8-2019

Hardware implementation of boost power factor correction converter.

Shruti Motilal Deore
University of Louisville

HARDWARE IMPLEMENTATION OF BOOST POWER FACTOR CORRECTION CONVERTER

By
Shruti Motilal Deore
B.Tech., Dr. Babasaheb Ambedkar Technological University, 2013
M.E., Savitribai Phule Pune University, 2017

A Thesis
Submitted to the Faculty of the
J.B. Speed School of Engineering of the University of Louisville
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science
in Electrical Engineering

Department of Electrical and Computer Engineering
University of Louisville
Louisville, Kentucky

August 2019

HARDWARE IMPLEMENTATION OF BOOST POWER FACTOR CORRECTION CONVERTER

By
Shruti Motilal Deore
B.Tech., Dr. Babasaheb Ambedkar Technological University, 2013
M.E., Savitribai Phule Pune University, 2017

A Thesis Approved on

Date 7/25/2019

by the following Thesis Committee:

_____
Dr. Michael McIntyre, Thesis Adviser

_____
Dr. Nicholas Jewell

_____
Dr. Christopher Richards

ACKNOWLEDGMENTS

A project of this magnitude has been a journey with various ups and downs. It was the support from adviser, colleagues and family, which has helped me in the successful accomplishment of this work. I am glad to express my sentiments of gratitude to all who rendered their valuable help for the successful completion of the thesis report.

I am thankful to my thesis adviser Dr. McIntyre, J.B. Speed school of Engineering, Louisville for his guidance and encouragement in this work. His expert suggestions and scholarly feedback had greatly enhanced the effectiveness of this work. I would also like to express my appreciation and thanks to all my colleagues and family members who knowingly or unknowingly have assisted and encouraged me throughout my journey.

ABSTRACT

HARDWARE IMPLEMENTATION OF BOOST POWER FACTOR CORRECTION CONVERTER

Shruti Deore

Date 7/25/2019

Nowadays, there has been an increasing demand of unity power factor in electrical power sector. Due to the nonlinear nature of load equipment, switching devices, source voltage and current are out of phase with each other. Many power converters topologies are used for the power factor correction. The boost converter with controller is most common for power factor correction circuits. The controller objective is to maintain the output voltage regulation and input current tracking with source voltage. The voltage ripple present due to the ac component of the current tracking objective, hence instead of ignoring that ripple, it is used in controller designing. The mathematical modeling of system depends on ac and dc dynamics of the circuit. The Lypunov stability analysis used for designing the controller of boost converter. In this work, experimental set-up for boost power factor correction converter was made with power pole board and NI compact RIO. The controller algorithm executed in LabVIEW FPGA module and results were verified. This novel controller ensures the convergence of the error signal by stability analysis

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Nowadays there has been increasing demand for high power factor and good power quality in the current drawn from the utility. Energy saving and low electromagnetic interference become the public concern and are now the major issues of many industries. The development of switched mode power electronics and equipment's also creates some problems of power supply industries. Due to switching characteristics of the power electronics causes the low power factor and harmonic distortion high. Low power factor adds up the losses in transmission and hence overall cost of power transmission increases. In the field of power electronics there has been a lot of research done in power conversion techniques. The following literature motivates the designing of boost power factor correction (PFC) converter.

Many power electronics topologies used for power factor correction circuits. A survey was done on single phase power factor correction circuits in [1] where, classification is done according to line current waveform and performance of circuits. A classical two stage approach includes the combination of two converters based on an energy management. In low power applications with low cost in order to maintain the harmonic regulations single stage converters are the best solutions. The boost converter is widely used because of simplicity, small inductor and high efficiency. Total harmonic distortion (THD) is the main factor while designing of power factor correction and designers always try to minimize the percentage of total harmonic distortion. Active PFC

can comply with IEC61000-3-2 and gives the high-power factor nearer to 1. Though passive PFC have simple and rugged circuitry, but they cannot operate on universal input range and fail to correct the nonlinear loads. Active PFC uses the controller with boost converter and able to minimize the THD up to 7.4% in [2].

In any PFC converter, as the input energy is pulsating it requires a storage element to provide the constant supply to the load. The capacitor used in PFC converters generally has a high voltage swing. To reduce the voltage swing in capacitor the series inductance interval topology operates in discontinues mode [3]. Depending on current through boost inductor during switching cycle, boost converter switch operates in current conduction mode and discontinues conduction mode. In current mode control the controller senses and limits the peak inductor current and tries to follow the desired sinusoidal current wave shape [4]. In order to increase the efficiency of PFC system bridgeless converter topology eliminates the forward voltage drop in the line current [5]. A design- semi bridgeless rectifier consist of two boost converter which operates complementary to each other at time uses the sliding mode control techniques [6].

To address the ripple component in PFC control systems, many controller designs uses the different control techniques. The ac-dc converter with pumped storage energy tank regulates the power configured by an inductor with switches and diodes. The input power decoupled into ac components and dc components ensuring the constant power output from the converter. There is small ripple present in the output voltage and hence the size of the capacitor also reduces [7]. Similarly, the power decoupling concept uses in photovoltaic and energy storage application in order to increase the reliability and

performance of the system. Earlier in PV system, the single-phase inverters contain the double line frequency power in pulsating nature but by introduction of active elements such as switches in inverter topology we can easily utilize the decoupled power [8].

Linear controllers are unable to perform optimally over the whole operating range, resulting in poor transient response and instability. In [9] three nonlinear controllers introduce, and comparison study performed. Nonlinear controllers based on control Lypunov function theory, differential flatness theory, and discrete energy function theory were built, and stability analysis performed. Nonlinear controllers have a very fast transient response and they handle variations in system parameters and disturbances of a dynamic system model.

