Paper

A New Three-Phase Boost-Type Voltage Regulator With Unity Input Power Factor

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Abstract

This paper presents a new configuration for high performance three-phase voltage boost regulator. For this new configuration, a control methodology is proposed to provide regulated ac output voltage. The new boost regulator has nearly unity input power factor for a change in the load voltage from 100% to more than 200% of the supply voltage. At these conditions, a nearly ripple free output voltage is achieved. The four-quadrant nature of the proposed regulator enables it to accept reactive loads. Theoretical analysis and practical controller implementation are presented and the efficacy of the proposed regulator has been confirmed.

Key words: voltage regulator; power factor correction.

1. Introduction

AC regulators are widely used in applications requiring power control, voltage regulation and reactive power compensation. These are also used in special motor drive systems such as self-starting induction motors and speed controllers for fans and pumps. Most of the existing systems are conventional line commutated ac controllers with thyristor technology. These conventional controllers cause discontinuity and significant harmonics in load and supply currents. Also, these systems are suitable only for buck mode applications. A thyristor-controlled transformer booster has been suggested and examined [1], but such devices are of limited range and introduce distortion in the voltage waveform. Saturable reactor voltage regulator with improved current waveform was obtained [2], but distortion was noticeable at low levels of output voltage. Different topologies and control techniques were proposed [3] to realize unity power factor at the ac source side, but large number of switches and sophisticated control techniques were required for the ac-dc-ac conversion system.

Line commutated ac regulators can be replaced by PWM ac regulators which have better overall performance. PWM ac regulators are designed with standard gate commutated devices like BJT, GTO, MOSFET, IGBT, etc. The advantages to be gained include sinusoidal input-output current/voltage waveforms, better input power factor and substantially smaller input/output filters. The PWM controlled ac/ac voltage regulators has been examined in [4,5]. Although high input power factor has been achieved, these types of regulators were used in the buck mode only. Another technique has been used for ac/ac regulation based on electronic transformer [6]. Several possible topologies employing static converters connected on the primary and secondary sides in combination with magnetic circuits were explored to realize a high frequency ac link. Although electronic transformer gave higher efficiency and better voltage regulation, large number of switches and sophisticated control techniques were required.

In this paper, a new topology for high performance three-phase boost regulator is proposed. The principle of operation and control of the regulator are presented. The new boost regulator has nearly unity input power factor. A 750VA laboratory prototype of the boost regulator has been built and tested. Simulation and experimental results are reported and discussed.

2. Proposed Topology

2.1 The power circuit

Fig.1 illustrates the bi-directional three-phase boost-type ac voltage regulator proposed in this paper. In this approach, only four ac switches, S_{aa}, S_{ac}, S_{bb}, S_{bc}, are used and arranged as shown in the figure. The ac switches and the boost inductors, L_{Ba}, L_{Bb}, L_{Bc}, are located between the ac source and the load. Moreover, three star-connected ac capacitors are located across the load terminals. The proposed approach has its inherent capability in the applications where bi-directional power flow is important, such as in a motor drive.

Since only four ac switches are to be controlled, it needs only four driving circuits for the corresponding ac switches. Moreover, the proposed arrangement of the ac switches prevents the switches from conducting simultaneously as in bridge leg configuration. So, no deadtime has to be considered in this topology. This will simplify the controller design greatly. The ac switch can be constituted by one or two power transistors [7]. It can conduct bi-directional currents when turned on and block ac voltages when turned off. Fig. 2 shows two schematics to configure an ac switch.

2.2 The control strategy

In the proposed regulator, only two independent hysteresis current controllers are used. Fig. 3 shows the block diagram of the control strategy. The voltage reference signal, V_{ref}, is set according to the required load voltage. This signal can be treated as a dc value which is proportional to the load phase voltage. Using a peak value detector, the phase voltage V_a is converted to a corresponding dc value, V_{adc}. This value is compared with the reference voltage signal, V_{ref}, and the error signal is passed through a proportional controller (k_{pv}).

