APPLICATION OF DSPACE FOR ANALYZING DIFFERENT CONVERTERS

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY

IN

[CONTROL AND INSTRUMENTATION]

Submitted by:

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CANDIDATE'S DECLARATION

I, (Akshat Jain), Roll No. 2K16/C&I/02 of M. Tech (Control & Instrumentation), hereby declare that the project Dissertation titled "Application of dSPACE for analyzing different converters" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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<u>CERTIFICATE</u>

I hereby certify that the Project Dissertation titled "Application of dSPACE for analyzing different converters" by [Akshat Jain], Roll No. 2K16/C&I/02 [Department of Electrical Engineering], Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

This report emphasizes on operation of dSPACE DS1104 R&D Controller Board, understanding some of the functions that it can perform and further analyzing these functions for some specific purpose. Here, the work has been done on this kit by successfully interfacing it with MATLAB Simulink. After completion of interfacing, some of its application using MATLAB Simulink like Digital Output, Digital Input, DAC Output, ADC Input and PWM waveforms would be studied. This report will also summarize how dSPACE DS1104 R&D Controller Board is better than other PWM signal sources.

Once the PWM patterns are obtained, these would be used as an application to power electronics for designing and analyzing different converters like Choppers and Inverters. These convertors would operate in open loop as well as closed loop. dSPACE facilitates the user with real time simulation using which the user can vary the parameters while programs is running and observe the real time changes in parameters, this function of dSPACE will also be utilized. PWM output of dSPACE can be used to control the switching of the MOSFET used as switch in the circuits.

Earlier TMS320F2812 DSP trainer kit was used for triggering switch. There were some cons in using it which was overcome by using dSPACE. This report will also present a comparative study of TMS320F2812 DSP trainer kit and dSPACE RS1104 controller board.

These convertors will not only be designed and analyzed in MATLAB but would also

be realized physically on general purpose PCB and breadboards. Hardware implementation and its troubleshooting is generally a rigorous and tedious process. This work will include hardware implementation of different converters and the challenges faced while its implementation and troubleshooting. Best possible results of those hardware circuits would be obtained and will also be enclosed in this report.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS AND SYMBOLS

V_o	Mean output voltage
T	Total time period of cycle
T_{on}	ON time of switch
T_{off}	OFF time of switch
V_s	Source voltage
V_{ref}	Reference voltage
D	Duty cycle
%D	Percentage duty cycle
I_o	Mean output current
R	Load resistance
L	Load inductance
E	Load EMF
V_{min}	Minimum output voltage
V_{max}	Maximum output voltage
I_{min}	Minimum output current
I_{max}	Maximum output current
$I_o(s)$	Output current in s-domain
$I_o(t)$	Output current in t-domain
$I_o(0)$	Initially stored current in inductor
MI	Modulation Index
V_m	Voltage amplitude of modulating signal
V_c	Voltage amplitude of carrier signal
V_{or}	RMS output voltage of single phase inverter
V_{or}^{*}	RMS output voltage of single phase SPWM inverter
V_{orll}	RMS line-line output voltage of 3-phase inverter
V_{orll}^{*}	RMS line-line output voltage of 3-phase SPWM inverter
V_{orph}	RMS phase output voltage of 3-phase inverter
d	Duration of pulse
%e	Percentage error

CHAPTER 1
INTRODUCTION

Switch is one of the most basic components of any electrical or electronic circuit. Switch is a device that is being used by each and every individual of the world in one way or other. Even an illiterate person also knows what a switch is and what may be the purpose of using that switch. If the use of switch is considered, it is used in the most basic gadget as well as in the biggest plants and setup.

A switch was considered a device which can only make or break the circuit. What other wonders it can do no one knew until it came into the hands of an engineer. With the development of electronic switches (like MOSFET, IGBT, etc.), there came a revolution in the research. Electronic switches were designed basically to obtain faster switching operation. These electronic switches with higher voltage and current operation formed the basis of power electronics. Today, a lot of research is going on in power electronics which only focuses on use of these switches in different configurations which can further give different applications. There are various DC – DC Converters, DC – AC Converters, AC – AC Converters and AC – AC converters that are already designed using these electronic switches and further researches are on the progress.

These switches require some triggering pulses to change their state of operation. These triggering pulses can be obtained from different triggering mediums like from a function generator, 555 timer IC operated in astable mode, microcontroller output or any other means. All of the above mentioned triggering mediums run on the principle of Digital Signal Processing (DSP), directly or indirectly. Digital Signal Processing is used in triggering of these switches because it provides flexibility to user to modulate amplitude, time, frequency, phase and space as per the user requirement. Because of the wide application of DSP, it is majorly used in triggering of these switches in various converters.

1.1   DIGITAL SIGNAL PROCESSING – AID TO POWER ELECTRONICS

Digital Signal Processing (DSP) has entangled its root in almost all parts of world. It has become an integral part of various developments across the world. In earlier practice there were a lot of switching schemes for switching of fast devices. Lot of commutations was implemented in those switching schemes. These switching schemes can be made much easier by using the applications of Digital Signal Processing. Implementation of Digital Signal Processing is coming with a great boom in the market and is slowly replacing the conventional switching schemes of power devices.

Digital Signal Processing (DSP) has opened wide scopes of research in various fields. Presently, Digital Signal Processing (DSP) and Power Electronics (PE) are one of the most searched topics by the researchers. Apart from doing research in Digital Signal Processing, there are various fields that use DSP as an application to it. In almost all fields of research, DSP applications are used as an integral part either directly or indirectly.

As the demand of DSP applications is high, accordingly adequate supply of the same should be there to stand by those demands. In order to discharge those demands, there are various DSP sources available in the market by various companies. Today, most of the sectors use DSP as an application like defence, manufacturing, production, DC power grid, operations of motors, automation of robots and various other applications. Use of DSP sources has eased the work of researcher by providing with the practical exposure to the DSP signals and using them further for some significant purposes. Any of the DSP sources can be chosen from the market depending upon the requirement of researcher.

These DSP triggering mediums come with a simulator which is provided by the manufacturing company to allow the user to design the programs through it and dump them in the kit for getting output as per the requirement. Operation of these simulators is generally tedious and difficult for everyone to understand. So, for better understanding and operation of using the default simulator, if one is able to interface it through MATLAB or MATLAB Simulink, it would become quite convenient to be programmed and operate. This project includes the interfacing of MATLAB Simulink with dSPACE DS1104 R&D Controller Board, analyzing its applications and further using these applications for the switching of different converters.

1.2 AIM

This project aims in designing and implementing various DC-DC Converters and DC-AC Converters using dSPACE and implement various control strategies on these converters. These converters will also be implemented on hardware by soldering it on a general purpose PCB. Some of the converters that will be designed and implemented using dSPACE are listed below:

- Open loop and closed loop operation of Class-A DC-DC Chopper
- Open loop single phase Inverter
- Open loop 3-phase Inverter

1.3 OBJECTIVE

In order to accomplish any aim within certain time limits, it is mandatory to lay down a set of objectives. These objectives formulate the steps to achieve that aim. Objectives for this project are:

- Investigate the problems occurred because of other DSP sources like microcontroller and DSP kit.
- Study the research work done in the field of DC-DC Converters, DC-AC Converters and dSPACE.
- Congregate the expert advice on the feasibility of this work.
- Designing of schematic models of various converters using different control strategies on MATLAB Simulink.
- Troubleshooting the errors in simulation.
- Implementing the converter on hardware using breadboard
- Testing the breadboard circuit in laboratory using dSPACE.
- Troubleshooting the hardware running issues.
- Designing the final hardware circuit by soldering it on general purpose PCB and then testing it.
- Selection and tuning of the controller for the practical use with different loading conditions.
- Finally, operating the circuit in closed loop if required.

1.4   REPORT LAYOUT

This report will cover work on DC-DC Converters and DC-AC Converters and analyzing the hardware circuit using dSPACE as the triggering medium. DC-DC Converters that are discussed in this report are Open Loop Class-A Chopper, Closed Loop Class-A Chopper and Open Loop Class-B Chopper. DC-AC Converters that are used here are Open Loop Single Phase SPWM Inverter and Open Loop 3-Phase SPWM Converter. Chapters are divided on the following basis.

- Chapter 1 covers the Introduction to the report.
- Chapter 2 covers the Literature Review of the study material that has been referred during the course of work.
- Chapter 3 shows the Mathematical Modeling of Converters
- Chapter 4 explains about dSPACE and its interfacing with MATLAB Simulink
- Chapter 5 covers the system design and implementation including designing of circuits in Simulink and on Hardware as well.
- Chapter 6 encloses the Results and Discussions chapter that focuses on the results obtained and the error calculations made.
- Chapter 7 is the Conclusion and Future Work where all the work done is been concluded and the future scope of this work is presented.

CHAPTER 2
LITERATURE REVIEW

Digital Signal Processing is not just a topic but it is a technique that has opened various research fields across the world. It serves as a vital application in almost all sectors like defense, automation, process control, manufacturing, production and many other fields. For its use in real world some DSP processors or DSP generating sources are required. For this dissertation, dSPACE is mainly used as a DSP application.

When talked about dSPACE, it is a system that converts a computer to a development system which can be used for fast control prototyping. It is a cost effective entry structure that has a real time processor facilitating the user to interface computer with the real world circuits and further obtain the outputs on ControlDesk software. dSPACE finds its application by providing a best solution in developing controllers for various fields like automation, drive control, aerospace etc. It is completely programmed from MATLAB Simulink making it easier for operation and analysis. There are a lot of researches that are done using dSPACE some of them are discussed here. According to Yang Shu, Hui Li and Qian Wu in 20008, dSPACE has the characteristics of favorable scalability, high reliability and has a powerful software. dSPACE is now the first choice for fast control prototyping corroboration and HIL simulation. It not only meets accuracy and reliability, but it also provides an effective way to shorten the project development cycle and diminish the cost [32].According to paper published by C. Lapusun and group in 2008, Rapid control prototyping is a technique, where a computer or some real time board momentarily replaces the actual controller and provides a way to swiftly test algorithms during the course of development. If there exist problems with a control algorithm while using a rapid control prototype, designers can instantly modify their code and get the results. Rapid control prototyping is time saving because the designers don't have to wait for complete

prototype of the final controller prior of testing one's control algorithms [9]. In year 2010, Tao He and Luntian Peng analyzed neural based PID using dSPACE [28].

There are many researches that are done on DC choppers and their closed loop control. In year 1980, Takahiko Iida and group used thyristor switched DC chopper for DC motor control [29]. In 2004, ripple analysis of DC converters was done by Mihajlovic Zoric, Brad Lehman and Chunxiao Sun and they aimed to reduce the ripples in output of a DC-DC chopper [33]. In year 2007, Huangsheng Xu, Kevin King and Yashwant Jani analyzed DC chopper for speed and current control of universal motors programming it with microcontroller [16]. In 2012, Anupam Agarwal modeled a DC chopper in order to minimize the voltage ripple in the output and he was successfully able to analyze it [1]. Then later in 2014, Shun Takeuchi and Keiji Wada implemented current control technique for the operation of closed loop DC chopper [27]. In 2016, M. Sahana, Sachin Angadi and A.B. Raju used Class-A chopper for controlling the speed of separately excited DC motor by controlling the armature voltage of DC motor in closed loop [21]. Then in year 2017, Yifan Lang, Xin Ge, Runan Gu and Yuanyuan Zhang implemented the closed loop buck chopper with better refined outputs by triggering it again by using microcontroller 8052 [31].

In inverters, lots of researches are carried out for the development of non-conventional energy sources, mainly Solar energy based electrical energy. In these applications Inverter plays a vital role. In year 2008, Guoqiao Shen, Dehong Xu, Luping Cao and Xuancai Zhu designed a better control strategy for voltage source inverters that are grid connected using an LCL filter by controlling current in closed loop [15]. In 2010, Hongbin Wu, Hui Sun, Liang Cai and Xiaofeng Tao designed a simulation on different control strategies for grid connected inverters. In year 2011, Dolly Renny published her work about the modeling and simulation of Space Vector PWM Inverter [10]. Then in 2014, Arti Gadekar and V.B. Virulkar used dSPACE for effective control of Inverter that can be used for PhotoVoltaic application [2]. In year 2016, Shilpi Bhattacharya and Ashok Mondal implemented a SPWM inverter using dSPACE which can be used for PhotoVoltaic applications [26].

All these literatures referred in this chapter were helpful in understanding the basics and the various researches carried out on DC-DC Converters and DC-AC Converters which further helped in the development of report and dissertation work.

CHAPTER 3
MODELING OF CONVERTERS

Whenever a circuit is designed, it uses different components like resistor, inductor, capacitor etc. values of which are necessary to be calculated for the exact analysis of circuit. Moreover, mathematical modeling is also helpful in designing of any circuit. This chapter covers the mathematical modeling of the converters realized in this report.

3.1   MATHEMATICAL MODELLING OF CHOPPER

Mathematical modeling of chopper includes the calculation of duty cycle, calculating output voltage and calculating load parameters.

(a)   (b)
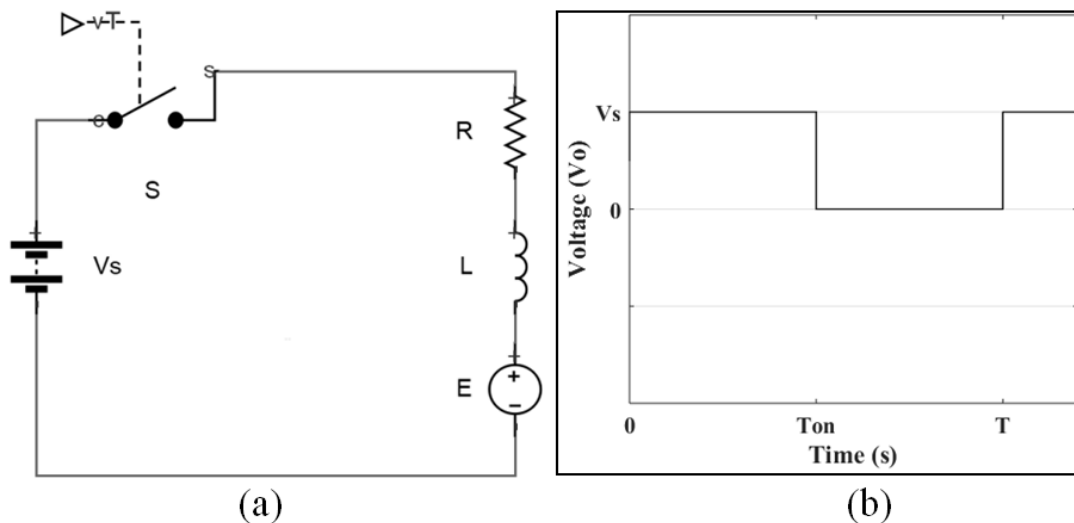
Figure 3.1: Modelling of Chopper:-(a) Model diagram of Chopper; (b) Model Output Waveform of Chopper

Circuit shown in fig 3.1(a) shows the model circuit of Chopper and its possible output waveform is shown in fig 3.1(b). As waveform in fig 3.1(b) is a DC voltage waveform so output voltage will be mean of above waveform.

$$V_o = \frac{1}{T}\int_0^{T_{on}} V_s dt \tag{3.1}$$

$$V_o = \frac{V_s}{T} \times [t]_0^{T_{on}} \tag{3.2}$$

$$V_o = V_s \times \frac{T_{on}}{T} \tag{3.3}$$

$$V_o = V_s \times D \tag{3.4}$$

$$\%D = D \times 100 \tag{3.5}$$

From equation 3.4, duty cycle can be calculated for different output voltages. For this report V_s is kept at 30V. For example if duty cycle for 15V output voltage is to be calculated, then

$$15 = 30 \times D$$

$$D = 0.5$$

From equation 3.5,

$$\%D = 50\%$$

Similarly duty cycle for different output voltage is calculated and tabulated below.

Table 3.1: Table showing the Different Duty Cycle at Different Voltage

Sr No.	V_s (in Volts)	V_o (in Volts)	D	%D (in %)
1.	30	5	0.1667	16.67
2.	30	10	0.3333	33.33
3.	30	15	0.5000	50.00
4.	30	20	0.6667	66.67
5.	30	25	0.8333	83.33

To calculate the load parameters, Kirchhoff's mesh analysis is applied on circuit shown in fig 3.1(a) and the mesh analysis equation is

$$V_s - I_o R - L \frac{dI_o}{dt} - E = 0 \tag{3.6}$$

Taking Laplace transform of equation 3.6,

$$\frac{V_s}{s} - RI_o(s) - L[sI_o(s) - I_o(0)] - \frac{E}{s} = 0 \tag{3.7}$$

When switch S is closed at t = 0, initial current $I_o(0) = I_{min}$,

$$I_o(s) = \frac{V_s - E}{Ls\left(s + \frac{R}{L}\right)} + \frac{I_{min}}{\left(s + \frac{R}{L}\right)} \tag{3.8}$$

Taking inverse Laplace Transform of equation 3.8,

$$I_o(t) = \frac{(V_s - E)}{R}\left[1 - e^{-\left(\frac{R}{L}\right)T}\right] + I_{min}e^{-\left(\frac{R}{L}\right)T} \tag{3.9}$$

From equation 3.3 and equation 3.4, it is found that

$$D = \frac{T_{on}}{T} \tag{3.10}$$

$$T_{on} = DT \tag{3.11}$$

$$T_{on} = D\left(T_{on} + T_{off}\right) \tag{3.12}$$

$$T_{off} = (1 - D)T \tag{3.13}$$

When switch S is switched OFF, $I_o(0) = I_{max}$ and $V_s = 0$, now using equation 3.8

$$I_o(s) = \frac{I_{max}}{\left(s + \frac{R}{L}\right)} - \frac{E}{Ls\left(s + \frac{R}{L}\right)} \tag{3.14}$$

Taking inverse Laplace Transform of equation 3.14,

$$I_o(t) = I_{max} e^{-\left(\frac{R}{L}\right)T} - \frac{E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)T}\right] \tag{3.15}$$

At $T = T_{on}$, $I_o(t) = I_{max}$, using equation 3.9 and equation 3.11

$$I_{max} = \frac{(V_s - E)}{R}\left[1 - e^{-\left(\frac{R}{L}\right)DT}\right] + I_{min} e^{-\left(\frac{R}{L}\right)DT} \tag{3.16}$$

At $T = T_{off}$, $I_o(t) = I_{min}$, using equation 3.15 and equation 3.13

$$I_{min} = I_{max} e^{-\left(\frac{R}{L}\right)(1-D)T} - \frac{E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)(1-D)T}\right] \tag{3.17}$$

On solving equation 3.16 and equation 3.17

$$I_{max} = \frac{V_s}{R}\left[\frac{1 - e^{-\left(\frac{R}{L}\right)DT}}{1 - e^{-\left(\frac{R}{L}\right)T}}\right] - \frac{E}{R} \tag{3.18}$$

$$I_{min} = \frac{V_s}{R}\left[\frac{e^{\left(\frac{R}{L}\right)DT} - 1}{e^{\left(\frac{R}{L}\right)T} - 1}\right] - \frac{E}{R} \tag{3.19}$$

Therefore output mean current I_o will be

$$I_o = I_{min} + \frac{(I_{max} - I_{min})}{D} \tag{3.20}$$

Using equation 3.20, 3.19 and 3.18, one can calculate the Load parameters. For this calculation of load parameters some of the parameters will be assume and other parameters will be calculated. These equations are valid for the calculation of load parameters for choppers as well as inverters.

3.2 MATHEMATICAL MODELLING OF INVERTER

For the analysis of single phase inverter RMS output voltage and for three phase inverter RMS value of line to line output voltage and phase voltage is to be calculated. Load parameters can be calculated by the equation 3.18, 3.19 and 3.20. In this report SPWM inverters are realized. In SPWM inverters modulating signal is sine wave and carrier signal is a high frequency triangular wave. So, output is the product of Modulation Index (MI) and Output Voltage.

MI should be approximately 0.9 for better performance of SPWM converters.

$$MI = \frac{V_m}{V_c} \qquad (3.21)$$

So magnitude of V_m would be known to the user and magnitude of V_c can be calculated from it easily.
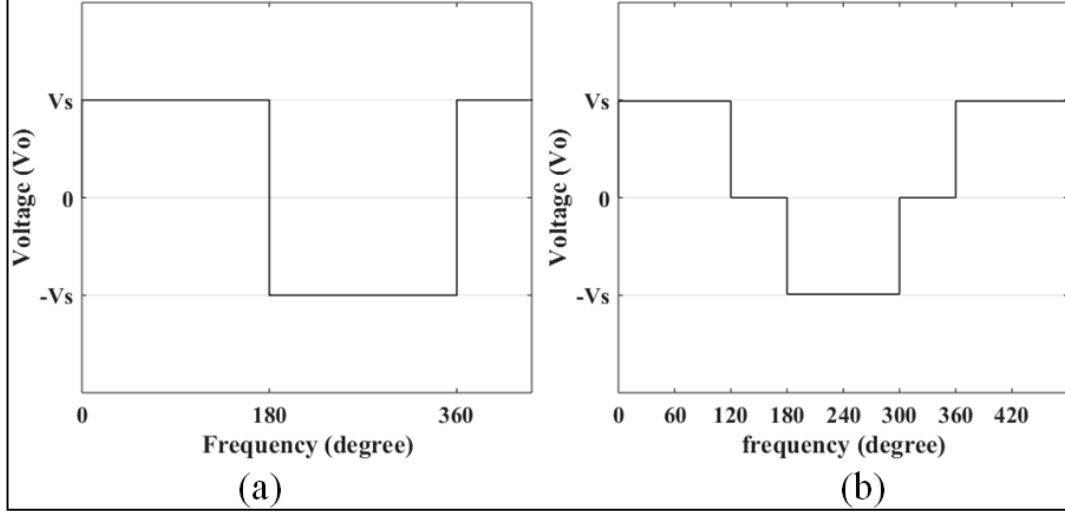
Figure 3.2: Model Waveform of Inverter:- (a) Model Waveform of Single Phase Inverter; (b) Model Waveform of Three Phase Inverter

Fig 3.2(a) shows the waveform of a single phase inverter.

$$V_{or} = \sqrt{\frac{1}{\pi} \int_0^\pi V_s^2 dt} \qquad (3.22)$$

$$V_{or} = \frac{V_s}{\sqrt{\pi}} \times \sqrt{[t]_0^\pi} \qquad (3.23)$$

$$V_{or} = V_s$$

For the SPWM single phase inverter,

$$V_{or}^* = MI \times V_s \qquad (3.24)$$

Fig 3.2(b) shows the line-line output voltage waveform of a three phase inverter.

$$V_{orll} = V_s\sqrt{\frac{d}{\pi}} \qquad (3.25)$$

Here, d = 2π/3 as shown in the waveform so on substituting the equation is

$$V_{orll} = V_s\sqrt{\frac{2}{3}} \qquad (3.26)$$

RMS value of phase voltage is

$$V_{orph} = \frac{V_s}{\sqrt{3}} \times \sqrt{\frac{2}{3}} = \frac{V_s\sqrt{2}}{3} \qquad (3.27)$$

For the SPWM three phase inverter,

$$V_{orll}^* = MI \times V_{orll} \qquad (3.28)$$

CHAPTER 4
DSPACE – INTERFACING AND FUNCTIONING

Electronic switches like MOSFET, IGBT, Thyristor, GTOs or power BJT require some external triggering for switching. This triggering is generally given through some triggering pulses. These triggering pulses can be taken from any fuction generator, Timer IC 555 (when operated in astable mode), any DSP IC, any DSP kit, FPGA or dSPACE. Now the thing which is common in all of the above mentioned pulse sources, is DSP (Digital Signal Processing). DSP serves as an application directly or indirectly to each of the sources mentioned above.

4.1   DIGITAL SIGNAL PROCESSING

Digital signal processing (DSP) is a process that includes analysis and modification of a signal in order to optimize its performance or improve its efficiency. It targets to produce a signal that is of higher quality than the original signal by applying diverse mathematical and computational algorithms to analog and digital signals. The digital signal process takes analog signals like audio, voice, video, temperature or pressure from real world through any analog to digital converter or any software compiler as DSP works on digital signals only and then finally it manipulates them mathematically. DSP is principally used to detect errors in analog signals and to filter and compress them.

For the operation of the converters analyzed during this course work, any of the above mentioned DSP applications can be used. During the time span of this work, TM320F2812 DSP Trainer Kit and dSPACE DS1104 Controller Board both are used as a triggering medium. Primarily, TMS320F2812 DSP trainer kit was used but it was not fulfilling all the criteria, so later on dSPACE DS1104 Controller Board was used for the system analysis and design.

4.2   TMS320F2812 DSP TRAINER KIT

TMS320F2812 DSP Trainer Kit from Texas Instruments is a highly

integrated, high-performance solution for demanding control applications and is the first 32-bit 150 MIPS DSP with on-chip flash memory and on-chip high-precision analog peripherals. It uses Code Composer Studio (CCS) as the simulator for the kit which is designed by Texas Instruments (TI) itself for making and dumping programs on the kit. TMS320F2812 DSP Trainer Kit has many features which are embedded on the kit itself like Digital to Analog Convertor (DAC) output, Analog to Digital Convertor (ADC) input, Pulse Width Modulation (PWM) signal generation and Digital input/outputs. All of these features can be used separately in various applications depending upon the requirement of the circuit.

4.2.1 Limitations of using TMS320F2812 DSP Kit

This kit is good but has some limitations in operation due to which it confines its scope. Some of the limitations witnessed during the course of work are mentioned below:

- It requires a tedious programming for its operation.
- It can also be used by interfacing it with MATLAB, but that too is a lengthy 16 step process.
- It requires a lot of supporting softwares for the interfacing and operation of code composer studio.
- It does not provide real time interface and real time control of the hardware circuit connected to it. Once the output is fed to the hardware circuit, that signal cannot be altered while the system is running. For altering the parameters one needs to stop the process, do the alteration in MATLAB, generate hex file, dump the file again in code composer studio and then run the program.
- TMS320F2812 kit is not reliable as there are a lot of real time issues that may occur randomly on the kit.

These were some of the issues that were practically faced while working with TMS320F2812 DSP kit. These issues can be rectified by using dSPACE DS1104 Controller Board.

4.3   DSPACE DS1104 CONTROLLER BOARD

The dSPACE DS1104 R&D Controller Board is a lucrative entry-level

system and it has I/O interfaces and a real-time processor on a single board. It can be plugged directly into a PC through expandable slots. It advances the computer to a development tool for rapid control prototyping and is perfect for developing smaller control applications and also for education purposes. Real-Time Interface (RTI) provides MATLAB Simulink blocks for graphical I/O configuration. The dSPACE DS1104 R&D Controller Board is highly integrated, high-performance solution for demanding control applications and has a 64-bit floating-point processor and 250MHz CPU clock with on-chip flash memory and on-chip high-precision analog peripherals. DS1104 controller board, is recommended to smooth the progress of developing and debugging of various designs.

To access the signals from dSPACE DS1104, it is required to have the following items:

- dSPACE DS1104 R&D Controller Board

Figure 4.1: dSPACE DS1104 R&D Controller Board

- Dongle license on a USB drive

Figure 4.2: Dongle license on USB Drive

- Connector panel CP1104

Figure 4.3: CP1104 Connector Panel

This control panel CP1104 comes with 8 ADC inputs, 8 DAC outputs, 20 Digital Input/Outputs, PWM outputs, UART and RS232 serial communication output.

4.3.1 ControlDesk Software

ControlDesk is the dSPACE experiment software for seamless ECU development. It performs all the necessary tasks and gives you a single working environment, from the start of experimentation right to the end. It provides access to simulation platforms which can make measurement, calibration and diagnostics on ECUs, e.g., via consistent ASAM interfaces. Its supple modular structure provides high scalability to meet the necessities of specific application cases. This constitutes in clear advantages of data handling, the amount of training needed, requisite computing power and costs.

4.3.2 dSPACE DS1104 over TMS320F2812 DSP Kit

For this dissertation work dSPACE DS1104 is chosen over TMS320F2812 DSP kit because dSPACE eliminates all the limitation that was faced while using TMS320F2812 kit. It can be justified by the following points:

- It does not require any sort of programming, it runs directly by interfacing with MATLAB Simulink and interfacing is an easy process when done with dSPACE.

- It facilitates user with real time interface and real time control because of which the user can change the parameters while the system is running and hence observe the result for change in real time.

- It is a very reliable device, as there was never any error or malfunction because

of dSPACE.

Moreover, it is also superior to the DSP kit in terms of technical specifications which can be understood through table 4.1.

Table 4.1: Comparison of technical specifications of TMS320F2812 kit and dSPACE DS1104

Sr No.	Feature	TMS320F2812 kit	dSPACE DS1104
1.	Processor	32-bit processor	64-bit floating point processor
2.	Operating frequency	150 MegaHertz	250 MegaHertz
3.	Global Memory	16 MB	32 MB
4.	Timers (32 bit)	3	4
5.	Interrupts	3 external	4 external
6.	Digital Encoder	Not present	2 are present
7.	Serial interface	Standard UART	UART, RS232, RS422, RS485

Because of all these features of dSPACE DS1104, it is preferred over TMS320F2812 DSP kit and hence for this thesis also dSPACE DS1104 is used instead of TMS320F2812.

4.4   INTERFACING MATLAB SIMULINK WITH CONTROLDESK

ControlDesk does not support any sort of programming as it is written in Java and has a cross-platform operating system, so it is required to interface it with some other software like MATLAB, MATLAB Simulink, PSpice, PSIM etc. For this project, developer has interfaced MATLAB Simulink with ControlDesk to make programming experience easier. As Simulink have pre-programmed blocks, it is easier to use Simulink with ControlDesk which can also open wide gates for research in future.

4.4.1   Software Requirements

To interface MATLAB Simulink with Control Desk, we need to have some necessary softwares and modules. These softwares are to be installed as per the requirement of MATLAB version installed. List of these software are mentioned below in Table 4.2

Table 4.2: Software requirements to interface Simulink with ControlDesk

S.No.	Software	Version

1.	MATLAB	R2011a or higher
2.	ControlDesk Next Generation	4.2.1 or later
3.	Java SDK	1.5 or above
4.	PostgreSQL	8.x
5.	Apache Maven	2.0.8 or above
6.	Apache Ant	1.7.x
7.	Jakarta Tomcat	5.0 or above
8.	Texas Instruments TMS320C3x/C4x C Compiler	4.7 or 5.11
9.	Microtec PowerPC C Compiler	3.8.4
10.	dSPACE DS1006 C Compiler	3.0
11.	RTLib1104	2.6

For this project, ControlDesk version 6.0 is used which is supported with MATLAB 2016a or higher versions of MATLAB

4.4.2 System Requirements

For interfacing MATLAB 2016a with ControlDesk version 6.0, this is the necessarily required configuration in computer or laptop:

- I3 processor or above
- 4GB RAM or higher
- At least 5.5GB of disk space
- A USB 2.0 or USB 3.0 port (for dongle plugging)
- 1 free 33 MHz/32-bit 5 V PCI slot
- Microsoft Windows 8 or Microsoft Windows 10

4.4.3 Interfacing MATLAB with ControlDesk Software

After installing all the above mentioned software make sure the versions mentioned are to be strictly followed and violating them may lead to unsatisfactory interfacing. Interfacing can be achieved by following the below mentioned steps, once the installation is done:

a. On opening of MATLAB it will ask to select dSPACE RTI Platform Support, and will show 5 options – RTI1005, RTI1006, RTI1103, RTI1104 and RTI1401, select RTI1104 from it as we are using this version of control board.

