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Power Factor Correction for Three- Phase AC-AC Buck Regulator

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ABSTRACT

This paper presents a new configuration of a three-phase AC-AC buck regulator to operate with a three phase inductive loads with a reduced number of controlled switches. It has a simple control with excellent performance. The proposed circuit has high efficiency for adjusting AC power; because it is composed of fewer switches and DC snubbers. The proposed regulator restrains more harmonics of output voltage and the input current flows continuously, thus a nearly unity input power factor is achieved. Also harmonics of input current and load current are almost negligible. The proposed method is implemented using a zero-crossing processing, which allows a greater accuracy than other methods. By simulation, these characteristics are investigated theoretically, and to correlate the measurements with theory, an experimental setup is presented to confirm the simulation results.

يقدم هذا البحث مقترحاً حديثاً لتصميم منظم خافض للجهد ثلاثى الأوجه يتمتع بكفائة عالية والذى يمتاز ببساطة التكوين حيث أنه يحتوى على عدد قليل من المفاتيح المتحكمة فى كل من التيار والجهد ، إلى جانب ذلك، تم أيضا تكوين دائرة تحكم ذات أداء متميز للتحكم فى قيمة الجهد والتيار. ويمتاز هذا المنظم بتحسين معامل القدرة وتقليل قيمة التوافقيات فى كل من الجهود والتيارات ، إضافةً إلى ذلك يتمتع هذا المنظم بالإستمرارية فى الأداء مهما تواجدت أى تشوهات فى مصدر التغذية وتم تحقيق هذا المقترح معملياً ومقارنة النتائج المعملية بالنظرية والتى أثبتت دقة وكفائة النموذج المقترح.

Key words: *AC-AC converter, power factor correction, harmonic distortion, hysteresis control, zero-crossing detector.*

I. INTRODUCTION

AC voltage regulators are widely used in applications requiring voltage regulation, reactive power compensation and power control [1-9]. There are some types of AC /AC converter to regulate the input voltage to a lower or higher output voltage. A winding transformer is widely used in voltage regulation fields such as power system, motor speed control and so on. However, because the winding ratio is changed by servo motor or by manual regulation, it has low regulation speed [8]. There are also other researches which use thyristor phase controlled circuit to do voltage regulation. These converters have been widely used as a soft-starter and a speed regulator of pumps and fans [2-4, 7]. Although it has a higher regulating speed than winding transformer, the low input power factor and the large amount of the low-order harmonic current are the major problems, the size of the passive filter becomes larger. Furthermore, these shortcomings affect the power quality. The reactive and harmonic currents generated by the thyristor commutation also produce extra power loss on the transmission lines. These problems can be solved by using high switching frequency AC chopper [5- 6]. Recently, a family of PWM AC–AC power converters has been proposed which uses gate turn-off switching devices like GTOs or IGBTs in its design [10-13]. The advantages to be gained are nearly sinusoidal input-output currents/ voltage waveforms, improved power factor, reduced harmonic current, a fast response speed and a smaller input filter size. It can protect sensitive equipment such as a computer or communication equipment; it can also be used to solve power quality problems caused by line voltage sags and swells, besides the wide and continuous range of control [14-15]. In order to reduce the power loss, researches have been conducted

to reduce the number of the switching devices. Three switches and four switches for single phase AC chopper were discussed in previously presented papers [9, 14, and 16]. Different working principles have also been presented to ensure the safety of the converter. The switching patterns are critical and an alternate path has to be established in dead time. DC regenerative snubber capacitor is used to realize the safe commutation and enhance efficiency [9, 16, and 17]. There are various researches that focus on the topology of the AC chopper converter and most of them are open loop control, so voltage regulation performance is restrained and a little attention has been given to the theoretical analysis of the input power factor. To solve the problems caused by the input voltage fluctuation, the output voltage closed loop feedback control system is proposed for a better dynamic performance.

In this paper, detailed analysis and modeling of an AC–AC buck converter in combination with static loads during the various operating modes are accomplished. For this converter a new configuration control with excellent performance is proposed also and then the waveforms of voltage, current and their harmonics spectrum and power factor are discussed and verified in detail. The state equations, which describe the operation of the proposed converter at different operating modes, are presented. Simulated and experimental results verifying the validity of the proposed analysis are presented.

II. Circuit Description and Principle of Operation

Figure1 shows the proposed three phase buck type voltage regulator. In this approach, only four unidirectional switches are used and arranged as shown in the figure, as a result, the circuit is simplified and cost is reduced. The input filter, consisting of resistor (R_a, R_b, and R_c), inductor (L_a, L_b, and L_C) and capacitor (C_{ia}, C_{ib}, and C_{ic}) absorbs the harmonic currents and provides continuity of the input current. The switches (S_{aa}, S_{bb} , S_{CC} and S_{abc}) are uni-directional. The using of uni-directional switch module is composed of one insulated gate bipolar transistors (IGBT). The used IGBT has inner diode which provides freewheeling currents path when the reverse voltage is encountered. The AC switches (S_{aa}, S_{bb}, and S_{CC}) are located between the AC source and the load. The switches are used to connect or disconnect the load to the supply, i.e., it regulates the power delivered to the load. The switch (S_{abc}) is connected in parallel across the load which provides a freewheeling path for the load current to discharge the stored energy of the load inductance L_{al}, L_{bl} and L_{cl} when the switches(S_{aa} ,S_{bb} , and S_{CC}) is turned off. C_1, C_2, C_3 and R_1, R_2, R_3 are the snubber capacitors and resistors respectively. The snubber circuits are connected in parallel with the switch (S_{abc}).

