HARDWARE DESIGN & IMPLEMENTATION OF SINGLE PHASE TWO SWITCH CYCLOCONVERTER

A Thesis

Submitted in partial fulfilment of the

requirements for the award of the Degree of

MASTER OF ENGINEERING

IN

ELECTRICAL ENGINEERING

(POWER ELECTRONICS)

BY

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(ME/EE/10007/2016)

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2018

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PO5: Demonstrate knowledge of engineering and management principles and apply to manage projects efficiently and economically with intellectual integrity and ethics for sustainable development of society.

PO6: Possess knowledge and understanding to recognize opportunities and contribute to collaborative-multidisciplinary research, demonstrate a capacity for teamwork, decision-making based on open-mindedness and rational analysis in order to achieve common goals.

<u>ME Power Electronics Project Thesis</u>

Code: MEE3101 **Credits**: 35.0

Duration: Semester III and IV

Course Title: HARWARE DESIGN & IMPLEMENTATION OF SINGLE PHASE TWO SWITCH CYCLOCONVERTER.

Pre-requisite(s): Power Electronics basic and advanced course, cycloconverter, microprocessor basics.

Topics covered: power electronics basics, cycloconverter, modified cycloconverter working principle, simulation of the modified circuit, hardware model design.

Project Evaluation Methodology: Periodic (once in a semester) assessment by presentation and viva, end-semester assessment by external expert (presentation and viva), thesis evaluation.

Project Objectives:

1. Explore new developments in the field of AC-AC Converter (Power Electronics).
2. To undertake practical design work in a new field.
3. Develop expertise to use simulation methods for design optimization
4. To become proficient in undertaking laboratory scale hardware implementation.
5. Develop critical ability to evaluate performance parameters of a system

Project Outcomes:

i. Identify, through literature survey, present state of development of as specific power electronic system.
ii. Develop proper understanding and knowledge of the various converters.
iii. Undertake practical design and optimization of power electronic systems.
iv. Hardware implementation of designed system and its performance Evaluation.
v. Prepare a thesis to document the project undertaken.

MAPPING BETWEEN PROJECT OBJECTIVES AND PROJECT OUTCOME

Project Objectives	Project Outcomes				
	I	II	III	IV	V
A	H	H	L	L	M
B	H	H	L	L	M
C	L	M	H	H	M
D	H	M	M	H	M
E	M	L	L	H	H

MAPPING BETWEEN PROJECT OBJECTIVES AND PROGRAM EDUCATIONAL OBJECTIVES

Project Objective	Program Educational Objectives			
	1	2	3	4
A	H	H	M	L
B	H	M	H	M
C	H	L	H	H
D	H	M	H	M
E	M	H	M	H

MAPPING BETWEEN PROJECT OUTCOME AND PROGRAM OUTCOME

Project Outcomes	Program Outcomes											
	a	b	c	d	e	f	g	h	i	j	k	l
I	H	H	L	M	H	M	M	M	M	L	H	M
II	H	H	L	M	L	M	L	L	H	M	L	H
III	M	L	M	H	M	L	M	L	H	M	H	M
IV	M	H	M	H	H	M	H	L	M	H	M	L
V	H	L	H	M	L	M	H	H	M	L	L	H

H- suggest high associativity

M- suggest medium associativity

L- suggest low associativity

ABSTRACT

The Era of power electronics started after the invention of transistor by Bell Laboratories in 1948, before it gas tubes were popularly used in industrial applications and vacuum tubes in the field of signal processing and communications. In 1958 GE introduced SCR this was the beginning of second electronics revolution. The use of thyristors and diodes has became popular in many different applications. Gradually, with the invention of power semiconductor devices, powerful digital signal processor(DSPs)/microprocessor, field-programmable gate array(FPGAs),advanced converter topologies, PWM techniques and advanced control techniques the has started the golden age of power electronics and presently being further advanced by the artificial intelligence (AI).

At present time the emphasis is now on energy saving with the help of power electronics because the cost of power electronics devices are decreasing along with the reduction of size and improvement of performance. The phase-controlled devices are now being dominated by self-controlled devices. The vector or field control technique has brought renaissance in modern high-performance control of the ac drives.

In this work hardware development and implementation of single phase cycloconverter using only two controllable switches has been done. The modified circuit can be made to work as voltage regulator, cycloconverter and rectifier. Simulation has been performed on MATLAB/Simulink software. The key features of Simulink has been discussed along with the Simulink output results for different operating conditions.

The prototype of hardware has been designed for both modified cycloconverter and the conventional cycloconverter. For the hardware module to work effectively various auxillary circuits i.e ZCD (Zero crossing detector), Voltage regulator Circuit, Gate Driver/Isolation Circuit has been designed and their corresponding output results has been shown. Arduino has been used here as the Microcontroller whose program code for Interrupt detection and gate firing signal generation has been provided.

ACKNOWLEDGEMENTS

I would like to express my gratitude to all who have helped me and put their efforts behind me in successful completion of this dissertation work. I would take this opportunity to thank my supervisor **Dr. S SHIVA KUMAR** and **Ms. Aparna Arunkumar Gautam** who has been constant source of encouragement, inspiration and support throughout this work. He has guided me in most difficult situations toward the path of success.

I would like to thank our Head of the Department, **Dr.P.R.THAKURA** for his excellent co-operation during the entire study at BIT, Mesra, Ranchi

I want to thank all the faculty members and staff of the Department of EEE for their direct and indirect support for helping me in completion of this project. I would take this opportunity to thank **Mrs. Aparna Arunkumar Gautam** for giving me design concepts and **Mr. Kamal Oraon** for hardware design and experimentation in Power Electronics lab, for their time to time help and support throughout this work.

Finally, I would like to thanks my parents, my family and friend for the love and constant support and providing me the opportunity and encouragement to pursue my goals.

DATE: SHIVAM BHARTI

(ME/EE/10007/2016)

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ABBREVIATIONS

SCR	Silicon Controlled Rectifier
AC	Alternating Current
DC	Direct Current
MATLAB	Matrix Laboratory
ZCD	Zero Crossing Detector
IGBT	Insulated-Gate Bipolar Transistor
ODE	Ordinary Differential Equations
PWM	Pulse Width Modulation
LED	Light Emitting Diode
DSO	Digital Storage Oscilloscope
RMS	Root Mean Square
CSR	Combined-Synchronous Rectifier
HFL	High-Frequency-Link
OCC	One Cycle Control
VTR	Voltage Transfer Ratio

CHAPTER 1

INTRODUCTION

1.1 POWER ELECTRONICS

Power electronics is a technology associated with the efficient conversion of electrical energy and control of electric power by using suitable power semiconductor devices. Before the development of power electronics glass-bulb, steel tank mercury arc for converting high voltage and high current, ignitron rectifiers and gas tube electronics (thyratrons and ignitrons) were known and were widely used in industry. In 1930 New York installed grid-connected mercury-arc rectifiers (3MW) for motor traction, and German railways introduced mercury-arc cycloconverter for universal motor tractional almost at the same time (1931). The first cycloconverter-based variable-voltage variable-frequency synchronous motor drive (400 hp) was installed by F.E Alexanderson of General Electric in the U.S. Logan power station in 1934 for induced draft (ID) fan drive. power electronics in that time was known as industrial electronics because in industrial applications gas tubes were mostly used, whereas vacuum tubes were used in the field signal processing and communication.

The development of power electronics has been closely related to the development of power semiconductors. In power semiconductor devices lightly doped material will present to withstand high voltage rating. In 1956 Bell laboratory developed thyristor or silicon controlled rectifier (SCR), which was later commercially introduced by General Electric in 1958, marked the beginning of the modern power electronic era. The rapid development of solid-state devices in terms of power rating, improved performance, cost and size has set off the transition of power electronics from a ‘device driven’ field to an ‘application driven’ field. This transition facilitates the extensive use of power electronics in the variety of electrical applications in industrial, commercial, residential, aerospace, military, utility, communication and transportation environments etc.

Power Electronics converter is a static electronic circuit which will convert and control electric power depending on the application. It can be classified into four types depending upon the function performed.

- **AC-DC CONVERTER:**

Rectifier Circuit will convert the AC (Alternating Current) power to DC (Direct Current) power whose average output voltage and current are finite. In rectifier circuit Semiconductor diodes are used extensively but the alpha angle delay cannot be implemented. The development of SCR by Bell laboratories has made phase angle control possible.

- **DC-DC CONVERTER:**

DC to DC converter will transfer DC power from one circuit to another at the required output voltage. Most of the Industrial applications requires the DC input supply. DC chopper is a static device which converts fixed DC voltage to variable DC voltage directly. The power semiconductor device for chopper circuit are power MOSFET, GTO or IGBT , force commutated thyristors etc.

- **DC-AC CONVERTER:**

Inverter circuit will convert input DC power to output AC power at required output voltage and frequency. The existing power supply provides input power to the inverter. The configuration of AC to DC converter and DC to AC inverter.is known as DC-link.

- **AC-AC CONVERTER:**

i. AC voltage regulator

ii. Cycloconverter

iii. Matrix converter

1.2 AC-AC CONVERTER

AC-AC Converter will control the AC power, they are of two types

1.2.1 AC VOLTAGE REGULATOR

AC voltage regulator are thyristor based devices It will control AC power by controlling output voltage with the fixed frequency. the control strategies used for regulating power in AC voltage regulators are: Phase control and Integral cycle control technique. They are used in:

(1) Speed Control of Induction motors where the narrow range of speed control is required.

(2) Voltage control in room heaters, lighting applications.

(3) Reactive power compensation in power systems.

1.2.2 CYCLOCONVERTER

It will control AC power by controlling output frequency. Fig 1.1 shows the circuit diagram of the single-phase to single-phase cycloconverter. It consists of a back-to-back connection of two full-wave rectifiers. Fig 1.2 shows the operating waveform for this converter with resistive load.

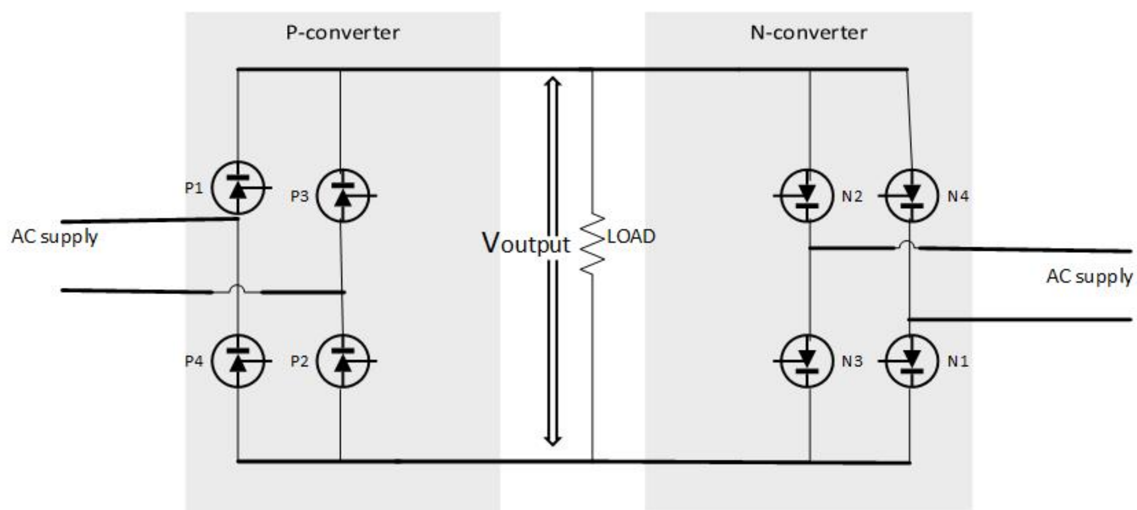

Fig1.1 shows the circuit diagram of single phase cycloconverter.

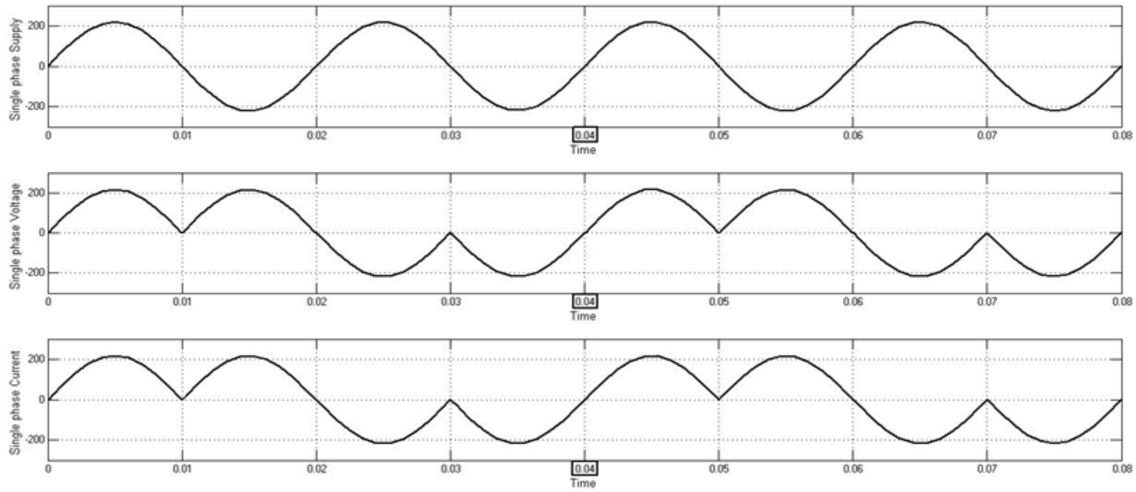

Fig1.2 shows the operating waveform for this converter with resistive load

With the innovation of fully controlled power semiconductor devices the control technique of conventional cycloconverter has become very simple. Cycloconverter can be used in speed control of Induction motor drives in low-speed applications such as cement mill drives, Ore grinding mills, Ship propulsion drives etc. some other applications are:

1. High-power and low-speed reversible AC motor drives with fixed input frequency.
2. To obtain constant output frequency power supplies with the variable input supply frequency.
3. Controllable VAR generators for better power factor correction.
4. AC system interties linking two different independent grid power systems.

1.3 OBJECTIVE OF THESIS

1. Detail study of cycloconverter.
2. Modeling and simulation of Single phase cycloconverter in MATLAB (Matrix Laboratory) /Simulink.
3. Hardware development of modified Single-phase cycloconverter.
4. Hardware development of Conventional Single-phase cycloconverter.
5. Comparison of the results of Conventional cycloconverter with the modified cycloconverter.

1.4 ORGANIZATION OF THE THESIS

This thesis has been organized as follows:

CHAPTER 1: briefly describes the introduction of Power electronics and different types of AC-AC converter topologies objectives of the research work.

CHAPTER 2: It includes literature survey done to develop the modified cycloconverter.

CHAPTER 3: It includes the introduction of cycloconverter, types of cycloconverter, modes of operations of the modified cycloconverter and its advantages and disadvantages over conventional cycloconverter.

CHAPTER 4: It includes the introduction about the MATLAB/Simulink software, key features of MATLAB/Simulink, Simulink model of modified single phase cycloconverter, Simulink model of the driver circuit

CHAPTER 5: Hardware Implementation and Experimental results, ZCD circuit, linear voltage regulator, gate driver circuit, power circuit and experimental results for 25Hz, 100Hz,12½ Hz etc.

CHAPTER 6: presents the conclusion derived from proposed research and scope for the future work.

CHAPTER 2

LITERATURE REVIEW

Shohei Komeda et.al. [1] presented a new control method of a direct ac-to-ac converter consisting of two half-bridge converters and a series-resonant circuit. A new switching sequence for phase-shift control is proposed to regulate the capacitor voltage in each half-bridge converter and to achieve both zero-voltage switching and synchronous rectification.

D Sri Vidhya et.al. [2] discuss the role of quazi-Z-source indirect matrix converter fed induction, motor drive in the flow control of the dye in the paper mill. For a variation of the duty ratio of the QZSN, the fuzzy logic controller has been presented. To control the IMC vector control with space vector modulation has been presented. The paper proposed the implementation of QZSIMC adjustable speed drive for the flow control of dye in paper mill during different voltage sag conditions. Simulation has been done in MATLAB/Simulink platform. The experimental results validate the maintenance of the speed of an induction motor at the set condition.

Michael J. Gorrnan et.al. [3] presented two-switch cycloconverter circuit that converts single-phase alternating current into an effective three-phase alternating current. it has a simple and inexpensive construction. the average value of the output voltage on the two switches is sinusoidal with a 60" difference in phase.

Wenjie Zhu et.al. [4] presented a high-performance “cycloconverter-type” high-frequency-link (HFL) single-phase rectifier with an active voltage clamper, which provides bidirectional two-stage galvanic isolation ac–dc power conversion . A prototype of the proposed HFL rectifier is built for evaluation. The experiment results demonstrate the efficacy of the soft-switching HFL rectifier and its highly promising control performance.

Jiarong Kan et.al. [5] presented a novel combined-synchronous rectifier high-frequency-link inverter. Three types of conventional HFL inverters are analyzed and their performance is summarized. The difference and correlation, and advantages and disadvantages, are analyzed between the CSR-HFL inverter and the conventional HFL inverter.

Sudip K. Mazumder et.al. [6] described a universal fuel-cell-based grid connected inverter design with digital-signal-processor-based digital control. Expolored the concept of dynamic transformer tapping to address the impact of varying input voltage on secondary-side voltage spike and inverter efficiency.

