AC 2011-1479: AN ACTIVE POWER FACTOR CORRECTION LABORATORY EXPERIMENT FOR POWER ELECTRONICS COURSE

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An Active Power Factor Correction Laboratory Experiment for Undergraduate Power Electronics Course

Abstract

The use of power factor correction (PFC) circuits has been proven to save electrical energy use by up to 25%. When electrical loads are predominantly linear, a simple shunt capacitor will generally be sufficient to improve the power factor. However, as the use of power electronics becomes more prevalent, a more advanced solution using active components is needed. One such active PFC circuit currently installed in today's off-line switching power supplies, such as those used in personal computers, is the boost-converter active PFC. Such an increasing use of active PFC demands understanding of its concept and operation for future power supply engineers. This paper presents a new laboratory experiment that was developed to enhance student's understanding of the boost-converter active PFC. The experiment consists of computer simulation and hardware setup enabling students to inspect and observe the benefits of using active PFC as compared to two conventional methods. Moreover, the hardware setup for the lab experiment uses a module that was built in a simple way such that it can be easily replicated. The content of the experiment including its simulation and hardware portions along with its sample results will be presented.

1. Introduction

Power electronics is an engineering discipline that deals with the conversion of electrical energy from one form to another. Power electronics has become increasingly important nowadays where billions of kilo-watts of electric power are being re-processed every day to provide the kind of power needed by loads[1]. Due to the rapid growth in power electronics technology, there has been an increased presence of engineering companies who come during the career fair at Cal Poly to recruit electrical engineering (EE) students with power electronics background. This in turn has triggered a great interest among our EE students in the field of power electronics as indicated by the steady increase in the number of students enrolled in power electronic courses[2]. To better prepare our EE students and to better align with industry needs, the three existing power electronic courses at Cal Poly have recently been redesigned which include the development of new lab experiments to introduce modern applications of power electronics. One newly developed lab experiment is the presented active power factor correction (PFC) experiment.

A Power Factor Correction (PFC) circuit is an auxiliary circuit attached to the original system's circuit to improve power factor into the system. In ac distribution system, power factor correction circuits typically consist of a capacitor bank that would normally be switched on or off depending on the reactive demand from the load. In power supply circuits, the necessity of using a PFC circuit surfaced due to the emergence and then increasing popularity of switched mode power supplies (SMPS). Since the advent of power electronics, the use of active PFC using switched mode dc-dc converter has become a very popular topic among researchers. The most well known PFC circuit is based on a boost converter and studies have been conducted extensively on different aspects of its performance[3-10]. Industry has also recognized the importance of using active PFC and some efforts have been put forward to enforce the use of active PFC in some applications. For example according to the Power Supply Design guide issued by Server System Infrastructure forum, the active PFC is a requirement for Server System Infrastructure (SSI) compliance: “The power supply modules shall incorporate universal power input with active power factor correction, which shall reduce line harmonics in accordance with … standards.”[11] Due to the increasing importance of active PFC, there is then the need to educate future electrical engineers to understand the operation and benefits of active PFC. At Cal Poly, we have addressed this issue by having one laboratory experiment on boost-converter active PFC in the second course of our power electronics series. This paper illustrates the content of the lab experiment as well as the computer simulation and hardware setup used for the experiment.

2. Computer Simulation

The main objective of the active PFC boost-converter experiment is to demonstrate the benefits of using active PFC compared to the traditional power factor correction methods. In particular, the experiment consists of three different methods of power factor correction: capacitor (C) only, inductor-capacitor (LC), and boost-converter. The experiment takes two lab periods. The first lab period (first week), students perform computer simulation using OrCAD Pspice to evaluate the performance of the passive power factor correction methods (C and LC), while the second lab period (second week) is used for students to analyze performance of the three power correction methods using hardware setup.

