A Simple DSP Based Control System Design for a Three-Phase High Power Factor Boost Rectifier

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***Abstract*-This paper presents the design and implementation of a simple control system for three-phase high power factor boost rectifiers in power-factor-corrected online UPS applications. The design and simulation of the control system are performed in Simulink using Texas Instruments DSP tools as the controlling units and the PLECS circuit models as the power converter unit, and then the verified design is converted into a DSP code to be implemented in a real DSP chip. The boost rectifier stage is realized as six-switch IGBT based PWM converter. Performance of the controller developed in Simulink platform by emulation method is experimentally verified. Consequently, the results confirm that the proposed controller achieves high power factor at the input and overall good dynamic response for the boost rectifier under sudden load and input voltage variations, and also demonstrate the applicability of the design methodology presented in the paper.**

I. INTRODUCTION

The current harmonics and low power factor caused by online UPS systems are two of major power quality problems. Therefore, simple and cost effective solutions are demanded by the UPS manufacturers. The solutions should provide advantages and competitiveness both in power converter topology and its control system. Using a voltage-source-inverter (VSI)-based converter at the utility side instead of an uncontrolled rectifier is one of the most common methods for online UPS applications [1]. The circuit topology of the boost rectifier based on VSI is shown in Fig. 1. This topology provides major advantages over the uncontrolled rectifiers such as instant reversal of power from dc-bus to input, which is especially critical when UPS is connected to motor loads, high efficiency, less EMI due to continuous-current mode operation, and easy filtering of switching noise. In addition, its control system is relatively simple. The closed-loop control of dc-bus voltage determines the amplitude of mains currents, and the PWM current control maintains these currents close to sinusoidal and in phase with ac mains voltages [1-3].

Accordingly, the goal of this project is to design and implement a simple digital control algorithm for three-phase power-factor-corrected online UPS systems. Digitally controlled systems provide many advantages both to manufacturers and also to the users. Features such as reliability, less number of components, and thus less cost, easy maintenance, and capability for remote monitoring and optimization of system parameters all contribute to the competitiveness in UPS market. There have been many research and developments in this area [1-13]. We have benefited from these dedicated studies.

For this task, advanced tools will be used such as Matlab/Simulink for the development and the design of the control algorithm, the PLECS simulator tool for the real time model of the converter, and the DSPs for the implementation. One more objective is to combine all the control work of an online UPS in a single chip. However, this paper focuses on the development of PFC stage at this time.

The circuit topology of the online UPS system to be implemented is shown in Fig 2. After the mains voltages are rectified into a fixed dc-bus voltage at 800 V, the rectified voltage is then inverted back to well-regulated three-phase 50 Hz, and 220 V line-to-neutral utilization voltages. The dc-bus is supported by two groups of battery packs. Each group is planned to accommodate 30 batteries that will have a floating voltage around 13.33 V per battery. However, by connecting additional buck-boost type converters between dc-bus and the battery packs, the system can be customized to accommodate less number of batteries when specified by the customer.

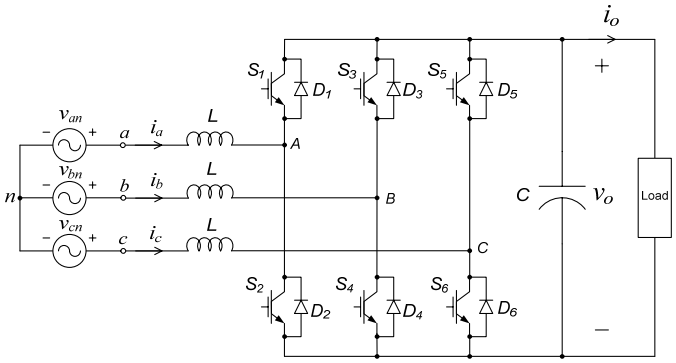

Figure 1. Three-phase boost rectifier.

II. ANALYSIS OF THE CONVERTER

The electrical circuit for the analytical analysis of the rectifier system is shown in Fig. 1. The main objective of this rectifier is to draw sinusoidal input currents that are in phase with input voltages while producing a fixed dc voltage at the output. It is evident from Fig. 1 that sinusoidal input current condition can be achieved if the rectifier input voltages v_{An} , v_{Bn} and v_{Cn} are all sinusoidal voltages with