Figure 4.4: dSPACE RTI Platform Support Window

b. Now type rti in command window of MATLAB, which will open RTI blocks library.
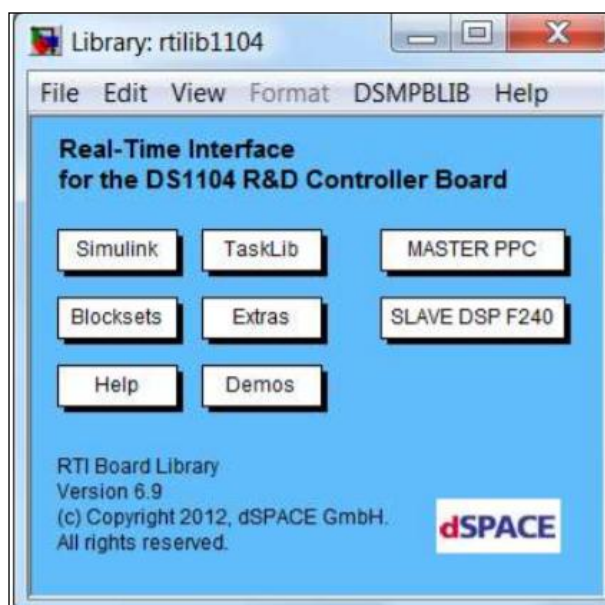
Figure 4.5: RTI Block Library

c. All the blocks of dSPACE will be present in either MASTER PPC or SLAVE DSP F240, from which we can choose any as per the program requirements.

d. Now open Simulink by clicking on the Simulink Library button from the toolbar.

e. When Simulink opens click on the Configure Model Parameters option from the drop down menu appeared when clicked on Simulation or we can simply use the shortcut Ctrl+E. This will open a window.

f. From the appeared window click on Solver appearing in left dialog box.

g. Now, write "inf" in stop time for infinite running of output through dSPACE and stopping it manually.

h. Select Fixed-step for type in solver options

i. Select any of the solver as per the required program.

j. Write the sample time of the schematic in Fixed-step size instead of automatic detection of sample time. Automatic detection may cause error in the output sometimes.
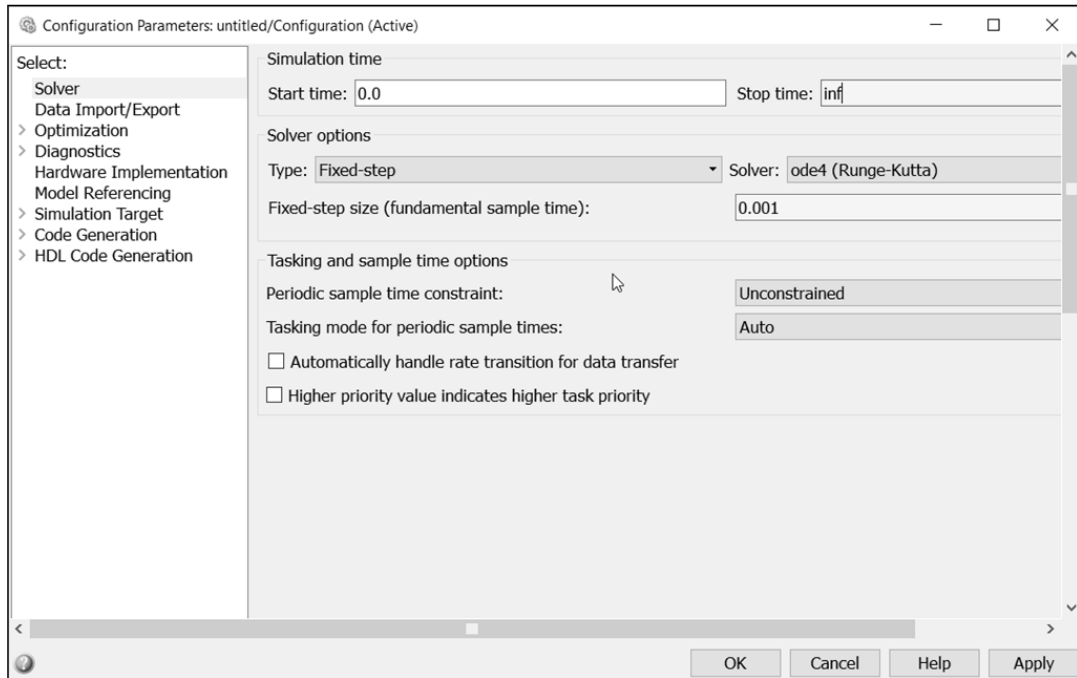
Figure 4.6: Configuration Parameters Window

k. Now, click on Code Generation from left appearing menu.

l. Browse for the system target file and select rti1104.tlc from the window appeared.
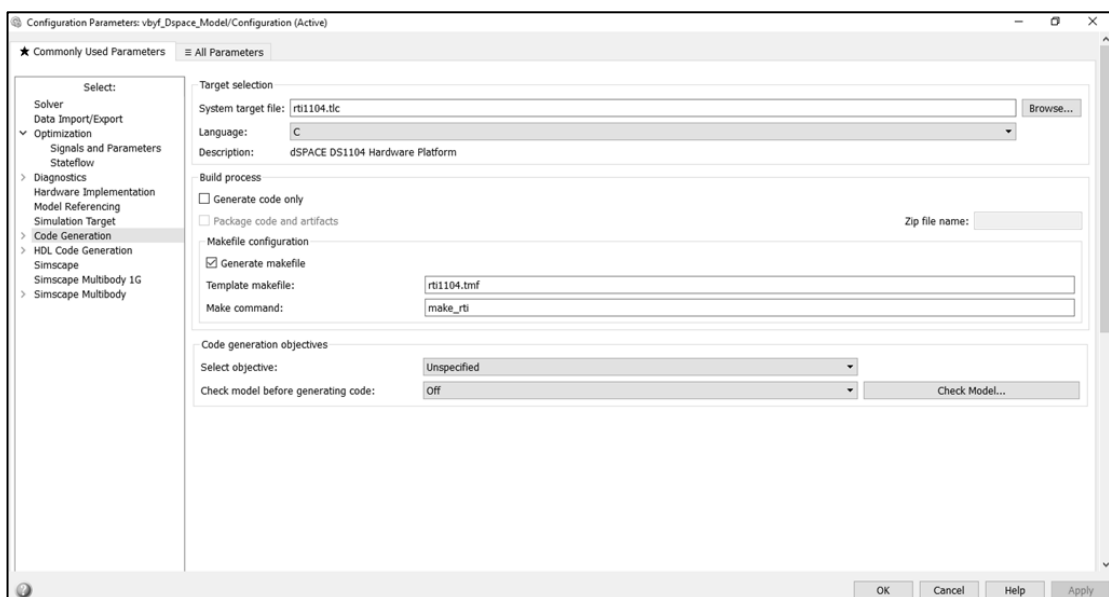
Figure 4.7: Selecting the target file

m. Now click on Code Generation → RTI load options and uncheck "load applications after build" option from the window appeared. This will avoid self loading of file in the hardware to avoid it from any damage.

n. Now, click on the "All Parameters" tab at top right corner and then select the "optimization" category. It will display the list of parameters. From the list appeared, uncheck the following parameters:

- Signal storage reuse
- Condition branch input execution
- Block reduction
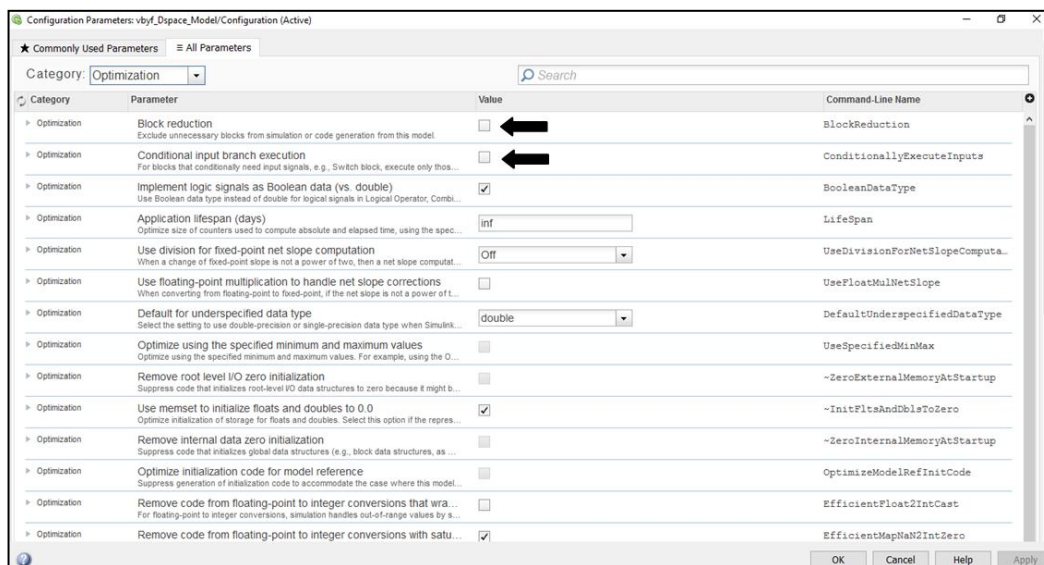
Figure 4.8: "All parameters" window where the parameters are to be unchecked

Now, interfacing has been done and MATLAB is ready to work with ControlDesk. These were the prerequisites which are necessary for interfacing and further use.

4.5   GETTING FAMILIAR WITH CONTROLDESK SOFTWARE

ControlDesk software requires ".*sdf*" file for its operation which can be generated by clicking on build model button in MATLAB Simulink. Once the build process is completed, it will automatically generate an ".*sdf*" file in the working directory of MATLAB
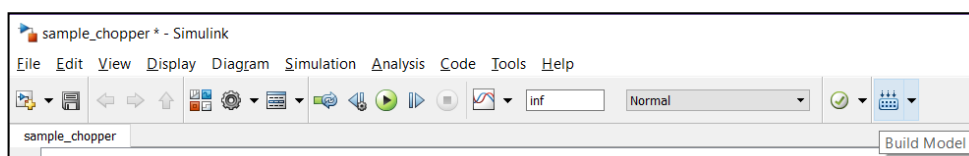
Figure 4.9: Clicking on Build Model in MATLAB Simulink window

After generating ".*sdf*" file, open the ControlDesk Software and then these steps are to be followed:

a. Create a new project by clicking on File → New → Project.

b. It will now open a layout screen. Give a name to the project and click next.

c. Give a name to experiment and click on next

d. Select the dSPACE module from it, i.e., ds1104

e. Load the .*sdf* file and click on finish.

f. Now click on project → variable → demo → Model Root and then select parameter to be displayed or controlled in the workspace.
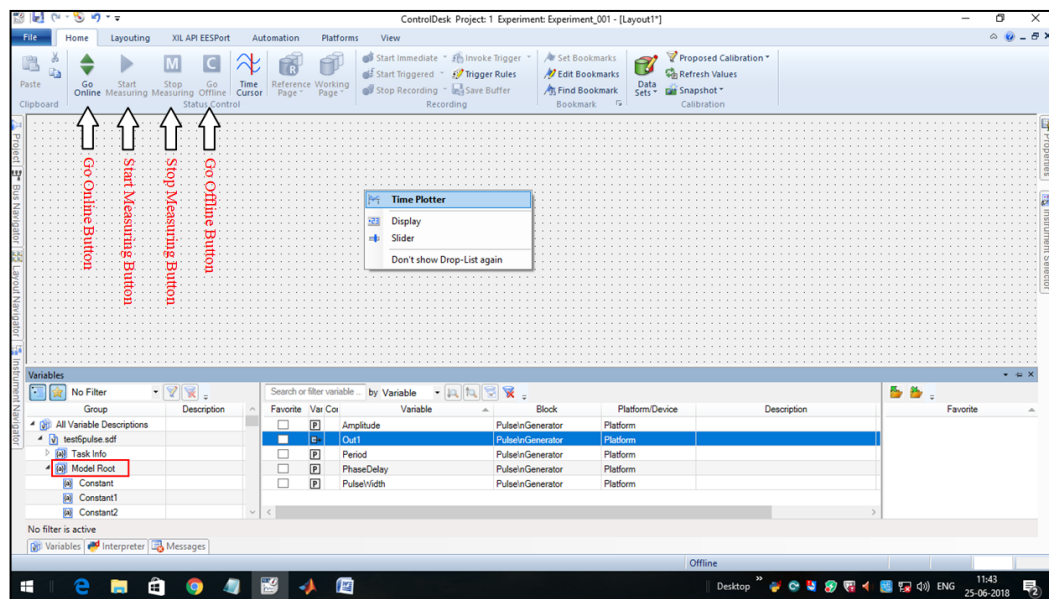
Figure 4.10: ControlDesk Software working window

g. There are a lot of options present in it, like scale, knob, gauge, numerical value, time plotter, etc. select any one of those as per the requirement.

h. Once all the parameters are attached and the user is ready to work, click on "Go Online" button to obtain the output from the connector panel.

i. And now finally click on "Start Measurement" button to view the parameters and waveforms on ControlDesk and to change the parameters of the model.

This can be better explained by showing a simple example which can explain the working in MATLAB Simulink and in ControlDesk software as well.
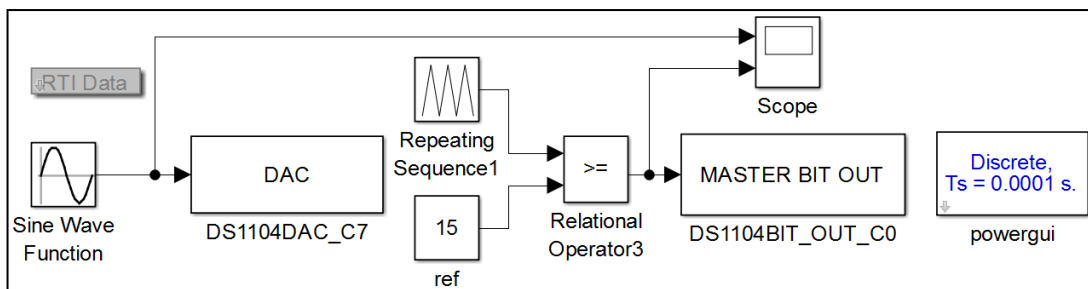
Figure 4.11: MATLAB program showing the dSPACE blocks in a sample schematic

This is a program developed in MATLAB Simulink, "*.sdf*" file of which will be further used in ControlDesk Software. Here, a DAC block is used for showing the output for any analog signal and then further giving it to real world. Master bit out is for the digital input/output, it gives the digital output to dSPACE and it has a tendency of working on a higher frequency. Once the program gets build, a block named "RTI Data" starts to appear on the window showing the access of RTI library.
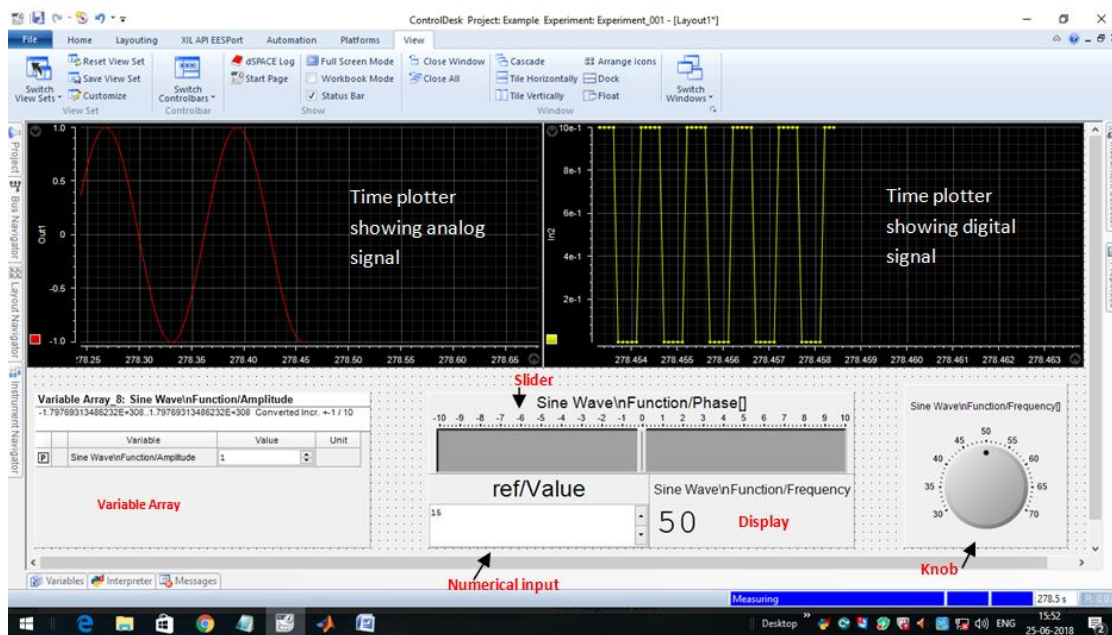
Figure 4.12: ControlDesk window showing the outputs for sample program

Fig 4.12 demonstrates the ControlDesk window which shows the output for schematic shown in fig 4.11. It shows the digital signal and analog signal drawn on a time plotter. It also has a variable array where different parameters can be put together and can be varied as per the convenience. There is a Numerical input box, slider and knob to vary the parameters. There is also a display which shows the value of the parameter required.

CHAPTER 5
SYSTEM DESIGN AND IMPLEMENTATION

5.1   PROBLEM FORMULATION

Every project requires a formulation of idea before its implementation. This formulation of idea leads to the design of the project which further proceeds to the journey of making an idea into success. Any idea developed to make a project further transforms into a design which is modulated again and again so that it becomes ready to implement which further leads to a successful project. This idea can be a success only if it is accompanied with adequate and appropriate design.

To generate a project first step is the formulation of topic, in which topic of dissertation work is chosen. It is the initial step of project building which is followed by idea generation. After the generation of idea, objectives are laid. Then project is introduced and introduction is formed. Introduction is then followed by data search which would include secondary as well as primary research. For this report only secondary research is used which includes studying books, journals, articles and conference papers that are relevant to topic and provide some useful information.

An inference is also needed to be drawn after the study of secondary data. After the completion of this task block diagram and circuit diagram would be formed which would provide a further direction to the progress of work. After this, schematic models would be designed which would be further simulated on MATLAB Simulink software and outputs would be observed. Once the simulation results are obtained, prime focus would be on implementing the same on hardware.
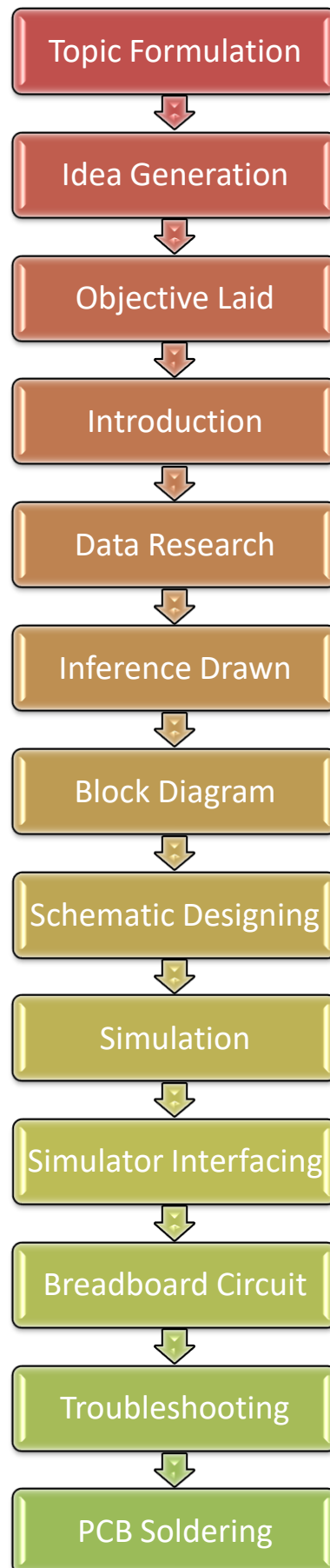
Figure 5.1: Block Diagram of whole project building process

For implementing the model on hardware, first and foremost step is to interface MATLAB Simulink with DSP Software (Code Composer Studio v5.2 for DSP kit TMS320F2812 and ControlDesk for dSPACE controller board). Once the interfacing is done, get the pulses from TMS320F2812 DSP kit or from dSPACE controller board and give the obtained pulses to the hardware circuit designed on breadboard. Hardware implementation of any circuit may lead to some errors, so the next step would be to rectify those hardware issues. Once all the issues are rectified, now finally solder the circuit on a General Purpose PCB or Copper PCB as per the requirement. This all processes will lead to the achievement of milestone of completing the work successfully with full fleshed requirements.

5.2   BLOCK DIAGRAM

In order to carry out any work, one needs to follow a proper hierarchy. This hierarchy can be very well understood by making the overall block diagram of the system. Construction of the block diagram provides with an overview of what are the tasks that are to be done while carrying out the experiment work and what should be the order to be followed in carrying out those tasks.

5.2.1   Block Diagram for dSPACE Interfacing with Real World

For switching the MOSFET, it requires triggering pulses that can be obtained from dSPACE. But the pulses obtained from dSPACE can not be directly fed to MOSFET. It needs some medium that can raise the current and voltage level of pulses, for the suitable triggering of MOSFET.
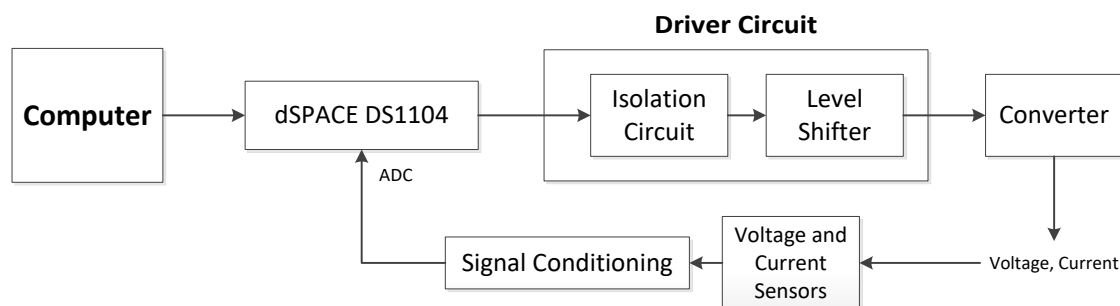
Figure 5.2: Block Diagram for dSPACE Interfacing with Real World

From the block diagram shown in fig 5.2, it can be understood that dSPACE receives the signal from Computer. dSPACE gives the signal to driver circuit which further

gives it to converter. Voltage and current sensor senses the voltage and current of the circuit respectively and further send it back to dSPACE after conditioning the signal so that the hardware output can be viewed on ControlDesk Software and the closed loop control can be applied if required. Driver circuit would require an isolation circuit and a level shifter circuit which could be better understood in section 5.3.

5.2.2 Block Diagram for Open Loop Configuration of Converter

This thesis work includes open loop operation of these converters – Class-A Chopper, Class-B Chopper, Single Phase Inverter and Three Phase Inverter. All these converters will follow the same block diagram as shown in fig 5.3.

Figure 5.3: Block Diagram for Open Loop Configuration of Converter

It can be seen that reference voltage is fed to pulse generator and which is further fed to converter. Output current and voltage is denoted by "*i*" and "*V*" respectively.

5.2.3 Block Diagram for Closed Loop Configuration of Converter

For realizing closed loop operation of any converter, block diagram of open loop configuration itself can be considered with some extra addition. For closed loop operation, output signal is required to be fed back so that a comparison can be made with reference signal and a controller is required to control this operation.
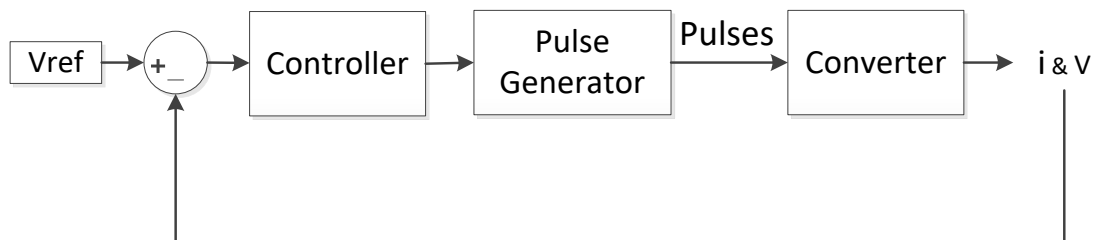
Figure 5.4: Block Diagram for Closed Loop Configuration of Converter

In this report closed loop control is discussed only on closed loop Class-A chopper, but the block diagram shown in fig 5.4 can be used in any closed loop control converter. In this project, PI controller is used as the controller.

5.3   DRIVER CIRCUIT

The electronic switch that is used here is for higher voltage and current rating. This sort of power switches generally require high driving voltage and high driving current to get triggered. For triggering these switches, triggering pulses are the first and foremost requirement. These pulses are generally taken from some Digital Signal Processing (DSP) source, which have a voltage level of not more than 7 volts. But power switches generally require gate voltage to be in the range of 13 volts to 20 volts and gate current requirement is generally 200 miliamperes or above. So it is necessary to raise the current and voltage level of triggering pulses sufficiently so that the switch can work appropriately. This requires some circuit in between of gate terminal of power switch and triggering pulse source, which can play the appropriate role. This sort of circuit is generally termed as gate driver circuit.

For this report a MOSFET IRF840 is used, which requires at least 14V gate voltage and approximately 250mA gate current. So here are some of the driver circuits that were implemented to achieve this goal.

5.3.1   Driver Circuit using an Optocoupler and an OPAMP

For this circuit, optocoupler IC 6N137 and OPAMP IC μA741 is used for realizing the driver circuit. Pulses are fed to input pin (pin no. 2) of 6N137 IC and output is taken from output pin (pin no. 6) of IC. Optocoupler is used to provide isolation between the circuit and DSP signal source. Both of these equipments are very costly, so if isolation is not provided than it may get damage.
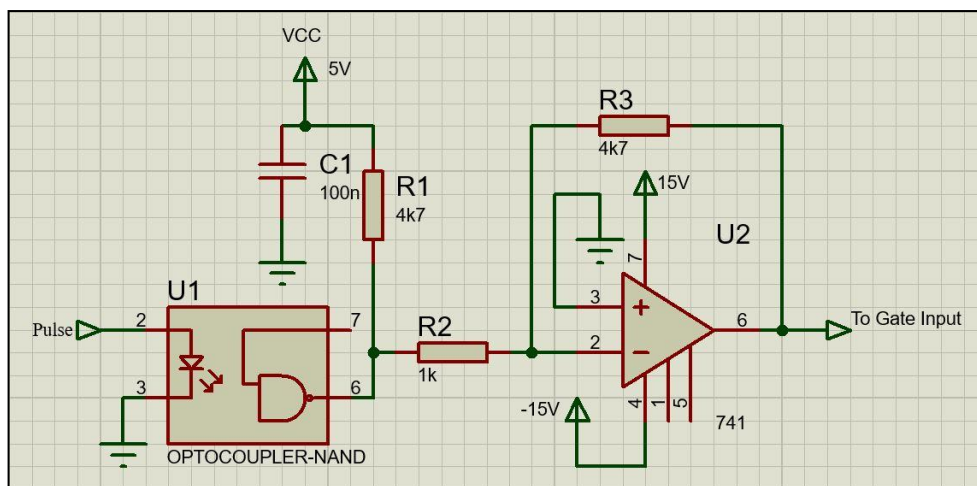
Figure 5.5: Driver circuit using Optocoupler and OPAMP

Output of 6N137 is fed to OPAMP for amplification of the signal. This circuit lacks in providing high source and sink current capability. Apart from this it does not provide path for the reverse current to flow. Because of these drawbacks, this circuit can not be used practically.

5.3.2   Driver Circuit using TLP250

TLP250 is 8-pin DIP package MOSFET gate Driver IC which provides optical isolation between controller and switch and also amplifies the voltage level to the desired level. It consists of light emitting diode and integrated phototransistor. Basically, it has an inbuilt optocoupler and output of which is fed to totem pole configuration of bipolar transistor.
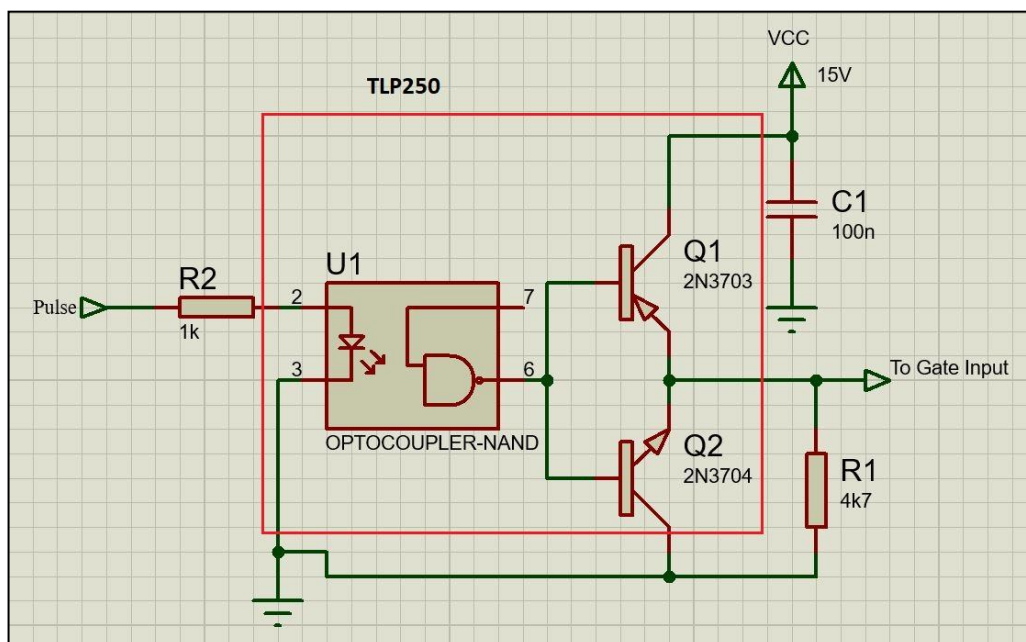
Figure 5.6: Driver Circuit using TLP250

The output is then taken from output pin (pin no. 6) of TLP250 IC and further given to the MOSFET. It has sourcing and sinking current capability up to 1.5 A, which works as an advantage for it. This circuit has a disadvantage due to which it is not used for taking the outputs for this report and that disadvantage is that this circuit does not provide a discharging path for internal capacitor of power MOSFET. Due to which when MOSFET is switched off, it takes some time to switch OFF properly. This time is very high as compared to the MOSFET turn OFF time.

5.3.3 Driver Circuit using 2N2222 Transistor

This driver circuit uses a NPN transistor 2N2222 for driving the switch. 2N2222 is a NPN bipolar transistor with a collector current capacity of 800mA and collector voltage capacity of 40V. This circuit works properly but it lacks isolation from dSPACE or DSP kit. Due to which dSPACE or DSP kit may get damaged if any reverse current flows through the circuit, so an isolation circuit is required in-between.
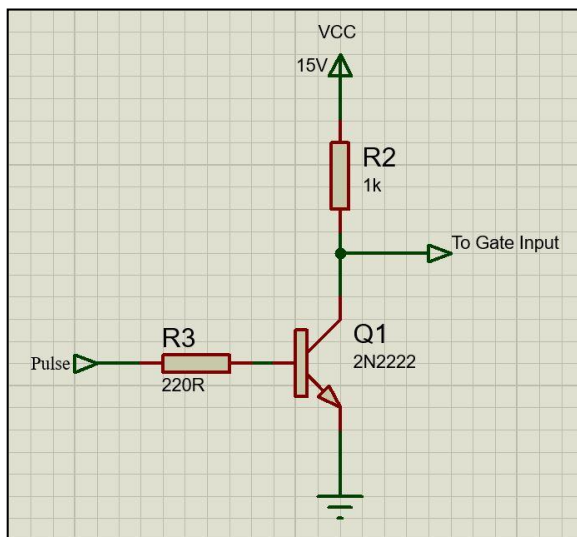
Figure 5.7: Driver circuit using transistor 2N2222

5.3.4 Driver Circuit using 2N2222 with Isolation

As discussed earlier isolation circuit is very necessary to protect dSPACE.
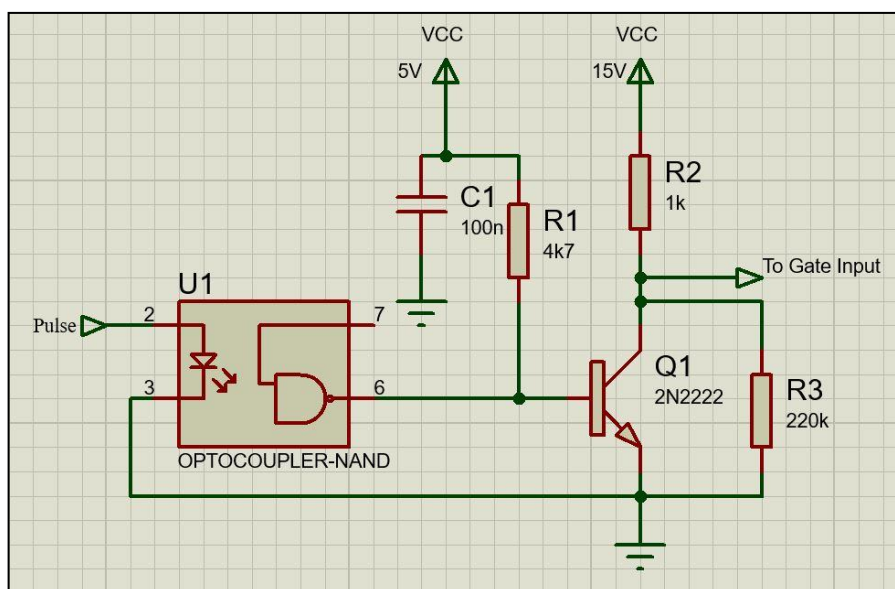
Figure 5.8: Driver circuit using 2N2222 with optocoupler

One can make the isolation circuit using any of the available techniques. Some of the popular techniques are by using – Hex Inverter IC 7406, Hex Buffer IC 7407 or optocoupler IC 6N137. For implementing this circuit optocoupler IC 6N137 is used as an isolator.

