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Research Article

Hardware Implementation of Fully Controlled Bridge Rectifier with Rapid Control Prototyping Approach

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Abstract— **In industrial applications, rapid prototyping of digital controls is important in terms of time, cost, and easier design steps. Especially the complexity of different power electronic converter circuits and their necessity of providing various operating conditions make digital control inevitable. However, developing a digital control system has many unknown details. In-the-loop simulation techniques evolved to simplify this stage during the last few decades. In this paper, a fully controlled bridge rectifier is designed and implemented by using a rapid control prototyping approach; its steps are accelerated with processor-in-the-loop and hardware-in-the-loop tests. Launchpad F28379D from Texas Instruments is used as an interface between the designed rectifier hardware circuit and MATLAB/Simulink Embedded Coder platform. Additionally, a driver control board is developed to provide switching signals and analog to digital measurements. The performance of the system is experimentally tested on a developed 500W rectifier prototype with a closed loop PI controller for voltage regulation at different parametric variations, such as step response, dynamic response, different load types. Step response rise time is 25ms, while the system continues stable operation under load change from 60% to 90% in 35ms.**

Index Terms— **Bridge Rectifier, In-the-loop simulation, Power Electronics, Rapid Prototyping.**

I. INTRODUCTION

THE NEED for embedded systems is increasing and daily diversifying in the market. Each complex system includes several embedded systems used for various purposes such as power electronic converters, monitoring systems, battery management systems, and alert systems. Rectifiers, one of the common embedded systems, are employed in low, medium, and high-power applications with a wide range of voltage and current ratings. Although switch mode power supplies are being started to use attaining regulated DC output, there is still a need for efficient and high-performance rectifiers. Rectifiers with various types of configurations operate to convert AC source to DC output in [1-3]. One of the common rectifier topologies is known as conventional rectifiers or line commutated rectifiers with low switching frequency in [4]. Conventional rectifiers, which are protecting their prevalence in the industry, are used in a wide variety of applications such as uninterruptible power supplies, synchronous motor field current control, the control of low power DC motors, and battery charging. These converters assure high reliability, simplicity, and fewer switching devices in [5-7]. The average load changes in a closed loop control in [1-4]. The embedded systems must react very fast against any disturbance and guarantee stability for different operating conditions.

Regarding this, physical device implementation is expensive and not feasible without simulation studies. Various simulation techniques are improved with different configurations and can be classified into two groups: offline simulation platforms and real time simulation. In the context of real time simulation, the transition between the simulation and physical hardware has been simplified with in-the-loop simulation techniques. Classification of techniques are Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), Processor-in-the-Loop (PIL), and Hardware-in-the-Loop (HIL) in [8-10]. The plant model and controller logic are simulated in a simulation program without hardware in MIL. SIL describes the simulation of a plant model with a digital controller model, while PIL is a test approach to design the controller running in an external digital platform. HIL is a technique to test the plant or controller running in a real time simulator, interacting with a real plant or controller, so HIL became an inevitable point for the initialization of microprocessors. Furthermore, HIL is a way to bridge the gap between simulation and real systems to test real operational conditions. Also, it supports the flexible testing platform for the first implementation. During the design, testing, and assembling of digital controls for power systems and power electronics, real time simulation, especially HIL testing is accepted as an effective approach in terms of cost, time, and reliability. The difficulty in the product design of the embedded systems can be diminished by using HIL implementation.

The design approach of controllers has significantly changed over the years. As a result, the reliability of designs is enhanced, and the design cycle is shortened in [11]. Many instances of in-the-loop simulation techniques have been examined in the literature with different aspects. A test platform for T-type converter is implemented in real time simulator from OPAL-

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RT in [12]. In [13], the examination and simulation of the buck converter by using discrete time mathematical model in HIL with FPGA are presented. A power hardware-in-the-loop (PHIL) testbed for grid-connected electric vehicle (EV) charger including modelling details is implemented in [14]. A boost converter and an H-bridge inverter with their state feedback control system have been evaluated using Real Time Virtual Test Bed in [15]. The classification of important real time tools for in-the-loop testing with respect to cost, sampling rate capability, software needs, and usability is mentioned with specific examples in [16]. Similarly, the history of real-time simulators is summarized, and important features are comprehensively reported in [17]. The architecture for real-time control is introduced elaborately and a controller is designed for PIL testing of three bi-directional DC-DC converters in electric vehicles to obtain a convenient power balance in [18]. Similarly, buck converter prototype is examined based on HIL simulation [19]. Besides the applications of power electronic converter management and controller design in the literature, in-the-loop testing methods are also significant for smart grid and microgrid studies due to their complexity in [20, 21]. HIL simulation is used to test low voltage grid-integrated multilevel converter stability [22]. A grid-connected wind energy system is analyzed with HIL testing using optimized design parameters [23].