A general scheme of an active power factor correction controlled by two feedback loops: inner loop is an input-current feedback loop and outer loop is an output voltage feedback loop. The PFC output produces the voltage ripple of twice the line frequency hence the provision is made to filter out this ripple otherwise a relatively high ripple would cause the considerable distortion in the reference of the line current feedback loop. Thus, the static behavior of a PFC with appreciable voltage ripple in the voltage feedback loop studied in [10].To eliminate the ripple component from the voltage loop [11] uses wide band width voltage loop. Implementation of a self-tuning digital filter improves output voltage transient response. Many approaches are used for improving the design of PFC controller. In [12] Stability analysis and the design of fast voltage loop compensator can be used with existing ripple influence methods. Issues like stability of system, dead zone elements and filters are well address using circle criteria.

For high line voltage and light load conditions [13] proposes the technique which can minimize the distortion and phase lead of the line current, it enhances the power quality and total harmonic distortion. In order to cancel the adverse effect of the phase leading currents due to filter capacitor the proposed method introduces the average inductor current reference and utilizes the duty ratio feedforward techniques. The hardware implementation of prototype model uses the DSP board for implementing the control algorithm. Experimental results show the given model reduces the switching losses due to switching dead zone, also it helps to improve the power factor especially in high line voltage and light load condition. In electrical vehicles, AC/DC converters has one input power factor correction stage. The controller was designed based on the control Lypunov function which eliminate the low bandwidth voltage control loop and operates with faster dynamic response [14].

In this work a parallel buffer with a bidirectional boost converter configuration as proposed in [15] selected for designing. To cancel out the double frequency component of the inverter load current, the boost converter buffer operates under input current tracking controller mode. The present work motivates from a nonlinear controller described in [16], a controller based on Lypunov analysis and experimentally verified by a dSPACE controller board. A single-phase boost PFC system consist of diode bridge connected to the dc-dc converter and operates in continuous conduction mode. The desired current trajectory of the source current calculated by balancing the energy transferred from input to output in one half cycle of the line frequency. The mathematical modeling of the adaptive controller based on exponential stability of the controlled system leads to error signal attains asymptotic stability. To obtain realistic results the given system modelled

with controller board and verification of control objectives is done. Similarly, the present work in this project starts from mathematical modeling of the PFC boost converter system and hardware implementation to verify the proposed controller.

The project work is arranged as: Section 2 describes the general overview of the PFC boost converter system. Section 3 mathematical modeling of the system based on Lypunov analysis and stability of the system presented. Section 4 shows the implementation of the proposed system in hardware model, the complete description of the components presented in this section, and Section 5 illustrates the designing of controller algorithm. Finally, in Section 5 results and analysis is done followed by conclusion remark.

2. OVERVIEW OF PFC BOOST CONVERTER SYSTEM

2.1. PFC BOOST CONVERTER SYSTEM

In electrical supply system the current distortion occurs due to the nonlinearities present in the load side. Electrical standard set the limit on allowable maximum current distortion. Power factor correction circuit allows the ac source current in phase with the source voltage. In this work, we consider active power factor correction circuit operates in average current conduction mode. The below figure 1 show the boost PFC circuit. The diode bridge connected to the boost converter. It mainly has three parts. First is ac supply then rectifier part and boost circuit. S1 is the Mosfet switch, D is the diode used in boost converter and C is the capacitor. The switching frequency of converter is quite greater than the supply frequency and hence to store the energy a big size of capacitor needed. The general goal of the PFC boost converter is to turn the switch S1 on and off rapidly with a varying duty cycle in order to make the input current (Iac) sinusoidal and in phase with the input voltage (Vac). The circuit operates in two mode- when mosfet switch S1 is on and when switch is off. When mosfet switch is closed, the inductor energized by ac supply through rectifier. At the same time diode becomes reverse biased, and capacitor provides energy to the load. In second state switch is open then inductor current decreases as it supplies energy to the load and charges the capacitor.

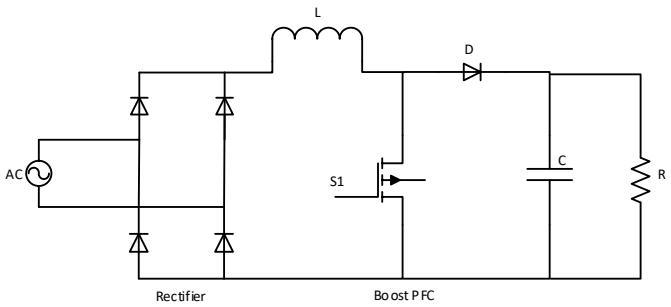

Figure 1: Typical Boost PFC Circuit

2.2. PFC BOOST CONTROL SYSTEM

The below figure 2 shows the controller with PFC boost converter system. A closed loop control system implemented to ensure that ac input current is in phase with ac voltage. Different types of control schemes like PID, nonlinear controllers can be implemented for PFC boost circuit operation. In this project control scheme based on Lypunov stability analysis is used. There are two objectives involved in controlling of PFC converters-inductor current tracking and a dc voltage regulation objective. These two objectives conflict with each other due to voltage ripple induced by the ac component of the current objective hence a novel control approach is used which separates the converter dynamics into AC and DC terms, and then develops control laws to jointly achieve the input current tracking and output voltage regulation objectives. The ripple can be decoupled from the voltage error so that it can be fed to the current control loop without propagating ripple. Designing of controller based on mathematical modeling and results are validated on hardware. In this project controller accepts four inputs and generates a pulse width modulated (PWM) signal output applied to the gate of S1 as shown in figure.