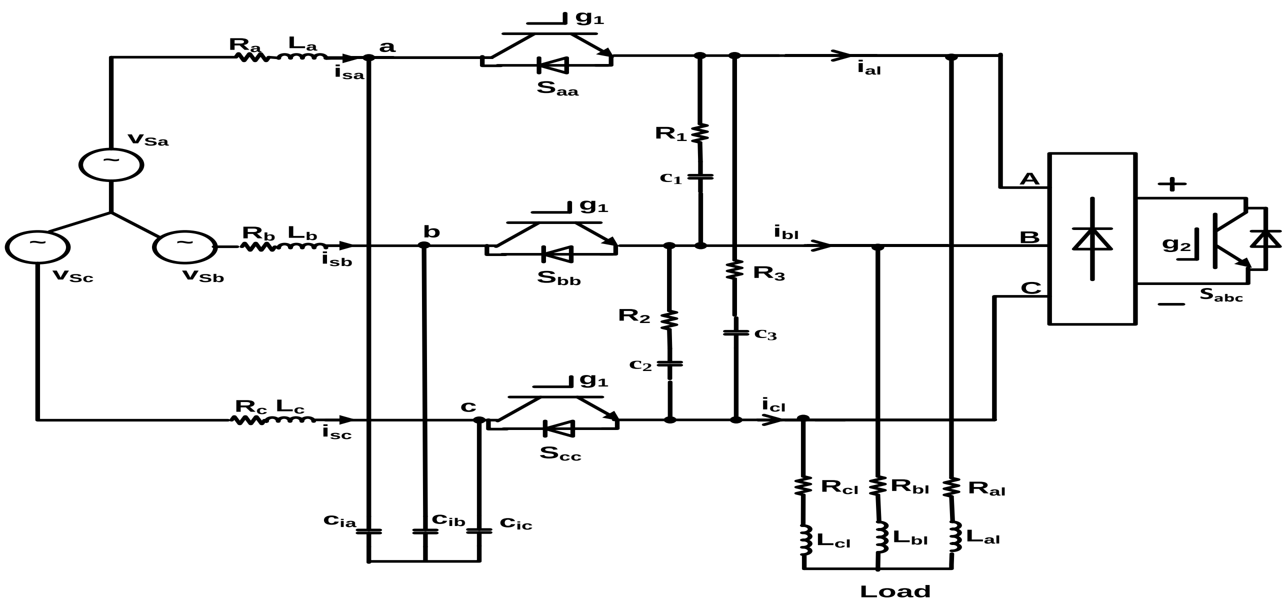


Fig.1 *The proposed three –phase AC-AC buck voltage regulator*

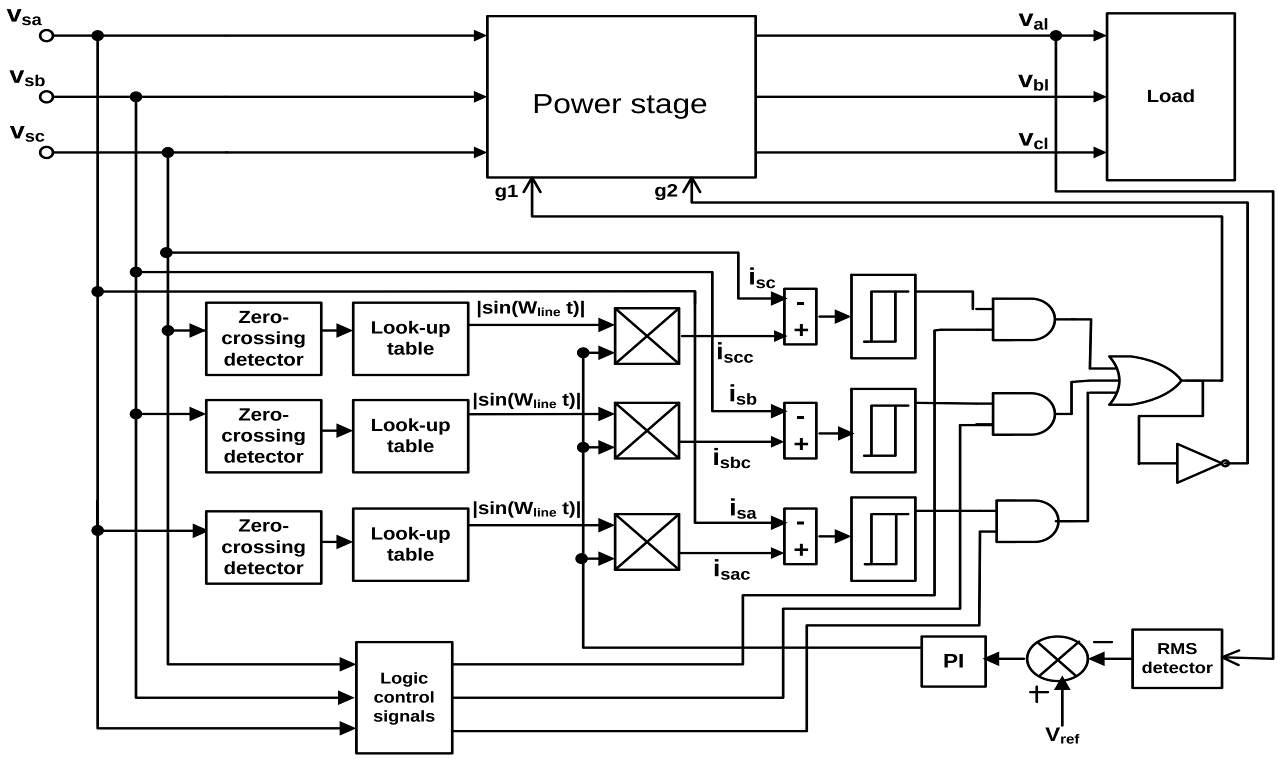


Fig.2 *Block diagram of the proposed control strategy.*

Although the circuit has four switches, it needs a simple control circuit to control the corresponding AC switches, and this will simplify the controller design greatly.

The switches (S_{aa}, S_{bb}, and S_{CC}) and (S_{abc}) work in complementary mode, thus the switches (S_{aa}, S_{bb}, and S_{CC}) and (S_{abc}) cannot be turned on simultaneously. For safe commutation, the switching dead-time is necessary which is done by the snubber capacitors and resistors.

The operation is divided into three modes: active mode, freewheeling mode and dead-time mode. The active mode is defined when the switches (S_{aa}, S_{bb}, and S_{CC}) are turned on, during the active mode, the load is supplied by the source and the load inductor storeges the energy. The freewheeling mode is defined when the modulated switch (S_{abc}) is turned on. In freewheeling mode, the load current freewheels and the inductors (L_{al}, L_{bl} and L_{cl}) discharge the energy through the switch (S_{abc}) with the help of the bridge rectifier according to the direction of the load current. Finally, the dead-time mode is defined when the switches (S_{abc}) and (S_{aa}, S_{bb}, and S_{CC}) are both all turned off. The dead-time is very short only about several microseconds. The snubber circuits can absorb the bidirectional turn-off spike energy.

Figure 2 shows the block diagram of the control strategy, in the proposed regulator; only three independent hysteresis current controllers are used. 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 RMS value detector, the phase voltage v_{al} is converted to a corresponding DC value. This value is compared with the reference voltage signal, v_{ref}, and the error signal is passed through a proportional integral (PI) controller.The output of the controller is then multiplied by the unit vector of the supply phase voltages v_{sa} , v_{sb} and v_{sc} to produce the command currents i_{sac}, i_{sbc} and i_{scc} respectively. These unit vectors are estimated by passing the input voltages through a zero-crossing detector, and the output of this detector is fed to sine wave look-up table which provides a rectified input voltage with unity amplitude. The zero-crossing detector is used with the proposed control method in order to achieve a good performance under distorted supply voltage. While the supply voltage has a distorted waveform, the zero-crossing detector does not affected by the shape of supply voltage waveform, so a sine wave voltage waveform with unity amplitude can be achieved even a non-sinusoidal supply voltage waveform is used, So this approach has a simple control compared with other methods. Then the supply currents i_{sa}, i_{sb} and i_{sc} are compared with their corresponding commands, i_{sac}, i_{sbc} and i_{scc} respectively, and the errors are processed through three independent hysteresis controllers. The outputs of the hysteresis controllers are processed through three logic AND gates and compared with the outputs of the logic control signals which detect the higher value of the supply currents i_{sa}, i_{sb} and i_{sc} then passed through a logic OR gate to produce the logic signals (pulses) for g_1 and g_2. These logic signals will be used to control 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. Since the pulses of g_1 are complementary of the pulses of g_2.The proposed buck regulator shown in Fig.1 has two modes of operations;

Active mode: S_{aa}, S_{bb} and S_{cc} ON and S_{abc} OFF: In this mode the supply voltage is connected directly to the load, supply currents flow to the load through series switches. At the same time, the load inductances are charged. This mode continues until the supply currents i_{sa}, i_{sb} and i_{sc} increase to be more than or equal to $\{(i_{sac}, i_{sbc}$ and $i_{scc}) + 0.5$ H$\}$, where H is the hysteresis band.