Real-time microcontroller expansion boards of different companies are utilized to implement the control platform during in-the-loop tests. Among the widespread alternatives, dSpace controllers, field programmable gate array (FPGA), and Texas Instruments C2000 series microcontrollers are well known examples. Several studies have presented the design and implementation of a control platform with in-the-loop tests using dSpace hardware in [8, 16], FPGA in [13, 15, 24, 25], and C2000 microcontrollers in [12, 18, 26, 27]. Microcontrollers can be programmed through MATLAB Simulink Embedded Coder in addition to attaining gate pulses with feedback control in [26]. As a recent application, HIL and experimental study are presented to control three phase voltage source inverters using C2000, PLECS, and RT-Box systems [28].

This paper attempts to present the contribution of in-the-loop techniques during the digital controller design by examining a single-phase full wave thyristor-controlled line commutated rectifier. The study is improved one more step and tested on real hardware. Discrete tests are also evaluated for the designed rectifier. The contributions of this paper are to design a driver control board to expand the capabilities of the launchpad and to validate the design by testing a 500W rated rectifier. The driver control board consists of circuits for measurements, gate triggering, and zero cross detection. Operational amplifiers are integrated for voltage measurements.

The rest of the paper is organized as follows. The comprehensive system architecture and its key elements are explained in Section 2. Section 3 describes the test platform configuration details. Then, Section 4 presents the experimental performance of single-phase full bridge rectifier implementation. Section 5 concludes the paper.

II. System Architecture

The system overall block diagram is given in Figure 1. A step-down transformer is integrated at the input side of the system to be able to adjust the output voltage of the rectifier circuit within the determined values. A fully controlled bridge rectifier is used for experimental validation so that the load current is continuous and ripple free. The fully controlled bridge converter consists of four thyristors of TH1, TH2, TH3, and TH4 are turned on by their gate signal and naturally turns off when a reverse voltage appears across it. In this case, the average output voltage can be determined by the following equation.

$$V_{out}^{avg} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_{max}\sin(wt)\,dwt = \frac{2V_{max}}{\pi}cos\alpha \qquad (1)$$

Capacitors are added to the output of the rectifier circuit as a filter to mitigate the output voltage ripple. A power supply board with multiple levels of voltage is utilized to supply integrated circuits on the control board, the zero-cross circuit, and the trigger circuit. The control board is designed to attain proper integration between the subcircuits of the boards. The zero cross circuit detects the points when the voltage crosses zero in either direction. The detection of the zero cross points is important to trigger the switching devices at the right time during continuous operation. The trigger circuit comprises four separate gate drive circuits for thyristors including gate pulse transformers, transistors, resistors, capacitors, and diodes. The trigger circuit converts the created PWM signals of the control board into a proper pulse signal train that can trigger the thyristors. The presented system includes an F28379D launchpad with dual core 32-bit floating-point microcontroller. The microprocessor board incorporates high-speed serial channels and uses Universal Serial Bus (USB) as an interface that is useful for interprocessor communications.

III. Test Platform Configuration

The launchpad or similar rapid prototyping systems use the same microprocessor family products as their industrial counterparts, so a prototype can be successfully developed and prepared. Furthermore, the developed software can be also integrated simply with the actual system. Coding in the program of code composer studio (CCS) generally used is harder to design and needs more time; therefore, embedded coder enables faster controller design than hand-write code. Whereas C-code at the quality of hand-written source code can be generated with less effort and at the level of an excellent programmer. Automatic generation of software code can be attained via MATLAB/Simulink Embedded Coder feature in a more practicable way.