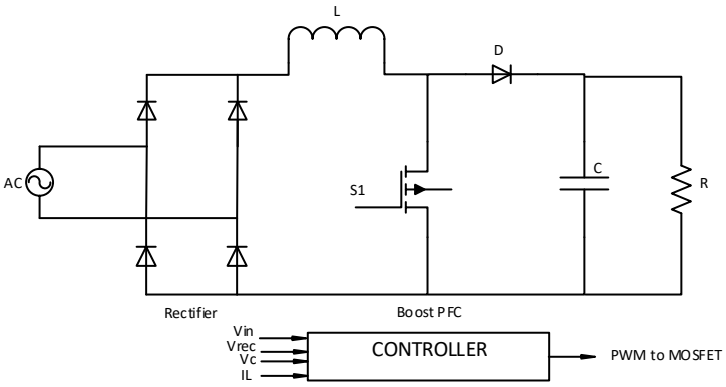

Figure 2: PFC Boost Converter System with Controller

3. SINGLE PHASE BOOST PFC CONVERTER SYSTEM

3.1. MATHEMATICAL MODELING

Mathematical modeling of power factor correction boost converter system based on dynamics of the system [18], [19]. In this project controller algorithm developed according to mathematical equations. The switching averaged dynamics of a boost converter can be expressed in terms of I_L and the capacitor voltage V_c as

$$L_f \dot{I}_L = V_{in} - uV_c \tag{1}$$

$$C_f \dot{V}_c = uI_L - I_o \tag{2}$$

where $V_{in} = V_d|\sin\theta|$ is the rectified AC source voltage with amplitudeV_d, $u = (1 - D)$ is the control input and $D \in [0,1]$ is the duty cycle of the converter, and I_o represents load current. The controller objective is to generate ac input current which is in phase with the ac source voltage. Thus, the inductor current I_L of the boost converter should be a rectified sine wave of the following form:

$$I_L^* \triangleq I_d|\sin\theta| \tag{3}$$

where θ is the known phase of the AC source and I_d is the amplitude of the reference current. I_L^* can be split into ac and dc components as –

$$I_L^* = I_{ac}^* + I_{dc}^* \tag{4}$$

$$I_{dc}^* \triangleq \frac{2I_d}{\pi} \tag{5}$$

$$I_{ac}^* = I_d|\sin\theta| - \frac{2I_d}{\pi} \tag{6}$$

Hence the inductor current error signal

$$\eta \triangleq I_L^* - I_L \tag{7}$$

As ac current component causes ripple in the capacitor voltage (2) rather than avoiding ripple voltage, it is included in desired capacitor as an ac term

$$V_c^* \triangleq V_{dc}^* + V_{ac}^* \tag{8}$$

Hence output voltage error signal

$$e \triangleq V_c^* - V_c \tag{9}$$

From equation (8) term V_{ac}^* used for reference capacitor voltage ripple, hence V_c^* also consist of same ripple. Actual V_c and reference V_c^* cancels out and error signal e will have only dc voltage error signal. Put values from (4) and (7) in equation (2).

$$C\dot{V}_c = u(I_{ac}^* + I_{dc}^* - \eta) - I_o \tag{10}$$

u is the control input which is also split into u_{DC} and u_{AC} . In designing of $\dot{V}_{ac}^*$, integrator like high pass filter used as we want $\dot{V}_{ac}^*$ to be purely ac as desired. Hence derivative of the ripple voltage as follows

$$\dot{V}_{ac}^* = \frac{1}{C}(uI_{ac}^* + u_{ac}I_{dc}^* - u\eta) \tag{11}$$

3.2. VOLTAGE REGULATION CONTROLLER

In designing of voltage control loop, we want error e signal converges to zero. Put equation (8) into (9) then taking derivative and multiplying by C error dynamics equation will be

$$C\dot{e} = C\dot{V}_{ac}^{*} - C\dot{V}_{c} \tag{12}$$

The DC reference current I_{dc}^{*} defined as follow. Where k_1a positive constant is gain and $\hat{I}_o$ is an estimate of the load current.

$$I_{dc}^{*} \triangleq \frac{1}{u_{dc}}\left(\hat{I}_o + k_1 e\right) \tag{13}$$

$$\dot{\hat{I}}_o \triangleq k_3 e \tag{14}$$

Finally, the closed loop error dynamics equation we obtain

$$C\dot{e} = -k_1 e + \tilde{I}_o \tag{15}$$

3.3. CURRENT TRACKING CONTROLLER

In current control loop for obtaining open loop error dynamics first take time derivative of the current error equation,

$$L\dot{\eta} = L\dot{I}_{ac}^{*} - V_{in} + uV_c \tag{16}$$

Like equation (5) and (6) we can easily define ac and dc components of the input voltage and substituting those values in above equation will get-

$$L\dot{\eta} = L\dot{I}_{ac}^{*} - V_{in_{dc}} - V_{in_{ac}} + u_{ac}V_c + u_{dc}V_{ac}^{*} + u_{dc}(V_{dc}^{*} - e) \tag{17}$$

We can identify dc and ac terms in designing of u_{DC} and u_{AC} respectively.

$$u_{dc} \triangleq \frac{V_{in_{dc}}}{V_{dc}^{*} - e} \tag{18}$$

$$u_{ac} \triangleq \frac{1}{V_c}\left(V_{in_{ac}} - L\dot{I}_{ac}^{*} - u_{dc}V_{ac}^{*} - k_2\eta\right) \tag{19}$$

k_2 is a positive feedback gain. The current control loop should be tuned for fast dynamic response with respect to voltage control loop.

$$L_f\dot{\eta} = -k_2\eta \tag{20}$$

3.4. STABILITY ANALYSIS

We begin by defining a positive definite Lypunov function $V(t)$ as follow

$$V \triangleq \frac{1}{2}Ce^2 + \frac{1}{2}L\eta^2 + \frac{1}{2}k_3^{-1}\tilde{I}_o^2 \tag{21}$$

Taking the time derivative of the above equation and substituting in the time derivative of below equation

$$\tilde{I}_o \triangleq I_o - \hat{I}_o \tag{22}$$

Also assume the unknown load bus current I_o is primarily dc hence its derivative is zero. Equation in (21) reduced to following equation

$$\dot{V} = C_f e\dot{e} + L_f\eta\dot{\eta} - k_o^{-1}\tilde{I}_o\dot{\hat{I}} \tag{23}$$

If we use equations from voltage control loop (14), (15) and current loop (20) in above equation we will end up with-

$$\dot{V} = -k_1e^2 - k_2\eta^2 \tag{24}$$

As function V is positive definite and $\dot{V}$ is negative semi-definite we can conclude that $e, \eta, \tilde{I}_o \in \mathcal{L}_\infty$. From closed loop error dynamic equation (15) we conclude that $\dot{e} \in \mathcal{L}_\infty$.

