International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:3, No:4, 2009

Evaluation of Power Factor Corrected AC - DC Converters and Controllers to meet UPS Performance Index

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***Abstract*—**Harmonic pollution and low power factor in power systems caused by power converters have been of great concern. To overcome these problems several converter topologies using advanced semiconductor devices and control schemes have been proposed. This investigation is to identify a low cost, small size, efficient and reliable ac to dc converter to meet the input performance index of UPS. The performance of single phase and three phase ac to dc converter along with various control techniques are studied and compared. The half bridge converter topology with linear current control is identified as most suitable. It is simple, energy efficient because of single switch power loss and transformer-less operation of UPS. The results are validated practically using a prototype built using IGBT and analog controller. The performance for both single and three-phase system is verified. Digital implementation of closed loop control achieves higher reliability. Its cost largely depends on chosen bit precision. The minimal bit precision for optimum converter performance is identified as 16-bit with fixed-point operation. From the investigation and practical implementation it is concluded that half bridge ac – dc converter along with digital linear controller meets the performance index of UPS for single and three phase systems.

***Keywords*—**PFC, energy efficient, half bridge, ac-dc converter, boost topology, linear current control, digital bit precision.

I. INTRODUCTION

SWITCH mode Power Factor Corrected (PFC) AC-DC converters with high efficiency and power density are being used as front end rectifiers for a variety of applications [1-3]. The converters are either buck or boost type topologies. The buck type topology provides variable output DC voltage, which is much lower than the input voltage amplitude. However when the instantaneous input voltage is below the output DC voltage, the current drops to zero that results in significant increase in input current THD. Even with input filters the buck converters provide only limited improvement in input current quality. On the other hand the boost type converter always produces the output voltage higher than the input instantaneous voltage amplitude. The boost inductor with appropriate choice helps to maintain continuous input current with good wave shape. This lead the converter control to maintain near unity power factor, low input current THD and good output voltage regulation. Hence, the boost type ac-dc converters have found wide spread use in various applications [4]. This work is to identify a low cost, small size, high efficient and reliable ac to dc converter to meet UPS input performance index such as input power factor near unity and input current distortion ≤ 5%, output voltage regulation and ripple ≤ 2%, converter η ≥ 97.5%. Various ac-dc converters based on boost type topology and closed loop regulator with different current controller types are investigated for UPS application. The following converter topologies are considered for the investigation.

i. Conventional single switch boost AC-DC converter
ii. Half Bridge AC-DC converter
iii. Full Bridge AC-DC converter
iv. Three-phase four wired AC-DC converter

The converter regulates the output voltage using PI controller at the outer loop and the input current using inner controller of the following type

i. Hysteresis current control
ii. Predictive current control
iii. Linear current control

The performance of above said ac-dc converters along with controllers are compared and evaluated for the input performance index [5]. The best indexed converter topology and current control scheme is tested practically. The prototype is built using IGBT and analog controller. The prototype results validate both converter & controller performance and their appropriateness for UPS application. Analog implementation of controller suffers from numerous disadvantages such as parts count, ageing and environment effects and limited flexibility & reliability. Digital implementation not only removes said drawbacks but also enhances the systems reliability. Hence the converter control design is implemented using digital systems/processors. The cost of the digital implementation largely depends on chosen bit precision. Hence identification of minimal bit precision for the desired converter performance is studied. The effect of bit precision on the converter performance is presented and compared. In the following sections the operation of converters and controllers are introduced, the converter performance for single and three phases are verified in simulation and experimentation, the minimal 16-bit precision with fixed-point digital controller is implemented and concluded that half bridge ac-dc converter with digital linear controller meets the performance index of UPS.

Manuscript received in August 2009. The research is supported in part by AICTE (Statutory Body, File No.: 8020/RID/TAPTEC-32/2001-02), Government of India and M/s Tetra Controls Private Limited, Chennai, India.

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II. VARIOUS CONVERTER TOPOLOGIES AND CONTROL SCHEMES

A. Performance Comparison of PFC Converters

The Power Factor Corrected (PFC) ac-dc converter topologies considered for performance comparisons are boost type. The single-phase conventional boost type ac-dc converter topology for uni-directional power flow is shown in Fig.1. It is realized by cascading single-phase diode bridge rectifier with boost chopper. The converter topology is cost effective due to single switch control. At any time, the number of device conducting is three, i.e. the control switch and two rectifier diodes. The switch operates with high switching frequency along with two power diodes. Hence this converter incurs high losses due to switching and conduction that results in low efficiency which is considered as disadvantage for UPS.

The circuit shown in Fig.2 is the boost type full bridge ac-dc converter. The advantage of this topology is that only two switches conduct at any time also shares the total voltage equally and hence reduces switch voltage stress, reduces conduction and switching losses and increases efficiency & reliability. This topology requires isolation transformer when cascaded with an inverter to have common neutral for UPS application [3]. Thus increases the size/volume and cost of the entire system (UPS), which is the drawback of this topology.

The circuit shown in Fig.3 is boost type half bridge converter circuit and its operation has been presented in [2]. The advantage is at any time only one semiconductor device conducts. Hence minimizes both switching and conduction losses and maximizes converter efficiency. The topology also has common neutral and hence dispenses isolation transformer for UPS applications. Relatively, the half bridge converter is simple, less in component count, cost-effective with higher efficiency and reliability. All these advantages are inherently present in three-phase four-wired AC-DC converter shown in Fig.4 which is deduced from half bridge topology. Hence boost type half bridge based topologies are the best for low/medium power UPS.