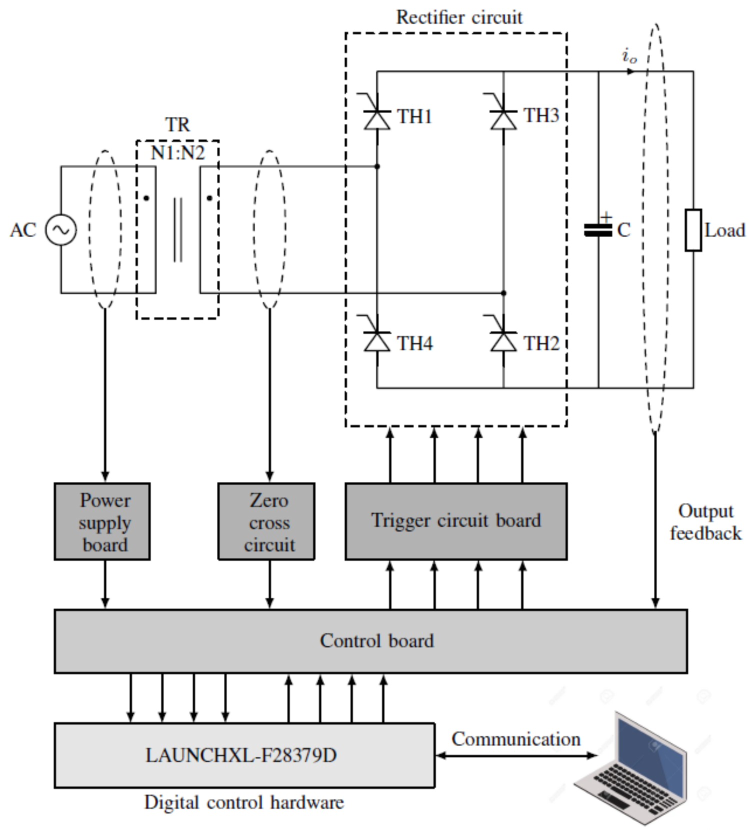


Fig. 1. System overall block diagram.

A simulation model of the controller with digital to analog signals (feedback) is created in Matlab/Simulink and then "Generator of production code (Hardware) Embedded Coder Support Package for TI 2000" is used for generating C-code and real time test with parameter tuning feature. The application of embedded coder includes initialization of target, I/O settings for target, the configurations of analog to digital converter (ADC), enhanced pulse width modulator (ePWM), and general-purpose input/output (GPIO) blocks, etc. Thanks to this method, minimum integration time and cost can be achievable in serial production. The graphical programming language of MATLAB helps to obtain simpler development even for complex systems. The time for programming and control design is reduced because the code is generated automatically. The following subsections deal with the peripheral requirements for the microprocessor.

A. ADC Configuration

Four independent ADC modules with the resolutions of 16-bit differential or 12-bit single-ended can be configured to sample analog pins and convert them to digital data. The value of output voltage and current feedback, detection of zero crosses, and the determination of phase quantities are determined by configured ADC pins. The output data type is selected as uint16 and the gain, offset, linearity of the data, and the conversion of the data to the measured units are set by using ADC calibration routines and limited between the saturation ranges. The scheme of the ADC configuration is shown in Figure 2.

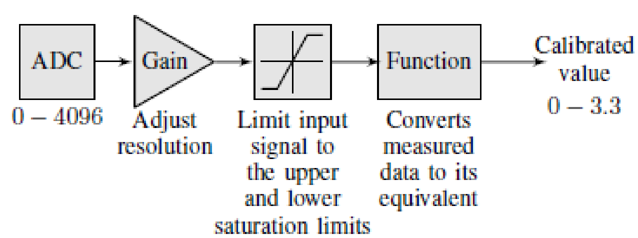


Fig. 2. The scheme of the ADC configuration.

B. ePWM Configuration

Pulse width modulation (PWM) is a prevalent technique that produces variable width pulses to adjust the amplitude of the feedback signal. The F28379D microprocessor has 16 ePWM modules with two outputs, being able to generate PWM waveforms with various adjustable functionalities. Three modules are configured with up-down count mode and dual edge symmetric waveform properties in the proposed system. Module output frequency is computed according to the following equation.

$$f_{PWM} = \frac{ePWM\ clock\ frequency}{2\ x\ TBCLK\ prescaler\ x\ timer\ period} \quad (2)$$

Where TBCLK is the time base clock. ePWM clock frequency is defined as 100MHz for each module. The first module is activated with an on/off switch which is connected to GPIO122 as the trip zone source, and it is used to control the gate signals compatible with zero cross signal. *TBCLK prescaler divider* is 16 and the timer period is 62,500 for the module to attain a 50*Hz* signal, the grid frequency. The counter compare parameters of the block are specified to adjust pulse widths according to output voltage feedback. The remaining two modules are used to trigger the thyristors in pairs. In that case, the *TBCLK prescaler divider* is 1 and the timer period is 50,000 for the frequency of 1*kHz* signals, the switching frequency.

