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Full Length Research Paper

Supply power factor and load current harmonic performance improvement of three phase AC voltage controller

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AC voltage controllers as power converters used in many application between power ranges from few watts up to fractions of megawatts, such as light dimmers, induction motor soft starter, industrial heating and cycloconverters. Overall efficiency of power system controlled by some advanced methods in power converters is very important which covers supply and load power factor, harmonic distortion at both supply and load side. One of these advanced methods that is best used is the conventional controller, with phase angle control (PAC) of thyristors and it is a known method in contolling AC voltage applied to specific loads. However, these controllers are found to create some problems whose main problems are introduction of high level low order harmonics in current at the load and supply side, poor supply power factor and also low efficiency. This paper presents a proposed three phase AC voltage contoller scheme which allows the application of extinction angle control (EAC) to overcome these problems. Also, a comparison is given between proposed and conventional controllers on the basis of simulation under this viewpoints. The improvements are obtained in terms of high supply power factor, low harmonic content in the load current and high efficiency by proposed controller on comparing to conventional controllers.

Key words: AC voltage controller, soft starter, thyristor, power factor, harmonic.

INTRODUCTION

Conventional AC voltage contollers consist of back to back connected of SCRs or triac as the power switch to control the output voltage. So, conventional controllers in which voltage is adjusted through employing PAC technique are used to control the AC voltage fed to any specific load. Thus, root mean square (rms) load voltage and power flow can be adjusted and preserved at a settled desired value. In consequence of the ability of adjusting of AC voltage applied to load, these controllers are used in many power electronics application, such as soft starter, heating, melting, wind turbines and so forth (Sueker et al., 1989; Gastli and Ahmed, 2005).

Many studies about PAC technique have been presented in literature and operation of AC voltage controllers that have been explained in details (Sen, 1987; Asghar, 2004). Phase control technique is reliable and has the ability to control large amount of power (Sivaranjani and Ramakrishnan, 2006). Conventional AC voltage controllers provide some advantages as low cost and simplicity. However, they suffer from inherent disadvantages as; retardation of firing angle, causes lagging current at supply side especially at large firing angles, thereby, resulting in poor supply power factor and high level low order harmonic content in both load and supply sides (Willliams, 1981; Barbi et al., 1991). Moreover, a discontinuity of current flow appears at both supply and load sides (Lock, 1987; Xu, 1992)

The performance of AC voltage controllers can be improved considerably by proposed scheme presented in this paper. Instead of SCRs used in conventional AC voltage controllers, employing IGBT's with series blocking diode that provides specific advantages as; leading current at supply side and thereby, resulting in higher supply power factor, lower low order harmonic content in load side. Besides, a discontinuity of current flow does not appear at load. It is useful to clarify that both methods have a constant load power factor angle for same value of load. Proposed scheme is made up of three dead time

Table 1. Simulated circuit parameters.

Parameter	Value
Maximum supply voltage	$220\sqrt{2}$ [V]
Supply frequency	50 [Hz]
Switching frequency	100 [Hz]
Dead time capacitor (only for proposed scheme)	10 [µF]
Load resistance	2 [Ω]
Load inductance	0, (1,7), (3,6), (6,3), (11), (23) [mH]
Load phase angle corresponding to value of load resistance and inductance	0, 15, 30, 45, 60, 75° (degree)

capacitor and twelve IGBTs as controlled switches with twelve series blocking diodes. Table 1 shows simulated circuit parameters for resistive and inductive loads.

Obtained waveforms of the phase currents and voltages are only for 30° of load phase angle. As the low order harmonics in the phase voltages and currents, only 3, 5, 7 and 9 order harmonics are investigated with variations of firing angle for 30° of load phase angle. Both total harmonic distortion (THD) in phase voltages and currents and supply power factors are examined for 0, 15, 30, 45, 60, 75° of load phase angle with variations of firing angle.

This paper introduces a proposed scheme for three phase AC voltage controller and gives a comparison based on simulation of Matlab/Simulink between proposed scheme and three phase conventional AC voltage controller with respect to power factor, harmonic performance of load current and efficiency.

CONVENTIONAL THREE PHASE AC VOLTAGE CONTROLLERS

In this section, one of the most common used conventional AC voltage controllers is introduced superficial and operation of it revealed. Scope of the figures obtained is based on Matlab/Simulink, belongs to operation form at specific values of firing and load phase angle, is about supply power factor, harmonic performance of load current and efficiency.