Louis J. Lawson et.al. [7] developed a high power capacity frequency conversion system that employs a unique combination of new semiconductor devices. Has putted emphasis on the application to high-performance terrestrial and rail vehicles.

Alexander Eigeles Emanuel et.al. [8] explained the concept of a simple cycloconverter. A three-phase 1-to-5-Hz, 5-kVA unit was built and typical oscillograms are presented.

Gerald M. Brown et.al. [10] discussed about two cycloconverters independently supply stator and rotor windings of a wound rotor induction machine. Derived the control strategy to stabilize this inherently unstable system from the double-fed machine matrix and the resulting algorithm was implemented in hardware with a simple field calculator.

Carmelo J. Amato et.al. [11] accurately simulated the significant static characteristics of an actual SCR in the cycloconverter are accurately simulated. Compared the recordings taken from the computer output with oscilloscope pictures from a hardware system.

Shanhu Li et.al. [12] proposed a novel multi-mode space vector overmodulation strategy. the output voltage harmonic distortion rate under three inverter modulation methods and the input current harmonic distortion rate under two rectifier modulation methods is analyzed. The proposed multi-mode overmodulation strategy not only extends the maximum voltage transfer ratio (VTR) to1.05, but also reduces the output low frequency harmonic voltage components of the overmodulation mode I and mode II.

Youngseok Kim et.al. [13] proposed cycloconverter with a tank circuit for induction heating which can deliver power to load while keeping the input displacement factor at 1.0.

Zhenyuan Wang et.al. [15] discussed the steady-state harmonic modeling and simulation of a cycloconverter drive system (CDS). The harmonic behaviors
of the entire system were studied under several worst operation conditions with special attention given to harmonic filtering and cancellation effect of converter coupling transformers.

Hiromichi Ohashi et. al. [16] reviewed the history of simulation technology with reference to power device modeling and discusses the future of power electronics system design.

Rivera et. al. [17] presented a finite control set model predictive current control strategy with a prediction horizon of one sampling time to control the single-phase matrix converter. By using a predictive cost function, the optimal switching state to be applied to the next sampling time is selected. The feasibility of the proposed strategy is verified by simulation and experimental results.

Luigi Malesani et.al. [18] introduced the family of quasi-direct converters, i.e., forced-commutated adddac converters including small energy storage devices in the dc link. discussed of the general properties of quasi-direct converters, design criteria of both power and control sections.

Zahirrudin Idris et.al. [19] presented work on modelling and simulation of cycloconverter using MATLAB/Simulink incorporating the SimPowerSystem blockset.

Md. Ali Azam et.al. [20] Introduced a new approach of Cycloconverter to improve Power Quality by reducing Total Harmonic Distortion(THD) of input line current, input Power Factor (Pf) and overall Efficiency (η) of the power conversion.

Arinjoy Biswas et.al. [21] Implemented staircase modulation technique to a single phase matrix converter for reducing the harmonic distortions in the output. The minimum total harmonic distortion (THD) obtained was 1.003% for cycloinverter and 1.209% for cyclo-converter, when only output frequency is varied keeping all other parameters constant at carrier frequency of 3 kHz.

M Raghuram et.al. [22] Single phase matrix converter has been developed to perform the functions of all operations in one converter that is a single circuit is developed that can perform cycloconverter, cycloinverter, ac voltage regulator, rectifier, inverter, chopper operations. IGBT with antiparallel diode is used as a switching device for controlling current waveform. Simulations were carried out using MATLAB/Simulink and results of simulations are presented to evaluate the behaviour and feasibility of the proposed topology.

Xudan Liu et.al. [23] introduced novel enabling window control (EWC) method to reduce the switching loss, and an active input bridge is used to replace the traditional diode bridge for high efficiency.electromagnetic interference noise and driving loss of the main switch can be reduced with the EWC method. the proposed method is verified by experimental results obtained from a 500-W prototype.

Ahmed Al-Busaidi et.al. [24] presented a new concept for single-phase diode bridge rectifier circuits applied to automotive applications. The operation and the performance of the proposed rectifier are simulated using Matlab/Simulink software.

Nimesh Vamanan et.al. [25] proposed a new control strategy called dual comparison OCC (DC-OCC), which eliminates the limitations of OCC. shown that the proposed DC-OCC does not have the light load instability concerns of conventional OCC. simulation and experimental studies was carried to validate the proposed control and the high performance.

Philip T. Krein et.al. [26] introduced multicarrier PWM approach to implement a high-frequency link inverter. Simulation and experimental results has been developed for a low-voltage ac link inverter, leading to a 48V fuel cell input design.

Yazhou Liu et.al. [27] The impact of cycloconverters on power quality is studied, and the relationships between power quality indices and cycloconverter control strategies are developed.

CHAPTER 3

CYCLOCONVERTER

3.1 INTRODUCTION

A cycloconverter is a Power Electronics AC-AC converter circuit which converters input AC voltage to the output AC voltage of required frequency without any intermediate DC link.

In 1958 GE introduced SCR this was the beginning of second electronics revolution. The use of thyristors and diodes has become popular in many different applications. Increasing emphasis is now on energy saving with the help of power electronics because the cost of power electronics devices are decreasing along with the reduction of size and improvement of performance. The phase-controlled devices are now being dominated by self-controlled devices. The conventional single phase cycloconverter circuit shown in Fig 3.1 consists of eight SCR's which increases the cost of the system and its control circuit also becomes complex. The development of new semiconductor devices and microprocessor has allowed a much greater flexibility in power circuit design. Fig 3.2 shows the modified Single Phase cycloconverter. This design features only two controllable switches which allow a simple and robust design for a variety of load applications. The modified cycloconverter power circuit comprises two full bridge rectifier and two IGBT (Insulated-Gate Bipolar Transistor) switches (IGBT1 and IGBT2) connected back to back across the load.

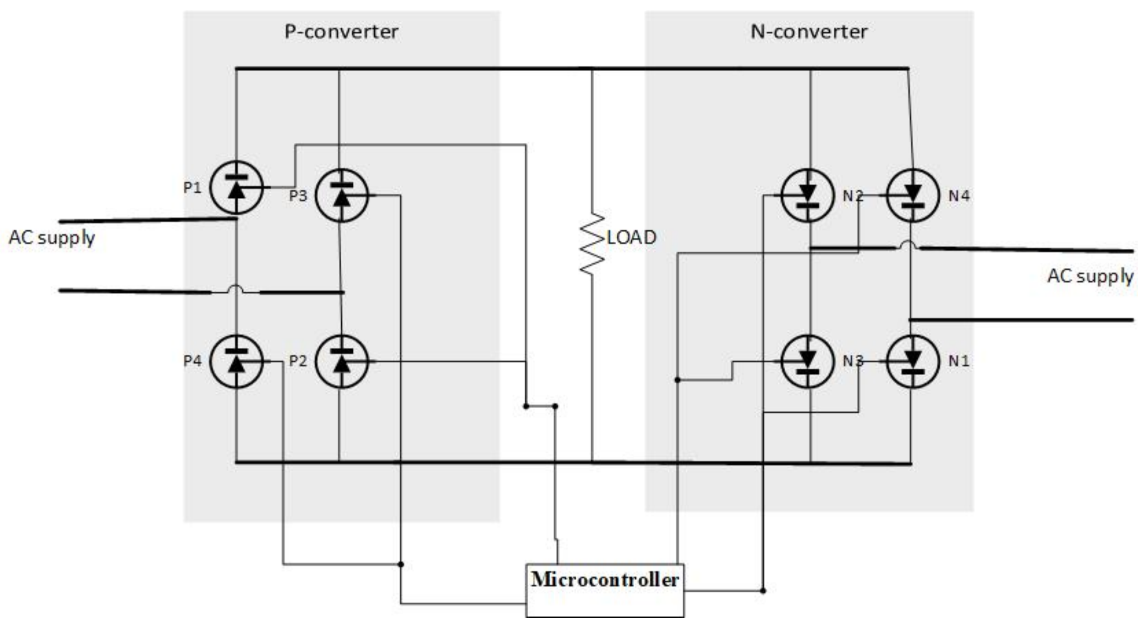

Fig. 3.1 shows the circuit diagram of conventional cycloconverter.

In modified cycloconverter by providing firing signal to IGBT1 and IGBT2 we can easily obtain the desired output frequency from the given input frequency.

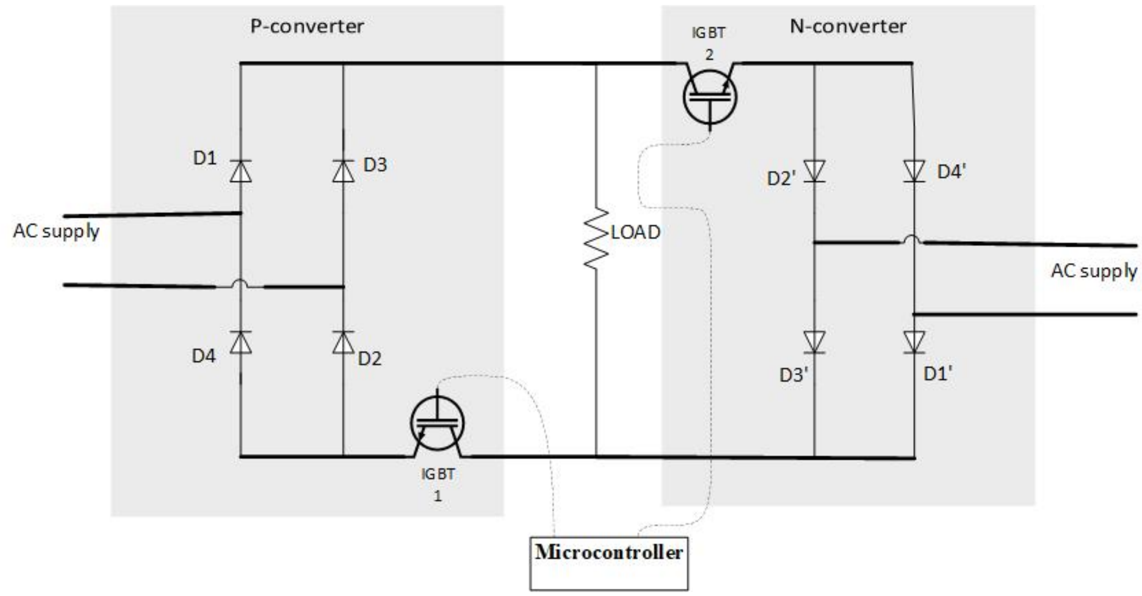

Fig. 3.2 The circuit diagram of modified cycloconverter

For the simplification of our understanding the working principle and dynamic analysis of the modified Cycloconverter few assumptions are made which is as follows :

1. All the diodes D1, D2, D3, D4, and D1', D2', D3' D4' are assumed to be as ideal.
2. The Circuit is lossless.
3. Switching loss of IGBT1 and IGBT2 are zero.

3.2 TYPES OF CYCLOCONVERTER

There are two types of cycloconverter. If the output frequency is less than the supplied input frequency then it is called to be step-down cycloconverter. Similarly, if the output frequency is greater than supplied input frequency then it is called step-up cycloconverter.

For step-up cycloconverter, $fo = fi \times n$ (1)

For step-down cycloconverter, $fo = fi \times (1/n)$ (2)

Here, 'fo' is the converter output frequency, 'fi' is the input frequency and 'n' is the constant. For step up cycloconverter the output frequency is equals the 'n' multiple times of the input supply frequency and for step down cycloconverter the output frequency is equals the '1/n' multiple times of the input supply frequency.

Thus the output voltage we will get will be as:

$$V_{output} = \frac{2\sqrt{2}}{\pi}\left(\frac{2Vm}{\pi}\cos\alpha\right) \qquad (3)$$

3.3 OPERATING PRINCIPLES

In conventional single phase cycloconverter there are eight switches used which increases the cost of the system and its control circuit also becomes complex. Whereas, the modified single phase cycloconverter features only two controlling switch.

The following section will describe the operating principles of the modified single phase cycloconverter

Mode I [IGBT1 is ON and IGBT2 is OFF]

In the operation of mode 1, the switch IGBT1 is turned ON whereas the IGBT2 is kept OFF. Fig 3.3 represents the operating condition of the circuit in mode 1.

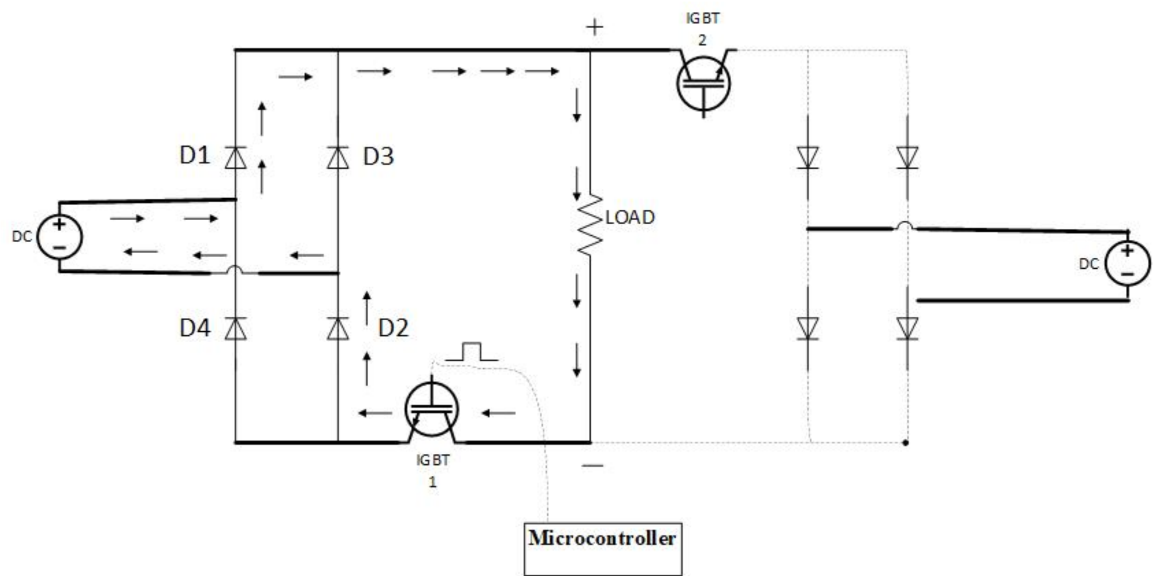

Fig 3.3 circuit diagram of cycloconverter in Mode 1

The voltage polarity across the load along with the current direction when IGBT1 is ON has been shown here. Thus we will continue to get positive half of the output side voltage across the load till we provide the firing signal to the IGBT1 through the microcontroller.

Mode II [IGBT1 is OFF and IGBT2 is ON]

In the operation of mode 2 the switch IGBT1 is turned OFF whereas the switch IGBT2 is kept ON. Fig 3.4 shows the circuit diagram for mode 2 operation.

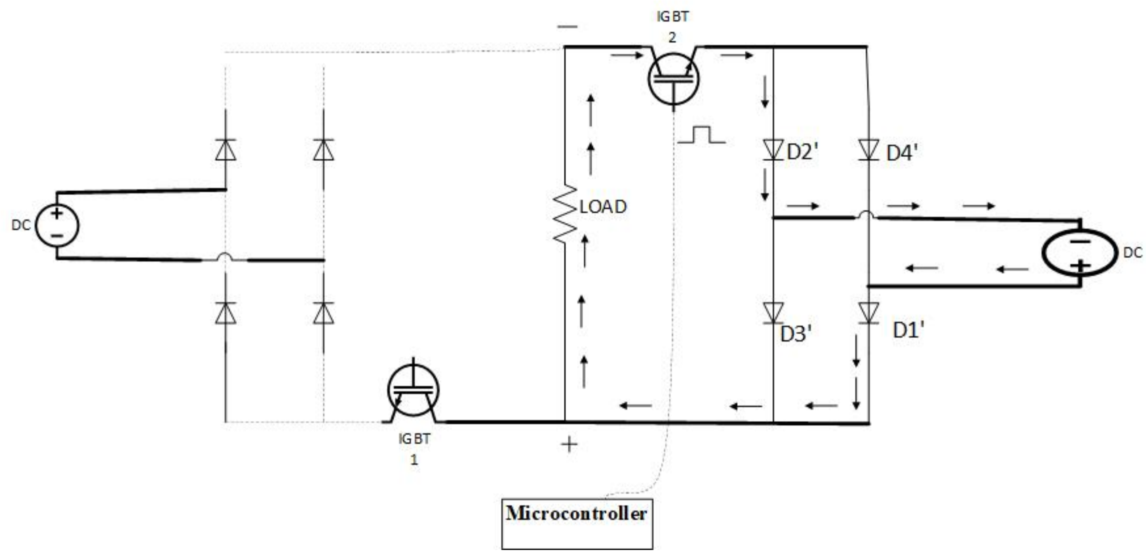

Fig 3.4 circuit diagram of cycloconverter in Mode 2

The voltage polarity across the load along with the current direction when IGBT2 is ON has been shown here. Thus we will continue to get negative half of the output side voltage across the load till we provide the firing signal to the IGBT2 through the microcontroller. Hence by controlling the firing period of IGBT1 and IGBT2, we can easily obtain the output voltage of desired frequency across the load.