Figures 1 and 2 show the OrCAD schematics used in the first part of the experiment which represent two commonly found circuits at the input stage of the SMPS. They both consist of a single-phase bridge rectifier following by a certain type of filter. In the first scenario, the filter employed is solely a capacitor used mainly to clean up the ripple at output voltage of the rectifier. In the second case, a 5-mH inductor is added between the output of rectifier and the capacitor, forming an LC type filter. The objective of placing this inductor is not only to help clean up output current of the rectifier, but also to help improve the input power factor. In both cases, the output capacitor is modelled as a pure inductance in parallel with some value of “bleed resistor”. The bleed resistor value was approximated by the time constant of the capacitor in the actual circuit when the circuit is not loaded.

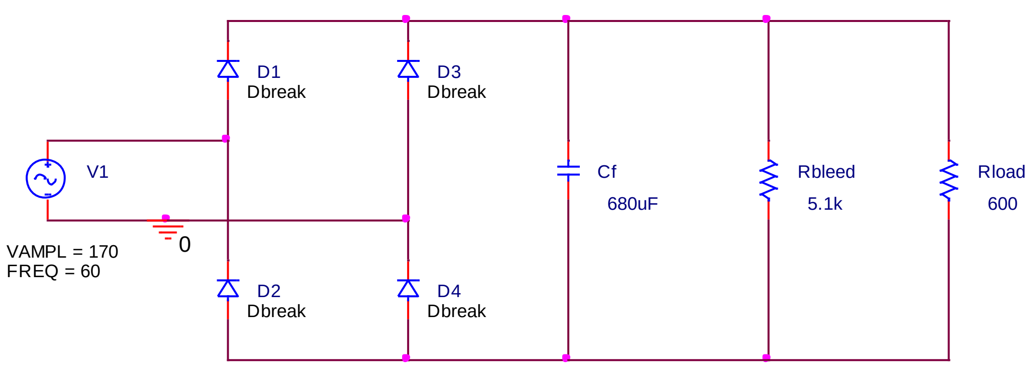

Figure 1. Input stage of SMPS with Capacitor filter

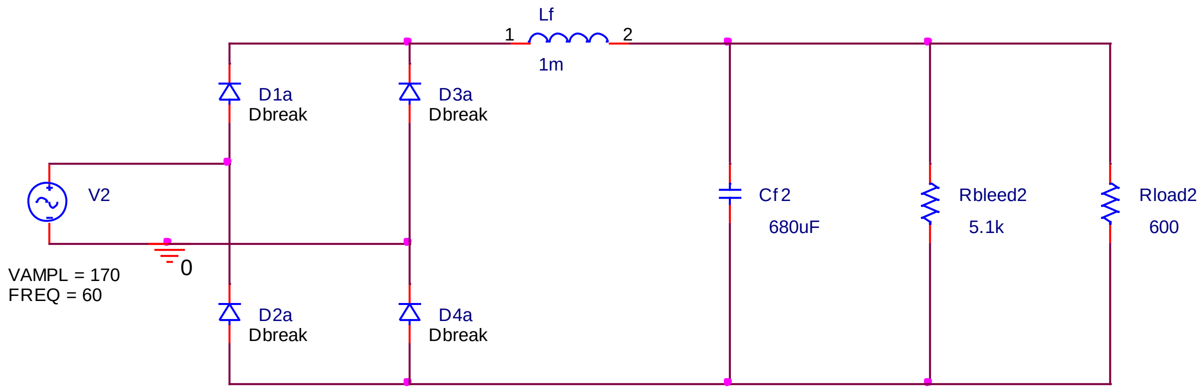

Figure 2. Input stage of SMPS with LC filter

Figure 3 depicts the ac input current waveforms from the two previous PFC circuits. As shown, the inclusion of the 5-mH inductor results in the elongation of the conduction angle of the input current waveform. The implication of extending the conduction angle would be the decrease in the displacement phase angle between the ac input voltage and ac input current, hence improving the displacement power factor DPF = cos ($\theta_V - \theta_I$), see Figure 4.