Description of the conventional scheme

Power flow can be controlled by varying rms value of the AC voltage applied to load by means of thyristor pairs connected back to back which are linked between three phase balanced supply and load series. This kind of power converter is known as an AC voltage controller. In spite of the fact that, there are many configurations for AC voltage controllers, conventional three phase AC voltage controller shown in Figure 1 is one of the most practical and frequently used configuration for high power industrial applications (Bose, 2006). In the branch-controlled circuits of Figure 1, each phase of AC voltage controllers operates independently from other two phases controllers (Malik et al., 1985; Muhammad, 1993). Since the supply voltage is AC and the thyristor is branch commutated, there is no need of extra commutation circuit and hence, conventional AC voltage controllers are simple and inexpensive (Ashou and Ibrahim, 2006).

Principle operation of the conventional scheme

In conventional controllers, power flow to the load can be controlled with PAC technique which sets off thyristor firing angle (α). As for firing angle α, it can be measured from the zero crossing of phase A voltage (Gastli and Ahmed, 2005). In PAC, a pair of phase-controlled inverse-parallel connected thyristors or a triac are commonly used to obtain the desired voltage variation. By delayed thyristor firing, the rms value of the load voltage and consequently current and power can be controlled (Malik et al., 1985). The six thyristors in Figure 1 are fired according to the supply phase voltages with a resistive load ($\varphi=0°$), α variation has to be in the range $0° < \alpha < 180°$ to control load current I_A. With a load phase angle (φ), I_A is controlled by α only in the range $\varphi < \alpha < 180°$. For $\alpha < \varphi$, control is lost and full sinusoidal current flow in the supply at a natural load phase angle.

It is explanatory to point out that minimum firing angle (α), extinction angle (β) and load power factor or phase angle (φ) are identical to each other. In case of inductive load, the current is not going to be in phase with controlled AC voltage at load side and this causes some troubles as poor supply power factor and high low order harmonic content at both supply and load side especially for large firing angles (Willliams, 1981; Barbi, 1991). Companion wave-forms of phase voltage and current for $\alpha = 90°$ and $\varphi = 30°$ both supply and load side are shown in Figure 2.

Power factor relationships in conventional scheme

The most important limitation of conventional AC voltage controller is poor supply power factor. Supply power factor for resistive loads is described as; as seen in

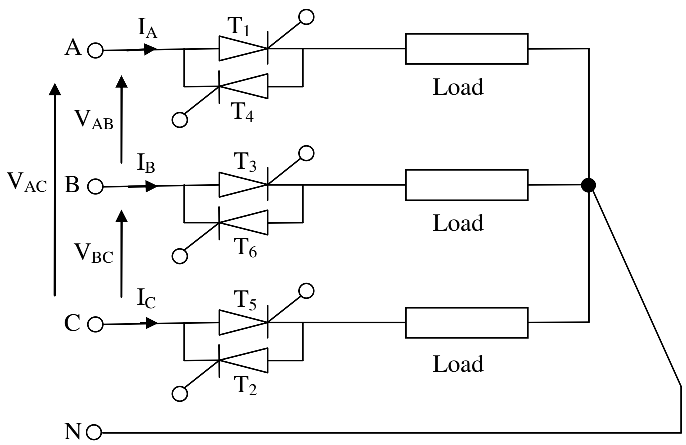

Figure 1. Three phase AC voltage contoller with four wire branch-controlled star connected load.

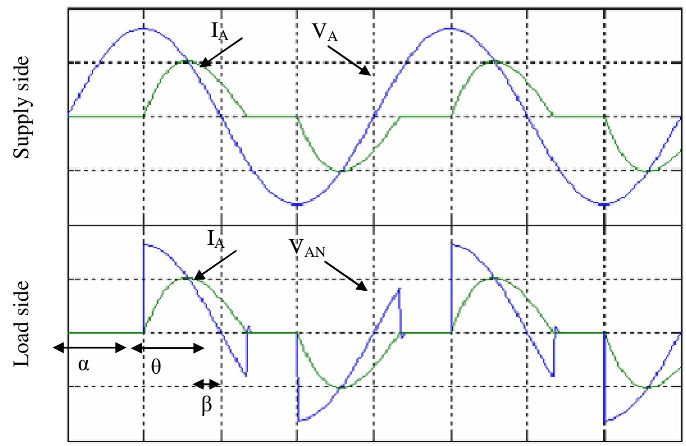

Figure 2. Voltage and current waveforms for α = 90° and φ = 30°.

