A NEW AC VOLTAGE BOOSTER WITH UNITY INPUT POWER FACTOR

A.E.Lashine, S.M.R.Tahoun and F.A.Saafan
Department of Electrical Engineering, Faculty of Engineering,
Menoufiya University, Shebin El-Kom, Egypt.

ABSTRACT

This paper presents a new ac voltage booster (ACVB) for inductive or dynamic loads. The new controller has a nearly unity power factor for a change in the load voltage from 100% to more than 200% of the supply voltage. The proposed approach has many advantages, including fewer semiconductor components, simplified control, and negligible distortion in the supply and load current waveforms. The new technique is applied and tested for both inductive and dynamic loads. Theoretical analysis is presented to confirm the experimental results and to show the efficient performance of the proposed system.

Keywords: Switched mode power supplies, AC voltage booster, Power factor improvements, Universal motor.

INTRODUCTION

AC voltage regulators have been widely used to obtain variable ac voltage from a fixed ac source. Phase angle control (PAC) is extensively employed in many applications such as industrial heating, lighting control, and starting and speed control of ac machines. This technique offers simplicity and ability of controlling large amount of power economically. However, a delayed firing angle causes discontinuity and significant harmonics in both the supply and load currents. lagging power factor also occurs at ac side even though the load is purely resistive[1]. A number of static VAR compensators for voltage regulation and power factor correction have been proposed and analyzed [2-4], but phase-controlled inductors introduce harmonic distortion. Thyristors could be used for switched capacitors[5], but voltage spikes and current surges may cause problems. A thyristor-controlled transformer booster have been suggested and examined [6-7], but such a proposal is of limited range and introduce distortion into the voltage waveform. It is possible to obtain thyristor controllers with improved current waveforms[8-10], but large number of thyristors and multi-winding transformer are required. However, the saturable reactor voltage regulator produces improved current waveforms[11-12], but distortion was noticeable at low levels of output voltage. Two alternative methods for realizing unity power factor at the ac source have been proposed [13], but large number of switches and complicated control are required for ac/dc/ac system in the single phase case. A symmetrical PWM technique of an ac chopper, which can improve the input displacement power factor, has been proposed [14], but the distortion factor becomes worse.

The present paper introduces a new ac voltage booster (ACVB) having a nearly unity supply power factor even though the load is inductive. The improvement of input power factor is based on forcing the supply current to be sinusoidally wave-shaped and in phase with the source voltage. The proposed voltage booster is a direct AC/AC voltage regulator, and accordingly, the number of electronic switches is limited and its control is simple. A 500VA prototype circuit is built. Analysis and design of the proposed regulator, along with the experimental results, are reported and discussed. The proposed technique is tested with both static and dynamic loads. R-L load has been used as a static loads, while the dynamic load is represented by a universal motor which is widely used in domestic applications. At constant input power, steady state and starting performance of the motor are reported. An analytical study is carried out and good agreement between measured and calculated results is achieved.

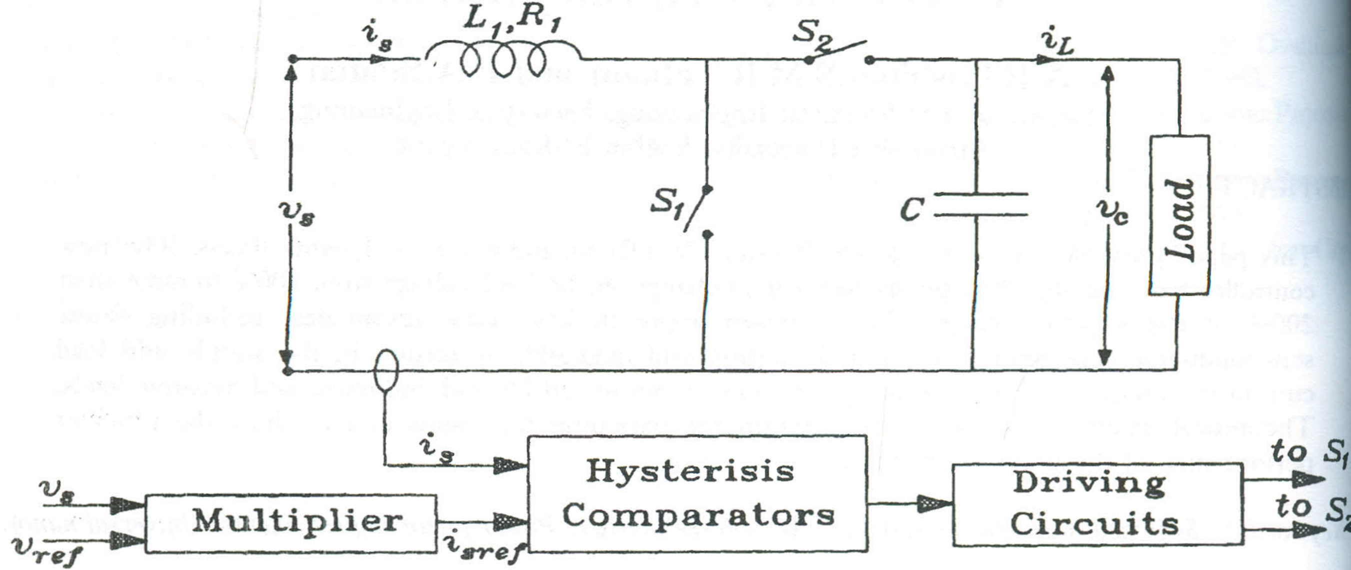


Figure 1. Schematic diagram of the proposed ac voltage boaster (ACVB).