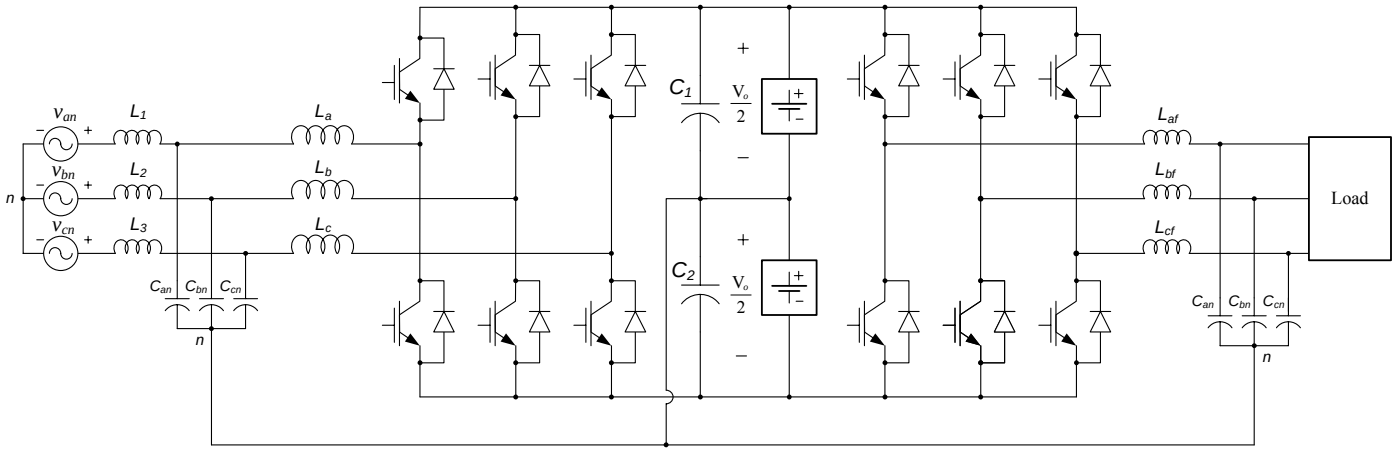

Figure 2. The circuit topology of a three-phase power-factor-corrected online UPS system.

adjustable magnitudes and phase shifts. This implies a voltage-source inverter operated backward as a rectifier [12]. Based on this approach, an equivalent circuit model for phase *a* of the rectifier with respect to the neutral point of input sources can be obtained, this circuit is shown in Fig. 3. The model assumes that the switching frequency components are removed from the waveforms. The state equation that describes this circuit can be written as

$$L\frac{di_a}{dt} = v_{an} - v_{An}\,. \tag{1}$$

Where v_{an} is the mains voltage; v_{An} is the voltage to be synthesized at the rectifier input. The proper control of switches adjusts the magnitude and phase shift of v_{An} with respect to mains voltage in order to achieve unity power factor and bidirectional real power flow [13].

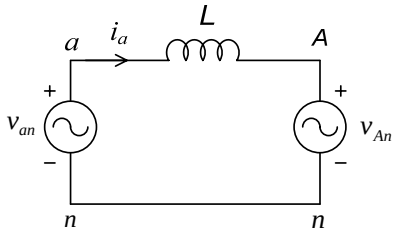

Figure 3. Equivalent circuit model for phase *a* of the rectifier shown in Fig. 1 with respect to the neutral point of input sources.

Consequently, the state equations that describe the steady-state operation of the converter under balanced three-phase voltages are given by (2) and (3), where d_1, d_3, and d_5 represent the duty cycles of the IGBTs S_1, S_3, and S_5, respectively (see Fig. 1).

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} - \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} d_1 \\ d_3 \\ d_5 \end{bmatrix} v_o \tag{2}$$

$$C\frac{dv_o}{dt} = \begin{bmatrix} d_1 & d_3 & d_5 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - i_o \tag{3}$$

In steady state with balanced inputs, the output voltage v_o and the output current i_o are constant variables with negligible ripple. As a result, equations (2) and (3) suggest that one way of producing sinusoidal currents at the input and similarly constant voltage at the output is to vary the duty cycles of the switches sinusoidally [12]. In the next section, a sinusoidal PWM control method will be developed based on this analysis.

III. Design of the Control System

A. Control Methodology

As mentioned in the previous section, the steady-state duty cycles of switches have to be sinusoidal functions, which make the use of classical feedback control techniques difficult. For that reason, most of the modeling and control design efforts for three-phase rectifier systems prefer transforming the three-phase quantities into rotating d-q coordinates since it is very convenient to apply conventional feedback control techniques [12]. This process also involves developing a linearized small-signal model of the converter in rotating coordinates, and then obtaining the transfer functions from control-to-input and control-to-output so that a proper closed loop compensator can be designed.