$$PF_S = \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \qquad (1)$$

Equation (1), if firing angle increases, supply power factor decreases. For inductive loads, this decreasing of supply power factor starts from load power factor angle (or say, load phase angle), as to load power factor, that is, equal to cosine of load phase angle. These relationships are shown in Figure 3 for different loadpower factor angles.

It is comprehended from Figure 3 that, supply power factor is equal to load power factor until firing angle goes by load phase angle, because control of AC voltage is impossible without that, AC voltage control becomes available as soon as firing angle leaves load phase angle behind. And so, supply current is more lagging than load current and larger firing angle makes supply power factor more lagging.

Harmonic relationships in conventional scheme

The other most important limitation are introduction of the harmonics in the supply current, resulted from waveform of load current, since the waveforms of the suppy and load sides current are same. Therefore, the harmonic content in suply current is same as in load current. The harmonic distortion increases and the quality of the input current decreases with increase of firing angle (Nigim and Heydt, 1985; Rodriguez et al., 2009).

As exhibited in Figure 2, firing angle takes a start from load phase angle on. Before this point, voltage control is impossible and pure sinusoidal current flow through load depending on nature of load and supply. By increasing of firing angle, fundamental component of load current decreases and the others have a magnitude depending on formation of load phase voltage resulted from firing angle. Variations of THD with firing angle at different load phase angles for current are demonstrated in Figure 4. THD can be obtained as;

$$THD = \frac{\sqrt{C_2^2 + C_3^2 + ... + C_N^2}}{C_1} \qquad (2)$$

Where, C_N is rms value of the harmonic, N order component and C_1 is the rms value of the fundamental component of the C signal. Note that THD of current is zero due to no control over AC voltage, this provided that firing angle is less than load phase angle. In this case, load phase voltage and current are full sinusoidal.

For the values of firing angle from load phase angle on, THD of current and load phase voltage is increased sharply depending on the harmonic content. This increement is calculated approximately via only the harmonics shown in Figure 4, this shows that fundamental magnitude of the current gets less than the other components for about 160° of firing angle and further values as well. As a result of that, the THD of the current was increased very sharply after this angle.

NEW AC VOLTAGE CONTROLLER SCHEME (PROPOSED SCHEME)

New AC voltage controller scheme (proposed scheme) designed based on control of AC voltage takes part in this section. All details about new scheme and control technique of it are given as associated with power factor and harmonic content at both supply and load side by controlling a static load. Simulation of proposed scheme is implemented based on matlab/simulink.

Description of the proposed scheme

Figure 5 shows the schematic represantation of the power

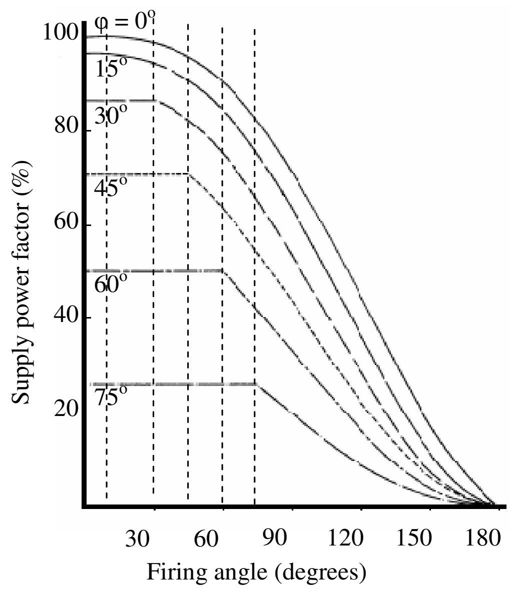

Figure 3. Supply power factor versus firing angle for conventional branch commutaded three phase AC voltage controllers.