Similarly, in current control loop from (20) we got $\dot{\eta} \in \mathcal{L}_\infty$. Error functions $\dot{e}, \dot{\eta} \in \mathcal{L}_\infty$. also $\ddot{V} \in \mathcal{L}_\infty$. As V is lower bounded, $\dot{V}$ is negative semi-definite, and $\ddot{V} \in \mathcal{L}_\infty$ By using Barbalat's Lemma {slotine book) we can states $\dot{V} \to 0$ as $t \to \infty$ .Hence from equation (24) as $t \to \infty$ the errors $e, \eta \to 0$.

As the controller input $u \in [0,1]$ so saturation also applies to u_{dc} and u_{ac}. From (13) the reciprocal of u_{DC} is bounded and by assumption $\hat{I}_o \in \mathcal{L}_\infty$ hence $I_{dc}^* \in \mathcal{L}_\infty$. From (11) in order to prove $\dot{V}_{ac}^* \in \mathcal{L}_\infty$ we are interested in $u, u_{ac}, I_{dc}^*, I_{ac}^*, \eta$ signals. From (5) and (6) $I_{ac}^* \in \mathcal{L}_\infty$. Hence it proved $\dot{V}_{ac}^* \in \mathcal{L}_\infty$, filter $H(s)$ is bounded input bounded output stable. As $V_{dc}^*, V_{ac}^*, e \in \mathcal{L}_\infty$ it proves that $V_c \in \mathcal{L}_\infty$. Following control block diagram motivates the designing of controller algorithm.

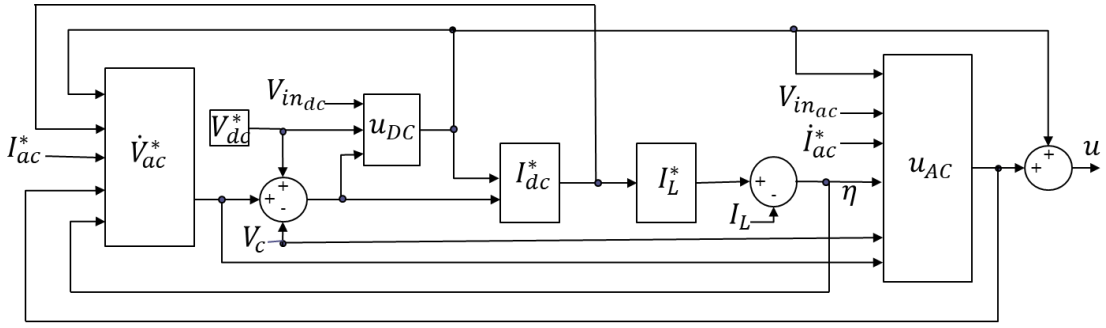

Figure 3: Control Block Diagram

4. HARDWARE IMPLEMENTATION OF BOOST PFC CONVERTER SYSTEM

A hardware prototype model was constructed for real time implementation of the PFC boost converter system. A power pole board connected in series with the bridge rectifier and Load resistor. An ac variable supply BK precision used for producing 10V ac voltage V_{in} and bridge rectifier produces rectified voltage V_{rec}. A LEM LA25-NP Hall-effect current sensor was used to obtain the inductor current measurement. A resistor value 50 ohm connected at load. The source voltage and source current waveforms were displayed on oscilloscope.

4.1 POWER POLE BOARD-

The Power Pole board was developed at the University of Minnesota (UMN) and commercialized by Hirel Systems it is widely used in U.S. universities for power electronics laboratory experiments [17]. The board can be configured as a buck-converter, boost converter, buck-boost converter, flyback converter, or forward converter. In this work, boost configuration on board was used. The PPB contains probe points to view relevant input, output, switching, and other pertinent signals on an oscilloscope. The below figures show the switches, jumpers, and potentiometers on the PPB. The leftmost switch when turned on delivers the pulse-width-modulated (PWM) switching signal to the MOSFET. The next block is a switch bank consisting of four switches for configuration as a boost converter, the leftmost switch is put in the bottom position to deliver the PWM

signal to the bottom MOSFET (corresponding to the right power pole of Figure). The second leftmost switch is put in the top position for enabling the external PWM signal on board. The new value of inductor was used in place of older inductor for inductor requirement in PFC operation. Inductor should be capable of carrying high value of current and withstand for switching frequency hence inductor of larger size selected. The new inductor value is 1 mH and can withstand up to 100 KHz for 5 amp maximum dc current. The modified power pole board as shown in figure 4,