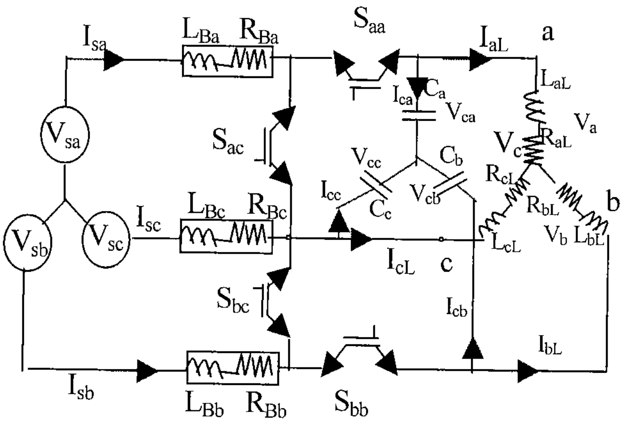


Fig. 1 The proposed three-phase boost-type voltage regulator.

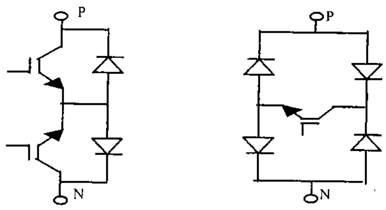


Fig. 2 Configuration of ac switches

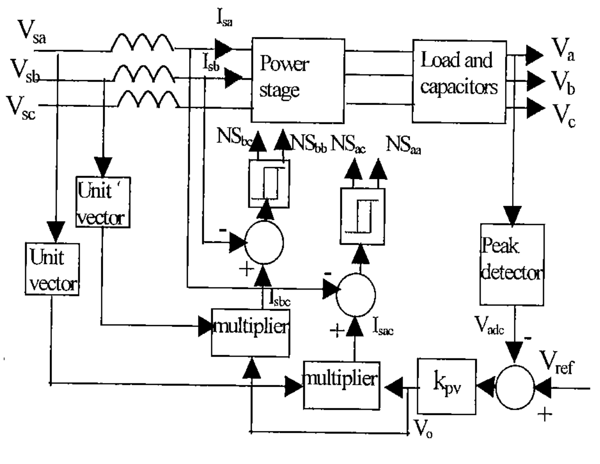


Fig. 3 Block diagram of the proposed control strategy.

The output of the controller, V_o is then multiplied by the unit vector of the supply phase voltages V_{sa} and/or V_{sb} to produce the command currents I_{sac} and I_{sbc}, respectively. The supply currents I_{sa} and I_{sb} are compared with their corresponding commands, I_{sac} and I_{sbc}, and the errors are processed through two independent hysteresis controllers. The outputs of the hysteresis controllers are in the form of binary signals, NS_{aa}, NS_{ac}, NS_{bb} and NS_{bc}. If the input current is greater than the current command, the digital signal is \`0\`. Otherwise it is \`1\` . Note that the logic NS_{ac} is a complementary of logic NS_{aa} and similarly, the logic NS_{bc} is a complementary of logic NS_{bb} as given in Table I. Those logic signals will be used to fire the four ac switches. If the supply current is controlled to follow the current command, it follows the supply voltage in its waveform and follows the reference voltage in its magnitude. This is easily achieved, since the reference current is generated from and synchronized with the supply voltage. This control strategy ensures that the input power factor is almost kept at unity over wide range of the load power factor by adjusting the capacitors.

2.3 Modes of operation

Since the logics NS_{ac} and NS_{bc} are complementary of logics NS_{aa} and NS_{bb}, respectively, the truth table can be established for the different modes of operation of the boost regulator as given in Table I. It seems from the truth table that four modes of operation are possible.

Mode 1: S_{aa}, S_{bb} ON and S_{ac}, S_{bc} OFF: In this mode the supply voltage is connected directly to the load. Supply currents flow to the load through the boost inductors. At the same time, the Y-connected capacitors are charged. This mode continues until the supply currents I_{sa} and/or I_{sb} decrease less than or equal to ($I_{s\ a,b,c}$-H), where H is the hysteresis band.

Mode 2: S_{ac}, S_{bc} ON and S_{aa}, S_{bb} OFF: In this mode, the control circuit allows the supply currents to increase. At the same time, the stored energy in capacitors discharges into the load. When I_{sa} and/or I_{sb} increase to be more than or equal to ($I_{s\ a,b,c}$+H), S_{ac} and/or S_{bc} are turned off.

