DSP Based Control Implementation of an AC/DC Converter with Improved Input Current Distortion

Pisit WISUTMETHEEKORN, Viboon CHUNKAG
Electrical Engineering Department,King Mongkut's University of Technology North Bangkok, Thailand
S5010190048@kmutnb.ac.th , vck@kmutnb.ac.th

***Abstract*—This paper presents a digital signal processor based control of an AC/DC converter with nearly unity power factor. Normally, the output voltage of a single-phase AC/DC converter comprises a voltage ripple with twice line-frequency. This affects the voltage control loop and leads to the converter input current distortion. The purposed method is designed to avoid the effect of the output voltage ripple. To verify the proposed control method, MATLAB/Simulink is used for system simulation. A hardware prototype is setup. A low cost digital signal processing chip dsPIC30F4011 is employed as a digital controller to control a CUK AC/DC converter. The converter specifications are 48V output voltage and 250W output power. From the simulation and the experimental results shown that the input current distortion of the purposed system is reduced and lower than the AC/DC converter that controlled by the conventional proportional-integral controller.**

***Index Terms*—AC/DC converter, converter, digital control, digital signal processing chip, power factor correction**

I. Introduction

From the harmonic problem in utility system, the limit current of each harmonic order of load current has been defined in an international standard harmonics regulation. Electronic equipment which consists of a rectifier circuit is an example of the equipment that draws harmonic currents from the AC line. Therefore the AC/DC converters with power factor correction [1]-[7] were proposed to minimize the harmonic currents. By flexible of using a programmable devices such as a microcontroller, a microprocessor, a field programmable gate array (FPGA) and a digital signal processor (DSP) as a digital controller, then the power converter that controlled by the digital controller has many advantages over the converter controlled by an analog circuit. The control algorithm in a digital controller can be easily changed or updated to increase the performance of the converter by reprogram the programmable memory of the digital controller. Moreover the modern microcontrollers and digital signal processors usually have a built in communication port that can be used for a supervisory control or a system monitoring purpose [8].

Generally the output voltage of the power factor correction (PFC) circuit does not contain only a pure DC voltage but it also has a double line frequency voltage ripple at the output. From the concept of the multiplier based PFC circuit as in [9], the control loops are an input current loop and an output voltage loop. The output voltage loop is used to control the output voltage to a desired level and the inner current loop is used to control the input current of a PFC circuit to follow a rectified line voltage waveform for a high power factor purpose. The output voltage control loop should be designed to have a closed loop bandwidth about 10 to 20 Hz for a low input current distortion of the AC/DC converter, then the voltage loop transient response is slow. Many solutions were proposed to improve only the dynamic response of the AC/DC converter. The digital notch filter [10] has been implemented to filter the voltage ripple from the feedback signal that sent to the output voltage controller. The dead zone digital controller [11] has been presented. By using the dead zone digital controller, the voltage control response can be improved. However the self adjustable dead zone controller should be used for light loads condition then the computation time is increased. By using the load current injection [12] and a method that is called a power balance control technique [13], a fast response in output voltage control can be achieved. The effect of a voltage control loop to the input current harmonic distortion has been discussed in [14]. However, only the relation between a compensated system crossover frequency and the input current distortion was presented.

This paper presents a low cost DSP based control implementation of a high power factor AC/DC converter using a digital proportional – integral (PI) controller with an average output voltage measurement that used to eliminate the effect of the output voltage ripple in the output voltage control loop. Therefore the input current distortion can be minimized. If the complex calculation is not required, the low cost DSP can be used and the remaining time of DSP is used for some communication task. The remaining of this paper is organized as follows. Section II, the over all of implemented system and the output voltage sampling method are introduced. The transfer function and controller design is shown in section III. The simulated results and the experimental results are shown in section IV and V respectively. Finally the conclusion is presented in section VI.

II. The Proposed System and Sampling Method

Fig. 1 shows a block diagram of the proposed system. The power circuit consists of a CUK topology based AC/DC converter and a diode bridge rectifier. The inner current loop controller of the PFC circuit is an analog hysteresis circuit that used to control the input inductor current to be track the

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rectified line voltage waveform. The output voltage controller is implemented on a dsPIC30F4011 DSP of Microchip. The block ZCD is a zero crossing detector circuit that used to detect a zero point of input line voltage waveform. The output signal of the ZCD circuit will be changed from a low level logic (0V) to a high level logic (5V) at zero crossing point of input line voltage and this signal is used to interrupt the DSP by send a signal from the ZCD circuit to an external interrupt INT0 pin of dsPIC30F4011. After DSP is interrupted, the interrupt service routine (ISR) is active and the software in INT0 ISR is executed to clear a variable of software counter block. The software counter is a variable that defined in a control program of DSP. The value of software counter is increased by one every 200 microsecond that time interval is generated by using a timer interrupt of dsPIC30F4011. The timer ISR is awaked at every 200 micro second, therefore a value of software counter is equal to 50 at 180 degree of an AC line voltage waveform. By above mechanism, the output voltage of an AC/DC converter at zero crossing point of AC line can be sampled. The CUK topology is chosen because of there are inductors at the both end of the circuit, therefore the input and the output current can be continuous. From the PFC power circuit as shown in Fig.2 an isolation transformer is used to isolate between load and the AC line. The power converter is designed to operate in a continuous conduction mode (CCM) by the calculation method that presented in [15].