B. Current Control Schemes for PFC Converter

Power factor corrected ac-dc converter topologies invariably use current control techniques to achieve near unity power factor and reduce current distortion (%THD) ≤ 5% at the converter input/utility [4-6]. Hence ac to dc converters with current control strategies have gained importance in high performance applications such as UPS with high performance index, fast response and high accuracy. Among various current control schemes, Hysteresis Control, Predictive Control and Linear Control are widely used. The current control schemes and their operating principle are briefly presented below.

(i) *Hysteresis current control*

The hysteresis control scheme is shown in Fig.5. The actual line current (i_{actual}) is measured. The reference current (i_{ref}) with desired magnitude and shape is derived from the voltage controller output. The instantaneous values of i_{actual} and i_{ref} are

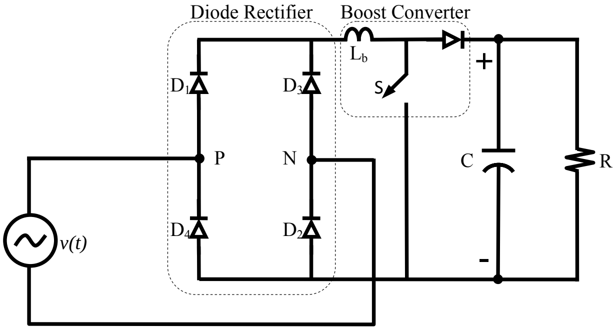


Fig. 1 Conventional Boost Type ac – dc Converter

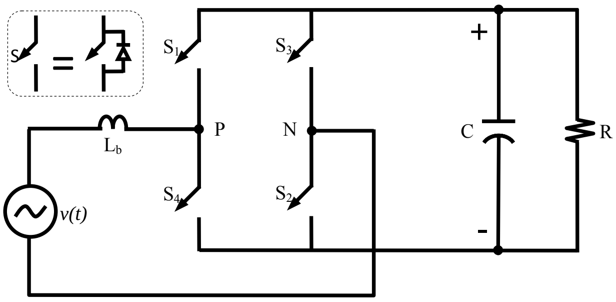


Fig. 2 Single Phase Full Bridge Boost Type Converter

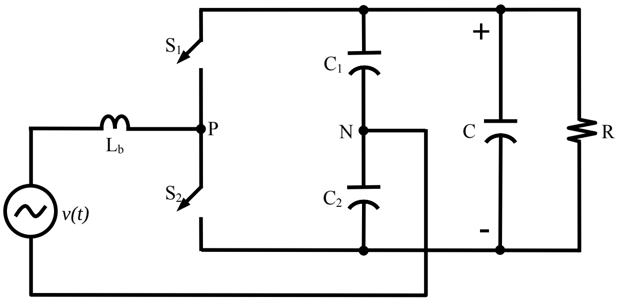


Fig. 3 Single Phase Half Bridge Boost Type Converter

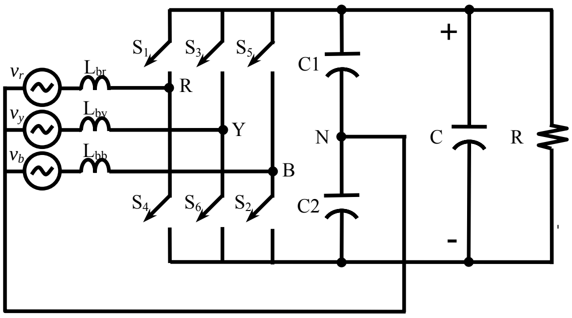


Fig. 4 Three Phase Four Wired Boost Type Converter

compared using hysteresis comparator with hysteresis band (ΔI). The result of comparison is the comparator output signal, which is used to control converter switches to make it ON/OFF. Thus the converter switches and their operation force input current to follow the desired reference within hysteresis band. Hence hysteresis current control technique is simple, accurate, and robust and hence advantages. However, the current regulation demands varying switching frequency which is considered as disadvantage [5].

(ii) *Predictive current control*

The predictive current control scheme is shown in Fig.6. Here the switch voltage is predicted at the beginning of each modulation/switching period. The prediction is based on the current error, input voltage, switching frequency and input filter inductor and load variables. The predicted switch voltage (V_{sw}^{*}) is compared with double-edge triangular carrier signal to generate PWM pulse to the switches. The carrier signal is chosen for fixed frequency operation but the amplitude of the carrier signal is modulated to accommodate the load voltage/current variation. In every switching/ modulation cycle, the switch voltage reference is predicated and used to generate gate pulses. This technique uses additional information along with error signal that improves converter dynamic performance but also increases cost on sensors and complexity in control [6, 7].

(iii) *Linear current control*

The linear control scheme is shown in Fig. 7. In which the actual current (i_{actual}) is compared to the reference current (i_{ref}) to obtain the current error (i_{error}). The error is processed by a proportional-integral controller to provide a modulating signal for a PWM modulator. The modulator produces gate pulses for the converter switches. The pulses are of constant-frequency with varying pulse width, which depends upon the magnitude of the modulating signal produced by the current controller. The controller parameters are tuned to optimize the PWM pulses such that the input current maintains near sinusoidal waveform with distortion < 5% and power factor near unity [8]. The controller requires minimum number of measured signals from converter and hence the implementation using standard integrated circuits becomes simple, straightforward, cost effective and reliable [7]. So, linear current control is preferred for ac – dc converter to meet the performance index of UPS.