3.4 ADVANTAGES AND DISADVANTAGES OF MODIFIED CYCLOCONVERTER

ADVANTAGES

1. The number of switches has been reduced from eight switches to two switches.
2. The cost of the module has been reduced.
3. The circuit complexity has become very lucid.
4. The switching losses has been reduced .
5. The programming code has become very simple.

DISADVANTAGES

1. The switch conduction loss will increase.

CHAPTER 4

SIMULINK MODEL OF CYCLOCONVERTER

4.1 INTRODUCTION

Simulation is an imitation of real-world process or system. In this chapter we have discussed the simulation model of the modified single phase cycloconverter working as step-up cycloconverter, step-down cycloconverter, voltage regulator, and rectifier.simulink results has also been shown.

4.2 MATLAB/Simulink SOFTWARE

MATLAB/Simulink is used as a tool to simulate the modified Cycloconverter and also to understand dynamic analysis and different waveform. The result obtained from the MATLAB simulation is found to be satisfactory. The modelling of the Cycloconverter was done in accordance with the given parameters in the Simulink. The given system was simulated for different duty cycle and also for the different frequency.

MATLAB is one of the most efficient simulators for power electronics simulation. It achieves fast simulation while providing excellent simulation accuracy. This makes it effective in simulating converter systems of any size and performing multiple cycle of simulation. It uses Simulink models which is the block diagram environment for different-domain simulation and Model-Based Design. It supports the system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editorial manager, customizable block libraries, and solvers for mimicking real systems. It is integrated with MATLAB, empowering to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

4.3 KEY FEATURES OF MATLAB/SIMULINK

a. Libraries of predefined blocks for the modelling of continuous-time and discrete-time systems.

b. Simulation engine with the fixed-step and variable-step ODE solvers.

c. Project and data managing tools for managing model files and data.

d.	Model analysis tools for refining model architecture and reducing simulation time.

e.	MATLAB Function block for importing MATLAB algorithms into models.

f.	Legacy Code Tool for importing the data from C and C++ code into models.

4.4 SIMULINK MODEL OF MODIFIED SINGLE PHASE CYCLOCONVERTER

The modified cycloconverter circuit before being implemented on hardware has first been simulated on the MATLAB/Simulink. The parameters selected for the simulation of Cycloconverter are:

Input Supply Voltage (Vin) = 230V

Input Supply Frequency (fin) = 50Hz

Load=100ohm

IGBT has been used here as the switch

Pulse Generator is used to generate the pulse for the IGBT switch

Fig 4.1 Shows the MATLAB Simulink model of the modified single phase cycloconverter

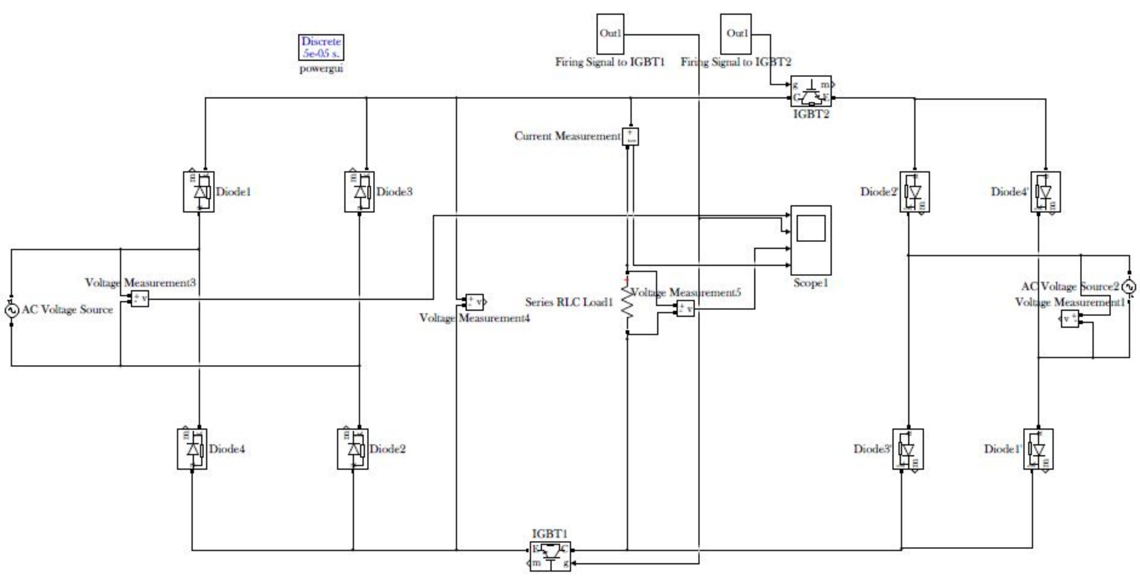

Fig 4.1 MATLAB/Simulink model of modified Cycloconverter

4.5 SIMULINK MODEL OF DRIVER CIRCUIT

PWM (Pulse Width Modulation) technique has been used here to produce firing signal to the IGBT1 and IGBT2. Fig 4.2 shows the driver circuit of the model. PWM pulses have been produced by comparing the sine wave with the repeating signal of triangular wave

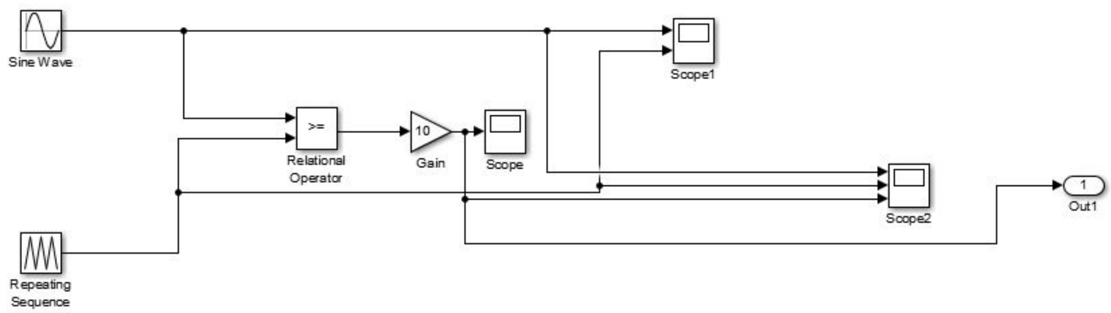

Fig 4.2 Gate Driving circuit to produce firing signal

Fig 4.3 Shows firing pulses given to IGBT1 and IGBT2 in the Simulation.

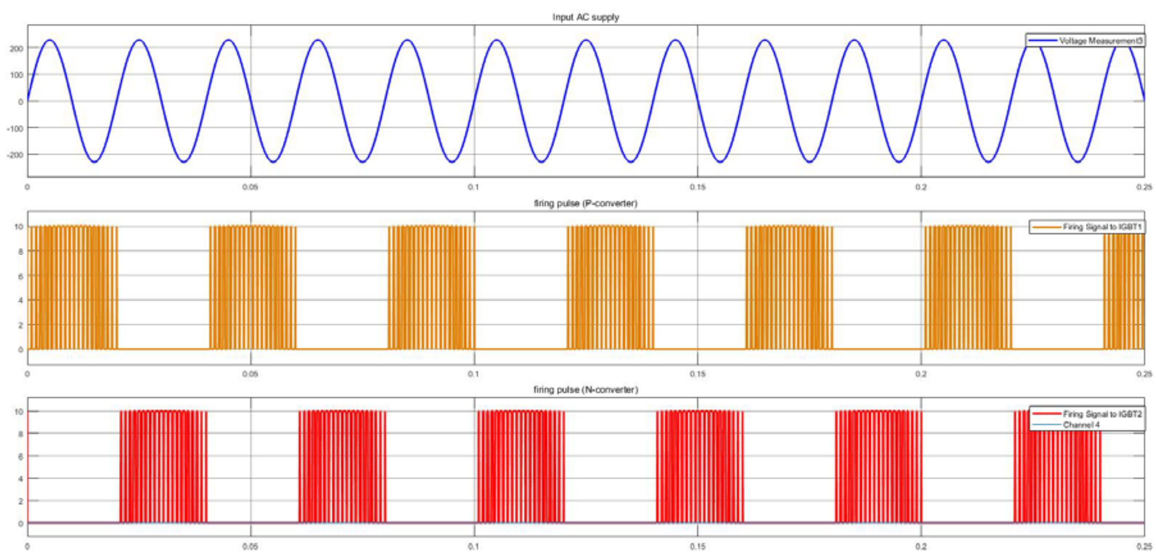

Fig 4.3 firing Pulse to IGBT1 and IGBT2

Fig. 4.4 shows the Simulink result for step down cycloconverter for an input supply of frequency 50Hz we will get an output of frequency 25Hz. Here IGBT1 has been fired for a period of 20 milliseconds and IGBT2 will be fired for the next period of 20 milliseconds.

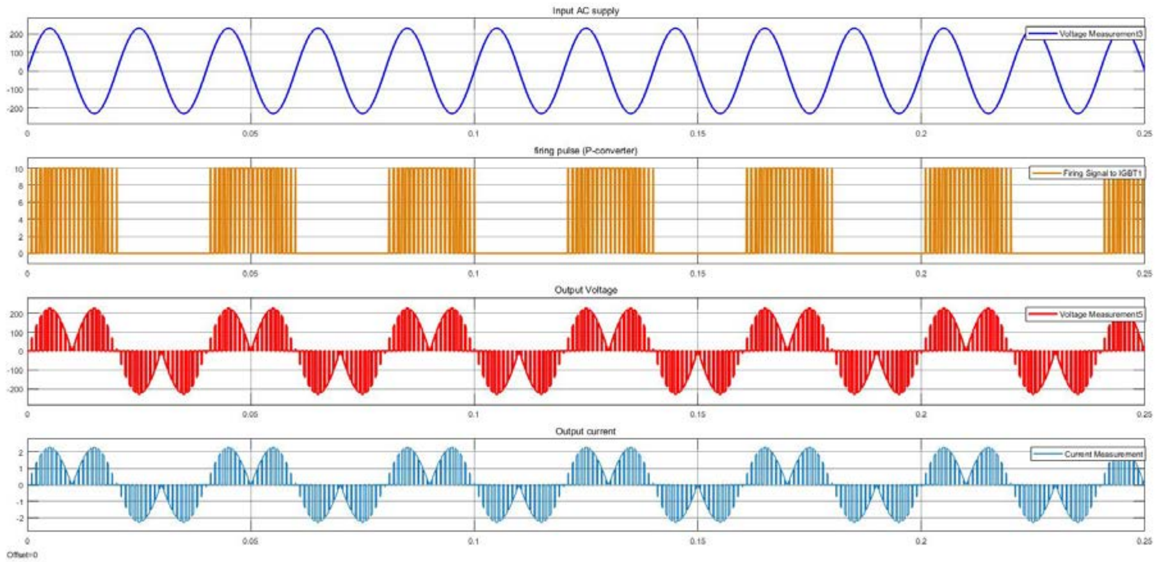

Fig 4.4 Simulation result of the output voltage at 25Hz

Fig 4.5 shows the Simulink result for the step up cycloconverter from input supply frequency 50Hz we will get an output of frequency 100Hz. Here IGBT1 has been fired for a period of 5 milliseconds and IGBT2 will be fired for the next period of 5 milliseconds.

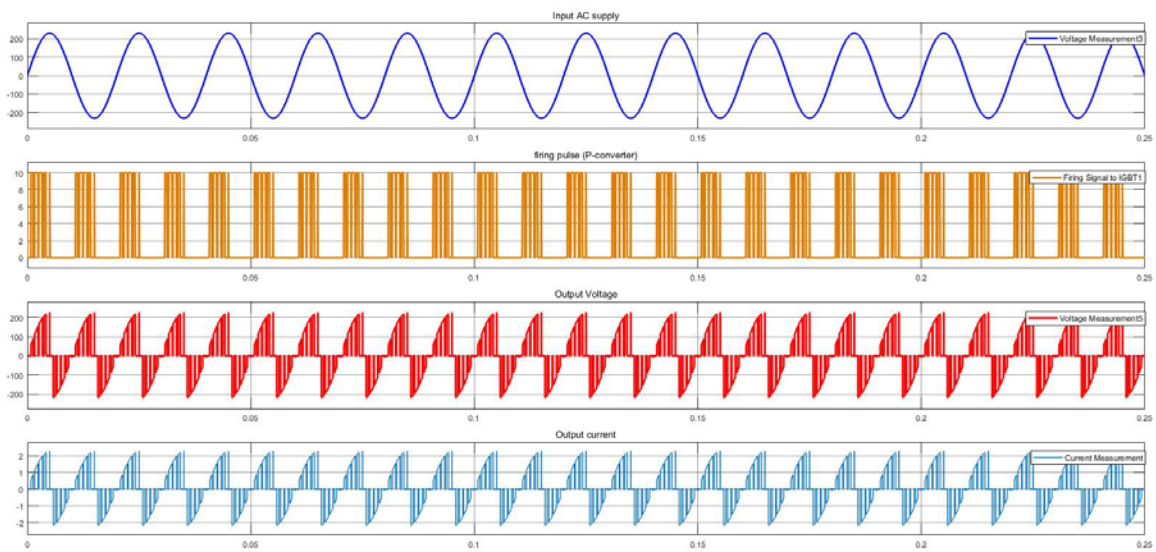

Fig 4.5 Simulation result of the output voltage at 100Hz

Fig 4.6 shows the Simulink result for the step down cycloconverter from input supply frequency 50Hz we will get an output of frequency 12½ Hz. Here IGBT1 has been fired for a period of 40 milliseconds and IGBT2 will be fired for the next period of 40 milliseconds.

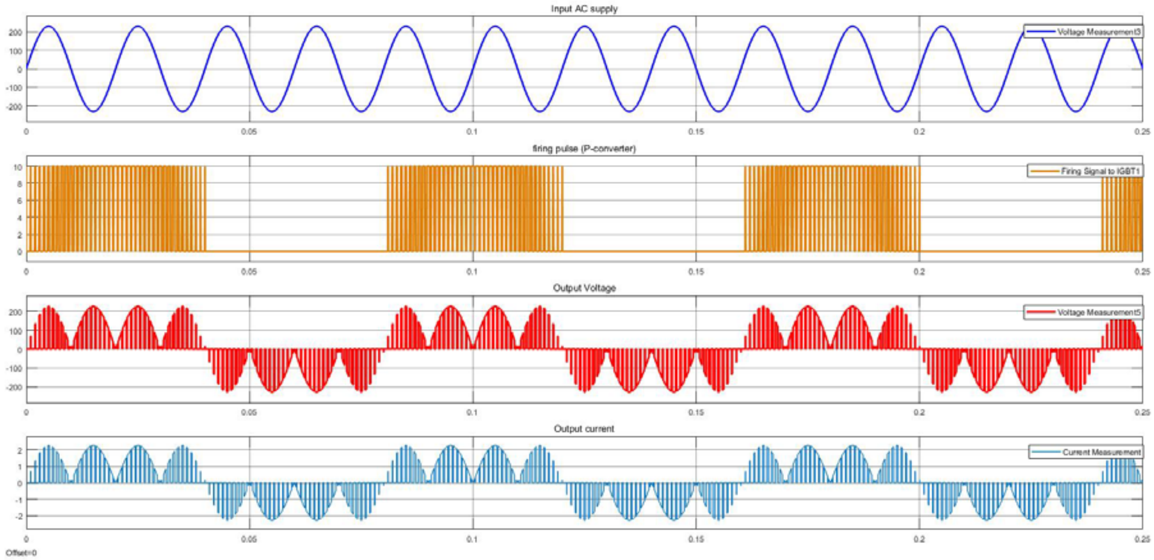

Fig 4.6 Simulation result of the output voltage at 12½ Hz

Hence by the MATLAB/Simulink simulation, one can easily analyse the theoretical result before designing the hardware.

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CHAPTER 5

HARDWARE IMPLEMENTATION AND EXPERIMENTAL RESULTS

5.1 BLOCK DIAGRAM OF HARDWARE

To verify the results obtained in the simulation prototype of both conventional single phase cycloconverter and modified Cycloconverter was built which works as both step-up cycloconverter (fo > fi) and step-down cycloconverter (fo < fi). In Fig 5.1 the Block Diagram of the Hardware Setup has been shown. The overall setup consists of four parts they are:

1. Zero Crossing Detector (ZCD) circuit,
2. Linear Voltage Regulator,
3. Gate Driver/Isolation Circuit and
4. The Power Circuit.