If η is an efficiency of the converter, the average power can be defined as in (1), and the instantaneous power is expressed as in (2) if voltage and current are in-phase.

$$p_{out}(t) = \eta \cdot p_{in}(t) \quad (1)$$

$$p_{out}(t) = \eta \cdot \hat{V}_g \sin(\omega t) \cdot \hat{I}_s \sin(\omega t) \quad (2)$$

Where $\hat{V}_g$ and $\hat{I}_s$ are peak input voltage and current of the converter respectively, and η is efficiency of the converter. Therefore the output power can be written as in (3).

$$p_{out}(t) = \eta \cdot \bar{V}_g \cdot \bar{I}_s (1 - \cos(2\omega t)) \quad (3)$$

Where $\bar{V}_g$ and $\bar{I}_s$ are rms value of input ac line voltage and current. By the power balance concept, the output inductor current i_{L2} can be written as in (4), where $\bar{V}_O$ is an average output voltage. The inductor current in (4) is composed of a DC current that is a load current and a sinusoidal part that is a capacitor current $i_{Co}(t)$. Therefore the output capacitor current is written as in (5). The output capacitor current is the current that causes a ripple in output voltage and the output voltage ripple can be obtained by integrating the output capacitor current in (5). The output voltage ripple is written as in (6).

$$i_{L2}(t) = \frac{\eta \cdot \bar{V}_g \cdot \bar{I}_s}{\bar{V}_o}(1 - \cos(2\omega t)) = I_o - \frac{\eta \cdot \bar{V}_g \cdot \bar{I}_s}{\bar{V}_o}\cos(2\omega t) \quad (4)$$

$$i_{Co}(t) = \frac{\eta \cdot \bar{V}_g \cdot \bar{I}_s}{\bar{V}_o}\cos(2\omega t) \quad (5)$$

$$v_{ripple}(t) = \frac{\eta \cdot \bar{V}_g \cdot \bar{I}_s}{2 \cdot \omega \cdot C_o \cdot \bar{V}_o}\sin(2\omega t + \pi) \quad (6)$$

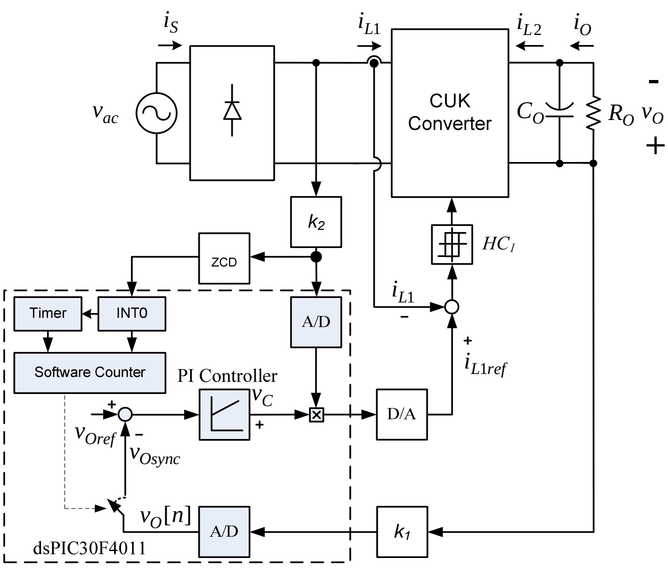

Figure 1. The proposed system

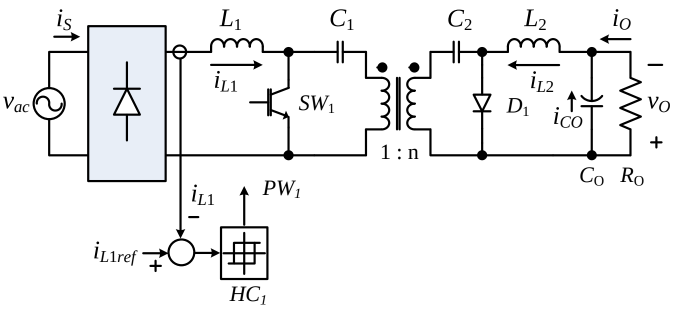

Figure 2. Power circuit of a CUK AC/DC converter

The output voltage ripple (v_{ripple}) as in (6) shows that the ripple frequency is running at twice line frequency. The simulated waveforms of the AC line voltage and the output voltage ripple can be drawn in Fig. 3. Therefore the average output voltage can be measured by reading the output voltage at the zero crossing point of the AC line voltage. In the proposed system, the average output voltage v_{Osync} can be read by using a zero crossing detector circuit, an external interrupt INT0 and the timer interrupt of the dsPIC30F4011. By using the proposed sampling method, the output voltage ripple can be eliminated from the output voltage control loop.