C. *Closed Loop Control for PFC ac-dc Converters*

The general block diagram of the closed loop control of PFC converter is shown in Fig.8. The objective is to regulate the power flow and meet the UPD input performance index such as output voltage regulation ≤ 2%, input power factor ≥ 0.95, input current distortion THD ≤ 5%. The output voltage is regulated by the outer voltage control loop. The input power factor and current wave shape are controlled by the inner current loop. Both controller are chosen as PI type compensator and represented by the transfer function $G_c(s)=K_p(1+1/T_i\,s)$. Where K_p and T_i are proportional gain and integral time constant respectively. The output voltage is

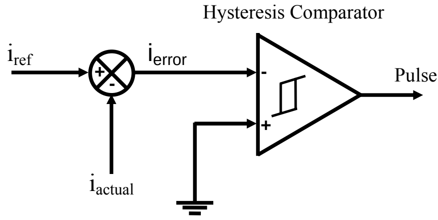


Fig. 5 Hysteresis Current Controller

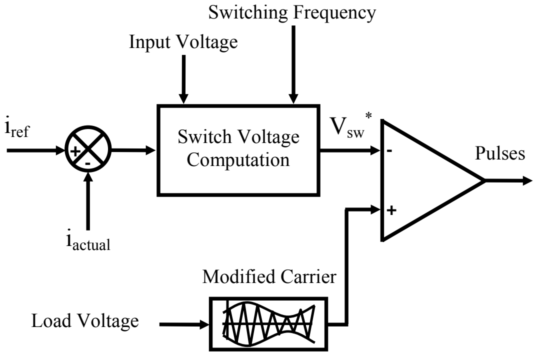


Fig. 6 Predictive Current Control

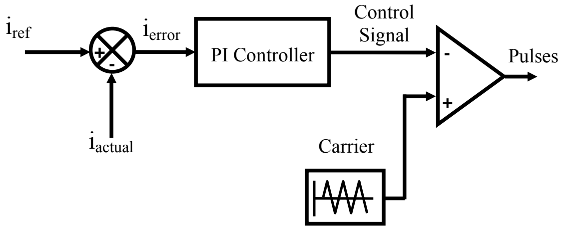


Fig.7 Linear current control

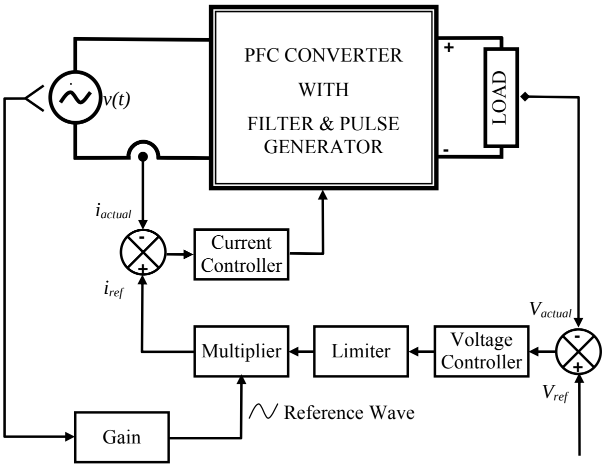


Fig.8 Closed Loop Control for PFC ac-dc Converter

regulated using voltage error (V_{error}) obtained by comparing the measured actual output voltage (V_{actual}) and desired reference voltage (V_{ref}). The V_{error} is processed by the voltage PI-controller whose output is the desired current magnitude and limited to a designed maximum value. It is multiplied with unity magnitude sine-wave reference derived from input voltage. The output of the multiplier is the desired sinusoidal input reference current signal (i_{ref}) with magnitude and phase angle. This signal is further processed by the linear current controller as detailed in Fig.7 and generates pulse width modulated gate pulses such that converter maintain input performance index.

The outer/voltage loop controller parameter values for K_p and T_i are designed to maintain constant output voltage irrespective of disturbance due to change in load/ input voltage. K_p and T_i are found from open loop converter output voltage response for a step load change [5]. Whereas the inner /current loop controller values for K_p and T_i are designed to optimize PWM pulses such that converter operation maintains input current near sinusoidal with limited distortion and power factor near unity. The controller parameters design for both loop have been verified [5]. The converter performance is evaluated and presented in following sections.

III. Performance Of PFC Converters

The performance study of above converters at 20 kHz switching frequency is carried using various current control schemes for various load conditions. The values of the boost inductor and output dc filter capacitor are calculated for desired input current ripple and output voltage ripple [4]. Reduced output voltage ripple are desired as it reduces third harmonic and %THD in the input current. A summary of converter performance obtained is presented in Table I to III. From Table I, it is observed that the boost converter has an efficiency of 70%, which is the lowest. The full bridge converter and the half bridge converter have higher efficiency of 92% and 95% respectively. Every current control scheme is observed to maintain an input power factor near unity. The hysterisis control has highest THD compared to linear/predictive control. However all current control schemes maintain a THD < 5%. The performance comparison among PFC converters is evaluated and derived the following inferences from Table II.

a. *Boost converter is simple to control but efficiency is low and components count is high.*
b. *Full bridge converter is relatively more efficient but control complexity and cost are high.*
c. *Half bridge converter is simple to control with reduced power devices and losses. Hence it exhibits high efficiency at a reduced cost.*

From the above it is concluded that half bridge converter topology is economical and efficient for UPS applications. Table III presents characteristic comparison various current control schemes. Hysteresis control is simple in structure but operates with varying switching frequency, Predictive control operates with constant switching frequency but structure is complex. Linear control operates with constant switching with simple structure. Hence linear control scheme is considered most suitable for practical implementation.