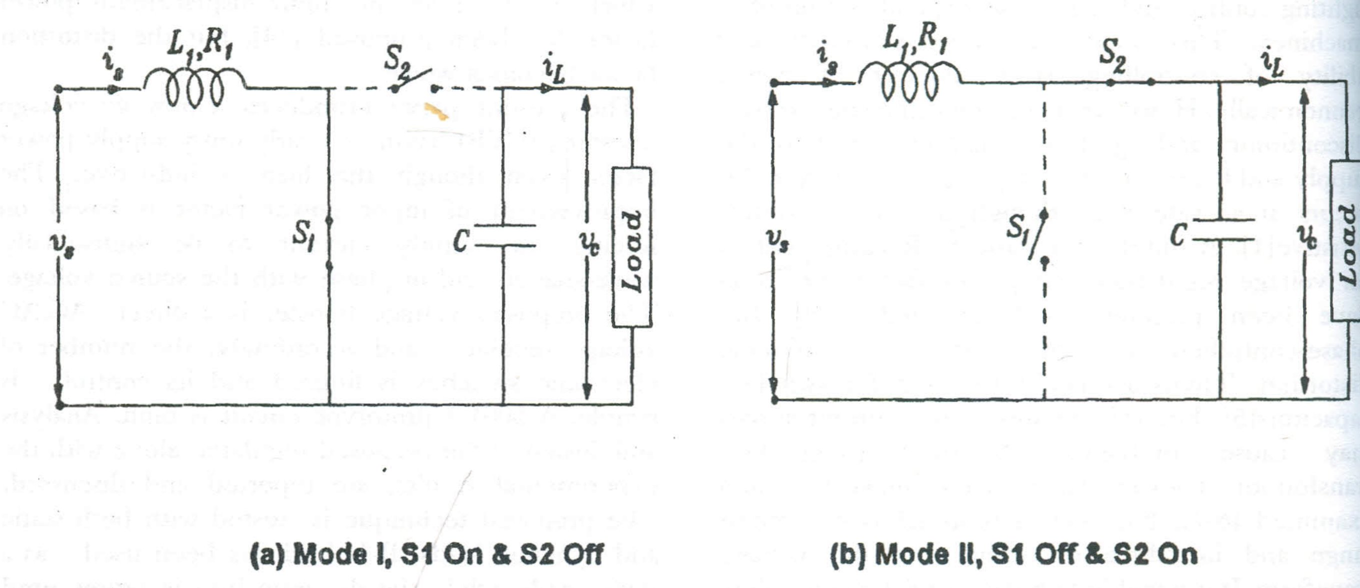


Figure 2. Modes of operation for ACVB.

SYSTEM DESCRIPTION AND OPERATION

Figure (1). illustrates the main components of the novel ac voltage booster (ACVB). The power circuit consists of two electronic switches S_1 and S_2 (IGBTs). Each switch can conduct current in both directions via a fast recovery diode bridge. The capacitor C acts as an energy store. L_1 is used as a boost inductor and also to assist shaping the supply current with the aid of S_1 and S_2. The control circuit consists of a multiplier, two hysteresis comparators width hysteresis width H and driving circuits. The action of this circuit determines the switching pattern of S_1 and S_2 which in turn acts to regulate the supply current and to achieve nearly unity power factor. During the positive half cycle of the supply voltage, if S_1 is on and S_2 is off (Mode I, Figure (2a)), the inductor L_1 is connected to the source via S_1. Therefore, the supply current i_s and accordingly the energy stored in the inductor increases. When i_s increases to be more than or equal to $(i_{s\,ref}+H/2)$, S_2 is turned on while S_1 is turned off (Mode II, Figure (2b)). In this case, the inductor current i_s circulates through the load and the capacitor C via S_2. As a result, i_s decreases giving rise to the capacitor voltage over the supply voltage. This is due to the boosting action of the inductor voltage. Accordingly, the capacitor supplies power to the load during Mode I. This mode starts when i_s decreases to be less than or equal to $(i_{s\,ref}-H/2)$ and due to the action of the control circuit S_1 is turned on and S_2 is turned off. However, during the negative half cycle of the supply voltage similar action occurs. If S_1 is on and S_2 is off (Mode I, Figure (2a)), i_s increases but in opposite direction. Accordingly, the energy stored in the inductor increases. When $|i_s|$ increases to be more than or equal to $[(i_{s\,ref}+H/2)]$, S_2 is turned on while S_1 is turned off (Mode II, Figure (2b)). As a result, $|i_s|$ decreases giving rise to the negative voltage through the inductor L_1 increasing the magnitude of the capacitor voltage in the opposite direction. However, Mode II starts when i_s decreases in the opposite direction to be less than or equal to $[(i_{s\,ref}-H/2)]$ and S_1 is turned on while S_2 is turned off. Accordingly, due to the above mechanism of operation the voltage across the capacitor alternates at the supply frequency. It will be higher in magnitude than the supply voltage (boosting action). The magnitude of the ac output voltage can be varied by varying the supply reference current $(i_{s\,ref})$ which in turn acts to regulate the input power to the circuit.

THE CONTROL CIRCUIT

The control circuit used to regulate the load power is shown in Figure (3). A multiplier is used to convert the reference voltage (V_{ref}) to a sinusoidal wave in phase and synchronism with the supply voltage. The multiplier output $(i_{s\,ref})$ and the detected current (i_s) is applied to the hysteresis comparator (1) to create a sinusoidally wave shaped supply current during the positive half-cycle. However, a cascade combination of two inverters and a similar hysteresis comparator (2) are used to create a sinusoidally wave shaped supply current at the negative half cycle. The hysteresis comparator acts as follows: The output is one when the current (i_s) decreases to be less than or equal to $[\,|i_{s\,ref}|-H/2]$, Mode I, and is zero when i_s increases to be more than or equal to $[\,|i_{s\,ref}|+H/2\,]$, Mode II. The required gate signal is accordingly given by the simple logic (NAND latch) shown in Figure (3). to achieve the condition that the on switch must not be off until the other one is on. The gate signals are amplified via the gate drive circuits to drive switches S_1 and S_2.