III. Transfer Function and Voltage Loop Design

This section shows step to find a system transfer function of the output voltage control loop and after that the controller parameters are calculated by using frequency response method. At the output node of the CUK AC/DC converter in Fig. 2, the current equation at the output node can be written as in (7).

$$i_{L2} = C_O \frac{dv_O}{dt} + i_O \quad (7)$$

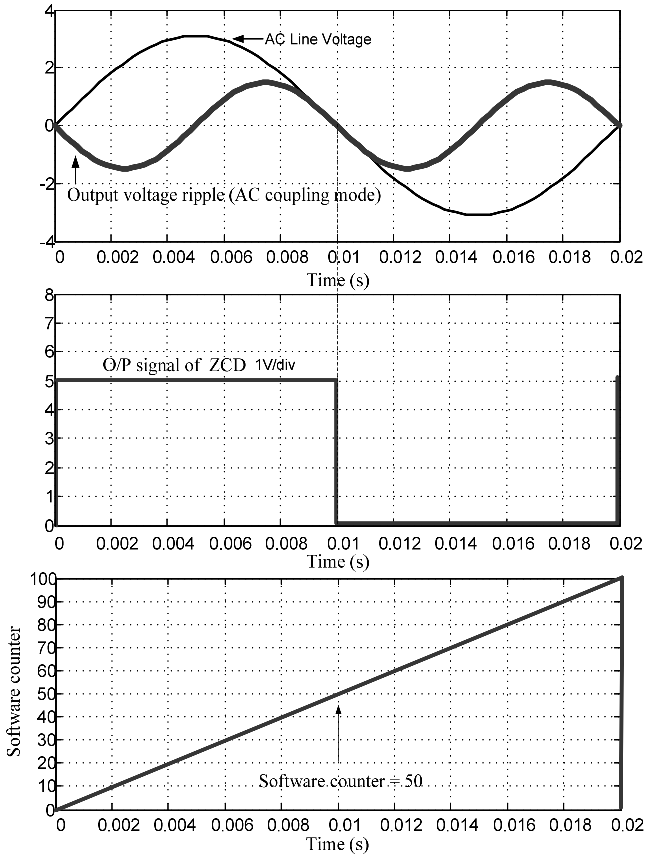

Figure 3. The simulated waveforms of input voltage,output voltage ripple, output of the ZCD circuit and value of software counter

By power balance in a half line cycle between input and output of the AC/DC converter, the output inductor current and the input inductor current can be written as in (8) and (9).

$$i_{L2}\cdot v_O=\frac{\hat{i}_{L1}\cdot\overline{V}_g}{\sqrt{2}} \quad (8) \qquad \hat{i}_{L1}=\frac{\sqrt{2}\cdot i_{load}\cdot v_O}{\overline{V}_g} \quad (9)$$

From the block diagram as shown in Fig. 1, the magnitude of the input inductor current command is obtained from the output signal of the output voltage controller. After that the magnitude of inductor current command is multiplied by an absolute sine wave that synchronized to the rectified line voltage. The obtained signal from multiplication is used as the input inductor current command i_{L1ref}. A PI controller is chosen as a voltage loop controller, the continuous-time transfer function is shown in (10).

$$G_C(s)=K_P+\frac{K_I}{s} \quad (10)$$

Where K_P is a proportional gain and K_I is an integral gain of the controller respectively. From (7)-(9), the perturbation is applied and using small signal approximation method. The results are shown in (11)-(13).

$$\tilde{v}_O=\frac{\tilde{i}_{L2}-\tilde{i}_{Load}}{C_O s} \quad (11)$$

$$\tilde{i}_{L2}=\frac{\overline{V}_g}{\sqrt{2}\cdot\overline{V}_O}\cdot\tilde{\hat{I}}_{L1}+\frac{\overline{I}_{L1}}{\sqrt{2}\cdot\overline{V}_O}\cdot\tilde{v}_g-\frac{\overline{I}_{L2}}{\overline{V}_O}\cdot\tilde{v}_O \quad (12)$$

$$\tilde{i}_{L1}=\frac{\sqrt{2}\overline{I}_{Load}}{\overline{V}_g}\cdot\tilde{v}_O+\frac{\sqrt{2}\overline{V}_O}{V_g}\cdot\tilde{i}_{Load}-\frac{\overline{I}_{L1}}{\sqrt{2}\overline{V}_g}\cdot\tilde{v}_g \quad (13)$$

From (11)-(13), the small signal variables are the variables with '~' and the variables with '-' are the steady state value. From (11)-(13), the block diagram can be drawn. Using the block diagram reduction method as in the classical control theory, the transfer function of output voltage to the output voltage command can be written as shown in (14).

$$\frac{\tilde{v}_O}{\tilde{v}_{Oref}}=\frac{G_C(s)\overline{V}_g}{\sqrt{2}\overline{V}_O C_O s+k_1 G_C(s)\overline{V}_g} \quad (14)$$

Where k_1 is the output voltage feedback gain that used to attenuate the output voltage to an appropriate range for A/D. From (14) the open loop transfer function is written as in (15). A required phase margin θ_R and a crossover frequency f_C of the compensated system are defined, after that by the frequency response method, a phase value of the controller θ_C and gains of the controller can be obtained from (16)-(18).

$$G_P(s)=\frac{k_1\overline{V}_g}{\sqrt{2}\overline{V}_O C_O s} \quad (15)$$

$$\theta_C=\frac{(90^\circ-\theta_R)\cdot\pi}{180} \quad (16)$$

$$K_P=\frac{\cos(\theta_C)}{G_{PO}} \quad (17)$$

$$K_I=\frac{\sin(\theta_C)\cdot 2\pi f_C}{G_{PO}} \quad (18)$$

Where G_{PO} is a magnitude of an open loop transfer function $G_P(s)$ at the crossover frequency f_C. The obtained gains of the controller are used to calculate a control signal $u(n)$ by an approximated equation of an analog controller as in (19).

$$u(n)=K_P\cdot e(n)+K_I\cdot T_s\sum_{k=1}^{n}e(n) \quad (19)$$

Where $e(n)$ is an error signal, T_s is a sampling time period.