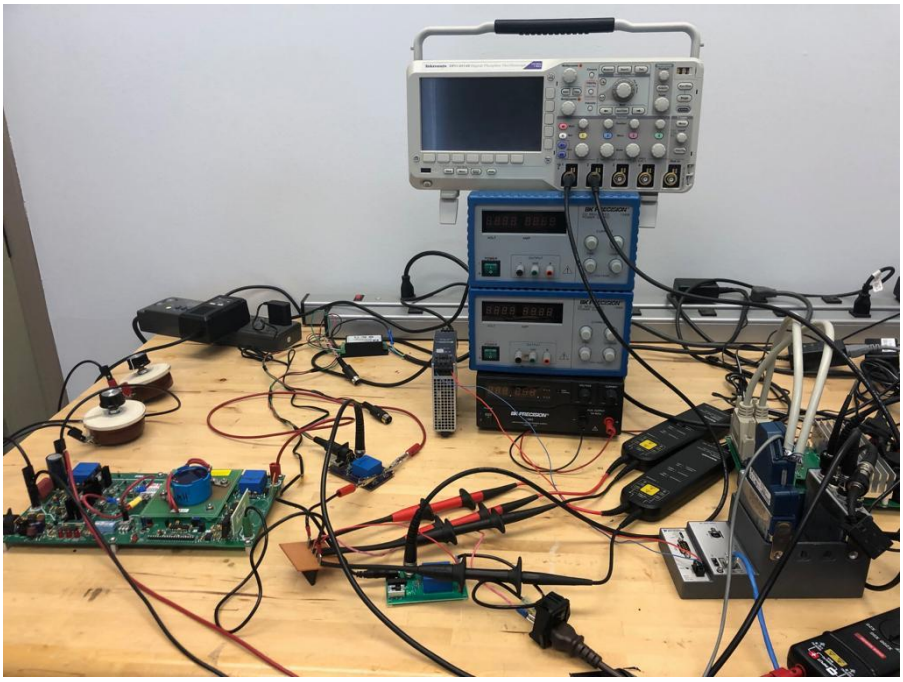

Figure 4: Hardware Setup

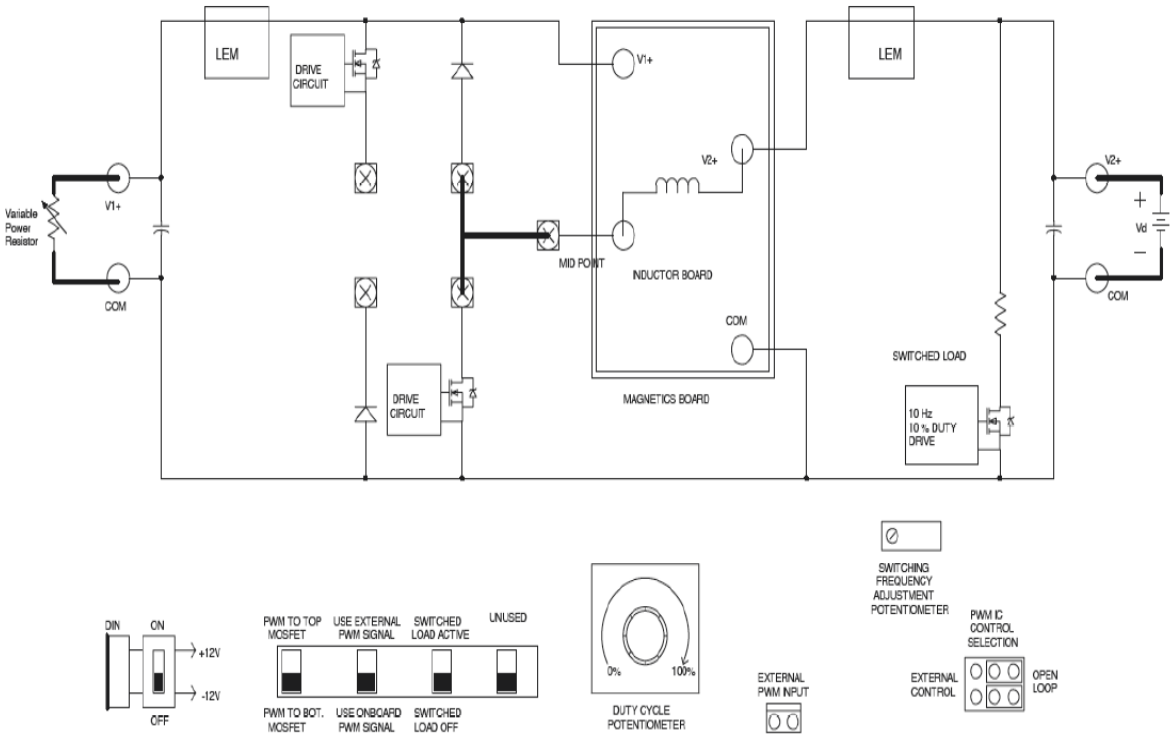

Figure 5: Schematic of Boost Converter

4.2 NI MODULE

A National Instruments Compact RIO device consisting of a cRIO-9063 controller used for controller designing. There are 5 modules were selected to meet the I/O requirements of the project. For generation of the PWM signal for MOSFET, an NI-9401 digital output module was used. An NI-9215 analog input module was used for measurement of the input voltage V_{in}, rectified voltage V_{rec} output capacitor voltage V_c and measurement of the inductor current sensor voltage output. An algorithm was executed at a switching frequency of 50KHz to obtain the experimental results.

5. LABVIEW FPGA MODULE

A compact RIO is a controller with processor and user-programmable FPGA consist of I/O modules. In this project algorithm designing done in FPGA module. Compact RIO in LabVIEW FPGA mode gives maximum performance and faster development in designing. FPGA VI contain all data acquisition and algorithm of controller in a programmable manner. Different versions of FPGA VI can be implemented to interface between real time VI and host VI. Real time data can be visualized on PC during the execution of project. An Ethernet wire was used for connecting the PC and compact RIO module. All the parameters involved in designing process displayed on front panel of FPGA VI. We can control the parameters of algorithm easily just by changing the values on front panel of FPGA VI. In this project FPGA VI runs at a sample rate of 65 KHz. The designing of controller algorithm based on mathematical modeling of system. For extracting the angular frequency and theta of input ac voltage, phase locked loop (PLL) VI used for single phase system. Four analog inputs and one digital output used for I/O module of FPGA VI as shown in figure. The algorithm uses the actual values of a hardware along with some arbitrary constant values used in designing. Parameters used in software designing is as shown in below table

Table 1: Boost PFC Model Parameters

Parameter	Value	Unit
Input voltage (V_{in})	7.07	V
Inductor (L)	1	mH
Capacitor (C)	680	µF
$Vdc^{*}ref$ (V)	10	V
Input voltage frequency	60	Hz
Switching frequency	50	KHz
K_1 (constant)	0.005	
K_2 (constant)	14	
K_3 (constant)	0.6	