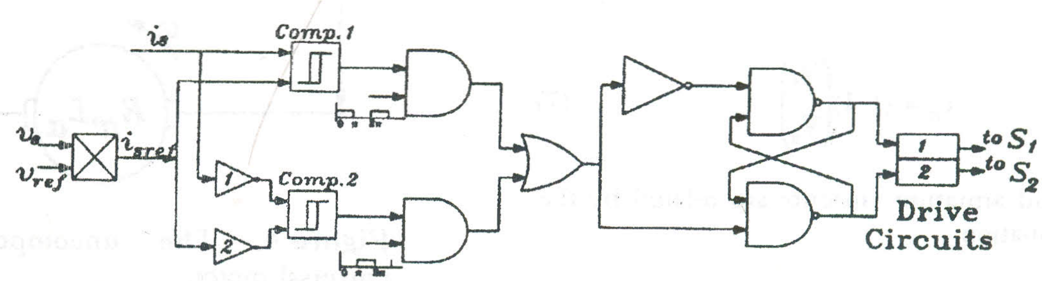


Figure 3. Schematic diagram of the control circuit.

SYSTEM MODELING AND EQUATIONS

Consider Figure (2a). The differential equations during Mode I can be written as follows:

$$v_s = i_s R_1 + L_1 \frac{di_s}{dt} \quad (1)$$

$$v_c = \frac{1}{c}\int -(i_L)\,dt \quad (2)$$

Just when the switch S_2 is turned on, S_1 will be turned off and the system changes to Mode II as shown in Figure (2b).

$$v_s = i_s R_1 + L_1 \frac{di_s}{dt} + v_c \quad (3)$$

$$v_c = \frac{1}{c}\int (i_s - i_L)\,dt \quad (4)$$

If a static inductive load is used, the load equation can be written as follows:

$$v_c = i_L R_L + L_L \frac{di_L}{dt} \quad (5)$$

However, an uncompensated universal motor shown in Figure (4) is used as a dynamic load. The equation which can be applied to predict the motor performance when excited from an ac supply can be written as [15-16].

$$\begin{pmatrix} v_f \\ v_a \end{pmatrix} = \begin{pmatrix} R_f + L_f p & 0 \\ -M\omega & R_a + L_a p \end{pmatrix} \begin{pmatrix} i_f \\ i_a \end{pmatrix} \quad (6)$$

Voltages across the field and armatur windings are related by:

$$v_c = (1\ 1)\begin{pmatrix} V_f \\ V_a \end{pmatrix} \quad (7)$$

The field and armature currents are related by the following equation:

$$\begin{pmatrix} i_f \\ i_a \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} i_L \quad (8)$$

Considering eqns. 7 and 8, the voltage equation can be rewritten as follows:

$$v_c = [R + LP - M\omega]\, i_L \quad (9)$$

Where

$$R = R_a + R_f \text{ and } L = L_a + L_f \quad (10)$$

The mechanical equation is:

$$T_e = T_L + J d\omega / dt + T_f \omega \quad (11)$$

Where

$$T_e = i_a M i_L \quad (12)$$

Parameters of the power circuit are chosen according to the range of the switching frequency and the acceptable hysteresis width. Consider equations 1,3 and 4, the rate of change of i_s is determined by the value of L_1 during Mode I and by the value of L_1 and c during Mode II. Accordingly, at certain hysteresis width the switching frequency is determined by the value of L_1 and C. However, the resonant frequency given by $f_r = 1/2\pi\sqrt{L_1 C}$ should be sufficiently lower than the switching frequency to prevent resonant phenomenon in the AC circuit.

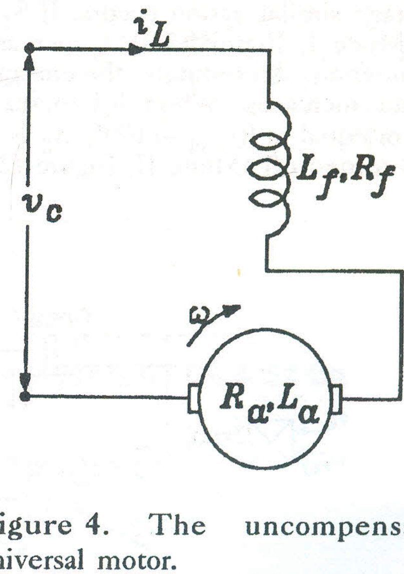


Figure 4. The uncompensated universal motor.

When the control circuit shown in Figure (3).

comes into effect, the switching frequency of S_1 and S_2 vary continuously. However, constants of the equivalent circuit and operating conditions of the experimental prototype are listed in Appendix A. Assuming I_{sn} is the rms. value of n-th harmonic component of supply current, the input distortion factor Df_s is defined as

$$DF_s = \sqrt{(\sum_{n=2}^{\infty} I_{sn}^2)/I_{sI}^2} \qquad (13)$$

I_{s1} is the rms. value of the fundamental component of supply current. The input power factor PF_s is given by

$$PF_S = \cos \Phi_1 \;/\; \sqrt{1+(DF_s)^2} \qquad (14)$$

ϕ_1 is the angle between I_{s1} and V_s.

Assuming I_{Ln} is the rms value of n-th harmonic component of the load current, the load distortion factor DF_L is defined as:

$$DF_L = \sqrt{(\sum_{n=2}^{\infty} I_{Ln}^2)/I_{L1}^2} \qquad (15)$$

I_{L1} is the rms value of the fundamental component of load current.