IV. THE SIMULATION RESULTS

To verify the proposed system, MATLAB/Simulink is used to show the transient and the steady state performance of the CUK AC/DC converter. The AC/DC converter model is written in MATLAB/Simulink by using the average model. For the controller that implemented on a software simulation, the control algorithm is written in m file as a user defined function of MATLAB/Simulink. The code in that m file can be adapted in to a C language code format for controlling the DSP chip. The parameters of the converter that used in the simulation and the experiment are shown in Table I. The proportional gain and the integral gain of the PI controller are calculated for the compensated system has 70° of phase margin with 15 Hz crossover frequency. The controller gain K_P and K_I are 3.6 and 123.7 with 200 μs sampling time period.

A. Transient Response

To show the dynamic performance of the proposed system compare to the CUK AC/DC converter controlled by the PI controller with a conventional sampling method, the proposed system is tested by step load at 100 W to 200 W and change back to 100 W. The simulated transient responses from using the conventional sampling method are shown in Fig. 4. The settling time when step load from 100 W to 200 W is about 100 ms and the overshoot of an output voltage is 2.739%.

Fig. 5 shows the simulated transient performance of the CUK AC/DC converter controlled by a PI controller with the nearly average output voltage measurement. The load condition of the simulated result in Fig. 5 is as same as the load condition that used in a simulation of the CUK AC/DC converter that controlled by a conventional PI controller. The transient responses in Fig. 4 and Fig. 5 are not significantly different.

B. Steady State Response

In this section the simulated steady state performance of the CUK AC/DC convertor that controlled by a PI controller with the conventional sampling method and the proposed scheme has been compared. Fig. 6 shows the input voltage and input current waveforms of the CUK AC/DC converter that controlled by a conventional PI controller at 200 W load power. The input current harmonics spectrum of Fig.6 is shown in Fig. 7. With 50 W load power the input current and voltage of the converter is shown in Fig. 8 and the input current harmonics spectrum of the converter is shown in Fig. 9. From these results, the CUK AC/DC converter controlled by a conventional PI controller has a higher input current distortion at a light load condition. By the proposed method, the same load conditions as the previous simulation are applied, the results are shown in Fig. 10 and Fig. 11 for 200 W output power.

TABLE I. THE CUK CONVERTER SPECIFICATIONS

Input Voltage	220 V / 50 Hz
Output Voltage	48 V
Power	250 W
C_1=C_2	0.68 μ F
L_1, L2	5 mH, 1 mH
C_O	23600 μ F

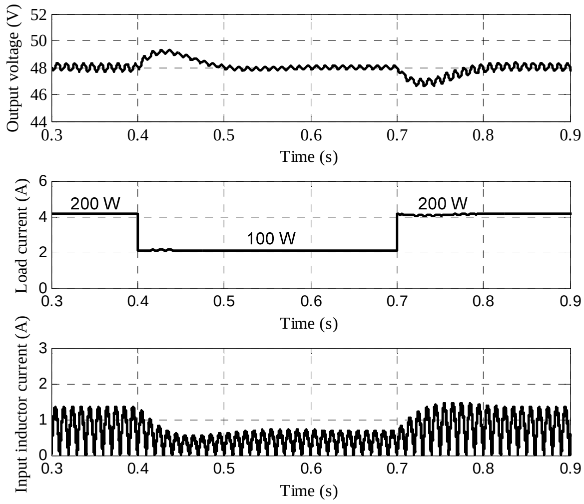

Figure 4. The simulated transient response of the CUK AC/DC converter with conventional sampling method

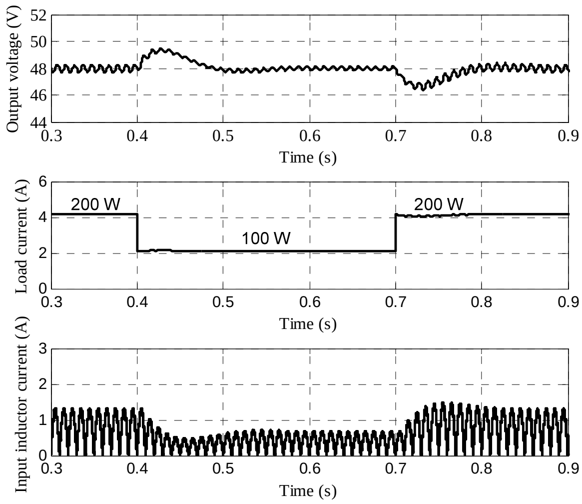

Figure 5. The simulated transient response of the CUK AC/DC converter with measured an average output voltage