C. GPIO Configuration

The GPIO peripheral configures the general-purpose input/output pins to control and detect the interaction with other components. The state of the input can be detected by reading the state of an internal register when configured as an input. Otherwise, it can be written to an internal register to control the state driven on the output pin when configured as an output. On-off control of the system and the protections are connected via GPIOs in the presented system.

D. Controller Design

The system must manage constant output voltage, current, and reliable operation in terms of sudden load variations according to requirements. Therefore, a control system must be integrated to satisfy the expected goals despite different operating conditions and disturbances. Throughout the controller development process, the model can move through MIL, SIL, PIL, and HIL testing stages.

In real run-time, the model is divided into two separate parts, the plant model and the controller for the *HIL* stage. The plant model is removed and generated code on the target is attached to the physical hardware during prototyping tests. At the *HIL* stage, physical hardware is connected to the Simulink environment in external mode to operate simultaneously, collect data in each step of the simulation, and tune the controller parameters. Then, the system can be analyzed and tested when whole parts are set up as hardware.

A proportional-integral (PI) controller is implemented to achieve robust output voltage despite parametric variations due to its easy implementation and fast response. The control is carried out by changing the firing angle of thyristors. The control structure is given in Figure 3. PI controller block is used after the comparison of measured output value with reference. The output of the controller block is used in the angle calculation function with the reference of measured input voltage determined zero crosses. The output of the function is proper to activate the thyristor trigger circuit. The plant transfer function is implemented in in-the-loop simulation stages before the prototype. The values of output voltage and output current are measured with the routine of ADC configuration.

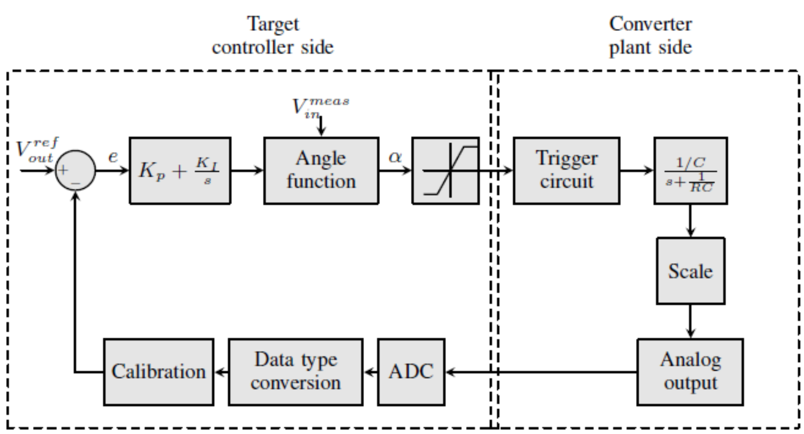


Fig. 3. Control structure.