MATLAB (SIMULINK) software was used to solve the above listed equations numerically. Equations (1-5) are used to study the system performance using a static inductive load of 0.6 power factor lagging. However, eqn. (5) is replaced by eqns. (6-12) to study the steady state and transient performance of the universal motor as a load. Parameters of this motor are listed in Appendix B.

SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental results are performed herein to investigate several characteristics of the proposed AC voltage booster. Figures (5) and (6) show the experimental and calculated supply current as well as the load voltage and current waveforms using an inductive load of 0.6 power factor lagging. The supply current is of nearly sinusoidal waveshape with a unity displacement power factor at different supply current levels. As shown in Figures (5) and (6), the proposed regulator controls the input current at nearly sinusoidal load voltage and current. Figure (7). shows the command pulses for driving S_1. It is seen that, the employed bang-bang hysteresis control forces the supply current to follow the sinusoidal reference. If the reference is varied, the output voltage can be varied from the supply voltage level to more than 240%, as shown in Figure (8). However, the input power factor (PF_S) is nearly 99% over a wide range of v_c, while at the load side the power factor (PF_L) is 60%. Since the circuit power rating is relatively low, efficiency is not high. Figure (9). shows the distortion factors of the supply and load currents. The supply current distortion factor is lower than 20% over a wide range of v_c. However, the load current distortion factor is lower than 10%.

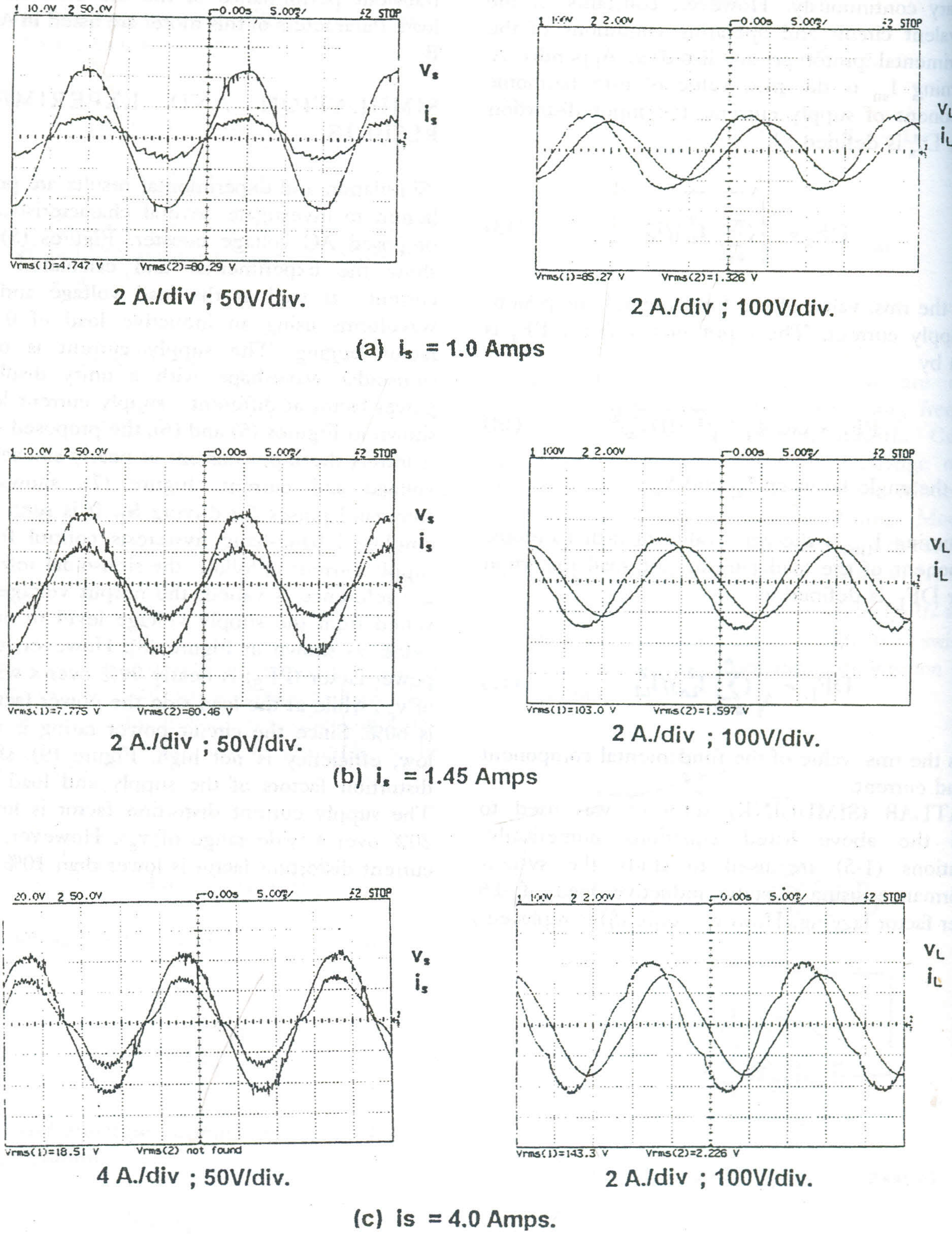
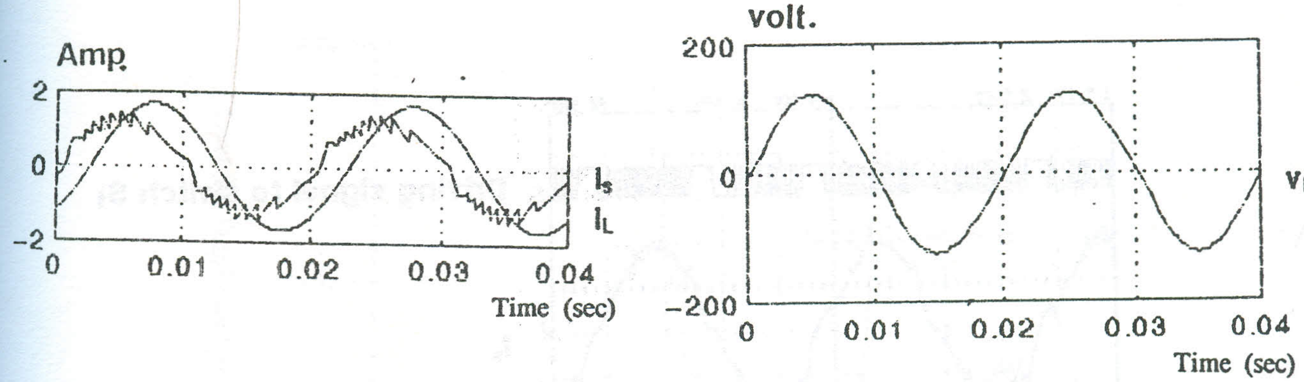
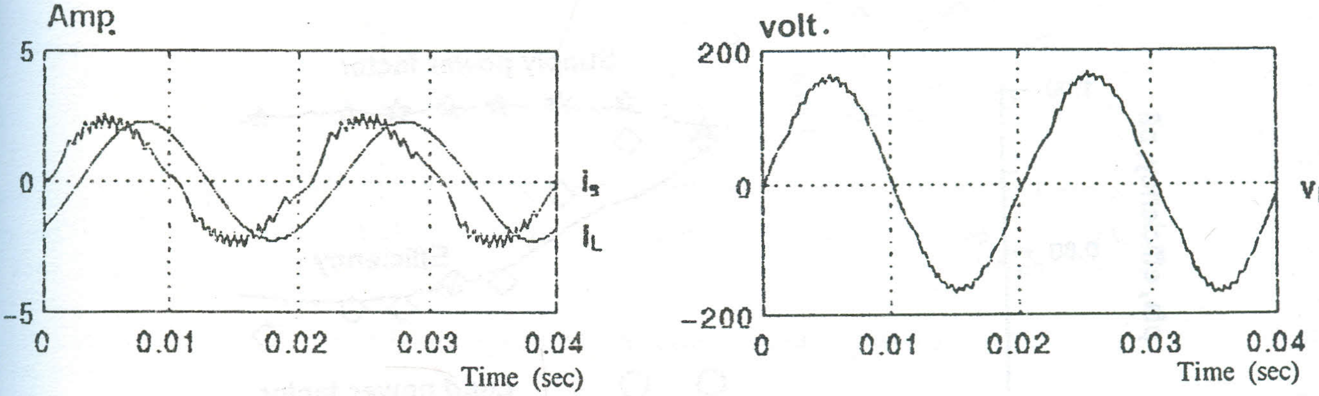