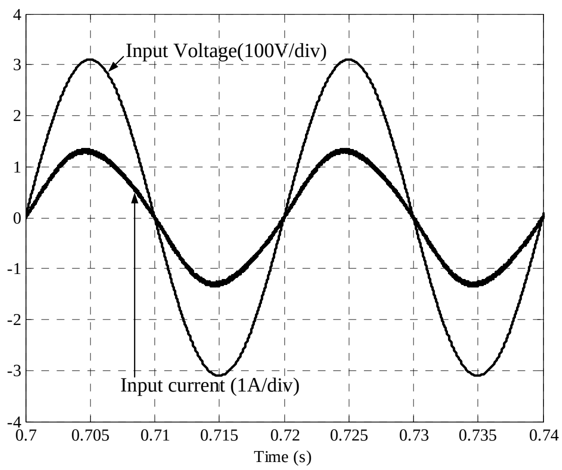

Figure 6. Input voltage and current at 200 W load power of the CUK AC/DC converter controlled by a conventional PI controller

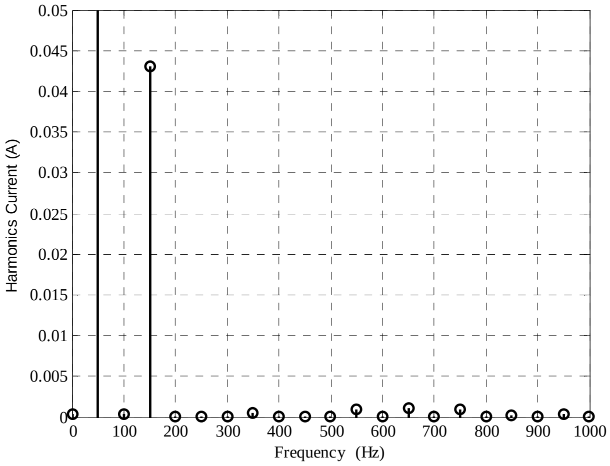

Figure 7. The harmonic spectrum of the input current of Fig. 6

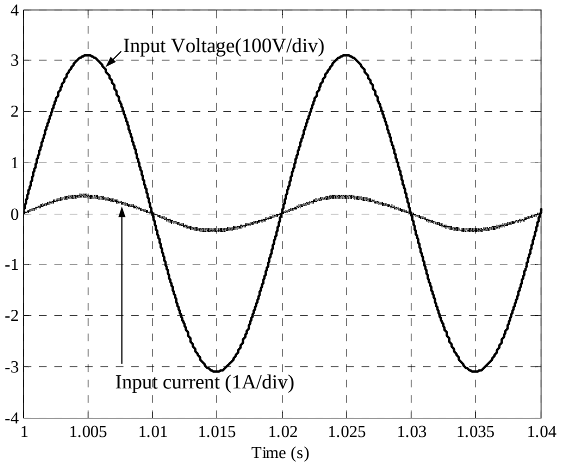

Figure 8. Input voltage and current of the CUK AC/DC converter at 50 W load power controlled by a conventional PI controller

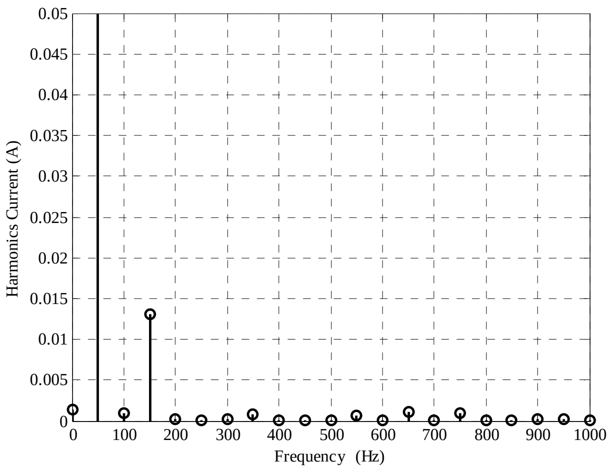

Figure 9. The harmonic spectrum of the input current of Fig. 8

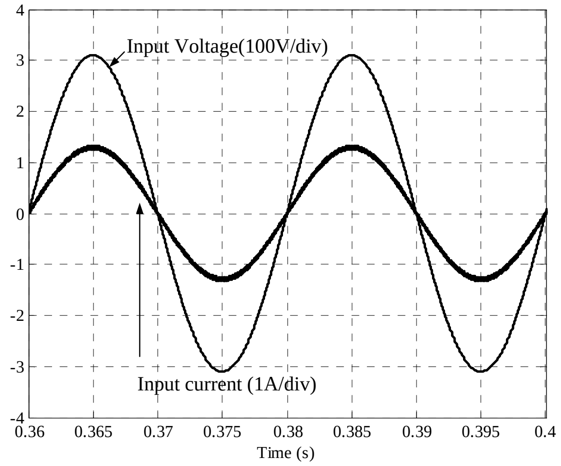

Figure 10. Input voltage and current at 200 W load power of the CUK AC/DC converter controlled by a proposed scheme