However, we have tried direct approach to design a sinusoidal PWM control without going through transformation and modeling steps. As pointed out earlier, this is also one objective of this study, investigation of the effectiveness of new design tools in rapid prototyping. For example, the power circuit of boost rectifier modeled in the PLECS simulator is directly used with Simulink control blocks. This method allows us to use the actual power converter instead of its small-signal average model while designing the feedback control system. The advantage of this method is that dynamics associated with the power converter are included in the control and compensator design. Therefore, it is more intuitive and an easy way to reduce long analysis, design, and optimization efforts especially for engineers in industry. The Simulink model of the proposed control algorithm is shown in Fig. 5. The PLECS circuit in the figure implements the power

converter stage. Also, the measurement unit emulates the function of 12-bit analog-to-digital converters of TMS320F2808, which is the Texas Instruments fixed-point DSP.

In the final step, verified simulation is converted into DSP code. For this task, we used the Simulink model shown in Fig. 6, where the measurement unit and the symmetrical PWM generation blocks (SPWM) shown in Fig. 5 are replaced by the ADC and the PWM blocks of F2808. Three of the total six PWM blocks are used to control the switches of the PFC stage. The other three are used to control the inverter stage.

In the following paragraphs, we will discuss the controller system and the criteria in the setting of the main design parameters.

B. Description of the Reading and the Measurement Units

First of all, all required readings and measurements should be done correctly and be cleaned from the noises to get a good performance from the controller. Fig. 4 shows the boost rectifier circuit, the control system in block diagrams, and the measurement points. The three input voltages, as shown in Fig. 4, are read and properly scaled before they are applied to ADC channels. Since the analog inputs only allow positive signals, all incoming ac signals are offsetted by 1.5 V. The maximum input to the analog channels is 3 V, so 1.5 V offset aligns the ac signals at center of full scale reading range of ADC blocks. Scaling of signals was done using rail-to-rail operational amplifiers and offset voltages were obtained using precision components to minimize the reading errors. Input ac currents are measured using hall-effect current sensors and similarly scaled and applied to ADC blocks.

Fig. 7 shows the details of the measurement unit. This unit models the analog measurements and emulates the ADC channels of F2808. The ADC channels of this particular DSP make 12-bit reading and output values in the range 0 to 4095. All variables in this unit are unsigned integer numbers. The outputs of this unit feed the data-scaling unit where all variables are transferred back to signed 32-bit fixed-point numbers with Q value set at 15. The details of the data-scaling unit are shown in Fig. 8.

C. Description of the Control System

As shown in Fig. 4, the control has three loops: an outer voltage loop, a feed forward loop, and an inner current loop. In the outer loop, first, the measured dc-bus voltage is compared to a reference voltage, and then the compensated error is multiplied by the sampled input voltage to create the reference current waveform. Next, this waveform is subtracted from the feed forward signal. Feed forward signal is the scaled input voltage and in phase with the reference waveform. After that, the new reference signal is compared to the measured current in the inner loop for current control, and the error is compensated for best tracking of reference current and correspondingly for the realization of unity power factor.