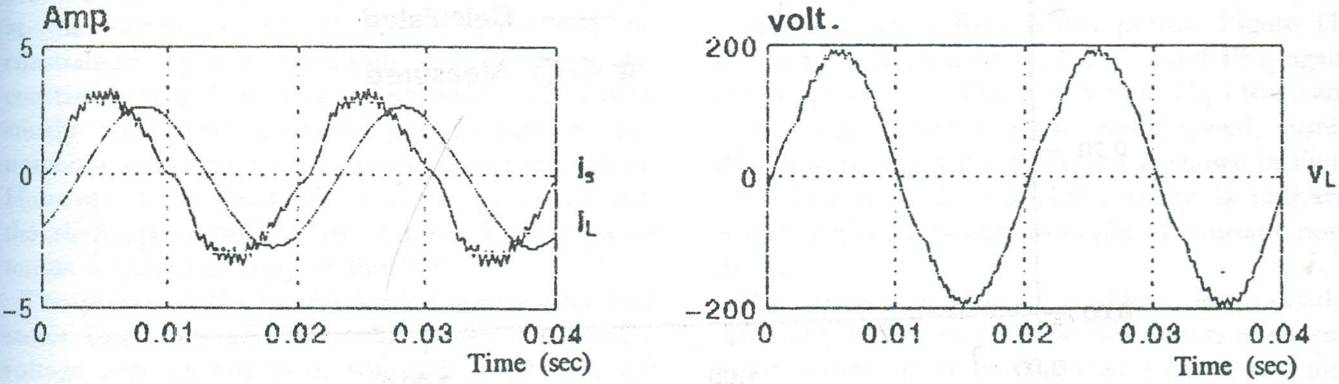
Figure 5. Recorded results of the inductive load.



(a) i_s = 1.0 Amps



(b) i_s = 1.45 Amps



(c) i_s = 4.0 Amps.

Figure 6. Measured and calculated results of the inductive load.