Freewheeling mode: S_{aa} ,S_{bb} and S_{cc} OFF and S_{abc} ON: In this mode, the control circuit allows the supply currents to decrease. At the same time, the stored energy in load inductances discharges into the load. This mode continuous until the supply currents i_{sa}, i_{sb} and i_{sc} decrease less than or equal to $\{(i_{sac}, i_{sbc}$ and $i_{scc}) - 0.5H\}$.

III. Analysis and circuit equations

The operation of the converter is divided into two modes, active and freewheeling modes. For these two modes of operations the following equations could be deduced:

A. Active mode

During the on state periods of the forward switches S_{aa}, S_{bb} and S_{cc}, the supply voltage appears across the load circuit forcing the current from the supply into the load, and applying Kirchhoff's voltage law to the system equivalent circuit as when S_{aa}, S_{bb} and S_{cc} ON and S_{abc} OFF, the following equations could be derived:

$$v_{sa} - v_{sb} = i_{sa} R_{Ba} + L_{Ba}\frac{di_{sa}}{dt} + v_{AB} - i_{sb}R_{Bb} - L_{Bb}\frac{di_{sb}}{dt} \quad (1)$$

$$v_{sb} - v_{sc} = i_{sb} R_{Bb} + L_{Bb}\frac{di_{sb}}{dt} + v_{BC} - i_{sc}R_{Bc} - L_{Bc}\frac{di_{sc}}{dt} \quad (2)$$

$$v_{sc} - v_{sa} = i_{sc} R_{Bc} + L_{Bc}\frac{di_{sc}}{dt} + v_{CA} - i_{sa}R_{Ba} - L_{Ba}\frac{di_{sa}}{dt} \quad (3)$$

Load equations:

$$v_{AB} = i_{al} R_{al} + L_{al}\frac{di_{al}}{dt} - i_{bl}R_{bl} - L_{bl}\frac{di_{bl}}{dt} \quad (4)$$

$$v_{BC} = i_{bl} R_{bl} + L_{bl}\frac{di_{bl}}{dt} - i_{cl}R_{cl} - L_{cl}\frac{di_{cl}}{dt} \quad (5)$$

$$v_{CA} = i_{cl} R_{cl} + L_{cl}\frac{di_{cl}}{dt} - i_{al}R_{al} - L_{al}\frac{di_{al}}{dt} \quad (6)$$

$$i_{al} + i_{bl} + i_{cl} = 0 \quad (7)$$

Current equation:

$$i_{sa} + i_{sb} + i_{sc} = 0 \quad (8)$$

$$v_{AB} = v_{ab} \quad , \quad v_{BC} = v_{bc} \quad , \quad v_{CA} = v_{ca} \quad (9)$$

B. Freewheeling mode

During the off state periods of the forward switches S_{aa}, S_{bb} and S_{cc}, the load circuit is isolated from the supply and the load terminals are short-circuited through the freewheeling path, implying that the voltage across the load terminal is zero. The load current will then naturally decay through the freewheeling path and the stored energy discharges through the freewheeling path, and applying Kirchhoff's voltage law to the system equivalent as when S_{aa} ,S_{bb} and S_{cc} OFF and S_{abc} ON, the following equations could be derived:

$$v_{sa} - v_{sb} = i_{sa} R_a + L_a\frac{di_{sa}}{dt} - i_{sb}R_b - L_b\frac{di_{sb}}{dt} + v_{ab} \quad (10)$$

$$v_{sb} - v_{sc} = i_{sb} R_b + L_b\frac{di_{sb}}{dt} - i_{sc}R_c - L_c\frac{di_{sc}}{dt} + v_{bc} \quad (11)$$

$$v_{sc} - v_{sa} = i_{sc} R_c + L_c\frac{di_{sc}}{dt} - i_{sa}R_a - L_a\frac{di_{sa}}{dt} + v_{ca} \quad (12)$$

$$v_{ab} = v_{c_{ia}} - v_{c_{ib}} \;, v_{bc} = v_{c_{ib}} - v_{c_{ic}} \;, v_{ca} = v_{c_{ic}} - v_{c_{ia}} \quad (13)$$

$$\Delta v_{c_{ia}} = \frac{1}{C_{ia}}\int i_{c_{ia}}\, dt \quad (14)$$

$$\Delta v_{c_{ib}} = \frac{1}{C_{ib}}\int i_{c_{ib}}\, dt \quad (15)$$

$$\Delta v_{c_{ic}} = \frac{1}{C_{ic}}\int i_{c_{ic}}\, dt \quad (16)$$

Load equations:

$$v_{AB} = 0 = i_{al} R_{al} + L_{al}\frac{di_{al}}{dt} - i_{bl}R_{bl} - L_{bl}\frac{di_{bl}}{dt} \quad (17)$$

$$v_{BC} = 0 = i_{bl} R_{bl} + L_{bl}\frac{di_{bl}}{dt} - i_{cl}R_{cl} - L_{cl}\frac{di_{cl}}{dt} \quad (18)$$

$$v_{CA} = 0 = i_{cl} R_{cl} + L_{cl}\frac{di_{cl}}{dt} - i_{al}R_{al} - L_{al}\frac{di_{al}}{dt} \quad (19)$$

$$i_{al} + i_{bl} + i_{cl} = 0 \quad (20)$$

Current equation:

$$i_{sa} + i_{sb} + i_{sc} = 0 \quad (21)$$

The rate of change of i_{sa}, i_{sb} and i_{sc} is determined by the values of the input inductances L_a, L_b and L_c and capacitors C_{ia}, C_{ib} and C_{ic} during the active mode, and depending on the load inductances L_{al}, L_{bl} and L_{cl} during the freewheeling mode. Accordingly, the switching frequency is determined by these values depending on the hysteresis band, H. 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 THD is defined as:

$$\mathrm{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} I_{sn}^{\;2}}{I_{s1}^{\;2}}} \quad (22)$$

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

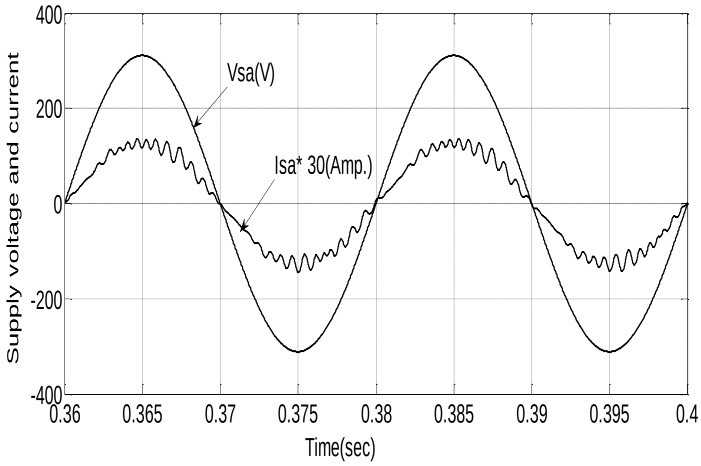
$$\mathrm{PF} = \frac{\cos\phi_1}{\sqrt{1 + THD^2}} \quad (23)$$

Where ϕ_1 is the angle between the fundamental component of the supply current and phase voltage.