5.4 IMPLEMENTATION

For the implementation of above discussed work, firstly a schematic model of the circuit is designed which is simulated in MATLAB Simulink. Once the Simulink results are obtained than the model is redesigned with dSPACE blocks and then the circuit is designed on breadboard. After finalizing the circuit on breadboard and troubleshooting it, finally the circuit is soldered on general PCB.

5.4.1 Implementation of Open Loop Class-A Chopper

Class-A Chopper is implemented in both open loop and closed loop configuration. It is realized with R load, RL load and RLE load in both configurations. Schematic model for both open loop and closed loop will be different. But the hardware that is designed for Chopper will remain same for both open loop as well as closed loop, because voltage and current sensors are connected in both open loop and closed loop. In open loop voltage sensors are used to view the results on ControlDesk Software window and in closed loop it is used to calculate the error in output and further reduce the error to maximum.
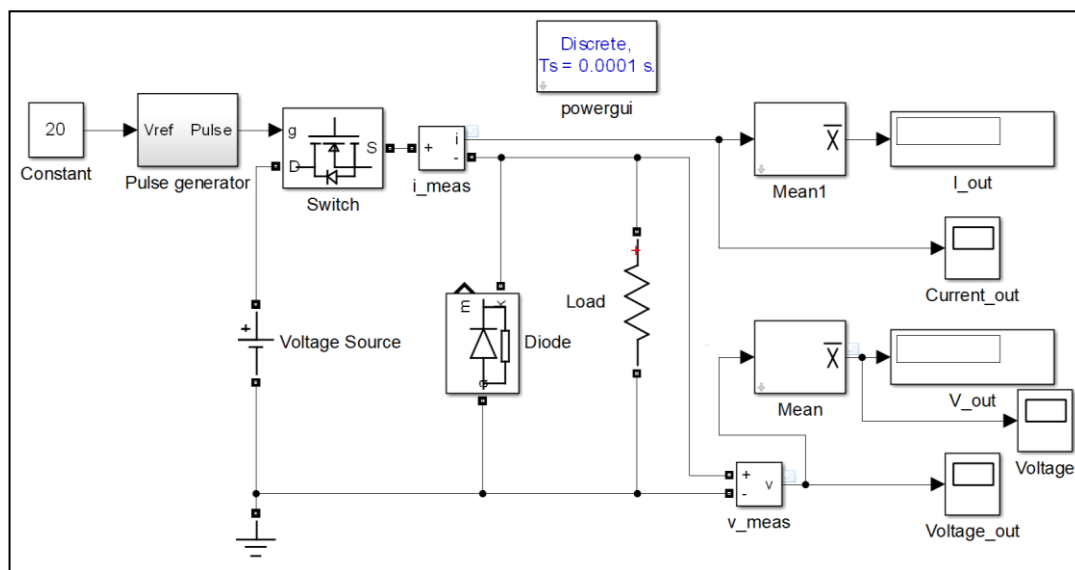
Figure 5.9: Schematic Model of Open Loop Class - A Chopper

Fig 5.9 shows the schematic model for open loop Class-A Chopper where pulses are fed to gate terminal of switch and a voltage is applied at drain of the switch. A diode is connected across the load, relevance of which can be found in Appendix 1. Load shown here is R load which can be replaced by RL load or RLE load as per user requirement.
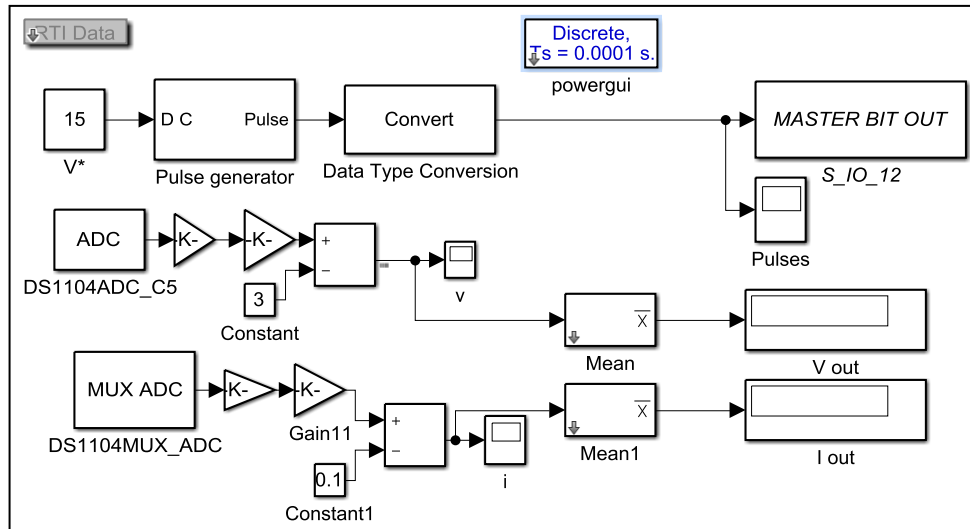
Figure 5.10: Schematic Model of Open Loop Class - A Chopper with RTI Library Blocks

Schematic model in fig 5.10 contains the RTI Library blocks which will be helpful in taking the output from dSPACE. Master bit out is the output of pulses which gives the output from digital I/O in this case. ADC blocks are used to fetch the current and voltage signal from output and the blocks preceding the ADC blocks are used for tuning of voltage and current sensor.
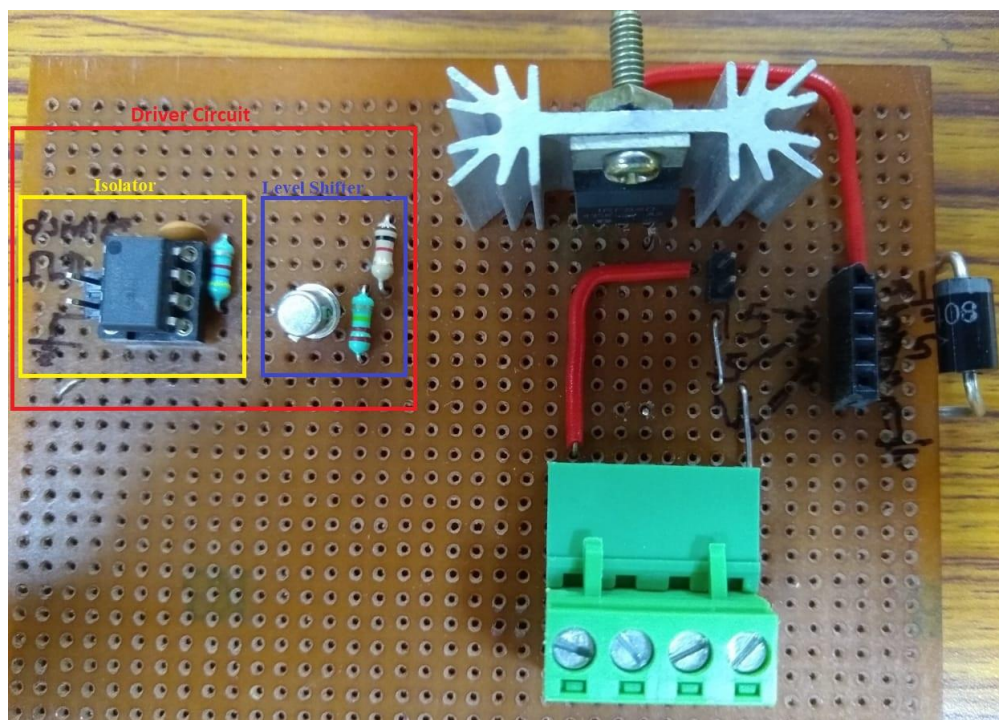
Figure 5.11: Circuit of Class-A Chopper Soldered on Universal PCB

Fig 5.11 is a Class-A Chopper with driver circuit soldered on a universal PCB. Driver Circuit contains isolator marked in yellow and level shifter which is marked in blue.

5.4.2 Implementation of Closed Loop Class-A Chopper

Closed loop Chopper is same as open loop Chopper, just feedback along with controller is extra added to the circuit. In that also only schematic model will change, whereas hardware circuit will be same for open loop as well closed loop.
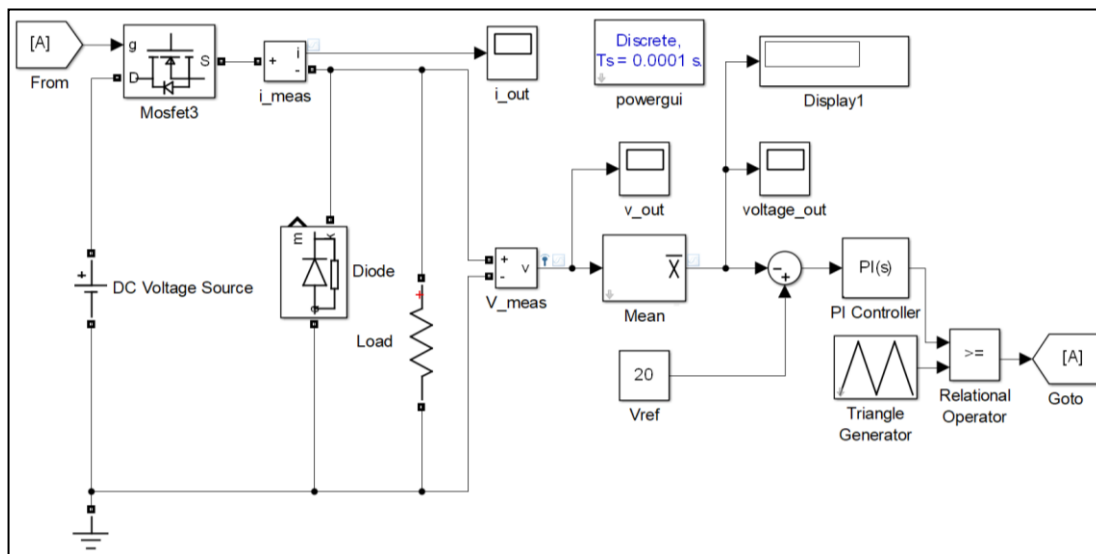
Figure 5.12: Schematic Model of Closed Loop Class-A Chopper

Fig 5.12 shows the schematic model of closed loop Class-A Chopper. Here voltage signal is sensed and is send as a feedback to gate terminal of MOSFET and a PI controller is used.
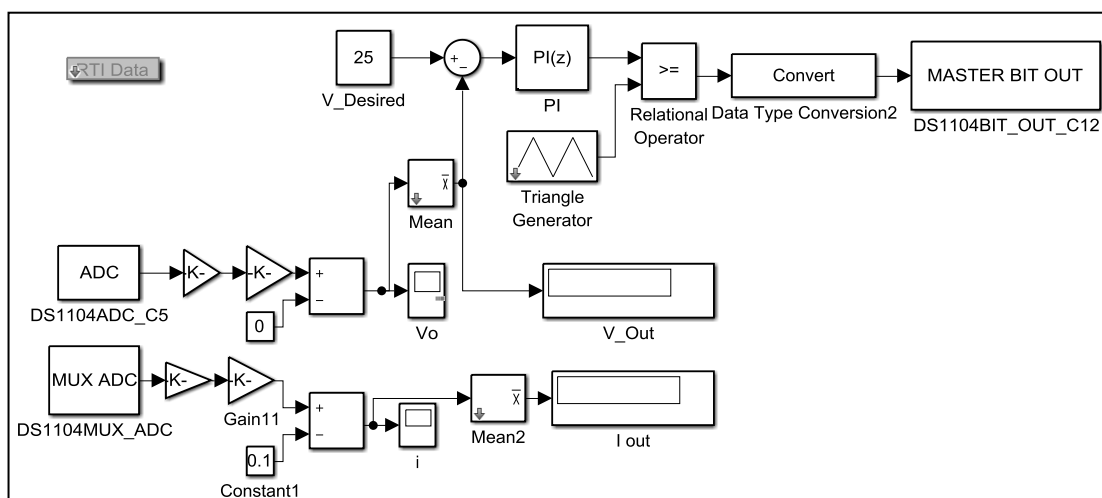
Figure 5.13: Schematic Model of Closed Loop Class-A Chopper with RTI Library Blocks

Fig 5.13 shows the Schematic Model for implementation of closed loop control on a Class-A Chopper using RTI Data library blocks.

5.4.3 Implementation of Class – B Chopper

Class – B Chopper has the similar design to Class-A Chopper but position of diode interchanges with that of switch. Moreover, Class – B Chopper result can be obtained only if RLE load is connected.
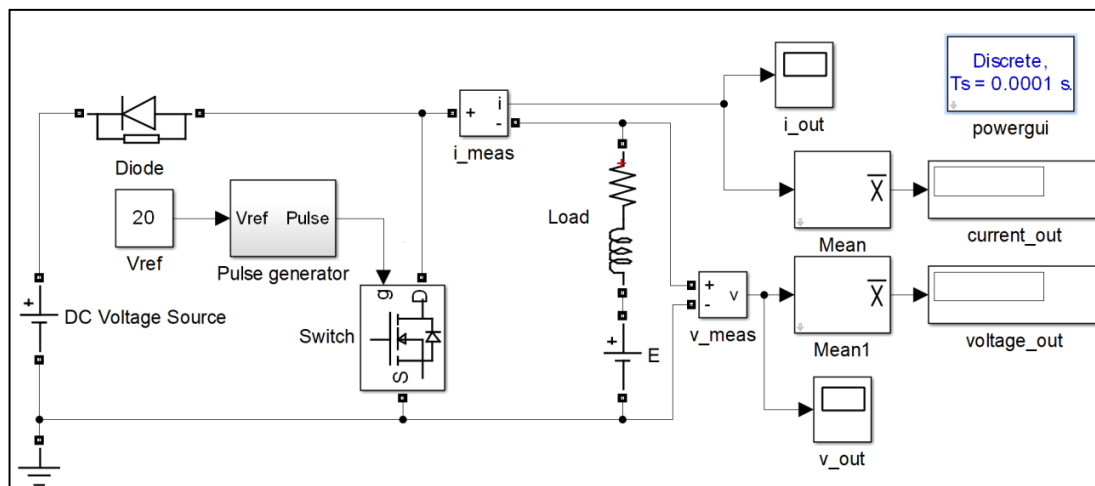
Figure 5.14: Schematic Model of Open Loop Class-B Chopper

It can be seen in fig 5.14, that the model is similar to that of Class-A Chopper with only change in position of MOSFET and diode.
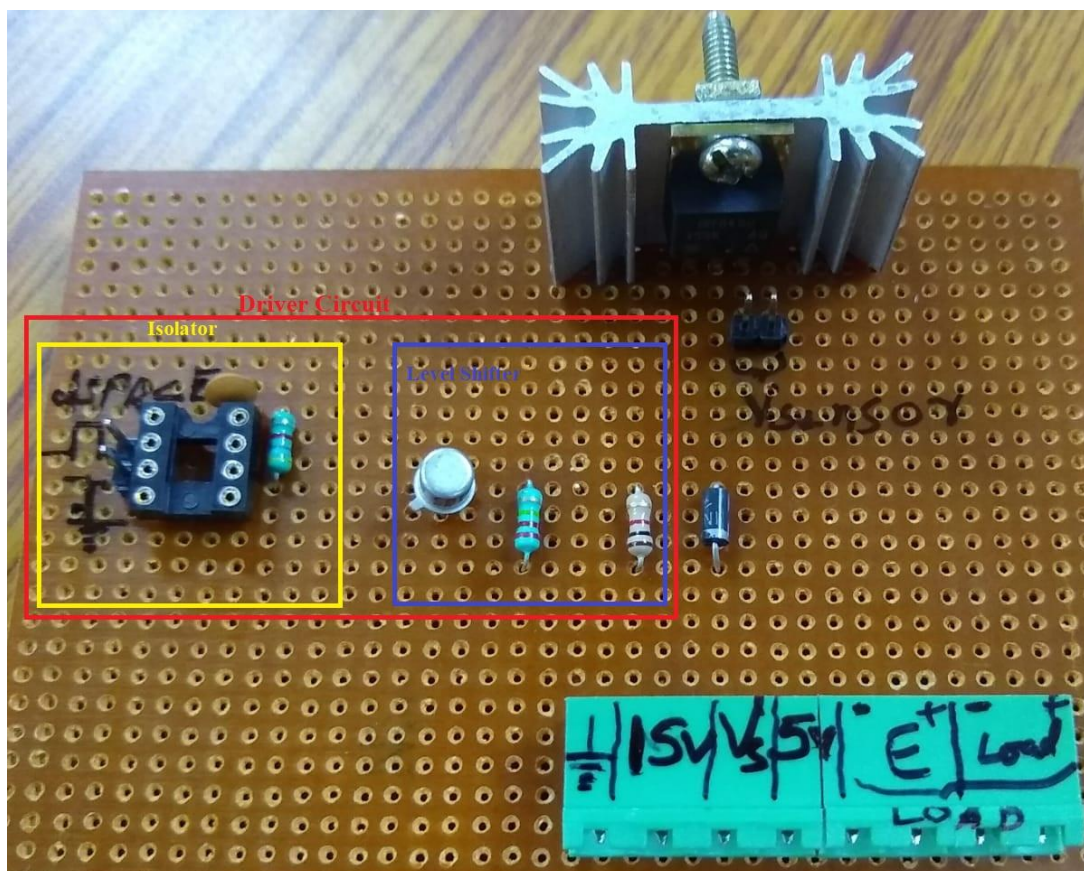
Figure 5.15: Circuit of Class-B Chopper Soldered on Universal PCB

Circuit made on PCB also has driver circuit on it along with other components.

5.4.4 Implementation of Three Phase Inverter

Three phase inverter has six switches which are to be switched separately at different instants, so there is a requirement of six set of pulses to operate a three phase inverter.
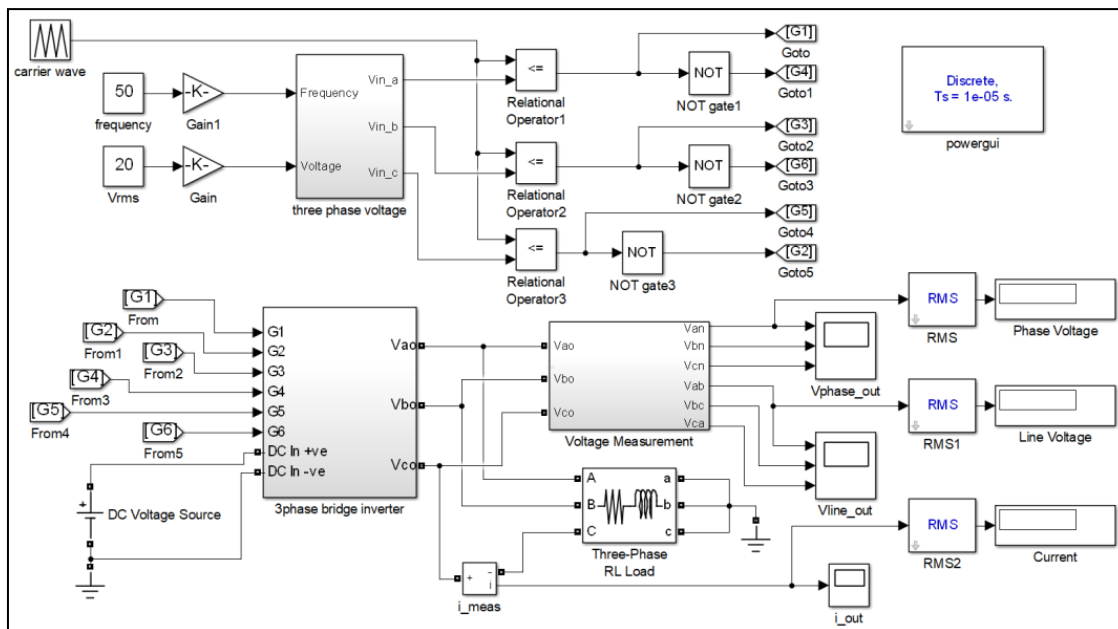
Figure 5.16: Schematic Model of Open Loop Three Phase Inverter

Fig 5.16 shows the schematic model of open loop 3-phase PWM Inverter, a voltage measurement block is made in it because phase voltage can not be obtained directly, it is necessary to do the vector analysis and form the equations in MATLAB accordingly.
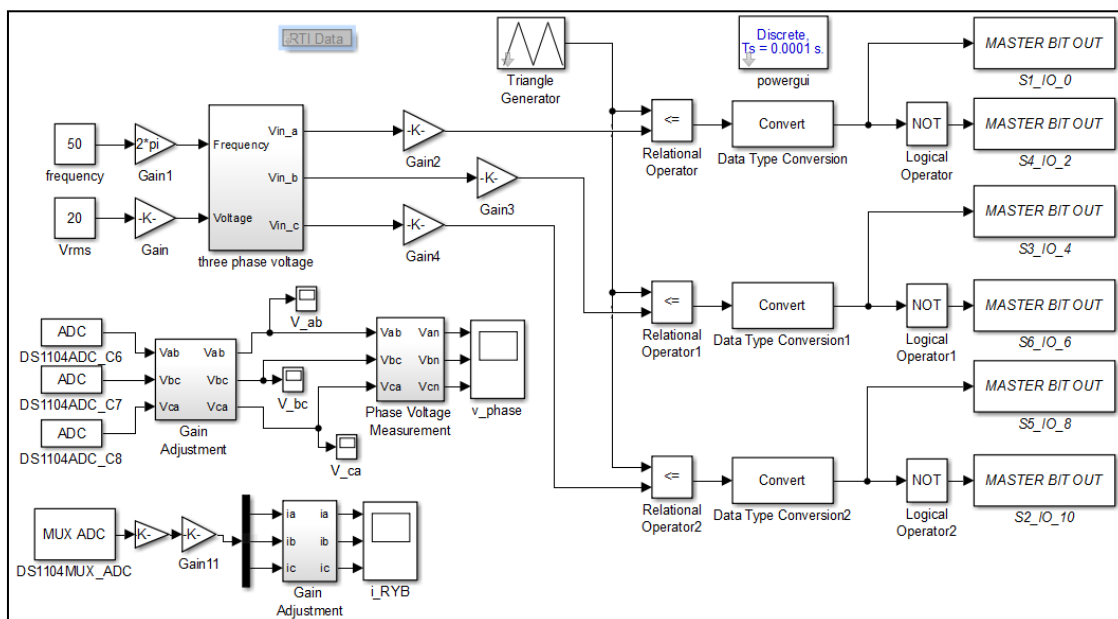
Figure 5.17: Schematic Model of Open Loop Three Phase Inverter with RTI Library Blocks

Fig 5.17 is the schematic model of open loop three phase Inverter with 6 PWM output

blocks and 6 ADC input blocks. 1 MUX ADC block is used instead of 3 separate ADC. Here PWM output blocks are used instead of Digital I/O block because in PWM block of dSPACE, there is an inbuilt deadband of 100ns which prevents the simultaneous switching of all four switches and hence prevents the shorting of voltage source.
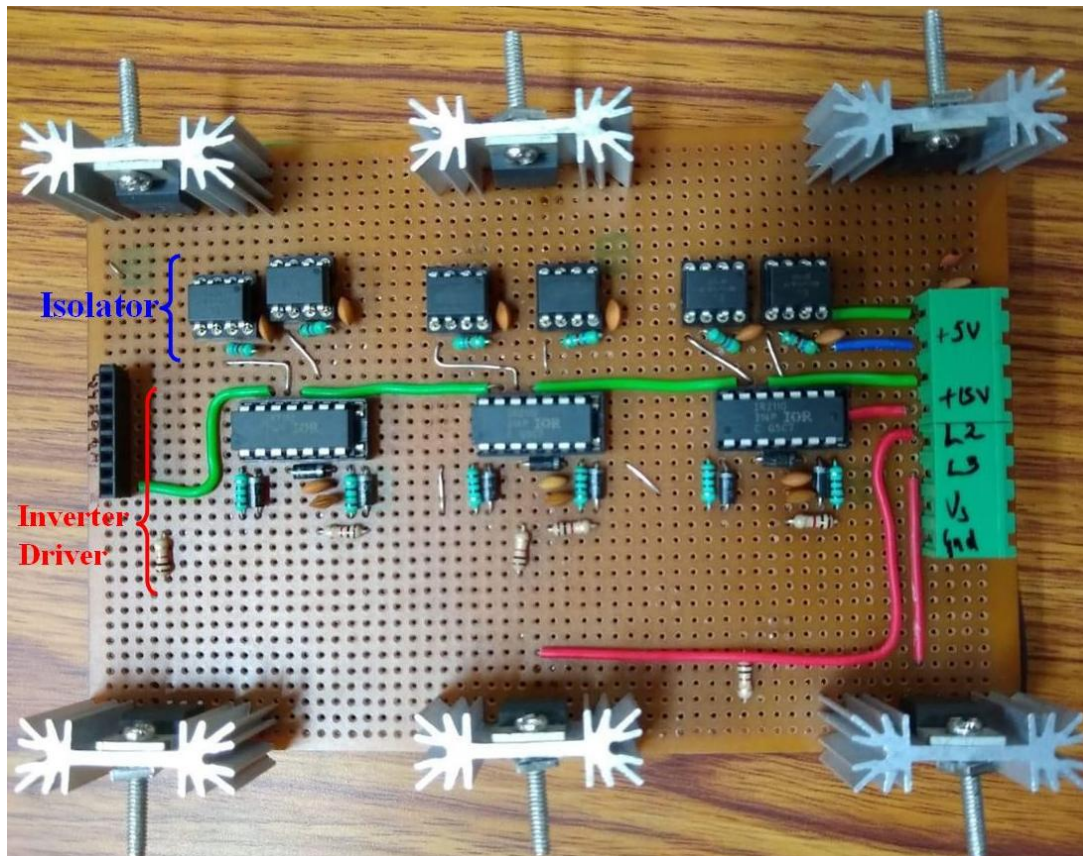
Figure 5.18: Circuit of Three Phase Inverter Soldered on Universal PCB

Fig 5.18 shows the circuit of 3-phase Inverter soldered on universal PCB. Here 6N137 optocoupler IC is used as an isolator and IR2110 inverter driver IC is used. IR2110 not only works as a level shifter but it also provides isolated supply to each MOSFET in any inverter leg. IR2110 Inverter Driver IC is discussed in detail in Appendix 2.

5.4.5 Implementation of Single Phase Inverter

Similarly single phase PWM Inverter can also be realized using 2 legs of Inverter. In single phase Inverter high side switch of one leg and low side switch of other leg gets the same pulses and remaining two switches gets the inverted pulses. Hardware circuit that is realized for 3-phase Inverter can also be used for realizing single phase inverter by not giving the pulses to the third leg of Inverter.
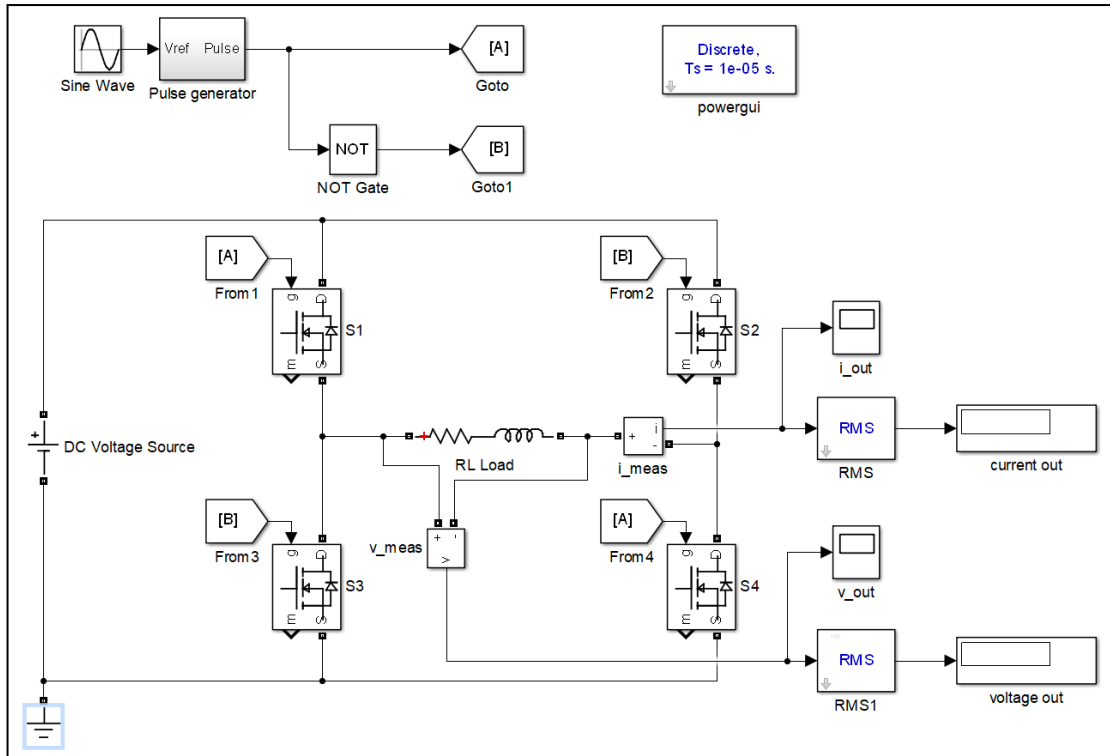
Figure 5.19: Schematic Model of Open Loop Single Phase Inverter

Fig 5.19 shows the schematic model of single phase SPWM Inverter with two legs and two MOSFET in each leg.
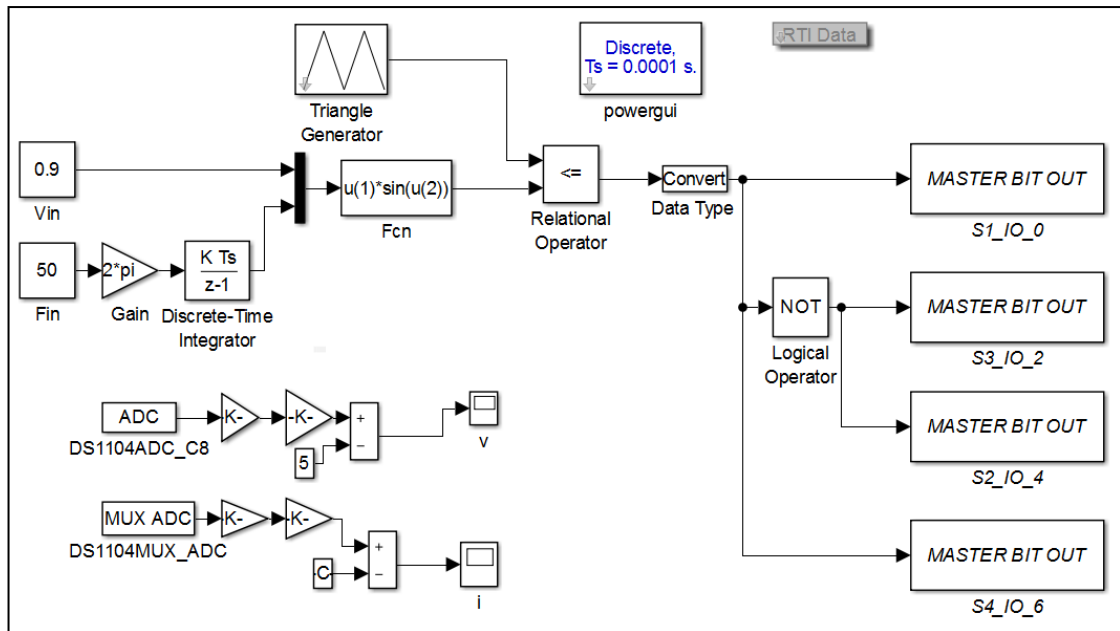
Figure 5.20: Schematic Model of Open Loop Single Phase Inverter with RTI Library Blocks

Fig 5.20 shows the schematic model of open loop single phase SPWM Inverter with RTI library blocks. Four PWM blocks are used for taking the output. This could have done by using 2 PWM blocks but as the circuit used is same for 3-phase Inverter and single phase inverter, so 4 blocks would be required.

CHAPTER 6
RESULTS AND DISCUSSIONS

As the name of the chapter suggests, the chapter contains the outputs of the work done and also the obtained results. Further, it will also put light on the analysis of those results. The chapter will include following steps:

- Obtaining the simulation results of schematic model drawn in MATLAB Simulink.
- Implementing the circuit on the hardware and observing the outputs on DSO or Control Desk window.
- Comparative study and analysis of hardware and simulation results.
- If simulation and hardware results are identical then good else rectifying the hardware issues and taking the outputs again unless best possible results are not obtained.