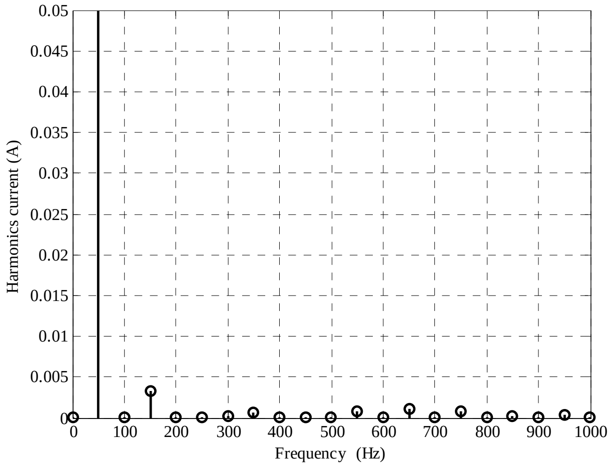

Figure 11. The harmonic spectrum of the input current of Fig. 10

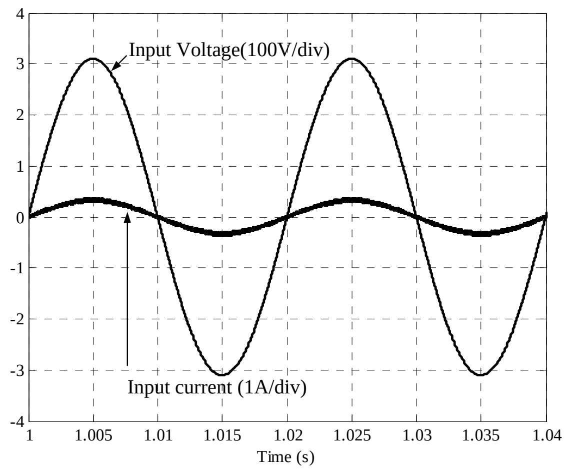

Figure 12. Input voltage and current at 50 W load power of the CUK AC/DC converter controlled by a proposed scheme

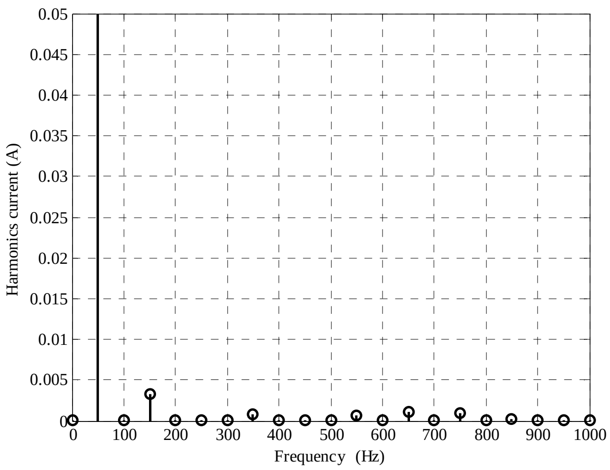

Figure 13. The harmonic spectrum of the input current of Fig. 12

The input voltage and current waveforms of the CUK AC/DC converter that controlled by the proposed scheme operated at 50 W output power are shown in Fig. 12.While the harmonic spectra of the input current is shown in Fig. 13. From Fig.10-Fig.13, it can be seen that the AC/DC converter controlled by the proposed method offers lower input current distortion than using the conventional digital PI controller even in light load condition.

V. The Experimental results

The experiment was setup to verify the proposed concept. The power converter and controller parameters that used in the experiment are the same as the parameters in the simulation. The dsPIC30F4011 digital signal processor is used as a digital controller to control a CUK AC/DC converter. To compare the performance of the converter controlled by a conventional digital controller and the proposed method, the transient response is evaluated by measure the output voltage, load current and the input inductor current at step load condition. The input inductor current and load current were measured by using current probes and the signals from current probes are connected to the digital oscilloscope model DSO6014A of Agilent Technologies. To evaluate steady state response, the input current of the AC/DC converter was measured and compare to the line voltage. Moreover the harmonic spectrum of the input current of the converter was also measured by using the FLUKE 43B power quality analyzer. All of waveforms were captured and sent to a personal computer via USB port of the oscilloscope and the power meter.

A. Transient Response

As the simulation results, the dynamic response of the converter in the experiment at step load condition are shown. The load condition is step from 200 W to 100 W and back to 200 W again. Fig. 14 shows the output voltage, load current and input inductor current of the CUK AC/DC converter controlled by a conventional digital PI controller.

By the same load condition as the result in Fig. 14, the dynamic response of the converter controlled by a digital PI controller with an average output voltage measurement is shown in Fig. 15.

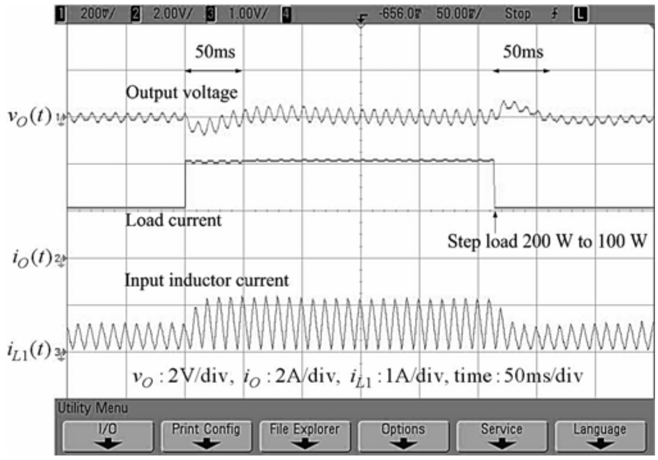

Figure 14. Transient response of the CUK AC/DC converter controlled by a conventional digital PI controller