Mode 3: S_{aa}, S_{bc} ON and S_{bb}, S_{ac} OFF: During this mode, the energy stored in the boost inductors is transferred to the capacitors giving rise to the capacitors voltage to increase. At the same time, I_{sb} flows through L_{Bb} and S_{bc} until its boosting period.

Mode 4: S_{bb}, S_{ac} ON and S_{aa}, S_{bc} OFF: This mode is similar to Mode 3, except that phases \`a\` and \`b\` are interchanged.

Table I. Truth table for the modes of operation.

$NS_{bc}=\overline{NS_{bb}}$	NS_{bb}	$NS_{ac}=\overline{NS_{aa}}$	NS_{aa}	Mode
0	1	0	1	1
1	0	1	0	2
1	0	0	1	3
0	1	1	0	4

3. Modeling and Analysis

For all modes of operations the following general equations can be deduced;

Load equations:

$$V_{ca} - V_{cb} = I_{aL} R_{aL} + L_{aL} \frac{dI_{aL}}{dt} - I_{bL} R_{bL} - L_{bL} \frac{dI_{bL}}{dt} \quad (1)$$

$$V_{cb} - V_{cc} = I_{bL} R_{bL} + L_{bL} \frac{dI_{bL}}{dt} - I_{cL} R_{cL} - L_{cL} \frac{dI_{cL}}{dt} \quad (2)$$

$$I_{cL} = -I_{aL} - I_{bL} \quad (3)$$

Capacitances equations:

$$V_{ca} = \frac{1}{Ca} \int I_{ca} dt \quad (4)$$

$$V_{cb} = \frac{1}{Cb} \int I_{cb} dt \quad (5)$$

$$V_{cc} = \frac{1}{Cc} \int I_{cc} dt \quad (6)$$

Currents equations

$$I_{cb} = -(I_{ca} + I_{cc}) \quad (7)$$

$$I_{sb} = -(I_{sa} + I_{sc}) \quad (8)$$

When switch S_{aa} is on the following equations can be derived:

$$V_{sa} - V_{sc} = I_{sa} R_{Ba} + L_{Ba} \frac{dI_{sa}}{dt} - I_{sc} R_{Bc} - L_{Bc} \frac{dI_{sc}}{dt} + V_{ca} - V_{cc} \quad (9)$$

$$I_{ca} = I_{sa} - I_{aL} \quad (10)$$

When switch S_{bb} is on the following equations can be derived:

$$V_{sb} - V_{sc} = I_{sb} R_{Bb} + L_{Bb} \frac{dI_{sb}}{dt} - I_{sc} R_{Bc} - L_{Bc} \frac{dI_{sc}}{dt} + V_{cb} - V_{cc} \quad (11)$$

$$I_{cc} = I_{sc} - I_{cL} \quad (12)$$

When switch S_{ac} is on the following equations can be derived:

$$V_{sa} - V_{sc} = I_{sa} R_{Ba} + L_{Ba} \frac{dI_{sa}}{dt} - I_{sc} R_{Bc} - L_{Bc} \frac{dI_{sc}}{dt} \quad (13)$$

$$I_{ca} = -I_{aL} \quad (14)$$

When switch S_{bc} is on the following equations can be derived:

$$V_{sb} - V_{sc} = I_{sb} R_{Bb} + L_{Bb} \frac{dI_{sb}}{dt} - I_{sc} R_{Bc} - L_{Bc} \frac{dI_{sc}}{dt} \quad (15)$$

$$I_{cb} = -I_{bL} \quad (16)$$

Equations(1-12) cover Mode 1, while Eqs. (1-8) and Eqs. (13-16) cover Mode 2. Also, Eqs (1-10) and Eqs.(15-16) cover Mode 3, while Eqs.(1-8) and Eqs (11-14) cover Mode 4.

The circuit parameters, boost inductors and output capacitors, can be determined according to the range of the switching frequency and acceptable percentage of the output ripple. Consider Eqs. (9-12) the rate of change of $I_{s\,a,b,c}$ is determined by the values of $L_{B\,a,b,c}$ during Mode 1 and by the values of $L_{B\,a,b,c}$ and $C_{a,b,c}$ during Mode 2. Accordingly, the switching frequency is determined by these values depending on the hysteresis band, H. The value of the hysteresis band, H, is set as 10% of the command current to give acceptable switching frequency and consequently low harmonics.