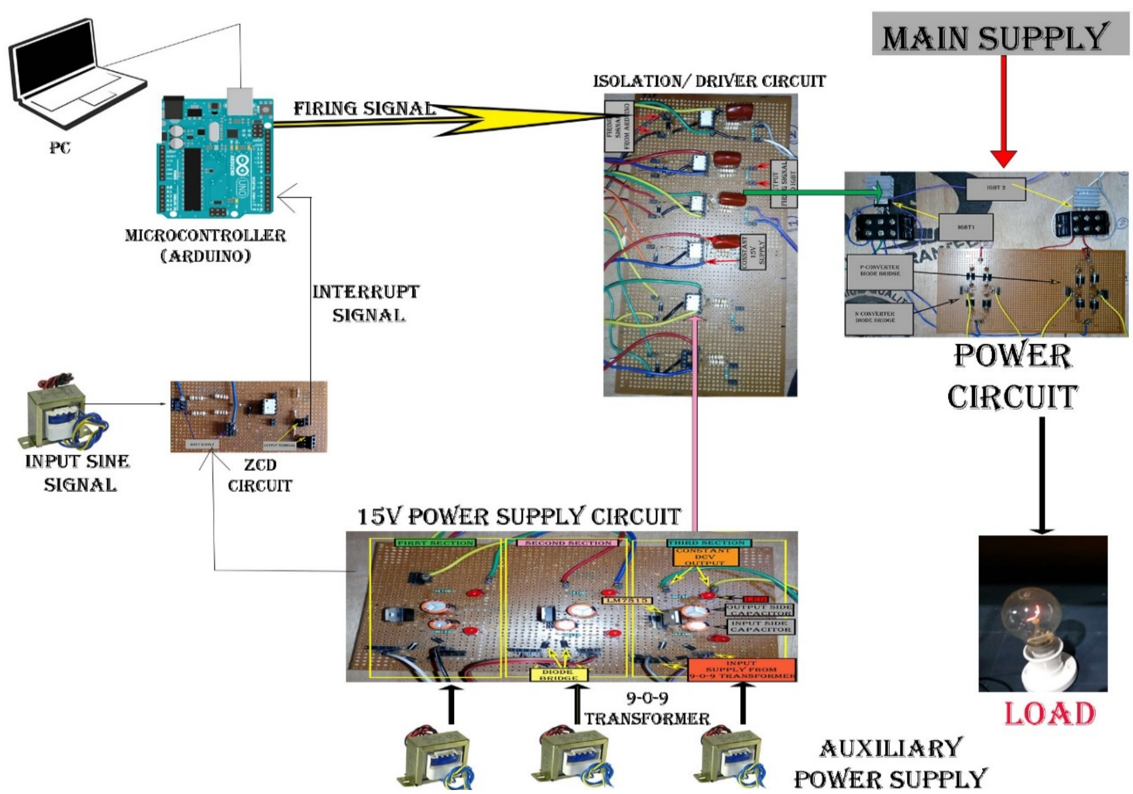


Fig 5.1 Block diagram of the hardware setup.

5.2 ZERO CROSSING DETECTOR

ZCD is used to synchronize the firing pulse to the IGBT switch with the input supply. Fig. 5.2. shows the ZCD circuit, the input sine wave to square wave is generated and is given to the pin2 and pin3 of TLP250 (LED side) and output is taken from pin5 and pin6 (photodetector as well as totem-pole driver stage side) having a voltage of 15V with voltage divider we obtain 5V and provided to the interrupt pin INT0 and INT1 of the Arduino. The output of the ZCD circuit is shown in Fig 5.3 where the input supply and the ZCD output have the same frequency.

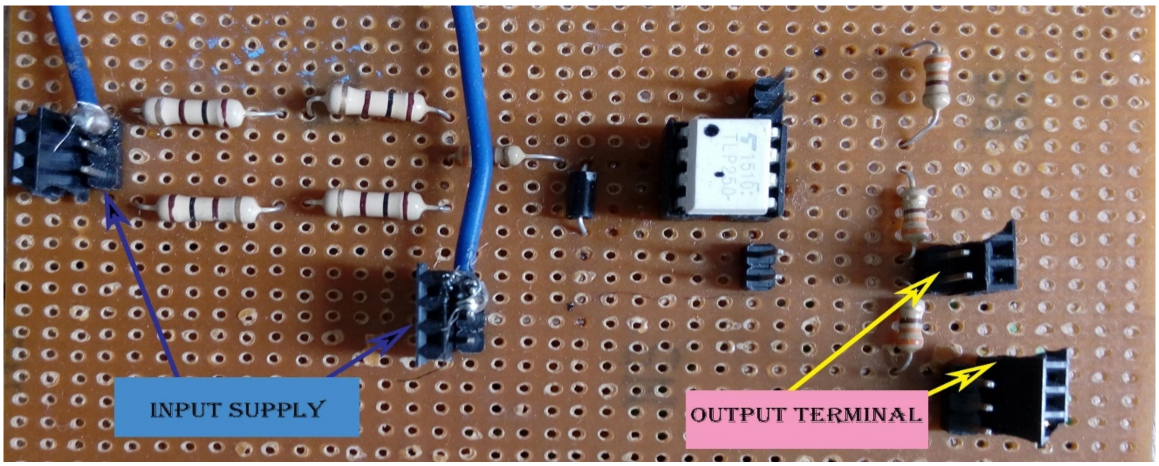


Fig. 5.2 ZCD circuit

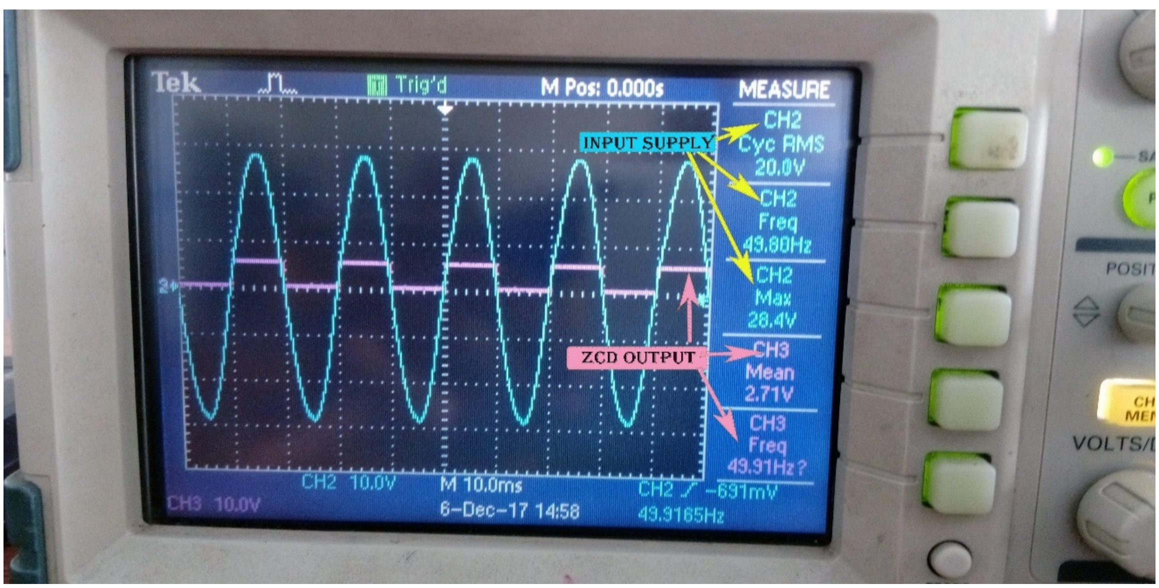


Fig.5.3 ZCD circuit output waveform

5.3 LINEAR VOLTAGE REGULATOR CIRCUIT

Fig. 5.4 shows the voltage regulator circuit providing supply to TLP250. LM7815 has been used here so as to provide a constant 15V at the output side. The input supply is given through step down transformer (9-0-9) and diode (IN4007) bridge rectifier, a capacitor of 100µf, 40V has been used at the input side and a capacitor of 470µf, 16V has been used at the output side. The led has been connected in series with 1K resistor across the load and input supply. Fig. 5.5 shows the output waveform of voltage regulator circuit.

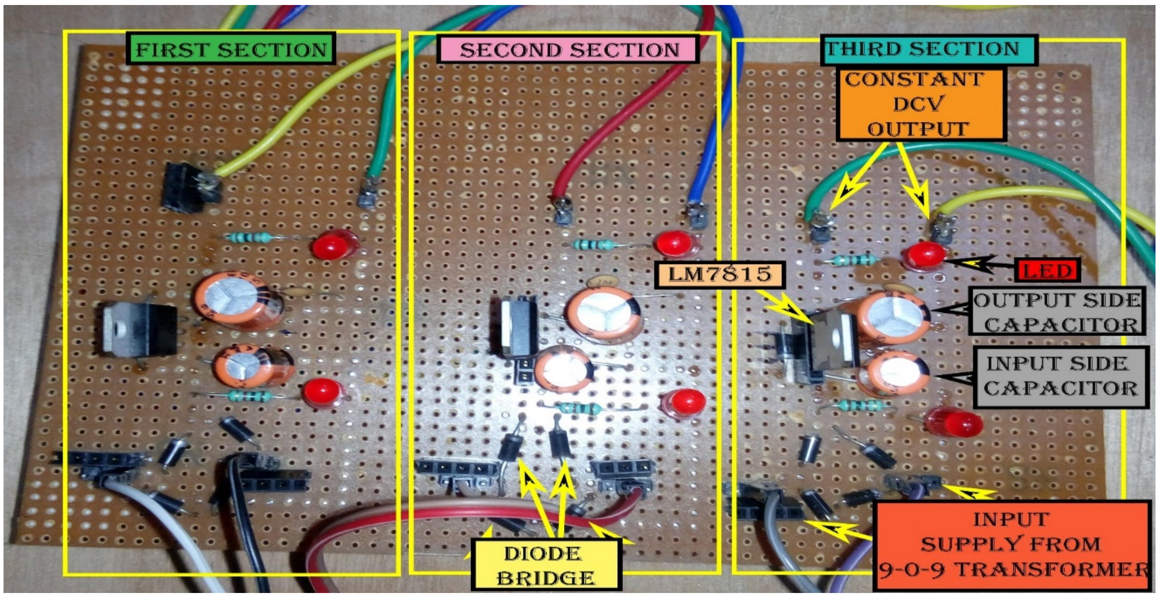


Fig. 5.4 Voltage Regulator circuit.

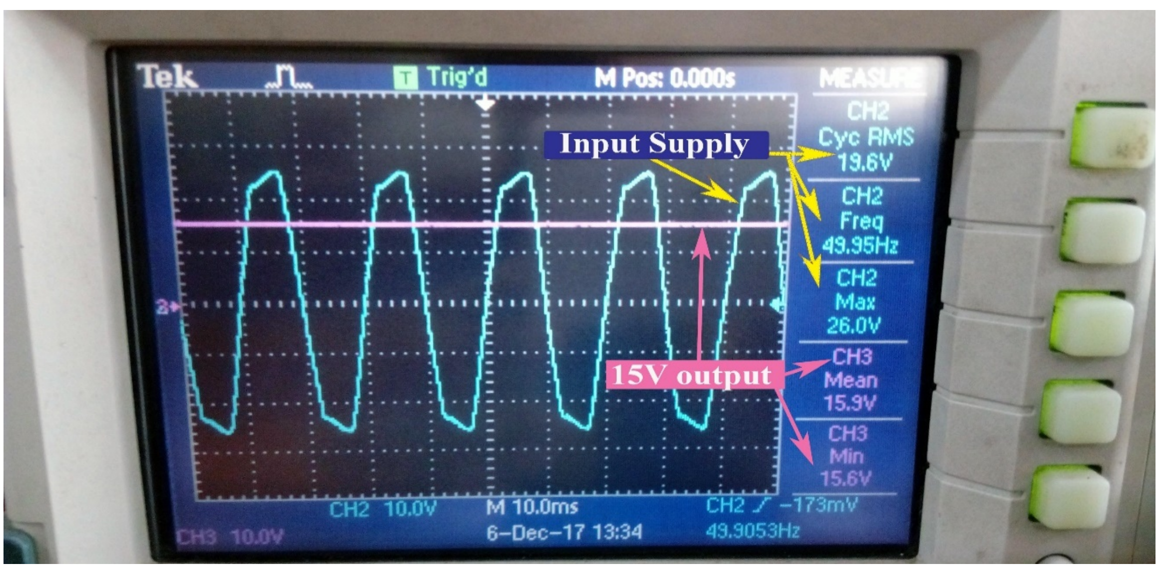


Fig. 5.5 Voltage Regulator circuit output.

5.4 GATE DRIVER/ISOLATION CIRCUIT

The Gate drive circuit/Isolation has been used here so as to create isolation between the input firing signal given from microcontroller and the output firing signal to the gate of IGBT. TLP250 has been used here as an optocoupler, diode (IN4007) has been connected in the input side so as to protect input led of the TLP250. Fig. 5.6 shows 6 Gate driver circuit out of which two are being used here, one for IGBT1 and another for IGBT2. Fig. 5.7 shows the output of one of the gate driver circuit. the input signal is from Arduino and accordingly we get output from gate drive circuit.

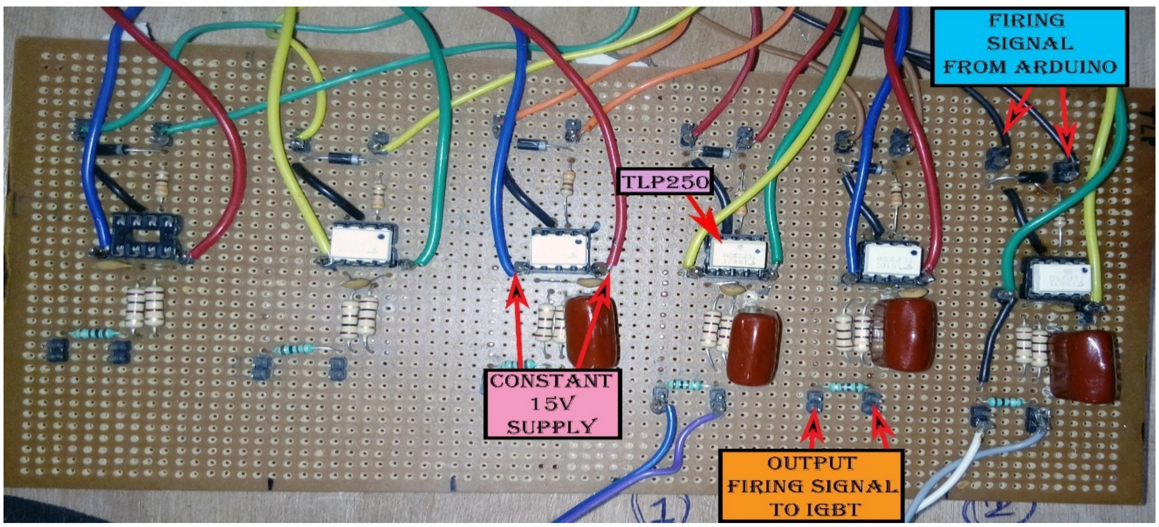


Fig. 5.6 Gate driver circuit.

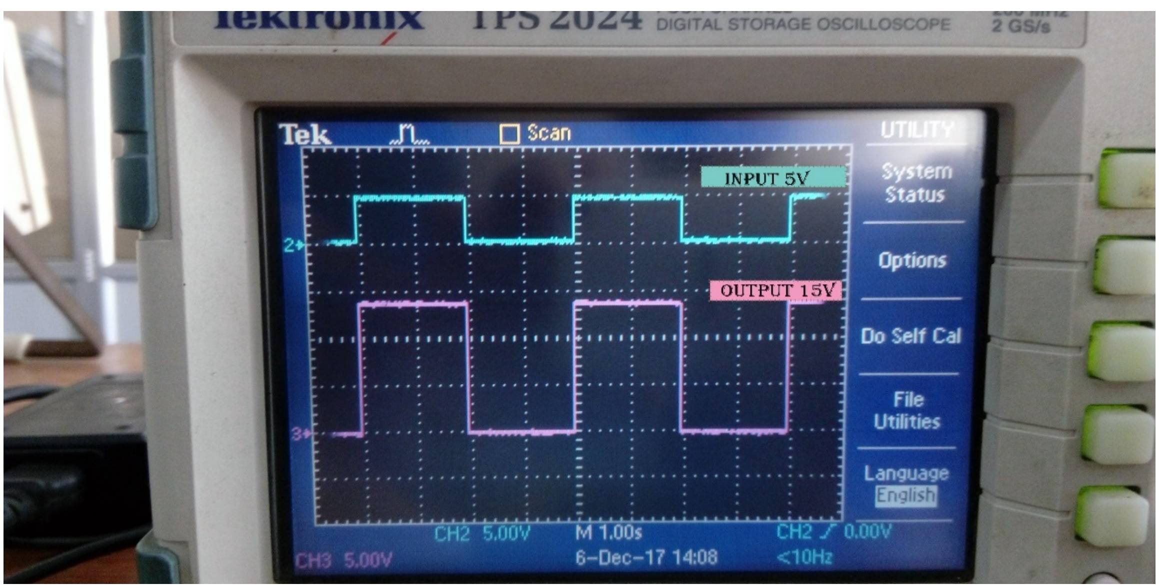


Fig. 5.7 Gate driver circuit output waveform.

5.5 POWER CIRCUIT

The power circuit of the modified single phase cycloconverter is consisting of two diode bridge and two IGBTs' connected back to back as shown in Fig 5.8 Diodes (6A10) of 6A rating has been used for the diode bridge circuit and IGBT (H20R1203) has been used here as the controlling switches.Fig 5.9 shows the experimental test bench of the hardware setup.