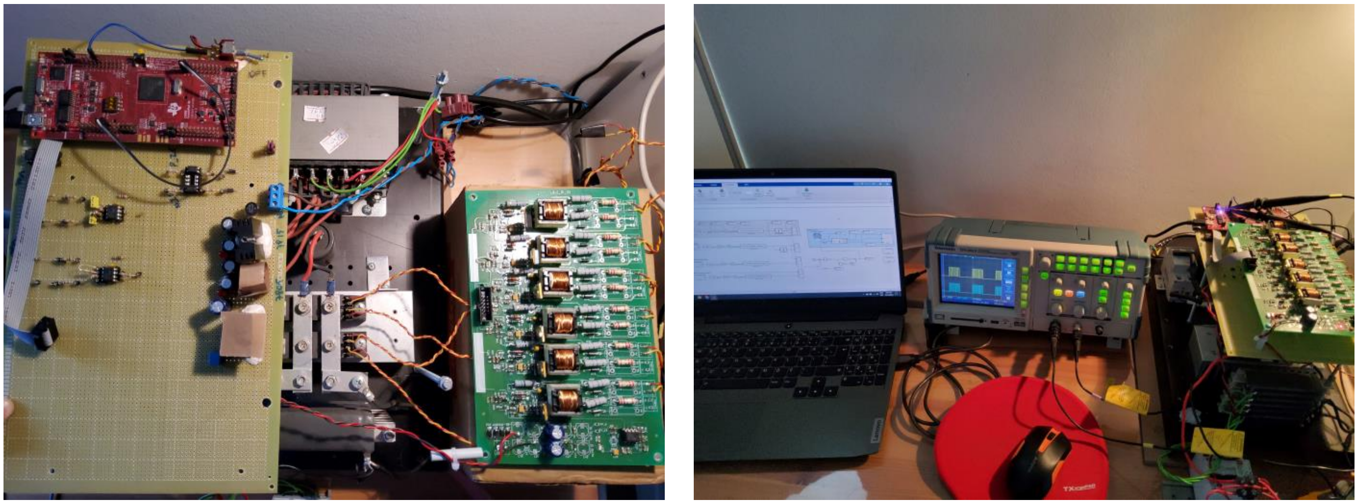
The same controller is tested in the system and directly implemented as final hardware, so the development time of the converter is improved. The interface algorithm determines how the signals are exchanged between simulation platform and physical system. The PIL and HIL simulations eliminated several iterations of pre-prototype hardware.

IV. Experimental Results

The validation of the proposed system is tested with a 500W power rated rectifier prototype with its peripheral circuits at various load levels. The experimental setup is given in Figure 4a and Figure 4b. Additionally, the specifications of the prototype are presented in Table I.

TABLE I
SYSTEM SPECIFICATIONS

Parameters	Values
Rated input voltage	$220V_{ac}$
Input voltage frequency	50Hz
Rated output voltage	$48V_{dc}$
Output power	500W
Input transformer ratings	220V/60V 1kW 50Hz
Output filter capacitance	2 x 470uF $100V_{dc}$
Thyristor modules	MCC44−12io1B
Switching frequency	1kHz



(a) Designed electronic cards and components detailed view. (b) Overall system.

Fig. 4. Experimental setup.

The system rated voltage is 220V$_{ac}$ with +/ − 10% range, while the output rated voltage is adjusted to 48Vdc. Figure 4a shows the designed electronic cards of the power supply board, control board, trigger circuit board, and launchpad besides the thyristor block and input transformer on the heat sink. Figure 4a presents the proposed system with whole components of complete experimental system, laptop communication, and oscilloscope connection. The setup is tested with a load of six parallel connected 25 Ω resistance groups.

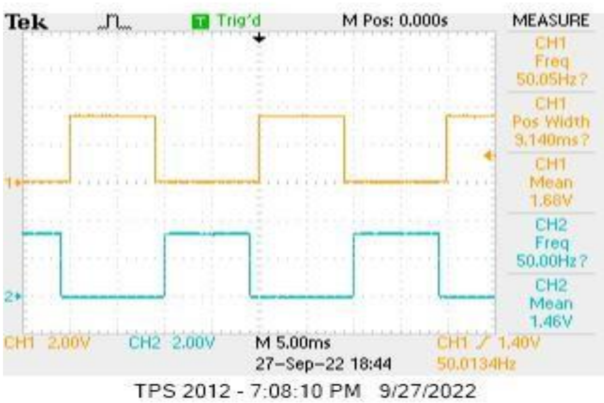


Fig. 5. EPWM1 block outputs in open loop operation.

Three of the existing sixteen pulse width modulation modules of the launchpad were configured to trigger four thyristors according to zero cross references in the proposed system. The first module was configured with respect to zero cross signal, while the others were configured by using the first module signal as a trip zone source for thyristors switching. EPWM1 outputs given in Figure 5 show the 50Hz frequency PWM outputs that are synchronized with zero crosses, and the signals are attained in the open loop operation with the full cycle switching process. Figure 6 shows channel A of EPWM1 and channel A of EPWM2 triggered by channel A of EPWM1 for zero cross and switching signal adaptation during full cycle switching case. Figure 7 shows channel A of EPWM1 and channel A of EPWM3 triggered by channel B of EPWM1 during full cycle switching operation. Channel B of EPWM2 and EPWM3 are the same as channel A to trigger thyristor pairs. The channel A outputs of EPWM2 and EPWM3 in closed loop operation with 50% load is given in Figure 8.