Assuming balanced three-phase supply and I_{sn} is the rms value of the n-th harmonic component of the supply current, the input distortion factor DF_s is defined as:

$$DF_S = \sqrt{\left(\sum_{n=2}^{\infty} I_{sn}^2\right) / I_{s1}^2} \quad (17)$$

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

$$PF_S = \cos\phi_1 / \sqrt{1 + (DF_S)^2} \quad (18)$$

where ϕ_1 is the angle between the fundamental component of the supply current , I_{s1} , and the phase supply voltage V_{sa}.

The load distortion factor DF_L is defined as:

$$DF_L = \sqrt{\left(\sum_{n=2}^{\infty} X_n^2\right) / X_1^2} \quad (19)$$

where X may represents current or voltage and X_n is the rms value of n-th harmonic component of the load voltage or the load current. On the other hand, X_1 is the rms value of the fundamental component of the load voltage or the load current.

Equations (1-16) are used to simulate the boost regulator by the help of Matlab/Simulink Toolbox [8]. The Simulink /Toolbox uses the metaphors of a block diagram to represent the system.

4. Real Time Implementation

The control scheme of Fig. 3 is implemented in real time using a 32-bit digital signal processor (DSP) (TMS320C31), as shown in Fig. 4. The ac switches are constructed using insulated gate bipolar transistors (IGBTs) with ultra-fast recovery diodes as a bridge. The voltage isolators sense the unit vectors of the supply voltages. These sensed signals are used for synchronization of the generated reference currents. The supply currents, I_{sa} and I_{sb}, are measured by using Hall-effect devices. The voltage and current signals are then fed to the DSP through 12-bit A/D converters. The output from the DSP (digital I/O) is in the form of logic pulses, NS_{aa}, NS_{ac}, NS_{bb} and NS_{bc}. These logic pulses are then fed to the ac switches through isolation and driving stage. The overall execution time of the control scheme is 45 µsec at sampling frequency of 20kHz.

5. Simulation and Experimental Results

An experimental three-phase boost-type voltage regulator with the proposed control strategy has been built and tested. The laboratory model has been constrained to power ratings of 750VA. However, the results reported here are applicable to other types of load and thus have universal applications by resorting to the usual scaling law.

Simulation and experiment are carried out to determine the characteristics of the proposed boost regulator. The circuit parameters of the prototype are listed in the Appendix. The supply voltage is kept constant at 35V/phase and the reference voltage is controlled to allow boosting of the output voltage.

Fig. 5 shows the simulation results of the three-phase regulator for the boosting of 150% of the input voltage. Fig. 5(a) shows the supply phase voltage (V_{sa}) and the supply phase current (I_{sa}). It is clear from Fig.5 (a) that the supply current follows the supply voltage in its wave shape with almost a unity displacement power factor. The use of two independent hysteresis current controllers ensures balanced three-phase currents, as shown in Fig.5 (b). Also, the proposed control strategy ensures symmetrical load voltages as shown in Fig. 5(c). Moreover, it is evident from Fig. 5(c) that the load voltage is almost 150% of the input voltage. The phase load voltage and current are shown in Fig. 5(d). The experimental results in Fig. 6 confirm, very closely, the corresponding simulated results of Fig. 5.

Similar results were obtained by setting the reference voltage for the boosting of 200%. Fig. 7 shows the simulation results of the proposed regulator in this case. In Fig. 7(a), the supply phase current (I_{sa}) is nearly in phase with the supply phase voltage (V_{sa}). Also, the controller has the ability not only to force balanced supply currents, but also to force balanced load voltages, as shown in Figs. 7(b) and (c). The per- phase load voltage and current are shown in Fig. 7(d). The experimental results of Fig. 8 also confirm the simulated results of Fig. 7. Fig.9 shows the power factor, distortion factor of the supply current and distortion factor of the load current over a wide range of load voltage. The results show the effectiveness and efficacy of the proposed controller for boosting operation.