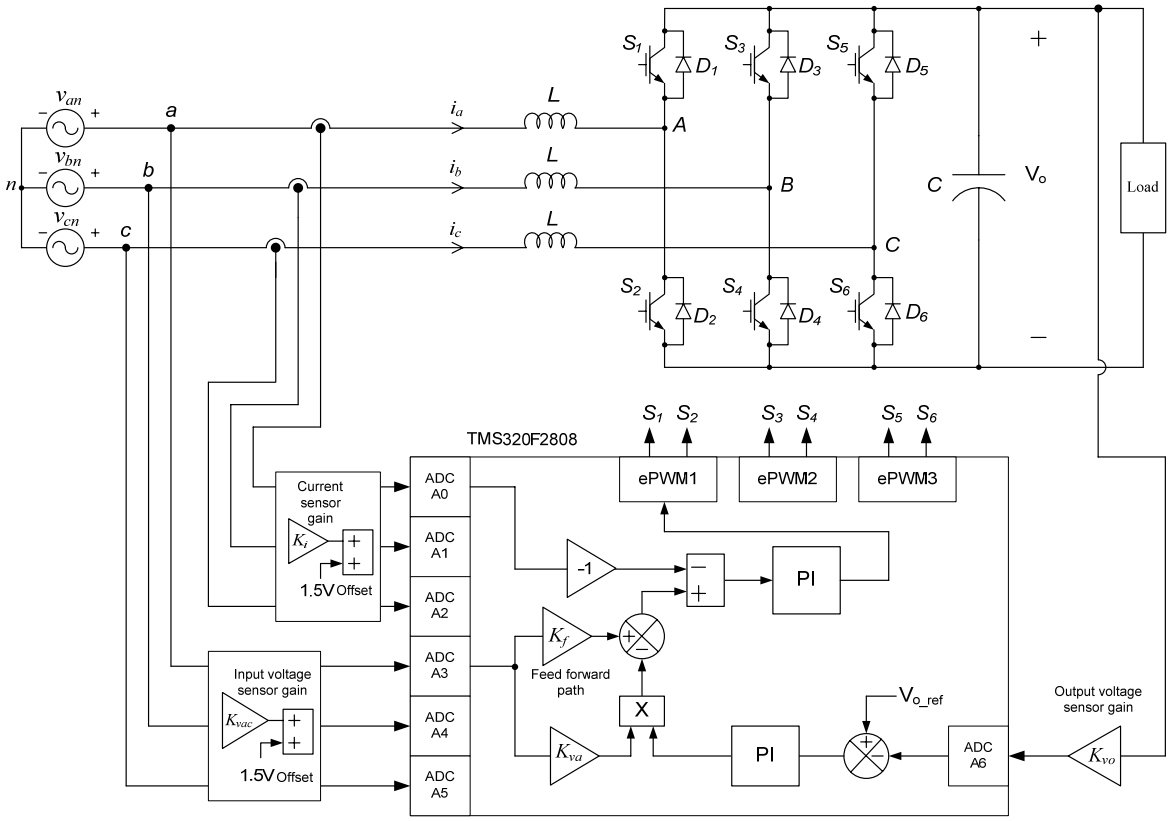

Figure 4. Three-phase boost rectifier and its control system. The control block diagrams shown within the large rectangular block are drawn only for the converter leg that is responsible for synthesizing the input current of phase *a*.

If the current sensors are placed to measure the current coming from the source side to the rectifier, they should be multiplied by -1 so that rectifier can be gated as if it is a VSI inverter. At the final stage of the controller, the control signal is compared to a triangular carrier signal to produce the pulses for the switches.

The objective of feed forward loop is to prevent boosting when there is no load, and also to provide good dynamic response when input voltages change suddenly. Its gain is adjusted such that there is no or very little power flow when all feedback signals are set to zero. Under this condition rectifier produces a voltage that is almost equal to the input voltage both in magnitude and phase. So, when v_{an} and v_{An} are equal in average sense then there is neither boosting nor any power flow either way. In any case, a resistive load in kilohm range should be put at the output so that stability is guaranteed even when there is no load.