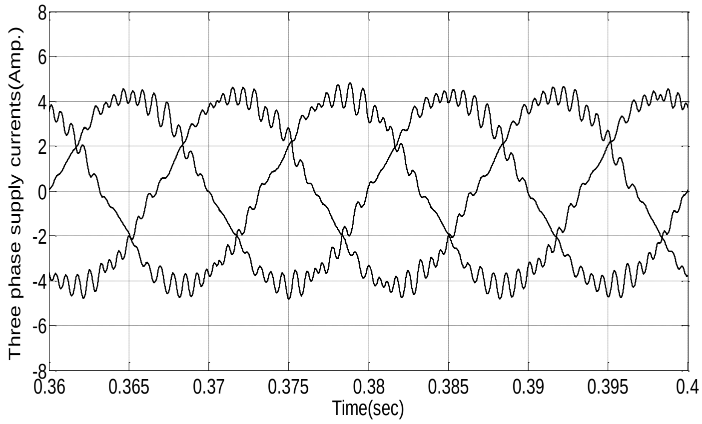
IV. Simulation Results

The control algorithm of the proposed control method has been developed and simulated using the MATLAB/SIMULNK software. The simulation allows investigation of both transient and steady-state operations for the proposed method which can also show the reduction in supply current harmonics distortion and improving the input power factor. The system parameters are reported in the appendix. The supply voltage is kept constant at 220V per phase and the reference voltage is controlled to allow bucking of the output voltage.

The steady state results of the proposed regulator at reference voltage 150V are shown in Fig.3.The steady-state supply phase voltage (v_{sa}) and the supply current (i_{sa}) waveforms are shown in Fig.3 (a). It is clear that the supply current follows the supply voltage in its wave shape with nearly unity power factor. The steady-state simulation results of input current and its harmonic spectrum for hysteresis current control method are shown in Fig.3 (b) and Fig.3 (c), respectively. From these results, it is clear that, by using of a new control methodology, balanced three-phase currents with low harmonic distortion is achieved and its total harmonic distortion is very low, 7.91% and the PF is 0.9996.The three phase load voltages and load currents are shown in Fig.3 (d)and Fig.3 (e), respectively. It is clear that with the aid of the new control methodology, the load voltages are symmetrical and almost equal the reference voltage (150V) and asymmetrical three phase load currents with good waveform and low harmonic distortion are achieved. The phase load voltage and current are shown in Fig.3 (f) which shows the validity of the proposed circuit of introducing a good performance, also by comparing Fig.3 (f) with Fig.3 (a), it could be detecting the improving of the input power factor approximately near to unity. Fig.3 (g) shows that by using such type of this new control it could be conclude that the input current doesn't change even if there is any abnormal disturbance in the supply voltage such as distorted supply voltage.



(a)



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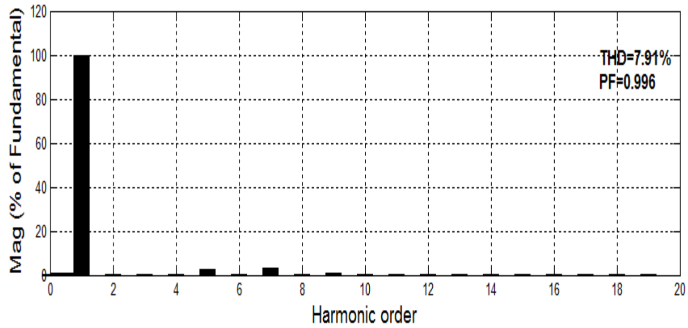

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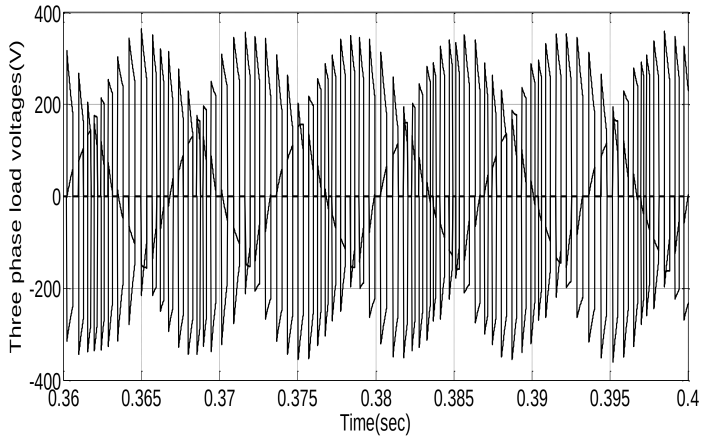
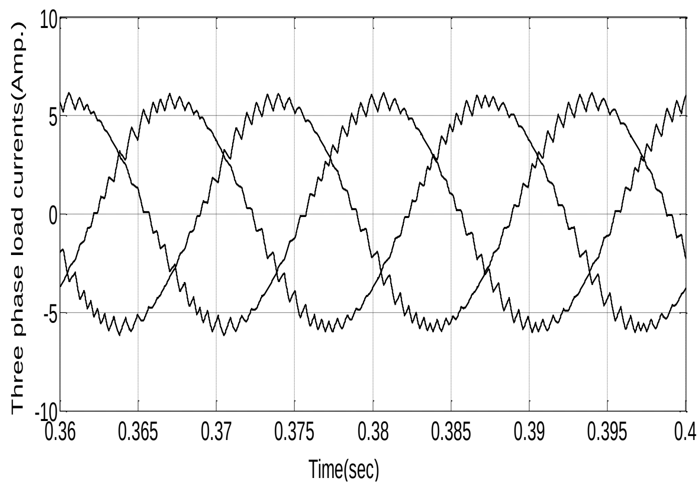
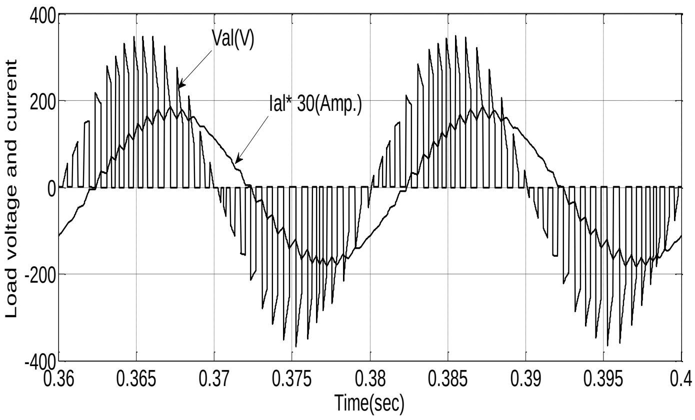