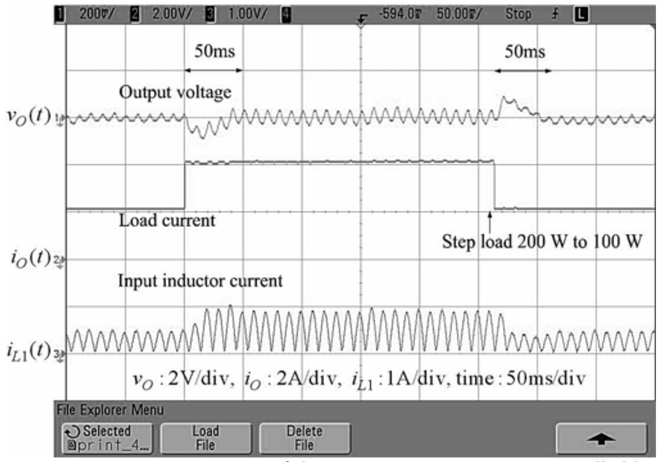

Figure 15. Transient response of the CUK AC/DC converter controlled by the proposed scheme

From the results in Fig. 14 and Fig. 15, the AC/DC converter controlled by a conventional controller has a less overshoot than the converter controlled by the proposed method. However by using the proposed method, the settling time of the output voltage response is less than the settling time of the converter controlled by the conventional controller.

B. Steady State Response

To evaluate the steady state performance, the input current and input line voltage were measured and the harmonics spectrum of the input current of the converter is also measured to show the input current harmonics of the converter. The result showed that the harmonic content were reduced by using the proposed method. The input current and input voltage of the AC/DC converter that controlled by the conventional method are shown in Fig. 16 and Fig. 18. In contrast, the input current and voltage of the converter control by the proposed method are shown in Fig. 17 and Fig. 19. The harmonic spectrums of the input current converter as shown in Fig. 16-19 are shown in Fig 20-23 respectively. It can be seen that the total harmonic distortion of input current was reduced by using the proposed control method, as summarize in the Table II.

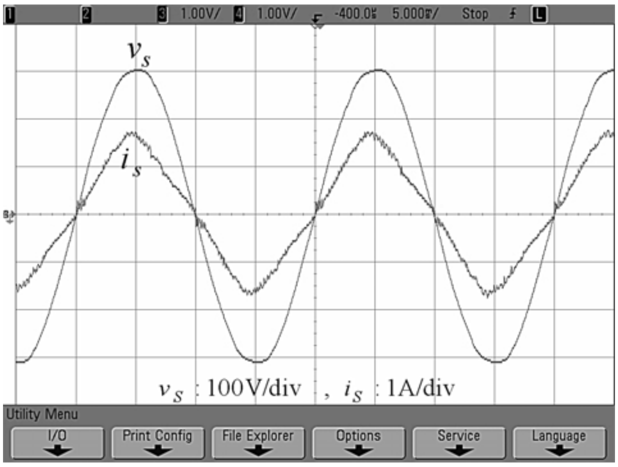

Figure 16. Input voltage and current at 200 W load power of the CUK AC/DC converter controlled by a conventional PI controller

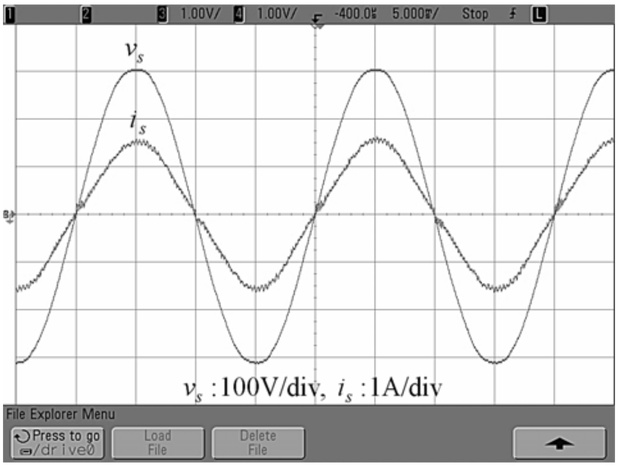

Figure 17. Input voltage and current at 200 W load power of the CUK AC/DC converter controlled by a proposed method

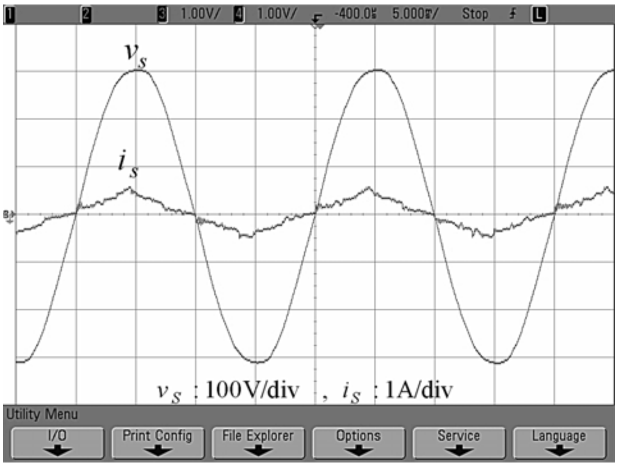

Figure 18. Input voltage and current at 50 W load power of the CUK AC/DC converter controlled by a conventional PI controller