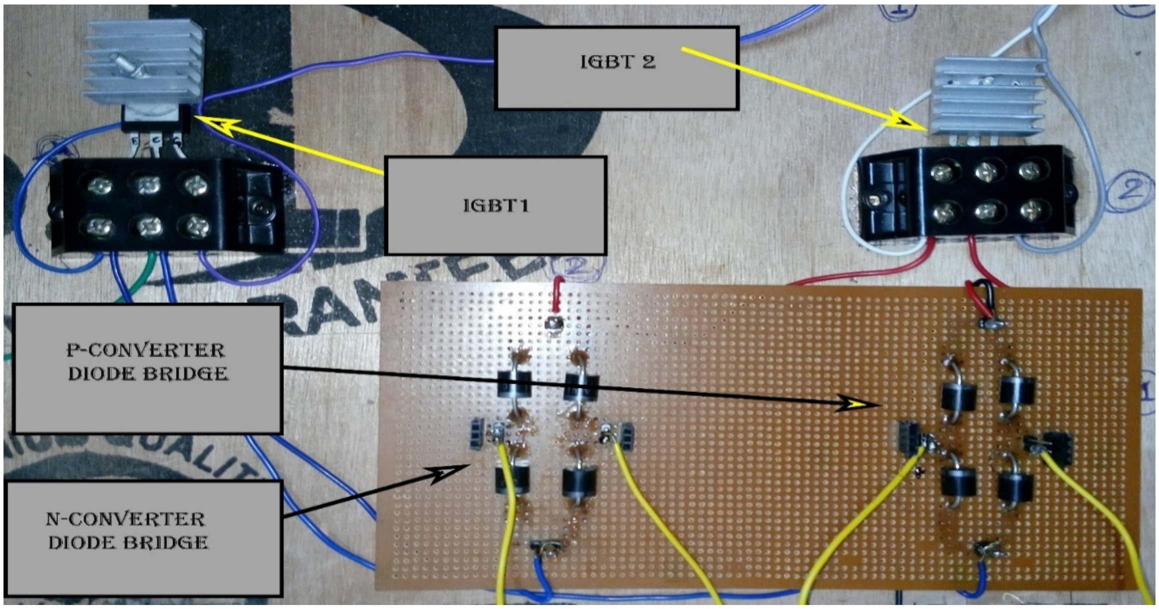


Fig. 5.8 Power Circuit.

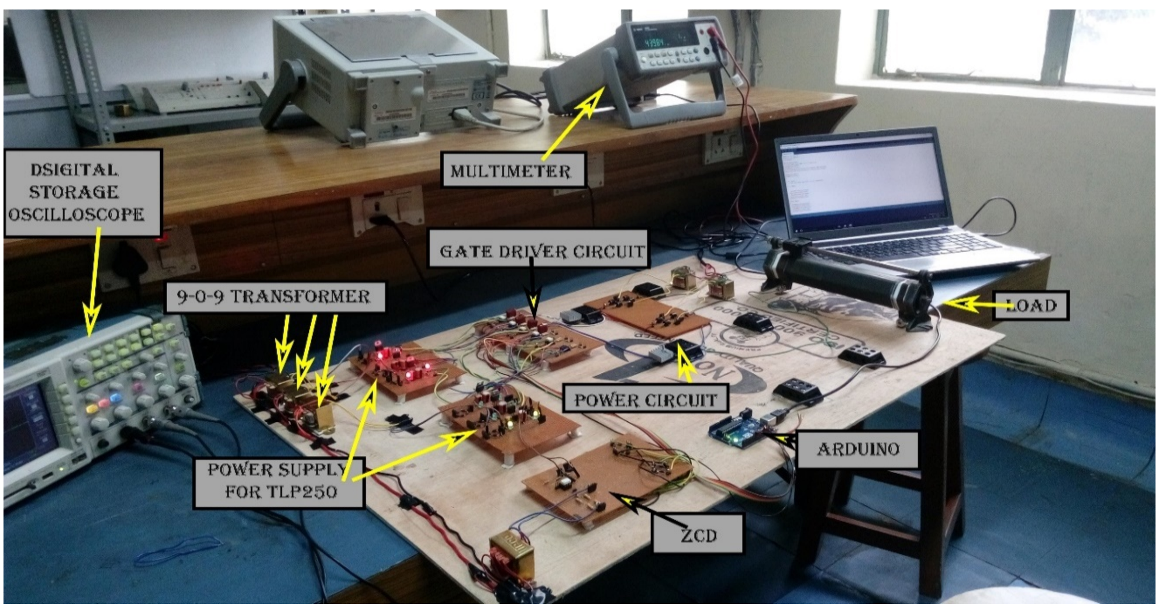


Fig 5.9 Experimental test bench.

5.6 HARDWARE RESULT

HARDWARE RESULT OF MODIFIED CIRCUIT

The results obtained from MATLAB /Simulink is compared with the hardware result of the setup working as the controlled rectifier, voltage regulator, cycloconverter. Output waveforms have been shown in Fig. 5.10 to Fig.5.22. The input parameters used for hardware implementation purpose and its output results has been shown in Table1. to Table4.

TABLE 1. FOR CYCLOCONVERTER (STEP-UP AND STEP-DOWN).

S. no	Input frequeny (Hz)	Input voltage (r.m.s)	Output frequency (Hz)	Output voltage (r.m.s)
1.	50	19.3	25	15.2
2.	50	19.3	12 ½	15.2
3.	50	19.3	100	15.2

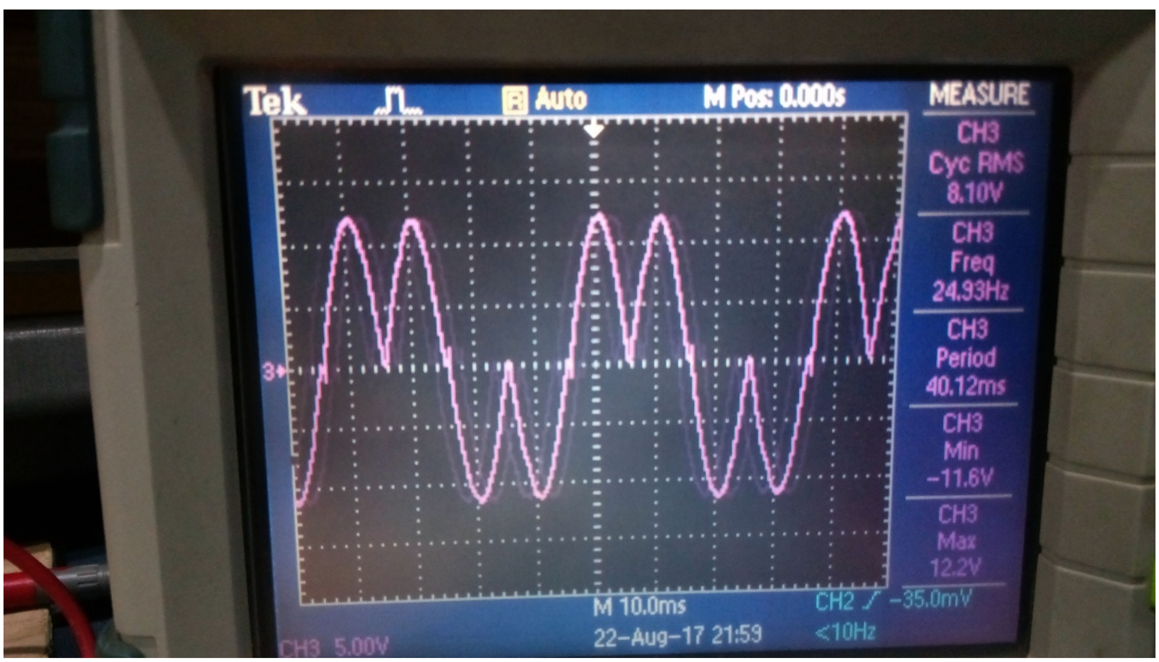


Fig 5.10 The voltage waveform of modified circuit as step-down Cycloconverter (25Hz).

Fig. 5.11 The voltage waveform of modifier circuit as step-up cycloconverter (100Hz).

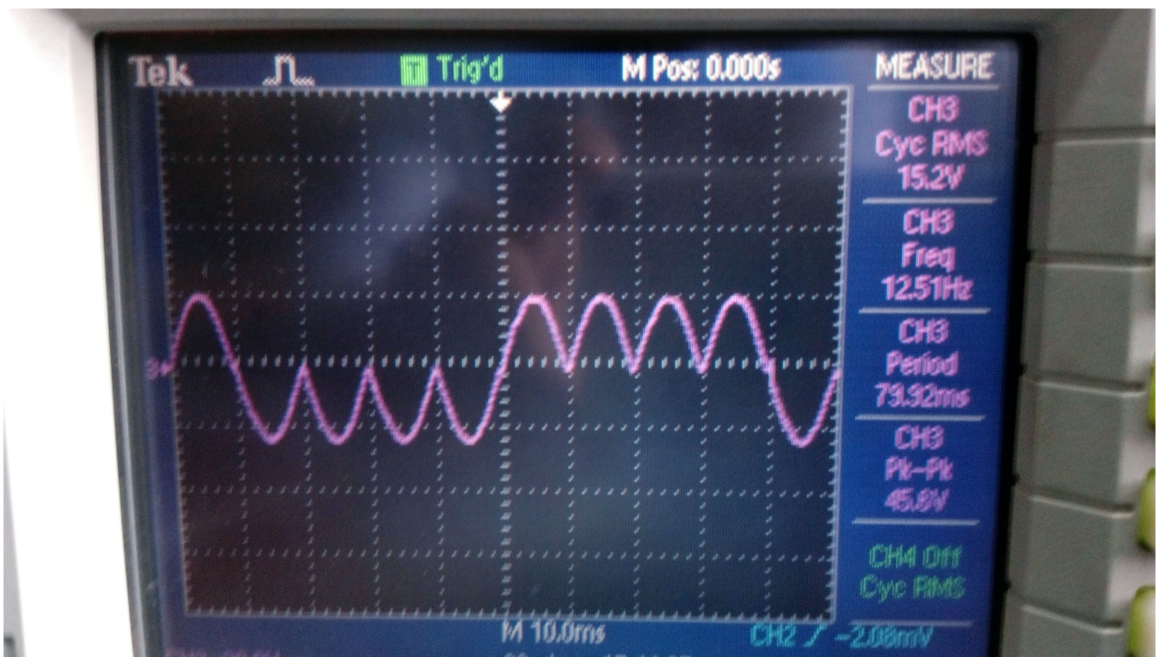


Fig 5.12 The voltage waveform of modified circuit as step-down Cycloconverter (12 ½ Hz).

TABLE 2. FOR CYCLOCONVERTER AS CONTROLLED RECTIFIER .

S. no	input voltage (r.m.s)	INPUT frequency (Hz)	Firing signal time period (millisecond)	output voltage (r.m.s)
1.	19.3	50	8.06	12.3
2.	19.3	50	7.08	10.8
3.	19.3	50	5	6.75

Fig 5.13 The waveforms of the modified cycloconverter circuit as a controlled rectifier.

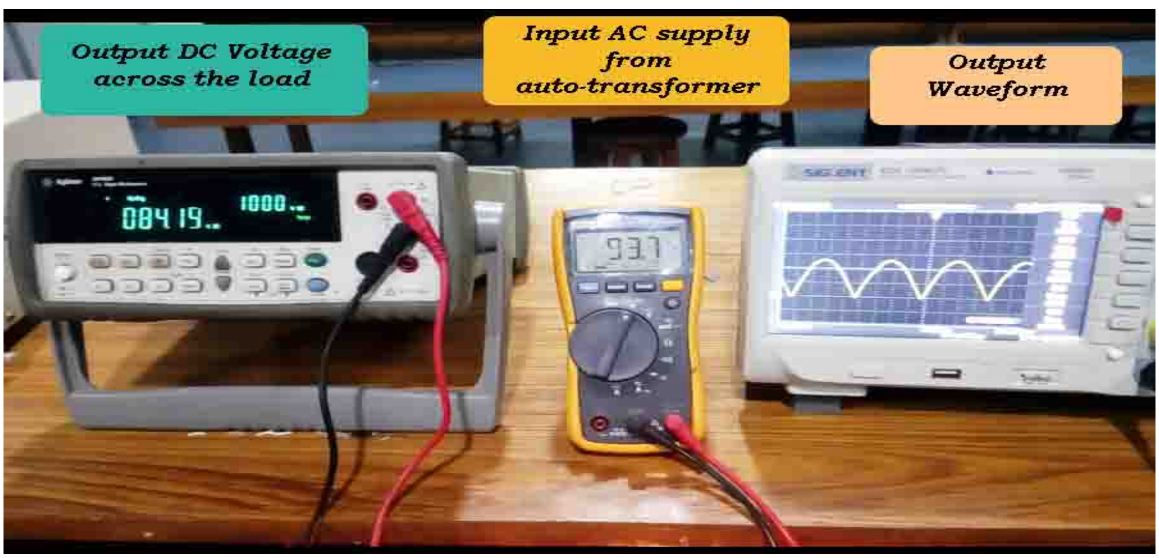


Fig 5.14 The input and output voltage of the modified cycloconverter circuit as rectifier.

TABLE 3. FOR MODIFIED CIRCUIT AS VOLTAGE REGULATOR.

S. no	input voltage (r.m.s)	INPUT frequency (Hz)	Firing signal time period (sec) out of 10msec	output voltage (r.m.s)
1.	19.3	50	9.859	15.4
2.	19.3	50	8.059	14.8
3.	19.3	50	5.079	10.9

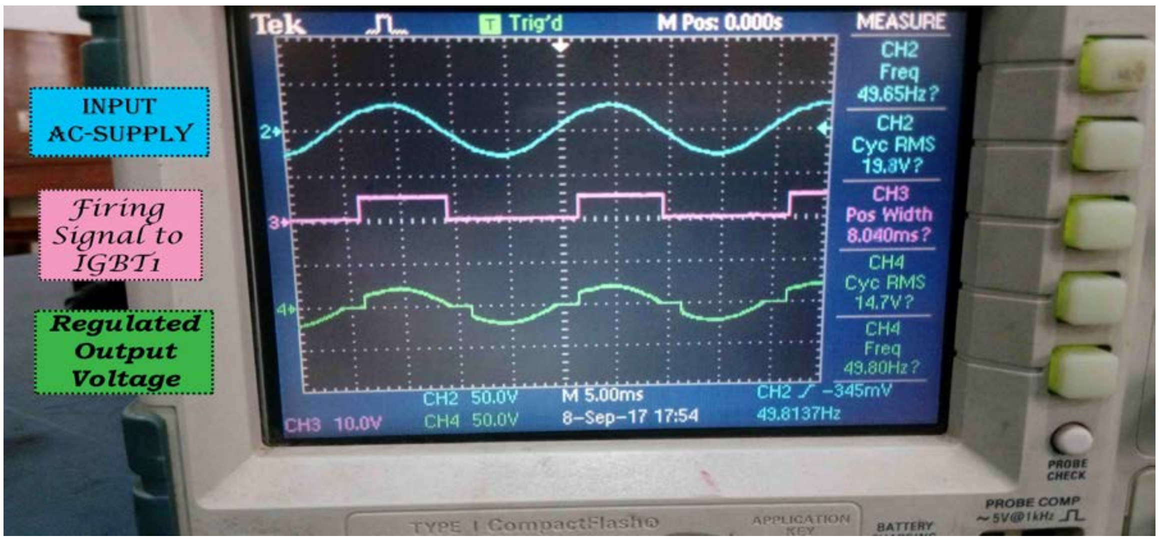


Fig. 5.15The output waveform of the converter as a Voltage regulator.

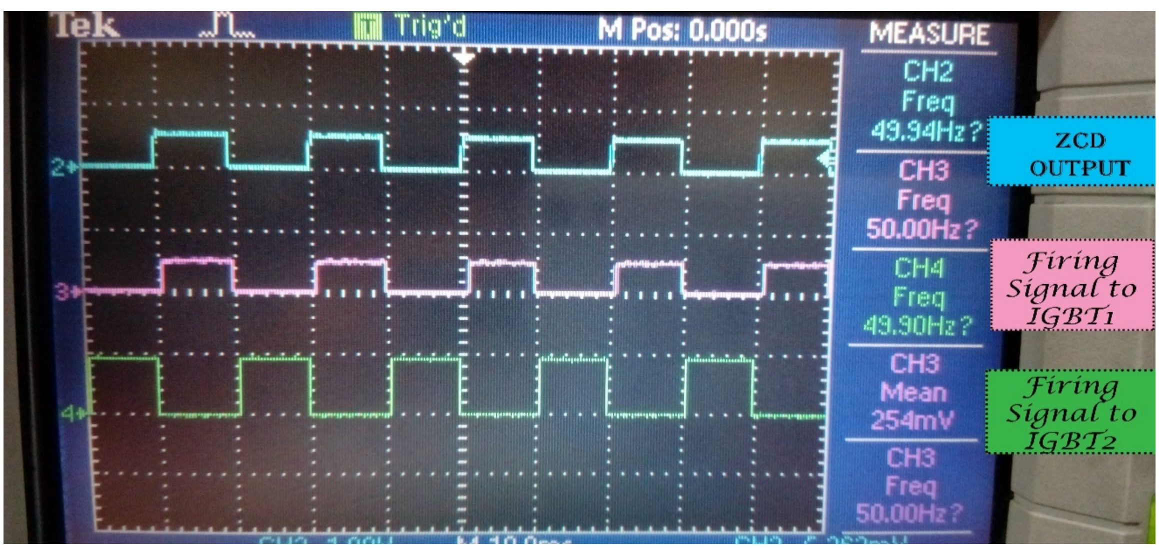


Fig. 5.16 The Output waveform of the ZCD circuit and the firing signals to IGBTs'.

HARDWARE RESULT OF CONVENTIONAL CYCLOCONVERTER CIRCUIT

For the comparison of the modified cycloconverter the hardware prototype of conventional Cycloconverter has been made.