Different results at different time instants are taken by adequately varying the parameters within the permissible range. The aim is to obtain the hardware results identical to the simulation results by using similar parameters on hardware as well as software simulation. Here, DC-DC converters like open loop and closed loop operation of Class-A Chopper are realized using dPSACE. DC-AC converters (single phase Inverter and three phase Inverter) are also realized using dSPACE. Results of all these converters at different parametric values will be windowed in this chapter. Calculation of different parameters and errors will also be done in this chapter itself. After acquiring all the results and error calculation, current chapter will also put light on the comparison of different results, this comparison will further help in concluding the report.

In all the waveforms attached in further report, some colour notations are followed which are tabulated below.

Table 6.1: Colour notation of different waveforms

Sr. No.	Waveform Colour	Waveform type
1.	RED Colour	Output Voltage
2.	Blue Colour	Output Current
3.	Green Colour	Mean Output Voltage

Apart from this, while making all the figures of result and outputs three type of waveform are clumped together one after other for better comparison and better understanding of Simulation outputs, DSO outputs and ControlDesk outputs. These waveforms are labeled as – A, B and (c) These waveforms will follow a general notation which is mentioned in Table 6.2.

Table 6.2: Significance of waveform labels of each result

Sr.No.	Waveform Label	Description
1.	A	Output obtained on running the schematic model of circuit on MATLAB Simulink
2.	B	Output of Class-A Chopper hardware circuit obtained on DSO
3.	C	Output of Class-A Chopper hardware circuit on ControlDesk software

6.1   OPEN LOOP CLASS-A CHOPPER

Class-A Chopper is realized in open loop configuration by connecting different loads like R load, RL load and RLE load. Different outputs are recorded for each type of load at different duty cycle. Output has also been recorded by varying the loading conditions like by changing the value of resistor for R load or changing the value of inductor for RL load. All of these results are taken from a constant voltage source of 30 volts.

6.1.1   Realization of Open Loop Class-A Chopper using R Load

Primarily, results are taken on simulation by varying the different parameters such as duty cycle and value of variable resistance. For taking all the outputs the source DC voltage has been set to 30 volts.

Figure 6.1: Voltage and current output of Open Loop Class–A Chopper at 50% duty cycle for R load:- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Figure 6.1 shows the output of open loop Class-A Chopper with resistive load obtained at 50% duty cycle. This implies that the desired output voltage is 15 volts. It can be seen that the output current is discontinuous because he load used is resistive and resistive load does not imply any differential or integral effect on the waveform.

Figure 6.2: Voltage and current output of Open Loop Class–A Chopper when duty cycle changed from 50% to 83.33% for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.2 shows the output of Class-A Chopper with resistive load obtained when duty cycle is suddenly increased from 50% to 83.33%, i.e., the desired output voltage is increased from 15V to 25V. When this change occurs, there is hardly any oscillation seen in the output, just a change in duty cycle is observed. It can be observed that output takes maximum 2 clock cycles to reach 25V from 15V, which is why oscillations are not observable.

Figure 6.3: Voltage and current output of Class–A Chopper when duty cycle changed from 83.33% to 33.33% for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Aim was to observe the result by suddenly decreasing the duty cycle. Fig 6.3 shows the output of open loop Class-A Chopper with resistive load obtained when duty cycle is suddenly decreased from 83.33% to 33.33%, i.e., the desired output voltage is abruptly decreased from 25V to 10V. It can be observed that output takes maximum of 2 clock cycles to reach 10V from 25V, which is why oscillations are not noticeable at the point

of change of duty cycle.

It can be observed from fig 6.1, 6.2 and 6.3 that maximum voltage almost remains constant throughout, however mean voltage is changing as per the user requirement. In open loop, change in mean voltage is sharp with negligible oscillations.

Figure 6.4: Voltage and current output of Class–A Chopper when R is varied from 70Ω to 15Ω for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk

Till now all the outputs were taken by varying the duty cycle and keeping the resistance

of load constant. Fig. 6.4 illustrates the outputs of open loop Class-A Chopper when load resistance is suddenly changed from R = 70Ω to R = 15Ω. It can be observed that the maximum current has increased from 0.43A to 1.7A. In simulation results, maximum output current is increased to 2A. If voltage waveform is observed closely, it can be seen that there is a slight dip in the maximum value of voltage and this can be clearly witnessed by looking at the mean value of voltage.

For better understanding of results a table has been made stating the different outputs at different parameters.

Table 6.3: Comparing the Simulation results with Hardware Results at different duty cycle for open loop Class-A Chopper with R load

Sr No.	Simulation Results (True)				Practical Results (Meas)				%D	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.442	0.075	30	5.16	0.44	0.112	29.3	4.24	16.67	-17.80
2.	0.442	0.146	30	9.95	0.46	0.181	29.2	8.89	33.33	-10.65
3.	0.442	0.221	30	15.04	0.43	0.223	29.2	14.43	50.00	-4.05
4.	0.442	0.296	30	20.13	0.48	0.332	29.3	19.18	66.67	-4.71
5.	0.442	0.367	30	24.92	0.48	0.405	29.3	24.01	83.33	-3.65

Results obtained by varying the duty cycle are mentioned in table 6.3. It can be observed that when desired output voltage is decreased, percentage error gets increased, which means that this configuration of class-A Chopper works best at higher duty cycle.

Table 6.4: Comparing the Simulation results with Hardware Results by changing the load for open loop Class-A Chopper with R load

Sr No.	Simulation Results (True)				Practical Results (Meas)				R(Ω)	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.442	0.296	30	20.13	0.480	0.332	29.3	19.18	70	-4.71
2.	2.000	1.337	29.8	19.98	1.543	1.058	28.0	17.90	15	-10.41

It can be seen in table 6.4, when resistance is decreased, percentage error increases. So it can be concluded that open loop class-A Chopper with R load should not be operated for very low resistances.

6.1.2   Realization of Open Loop Class-A Chopper using RL Load

To check the diversity and widespread application of designed Class-A Chopper, different types of loads are tested on the Chopper in open loop as well closed loop. This part of report focuses on the use of resistive as well as inductive load, i.e., RL load for testing the Class-A Chopper.

Figure 6.5: Voltage and current output of Class–A Chopper at 50% duty cycle for RL load:- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Fig 6.5 shows the output of an open loop Class-A Chopper with RL load obtained at 50% duty cycle. This implies that the desired output voltage is 15 volts. It can be seen than the current is never zero unlike it was in resistive load. Inductor here has the integrating effect on voltage waveform due to which current waveform appears to be a triangular continuous wave.
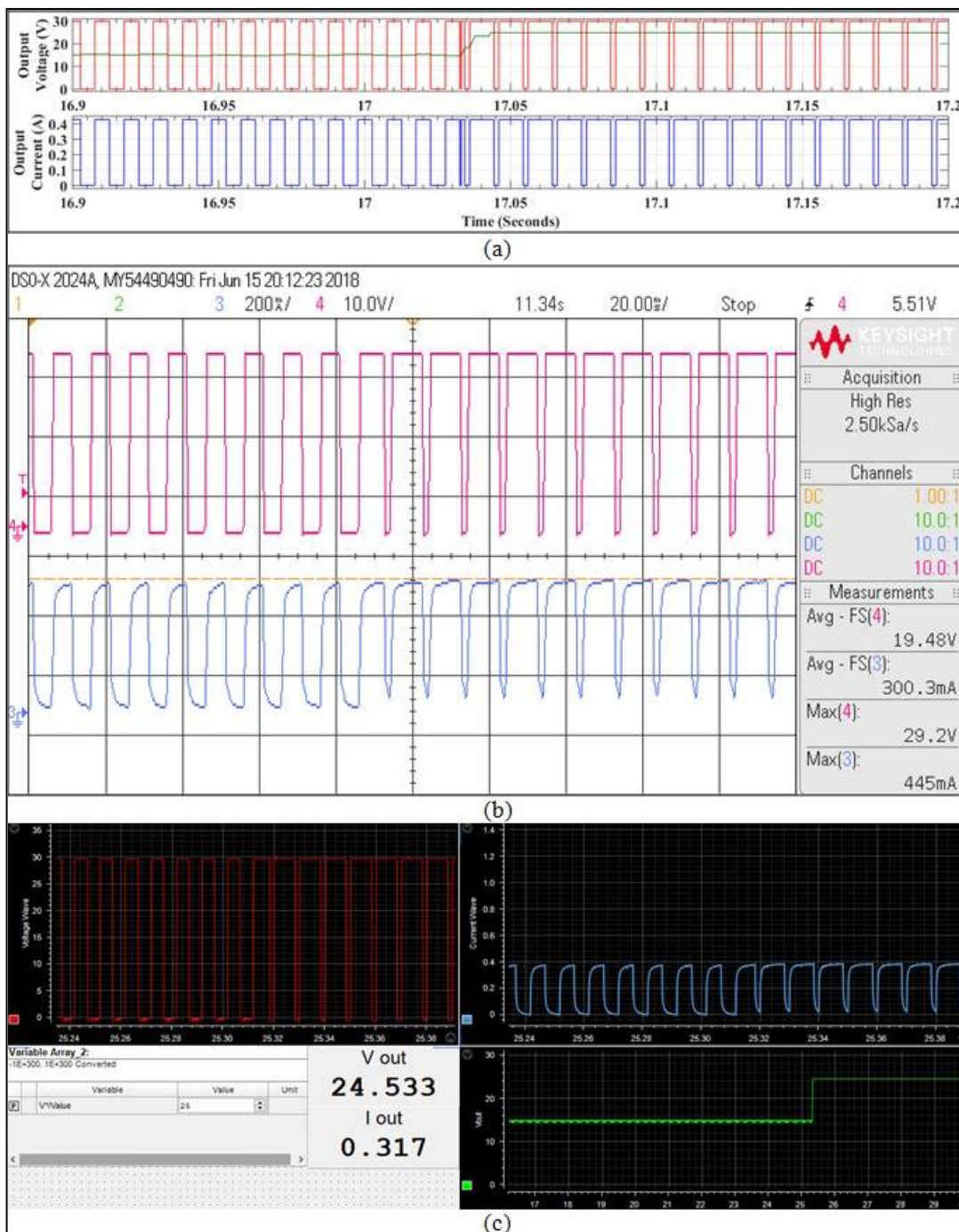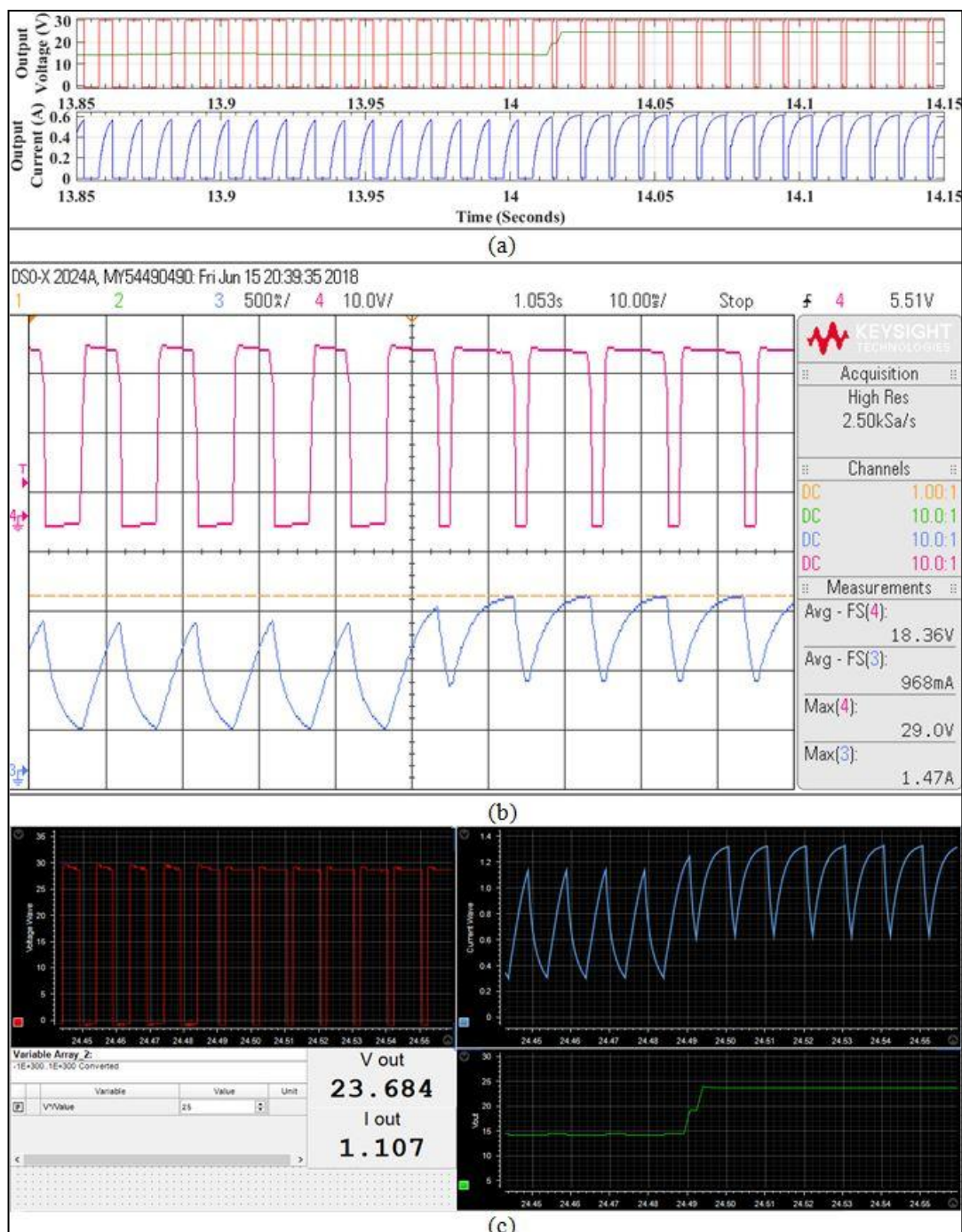
Figure 6.6: Voltage and current output of Class–A Chopper when duty cycle changed from 50% to 83.33% for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.6 shows the output of Class-A Chopper with RL load obtained when duty cycle is suddenly increased from 50% to 83.33%, i.e., the desired output voltage is increased from 15V to 25V. It can be observed that output takes almost 1 clock cycles to reach 25V from 15V. It can be seen that the maximum current is increasing when duty cycle is increased. This is because of the continuous current flowing through the circuit. Oscillations are negligible in both current and voltage waveform.
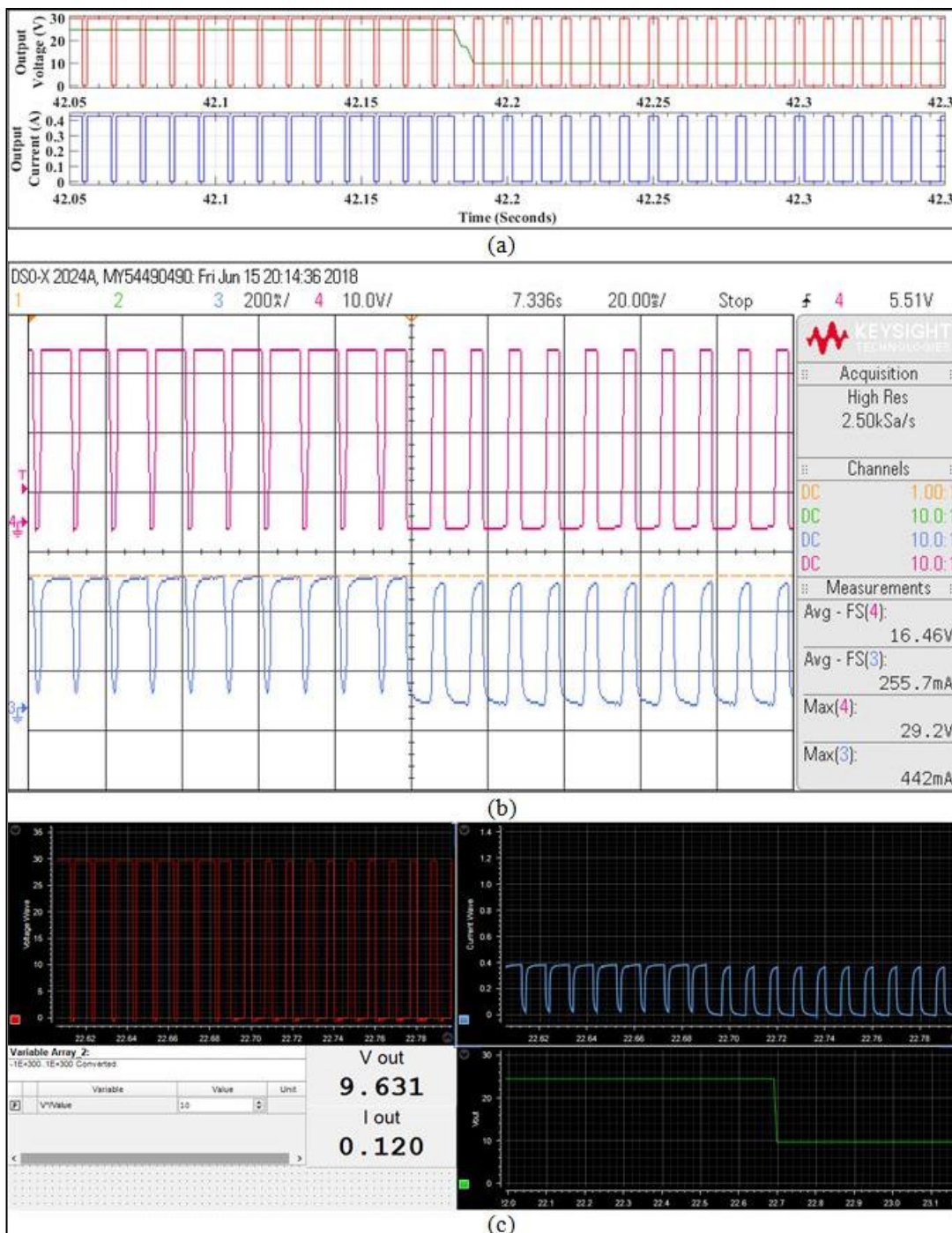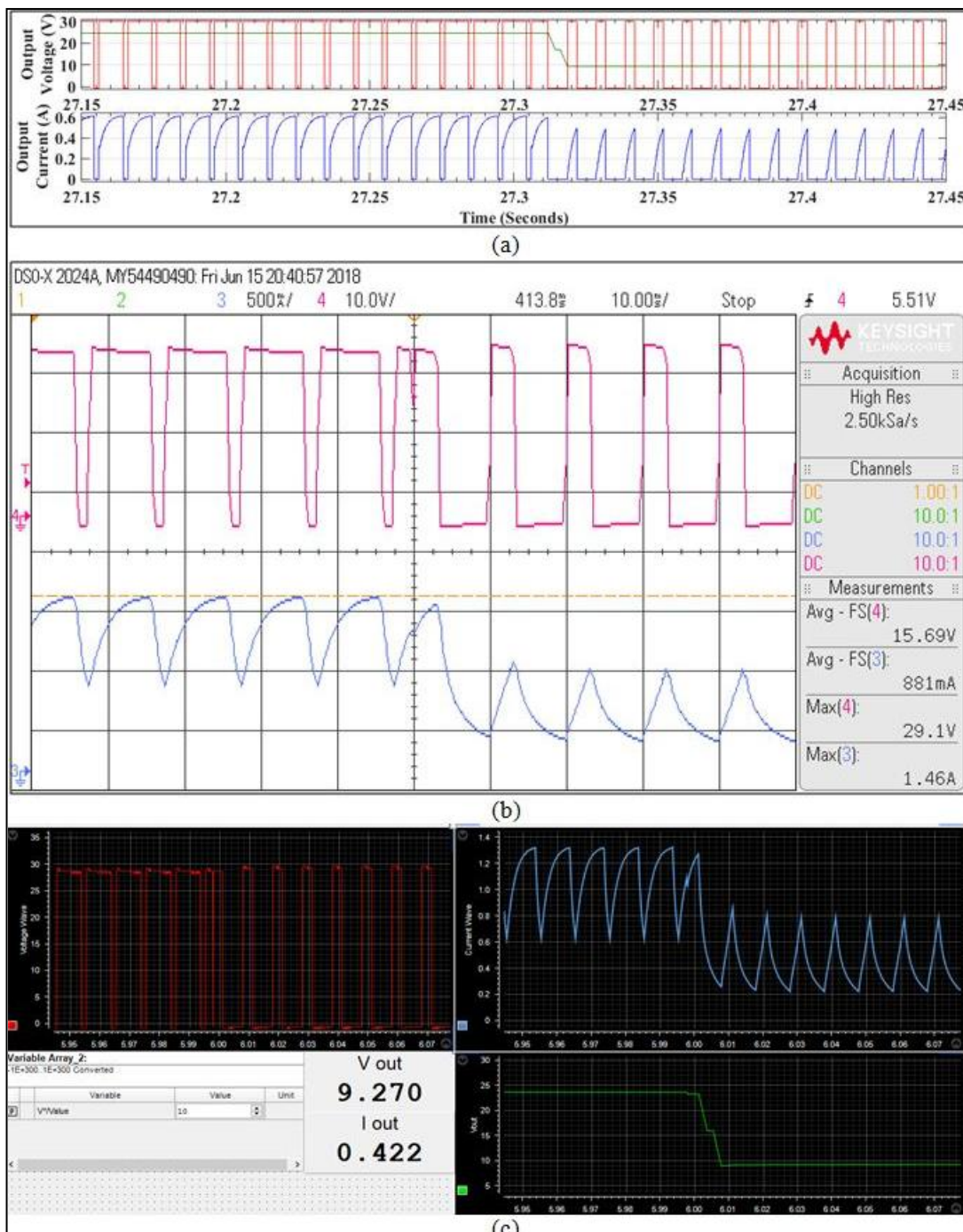
Figure 6.7: Voltage and current output of Class–A Chopper when duty cycle changed from 83.33% to 33.33% for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Aim was to observe the result by suddenly decreasing the duty cycle for RL load. Fig 6.7 shows the output of Class-A Chopper with RL load obtained when duty cycle is suddenly decreased from 83.33% to 33.33%, i.e., the desired output voltage is abruptly decreased from 25V to 10V. It can be observed that output takes almost 1 clock cycles to reach 10V from 25V. A significant decrease in maximum current can be observed as the current is continuous and oscillations are negligible.
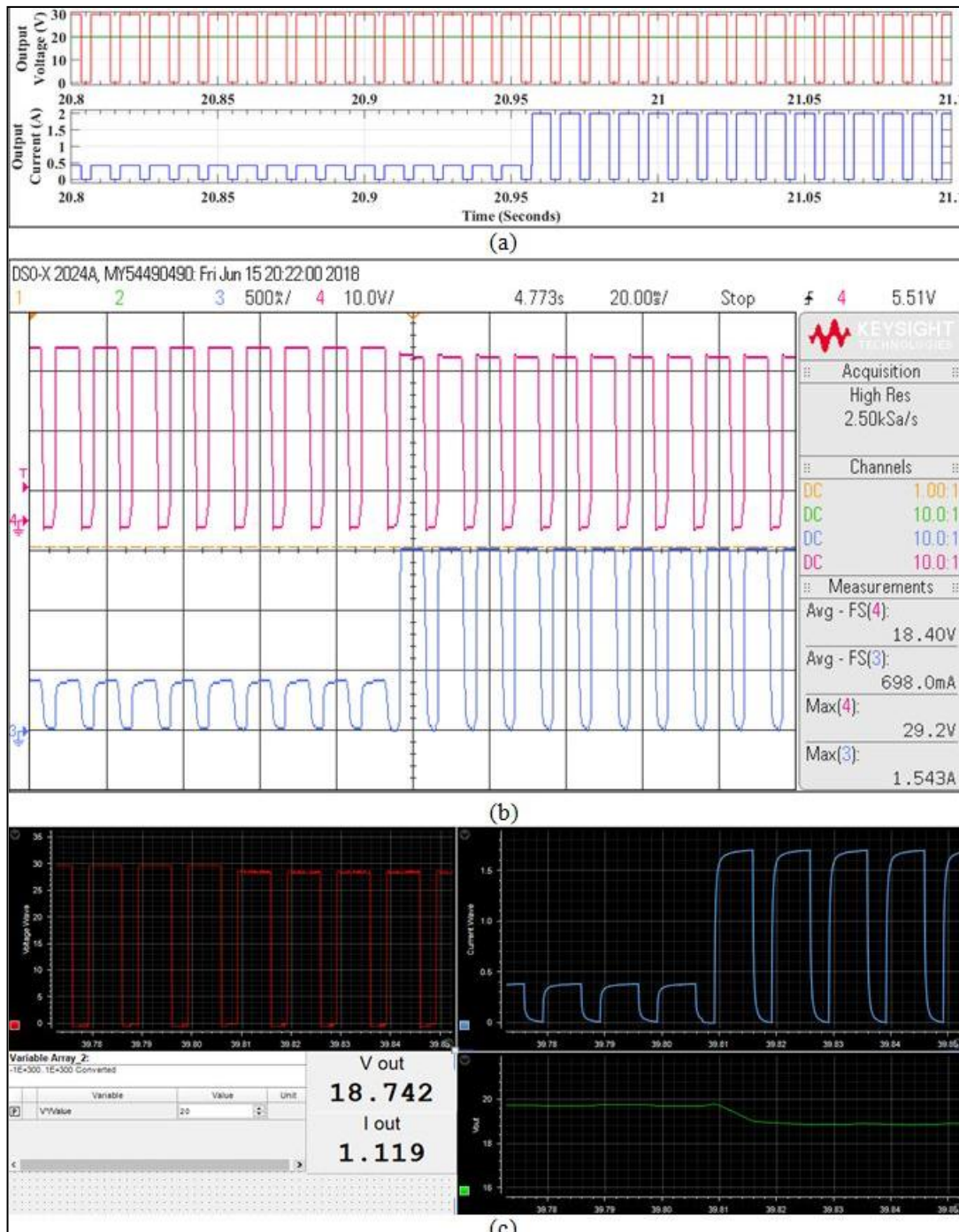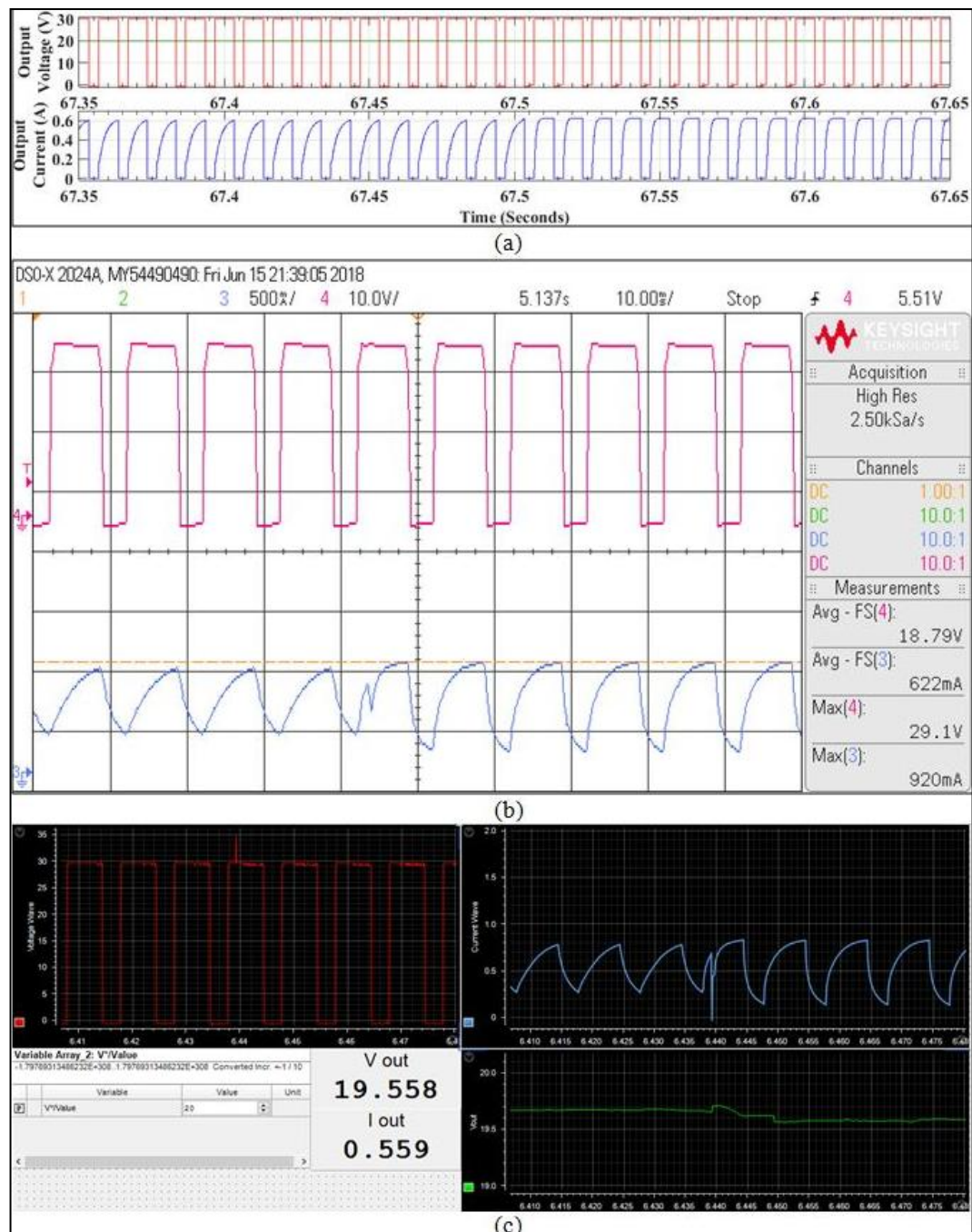
Figure 6.8: Voltage and current output of Class–A Chopper when L is reduced for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Fig 6.8 shows the change in voltage and current waveform when inductance is suddenly halved for an open loop Class-A Chopper operated with RL load. From the output waveforms it can be seen that there is a transient in current and voltage waveform at the point of change of inductance. Mean output voltage also reduces after the inductance is reduced. It can be seen that the minimum value of current is also reduced. It can be concluded that if the inductance is further reduced, than current waveform may even

become discontinuous.
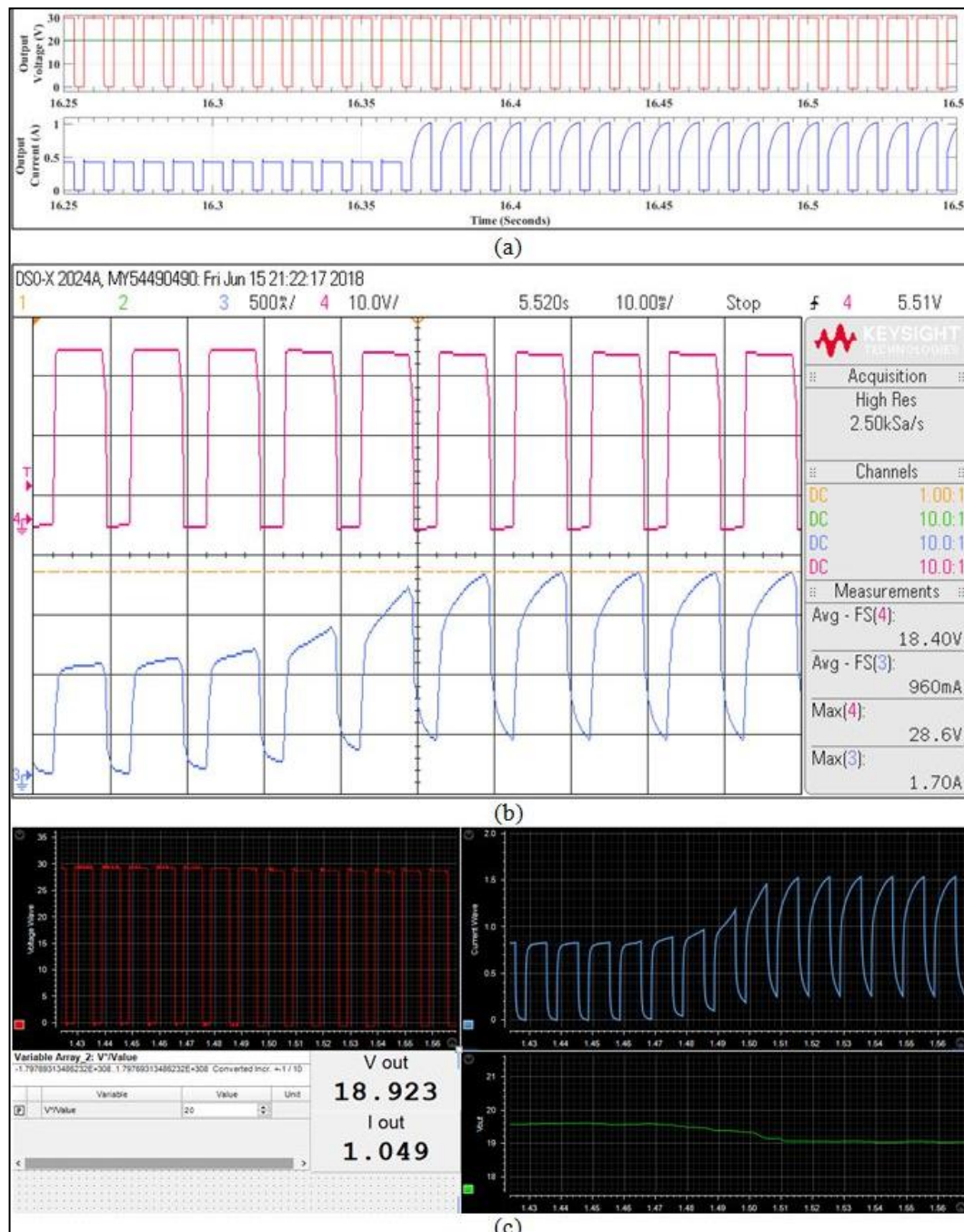
Figure 6.9: Voltage and current output of Class–A Chopper when R is switched parallel to RL:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk

Here, an open loop class-A Chopper was operating with R load and suddenly a RL load is connected parallel to the R load, fig. 6.9 shows the output voltage and current waveform for the same. It can be observed, when only R load was connected, current was discontinuous and as RL is connected in parallel, the current becomes continuous. Moreover, the maximum current also increases because when an RL load is connected

parallel to R load, overall resistance of the load decreases as a result current in circuit increases. Apart from this, there is a subsequent decrease in mean output voltage.