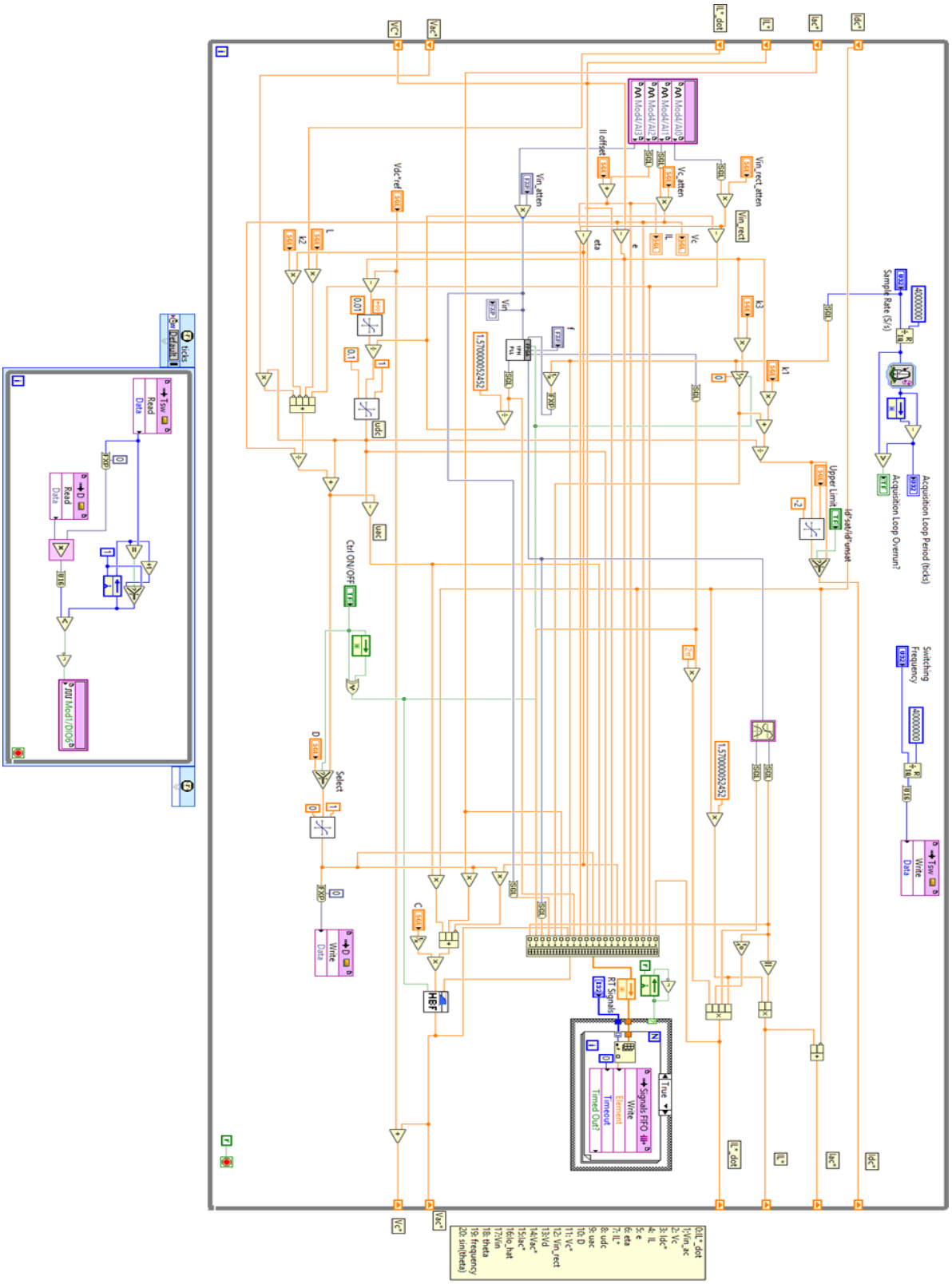

Figure 6: Controller Algorithm in LabVIEW FPGA

6. RESULTS AND DISCUSSION

A controller algorithm was executed in the FPGA and results were verified with boost converter protoboard. The parameters for experiment selected as shown in table 1. A resistive load of 50 ohm connected to the load side of boost converter. All the measured signals in algorithm are recorded in FPGA window. The results of the experiment are shown in fig. In fig we see that the output voltage V_c with reference voltage V_c^*, which consist of V_{dc}^* as well as the reference ripple V_{ac}^*. The current trajectory consists of ac component, which is accountable during ripple calculation, hence the voltage error e signal tries to converge at zero as shown in fig . For calculation of dc current reference I_{dc}^* we used (13) and signal is quite stable at 0.4 ampere value. The reference of dc current is useful while maintaining the voltage regulation. The I_{dc}^* is used for inductor current reference value calculation and this reference current compared with actual inductor current as shown in fig. The current tracking controller generates u_{dc} and u_{ac} signals and verification of those signal can be seen in fig. The behavior of u_{dc} and u_{ac} accurately follows the assumption. In fig shows the two waveforms on oscilloscope, the ac source voltage and current are in phase, achieves the unity power factor.