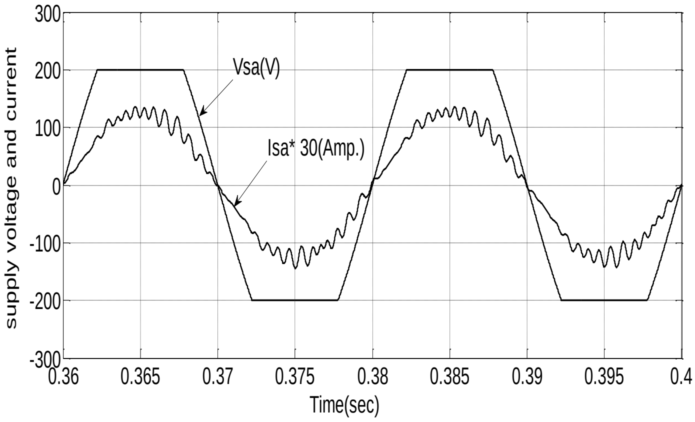
(d)



(e)



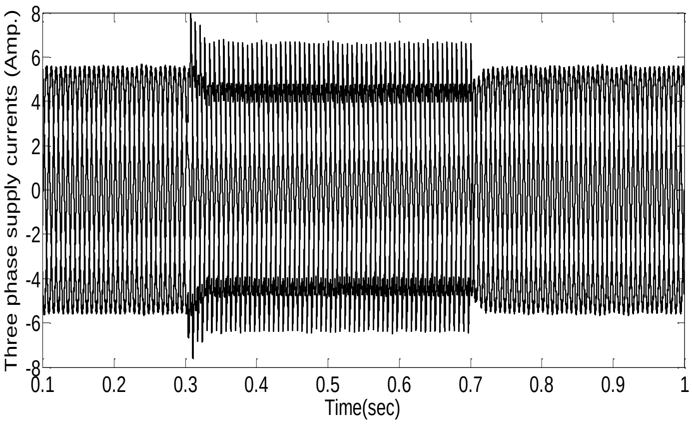
(f)



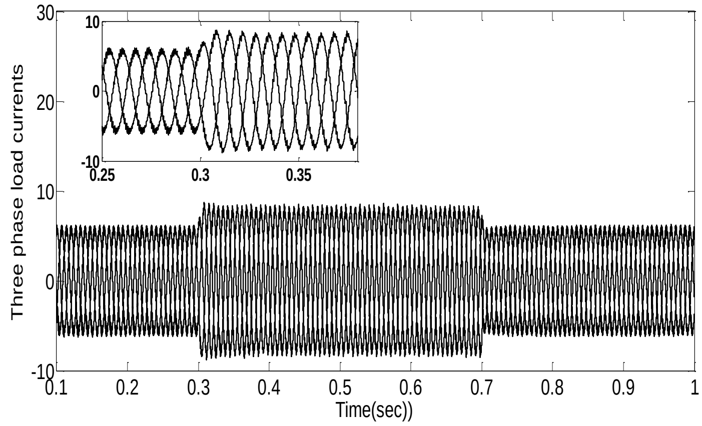
(g)

Fig. 3*The steady state simulation results of the proposed circuit; (a) Supply voltage and current; (b) Three phase supply currents; (c) Harmonics spectrum of supply current.; (d) Three phase load voltages; (e)Three phase load currents;(f)Load voltage and current; and (g) Input voltage and current for distorted supply voltage*.

The simulation results of supply and load currents due to ±34% step change in the load for the proposed method are shown in Fig.4 (a) and Fig.4 (b), respectively. As seen from these figures, it could be detected that both the supply currents and load currents are increased when the load increased and vice versa. Also from Fig.4 (c), it could be indicate that the RMS value of the load voltage v_{al} has a fast response back to the reference value during the load change.



(a)



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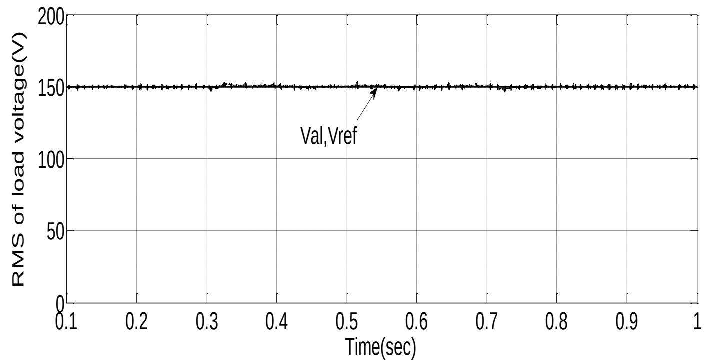
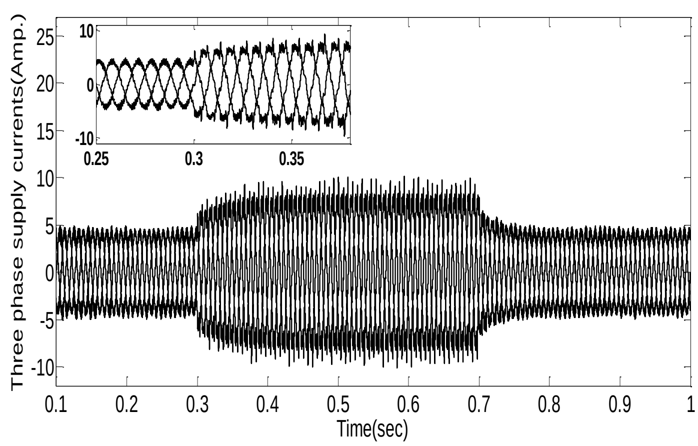


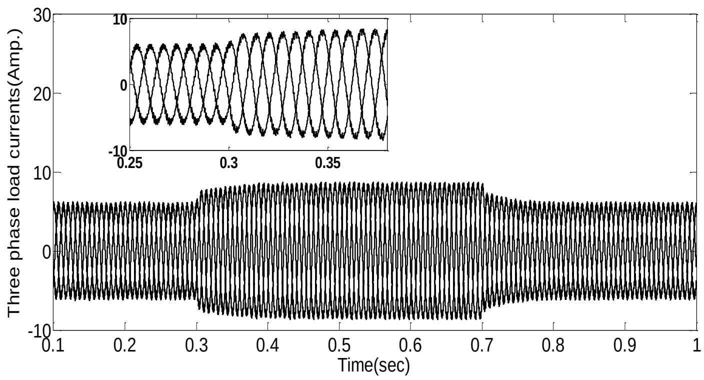
(c)

Fig. 4 *The transient state simulation results (±34% increase in load); (a) Three phase supply currents; (b) Three phase load currents; (c) RMS of load voltage(v_{al}).*

The simulation results of supply and load currents due to ±20% step change in the reference voltage from 150V to 180Vthen decreased to 150V again for the proposed method are shown in Fig.5 (a) and Fig.5 (b), respectively. As indicated from figures, it could be detected that, both the supply currents load currents are increased when the reference voltage increased and vice versa (proportional relationship), Also it could be deduced from results that the figures have a high quality waveform (low harmonics component).Also, Fig.5 (c)shows the transient response of the RMS value of the load voltage (v_{al}) during the change in the reference voltage.