For better understanding of results it is required to have a comparative study between the MATLAB simulation and Hardware results. So, comparison between the results of open loop Class-A Chopper using R load is tabulated below in table 6.5.

Table 6.5: Comparing the MATLAB Simulation and hardware results of Open loop Class-A Chopper with RL load at different duty cycles

Sr No.	Simulation Results (True)				Practical Results (Meas)				%D	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.442	0.075	30	5.16	0.44	0.112	29.3	4.24	16.67	-17.80
2.	0.442	0.146	30	9.95	0.46	0.181	29.2	8.89	33.33	-10.65
3.	0.442	0.221	30	15.04	0.43	0.223	29.2	14.43	50.00	-4.05
4.	0.442	0.296	30	20.13	0.48	0.332	29.3	19.18	66.67	-4.71
5.	0.442	0.367	30	24.92	0.48	0.405	29.3	24.01	83.33	-3.65

Results obtained by varying the duty cycle are mentioned in table 6.5. It can be observed that when desired output voltage is decreased, percentage error gets increased, which means that this configuration of class-A Chopper works best at higher duty cycle.

Table 6.6: Comparing the MATLAB Simulation and hardware results of Open loop Class-A Chopper with RL load by changing the load

Sr No.	Simulation Results (True)				Practical Results (Meas)				R(Ω)	L(H)	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o			
1.	0.980	0.525	30	19.80	0.60	0.451	29.4	18.99	70	0.050	-4.09
2.	1.405	0.800	30	19.75	1.70	1.173	28.3	18.17	15	0.050	-8.00
3.	0.996	0.586	30	19.79	0.92	0.623	28.9	18.79	70	0.025	-5.05

In table 6.6, it can be observed that when resistance is decreased than % error increases, similarly as it was for R load. On the other hand when R is kept constant and L is varied, percentage error remains almost in the tolerance band.

6.1.3   Realization of Open loop Class-A Chopper using RLE Load

For realizing the Open loop Class-A Chopper using RLE load, source is set at a constant voltage of 30V. As already discussed in chapter 5, here a resistive load, inductive load and a DC motor of 12V rating will be connected in series. Back EMF (E_B) of DC motor fulfills the purpose of EMF load here. Results would be recorded at different duty cycle and the change in response will be witnessed.
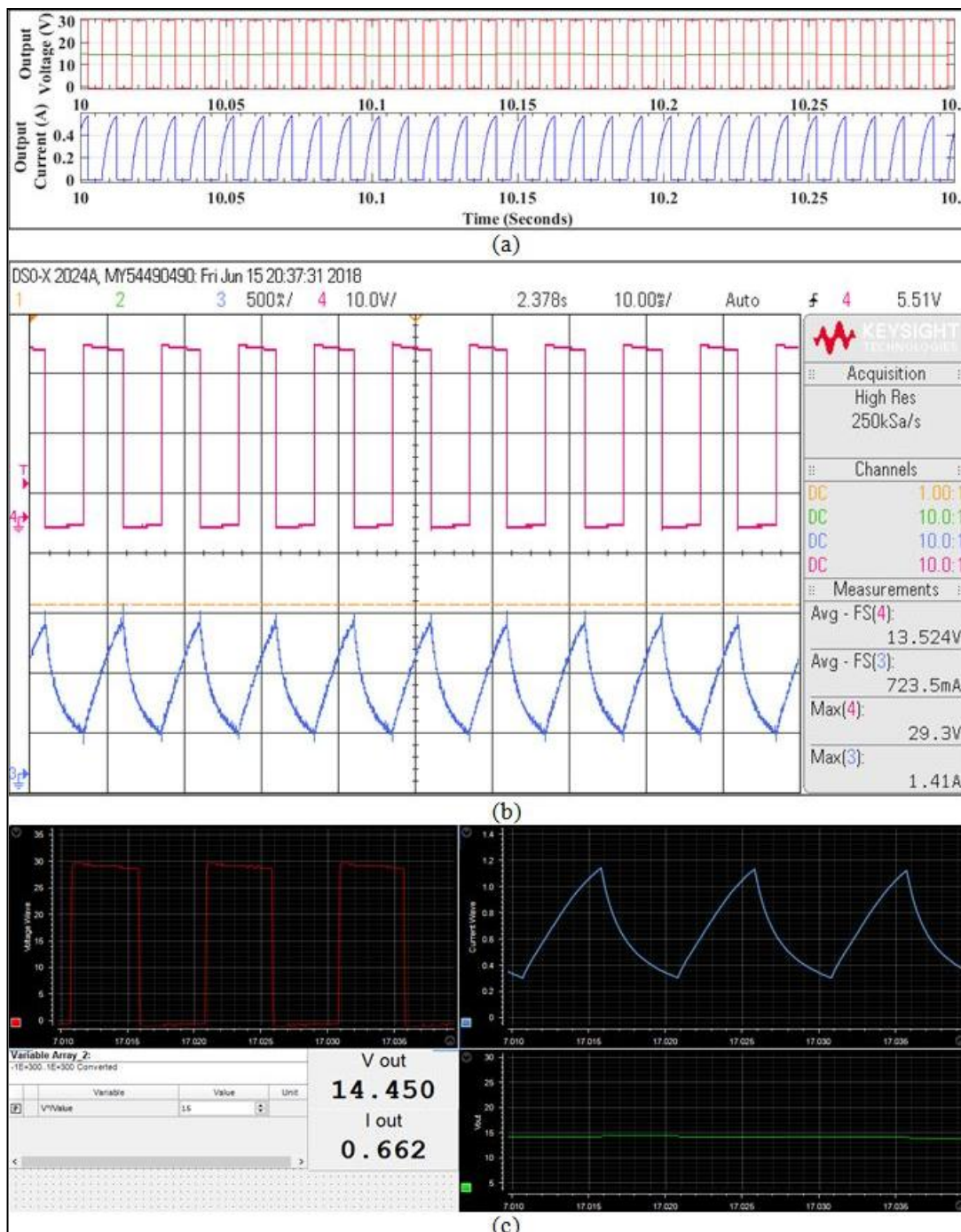
Figure 6.10: Voltage and current output of open loop Class–A Chopper at 50% duty cycle for RLE load :- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Fig 6.10 shows the voltage and current output of open loop Class-A Chopper with RLE load. The current obtained in hardware output is continuous. As the inductance is high, so the ripple in output current is very less, as a result it almost appears as a pulsating DC current. Output voltage is also very near to 15V, as seen from the DSO output mean output voltage is 14.19V.

Figure 6.11: Voltage and current output of open loop Class–A Chopper when duty cycle changed from 50% to 83.33% for RLE load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.11 shows the voltage and current output of open loop Class-A Chopper with RLE load when duty cycle is suddenly changed from 50% to 83.33%. From the waveform it can be seen that the current suddenly increases and takes some time to settle. This is because when duty cycle is increased, output voltage will also be increased and hence

speed of the motor will increase. Therefore when output voltage is increased, initially motor will require more current to reach the desired speed.

Figure 6.12: Voltage and current output of open loop Class–A Chopper when duty cycle changed from 83.33% to 33.33% for RLE load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Voltage and current waveform of open loop Class-A Chopper when duty cycle is decreased from 83.33% to 33.33% is recorded here as shown in fig 6.12. It can be seen that when the duty cycle is decreased, current becomes almost zero for few seconds,

this is because back EMF of DC motor was very high when it was operating at 25V, but when voltage is decreased to10V, then this 10V was less than the Back EMF of motor, so the load becomes almost open circuited until back EMF becomes equal or less than 10V. Once it reaches 10V, again current starts flowing in the circuit and gradually gets increased.

Apart from changing the duty cycle an output was also taken by providing external loading to the motor.
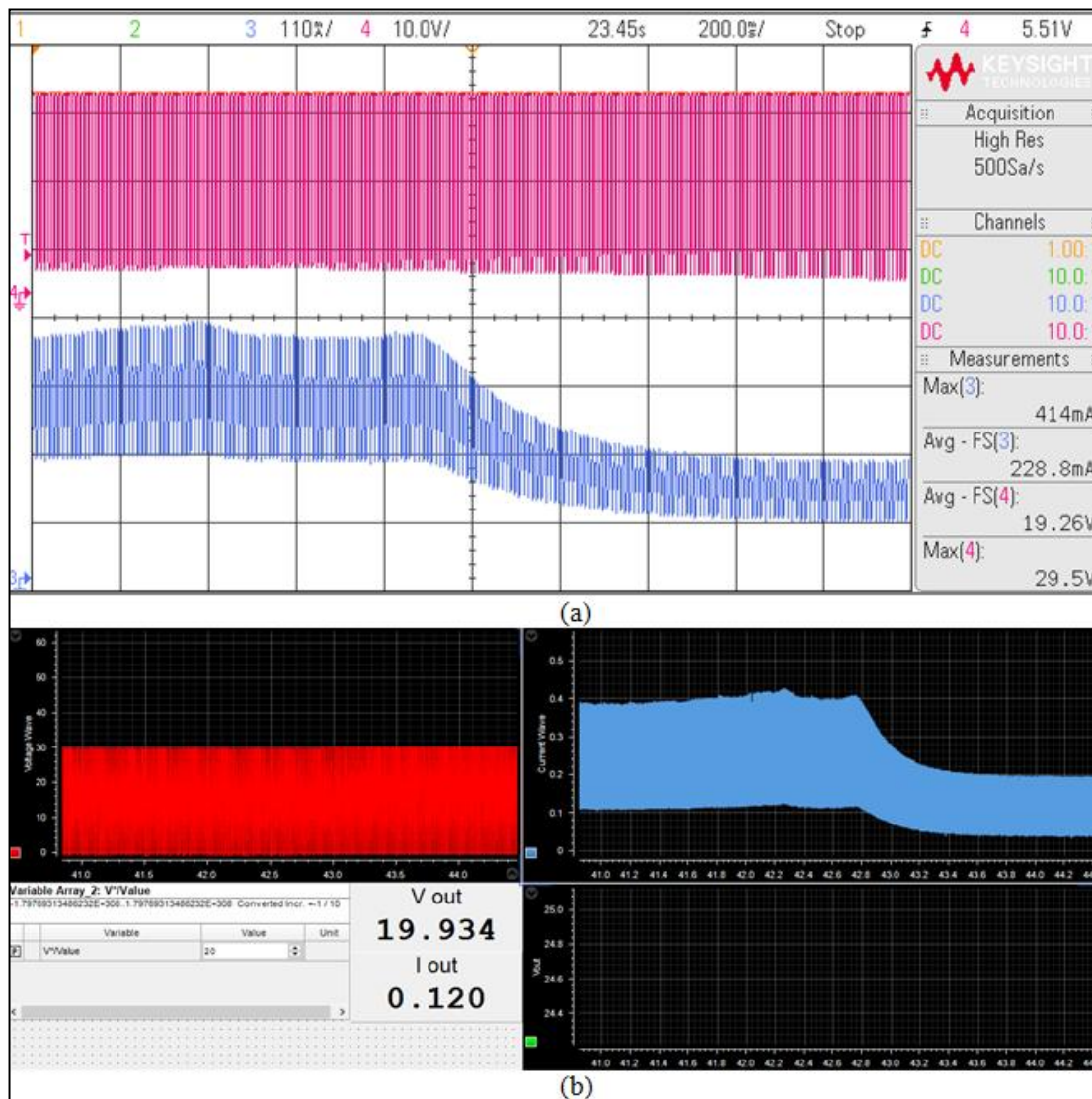
Figure 6.13: Voltage and current waveform of open loop Class - A Chopper with RLE load when External loading is suddenly removed:- (a) Output of hardware at DSO; B: Output of hardware at ControlDesk Software

External loading is applied on DC motor by forcefully stopping the motor using mechanical force and then suddenly loading is removed, output of which is shown in fig 6.13. It can be seen that when loading was provided current was high and

as the loading was removed current decreases and settles to a lower value. This is because an external force is applied against the direction of rotation of motor, so the speed of motor becomes lower than the actual speed. As the speed is less than the actual speed, stator winding will draw more current in order to attain the required speed. Therefore the current is more when external force is applied on motor as loading.

6.2   CLOSED LOOP CLASS-A CHOPPER

As open loop Class-A Chopper was realized by using different types of loads (R load, RL load and RLE load), similarly closed loop Class-A Chopper is also realized using the same approach. Whatever outputs were taken for open loop Class-A Chopper, similar outputs would be taken for closed loop Class-A Chopper with identical working conditions. Closed loop Class-A Chopper is realized in order to get the comparative study between open loop control and closed loop control. Closed loop control can be considered valid only if the error calculated with closed loop control is less than the error calculated with open loop control and the response obtained is better than that of open loop control.

6.2.1   Realization of Closed loop Class-A Chopper using R Load

For realizing the closed loop Class-A Chopper also source voltage will be set at 30V. Different waveforms will be taken by varying the duty cycle and resistance of the load in the same pattern as it was done for open loop Class-A Chopper.
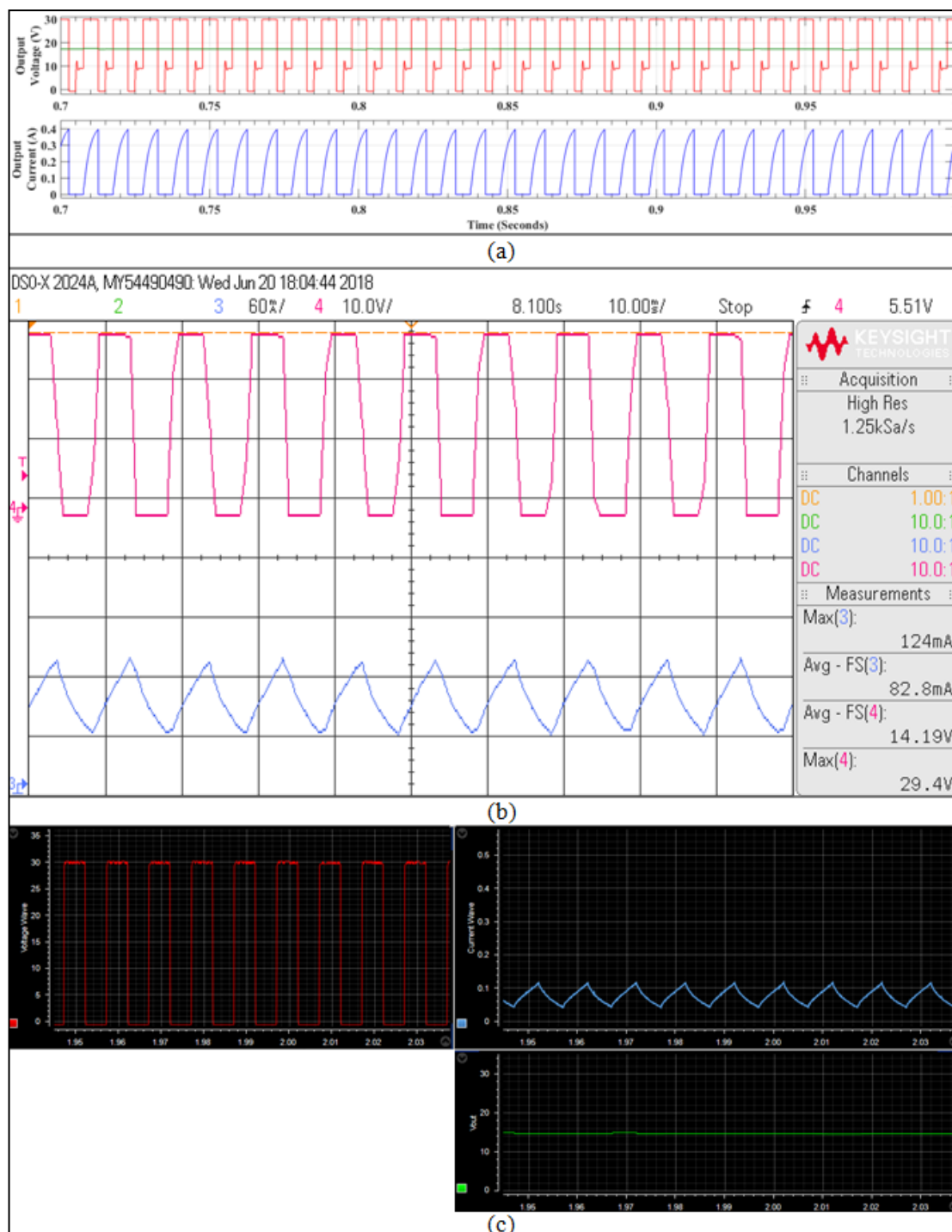
Figure 6.14: Voltage and current output of Closed Loop Class–A Chopper at 50% duty cycle for R load:- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Figure 6.14 shows the output of closed loop Class-A Chopper with resistive load obtained at 50% duty cycle. This implies that the desired output voltage is 15 volts. If compared with open loop results in fig 6.1, output is finer and the mean output voltage is a constant 15V output with no distortions. Moreover, the mean output voltage is very close to 15V unlike the open loop response.
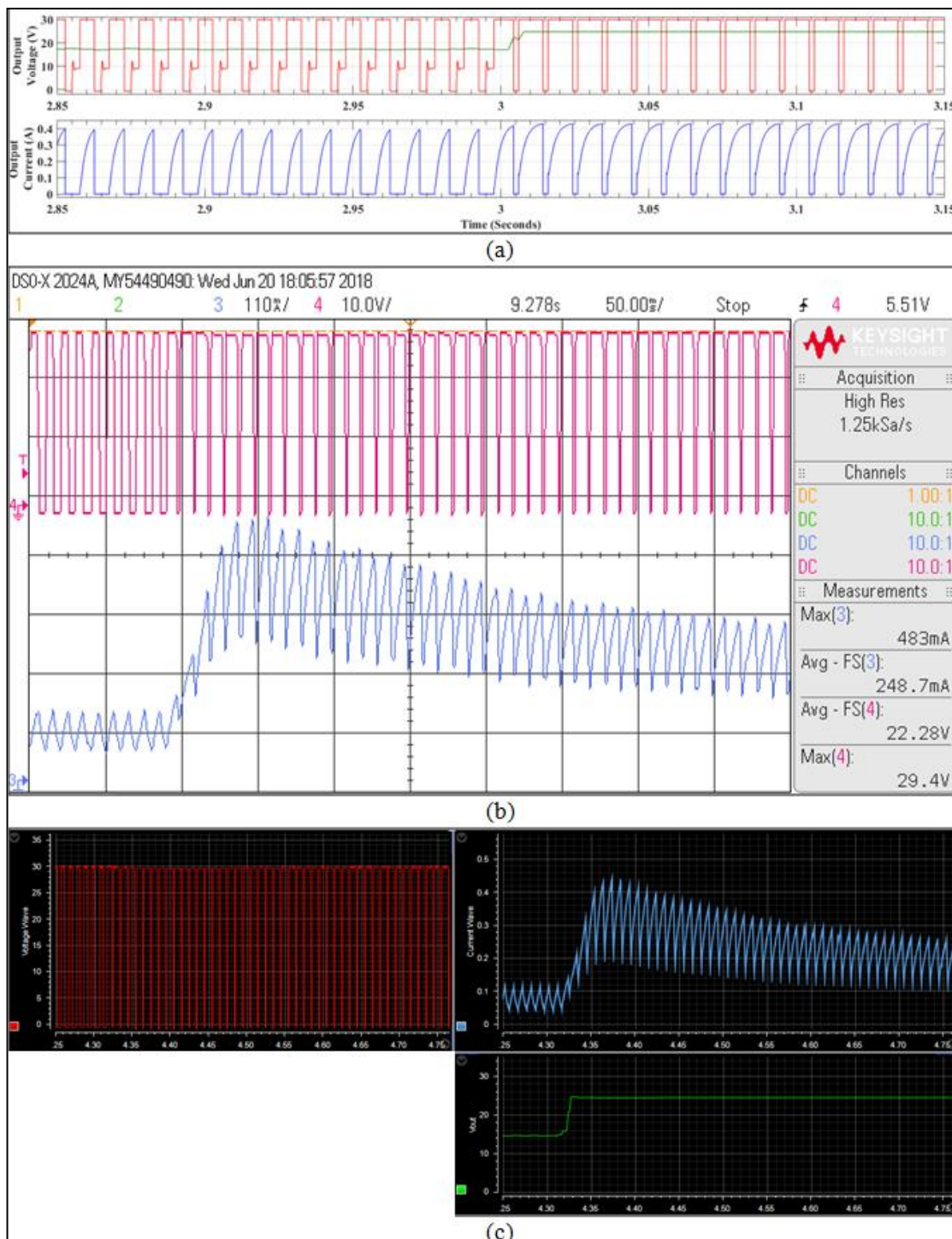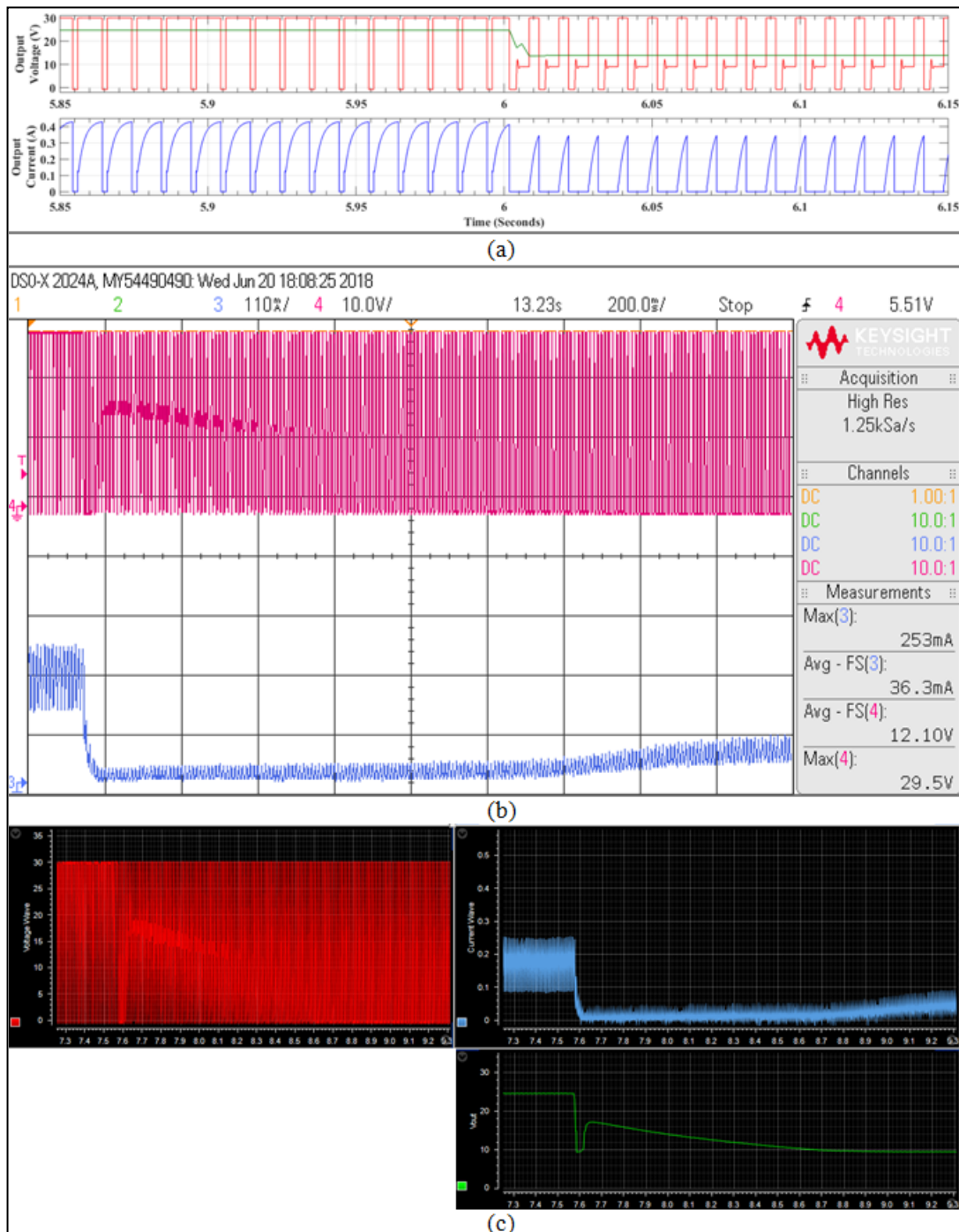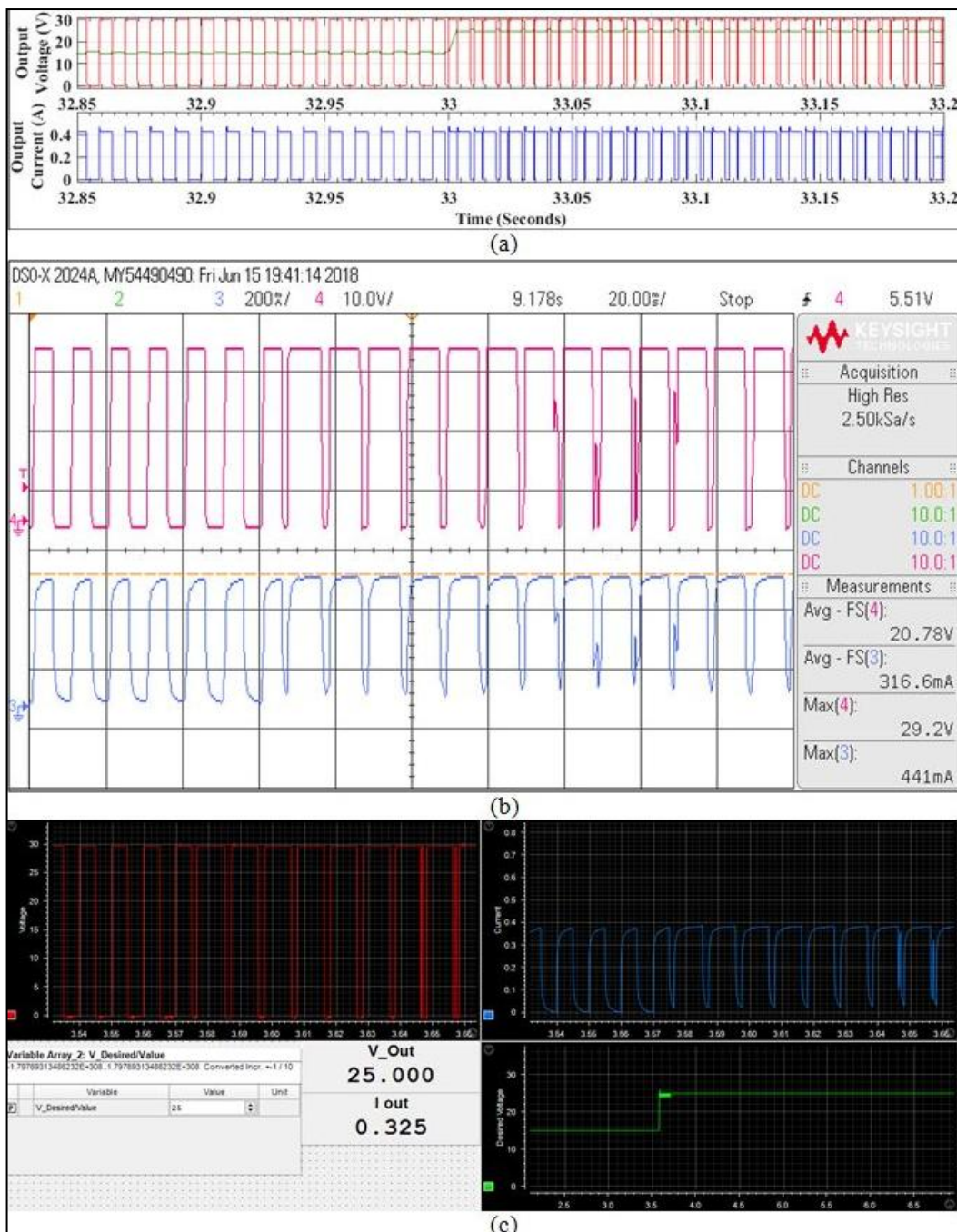
Figure 6.15: Voltage and current output of Closed Loop Class–A Chopper when duty cycle changed from 50% to 83.33% for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.15 shows the output of closed loop Class-A Chopper with resistive load obtained when duty cycle is suddenly increased from 50% to 83.33%, i.e., the desired output voltage is increased from 15V to 25V. It can be seen that the output waveform of voltage and current are finer than the output of open loop Class-A Chopper as shown in fig 6.2. Some oscillations can be seen as duty cycle increases because Chopper circuit is continuously comparing the output with reference value to make output voltage equal