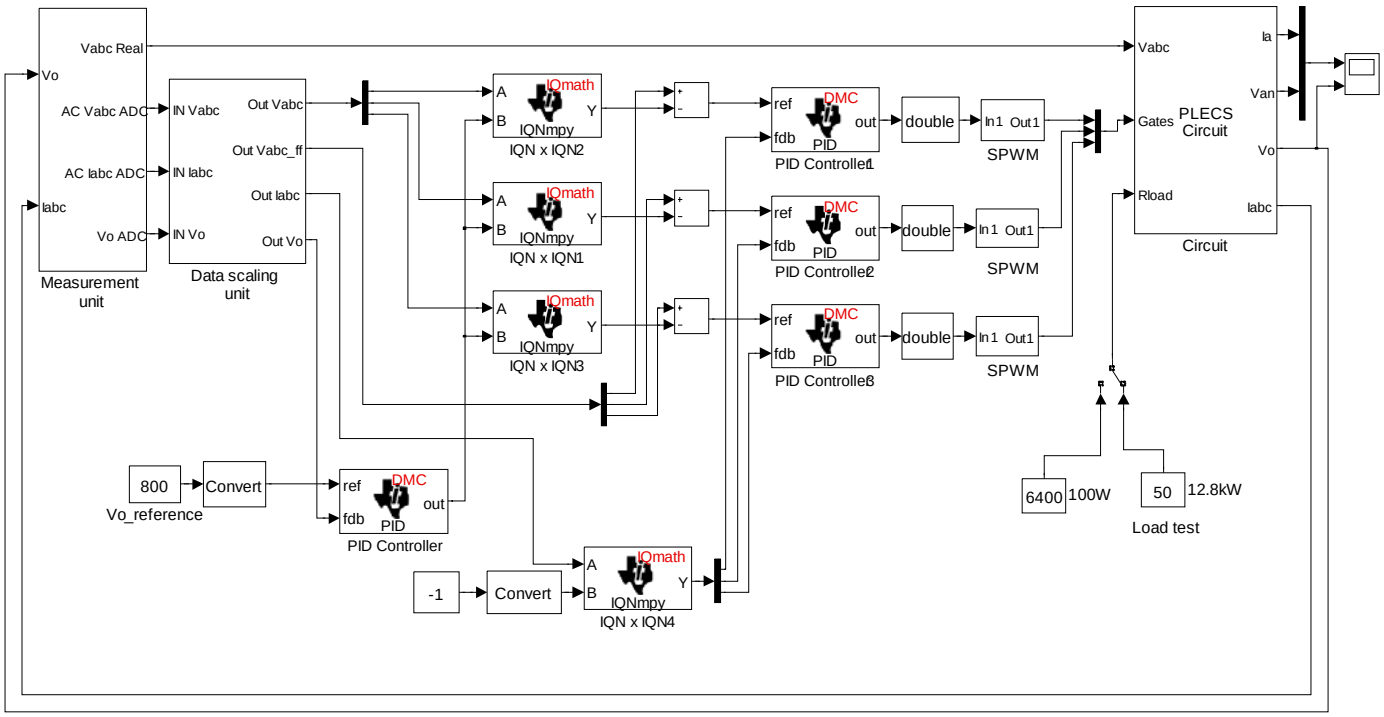

Figure 5. Simulink model of the controller and the boost rectifier which is modeled using PLECS simulator circuit models.

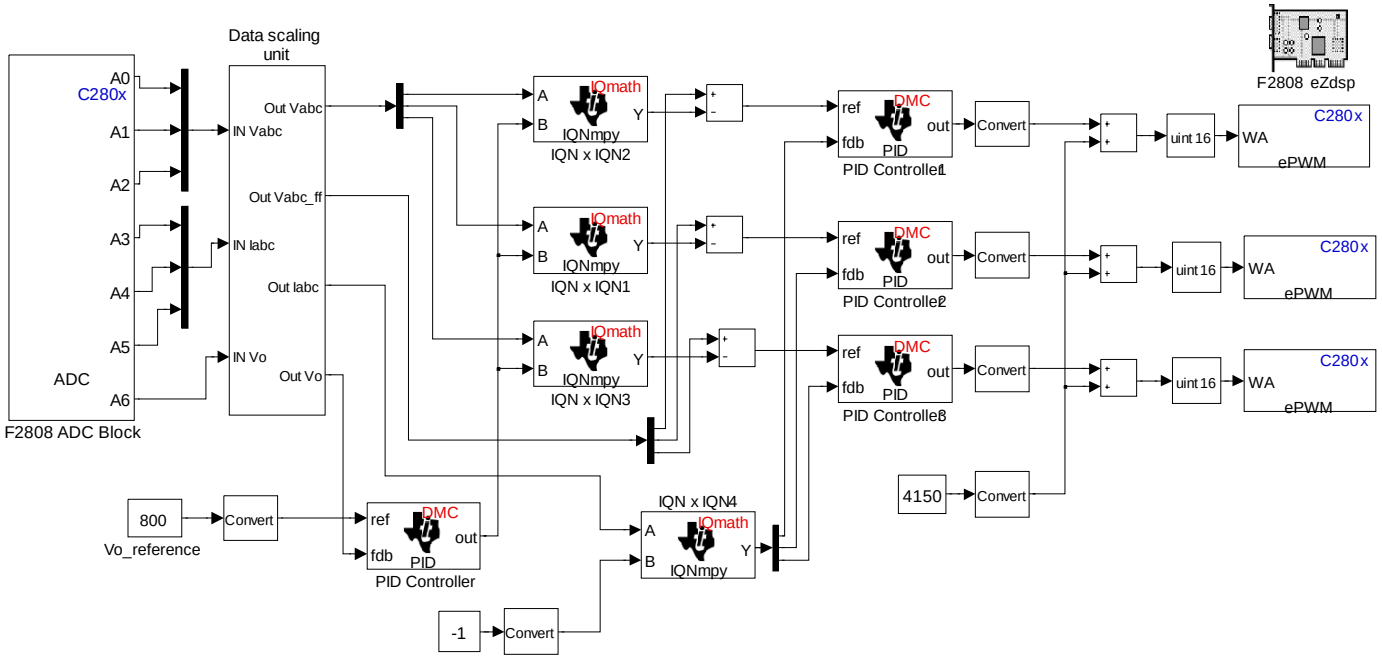

Figure 6. Simulink model that is used to build the code for the Texas Instruments TMS320F2808 fixed-point DSP.