(a)



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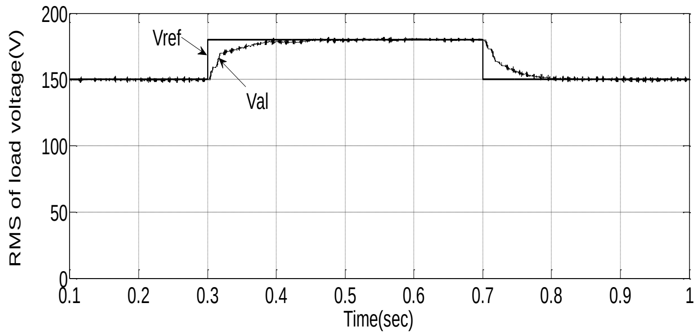
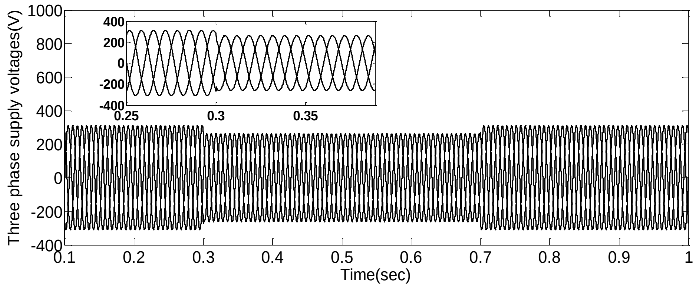


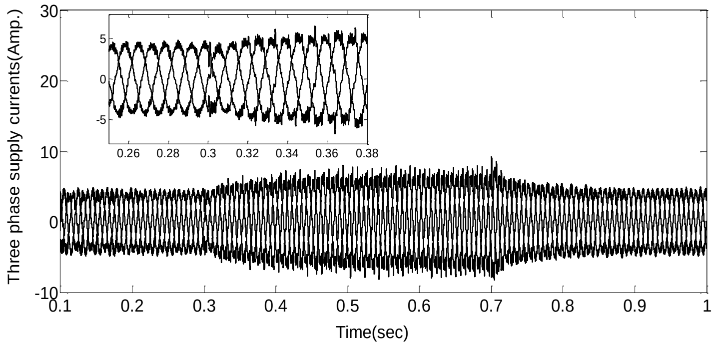
(c)

Fig. 5 *The transient state simulation results (±20% step change in reference voltage); (a) Three phase supply currents; (b) Three phase load currents; (c) RMS of load voltage (v_{al}).*

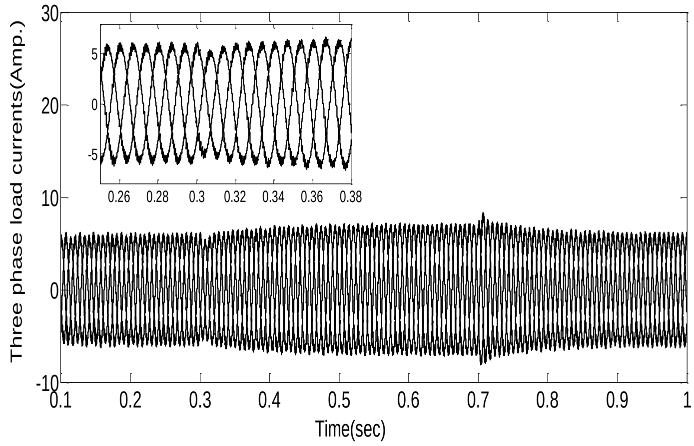
Figure 6 (a, b, c and d) shows other transient state results were obtained by making a change in the supply voltage by ±25 % (220 to 170 and then increased to 220 again). Which indicate that if there is a drop in the supply voltage, what will be the reaction of the control circuit, Figs. 6 (b, c and d) and all the figures above show that the control methodology proposed a high quality response with a good performance at any change or disturbance in the circuit.



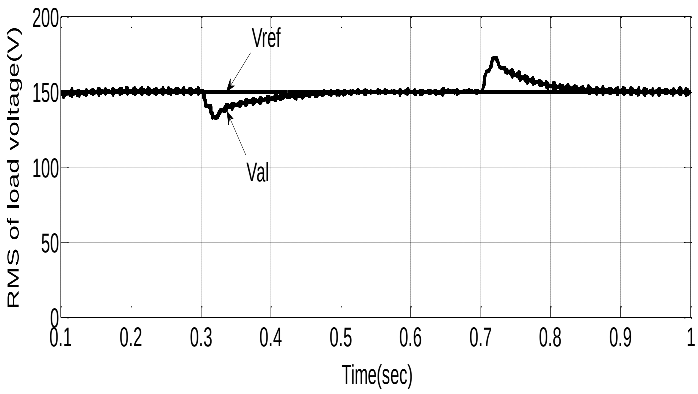
(a)



(b)



(c)



(d)

Fig. 6 *The transient state simulation results(±25% step change in supply voltage); (a) Three phase supply voltages; (b)Three phase supply currents; (c)Three phase load currents; (d) RMS of load voltage(v_{al}).*

V. EXPERIMENTAL RESULTS

With the objective of evaluating the employed topology, a laboratory prototype is setup. The block diagram of the experimental setup and a real view of the complete control system are shown in Figs.7 and 8, respectively. The main components of the system which labeled as in Fig. 8 are listed in table I. The proposed new control is done on a digital signal processor board dSPACE (DS1104) plugged into a computer. The control algorithm is executed by 'Matlab/Simulink', and downloaded to the board through host computer. The output of the board is logic signals, which is fed to IGBTS through driver and isolation circuits. The system parameters are reported in the appendix.