to 25V. Mean output voltage after oscillation is exact 25V.
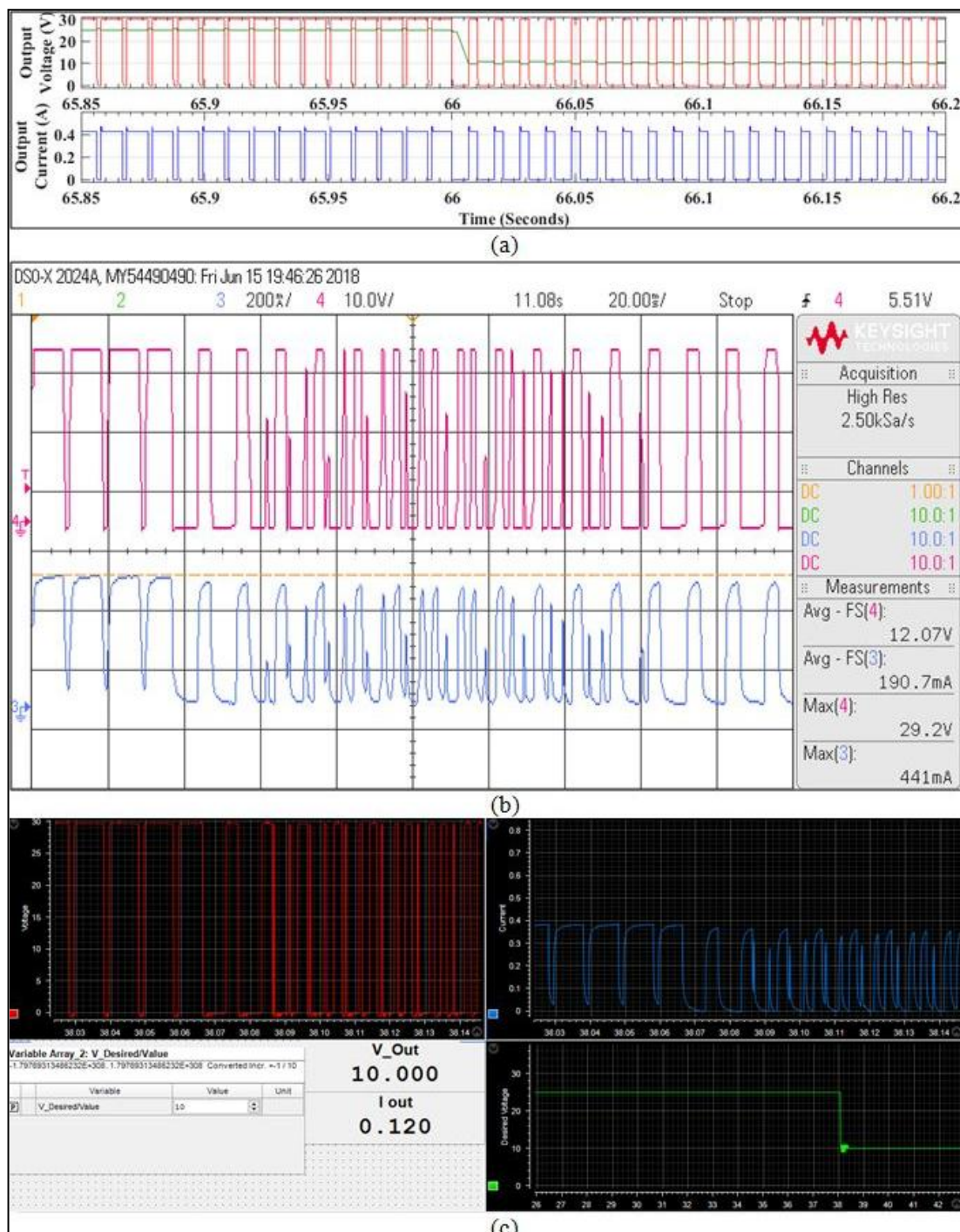
Figure 6.16: Voltage and current output of Closed loop Class–A Chopper when duty cycle changed from 83.33% to 33.33% for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Fig 6.16 shows the output of closed loop Class-A Chopper with resistive load obtained when duty cycle is suddenly decreased from 83.33% to 33.33%, i.e., the desired output voltage is abruptly decreased from 25V to 10V. Some oscillations can be seen as the duty cycle decreases but after oscillation, mean output voltage is exact 10V.
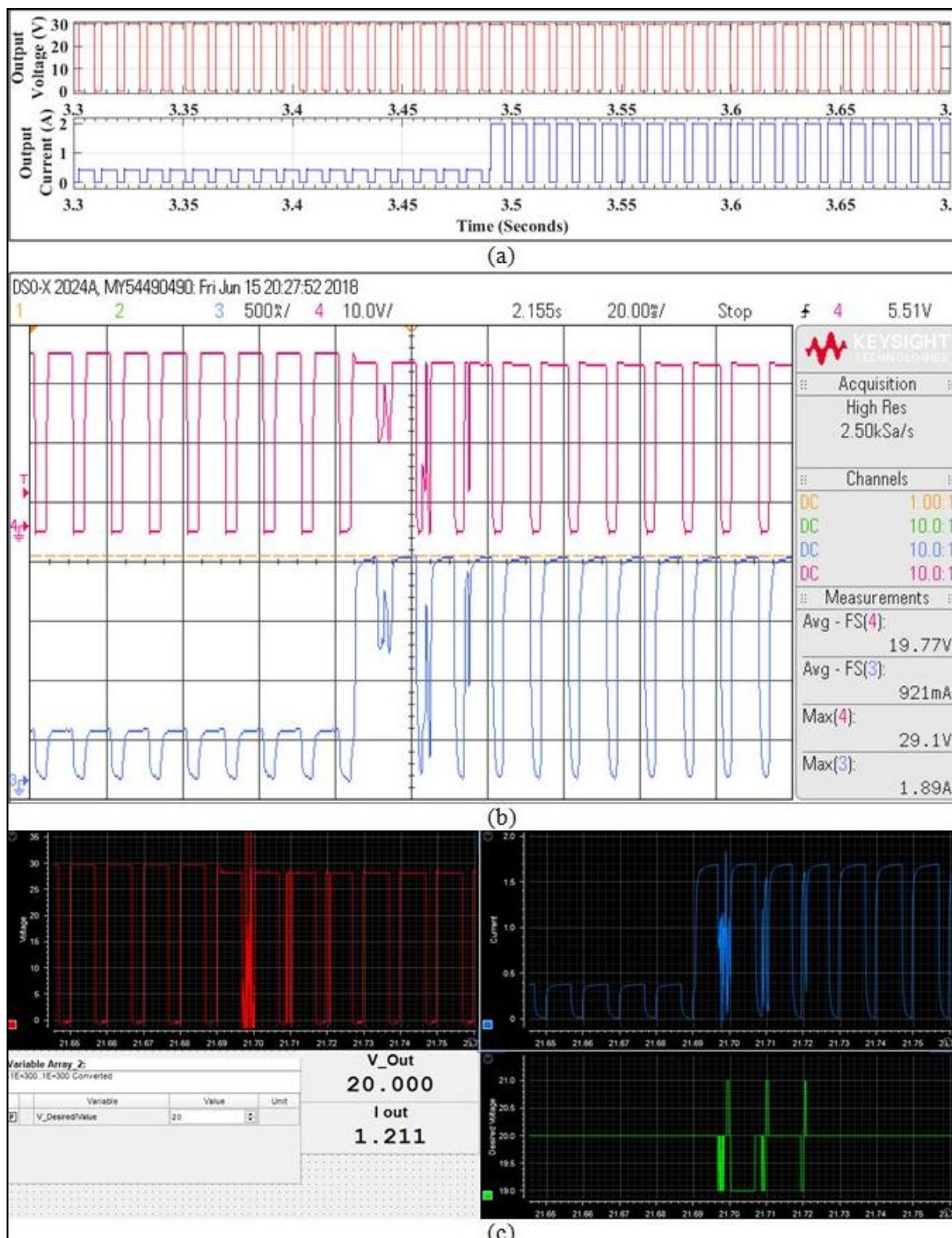
Figure 6.17: Voltage and current output of Closed loop Class–A Chopper when R is varied from 70Ω to 15Ω for R load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk

Fig. 6.17 illustrates the outputs of closed loop Class-A Chopper when load resistance is suddenly changed from R = 70Ω to R = 15Ω. It can be observed that the maximum current has increased from 0.43A to 1.7A. A dip in the maximum voltage can be observed but it can also be observed that the mean output voltage settles back to 20V after few oscillations, i.e., mean output voltage remains constant.

A comparative study between the MATLAB simulation and Hardware results is required for better understanding of results. So, comparison between the results of closed loop Class-A Chopper using R load is tabulated below in table 6.7.

Table 6.7: Comparing the MATLAB Simulation and hardware results of Closed loop Class-A Chopper with R load at different duty cycles

Sr No.	Simulation Results (True)				Practical Results (Meas)				%D	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.43	0.065	30	5	0.450	0.129	29.2	4.79	16.67	-4.20
2.	0.43	0.142	30	10	0.470	0.199	29.2	9.65	33.33	-3.50
3.	0.43	0.213	30	15	0.421	0.221	29.3	15.23	50.00	1.53
4.	0.43	0.279	30	20	0.490	0.351	29.2	19.65	66.67	-1.75
5.	0.43	0.357	30	25	0.490	0.431	29.2	25.08	83.33	0.32

It can be observed in table 6.7 that the percentage error in output voltage lays within ±5% tolerance band. This implies that this error is in the acceptable range. The error is both positive and negative. Maximum voltage almost remains constant throughout.

Table 6.8: Comparing the MATLAB Simulation and hardware results of Closed loop Class-A Chopper with R load by varying the load

Sr No.	Simulation Results (True)				Practical Results (Meas)				$R(\Omega)$	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.43	0.279	30	20	0.490	0.351	29.2	19.65	70	-1.75
2.	1.05	0.700	30	20	1.880	1.359	27.7	19.64	15	-1.80

It can be seen in table 6.8, the maximum voltage decreases when the load resistance decreases and current increases in the same proportion as the resistance decreases. Most important point here is, output voltage remains almost constant as a result % error is constant in both whereas it was seen in open loop Class-A Chopper with R load that when resistance decreased, % error gets increased.

6.2.2 Realization of Closed Loop Class-A Chopper using RL Load

This part of report focuses on the use of resistive as well as inductive load, i.e., RL load for testing the Class-A Chopper in closed loop configuration. As the parameters were varied for open loop Class-A Chopper for RL load, similarly it would be observed for closed loop Class-A Chopper for RL load and later a closed loop Chopper results will be compared with open loop results.

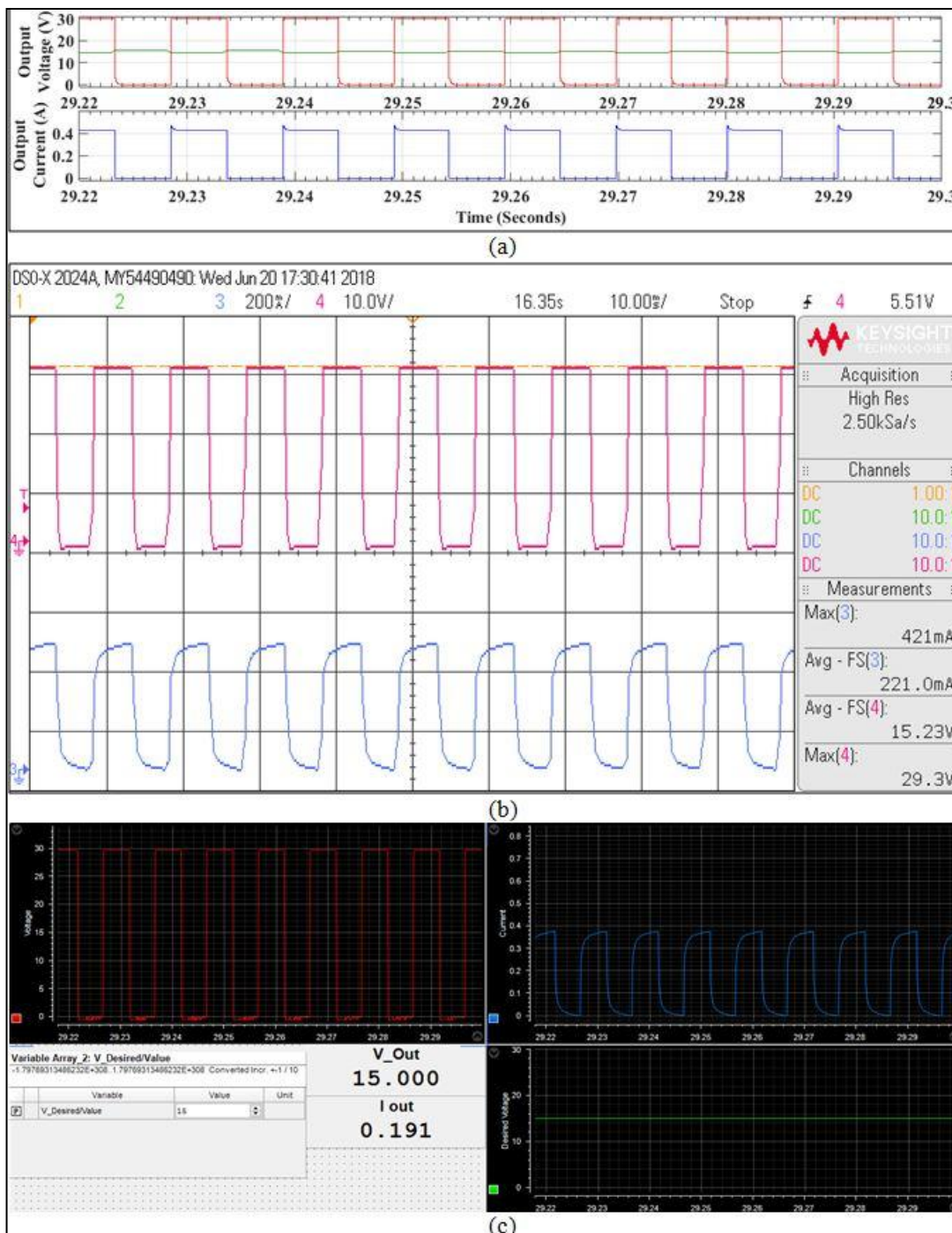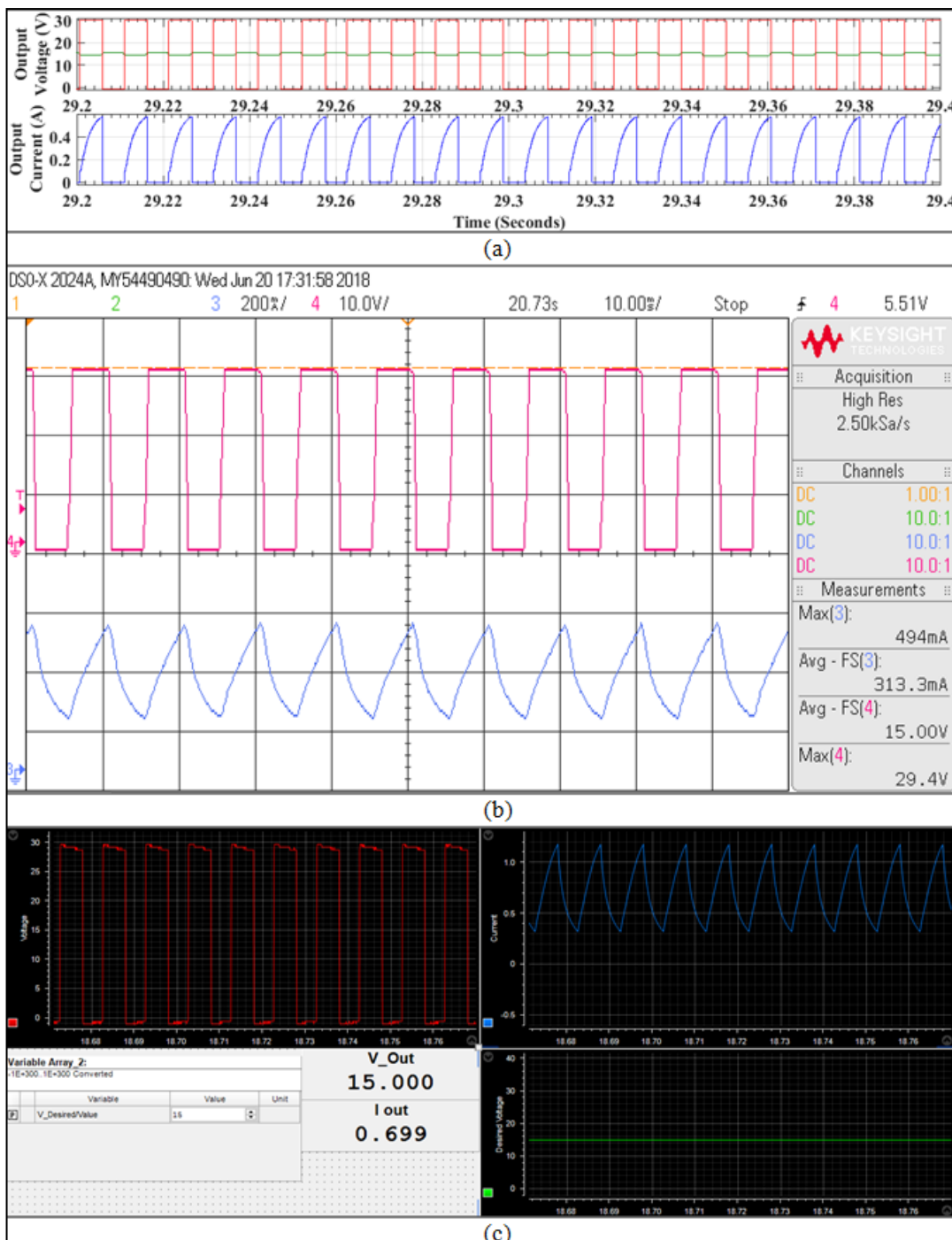**Figure 6.18: Voltage and current output of Class–A Chopper at 50% duty cycle for RL load:- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software**

Figure 6.18 shows the output of a closed loop Class-A Chopper with RL load obtained at 50% duty cycle. This implies that the desired output voltage is 15 volts. It can be observed that the mean output voltage is exact 15V that too without any observable distortions. Output current is a continuous current without any distortions in it.
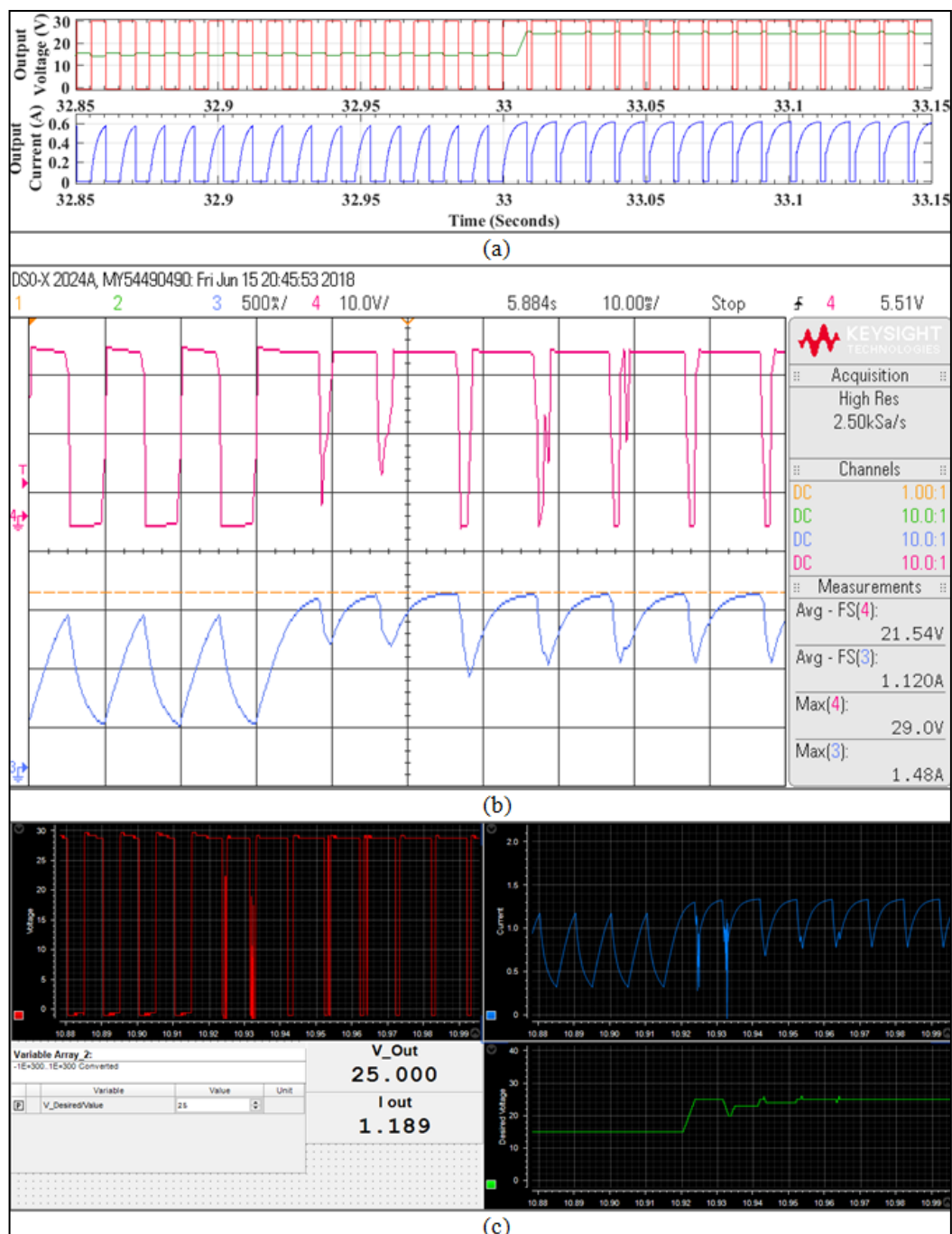
Figure 6.19: Voltage and current output of Class–A Chopper when duty cycle changed from 50% to 83.33% for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.19 shows the output of closed loop Class-A Chopper with RL load obtained when duty cycle is suddenly increased from 50% to 83.33%, i.e., the desired output voltage is increased from 15V to 25V. Some oscillations can be seen as duty cycle increases because Chopper circuit is continuously comparing the output with reference value to make output voltage equal to 25V. Mean output voltage after oscillation is exact 25V.
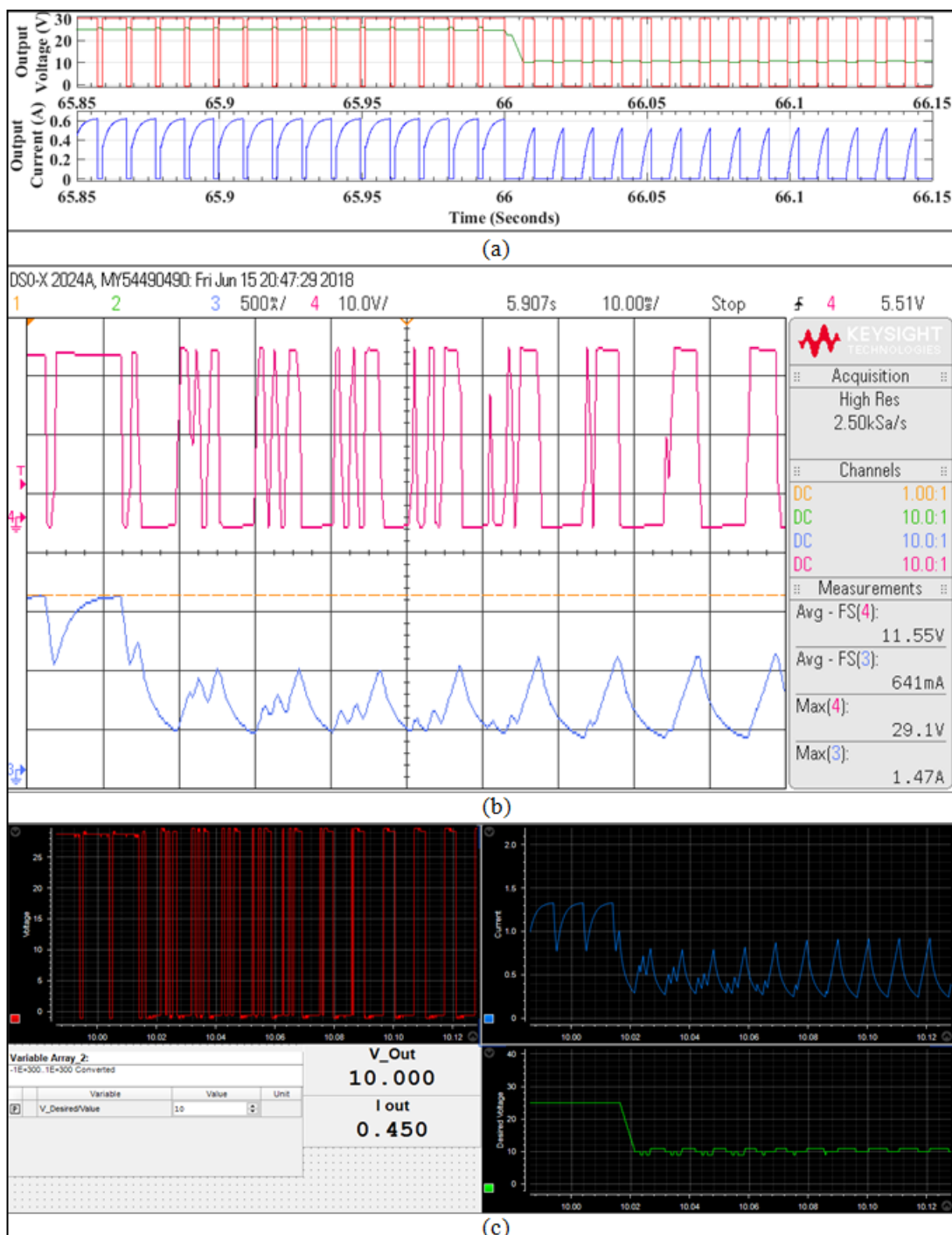
Figure 6.20: Voltage and current output of Class–A Chopper when duty cycle changed from 83.33% to 33.33% for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Fig 6.20 shows the output of closed loop Class-A Chopper with RL load obtained when duty cycle is suddenly decreased from 83.33% to 33.33%, i.e., the desired output voltage is abruptly decreased from 25V to 10V. Some oscillations can be seen as the duty cycle decreases but after oscillation, mean output voltage reaches to 10V. Oscillations are for more duration, when duty cycle is suddenly decreased.
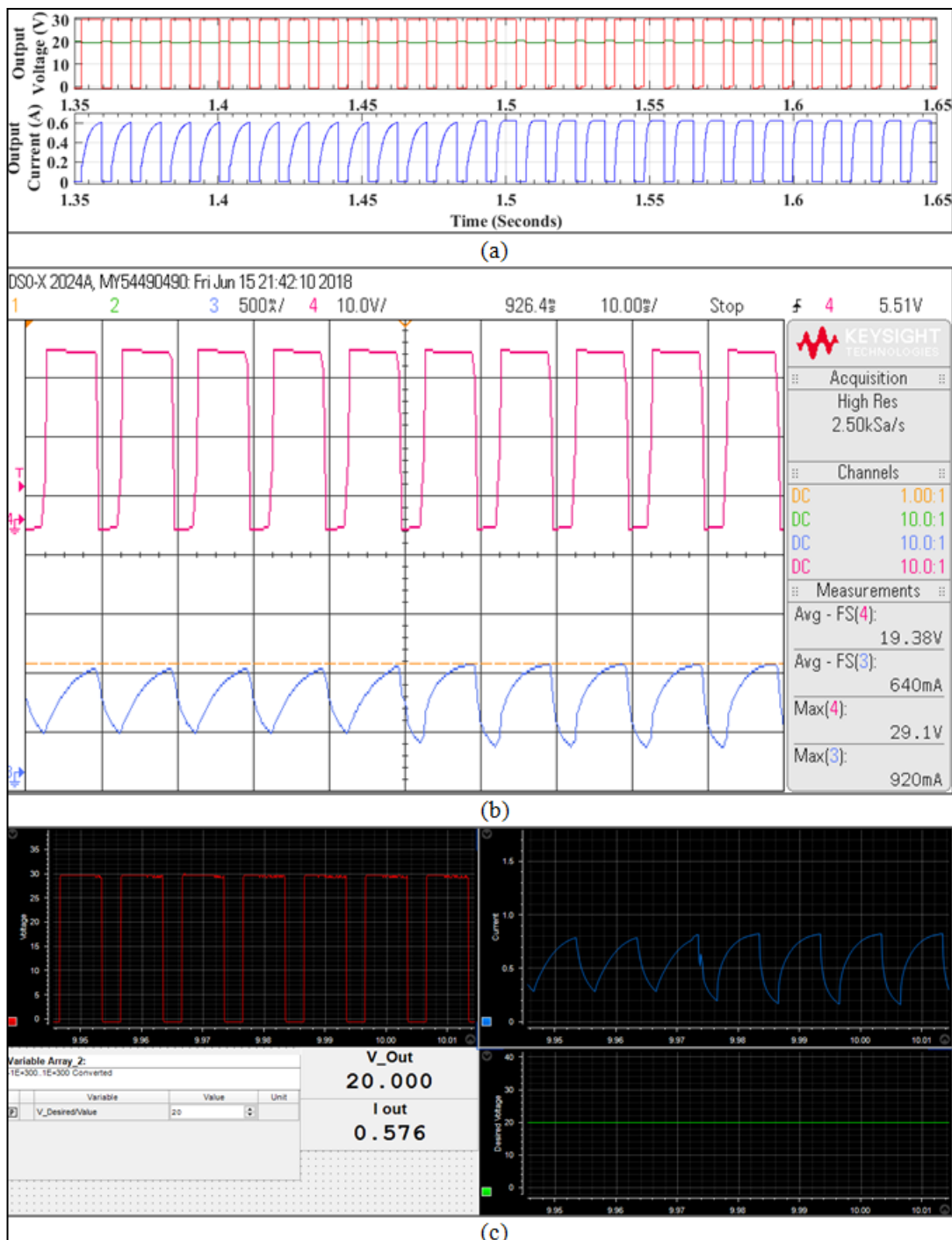
Figure 6.21: Voltage and current output of Class–A Chopper when L is reduced for RL load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Fig 6.21 shows the change in voltage and current waveform when inductance is suddenly halved for a closed loop Class-A Chopper operated with RL load. On suddenly reducing the load inductance to half, it can be observed that the mean output voltage remains constant at 20V without any noticeable oscillation. There is a change is current waveform with very small oscillation.
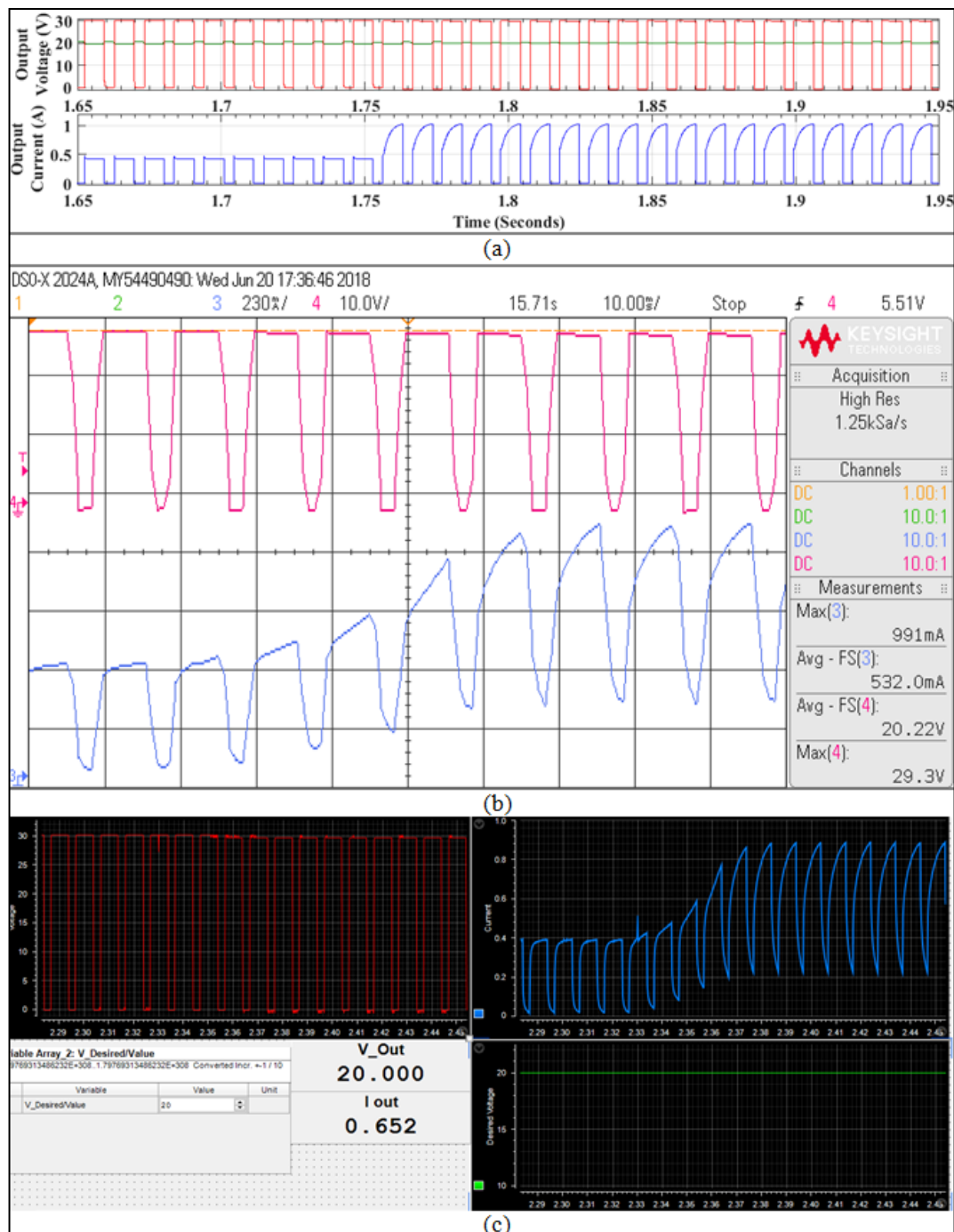
Figure 6.22: Voltage and current output of Class–A Chopper when R is switched parallel to RL:-
(a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at
ControlDesk

Here, a closed loop class-A Chopper was operating with R load and suddenly a RL load is connected parallel to the R load, fig 6.22 shows the output voltage and current waveform for the same. Again it can be observed that on changing load there is very small oscillation in output current waveform while mean output voltage remains constant at 20V with almost zero oscillations. From the obtained results it can be concluded that in closed loop control of Class-A Chopper with RL load, mean voltage

almost remains constant for all load variations.