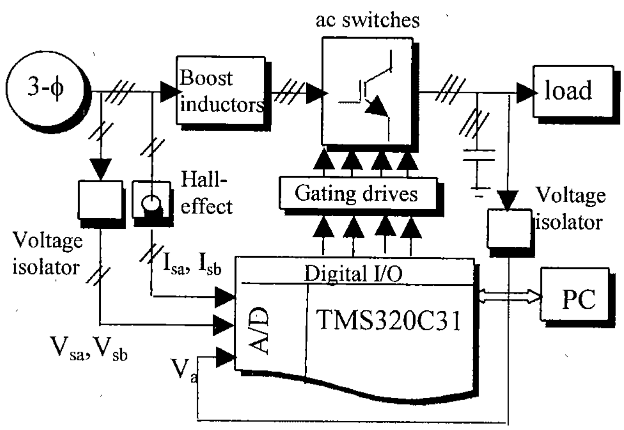


Fig. 4 Hardware implementation

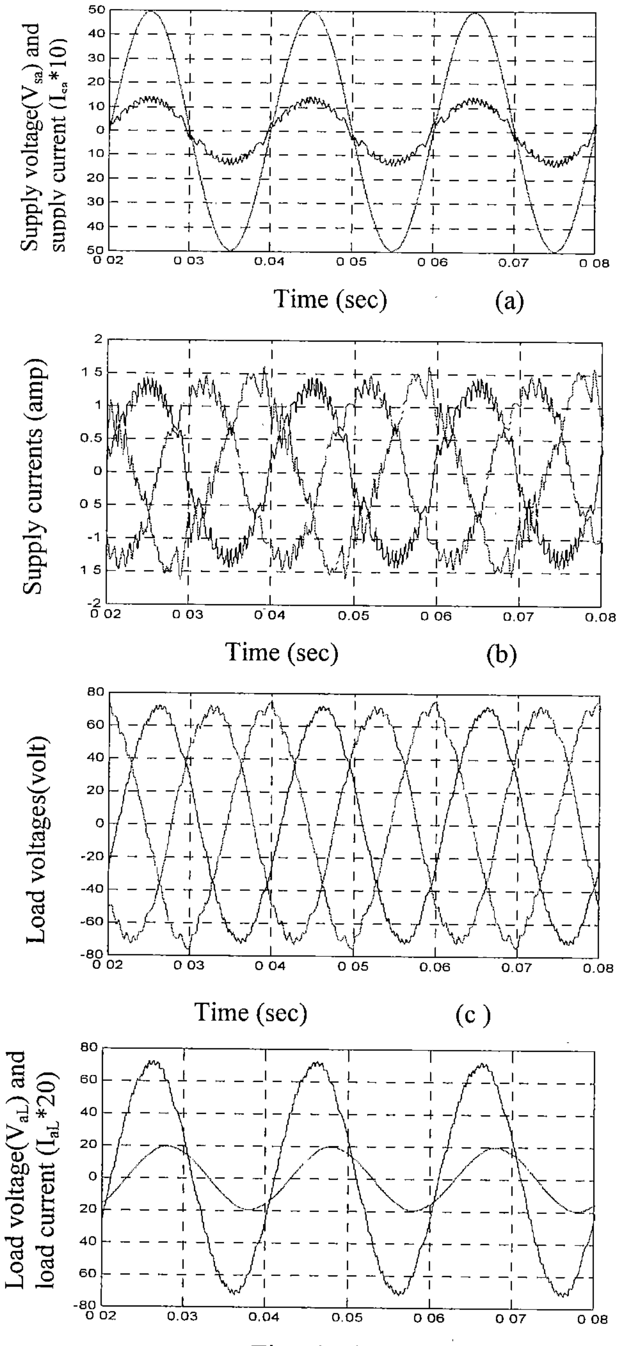
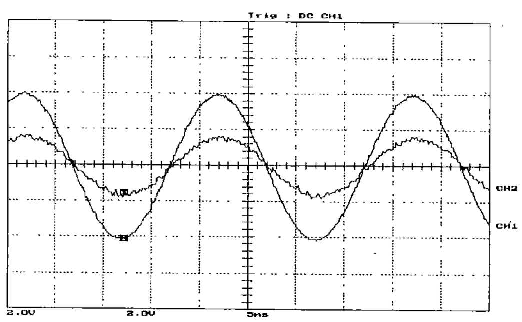
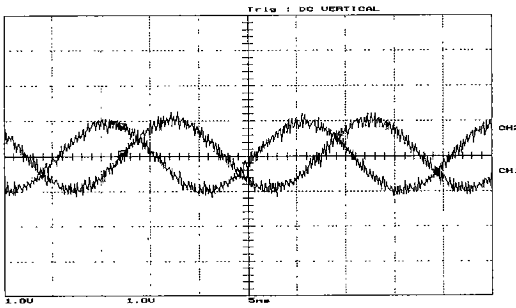