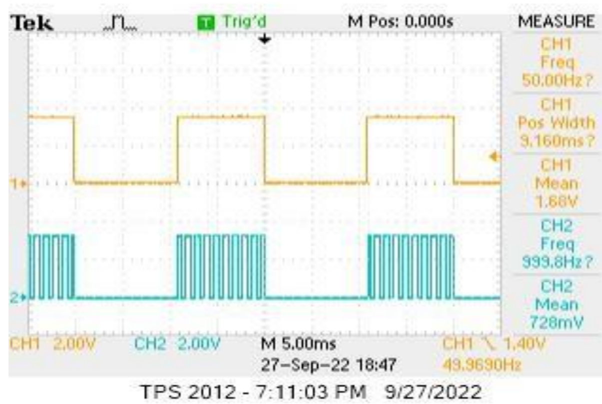


Fig. 6. Channel A outputs of EPWM1 and EPWM2 in open loop operation.

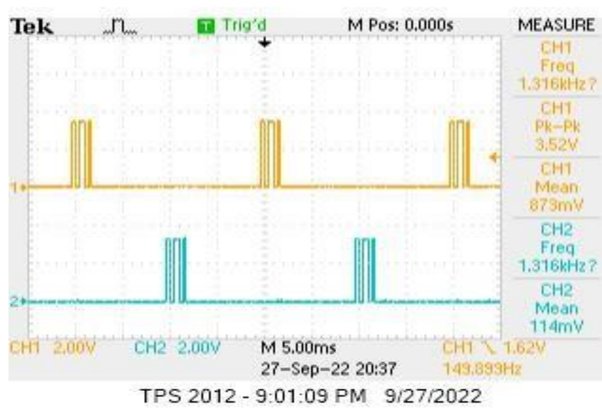


Fig. 7. Channel A outputs of EPWM1 and EPWM3 in open loop operation.

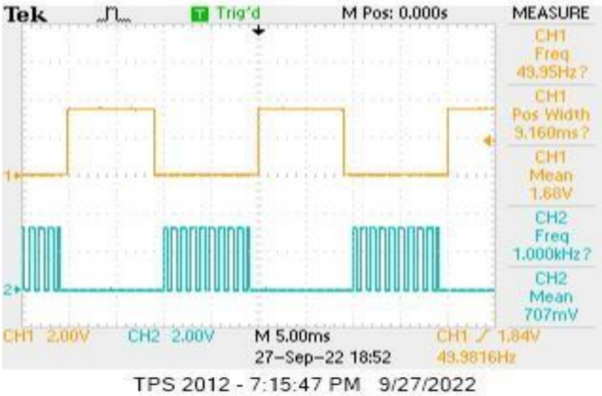


Fig. 8. Channel A outputs of EPWM2 and EPWM3 in closed loop operation with 50% load.

The operation of experimental setup is improved with additional features for reliable operation. Therefore, one of the general-purpose input/output pins, GPIO122 is configured as an input to turn on/off the rectifier circuit by controlling the PWM signals manually with a switch or remotely with software codes. When on command has activated, the PWM signals are initialized within 20ms. The initialization of the PWM channels with ON signal is shown in Figure 9. In addition, some protections such as over temperature and output short circuits are reserved with a similar method.

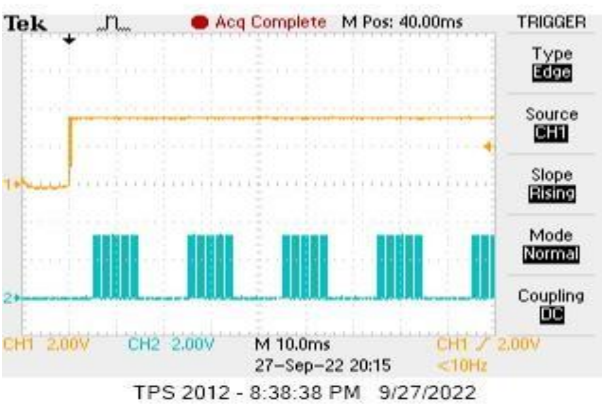


Fig. 9. PWM initialization with on command.

Figure 10 shows the step response of the closed loop control at 10% load level when the controller gains K_p and K_i are tuned as 3 and 300, respectively. The controller parameters are determined with the help of PIL and HIL simulations and the gains that show the best performance in the step response and load regulation is defined as the prototype controller gains. The settling time of the system is around 25ms and there is no oscillation in the step response performance.