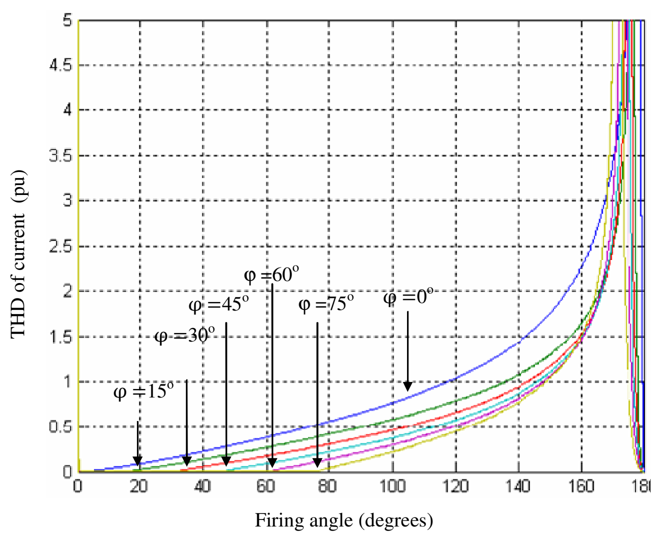

Figure 4. Variations of THD of the current versus firing angle for different load phase angles.

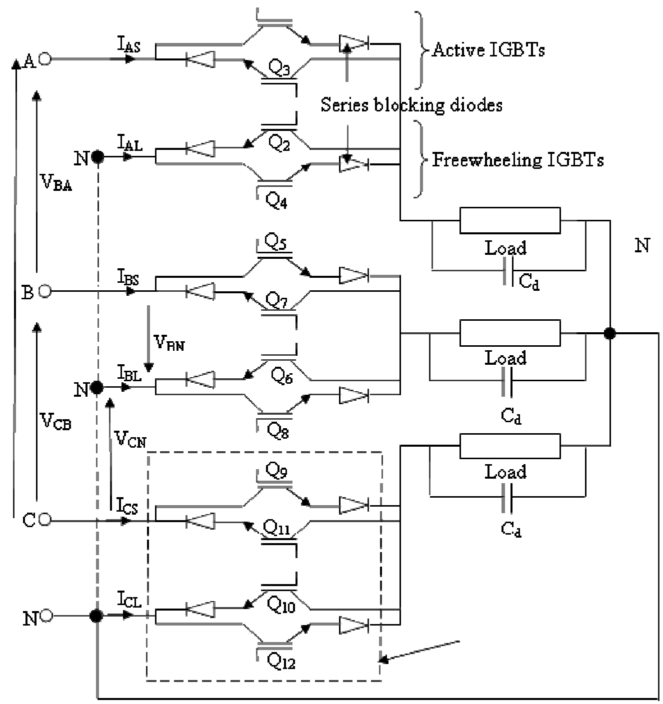

Figure 5. Three phase AC voltage contoller with four wire branch-controlled star connected load.

circuit configuration that contains a four wire star connected static load and connected to an AC supply through an AC voltage controller. This proposed scheme for three phase AC voltage controllers, also, can be used as single phase. Each phase AC voltage controllers operates independently of other two phases controllers.

Each phase which are controlling AC voltage applied to load consists of four IGBTs as two IGBTs are active and other two IGBTs freewheeling mode operation. Inverse diode are used in many application to provide continuity of load current which connected to IGBTs inverse-parallel that are not used in this scheme. Instead of these freewheeling diodes, two IGBTs of freewheeling mode are used to achieve continuity of load current. Reason of that, IGBTs of active mode are in linked series between supply and load for each phase. Consequently, other two IGBTs of freewheeling mode are connected in parallel with the load terminals for each phase. These switches achieves a freewheeling path for load phase current. A capacitor C_d connected parallel between points of load is used for providing freewheeling path during dead time when all switches are turns off.

This capacitor has enough low capacity as much as, it does not affect load phase angle. Sinusoidal supply voltage is applied to power swtiches directly in this scheme. So, power switches used in such power converter are to be symmetric blocking device. Although, thyristor is symmetric blocking device, IGBTs are not. When inverse voltage is applied to a IGBT, a series blocking diode settled in same direction as collector current of IGBT avoids breakdown of IGBT. Therefore, An IGBT as a switch that have conduction characteristic of transistor converted into symmetric blocking device becomes suitable for the controller in this way.