As pointed out in previous section, all of the control parameters such as the scaling factors for measured voltage and current signals, reference values, gains of PI controllers, and the IQ number formats for the IQmath function blocks are determined and optimized during the simulation performed by the model shown in Fig. 5. Then, the Simulink model shown in Fig. 6 is created for building the DSP code. In this model, in addition to the replacement of the measurement unit and the SPWM blocks by the actual ADC and the PWM blocks of F2808, a further modification is required before the control signals are applied to the PWM channels. This is the offsetting of the control signals as shown in Fig. 6 because the carrier signals generated by the PWM channels are unidirectional. Besides, the carrier signal magnitude is linearly dependent on the selected carrier frequency. Therefore, the number 4150 means the half of the magnitude of the carrier signal of this particular DSP when the carrier frequency is selected as 12 kHz, which is our switching frequency. As another example, the peak value of the carrier is 10000 when the frequency is 10 kHz. Also note that the PLECS circuit is removed from the model, too.

IV. Design of Power Converter Stage

First of all, nominal operating conditions and design specifications should be determined. The nominal input voltage is 220 V, but the rectifier should be able to draw sinusoidal currents and provide high-power quality for the input voltage variations from 154 V to 283 V, corresponding to approximately ±30% of nominal range. Then, the dc-bus will be regulated at 800 V because we want to reduce the IGBT currents in the inverter stage. Finally, an input current THD that is less than 3%, a power factor close to unity and a nominal power rating of 10 kW are also specified.

Component values and switching element ratings have been determined based on the simulation studies. From the simulation of the circuit in Fig. 5, a boost inductance of 5 mH, a dc-bus capacitance of 1,100 µF, and a switching frequency of 12 kHz were determined as the right combination to achieve the given specifications. When the input voltages are balanced, small value of capacitance can be used such as 470µF. But, when there is some unbalance in the input voltages, the dc-bus starts to have second-harmonic ripple. For this reason, a larger value of capacitance is chosen to reduce this ripple. After the design, a prototype boost rectifier shown in Fig. 9 was built.

As the main switching elements, we used 1200 V, 100 A Mitsubishi CM100DY-24NF part numbered IGBTs for the rectifier stage. Two 2,200 µF 450 V capacitors from Kendeil were connected in series across the dc-bus with balancing resistors. The boost inductors were wound on Kool Mu powder E cores from Magnetics. Core pairs were stacked side by side to get more area and allow more flux as shown in Fig. 9. In addition, an LC filter at the input is placed to further reduce the THD of the current and EMI by filtering the high frequency switching noise. We also included a capacitor from the neutral point to the ground. The resistive loads were used for testing the system.

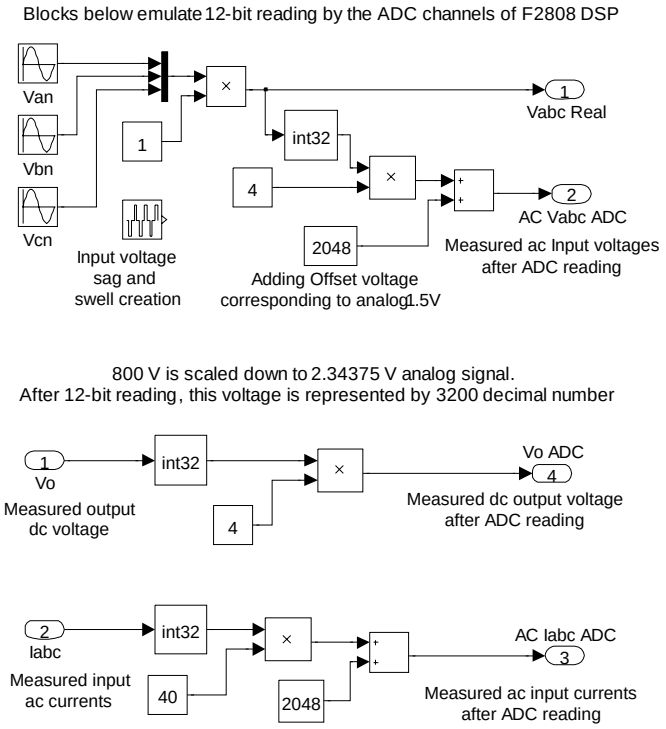

Figure 7. The details of the measurement unit shown in Fig. 5.