From the above performance analysis, it is concluded that half bridge converter and linear current control meets the required input performance index and offers cost effective solution for low/medium power UPS. The performance of half bridge converter and control scheme is validated practically for single and three phase systems. The experimental results are presented and discussed in the next section.

IV. Simulation And Experimental Results

A. Half bridge converter

A single-phase half bridge converter with input voltage of range (85V-130V) for a load of range (200W-1KW) is built and tested. For an input voltage of 110V and a load of 800W, the experimental and simulation results are presented in Fig.9 and Fig.10 respectively. The input voltage and current waveform are presented in 9(a) and 10(a) is identical and maintains same input power factor. But the input current distortion is high in case of practical and caused by supply voltage distortion (V_{THD}) that measured as 3.59%. To validate this fact, the simulation voltage source is added voltage harmonics artificially to derive distortion 3.59%. Figures 9(b) and 10(b) demonstrate that with similar input voltage, the converter input current I_{THD} is same in both simulation and

TABLE I
PERFORMANCE OF VARIOUS CONVERTERS AND CONTROL SCHEMES

Rectifier	Hysteresis		Predictive		Linear		η %
	PF	THD%	PF	THD%	PF	THD%	
Boost	0.97	4.6	0.98	3.1	0.98	3.8	70
Full bridge	0.96	4.4	0.99	3.2	0.97	3.8	92
Half bridge	0.98	4.2	0.99	3.2	0.98	3.7	96
Three phase	0.98	4.2	0.98	2.4	0.98	3.5	95

TABLE II
PERFORMANCE EVALUATION OF VARIOUS CONVERTERS

Parameters	**Converter Topologies**		
	Boost	Half bridge	Full bridge
Voltage stress	High	Medium	Low
Losses	Very High	Low	High
Efficiency	Very Low	Very high	High
Cost	Low	High	Very High
Power factor	Near Unity	Near Unity	Near Unity
THD	Minimum	Minimum	Minimum
Power flow	Unidirectional	Bi-directional	Bi-directional

TABLE III
CHARACTERISTIC COMPARISON OF VARIOUS CURRENT CONTROL SCHEMES

Parameters	**Current Control Schemes**		
	Hysteresis	Predictive	Linear
Structure	Simple	Complex	Simple
Response	Slow	Very Fast	Fast
Switching frequency	Vary	Constant	Constant
Carrier Amplitude	--	Vary	Constant
Sensors required	Less	More	Less
Cost	Low	High	Low

practical. The figures 9(c)&(d) and figures 10(c)&(d) show the output voltage and current respectively. Figures 9(e)&(f) and figures 10(e)&(f) show voltage and current PI controller output. The waveforms and their characteristic values are identical in both simulation and experimentation. The prototype results practical verify linear current controller operation/design and half bridge converter performance obtained through simulation.