Fig. 8 *Experimental setup of the proposed circuit.*

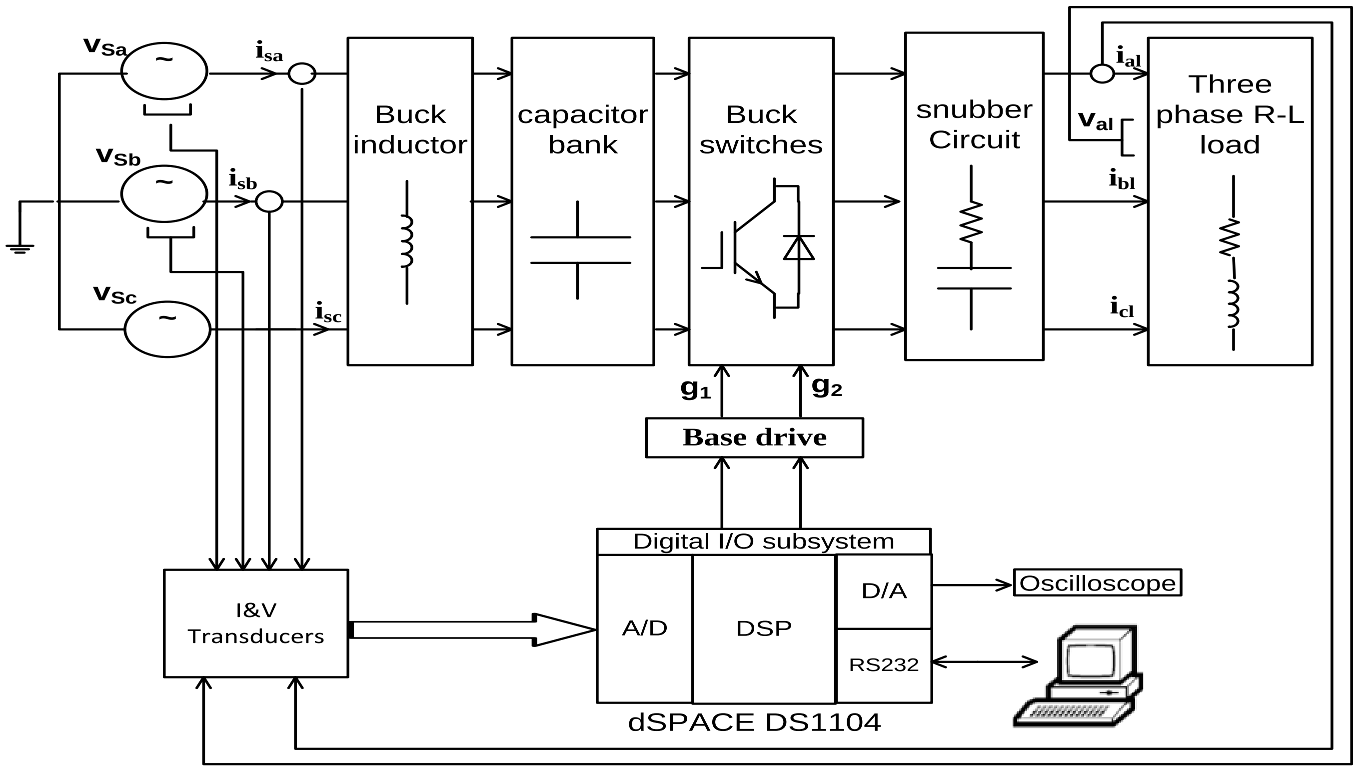


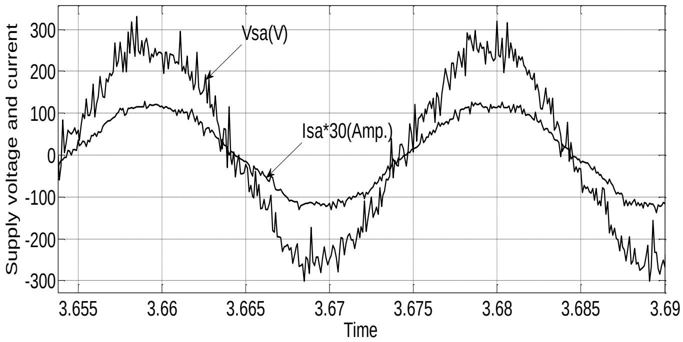
Fig.7 *Block diagram of the experimental setup of the proposed circuit.*

Table I

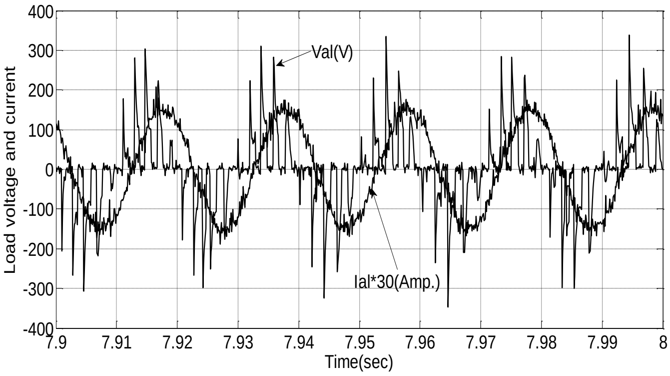
Label	Component	Label	Component
PC	Personal Computer	T	Fast recovery diodes
I	DSP Interface circuit	C	Capacitors
P.S	All other suppliers	L	Three phase inductance
P	Variable AC power supply	S	IGBT Switches
H	Voltage and current transducers	Z	Three phase RL load
B	Drive circuit	O	Oscilloscope

Figure 9 *shows the steady-state experimental results of the proposed circuit using the new control methodology. It is shown that, the supply current has a nearly sinusoidal waveform*

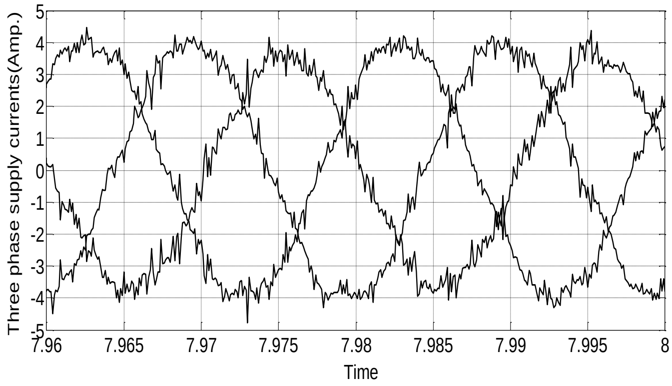
and it is in phase with the input voltage as shown in fig.9 (a), also by comparing this figure with Fig. 9(b),it could be detecting the improving of the input power factor approximately near to unity. Figs.9(c) and 9(d) show the waveforms of the three phase supply currents and the harmonics spectrum of the supply current. It is observed that, the input current has a low THD of 11.4% with a high power factor of 0.992. Figs.9 (e) shows the three phase load currents; it is shown from this figure the validity of the proposed circuit with the new control algorithm.



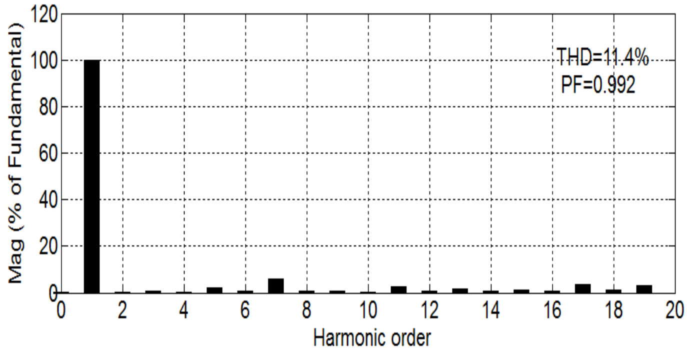
(a)



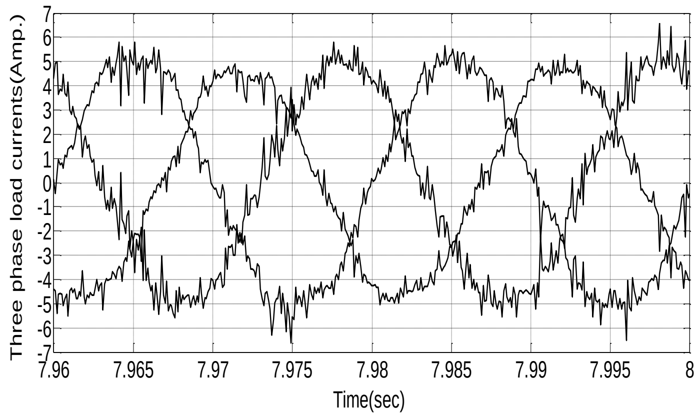
(b)



(c)