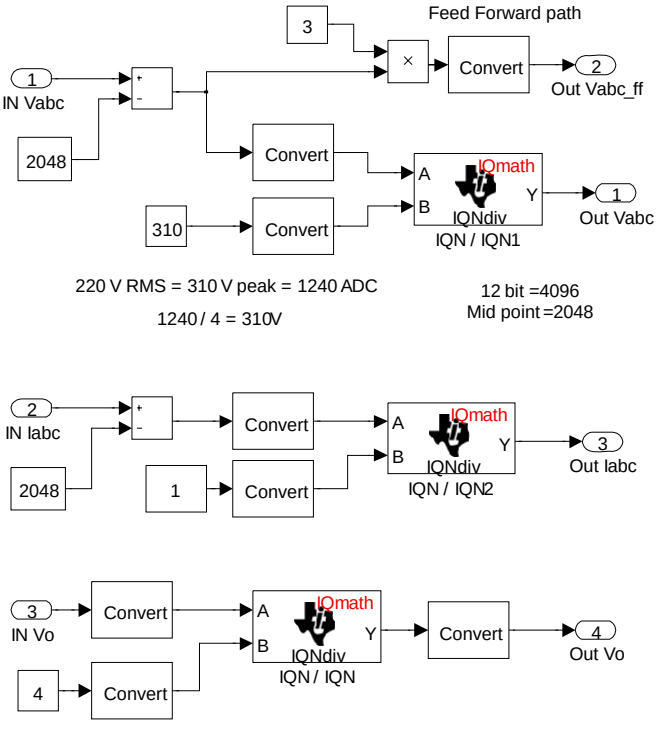

Figure 8. The details of the data-scaling unit shown in Fig. 5.

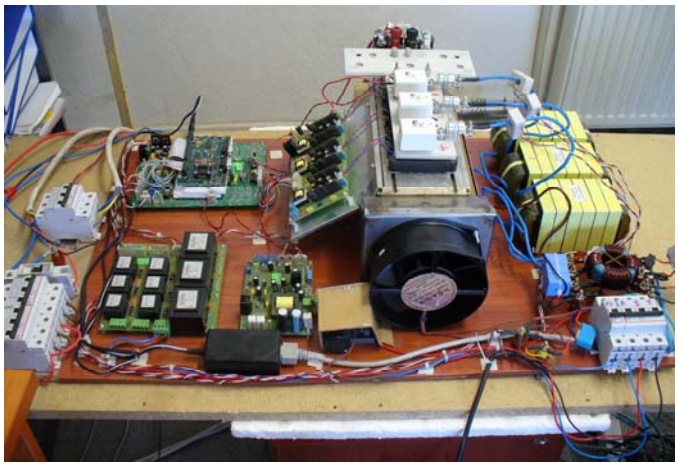

Figure 9. The hardware of the prototype boost rectifier.

V. EXPERIMENTAL RESULTS

As shown in Fig. 10, the input current is sinusoidal with very small distortion and also almost in phase with the input voltage. The THD of this current waveform is measured as 1.7% as shown in Fig. 11, which is well below 3% specification. The power factor is also measured unity as displayed in Fig. 12. Moreover, we observe no significant variations and oscillations on the dc-bus voltage, as shown in Fig. 13, when the load is changed from no load to a full load at 7800 W. Similarly, Fig. 14 shows the transient response to a 10% sudden increase in the input voltage. As seen from the same figure, the effect of this increase on the dc-bus voltage is not noticeable.

In conclusion, the experimental results have proved the validity of strategy, which is the design of a digital controller via emulation method in Simulink, and also they confirmed the performance of controller in achieving the desired specifications.

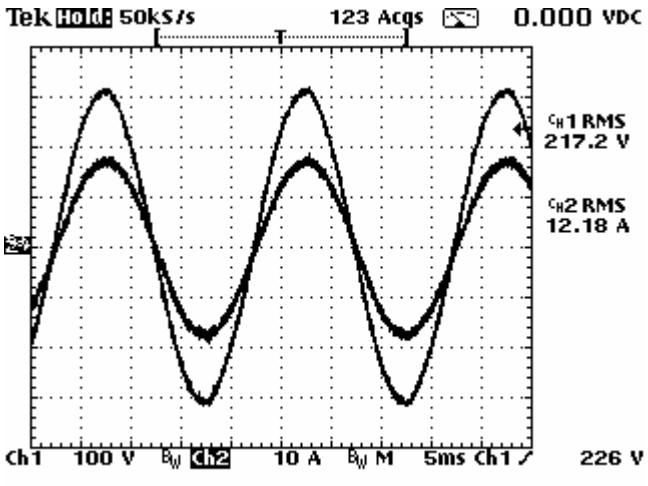

Figure 10. The experimental waveforms of input voltage and the current at the utility side of the rectifier.

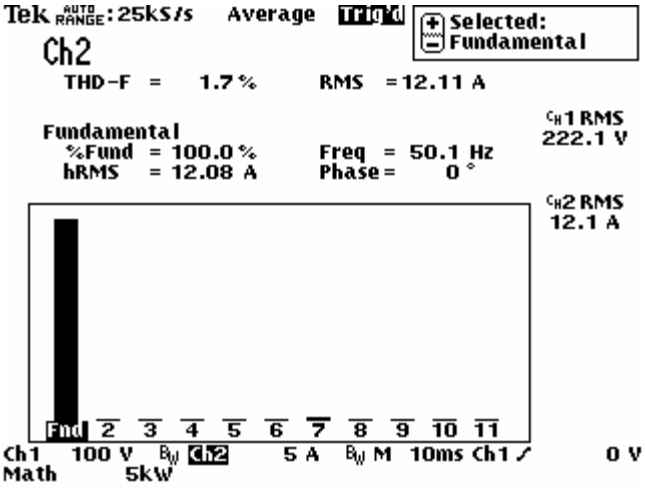

Figure 11. The THD and the harmonic spectrum of the input current.