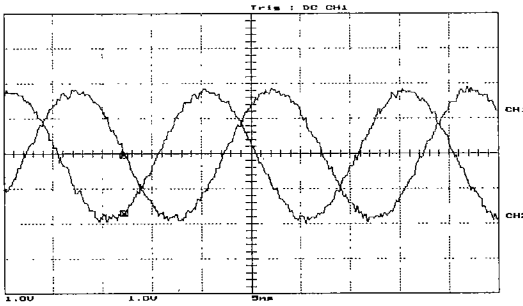
Fig. 5 Simulation of 150% boosting mode; (a) supply voltage and current; (b) supply currents; (c) load voltages; and (d) load voltage and current.



(a)

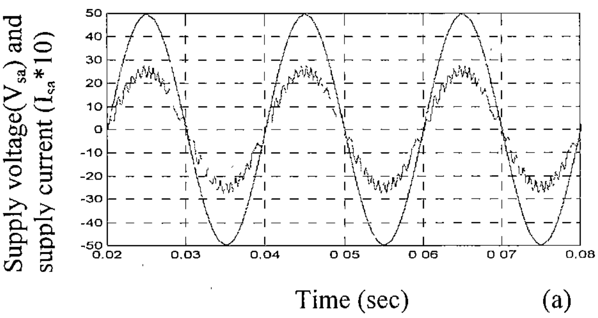


(b)

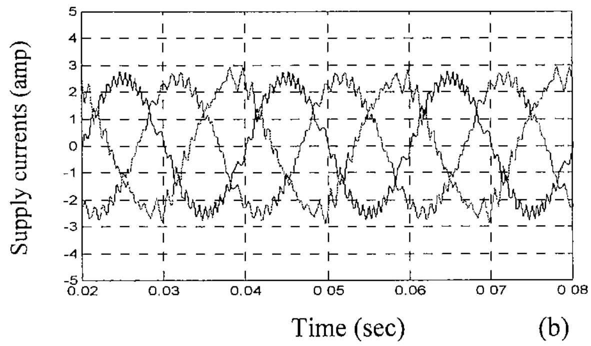


(c)

Fig.6 Experimental results of 150% boosting mode; (a) supply voltage and current, V_{sa}=25V/div, I_{sa}=2A/div; (b) supply currents, 1.5A/div; (c) load voltages, 40V/div.



(a)



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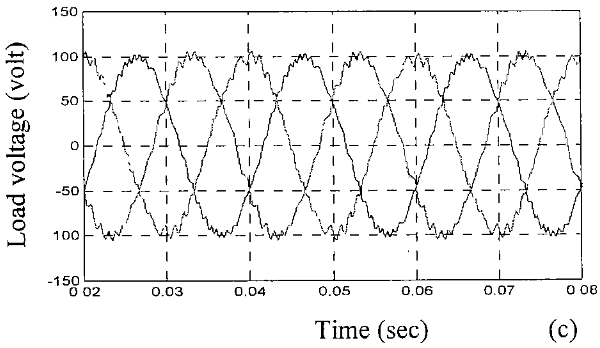
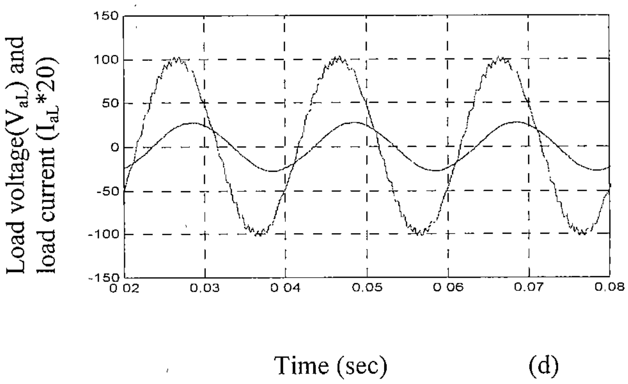
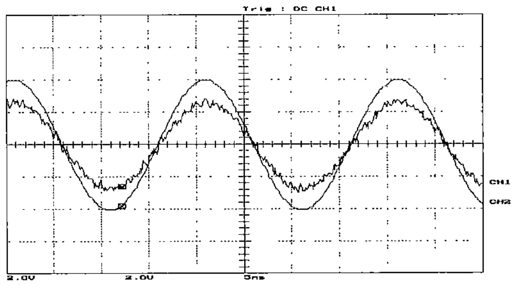