In order to comprehend the results, a relative study of MATLAB Simulations and Hardware results is desirable. So, results of closed loop Class-A Chopper with RL load are compared in the following table. Simulation results are considered as theoretical results here.

Table 6.9: Comparing the MATLAB Simulation and hardware results of Closed loop Class-A Chopper with RL load at different duty cycles

Sr No.	Simulation Results (True)				Practical Results (Meas)				%D	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o		
1.	0.06	0.064	30	5	0.2	0.159	29.5	4.76	16.67	-4.80
2.	0.85	0.200	30	9.85	0.39	0.265	29.4	9.38	33.33	-4.77
3.	0.95	0.356	30	15	0.494	0.313	29.4	15.00	50.00	0.00
4.	0.98	0.525	30	20	0.63	0.478	29.3	19.58	66.67	-2.10
5.	0.99	0.720	30	25	0.670	0.592	29.2	24.93	83.33	-0.28

In table 6.9 it can be noticed that the percentage error in output voltage lies within ±5% tolerance band, which is considered as acceptable. It can be observed that at 50% duty cycle there is zero error. As the duty cycle increases, maximum current in the circuit increases.

Table 6.10: Comparing the MATLAB Simulation and hardware results of Closed loop Class-A Chopper with RL load by varying the load

Sr No.	Simulation Results (True)				Practical Results (Meas)				$R(\Omega)$	$L(H)$	%e in V_o
	I_{max}	I_o	V_{max}	V_o	I_{max}	I_o	V_{max}	V_o			
1.	0.98	0.525	30	20	0.63	0.478	29.3	19.58	70	0.050	-2.1
2.	1.40	0.840	30	20	0.99	0.532	29.3	20.00	15	0.050	0.0
3.	0.99	0.600	30	20	0.93	0.646	29.0	19.36	70	0.025	-3.2

Table 6.10 shows the comparison of simulation and hardware results of closed loop Class-A Chopper using RL load. It can be seen the error is very less and within the permissible range. It can be seen that when the resistance is reduced and inductance is kept constant error is exactly zero.

6.2.3 Realization of Closed Loop Class-A Chopper using RLE Load

As the response of open loop Class-A Chopper using RLE load was observed similarly closed loop response of the same will also be recorded and observed at different duty cycle. Result of external loading will also be observed here.
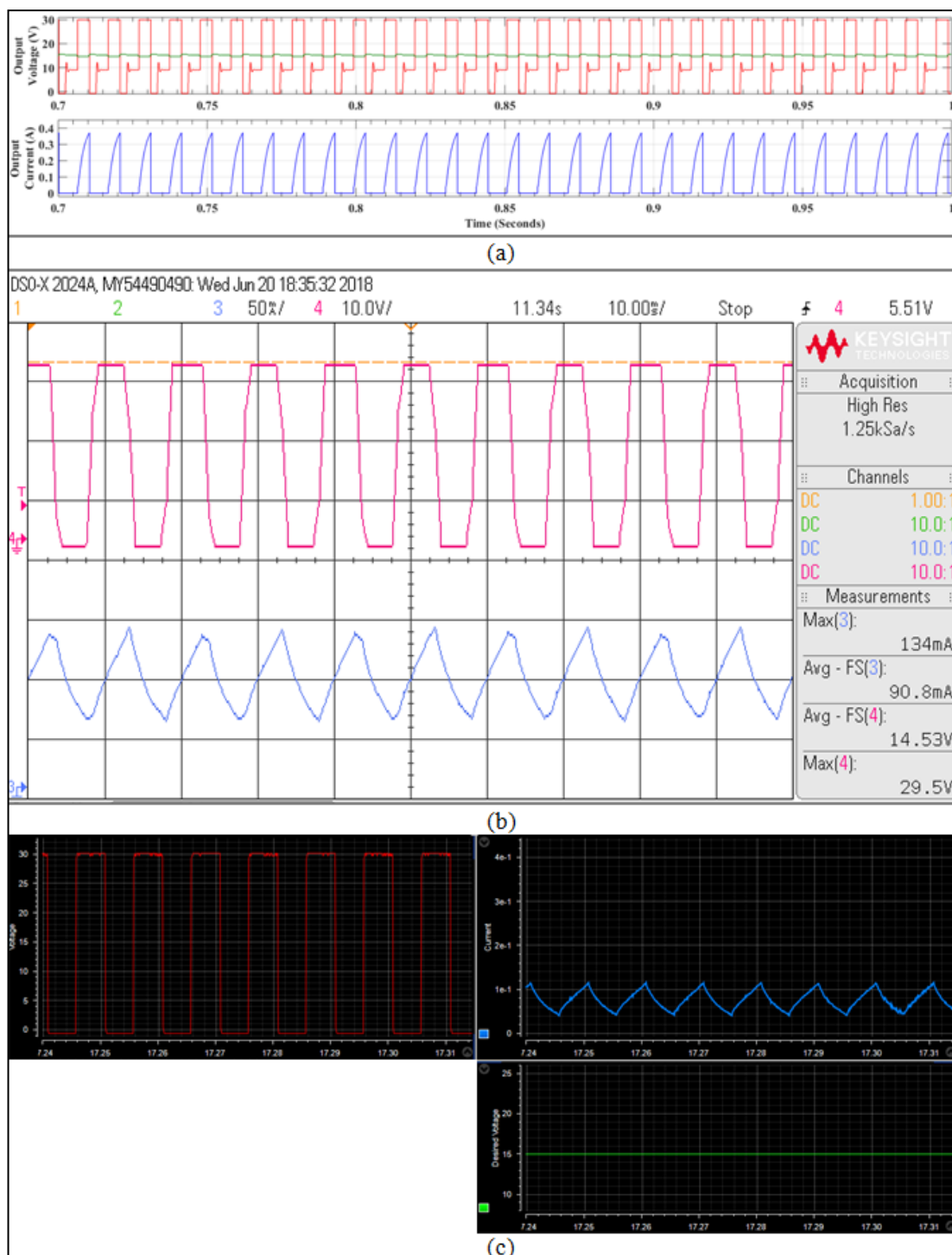
Figure 6.23: Voltage and current output of closed loop Class–A Chopper at 50% duty cycle for RLE load :- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Fig 6.23 shows the voltage and current output of open loop Class-A Chopper with RLE load. The current obtained in hardware output is continuous. As the inductance is high, so the ripple in output current is very less, as a result it almost appears as a pulsating DC current. Output voltage is also very near to 15V, as seen from the DSO output mean

output voltage is 14.53V. Results are identical to open loop Class-A Chopper with RLE load but output voltage is better in closed loop control of the Chopper.
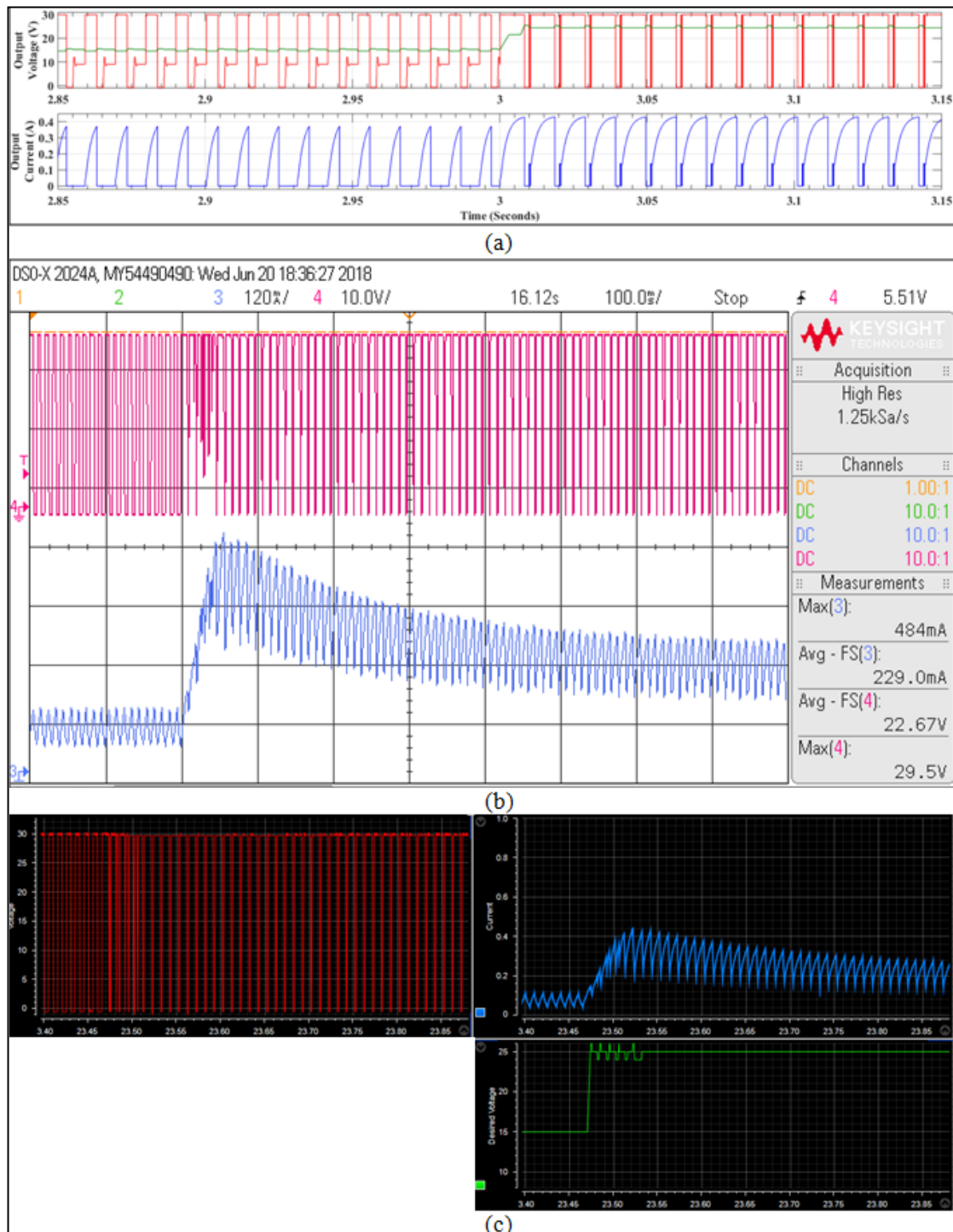
Figure 6.24: Voltage and current output of closed loop Class–A Chopper when duty cycle changed from 50% to 83.33% for RLE load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.24 shows the voltage and current output of closed loop Class-A Chopper with RLE load when duty cycle is suddenly changed from 50% to 83.33%, i.e., switching

output voltage from 15V to 25V. Current and voltage waveforms are identical to those of open loop Class-A Chopper with RLE load. The only difference is, output voltage settles at exact 25V after few oscillations and current waveform takes lesser time to settle.
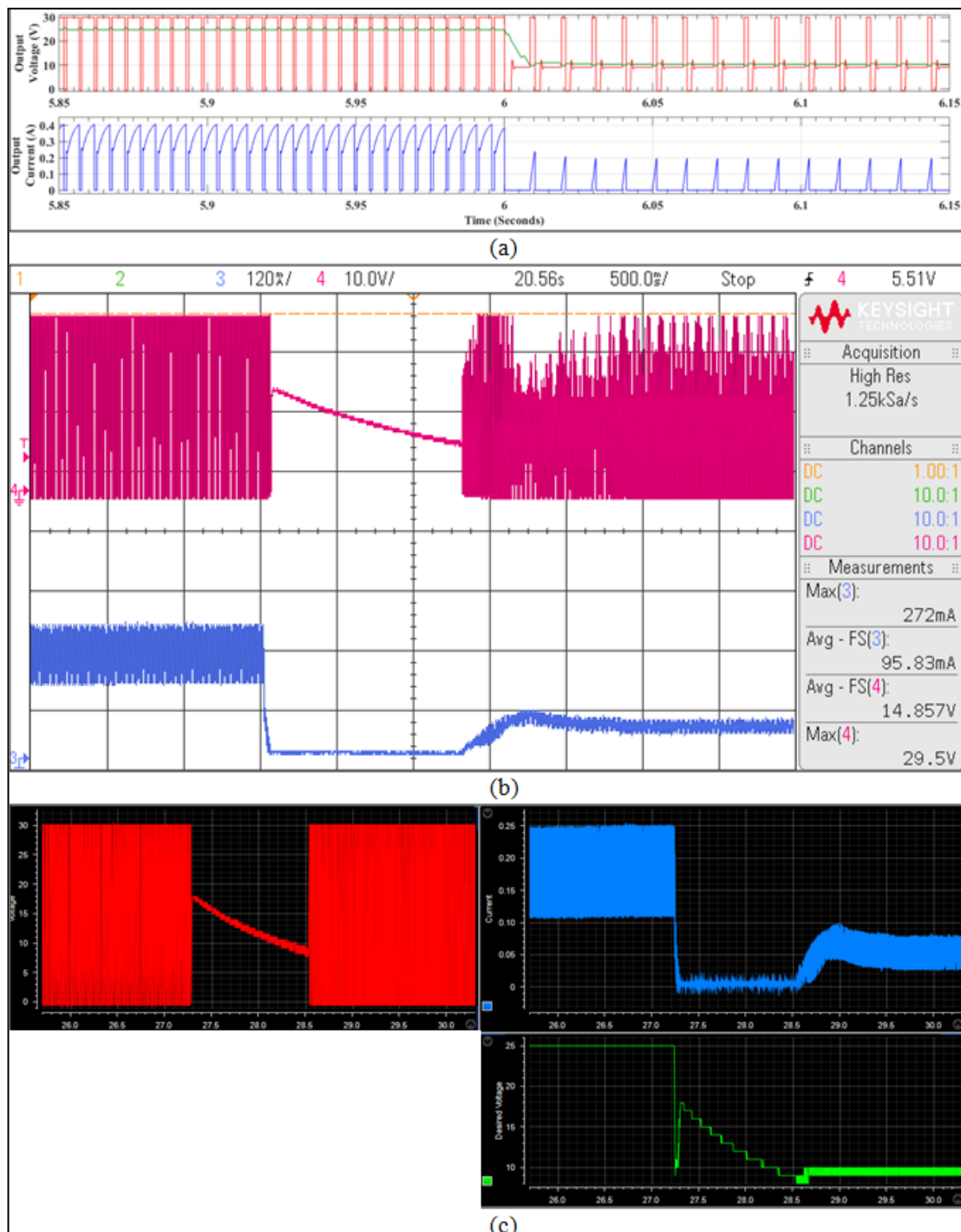
Figure 6.25: Voltage and current output of closed loop Class–A Chopper when duty cycle changed from 83.33% to 33.33% for RLE load:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware at ControlDesk Software

Fig 6.25 shows the voltage and current waveform of closed loop Class-A Chopper for

RLE load when duty cycle is suddenly reduced from 83.33% to 33.33%, i.e., switching output voltage from 25V to 10V. Current and voltage waveforms are identical to those of open loop Class-A Chopper with RLE load. It can be observed that the output current becomes zero at the switching instant for few seconds and the time duration for which current is zero is less than that of open loop RLE load current waveform. It can be seen that when current is zero voltage is decreasing from 18V to 9V, this is because the back EMF of voltage is getting decreased and as and when it becomes less than 10V, current starts increasing and settles to desired current.

Apart from changing the duty cycle an output was also taken by providing external loading to the motor.
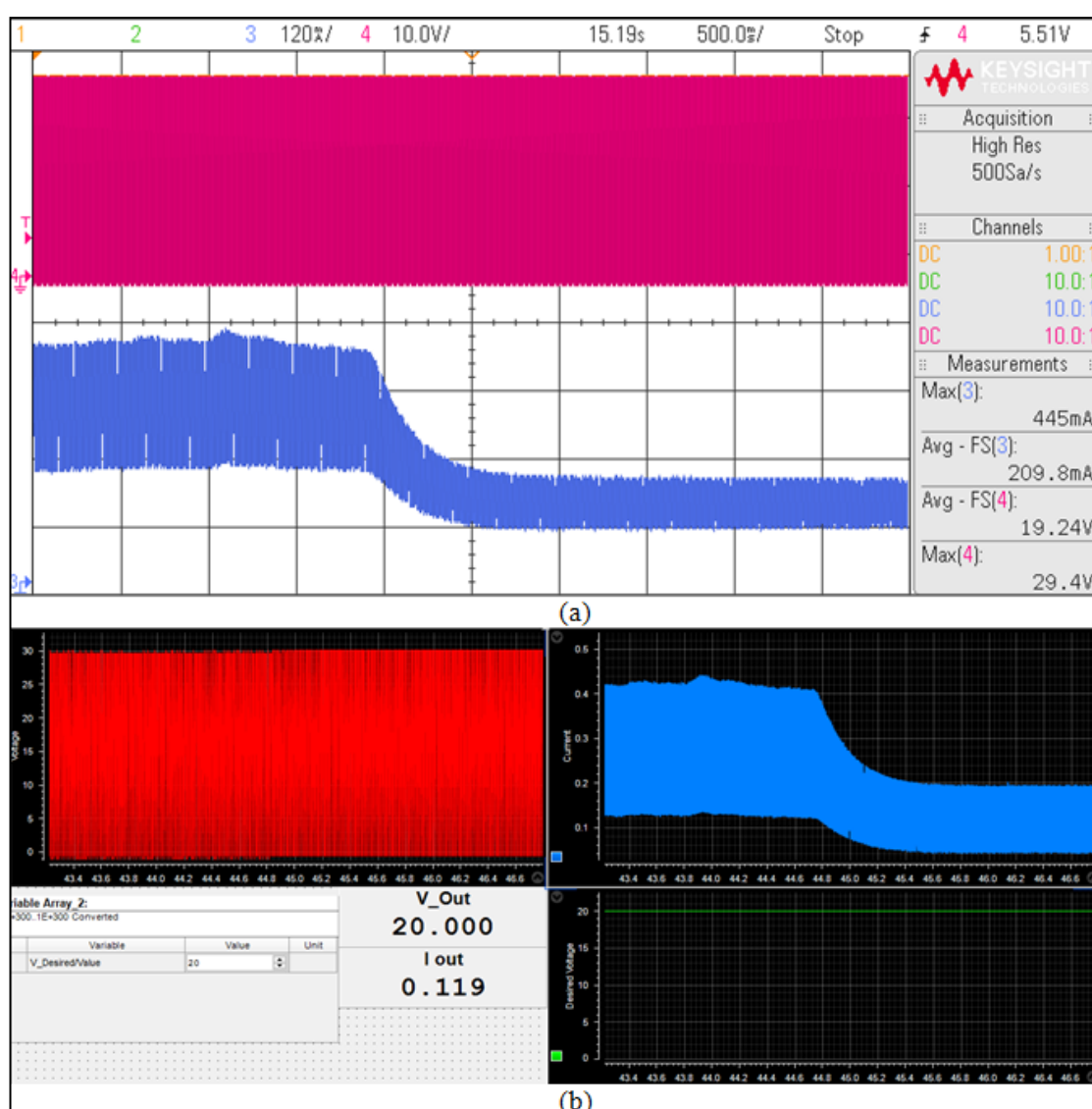
Figure 6.26: Voltage and current waveform of closed loop Class - A Chopper with RLE load when External loading is suddenly removed:- (a) Output of hardware at DSO; B: Output of hardware at ControlDesk Software

Fig 6.26 shows the output of closed loop Class-A Chopper with RLE load when external loading is suddenly removed. Concept of external loading is same as it was for the open loop Class-A Chopper with same RLE load. It can be seen that all the waveforms are identical to that of open loop Class-A Chopper. The only noticeable difference is the time taken by circuit to settle down is lesser than open loop control.

6.3   OPEN LOOP CLASS – B CHOPPER

Choppers can be classified on the basis of operating quadrants according to the VI graph. Class-A chopper and Class-B chopper are single quadrant choppers as these operate in any one quadrant of VI graph. Class-A chopper operates in first quadrant of VI graph, i.e., Voltage and current is always positive but Class-B chopper operates in second quadrant of VI graph, i.e., voltage is positive but current is negative.
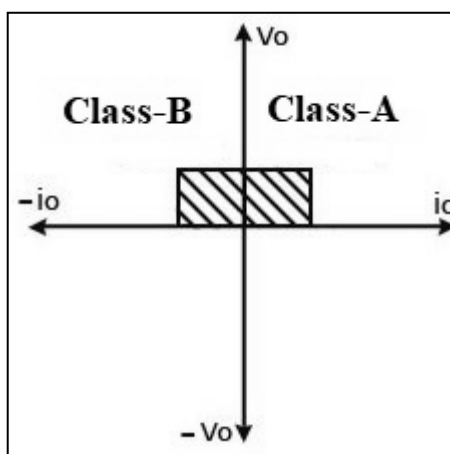
Figure 6.27: VI Graph showing the Operating Quadrant of Chopper

Class-B chopper require RLE load for its operation. For the analysis of Class-B chopper, source voltage of 30V and in load a resistor of 48Ω, an inductor of 100mH and an EMF of 15V is used. Current in Class-B chopper is negative and it flows back to source which can be used in regenerative braking.
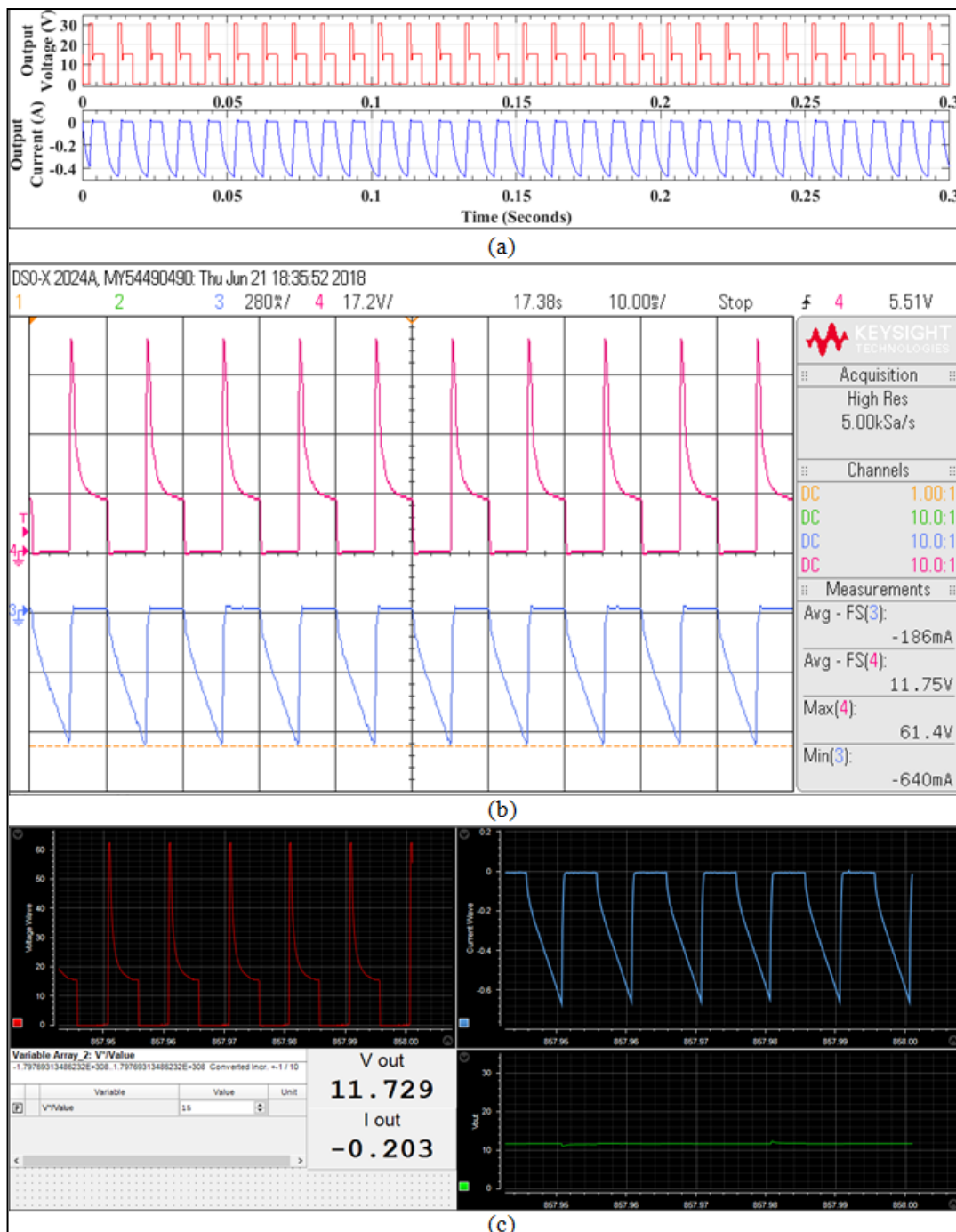
Figure 6.28: Voltage and current output of Open Loop Class–B Chopper at 50% duty cycle:- (a) Output of Schematic in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk Software

Fig 6.28 shows the voltage and current output of open loop Class-B chopper at 50% duty cycle, i.e, 15V desired output voltage. It can be seen that the current flowing is negative and there is a peak seen in the voltage waveform, this is because of the load EMF and load inductance. Inductance has stored current which it supplies to source when switch is OFF which increases the source voltage, when switch is turned ON inductor current slowly decreases resulting in decrease of source voltage.
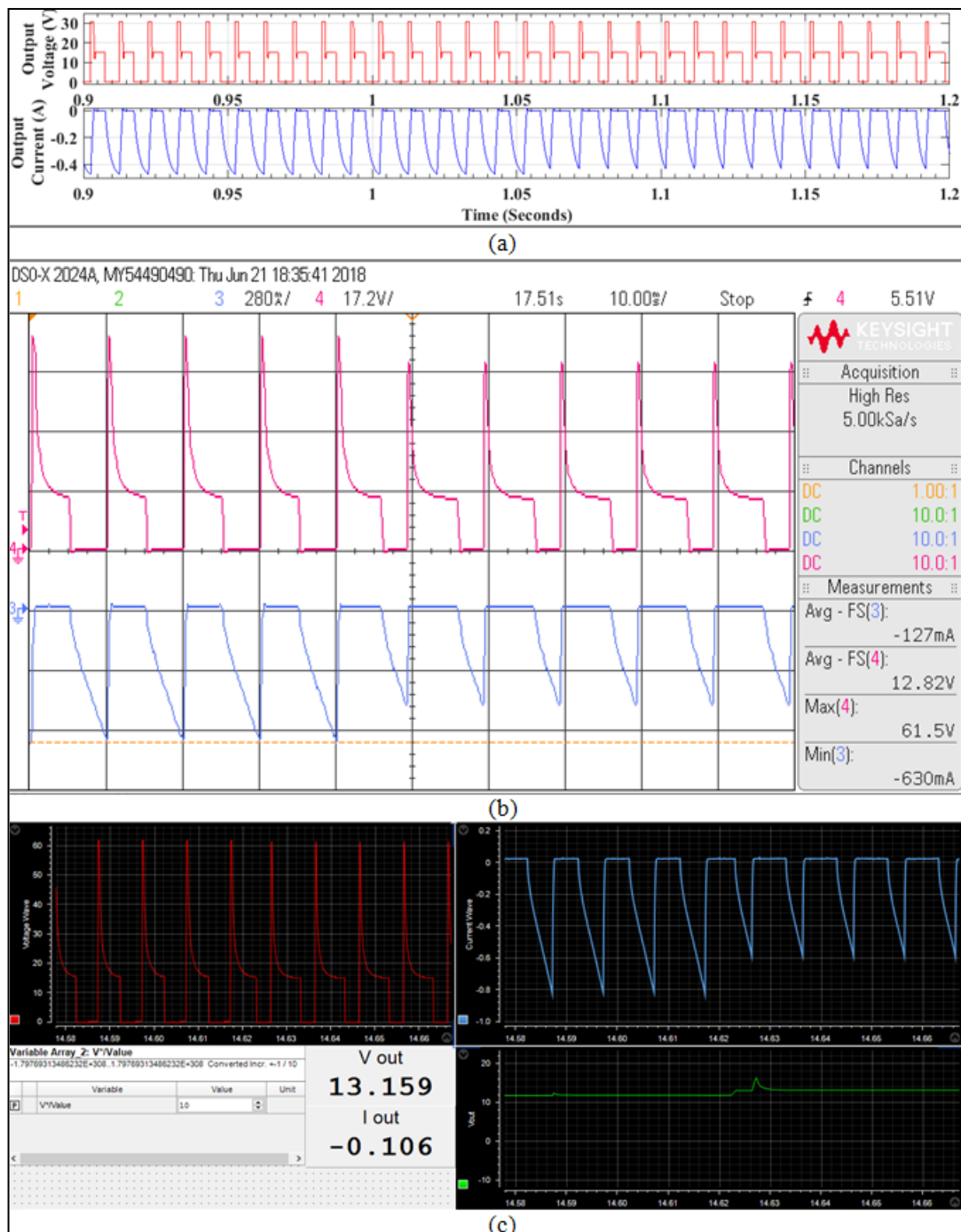
Figure 6.29: Voltage and current output of open loop Class–B Chopper when duty cycle changed from 50% to 33.33%:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.29 shows the change in voltage and current waveform of open loop Class-B chopper when duty cycle is suddenly changed from 50% to 33.33%, i.e., desired output voltage is reduced to 10V from 15V. Average output voltage is seen approximately 13V which is very high than 10V because maximum voltage when switch is OFF can never be less than load EMF, i.e, 10V. It can also be observed when the voltage is suddenly decreased then magnitude of current also gets reduced.
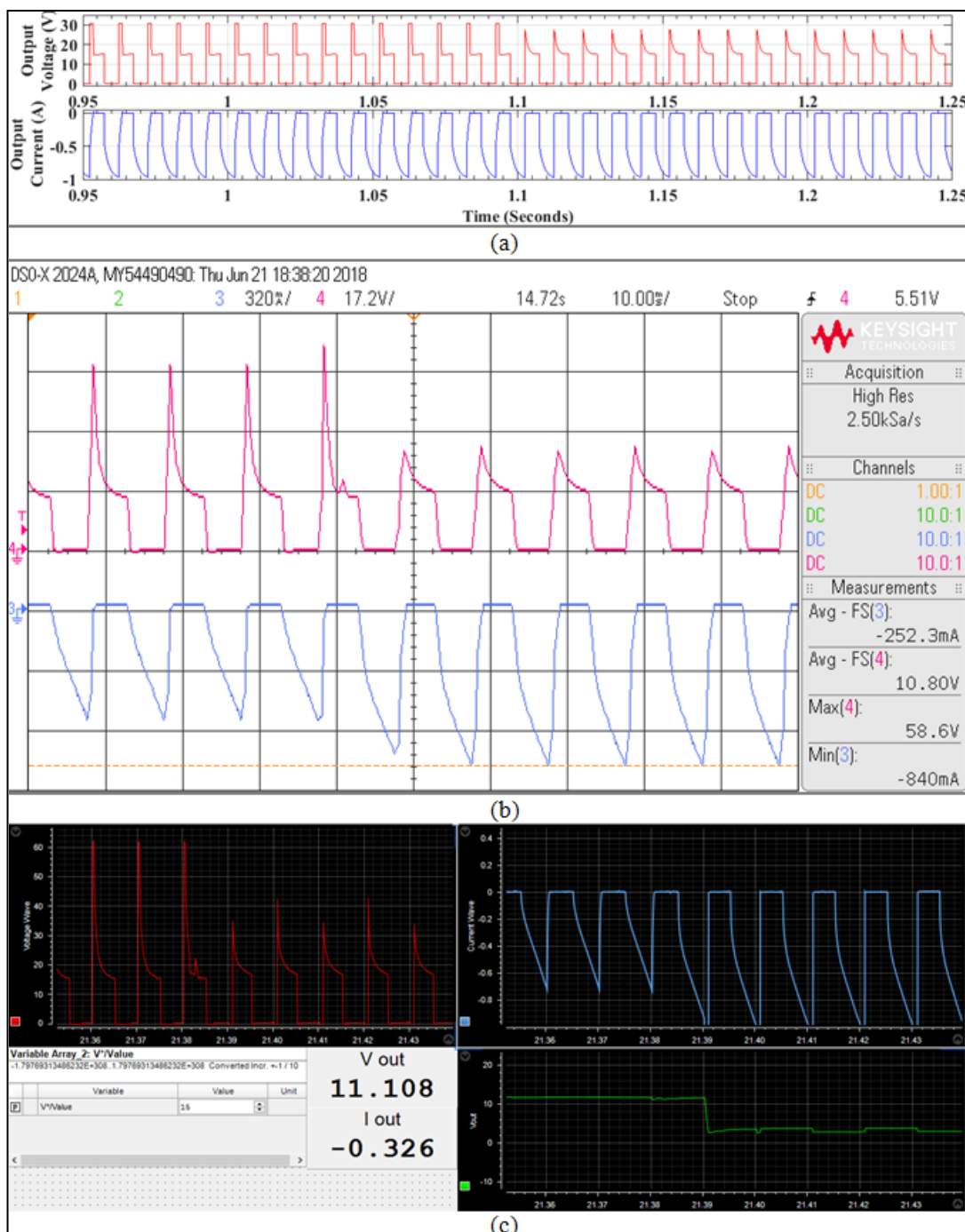
Figure 6.30: Voltage and current output of open loop Class–B Chopper when R is varied from 30Ω to 15Ω:- (a) Output in MATLAB Simulink; (b) Output of Hardware at DSO; (c) Output of Hardware in ControlDesk

Fig 6.30 shows the voltage and current waveform of open loop Class-B chopper when load resistance is suddenly decreased to 15Ω from 48Ω. This can be achieved by switching a R load that is kept connected parallel to RL load. It can be observed that when the resistance decreases, magnitude of current gets increased. If fig 6.28, 6.29 and 6.30 are observed, it can be found current is negative but discontinuous, it can be made continuous by increasing the value of load inductance.