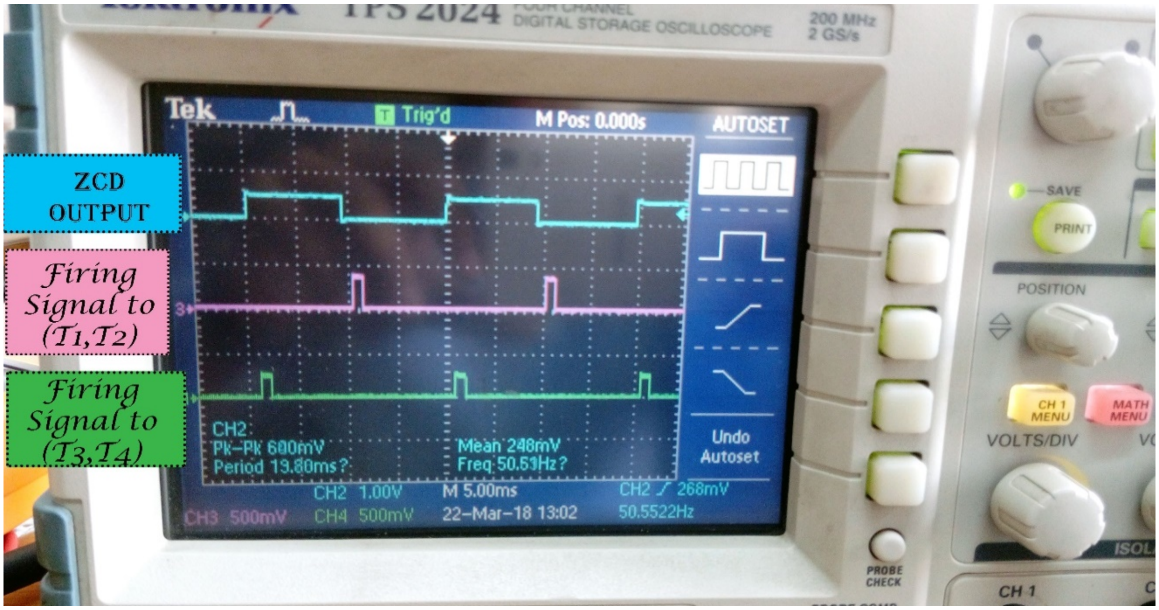


Fig. 5.17 The Output waveform of the ZCD circuit and the firing signals to SCRs' for the circuit to work as rectifier.

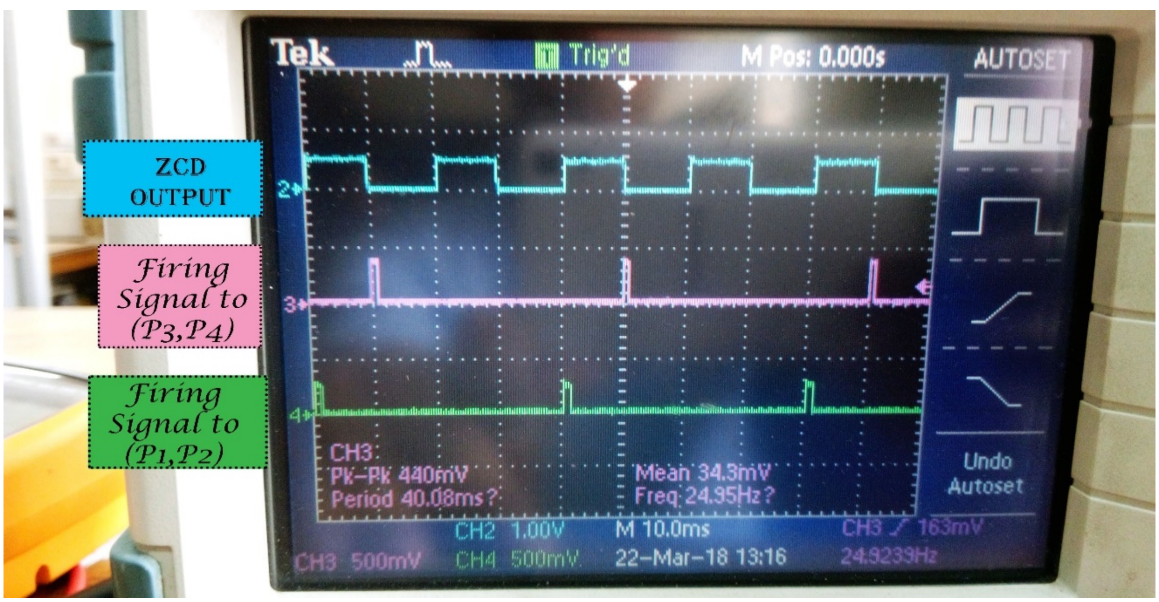


Fig. 5.18 The Output waveform of the ZCD circuit and the firing signals to the SCRs' for the circuit to work as step-down cycloconverter (25Hz).

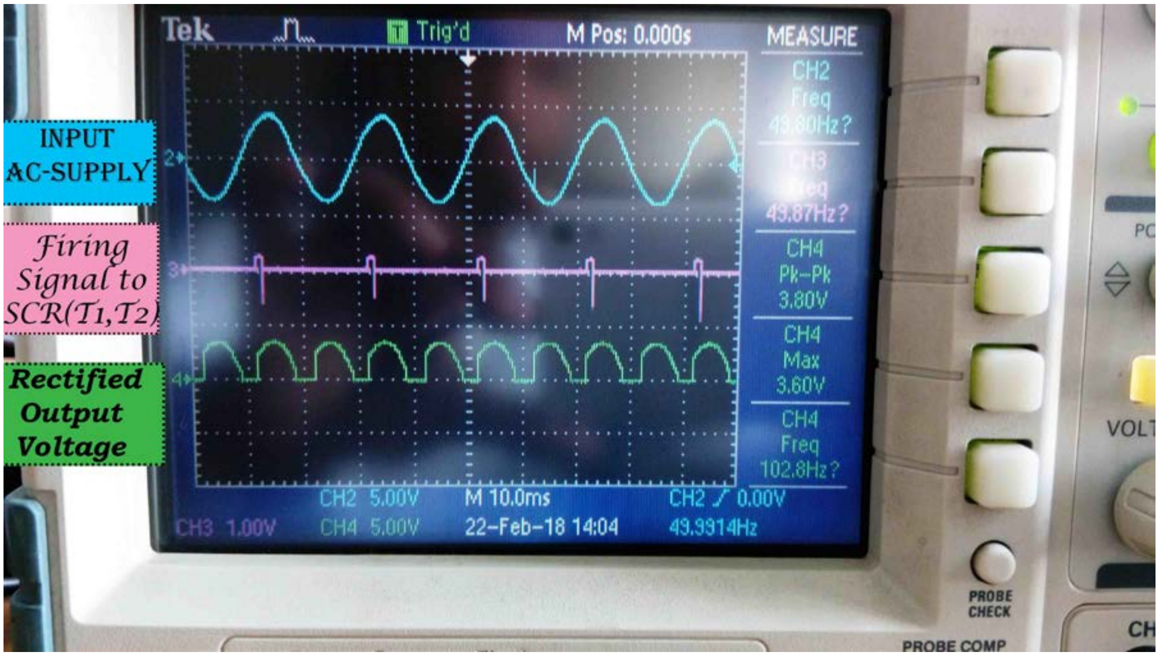


Fig. 5.19 The Output waveform of the conventional circuit working as rectifier.

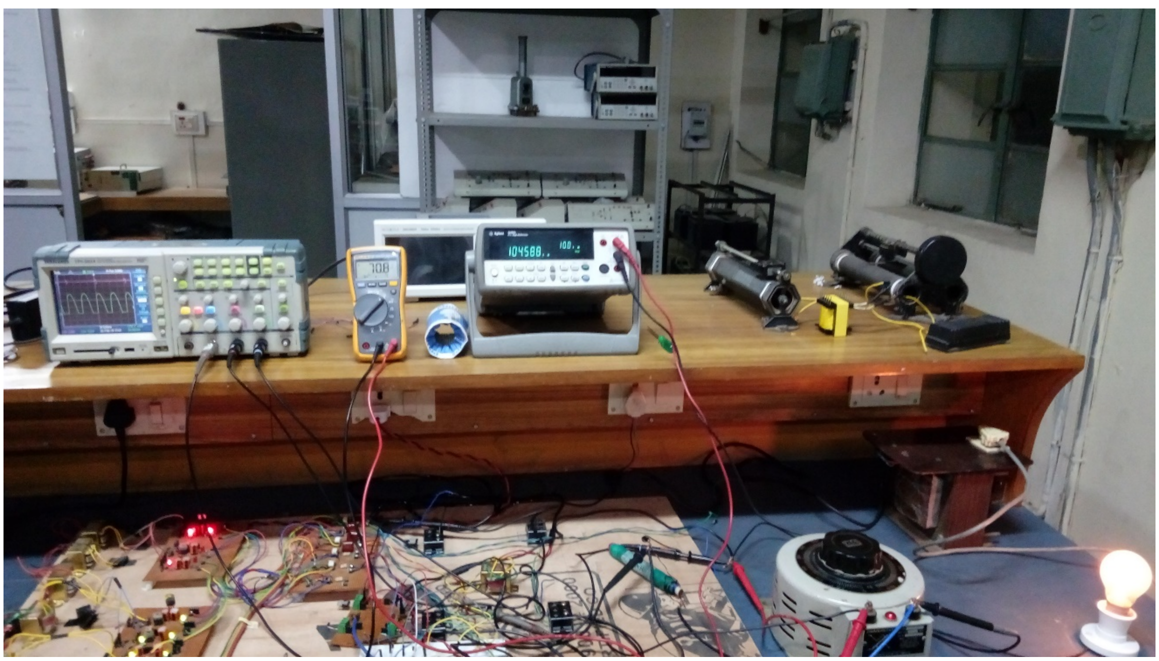


Fig. 5.20 The conventional circuit test bench.

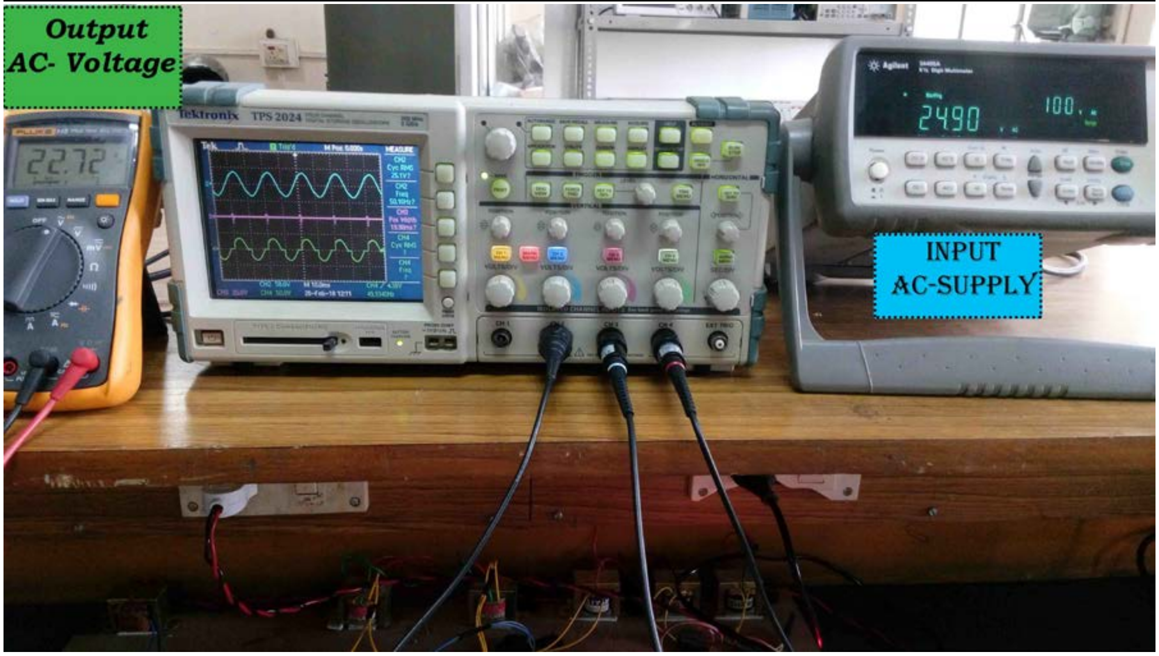


Fig. 5.21 The Output waveform of the conventional circuit working as voltage regulator.

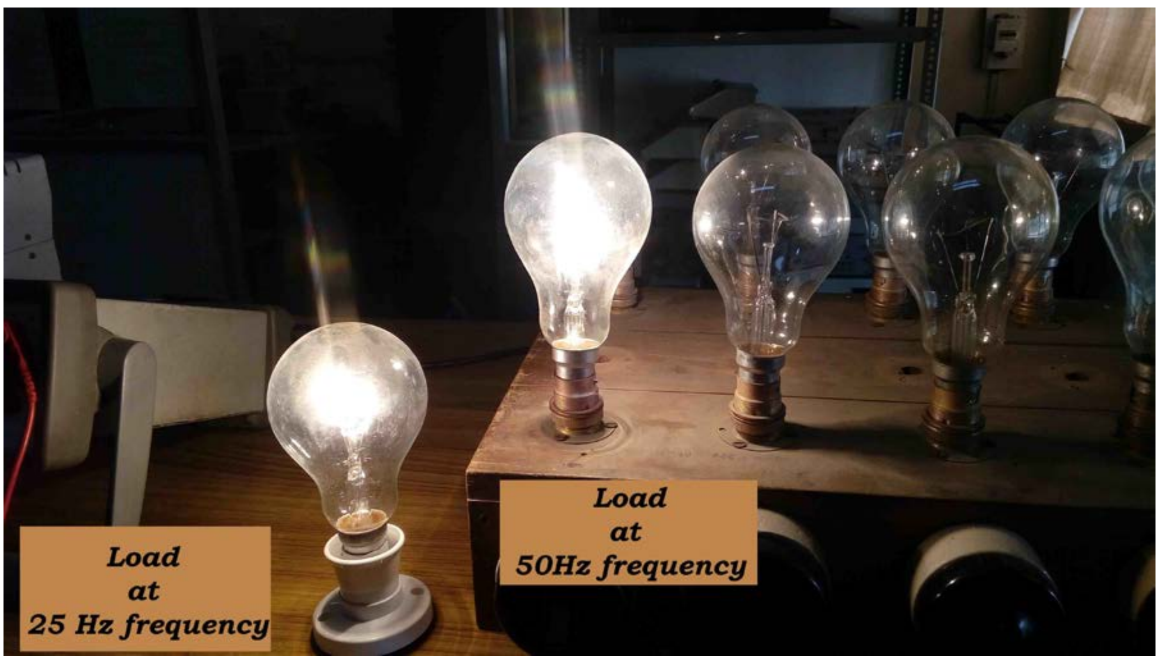


Fig. 5.22 The loads operating at different frequency (50Hz & 25Hz).

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The Prototype of Conventional single phase cycloconverter circuit has been developed. Simulation has been done on MATLAB/Simulink platform for the modified single phase cycloconverter to obtain different output frequency of 25 Hz, 12½ Hz, 100 Hz. The results obtained from the hardware prototype was similar to those obtained from the simulation. To further validate the modified circuit prototype of conventional single phase cycloconverter has been developed and also made to perform as rectifier and voltage regulator. Now both the conventional and modified single phase cycloconverter has been compared and the satisfactory results has been observed.

For the hardware prototype various auxiliary circuits has been made, they are ZCD circuit, voltage regulator circuit, gate driver circuit and power circuit of both conventional and modified circuit. There hardware as well as output results has been shown.

6.2 PRACTICAL DIFFICULTIES

While working with the prototype circuit as the input power level was raised the soldering made on the Veroboard has started melting thus for high power level the power circuit was again made with the help of HT3 connectors.

The output signal from the ZCD circuit was perfect but sending this signal to the microcontroller (Arduinio) as an Interrupt was causing false firing pulses to the switches as shown in fig 6.1. After several modification in the program code so as to reduce the number of lines to be executed and hence making it run faster (as Interrupts run in microseconds).

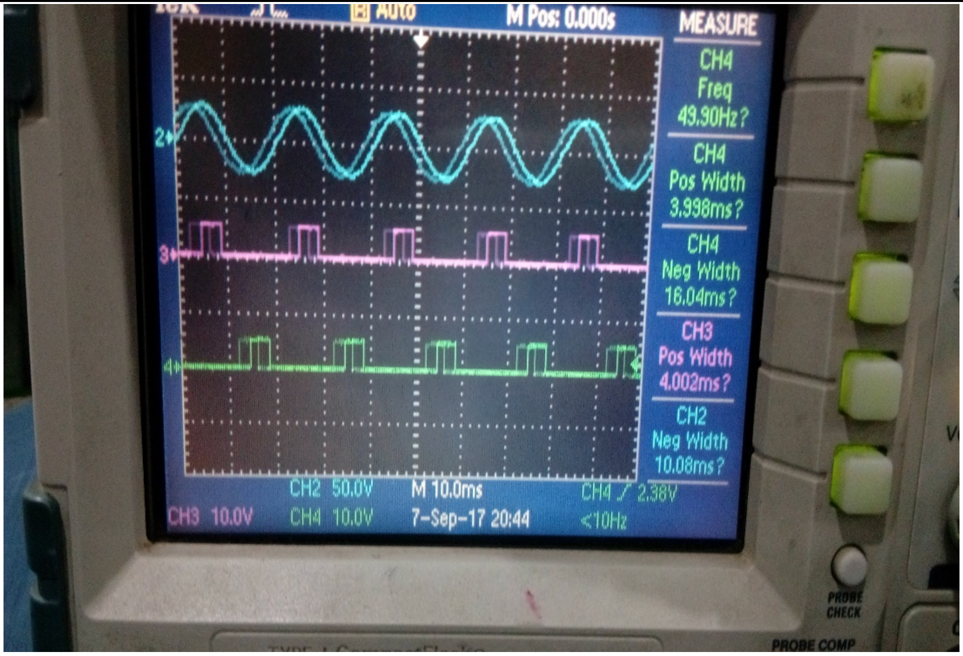


Fig 6.1 The false firing pulses to the switches

Since, we were working with RISING and FALLING edge it was observed that Arduino gives false firing signal due to very little noises present in the ZCD output signal. So, we soldered a .1µF Ceramic capacitor (shown in fig 6.2)at the input side of interrupt pin of Arduino. .Hence the problem was solved by hardware debugging.