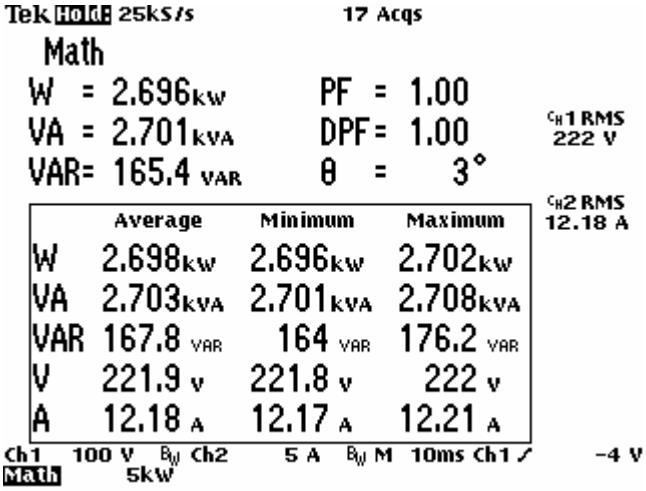

Figure 12. The power and power-factor information at the utility side of the rectifier system.

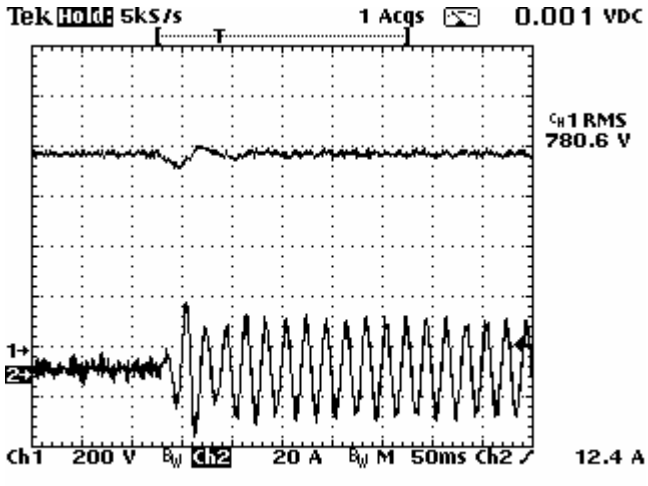

Figure 13. The output voltage transient during sudden load change from no load to a full load.

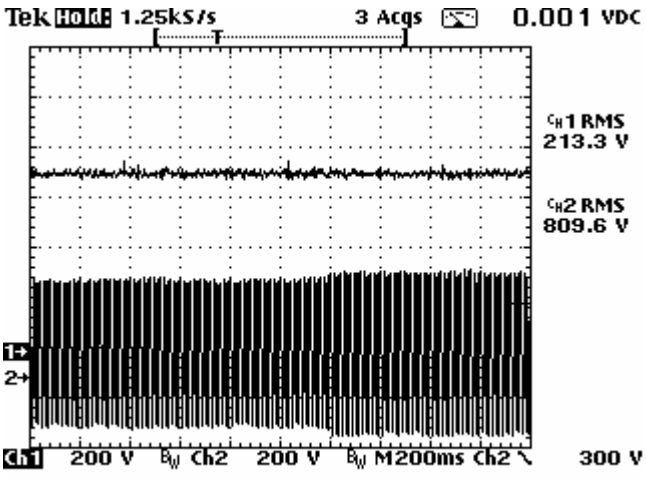

Figure 14. The response of output voltage to increase in input voltage. The increase is around 10%.

VI. CONCLUSIONS

This study demonstrates that the proposed digital PFC controller provides high power quality at the input of three-phase PWM boost rectifiers. A power factor close to unity and mains current THD less than 2% are all achieved with a simple method. The various system dynamics are measured to be as within acceptable limits. Moreover, it has been shown that Simulink provides an easy platform for quick and successful digital control development and implementation capability for the power electronic systems to be controlled by Texas Instruments DSPs. Finally, it is also shown that full control of an online UPS system can be performed in a single DSP chip, which can result in a simple and flexible design in less time and with less cost to the manufacturers.

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