Principle operation of the proposed scheme

AC voltage control is implemented by using EACtechnique in this proposed scheme. EAC technique for AC

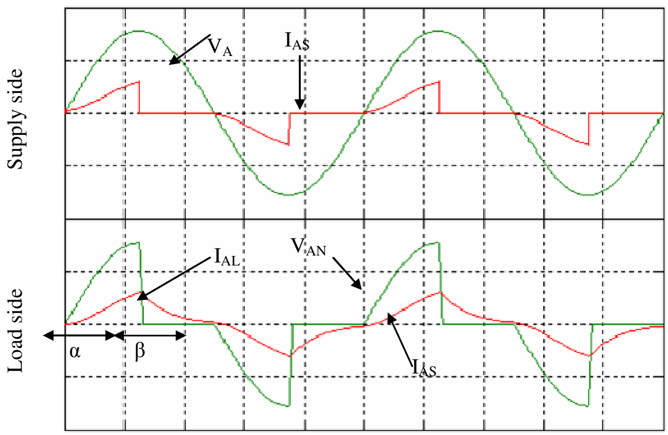

Figure 6. Voltage and current waveforms for α = 90° and φ = 30° .

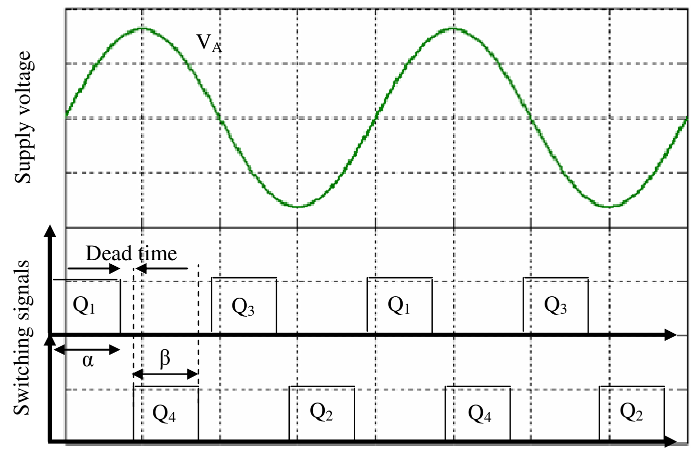

Figure 7. Switching waveforms for α=90° and φ=30°.

voltage controllers was first put forward by Ahmed and El-Zohri (2003), for single phase and then by Eltamaly et al. (2007) improved for three phase induction motor performances analysis. They called control technique used in their study extinction angle control (EAC) and concerned with input (supply) power factor and performance of the single and three phase induction motor they controlled. Proposed new scheme in this study becomes possibility to the application of EAC technique to three phase AC voltage controller. The load current is always continuous in this new EAC technique by means of C_d capacitor. Proposed new scheme utilizes EAC technique, but opposite of PAC technique in terms of firing angle that starts from end of a positive or negative alternance for a period of supply phase voltage. For a inductive load, waveforms of a phase voltage and current at α = 90° and φ = 30° for both supply and load side are shown in Figure 6.

Though, supply and load currents are not same for conventional PAC without φ = 0°, as shown in Figure 6., until firing angle, waveforms of supply and load have same waveform. Hovewer, as from firing angle, supply current is equal to zero and the load current flowing through load is provided by means of IGBTs of freewheeling mode settled in a phase. And so, continuity of load current is guarented. This causes harmonics distortion in the load current reduced and supply power factor increased. If operation is explained schematically; first, active Q_1 switch is conducted at ωt = 0 for a positive alternance of supply voltage and a load I_{AS} current occur was caused by supply.

After Q_1 is turned off at a pecified firing angle (ωt=α=π/2), all switches are remained turning off during a dead time, load current freewheels through dead time capacitor C_d to avoid commutation problem, due to non ideality of switching devices. Moreover, this capacitor protects switching devices against voltage spike due to instantaneous change in current direction. And then, freewheeling Q_4 swtich is conducted for a given firing angle (ωt = α = π/2+dead time), load I_{AL} current occur was caused by discharge of the stored energy of the load inductance. In a negative alternance, Q_3 and Q_2 are conducted in sequence same as positive alternance. In EAC technique firing angle has to be in the range 0° < α < 180° to control load current I_A. I_A and V_{AN} have exacsinusoidal waveform depending on state of load in the case of α = 0° and supply power factor is equal to natural load power factor in this case.