Fig 6.2 shows .1µF Ceramic capacitor

While making the modified cycloconverter giving output of 25Hz frequency shown in fig 6.3. It was required to have four different firing pulse since, it consists four modes of operation. This task was achieved through programming. There is a bug in the Arduino Mega2560 that even after detaching the Interrupt it does not clears the interrupt flag automatically which causes problem sometimes so the flag needs to be cleared manually by using the command line (EIFR |= 0xFF; //clear all flags) at the end of Interrupt cycle.

Many powerful microprocessors such as TI Launch Pad are there in the market so using Arduino Mega was a bit difficult task while working with many Interrupts Since Arduino itself takes some time to execute the line codes, it was difficult to get output.

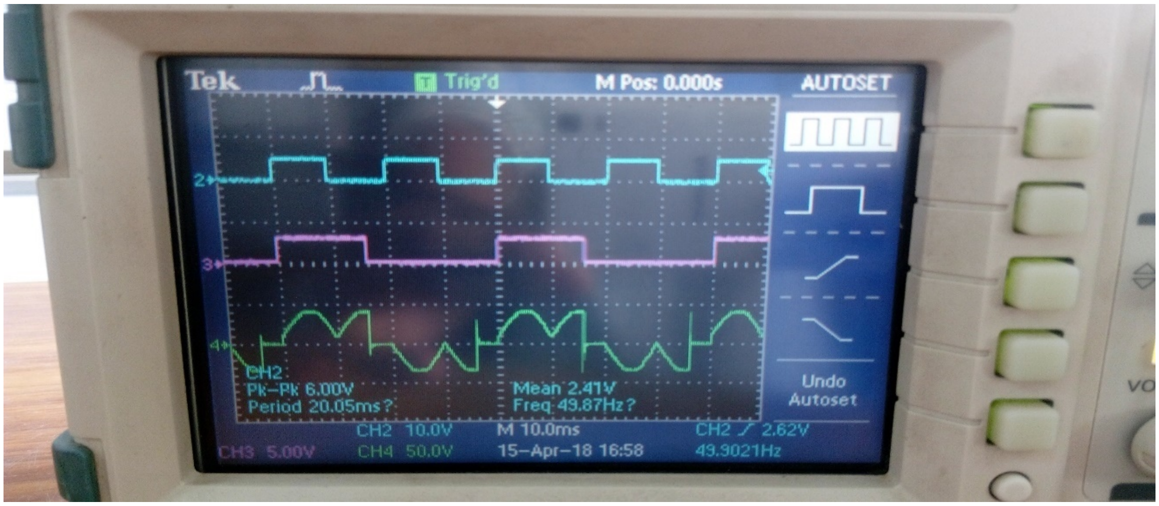


Fig 6.3 cycloconverter at 25Hz frequency

While operating with the conventional SCRs' based cycloconverter.at the supply voltage of 200V a fault in the load has caused a large reverse biased voltage across the switches causing all eight switches to get burned. Whereas in modified cycloconverter circuit only two switch might get damaged. So the repairing cost as well as time will be less in the modified circuit.

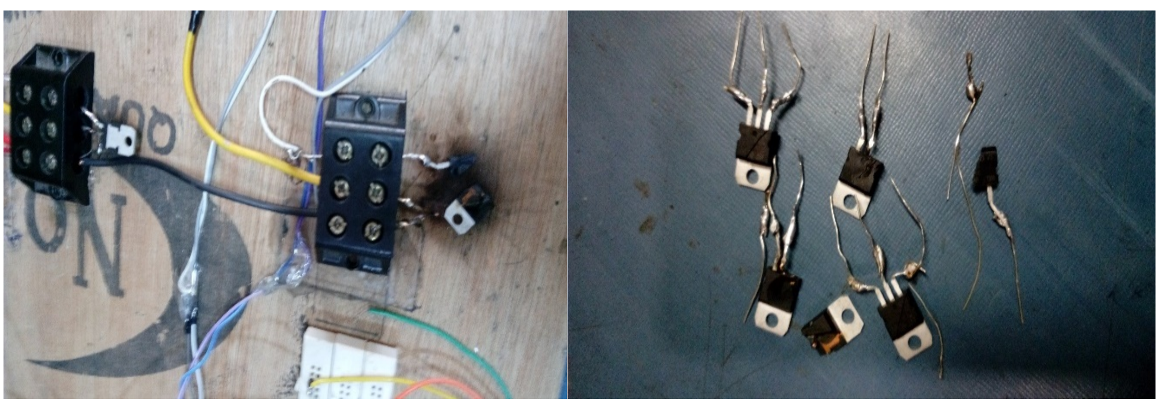


Fig 6.4 SCRs' due to large reverse biased voltage

6.3 FUTURE SCOPE

The system has been made compact and the circuit complexity has been reduced. As the project was successfully done still there are a lot of scopes of research which can be carried out in this direction by improving the stability and control technique.

The given module can be made to perform as cycloconverter, rectifier, voltage regulator and for the input dc supply we can made this topology to work as an inverter. The module can be developed using FPGA and smart controlling technique such as AI can be implemented.

PUBLICATIONS

1. Shivam Bharti, Amit Karmakar and Aparna Gautam "Hardware Development and Implementation of Single Phase Two Switch Cycloconverter" International Journal of Electronics, Electrical and Computational System IJEECS, ISSN 2348-117X, Volume 6, Issue 9,September 2017.
2. Shivam Bharti and Aparna Arunkumar Gautam "Hardware Design and Implementation of Multiconverter Module" in IEEE 4th International Conference on Electrical Energy System (ICEES 2018) during February 07-09,2018.

REFERECE

[1] Shohei Komeda, Hideaki Fujita "A Phase-Shift-Controlled Direct AC-to-AC Converter for Induction Heaters", IEEE Transaction on Power Electronics, AUGUST 2015.

[2] D Sri Vidhya and T. Venkatesan "Quasi-Z-Source Indirect Matrix Converter Fed Induction Motor Drive for Flow Control of Dye in Paper Mill", IEEE Transactions, Power March 2017.

[3] Michael J. Gorrnan. Member, IEEE, and Malik E. Elbuluk, Member, IEEE "A Simple Two-Switch Cycloconverter for Variable-Frequency Low-Speed Applications", IEEE Transactions on Power Electronics, VOL 6, NO 1, October 1991.

[4] Wenjie Zhu, Keliang Zhou, Ming Cheng and Fei Peng "A High-Frequency–Link Single-Phase PWM Rectifier", IEEE Transaction on Industrial Electronics, January 2015.

[5] Jiarong Kan, Shaojun Xie, Yunya Wu, Yu Tang, Zhilei Yao and Rong Chen "High-Frequency-Link Inverter Using Combined Synchronous Rectifiers", IEEE Transcations on Industrial Electronics, December 2014.

[6] Sudip K. Mazumder, Rajini k. Burra, Rongjun Huang, Muhammad Tahir and Kaustuva Acharya "A Universal Grid-Connected Fuel-Cell Inverter Residential Application" , IEEE Transactions on Industrial Electronics October, 2010.

[7] Louis J. Lawson "The Practical Cycloconverter" in IEEE Transcation on Industry and General Applications, March 1968.

[8] Alexander Eigeles Emanuel and Richard A. Dziura "A Simplified Dual Cycloconverter" in IEEE Transactions on Industrial Electronics and Control Instrument November 1981.

[9] Louis J. Lawson, IEEE "The Practical Cycloconverter" in IEEE Transactions on Industry and General Applications, Vol. Iga4, No.2, March/April 1968.

[10] Gerald M. Brown, Barna Szabados, Gerard J. Hoolboom and Michel E. Poloujadoff "High-Power Cycloconverter Drive for Doubl-Fed Induction Motors" in IEEE Transactions on Industrial Electronics June 1992.

[11] Carmelo J. Amato, Member, IEEE "An AC Equivalent Circuit for a Cycloconverter" in IEEE Transactions on Industry and General Applications Vol. 2, No. 5 Sept/Oct 1966.

[12] Shanhu Li, Wei Chen, Yan Yan , Tingna Shi, And Changliang Xia "A Multi mode Space Vector Overmodulation Strategy for Ultra Sparse Matrix Converter With Improved Fundamental Voltage Transfer Ratio" in IEEE Transactions on Power Electronics, February 2017.

[13] Youngseok Kim, Shigeru Okuma and Koji Iwata "Characteristics and Starting Method of a Cycloconverter with a Tank Circuit for Induction Heating" in IEEE Transactions On Power Electronics, VOL. 3, NO. 2, APRIL 1988.

[14] Hiroshi nomura, Keinchiro Fujiwara and Hisaaki Kawakami "A Power Factor compensator using a force-commutated cycloconverter" IEEE Transactions On Industry Applications, VOL.26, NO.4, July/August 1990.

[15] Zhenyuan Wang and Yilu Liu "Modeling and Simulation of a Cycloconverter Drive System for Harmonic Studies" IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 47, NO. 3, June 2000.

[16] Hiromichi Ohashi and Ichiro Omura "Role of Simulation Technology for the Progress in Power devices and Their Applications" IEEE TRANSACTION ON ELECTRON DEVICES, volume 60, number 2, page range 528-536, year 2013

[17] Rivera, Marco and Rojas, S. and Wheeler, Patrick and Rodriguez "A predictive control strategy for a single-phase AC-AC converter" 7th PowerElectronics, Drive Systems and Technologies Conference (PEDSTC 2016), 16-18 Feb 2016.

[18] Luigi Malesani, Leopoldo Rossetto, Paolo Tenti and Paolo Tomasin "AC/DC/AC PWM Converter with Reduced Energy Storage in the DC Link" IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 31, NO. 2, march/april 1995.

[19] Zahirrudin Idris, Mustafar Kamal Hamzah, Ngah Ramzi Hamzah "Modelling & Simulation of a new Single-phase to Single-phase Cycloconverter based on Single-phaseMatnx Converter Topology with Sinusoidal PulseWidth Modulation Using MATLAB/Simulink" IEEE Power Electronics and Drive Systems, 2005.

[20] Md. Ali Azam, Ahmed Nasim Azad, Hossain Toufiq Imam, Md. Ashfanoor Kabir, M. Nasir Uddin, M. Nasir Uddin and M.A. Choudhury "Three to Single Phase Buck-Boost Regulated High Power Quality Cycloconverter", IEEE Power & Energy Society (PES) and Innovative Smart Grid Technologies, 2012.

[21] Arinjoy Biswas, Jawahar Lal Jaiswal and Vineeta Agarwal "A Study of Staircase Modulation Technique for Single Phase Matrix Converter", 2nd International Conference on Power, Control and Embedded Systems, 2012.

[22] M Raghuram and Anshul Agarwal "Simulation of Single Phase Matrix converter as All in One Converter" International Conference on Power, Signals, Controls and Computation (EPSCICON), 8 – 10 January 2014.

[23] Xudan Liu, Dehong Xu, Changsheng Hu, Heng Yue, Yashun Li, Ping Lin, and Hangwen Pan " A High-Efficiency Single-Phase AC/DC Converter With Enabling Window Control and ActiveInput Bridge, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 27, NO. 6, June 2012.

[24] Ahmed Al-Busaidi, Volker Pickert and Shady Gadoue "Single-phase rectifier circuit with output voltage enhancement for automotive generators" IET Journal ISSN 2042-9738, 14th November 2014.

[25] Nimesh Vamanan and Vinod John, " Dual Comparison One Cycle Control for Single Phase AC to DC Converters" IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 52, NO. 4, July/august 2016.

[26] Philip T. Krein, Robert S. Balog and Xin Geng " High-Frequency Link Inverter for Fuel Cells Based on Multiple-Carrier PWM" IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 19, NO. 5, september 2004.

[27] Yazhou Liu, Gerald Thomas Heydt and Ron F. Chu " The Power Quality Impact of CycloconverterControl Strategies" IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 20, NO. 2, april 2005.

APPENDIX A

ARDUINO PROGRAM FOR MODIFIED SINGLE PHASE CYCLOCONVERTER

The Code has been written on Arduino platform so as to detect RISING EDGE and FALLING EDGE of the ZCD and accordingly we will apply the firing signal.

The code used for the modified single phase cycloconverter to provide firing signal to the IGBT1 and IGBT2. The following code has been used:

```
volatile int a,a1=0;

volatile int b=0;

void setup() {

pinMode (13, OUTPUT);

pinMode (12, OUTPUT);

attachInterrupt(digitalPinToInterrupt(2),ISRr,RISING);

attachInterrupt(digitalPinToInterrupt(3),ISRf,FALLING);

pinMode (2, INPUT);

pinMode (3, INPUT);

pinMode(A0,INPUT);

Serial.begin(9600);

}

void loop() {

a1=analogRead(A0);
```

```
a=map(a1,0,1023,0,8950);

b=8950-a;

Serial.println("a=");

Serial.println(a);

Serial.println("\n");

Serial.println("b=");

Serial.println(b);

Serial.println("\n");

}

void ISRr() {

delayMicroseconds(a);

digitalWrite(13,HIGH);

delayMicroseconds(1000);

digitalWrite(13,LOW);

delayMicroseconds(b);

}

void ISRf() {

delayMicroseconds(a);

digitalWrite(12,HIGH);

delayMicroseconds(1000);

digitalWrite(12,LOW);
```

```
delayMicroseconds(b);

}
```

ARDUINO PROGRAM FOR CONVENTIONAL SINGLE PHASE CYCLOCONVERTER

Similarly code has been written for the conventional cycloconverter so as to provide the firing signal to the 8 SCR’s

```
volatile int a,a1=0;

volatile int b=0;

void setup() {

pinMode (13, OUTPUT);

pinMode (12, OUTPUT);

pinMode (11, OUTPUT);

pinMode (10, OUTPUT);

attachInterrupt(digitalPinToInterrupt(2),ISRr,RISING);

attachInterrupt(digitalPinToInterrupt(3),ISRf,FALLING);

attachInterrupt(digitalPinToInterrupt(18),ISRR,RISING);

attachInterrupt(digitalPinToInterrupt(19),ISRF,FALLING);

pinMode (2, INPUT);

pinMode (3, INPUT);

pinMode (18, INPUT);

pinMode (19, INPUT);

Serial.begin(9600);
```

```
}

void loop() {

}

void ISRr() {

delayMicroseconds(300);

digitalWrite(13,HIGH);

delayMicroseconds(1200);

digitalWrite(13,LOW);

delayMicroseconds(1000);

detachInterrupt (digitalPinToInterrupt(2));

EIFR |= 0xFF;

attachInterrupt(digitalPinToInterrupt(18),ISRR,RISING);

}

void ISRf() {

delayMicroseconds(300);

digitalWrite(12,HIGH);

delayMicroseconds(1200);

digitalWrite(12,LOW);

delayMicroseconds(1000);

detachInterrupt (digitalPinToInterrupt(3));

EIFR |= 0xFF;
```

```
attachInterrupt(digitalPinToInterrupt(19),ISRF,FALLING);

}

void ISRR() {

delayMicroseconds(300);

digitalWrite(11,HIGH);

delayMicroseconds(1200);

digitalWrite(11,LOW);

delayMicroseconds(1000);

detachInterrupt (digitalPinToInterrupt(18));

EIFR |= 0xFF;

attachInterrupt(digitalPinToInterrupt(2),ISRr,RISING);

}

void ISRF() {

delayMicroseconds(300);

digitalWrite(10,HIGH);

delayMicroseconds(1200);

digitalWrite(10,LOW);

delayMicroseconds(1000);

detachInterrupt (digitalPinToInterrupt(19));

EIFR |= 0xFF;

attachInterrupt(digitalPinToInterrupt(3),ISRf,FALLING); }}
```

DIODES INCORPORATED

6A05 - 6A10

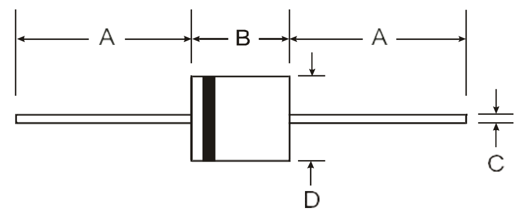
6.0A SILICON RECTIFIER

Features

- High Surge Current Capability
- Low Leakage and Forward Voltage Drop
- **Lead Free Finish, RoHS Compliant (Note 1)**

Mechanical Data

- Case: R-6
- Case Material: Molded Plastic. UL Flammability Classification Rating 94V-0
- Moisture Sensitivity: Level 1 per J-STD-020C
- Terminals: Finish ↓ Tin. Axial Leads, Solderable per MIL-STD-202, Method 208 e3
- Polarity: Color Band Indicates Cathode
- Ordering Information: See Page 3
- Approximate Weight: 2.1 grams



R-6		
Dim	**Min**	**Max**
A	25.40	-
B	8.60	9.10
C	1.20	1.30
D	8.60	9.10
All Dimensions in mm		

Maximum Ratings and Electrical Characteristics @T_A = 25°C unless otherwise specified

Ratings at 25°C ambient temperature unless otherwise specified.
Single phase, halfwave, 60Hz, resistive or inductive load.