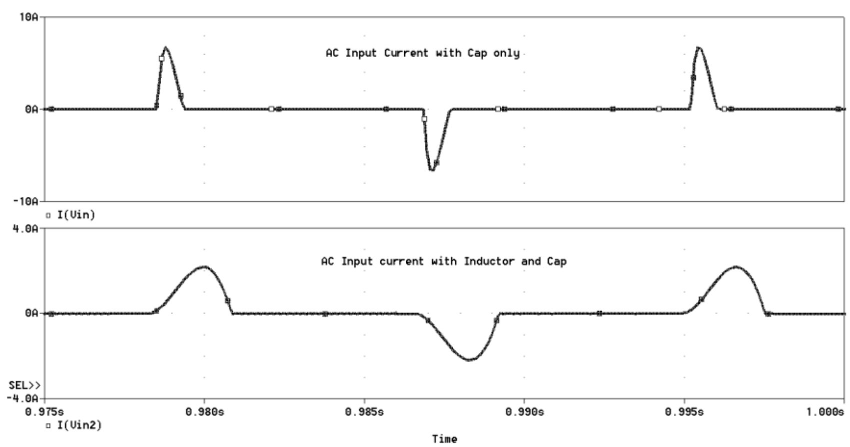

Figure 3. AC input current with capacitor only (top) and with inductor-capacitor (bottom)

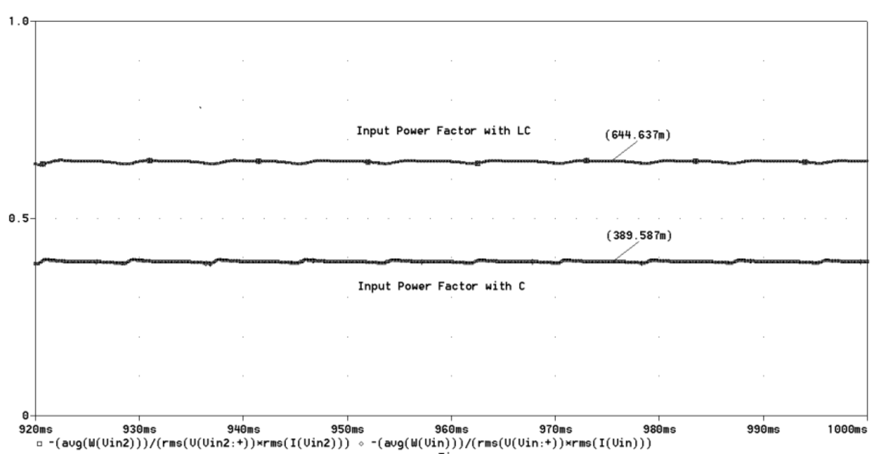

Figure 4. Input power factor with capacitor only (top) and with inductor-capacitor (bottom)

3. Hardware Setup

The PFC module used for the hardware setup is shown in Figure 5. The board consists of three PFC circuits. Each circuit has a single-phase bridge rectifier at its input. In the first circuit, the rectifier is followed by a capacitor as the PFC as depicted in Figure 1, while in circuit 2 the rectifier is followed by an LC PFC as shown Figure 3, and in circuit 3 the rectifier is followed by a boost-converter PFC circuit. Each circuit is rated 120 Vrms input and 250 Watts output. The boost-converter PFC circuit uses a pre-made Texas Instruments (TI) PFC evaluation board whose circuit diagram is shown in Figure 6. The TI's evaluation board is available to purchase from TI's website with a part number of UCC28070EVM and listed price of $ 149 per module. The use of the commercially available boost-converter PFC circuit provides a simple and economic way of constructing the hardware module for the PFC lab experiment.