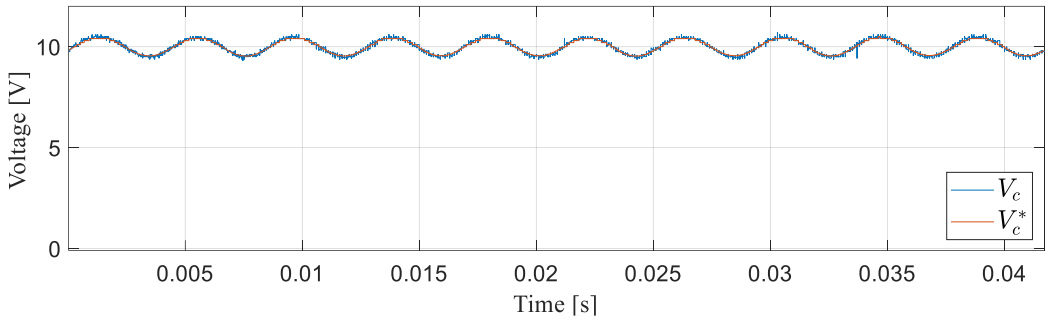

Figure 7: Capacitor voltage V_c and reference voltage V_c^*

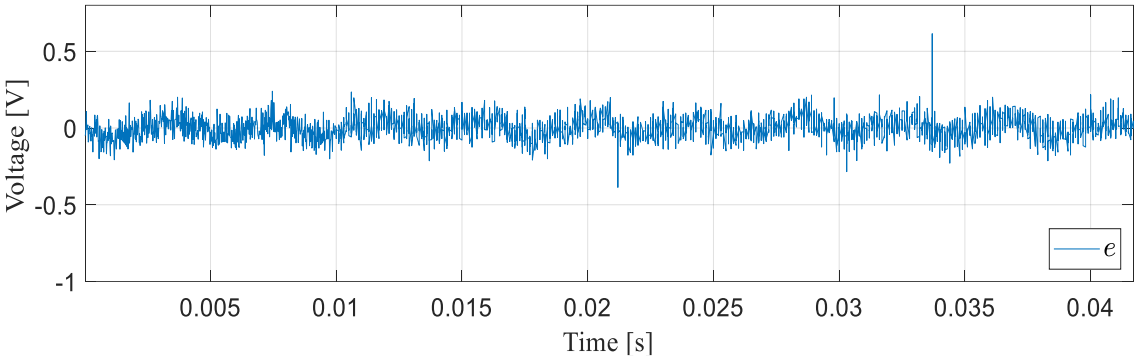

Figure 8: Capacitor voltage regulation error signal e

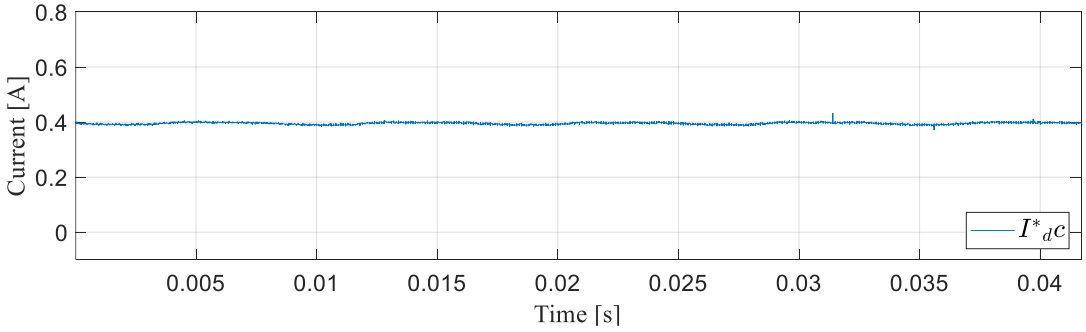

Figure 9:DC inductor reference current I_{dc}^*

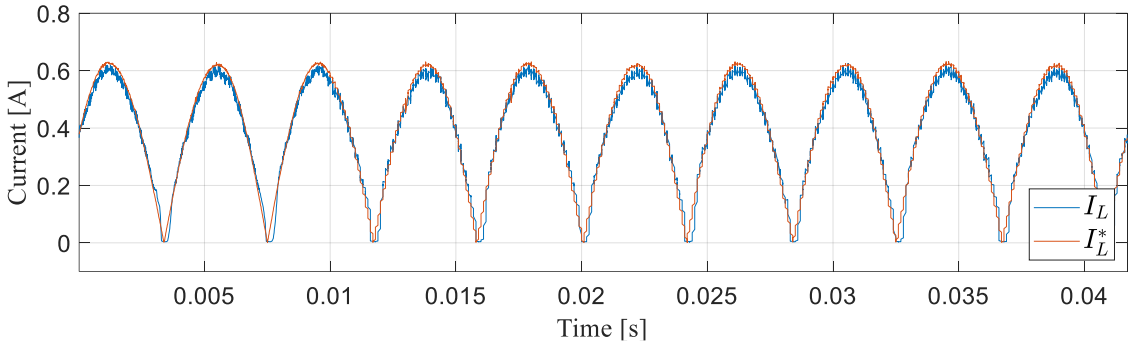

Figure 10: Convergence of the inductor current I_L to its reference current I_L^*

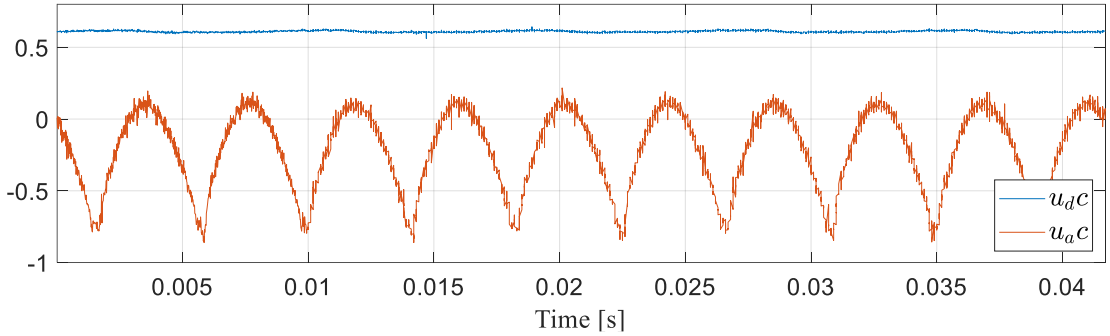

Figure 11: The ac and dc component of the controller input u

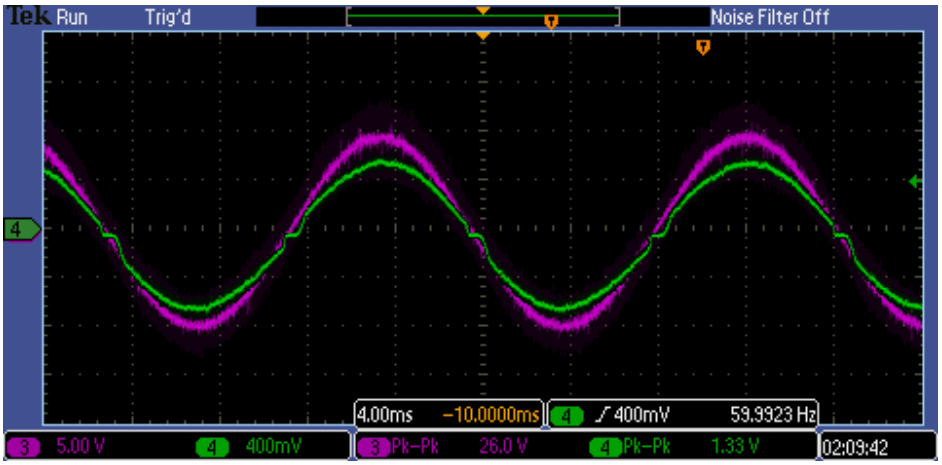

Figure 12: AC source voltage and current waveforms on oscilloscope

7. CONCLUSION

In this work, a novel controller was designed for power factor correction. The controller was developed based on Lypunov stability analysis. The input current tacking and output voltage regulation objectives were achieved simultaneously. Instead of ignoring the voltage ripple, it was considered while modeling the voltage and current control loops. For experiment, the boost converter protoboard was used with NI module and results were verified. The controller algorithm was executed in LabVIEW FPGA environment. The boost converter protoboard was modified according to the hardware requirements for power factor correction circuit. The experimental results show the convergence of error signals and power factor nearer to unity value. In future scope, the given controller design can be compared with the advanced PFC controllers and performance can be evaluated.