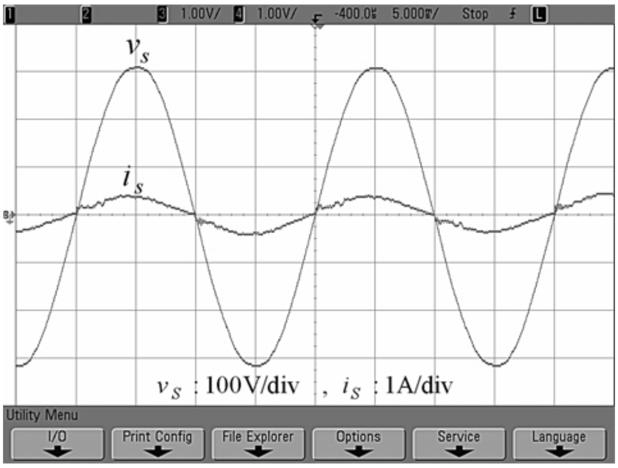

Figure 19. Input voltage and current at 50 W load power of the CUK AC/DC converter controlled by a proposed method

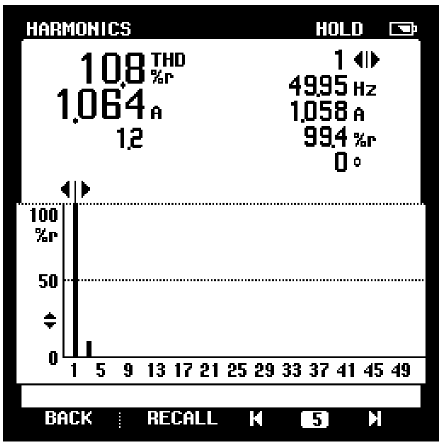

Figure 20. Harmonic spectrum of the input current at 200 W using a conventional digital PI controller

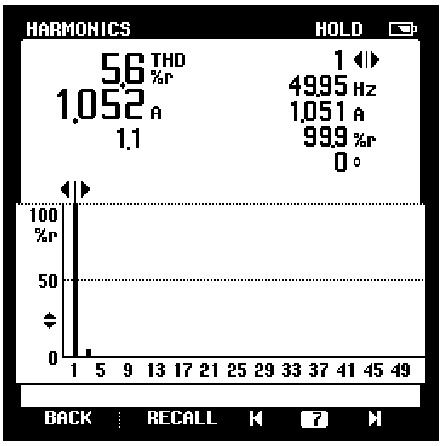

Figure 21. Harmonic spectrum of the input current at 200 W using the proposed method

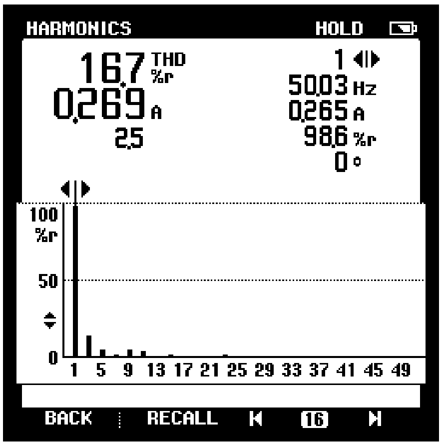

Figure 22. Harmonic spectrum of the input current at 50 W using a conventional digital PI controller

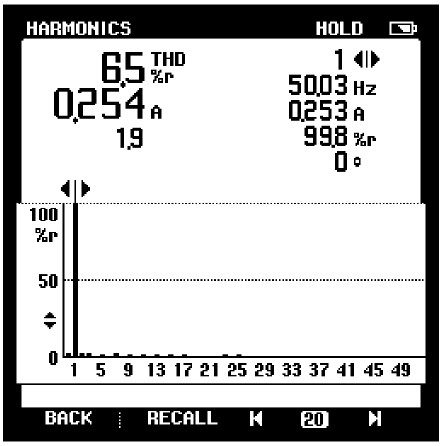

Figure 23. Harmonic spectrum of the input current at 50 W using the proposed method

TABLE II. THE TOTAL HARMONIC DISTORTION OF INPUT CURRENT OF THE AC/DC CONVERTER

Load power (w)	%THD of input current of the converter	
	Proposed method	Conventional method
50	6.5	16.7
200	5.6	10.8

VI. CONCLUSION

The DSP based control implementation of the CUK AC/DC converter has been presented. By using an external interrupt and internal timer interrupt of dsPIC30F4011 and the zero crossing detector circuit, the nearly average output voltage can be sampled. Therefore the effect of an output voltage ripple to the output voltage loop control is eliminated. To verify the proposed method, the simulation and the experiment has been setup. The transient and the steady state response with the same load condition of the CUK AC/DC converter controlled by the proposed method has been compared to the CUK AC/DC converter that controlled by the conventional digital PI controller using the conventional sampling method. From both simulation and the experimental results, the proposed method has a dynamic response of the output voltage control as fast as using the conventional controller. However, by using the proposed method, the PFC circuit has a lower input current harmonics than the converter that controlled by the conventional controller even at a low output power condition. The THD of the input current without using the input line filter circuit at load 50 W and 200 W are 6.5% and 5.6% respectively.

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