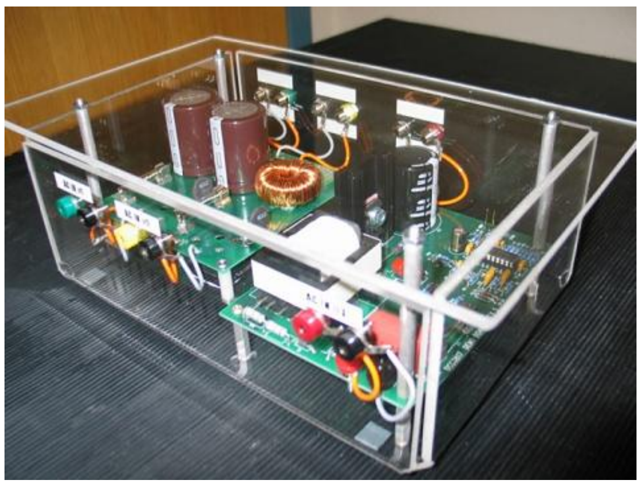

Figure 5. Three-in-one PFC circuit board

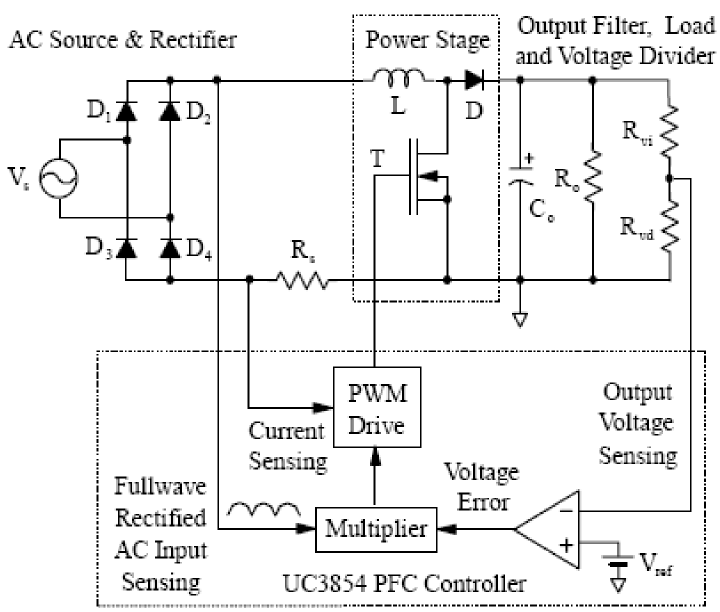

Figure 6. Circuit diagram for UCC28070EVM[11]

Figure 7 shows the actual laboratory setup for the Power Factor measurements. The main objective of the setup is to measure the input power factor and efficiency as the output power is varied from 10% to 100%.

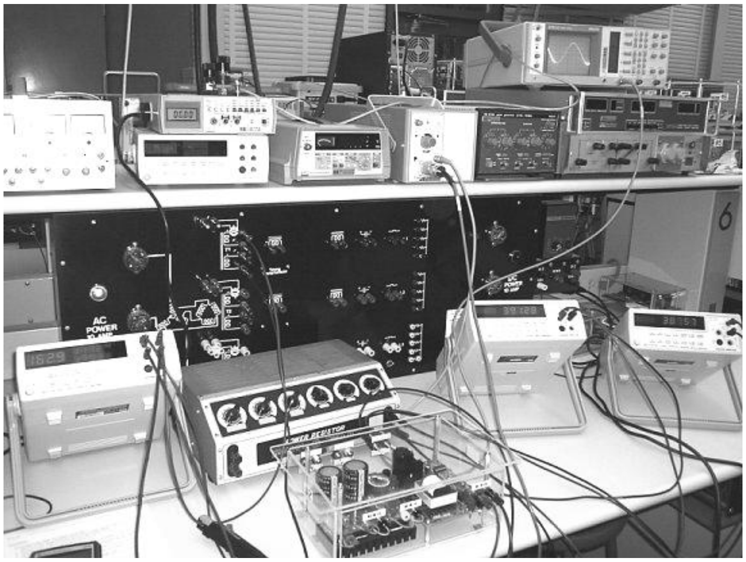

Figure 7. Laboratory setup for PFC circuit measurements

To exhibit the performance of each power factor correction circuit, students are required to observe the input current waveform to each circuit through an oscilloscope. Examples of scope screenshots of the input waveform is shown in Figure 8. As expected, the L and LC PFC circuits draw a pulsating ac input current which will yield poor input power factor. In contrast, the resulting ac input waveform is from the boost-converter active PFC is way different. More specifically, the boost PFC results in a much nicer, sinusoidal ac input current waveform.