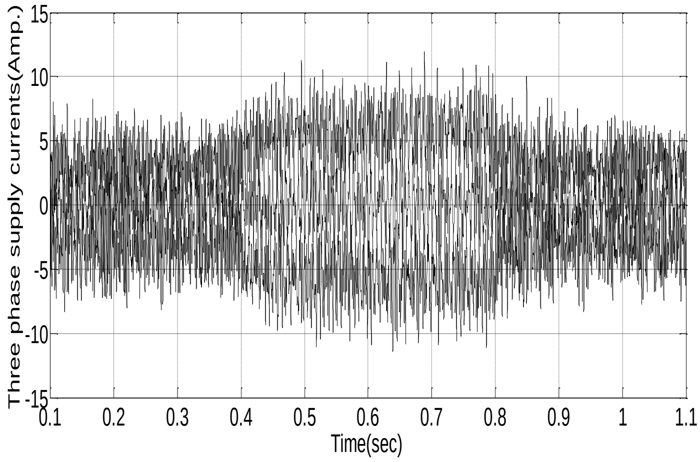
(d)



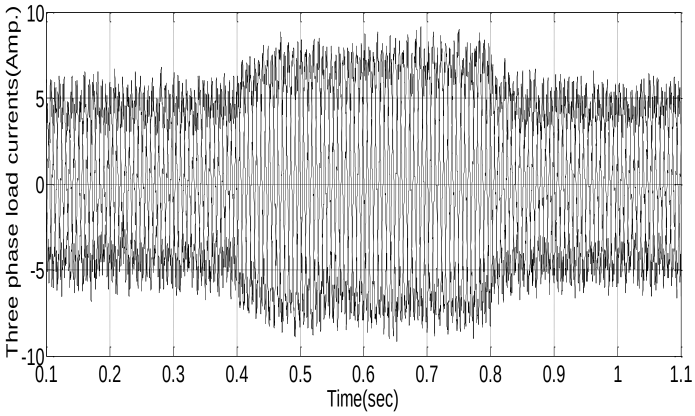
(e)

Fig. 9 *The experimental results of the proposed circuit; (a) Supply voltage and current; (b) Load voltage and current;(c) Three phase supply currents;(d) Harmonics spectrum of supply current; (e) Three phase load currents.*

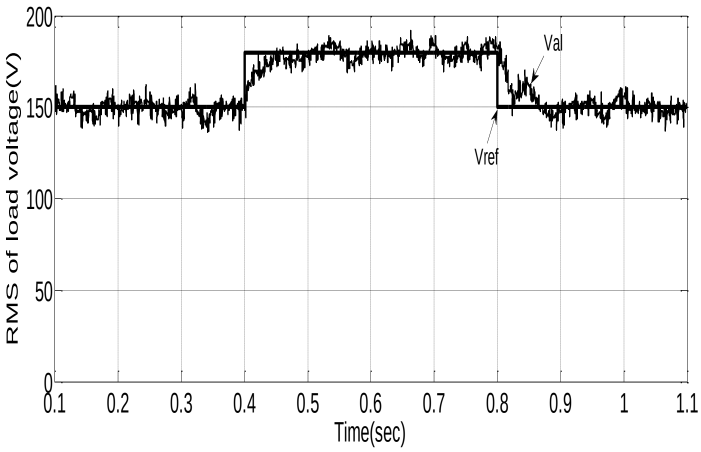
The experimental results of the three phase supply currents, three phase load currents, and RMS value of load voltage due to a step change in reference voltage from 150V to 180V and return to 150V again are shown in Fig.10, respectively. It is shown that, the load voltage follows the desired reference voltage and hence, both the supply and load currents follow the variation in load voltage that ensures the high response of the proposed circuit.



(a)



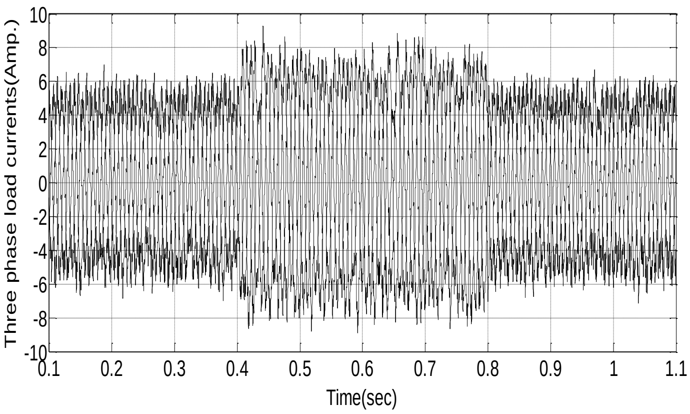
(b)



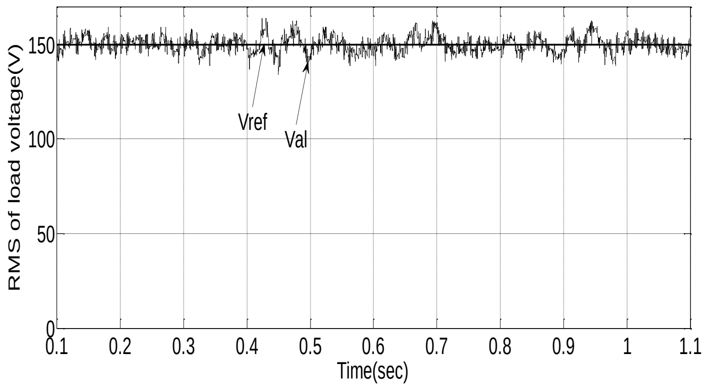
(c)

Fig. 10 *The experimental results (±20% step change in reference voltage);(a) Three phase supply currents; (b) Three phase load currents; and (c) RMS value of load voltage(v_{al}).*

The experimental results of load currents and RMS value of load voltage due to ±34% step change in the load for the proposed method are shown in Fig.11 (a) and Fig.11 (b), respectively. As seen from these figures, it could be detected that the proposed circuit with its new control has a fast response during the load change.



(a)



(b)

Fig. 11 *The experimental results (±34% step change in load voltage) ;(a) Three phase load currents; and (b) RMS value of load voltage (v_{al}).*

There are slight differences between the simulation and experimental results because in simulation results the supply voltage has an ideal sine waveform, but in experimental results supply voltage is not ideal sine waveform. Also, the simulation results are done with sampling time $1e^{-5}$ Sec. But, the experimental results are done with dSPACE (DS1104) with sampling time of $1e^{-4}$ Sec.

VI. CONCLUSION

This paper presents a new configuration for high performance three-phase AC-AC buck regulator. It has a simple control with excellent performance. The proposed circuit has high efficiency for adjusting AC power; because it is composed of fewer switches. The proposed regulator has a nearly unity input power factor with low harmonics at both input and output side. Also, the proposed circuit is implemented using a zero-crossing processing, which allows a greater accuracy than other methods. Input current of the proposed regulator flows continuously, therefore, the total harmonics distortion at the supply is very low. Also the proposed circuit presents good response and high efficiency. A good qualitative and quantitative agreement between the experimental and simulated results is evident, which verifies the validity of the proposed analysis.

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Appendix A

Data and circuit parameters

$V_{sa} = V_{sb} = V_{sc} = 220$ V $\quad L_a = L_b = L_c = 7$ mH

$R_a = R_b = R_c = 1\Omega$ $\quad C_{ia} = C_{ib} = C_{ic} = 12\mu F$

$R_1 = R_2 = R_3 = 180\Omega$ $\quad C_1 = C_2 = C_3 = 22\mu F$

Load side; three phase balanced R-L with $R_L = 20\Omega$ and $L_L =$ 50 mH.