REFERENCES

[1] O. Garcia, J. A. Cobos, R. Prieto, P. Alou and J. Uceda, "Single phase power factor correction: a survey," in *IEEE Transactions on Power Electronics*, vol. 18, no. 3, pp. 749-755, May 2003

[2] P. R. Mohanty, A. K. Panda and D. Das, "An active PFC boost converter topology for power factor correction," *2015 Annual IEEE India Conference (INDICON)*, New Delhi, 2015, pp. 1-5

[3] A. Lazaro, A. Barrado, M. Sanz, V. Salas and E. Olias, "New Power Factor Correction AC-DC Converter with Reduced Storage Capacitor Voltage," in *IEEE Transactions on Industrial Electronics*, vol. 54, no. 1, pp. 384-397, Feb. 2007.

[4] K. S. H. Babu, R. Holde, B. K. Singh and V. S. Chippalkatti, "Power factor correction using Boost converter operating in CCM for front-end AC to DC conversion," *2018 Technologies for Smart-City Energy Security and Power (ICSESP)*, Bhubaneswar, 2018, pp. 1-6.

[5] L. Huber, Y. Jang and M. M. Jovanovic, "Performance Evaluation of Bridgeless PFC Boost Rectifiers," in *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1381-1390, May 2008

[6] A. Marcos-Pastor, E. Vidal-Idiarte, A. Cid-Pastor and L. Martínez-Salamero, "Loss-Free Resistor-Based Power Factor Correction Using a Semi-Bridgeless Boost Rectifier in Sliding-Mode Control," in *IEEE Transactions on Power Electronics*, vol. 30, no. 10, pp. 5842-5853, Oct. 2015.

[7] W. Chen, T. Wu, Y. Hsieh, C. Moo and P. Wen, "Power-Factor-Correction with Power Decoupling for AC-to-DC Converter," *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, Niigata, 2018, pp. 3544-3548

[8] S. Fan, Y. Xue and K. Zhang, "A novel active power decoupling method for single-phase photovoltaic or energy storage applications," *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, 2012, pp. 2439-2446

[9] M. Pahlevaninezhad, P. Das, G. Moschopoulos and P. Jain, "A study of nonlinear controllers for AC/DC boost PFC converters," *2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, 2013, pp. 1878-1883

[10] J. SebastiÁn, D. G. Lamar, M. M. Hernando, A. RodrÍguez-Alonso and A. FernÁndez, "Steady-State Analysis and Modeling of Power Factor Correctors With Appreciable Voltage Ripple in the Output-Voltage Feedback Loop to Achieve Fast Transient Response," in *IEEE Transactions on Power Electronics*, vol. 24, no. 11, pp. 2555-2566, Nov. 2009.

[11] A. Prodic, Jingquan Chen, D. Maksimovic and R. W. Erickson, "Self-tuning digitally controlled low-harmonic rectifier having fast dynamic response," in *IEEE Transactions on Power Electronics*, vol. 18, no. 1, pp. 420-428, Jan. 2003.

[12] A. Prodic, "Compensator Design and Stability Assessment for Fast Voltage Loops of Power Factor Correction Rectifiers," in *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1719-1730, Sept. 2007

[13] H. Youn, J. Lee, J. Baek and G. Moon, "A Digital Phase Leading Filter Current Compensation (PLFCC) Technique for CCM Boost PFC Converter to Improve PF in High Line Voltage and Light Load Conditions," in *IEEE Transactions on Power Electronics*, vol. 31, no. 9, pp. 6596-6606, Sept. 2016.

[14] M. Pahlevaninezhad, P. Das, J. Drobnik, G. Moschopoulos, P. K. Jain and A. Bakhshai, "A Nonlinear Optimal Control Approach Based on the Control-Lyapunov Function for an AC/DC Converter Used in Electric Vehicles," in *IEEE Transactions on Industrial Informatics*, vol. 8, no. 3, pp. 596-614, Aug. 2012.

[15] A. C. Kyritsis, N. P. Papanikolaou and E. C. Tatakis, "A novel Parallel Active Filter for Current Pulsation Smoothing on single stage grid-connected AC-PV modules," *2007 European Conference on Power Electronics and Applications*, Aalborg, 2007, pp. 1-10.

[16] V. M. Rao, A. K. Jain, K. K. Reddy and A. Behal, "Nonlinear Control of a Single-Phase Unity Power Factor Rectifier: Design, Analysis, and Experimental Results," in *IEEE Transactions on Control Systems Technology*, vol. 16, no. 6, pp. 1301-1307, Nov. 2008.

[17] Power Electronics user lab manual by University of Minnesota.

[18] J. Slotine and W. Li, Applied Nonlinear Control, Englewood Cliffs, NJ: Prentice Hall, 1991.

[19] D. Hart, "Power Electronics," in *DC-DC Converters*, New York, McGraw-Hill, 2011, pp. 211-214

CURRICULUM VITAE

NAME: Shruti Motilal Deore

ADDRESS: Department of Electrical and Computer Engineering

University of Louisville

Louisville, KY 40292

EDUCATION: B.Tech., Electrical Engineering,

Dr. Babasaheb Ambedkar Technological University,

2009-2013.

M.E., Power System,

Savitribai Phule Pune University,

2013-2017.