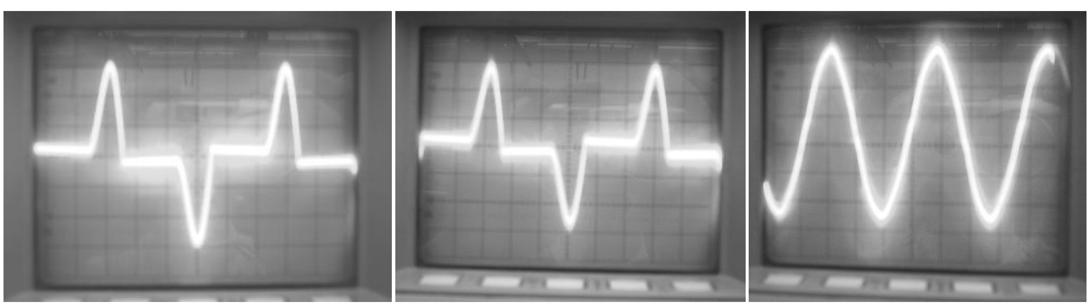

Figure 8. AC input current waveform: C (left), LC (middle), boost (right)

Once input waveform for each circuit is observed, students will then measure and inspect the performance of the three circuits in terms of their power factor correcting ability and overall efficiency. To do these, students measure the input power factor and efficiency at various load points using electronic load. Results from these measurements are then plotted as depicted in Figure 9. From these plots, students will clearly observe the overall benefits of using the active approach in power factor correction compared to the conventional ones.

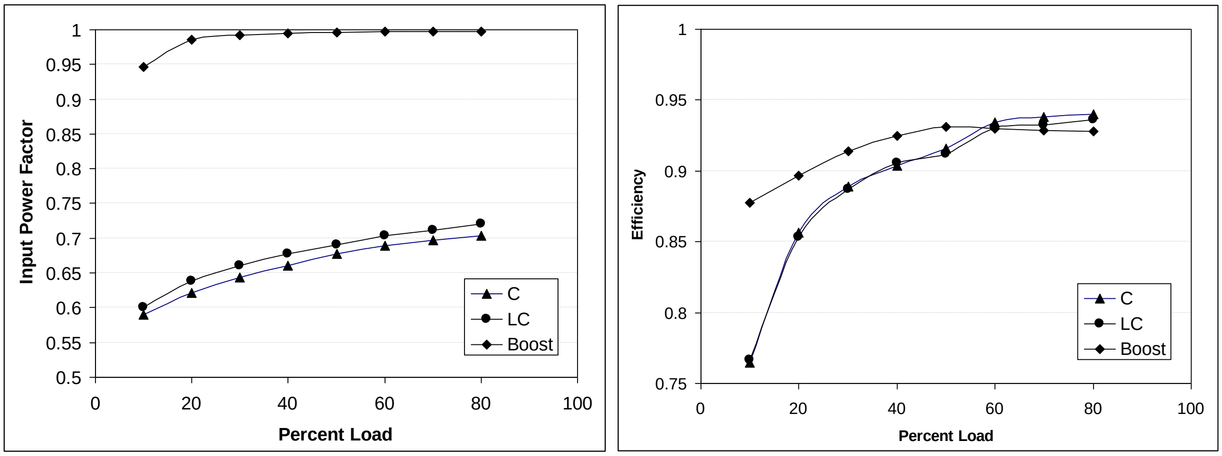

Figure 9. Input PF (left) and efficiency (right) of C, LC, and Boost PFC circuits

Conclusion

A new lab experiment on input power factor and efficiency performance of three different circuits commonly used in existing SMPS has been presented. The lab experiment has been introduced in an advanced undergraduate power electronic course at Cal Poly. The use of an existing and commercially available PFC evaluation module provides convenient hardware setup for the lab experiment and hence it is relatively easy to replicate.