6.4   OPEN LOOP SINGLE PHASE INVERTER

Apart from realizing DC – DC Converters, DC – AC converters are also realized but in open loop mode only. Later on by implementing any of the closed loop techniques, closed loop operation of Inverter can be implemented. Here the Sine Pulse Width Modulation (SPWM) based operation of single phase Inverter has been performed. Results are taken for RL load because 80% of grid load is Inductive load.
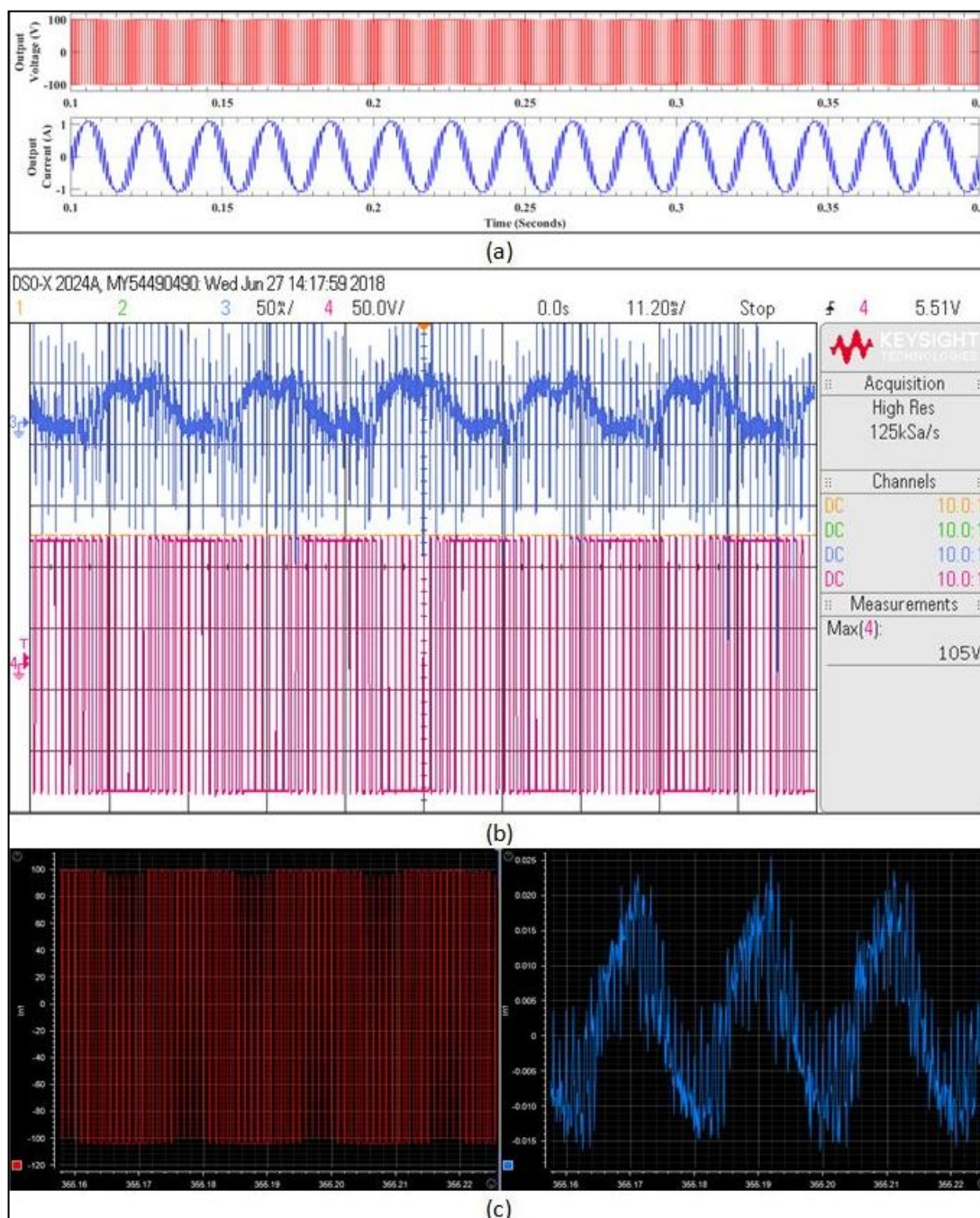
Figure 6.31: Output Voltage and Current Waveform of Single phase SPWM Inverter:- (a) Output in MATLAB Simulink (b) Output of hardware on DSO (c) Output of hardware on ControlDesk

It can be seen from the waveform of single phase SPWM inverter shown in fig 6.31 that voltage waveform almost remains constant but there are distortions in hardware current waveform. This is because inductor connected in load gets saturated after some time and a wire-wound resistor is used which is a lossy resistor. For refining this output, filter is required to be connected at the output.

6.5   OPEN LOOP THREE PHASE INVERTER

As the outputs were taken for open loop single phase inverter, similarly outputs have been taken for three phase SPWM inverter also. Source voltage is taken as 250V for this analysis and the load connected is a three phase induction motor.
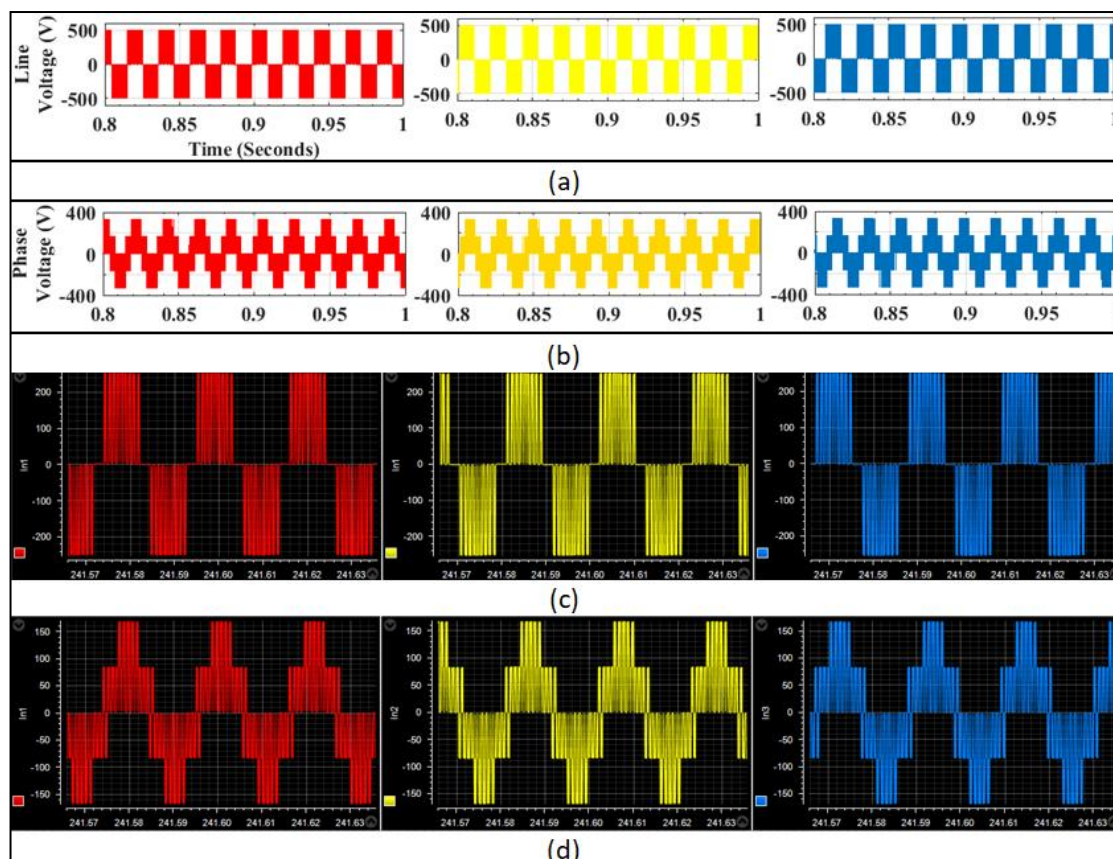
Figure 6.32: Line voltage and phase voltage output of open loop three phase SPWM inverter:- (a) Line voltage output in simulink (b) Phase voltage output in Simulink (c) Line voltage output of hardware on ControlDesk (d) Phase voltage output of hardware on ControlDesk

Fig 6.32 shows the line voltage and phase voltage output of open loop three phase SPWM inverter, it can be observed that line voltage is a quasi square wave as it should have been and the phase voltage is a perfect six step waveform. It can also be known as three level waveform. Fig 6.32(a) and 6.32(b) shows the line and phase voltage

respectively of schematic model in Simulink while fig 6.32(c) and 6.32(d) shows the line and phase voltage respectively of hardware circuit on ControlDesk software. Voltage waveform of simulation and hardware are almost same.
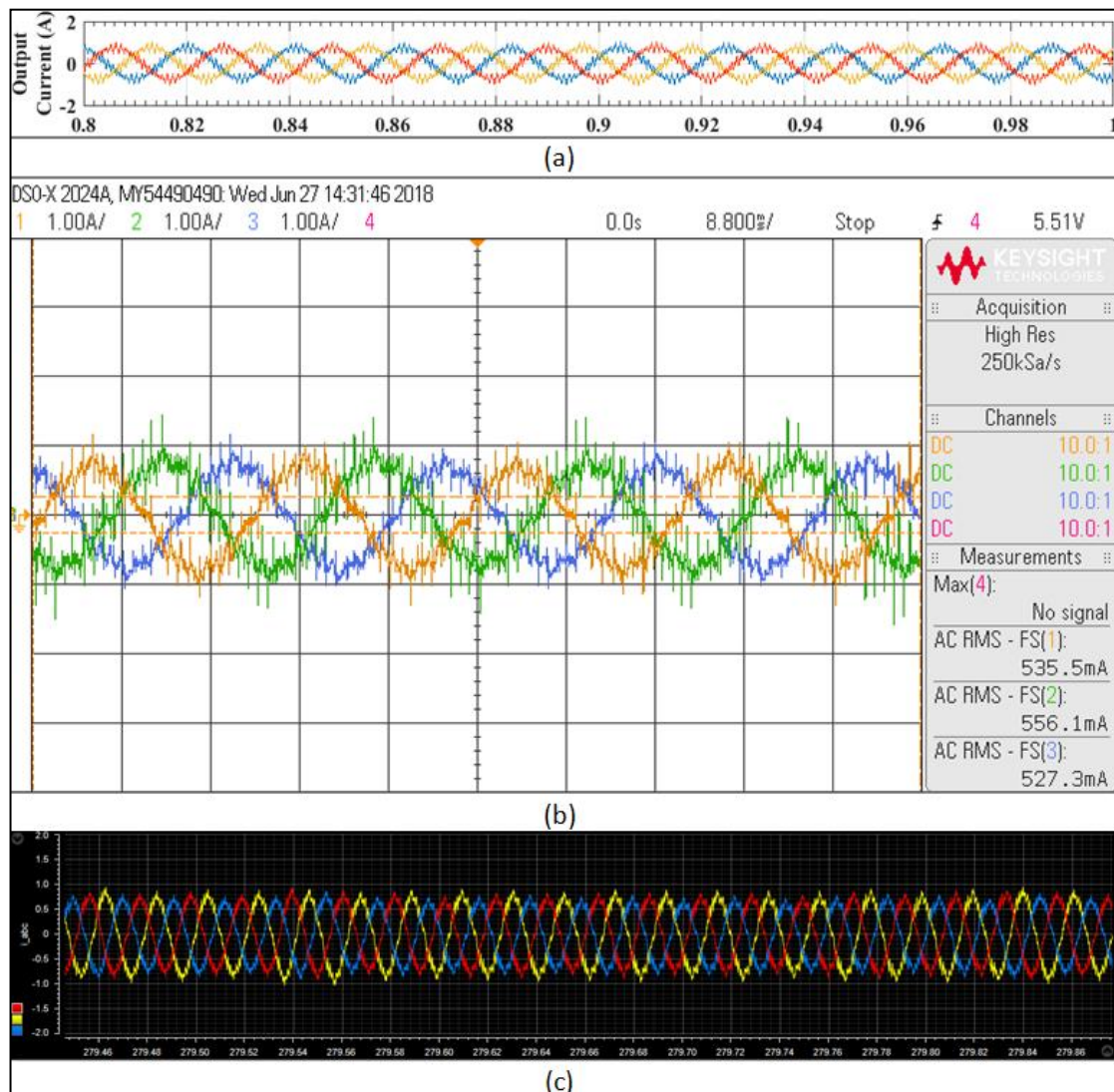
Figure 6.33: Output current of a three phase SPWM Inverter:- (a) Output current in Simulink (b) Output current of hardware on DSO (c) Output current of hardware on ControlDesk

Fig 6.33 shows the current output of open loop three phase SPWM inverter. It can be seen that the current output is sinusoidal with some distortions. Distortions can be seen in simulation as well as hardware output current. These distortions can be eliminated by connecting a filter after the output. Distortions in ControlDesk output are comparatively lesser than the output on DSO because there is a Butterworth filter connected in the dSPACE Simulink model. These distortions can be reduced by connecting the three phase inverter in closed loop and it can be eliminated if a proper second order filter is connected after output.

CHAPTER 7
CONCLUSION AND FUTURE SCOPE

Aim of the dissertation report suggested that the report will focus on the realization of different DC-DC converters and different DC-AC converters using dSPACE. For the realization of these converters, dSPACE is used as the triggering medium. To use the dSPACE, it was required to interface it with MATLAB Simulink which was done and is also explained in chapter 4 in detail. For this dissertation report, three features of dSPACE were used – Digital Output for giving the triggering pulses to chopper, PWM output for giving triggering pulses to inverter and ADC for receiving the voltage and current signals from the converters using the voltage and current sensors.

In DC-DC converters, open loop Class-A chopper, closed loop Class-A chopper and open loop Class-B chopper was realized and for DC-AC converters, open loop single phase SPWM inverter and open loop three phase SPWM inverter was realized. All of these converters were realized first on MATLAB Simulink and than hardware circuit was designed on breadboard for the same. On troubleshooting the hardware errors, final circuit was soldered on a universal PCB. Simulation, Hardware and ControlDesk software results were rigorously compared and analyzed, and it was found that the results of simulation and hardware are almost identical.

For this dissertation work, Class-A chopper was thoroughly analyzed and other converters were implemented to show the possible applications of dSPACE. Error is calculated for open loop Class-A chopper considering simulation results as the theoretical value and the hardware results as the experimental value. Similarly, error is also calculated for closed loop Class-A chopper. On calculating the error it was found that the percentage error in open loop configuration was more than ±5% for some parametric conditions while after applying the closed loop control error for, each and every change in the parameters, percentage error lies within ±5%, i.e., in the tolerance band. Error that does not lie in tolerance band is not acceptable. For the realization of

these converters different driver circuits were designed and tested which are discussed in chapter 5 of the report.

The work done in the course of past 2 years can be used for further research and can be efficiently utilized which further forms the scope of future work.

7.1   FUTURE SCOPE

Today we are using conventional sources for electrical energy like hydro power, thermal power, gas energy and nuclear power. Most of these conventional sources of energy are dependent on fossil fuels. Fossil fuels are getting extinct day by day and as per the survey reports of some scholars, earth will run out of coal, natural gas and oil by year 2088. So, this is the high time to switch to non-conventional sources of energy like Solar Energy, Tidal Energy and Wind Energy. Sun is a never ending source of energy, so economical generation and utilization of electricity from solar energy is getting encouraged day by day.

For this dissertation report, Class-A chopper has been already realized and analyzed thoroughly in open loop as well as closed loop. In future, closed loop can be applied on Class-B chopper also. There are lot of closed loop strategies for control of three phase inverters one of the best amongst those is Space Vector Modulation that can be applied for the closed loop control of inverter. For this thesis work, PI controller is used there are other controllers that can be used instead of PI controller like Artificial Neural Network (ANN) and fuzzy controller.

Once these converters are realized in closed loop also, then it can be used for the optimum utilization of electricity generated using solar energy. Closed loop Class-A Chopper can be used for storage of DC power and it can also be used to control the DC link voltage to inverters. Closed loop inverters can be used to connect Solar Energy to AC power grid. Closed loop Class-B chopper can be used for regenerative braking in electric trains. There could be some application where all these converters can be used altogether and best utilization of these converters can be done.

Apart from this, using these DC-DC converters and DC-AC converters, hybrid converter can also be designed in future. This hybrid converter has a tendency to work as a chopper as well as like inverter in one circuit itself. All types of choppers and single phase inverter could be realized using a single hybrid converter.

APPENDIX 1 RECTIFICATION OF CLASS-A CHOPPER RESULTS

When a resistive load is connected in a Chopper, voltage and current waveform should be identical in shape and behavior.
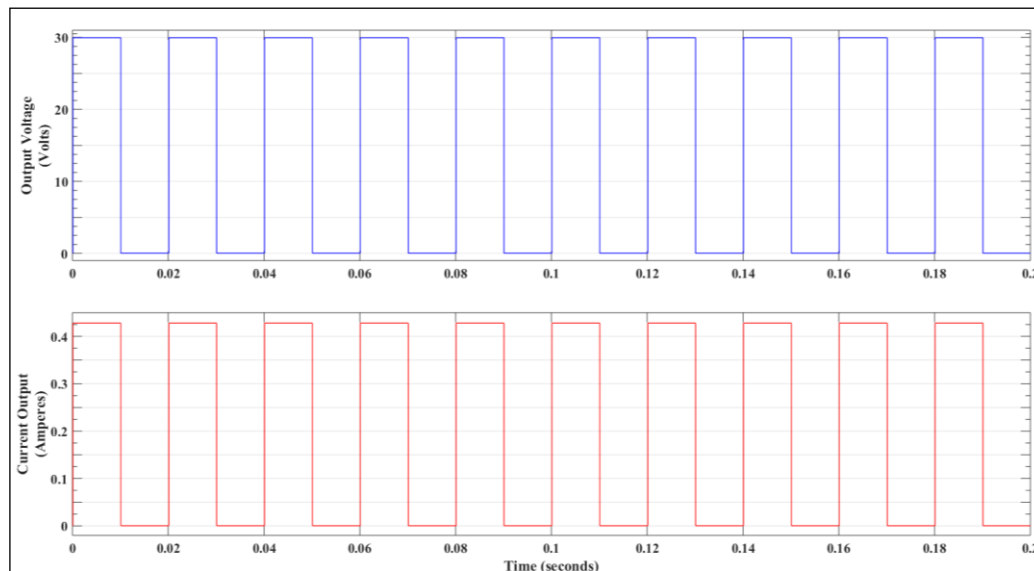
Figure A1.1: Simulation results of open loop class - A Chopper with R load

Figure A1.1 shows the output of Class-A Chopper using R load with 50% duty cycle. As it can be seen, when the switch is ON, the output is 30V, i.e., source voltage and when the switch is OFF, output is zero. Similarly, current waveform also follows the same pattern but with reduced magnitude. Taking simulation results as the reference, hardware circuit is implemented on breadboard followed by making it on general purpose PCB. Aim was to obtain a result which is identical to the simulation results.

Figure A1.2: Voltage and current output of Chopper hardware with biasing problem

This is the output of Chopper when implemented first time on hardware as shown in fig A1.3.
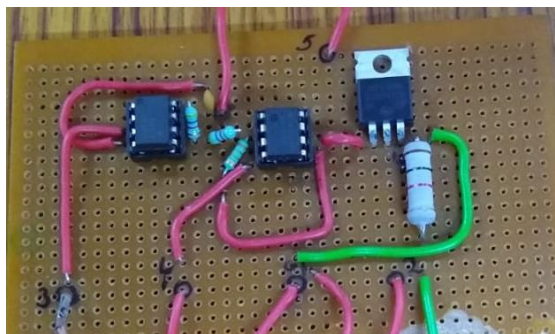
Figure A1.3: 1st circuit of Class - A Chopper designed on Universal PCB

On analyzing this output, one can see there exists a lot of negative and positive spikes at the switching instant. It can also be observed that the maximum amplitude is 3.09 volts only, but in actual maximum amplitude should have been 30 volts. This is because the switch is getting saturated. There is a problem with biasing of the switch, so the outputs are taken by connecting the switch in low side configuration of MOSFET.
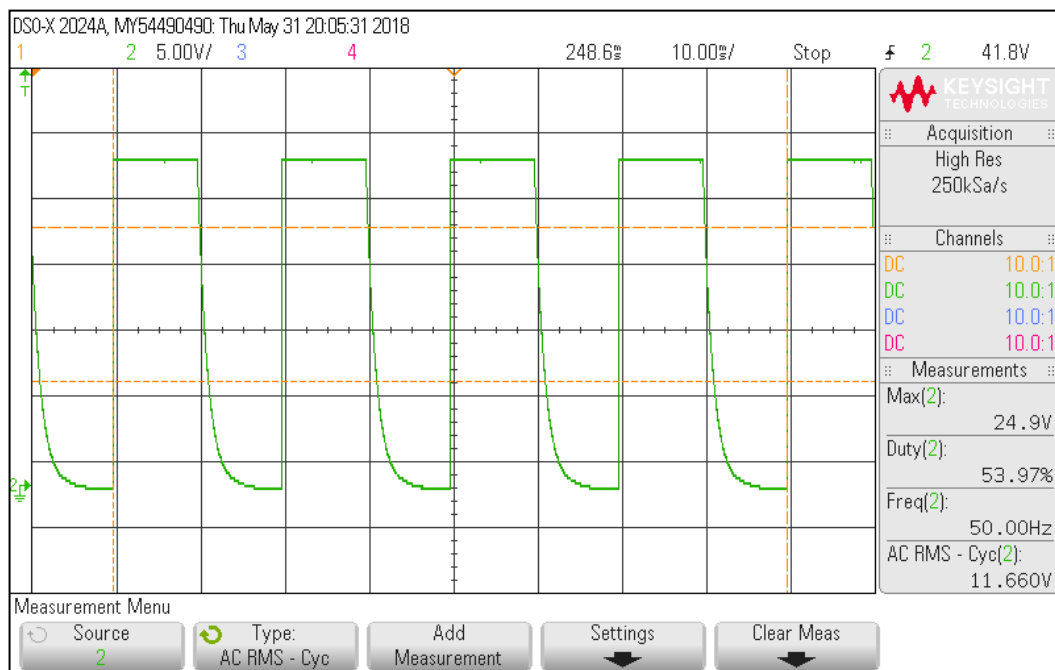
Figure A1.4: Voltage and current output of Chopper hardware for low side configuration

For taking this output a 25 volts supply voltage is connected to the Chopper circuit and in the output max amplitude is 24.9 volts which is approximately 25 volts, so the biasing problem that occurred is now rectified but in the OFF duration of output the result is improper. This has occurred because internal capacitor of MOSFET is taking some time to discharge which cannot be further rectified in low side configuration. So finally the switch is to be connected in high side configuration with proper biasing.
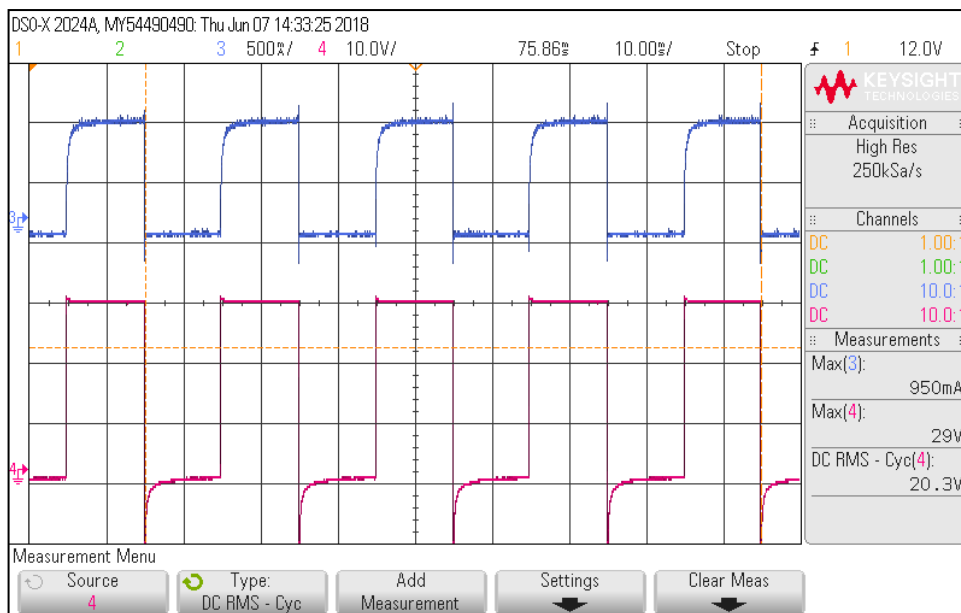
Figure A1.5: Voltage and current output of class-A Chopper with proper biasing

If the voltage waveform is observed (red waveform), negative peaks are seen in the figure. The resistor that is used in this circuit is a wire-wound resistor which will definitely have some inductance effect in it. Due to which there is a negative peak in output voltage and there also exists a curve on the top of current waveform (blue waveform). This negative peak can be removed by connecting a diode in anti-parallel configuration across load.
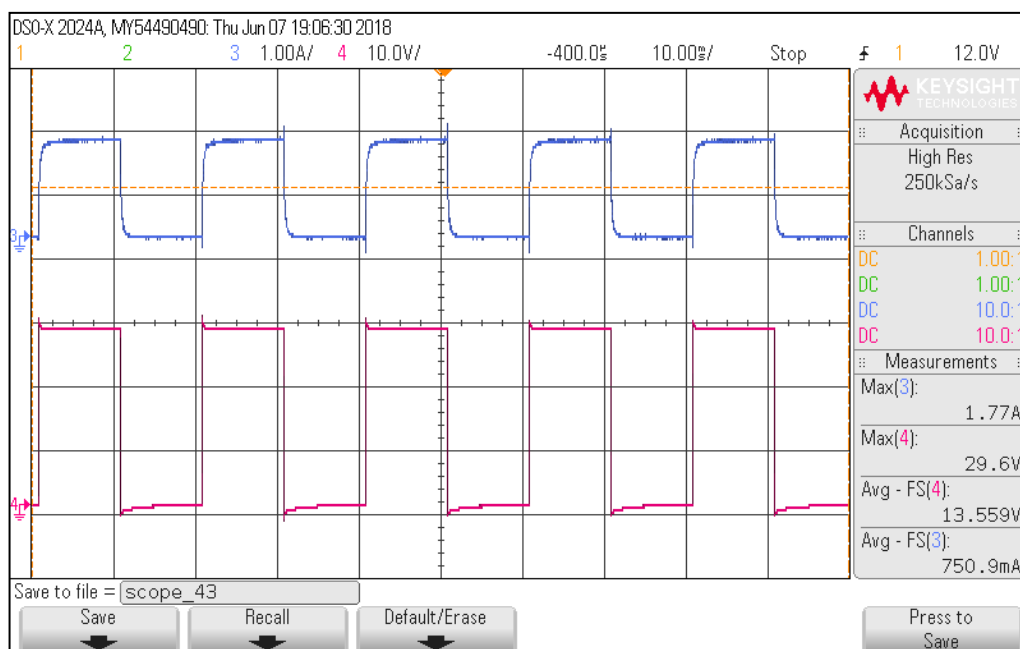
Figure A1.6: Final rectified output of Chopper hardware

This is almost exact waveform that has been obtained after doing all the rectifications. On giving an input voltage of 30 volts, maximum amplitude of output is 29.6 volts.

APPENDIX 2 SETUP INSTALLATION

Here, the photograph of experimental setup in laboratory is attached.

Figure A2.1: Picture of Experimental Setup in Laboratory

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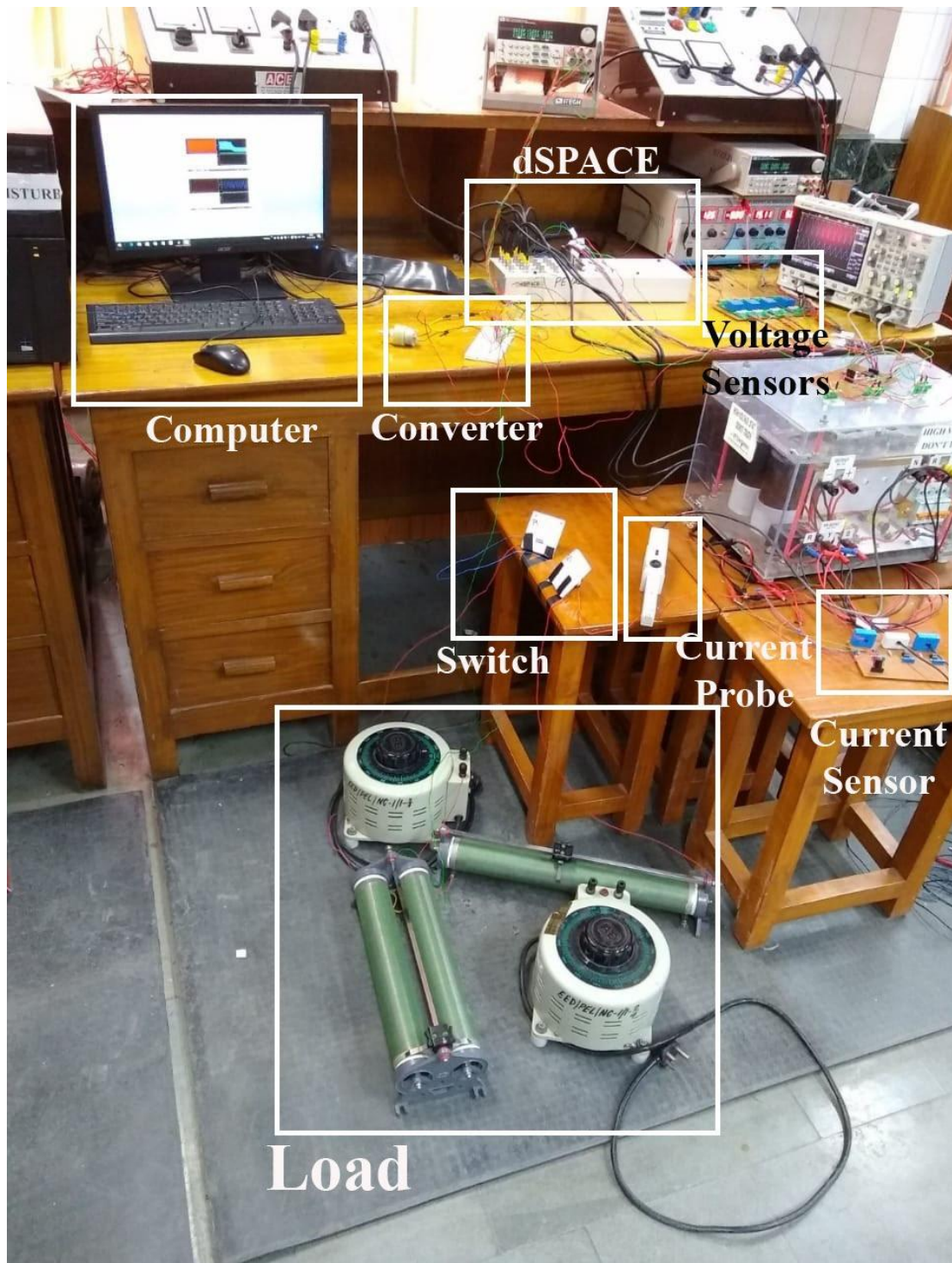**[2]** A. Gadekar and V.B. Virulkar, (2014). "Effective dspace Inverter Controller for PV Application". In *2014 IEEE Students' Conference on Electrical, Electronics and Computer Science*. Bhopal, India, 1-2 March, 2014. IEEE

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