The switching pulses shown in Figure 7 are synchronized with supply voltage and output voltage is controlled by varying the α from 0 to π to vary rms output voltage from rated input voltage to zero. So, the operation is divided into three modes; active, freewheeling and dead time modes.

Direction of the power flow is from supply toward load during the active mode if the current flows from supply to load. During the dead time mode, dead time capacitor provides freewheeling path for load cur-rent. Furthermore, the capacity of capacitor is determined by having enough small capacity so as not to affect the load phase angle φ during the active mode depending on power of load. Also, during the freewheeling mode, freewheeling IGBTs provides freewheeling path up to the end of the alternance in which alternance is present.

Figure 8 shows changing of rms values of the output phase voltage with the extinction angle β. As shown in Figure 8, output voltage characteristics of both PAC and EAC techniques are very similar to each other because the supply voltage is choppen from the end by EAC and from the start by PAC. EAC and PAC control techniques have same switching frequency that is twice as supply frequency. This value is very low for fast switching IGBTs and thereby there is no more switching loss, conduction loss also depends on characteristic of IGBT used in EAC as well.

Power factor and efficiency relationships in proposed scheme

As a result of this kind of using scheme and switching

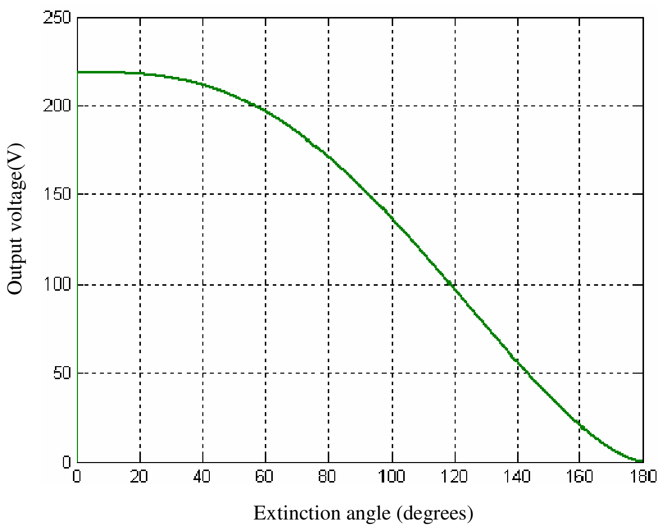

Figure 8. Changing of the rms output voltage with the extinction angle.

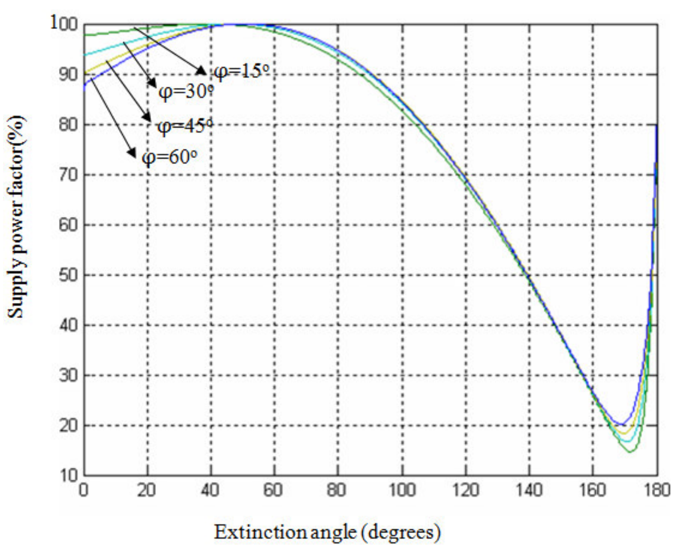

Figure 9. Supply power factor versus firing angle for proposed three phase AC voltage controller.

IGBTs, fundamental component of the supply current leads the supply voltage as shown in Figure 6 and hence, supply power factor is leading. This feature might be desirable for compensating for line voltage drops in some applications. Thus, EAC is similar to PAC, except supply power factor is leading while lagging in PAC.

As shown in Figure 9, all values of supply power factor versus firing angle are very close to each other for all load phase angle. As the rms output voltage decreases the extinction angle increases, the supply power factor is improved gradually from its lagging value and becomes leading after the extinction angle exceeds the load angle and goes more leading as the extinction angle increases.