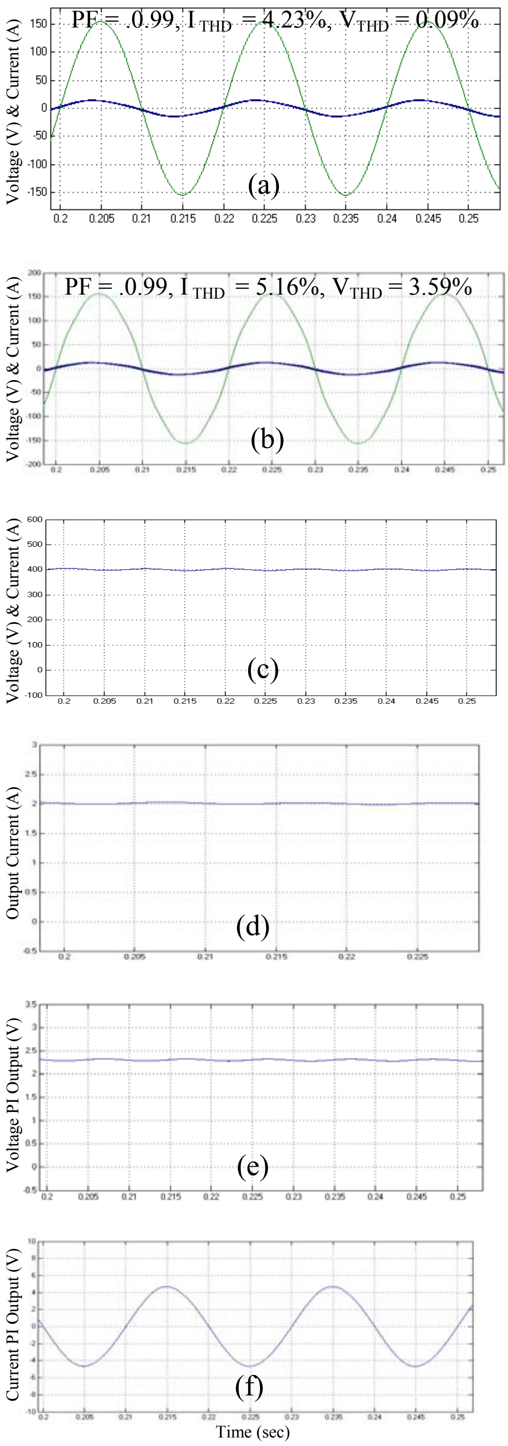


Fig. 9 Simulation Results; Performance of half bridge converter

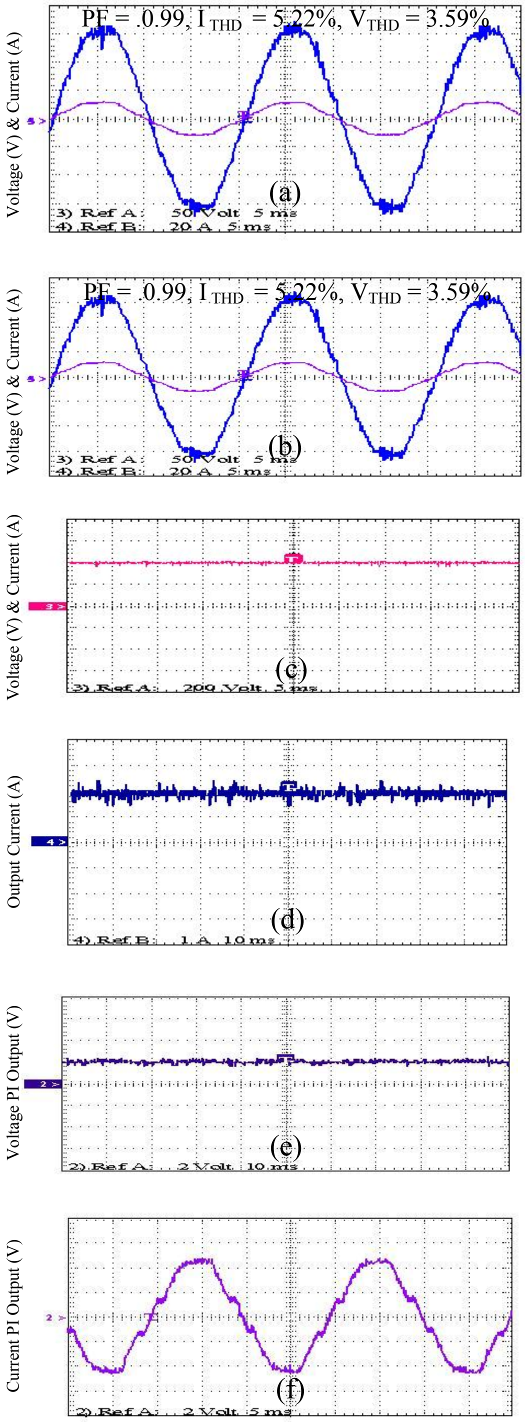


Fig. 10 Experimental Results; Performance of half bridge converter

B. Three-phase four-wired AC- DC converter

A three-phase converter with input voltage range (85V-130V) and load range (600W-3KW) is built and tested. The simulation and practical results are compared and results at 110V input voltage with 2800W load is presented in Fig.11 and Fig.12 respectively. The figures 11(a),(b),(c) and 12(a),(b),(c) demonstrate waveforms of input voltage and current in the three-phases. Figures 11(d),(e) and 12(d),(e) show converter output voltage with ripples and converter output current. The respective practical and simulation results are identical in values and shapes. Hence half bridge converter performance and closed loop controller design are verified practically for both single phase and three-phase converter. The converter maintains near unity power factor, input current THD less than 5 % and efficiency more than 95%. Hence the performance of a half bridge boost type ac-dc converter matches the desired input performance index of UPS.