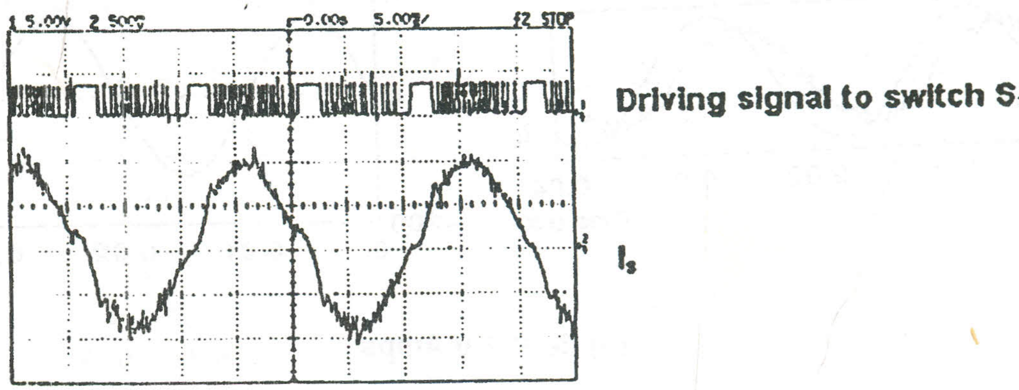


Figure 7. Recorded command signal for driving S_1, with supply current.

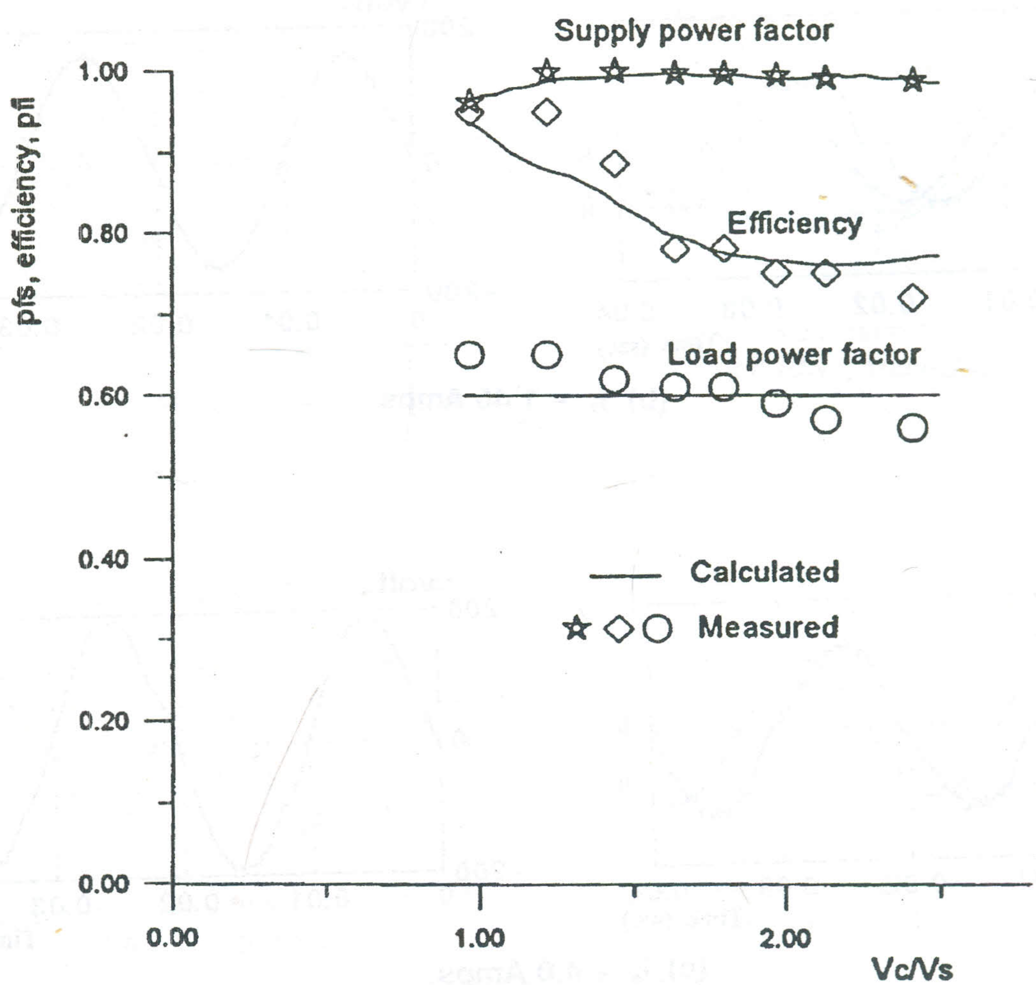


Figure 8. Power factor and efficiency versus v_c/v_s.