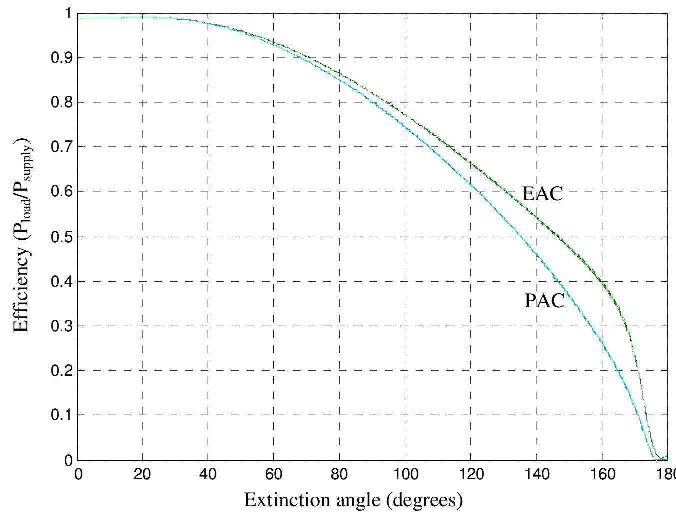

Figure 10. Efficiency versus firing angle (φ=15°).

This characteristics of EAC technique is because of the fact that fundamental component of supply currents leads to relative supply voltage (Ahmed and El-Zohri, 2003). Furthermore, it is necessary to emphasize that supply power factor in EAC depends on α rather than φ largely, on the contrary PAC. Change of efficiency corresponding to related firing angle are shown in Figure 10 and formulized below. As shown in the figure, efficiency is very close to each other before load phase angle. After load phase angle, efficiency develops into more acceptable EAC, particularly for large firing angles.

$$\frac{P_{out}}{P_{in}} \times 100 \qquad (3)$$

Harmonic relationships in proposed scheme

EAC has better THD of load current than PAC. Because, there is continuity of load current if load is inductive. Although, if (α > φ) firing angle is larger than load phase angle in PAC technique, load current develops into discontinuous time, continuity of load current at each instant in time provides better THD in EAC technique. Figure 11 shows THD of load current for different φ. It is clear that, THD characteristic of EAC technique is getting better on condition that inductance rate of load is higher which enlarges the continuity of load current.

CONCLUSIONS

The paper presents employing of new EAC technique on three phase AC voltage controllers. In this context, observed improvements are comprated with PAC. The three phase AC voltage controller with EAC technique has been

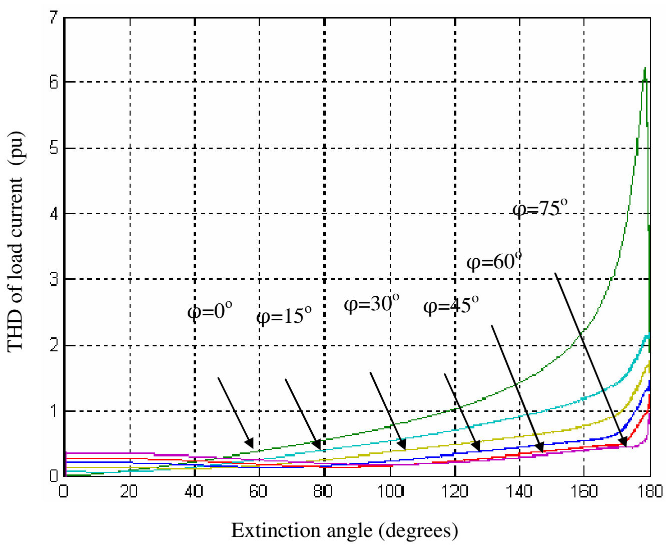

Figure 11. Supply power factor versus firing angle for proposed three phase AC voltage controller.

implemented on only static load based on simulation. The significant improvement in input power factor and efficiency are observed with EAC. Besides, THD of load current are better than PAC, if load characteristic is inductive and higher inductive results are in better THD of load current. When taking into conside-ration, most AC motors have high inductive structure, this capability of EAC is very useful for meeting harmonic troubles like heating up, power loss and torq ripples. Thanks to all improvements obtained, EAC is found efficiency-effective, but PAC technique cost-effective. For static loads, full control range of a high efficiency AC output power are obtained.

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