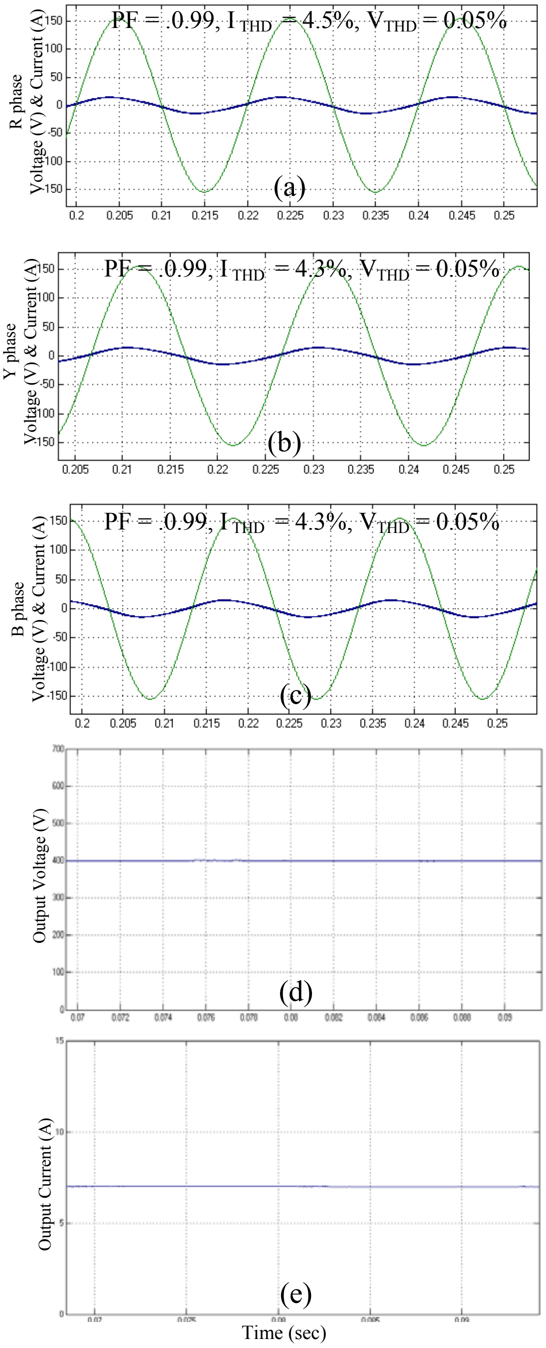


Fig. 11 Simulation Results; Performance of Three phase Converter

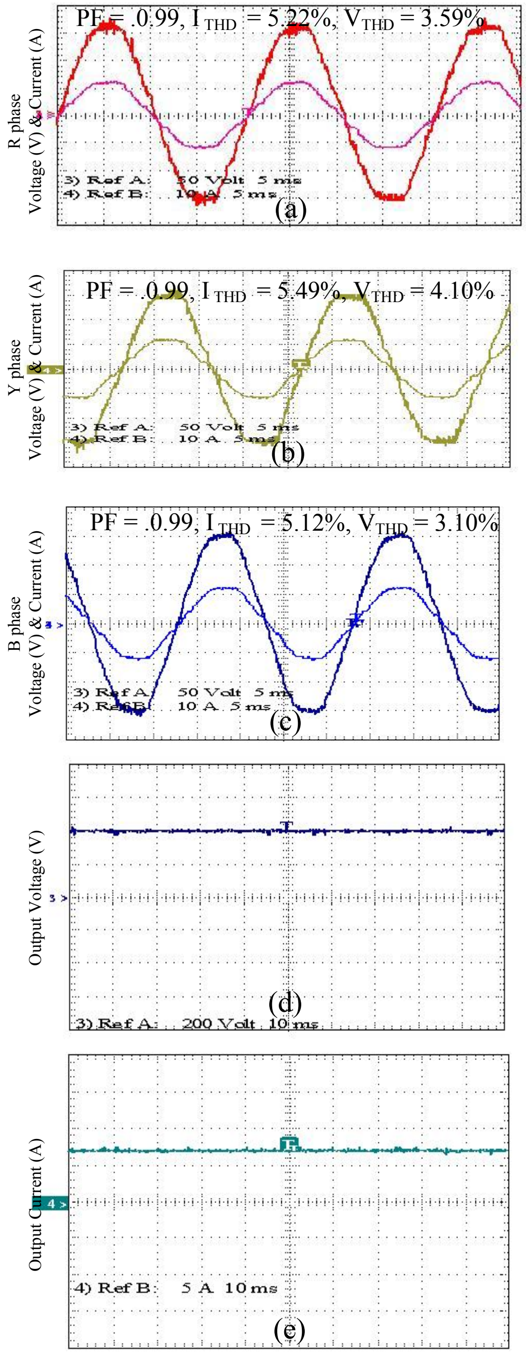


Fig. 12 Experimental Results; Performance of Three phase Converter

V. DIGITAL IMPLEMENTATION OF CLOSED LOOP CONTROLLER FOR PFC CONVERTER

A single-phase half bridge converter scaled to 7kVA designed and tested with closed loop control for various input voltages and load. The parameters of converter and controllers are given in Table VI. The converter performance is presented in Table V for various input voltages and load. The results verify the controller design and converter performance. The converter waveforms for normal input voltage and full load are given in Fig. 13. The closed loop controlled converter maintains output voltage regulation along with near unity power factor and reduced current THD at the input.

A. *Digital based closed loop controller*

To increase systems reliability, it is proposed to implement converter controls in digital domain. Digital implementation also enhances systems programmability and reliability by removing few drawbacks of analog implementation such as parts count, ageing and environment effects and limited flexibility. The recently available high-speed digital signal processor executes controller algorithm faster and enhances converter-switching frequency to 20 kHz and higher. The control algorithm written in high-level language provides ease and flexibility. The digital implementation reduces number of components, increases reliability and hence attractive for UPS application.

TABLE IV
CONVERTER RATING AND CONTROLLER PARAMETERS

Voltage controller		Current controller		Specifications		
K_p	K_I	K_p	K_I	Input Voltage (V)	Output Voltage (V)	Output KVA
2	**100**	**3**	**500**	**230**	**780**	**7**

TABLE V
CLOSED LOOP CONVERTER PERFORMANCE FOR VARIOUS INPUT VOLTAGE AND LOAD

V_s (V)	I_s (A)	I_{s1} (A)	PF	I/P Power (W)	V_{dc} (V)	I_L (A)	O/P Power (W)	I_S THD (%)	V_s THD (%)	Efficiency (%)
210	34.3	32.5	0.998	7195	780	9.0	6940	3.30	0.1	96.45
230	32.3	32.0	0.995	7109	780	9.0	6940	3.76	0.1	97.62
250	29.1	28.5	0.992	7210	780	9.0	6940	4.10	0.1	96.25
230	22.6	21.9	0.961	4240	780	4.5	3948	4.50	0.1	92.10

