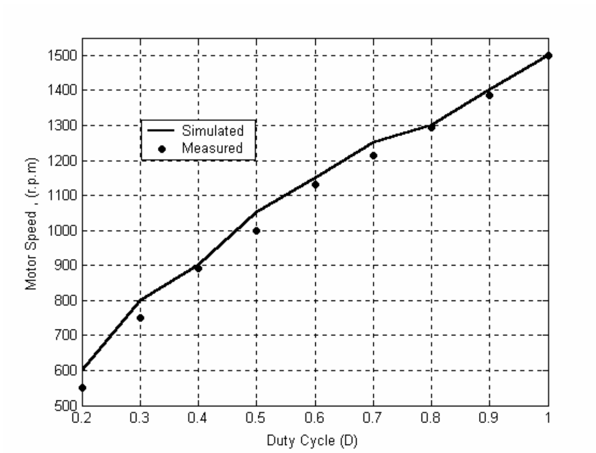

Fig. 13 Variation of the motor speed with the duty cycle for PWM technique

Fig. 14 demonstrates the variation of the motor efficiency versus the motor voltage with the different control techniques where PWM is considered the best technique from motor efficiency point of view as shown in Fig. 14.

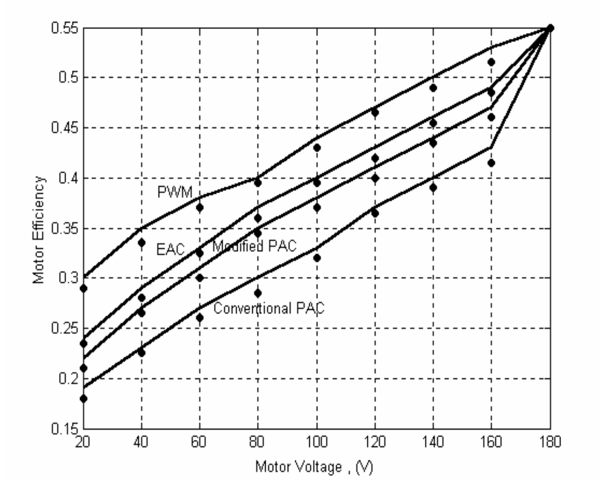

Fig. 14 Variation of the motor efficiency versus motor voltage with different control techniques.

IV. CONCLUSIONS

Comparative study with different power factor improvement techniques for single-phase AC-AC voltage regulators has been presented. The EAC technique was found to be superior from utility AC side power factor improvement point of view as the utility supply power factor not only improved from the load power factor but it became leading as the extinction angle exceeds the load angle. This improvement was mainly due to the significant improvement in the displacement factor. The PWM technique shifts the harmonic contents towards high frequency levels which facilitate the filtering requirements.

In the future the advanced AC-AC voltage regulator using reverse blocking IGBT's should be evaluated and discussed.

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