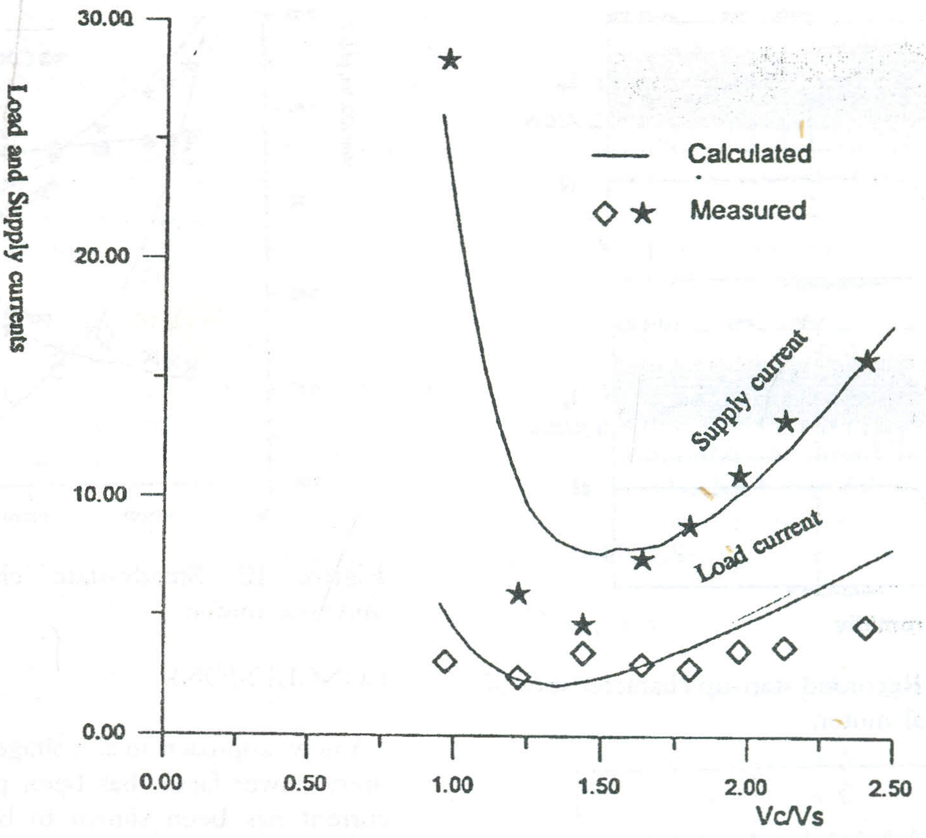


Figure 9. Current distortion factor versus v_c/v_s.

The new technique of control effectively ensures constant input power to the load according to the reference. The supply power factor is usually near the unity. At fixed load parameters, the output voltage varies to match the input power with that drawn by the load. So if a dynamic load is connected at the output terminals, its behavior will be constrained by this condition of excitation, e.g. constant power. It may be of interest to study both steady state and transient performance of the universal motor under a constant power excitation. However, if the input power to the motor is fixed, the shaft speed will be determined by the motor torque required to support the load.

The proposed circuit was loaded with a universal motor (see Appendix B) under load. the supply voltage and current were adjusted at 80 volt, 2.0 amps. rms., respectively. The circuit was switched on to the supply. The motor current and speed as well as the supply current were recorded during starting as shown in Figures (10) and (11). Due to the fixed input power the motor current is limited but on the expense of longer rise time as the recorded speed shows. This indicates that, the proposed circuit is effective for motor starting without over current.

The motor behavior in the steady state is constrained by a fixed input power. Figure (12), shows the variation of v_c ,I_L, T_L, and PF_L against motor speed (N). The load torque (T_L) was varied over a wide range and the motor speed, current, PF_L, and voltage were measured as shown in Figure (11). The torque/speed characteristic is indicative where it gives a typical example of constant power drive.

The proposed circuit is ideal for providing laboratory means to examine the motors at constant input power. If at certain load torque, the input power is varied the motor speed will vary accordingly. Thus the motor speed can be regulated via the input current reference.

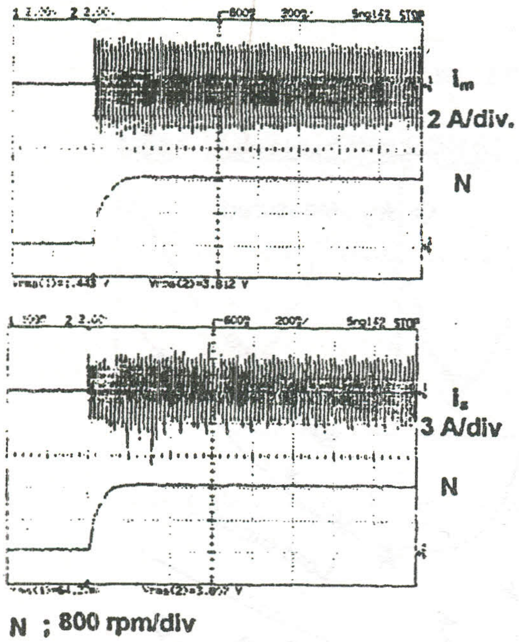


Figure 10. Recorded start-up characteristics of the universal motor.

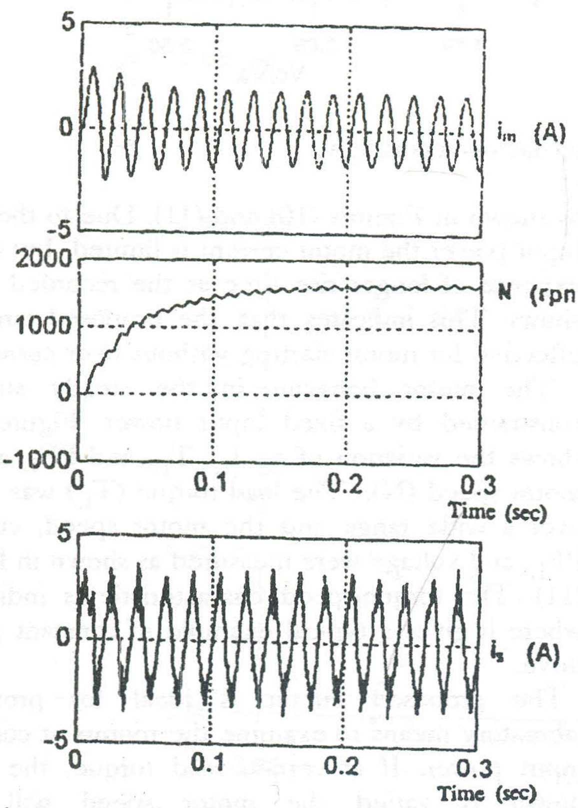


Figure 11. Calculated start-up characteristics of the universal motor.