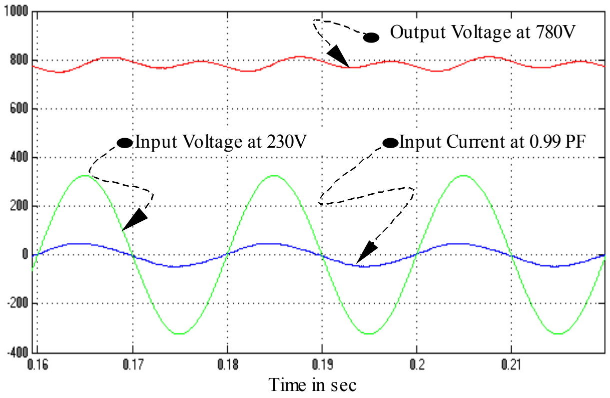


Fig. 13 Converter Output Voltage and Input Voltage and Current

B. *Selection of bit-precision for digital implementation*

Digital implementation of the closed loop controller shown in Fig.8 is evaluated in discrete domain. The inputs to the controller are input reference voltage, converter output voltage and input/boost inductor current. The measured signals are sampled. The sampling time limits system performance and hence need to be very low. It is the time required to execute the complete closed loop digital control algorithm. The implemented closed loop digital controller algorithm including initialization process requires 2307 clock cycles, which is shown in pipeline display of CCS in Fig.15. Excluding initialization, the repetitive execution requires only 418 clock cycles as shown in Fig.14. This number when multiplied with operating clock period determines minimum sampling time and maximum sampling rate for digital systems.

Further, to choose between fixed-point and floating-point number, the proposed digital closed loop controller is implemented in both types. The number of clock cycles required by the DSP to execute the control algorithm in fixed and floating point are found using Code Composer Studio (CCS) and given as 418 and 6877 clock cycles respectively. The floating-point implementation demands higher execution time for the controller and increases system/signal sampling time. To reduce sampling time without losing accuracy, floating-point number is converted to equivalent fixed-point number. To determine suitable number bits or bit-precision for ac-dc converter application, the closed loop control logarithm is implemented with 8-bit floating point, 8-bit fixed point and 16-bit fixed point.

The converter performance in closed loop digital controller with various bit precision is compared. Voltage PI controller output measured in volts for fixed point (8-bit, 16-bit) and floating point (8-bit) is shown in Fig. 16(a). The respective converter output voltages are given in Fig. 16(b). The 8-bit fixed point could not distinguish a variation of 0.001 and hence the controller losses control and failed to regulate converter output voltage. The above result reveals that 8-bit fixed point based controller is not suitable. But interestingly performance of the controller with 16-bit fixed point and 8-bit floating-point implementation are same and the converter output is regulated. The digital controller with 16-bit fixed-point implementation achieves both accuracy and lower sample time and hence 16-bit precision is identified as most suitable for the closed control of ac to dc converter.

C. *Performance Evaluation with 16-bit digital controller*

The performance of a 16-bit fixed point digital controller is verified using TMS320F2407 and its emulation environment. The controller maintains constant converter output voltage and unity power factor with reduced current THD at the input. The controller performance for a step change in line voltage at 0.4

and 0.8 seconds is shown in Fig.17, and for a step change in load at 0.8 second is shown in Fig.18. In both case, the digital controller implementation maintains the converter output voltage constant.

Hence 16-bit fixed-point processor is the minimum and hence TMS320F2407 with 10-bit A/D with operating frequency of 40MHz is suitable for the closed loop control of above ac – dc converter. Considering the complete controller implementation for UPS application, with converter and inverter operating with a switching frequency of 20 kHz, 16/32-bit processor with 150 MHz clock frequency and 25 µs sampling time is identified as the most suitable system for digital controller implementation.

The prototype for single-phase half bridge ac-dc converter is built using IGBT and the closed loop controller is implemented using TMS320F2407. Digital controller algorithm presented in Fig.14 is coded using C-language and down loaded to TMS320F2407 starter kit using JTAG emulator. The DSP based controller along with converter is tested. The practical results of the converter performance results for various input voltage and loads are given in Table V. The second row presents the best performance of half bridge converter and demonstrate that the digital controller maintains converter output voltage constant and input current sinusoidal with near unity power factor. The simulation waveforms are given in Fig.13. The simulation results are validated practically in Table V. The prototype results validate digital controller implementation using DSP TMS320F2407. The complete digital control of UPS requires processors with higher operating clock frequency of 150MHz.

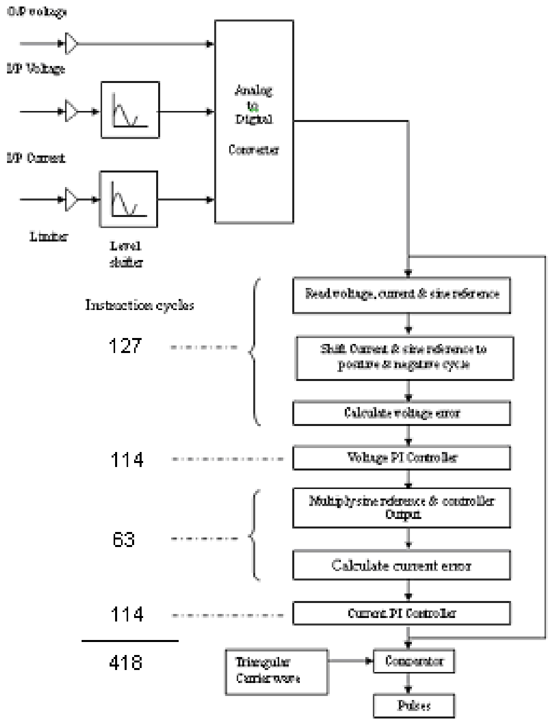
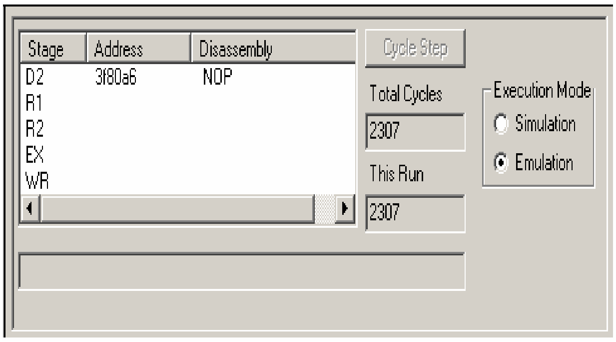