The system is tested and evaluated with inductive load at maximum load level. The load has a resistance of 12.5Ω and the inductance of 160uH. The output voltage waveform with RL load is given in Figure 11.

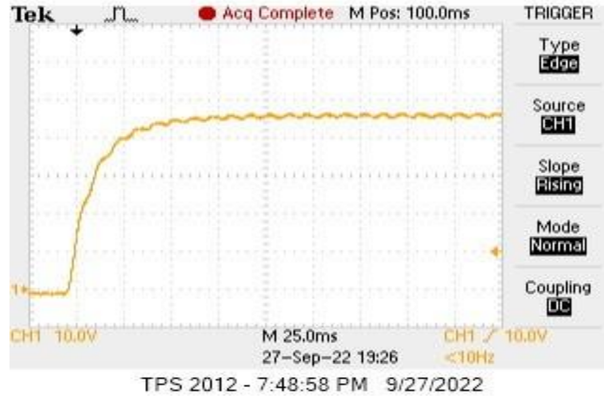


Fig. 10. Step response of the closed-loop control.

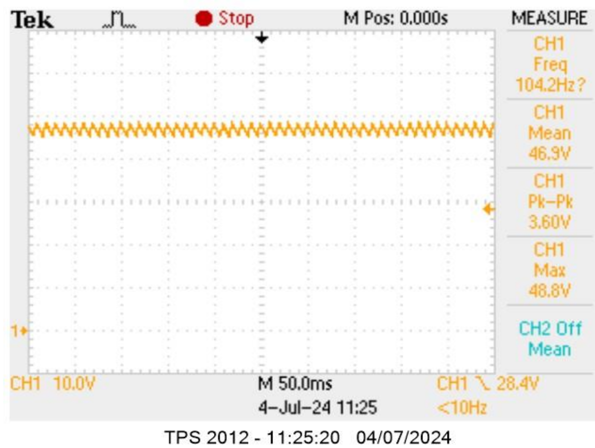


Fig. 11. The output voltage waveform with RL load at full load.

The dynamic response of the designed rectifier is also investigated for further analysis. Figure 12 shows the dynamic response of the designed converter when output load changes from 60% to 90% load level. The output voltage remains constant against output load increment. The ripple voltage value is 2.6V.

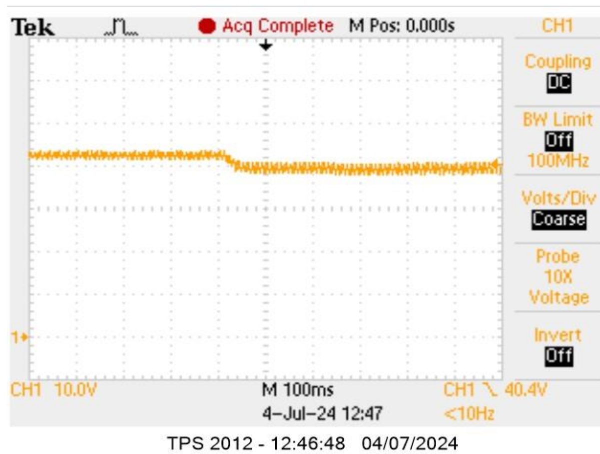


Fig. 12. Output voltage under dynamic changes from 60% to 90% load increase.

V. Conclusion

The difficulties in the design process steps, the lack of time, the risk of damage, and cost concerns cause the new developments through the way to real hardware. The approach of developing digital controls for power electronics has been described in this paper. The proposed test platform for rapid prototyping of a single-phase conventional rectifier is examined. Finally, the validated test results were employed to analyze the performance of a conventional rectifier. The experimental results were presented to confirm the system and controller performance. The performance of the system was experimentally tested on a developed 500W rectifier prototype with a closed loop PI controller. The step response of the output voltage was examined, and the rise time of the response was obtained as 25ms. The prototype was tested with resistive and inductive load. Both load types presented stable operation. Finally, the dynamic performance was investigated under load change from 60% to 90%.

This paper presents an open road map for academic studies and industry. The system can be used in lectures to explain the principles of power electronic converters, and it could be possible to teach the learning outcomes also as online because the importance of online supported studies arose during the pandemic period.

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BIOGRAPHY

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