(c)

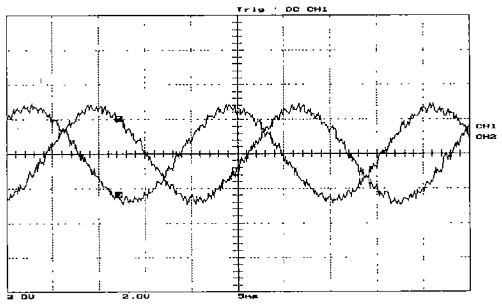


(d)

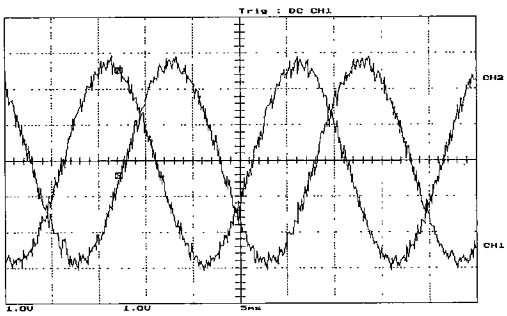
Fig. 7 Simulation of 200% boosting mode; (a) supply voltage and current; (b) supply currents; (c) load voltages; and (d) load voltage and current.



(a)



(b)



(c)

Fig.8 Experimental results of 200% boosting mode; (a) supply voltage and current, V_{sa}=25V/div, I_{sa}=2.2A/div; (b) supply currents, 2.2A/div; (c) load voltages, 35V/div.

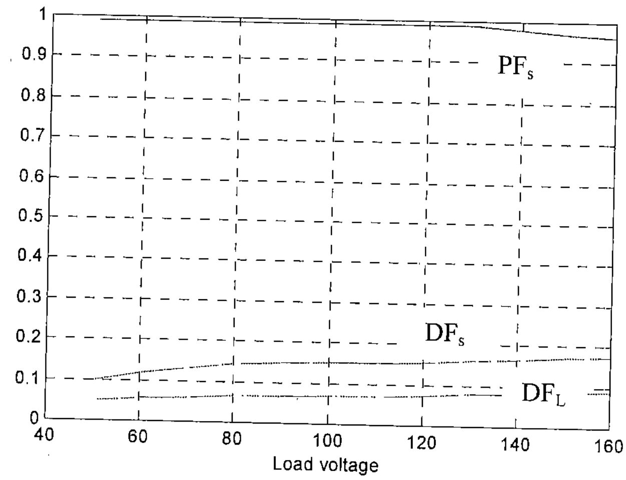


Fig. 9 Simulated results of supply power factor, supply current distortion factor and load current distortion factor versus load voltage.

6. Conclusions

A new three-phase boost-type voltage regulator with nearly unity input power factor has been proposed. A control scheme using two independent hysteresis current controllers has been also proposed. The operation and modeling of the boost regulator have been described and analyzed. Since the regulator employed only four ac switches, the presented approach makes the operational principles clear and gives the possibility of simple control design and implementation. Only two of the four-ac switches are controlled at a time. This reduces the overall switching power losses. The regulator is effectively an electronic step-up coreless transformer. It has the ability to step up the voltage to more than 200%. An experimental regulator has been built and tested to explore the advantages and the practical limitations of this new three-phase boost-type voltage regulator.

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Appendix I

Data and circuit parameters

$V_{sa}=V_{sb}=V_{sc}=35$ V, $L_{Ba}=L_{Bb}=L_{Bc}=30$ mH

$R_{Ba}=R_{Bb}=R_{Bc}=1.4\Omega$, $C_a=C_b=C_c=15$ μF

Load side; three phase balanced R-L with $R_L=60\Omega$ and $L_L=130$ mH. Proportional gain, Kpv=5.

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