Fig. 14 Execution Cycles for Digital Loop Control Algorithm



Stage	Address	Disassembly
D2	3f80a6	NOP
R1		
R2		
EX		
WR		

Total Cycles: 2307
This Run: 2307
Execution Mode: ○ Simulation ● Emulation

Fig.15 CCS Pipeline Display Showing Execution Cycles for Digital Loop Control Algorithm

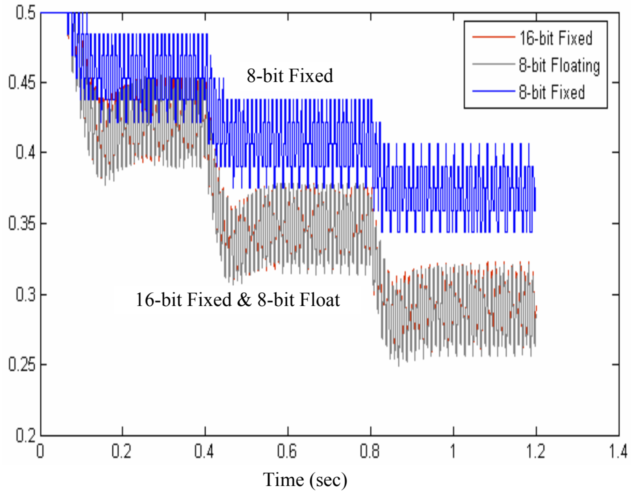


Fig. 16(a) Voltage Controller Output for various bit length and Number representation

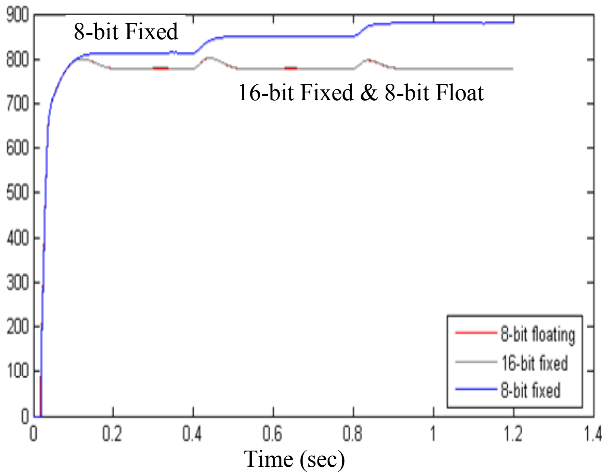


Fig. 16(b) Converter Output Voltage for various bit-length and Number representation

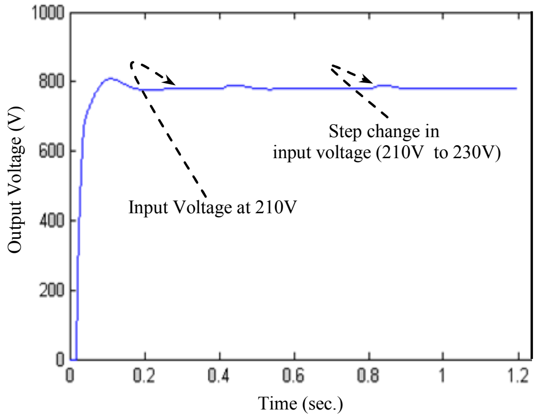


Fig. 17 Closed Loop Performance of ac-dc Converter for a step change in input voltage.

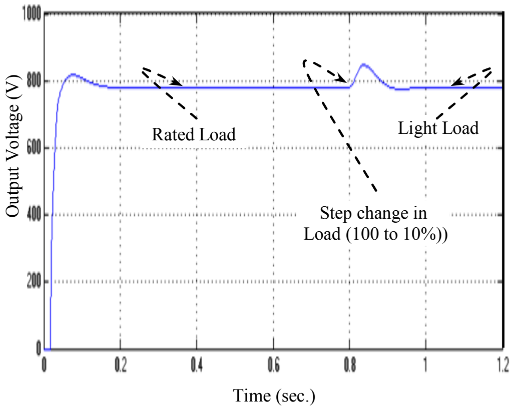


Fig. 18 Closed loop performance of ac-dc converter for a step change in load.

V. CONCLUSION

The closed loop operation of various PFC converters and various control schemes is studied through simulation. A comprehensive summary of the performance of various converter topologies using current control scheme is presented. The performance evaluation study has identified that half bridge topology with linear control is the best to meet the input performance index of UPS for low/medium power applications. A prototype of the converter using IGBT and analog controller are implemented practically for single/three phase system. The experimental results validate the control design and converter performance. The digital controller performance for fixed and floating-point number using various bit precision is reported. Fixed-point 16-bit precision digital controller delivers satisfactory converter performance in closed loop. The DSP based controller along with prototype converter is tested practically. The performance of the closed loop controlled half bridge boost type converter meets the desired input performance index of UPS.

ACKNOWLEDGMENT

Work Station used for simulation is purchased from the research fund sanctioned by AICTE with File No: *8020/RID/TAPTEC-32/2001-02.* M/s Tetra Controls Private Limited, Madras has supported to build and test the prototype. The authors profusely acknowledged both organizations for the support.

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