Lessons learned from conducting the experiment suggest that students' understanding on the different methods of power factor correction circuits are enhanced especially after looking at the hardware results which show the contrast in the performance of active PFC compared to the conventional techniques. Another observation entails the complexity and hence cost of the active boost PFC which constitutes the trade-off of using active PFC method. By visual inspection, students quickly realize the higher level of complexity involved in building the boost-active PFC compared to just a simple connection of capacitor or inductor-capacitor combination.

Future assessment activity is planned the next time the lab course is offered to assess and hence verify whether the lab experiment meets the objective of increasing students' understanding of power factor correction circuits, along with their advantages and drawbacks.

References

1. M.H.L. Chow and C.K. Tse, "Theoretical study of performance of continuous-mode boost converters for power-factor-correction applications," Proc. 1997 International Conference Power Electronics and Drive Systems, Vol. 2, pp. 590 – 595, 26-29 May 1997.
2. C.S. Lin, T.M. Chen, and C.L. Chen, "Analysis of low frequency harmonics for continuous-conduction-mode boost power-factor correction," Proc. IEE Electric Power Applications, Vol. 148, Issue 2, pp. 202 – 206, March 2001.
3. B. Choi, S. Hong, and H. Park, "Modeling and small-signal analysis of controlled on-time boost power-factor-correction circuit," IEEE Trans. On Industrial Electronics, Vol. 48, Issue 1, pp. 136 – 142, Feb. 2001.

4. M. Orabi, T. Ninomiya, and J. Chunfeng, “Nonlinear dynamics and stability analyses of boost power-factor-correction circuit,” Proc. 2002 International Conference on Power System Technology, Vol. 1, pp. 600 – 605, Oct. 2002.
5. K.D. Gusseme, D.M. Van de Sype, A.P.M. Van den Bossche, and J.A. Melkebeek, “Digitally controlled boost power-factor-correction converters operating in both continuous and discontinuous conduction mode,” IEEE Transactions on Industrial Electronics, Vol. 52, Issue 1, pp. 88 – 97, Feb. 2005.
6. O. Pop, G. Chindris, A. Grama, and F. Hurgoi, “Power factor correction circuit with a new modified SEPIC converter,” Proc. 24th International Spring Seminar on Electronics Technology: Concurrent Engineering in Electronic Packaging, pp. 117 – 120, May 2001.
7. K. Matsui, I. Yamamoto, T. Kishi, M. Hasegawa, H. Mori, and F. Ueda, “A comparison of various buck-boost converters and their application to PFC,” Proc. IEEE 28th Annual Conference on Industrial Electronics Society, Vol. 1, pp. 30 – 36, Nov. 2002.
8. K. Sangsun and P.N. Enjeti, “A parallel-connected single phase power factor correction approach with improved efficiency,” Proc. 17th Annual IEEE Applied Power Electronics Conference and Exposition, Vol. 1, pp. 263 – 269, March 2002.
9. T. Tanitteerapan and S. Mori, “Soft-switching boost power factor correction converter with negative slope ramp carrier control,” Proc. International Symposium on Circuits and Systems, Vol. 3, pp. III-272 - III-275, May 2003.
10. K.W.E. Cheng and S.Y.H. Hui, “Zero switching low output voltage power factor correction circuits,” Proc. 26th Annual IEEE Power Electronics Specialists Conference, Vol. 2, pp. 920 – 925, June 1995.
11. http://focus.ti.com/docs/toolsw/folders/print/ucc28070evm.html, retrieved January 2011.