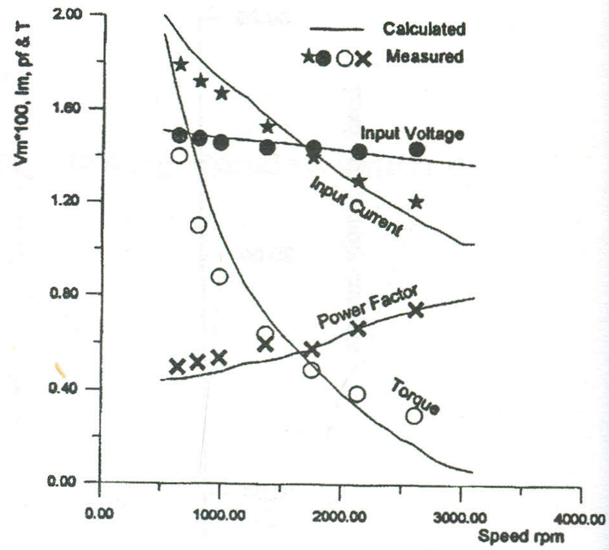


Figure 12. Steady-state characteristics of the universal motor.

CONCLUSIONS

A new approach to ac voltage boosters with nearly unity power factor has been presented. The input current has been shown to be in phase with the supply voltage irrespective of the input power level or the load power factor. However, the load voltage is varied in response to control of the input power. It has been shown that, the output voltage can be varied from 100% to 240% of the input voltage. The proposed circuit is effectively a power controller and so, it is suitable for examining ac motor behavior under the condition of constant input power. Results of work carried out using R-L static load and a universal motor are reported. Theoretical and test results are compared and shown to be in good agreement.

REFERENCES

[1] A.S. Abd El-Karim. "Reactive and Active Power Balance in the Thyristor-Rair Regulator Circuit", *ENG. research Bulletin, Faculty of Eng. and Tech.* Menoufiya University, vol. 5, Part II, pp. 133-146, 1983.

[2] P.C. Sen "Smooth Control of Reactive Power Using Static Devices", *IEEE Trans.* on Magnetics, MAG-4, No, 3, pp. 325-329, 1979.

[3] L. Gyugyi "Reactive Power Generation and Control by Thyristor Circuit", *IEEE Trans. on Industry Applications*, IA-15, No, 5, pp. 521-532, 1979.

[4] J.C. De Oliveira and J.W.Resende, " Phase Control and Three Phase Harmonic Calculations For Thyristor Controlled Reactor Compensator", *Proc. of the UPEC*, U.K. 3.P.5, 1984.

[5] F.I. Ahmed, A.S. Abd El-Karim and A. Abdel-Ghaffar, "A Digital Power Factor Regulator For Inductive Loads", *Proc. of the 9 th annual Conf. on Operation Research and Applications, Zagazig University*, EGYPT, pp. 142-150, 1983.

[6] J. Arrillage, B. Barrett, and N.A. Vovus, "Thyristor Controlled Regulating Transformer For Variable voltage Boosting", *Proc. of the IEE*, 123, No. 10, pp. 105-109, 1976.

[7] J. Arrillage and R.M. Duke, " A Static Alternative to the Transformer on- Load Tap Changer", *IEEE Trans. on Power Apparatus and Systems*, PAS-99, No. 1, pp. 86-91, 1980.

[8] S. Lioyd, "A Thyristor AC Regulator With Sinusoidal Output", *IEE Conf. on Power Thyristor*, pp. 168-176, 1969.

[9] A.S. Abd El-Karim, A.I.Taalab, and A.E.Lashine, "A Fast Thyristor Controlled AC voltage Regulator", *Electric Machines and Power System*, USA, vol. 16, pp. 225-238, 1989.

[10] A.E.Lashine, "A variable Inductor For Power Applications Using Coupled Circuit", *Electric Machines and Power System*, USA, vol. 20, pp. 513-525, 1992.

[11] A.S. El- Basamy, P. Mehta and T. Thomson, "A Controlable Impedeance For Power System Applications", *Proc. of the 13 th Univ. Power Eng. Conf.*, Heriot- Watt Univ. , 6.B.5, 1978.

[12] A.E. Lashine, "A Thyristorized Saturable Reactor With Self-Excitation", *Electric Machines and Power System*, USA, vol. 24, pp. 437-449, 1996.

[13] D.M. Divan, "Inverter Topologies and Control For Sinusoidal Output Power Supplies", *IEEE, APEC*, pp. 81-87, 1991.

[14] Do-Hyun Janj, and Gyu-Ha Choe, "Improvement of Input Power Factor in AC Choppers Using Asymmetrical PWM Technique", *IEEE Trans. on Industrial Electronics*, vol. 42, No 2, pp. 179-185, 1995.

[15] M. EL-Shanawany, "Operation and Performance of the Universal Motor; A Comparative Study", *Eng. Research Bulletin*, Faculty of Eng. Menoufiya Univ., vol 17, Part 2, pp. 101-122, 1984.

[16] M.E. EL-Shebiny, S.M.R.Tahoun and M.M. Khater,"Transient Performance of the Universal Motor", *International Conf. on Electrical Machines and Power Electronics*, 5-7, June, TURKEY, vol 2/2, pp. 425-430, 1995.

APPENDICES

Appendix A

Data and parameters of the experimental set up

v_s	= 80 V	H	= 0.4 A
L_1	= 24 mH	R_1	= 1.4 Ω
C	= 30μf		

Static load parameters

R_L = 42 Ω L_L =178 mH

Appendix B

The universal motor has the following rated values and parameters:

Rated voltage	= 220 V
Armature resistance (R_a)	= 2.46 Ω
Field resistance (R_f)	= 4.00 Ω
Armature leakage inductance (L_a)	= 0.120 H
Field leakage inductance (L_f)	= 0.110 H
Mutual inductance (M)	= 0.380 H
Full load speed (N)	= 3000 rpm
Motor inertia (J)	= 0.00065 Nm/rad/sec^2
Friction constant (T_f)	= 0.0019 Nm/rad/sec.