Characteristic	Symbol	6A05	6A1	6A2	6A4	6A6	6A8	6A10	Unit
Maximum Recurrent Peak Reverse Voltage	V_{RRM}	50	100	200	400	600	800	1000	V
Maximum RMS Voltage	V_{RMS}	35	70	140	280	420	560	700	V
Maximum DC Blocking Voltage	V_{DC}	50	100	200	400	600	800	1000	V
Maximum Average Forward Rectified Current 9.5mm lead length @ T_A = 75°C (See Fig. 1)	$I_{(AV)}$	6.0							A
Peak Forward Surge Current 8.3 ms single half sine-wave superimposed on rated load	I_{FSM}	400							A
Maximum Instantaneous Forward Voltage at 6.0A DC	V_{FM}	0.90							V
Maximum DC Reverse Current @ T_A = 25°C at Rated Blocking Voltage @ T_A = 100°C	I_{RM}	10 100							µA
Operating and Storage Temperature Range	T_j, T_{STG}	-65 to +175							°C

Notes: 1. RoHS revision 13.2.2003. Glass and high temperature solder exemptions applied, see *EU Directive Annex Notes 5 and 7.*

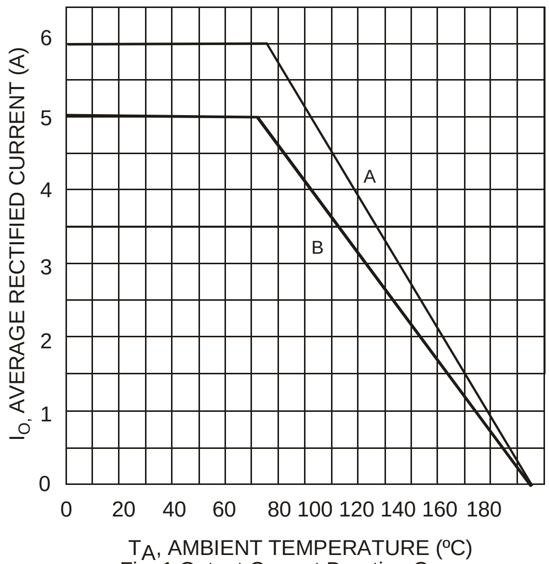
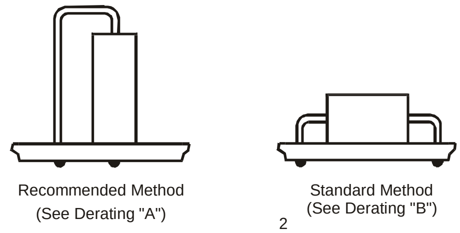


Fig. 1 Output Current Derating Curve



Ground Plane: 25mm^2 equivalent copper surface area

Printed Circuit Board Mounting Method

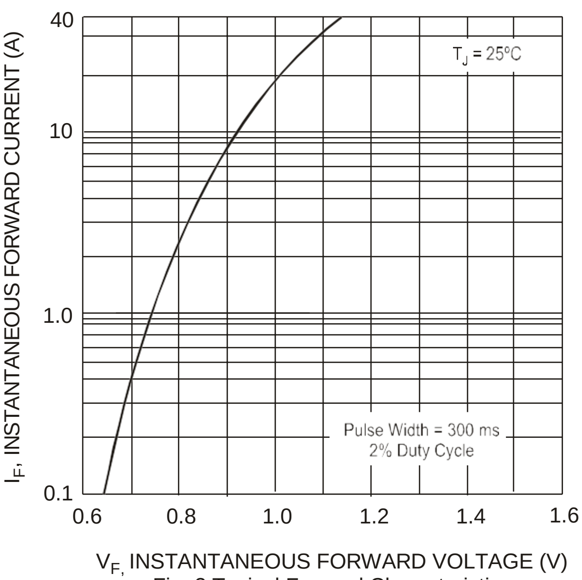


Fig. 2 Typical Forward Characteristics

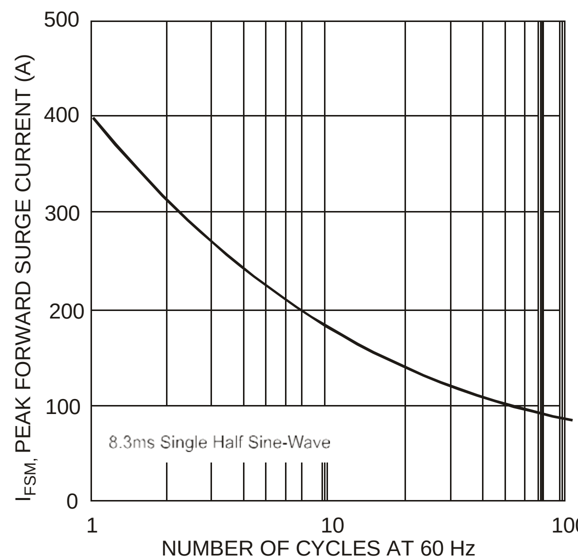


Fig. 3 Maximum Non-Repetitive Peak Forward Surge Current

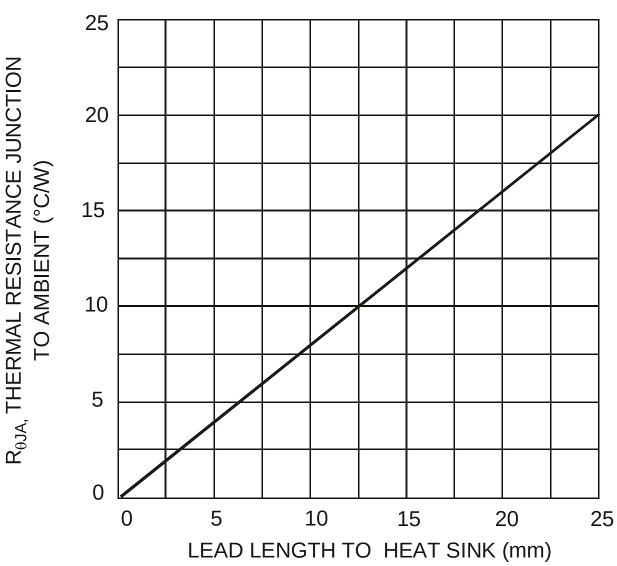


Fig. 4 Typical Thermal Resistance
(Using Standard Mounting Method "B")

Ordering Information (Note 2)

Device	Packaging	Shipping
6A05-T	R-6	500/Tape & Reel, 13-inch
6A1-T	R-6	500/Tape & Reel, 13-inch
6A2-T	R-6	500/Tape & Reel, 13-inch
6A4-T	R-6	500/Tape & Reel, 13-inch
6A6-T	R-6	500/Tape & Reel, 13-inch
6A8-T	R-6	500/Tape & Reel, 13-inch
6A10-T	R-6	500/Tape & Reel, 13-inch

Notes: 2. For packaging details, go to our website at http://www.diodes.com/datasheets/ap02008.pdf.

APPENDIX C

Resonant Switching Series

Reverse conducting IGBT with monolithic body diode

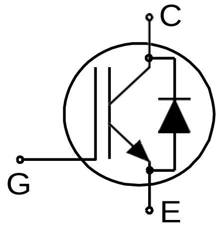
IHW20N120R3

Data sheet

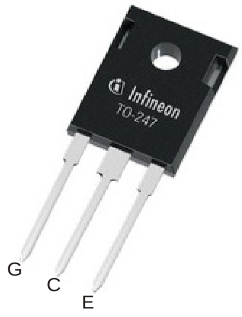
Industrial Power Control

Reverse conducting IGBT with monolithic body diode

Features:



- Powerful monolithic body diode with low forward voltage designed for soft commutation only
- TRENCHSTOP™ technology applications offers:
  - very tight parameter distribution
  - high ruggedness, temperature stable behavior
  - low V_{CEsat}
  - easy parallel switching capability due to positive temperature coefficient in V_{CEsat}
- Low EMI
- Qualified according to JESD-022 for target applications
- Pb-free lead plating; RoHS compliant
- Complete product spectrum and PSpice Models: http://www.infineon.com/igbt/



Applications:

- Inductive cooking
- Inverterized microwave ovens
- Resonant converters
- Soft switching applications

Key Performance and Package Parameters

Type	V_{CE}	I_C	V_{CEsat}, T_{vj}=25°C	T_{vjmax}	Marking	Package
IHW20N120R3	1200V	20A	1.48V	175°C	H20R1203	PG-TO247-3

Table of Contents

Maximum Ratings

For optimum lifetime and reliability, Infineon recommends operating conditions that do not exceed 80% of the maximum ratings stated in this datasheet.

Parameter	Symbol	Value	Unit
Collector-emitter voltage	V_{CE}	1200	V
DC collector current, limited by T_{vjmax} $T_C = 25°C$ $T_C = 100°C$	I_C	40.0 20.0	A
Pulsed collector current, t_p limited by T_{vjmax}	I_{Cpuls}	60.0	A
Turn off safe operating area $V_{CE} \leq 1200V$, $T_{vj} \leq 175°C$	-	60.0	A
Diode forward current, limited by T_{vjmax} $T_C = 25°C$ $T_C = 100°C$	I_F	40.0 20.0	A
Diode pulsed current, t_p limited by T_{vjmax}	I_{Fpuls}	60.0	A
Gate-emitter voltage Transient Gate-emitter voltage ($t_p \leq 10\mu s$, D < 0.010)	V_{GE}	±20 ±25	V
Power dissipation $T_C = 25°C$ Power dissipation $T_C = 100°C$	P_{tot}	310.0 155.0	W
Operating junction temperature	T_{vj}	-40...+175	°C
Storage temperature	T_{stg}	-55...+175	°C
Soldering temperature, wave soldering 1.6mm (0.063in.) from case for 10s		260	°C
Mounting torque, M3 screw Maximum of mounting processes: 3	M	0.6	Nm

Thermal Resistance

Parameter	Symbol	Conditions	Max. Value	Unit
Characteristic				
IGBT thermal resistance, junction - case	$R_{th(j-c)}$		0.48	K/W
Diode thermal resistance, junction - case	$R_{th(j-c)}$		0.48	K/W
Thermal resistance junction - ambient	$R_{th(j-a)}$		40	K/W

Electrical Characteristic, at T_{vj} = 25°C, unless otherwise specified

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
Static Characteristic						
Collector-emitter breakdown voltage	$V_{(BR)CES}$	V_{GE} = 0V, I_C = 0.50mA	1200	-	-	V
Collector-emitter saturation voltage	V_{CEsat}	V_{GE} = 15.0V, I_C = 20.0A T_{vj} = 25°C T_{vj} = 125°C T_{vj} = 175°C	- - -	1.48 1.70 1.80	1.70 - -	V
Diode forward voltage	V_F	V_{GE} = 0V, I_F = 20.0A T_{vj} = 25°C T_{vj} = 125°C T_{vj} = 175°C	- - -	1.55 1.70 1.80	1.75 - -	V
Gate-emitter threshold voltage	$V_{GE(th)}$	I_C = 0.50mA, V_{CE} = V_{GE}	5.1	5.8	6.4	V
Zero gate voltage collector current	I_{CES}	V_{CE} = 1200V, V_{GE} = 0V T_{vj} = 25°C T_{vj} = 175°C	- -	- -	100.0 2500.0	µA
Gate-emitter leakage current	I_{GES}	V_{CE} = 0V, V_{GE} = 20V	-	-	100	nA
Transconductance	g_{fs}	V_{CE} = 20V, I_C = 20.0A	-	18.3	-	S
Integrated gate resistor	r_G			none		Ω

Electrical Characteristic, at T_{vj} = 25°C, unless otherwise specified

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
Dynamic Characteristic						
Input capacitance	C_{ies}	V_{CE} = 25V, V_{GE} = 0V, f = 1MHz	-	1503	-	pF
Output capacitance	C_{oes}		-	50	-	
Reverse transfer capacitance	C_{res}		-	42	-	
Gate charge	Q_G	V_{CC} = 960V, I_C = 20.0A, V_{GE} = 15V	-	211.0	-	nC
Internal emitter inductance measured 5mm (0.197 in.) from case	L_E		-	13.0	-	nH

Switching Characteristic, Inductive Load

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
IGBT Characteristic, at T_{vj} = 25°C						
Turn-off delay time	$t_{d(off)}$	T_{vj} = 25°C, V_{CC} = 600V, I_C = 20.0A, V_{GE} = 0.0/15.0V, $R_{G(on)}$ = 15.0Ω, $R_{G(off)}$ = 15.0Ω, $L\sigma$ = 180nH, $C\sigma$ = 39pF $L\sigma$, $C\sigma$ from Fig. E Energy losses include “tail” and diode reverse recovery.	-	387	-	ns
Fall time	t_f		-	25	-	ns
Turn-off energy	E_{off}		-	0.95	-	mJ

Switching Characteristic, Inductive Load

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
IGBT Characteristic, at T_{vj} = 175°C						
Turn-off delay time	$t_{d(off)}$	T_{vj} = 175°C, V_{CC} = 600V, I_C = 20.0A, V_{GE} = 0.0/15.0V, $R_{G(on)}$ = 15.0Ω, $R_{G(off)}$ = 15.0Ω, $L\sigma$ = 180nH, $C\sigma$ = 39pF $L\sigma$, $C\sigma$ from Fig. E Energy losses include “tail” and diode reverse recovery.	-	454	-	ns
Fall time	t_f		-	84	-	ns
Turn-off energy	E_{off}		-	1.65	-	mJ

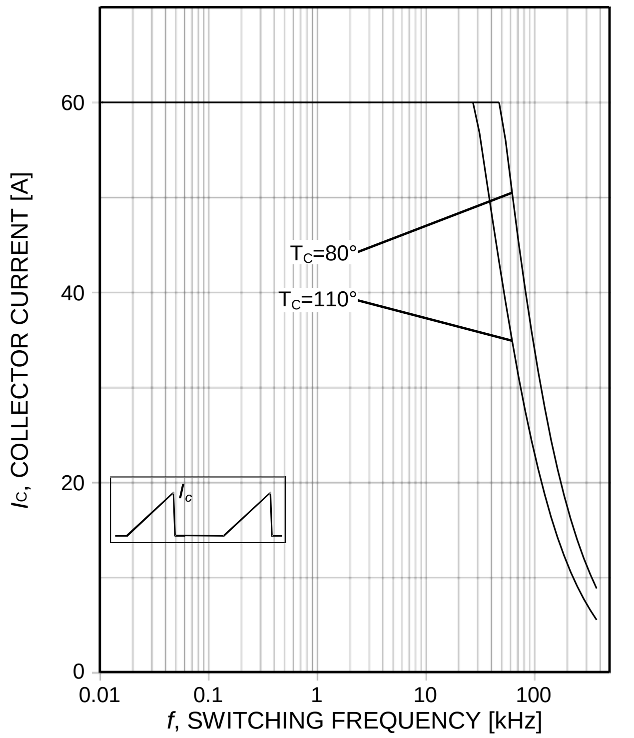


Figure 1. **Collector current as a function of switching frequency**
(T_j≤175°C, D=0.5, V_{CE}=600V, V_{GE}=0/15V, R_G=15Ω)

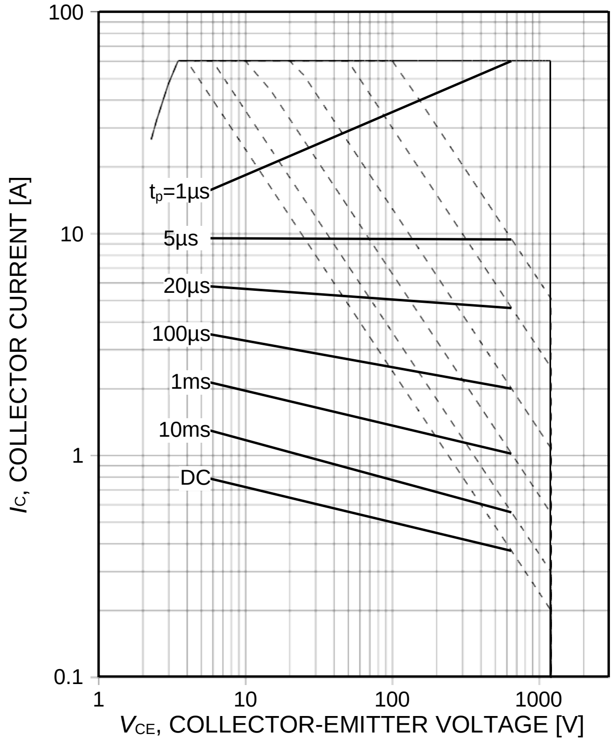


Figure 2. **Forward bias safe operating area**
(D=0, T_C=25°C, T_j≤175°C; V_{GE}=15V)

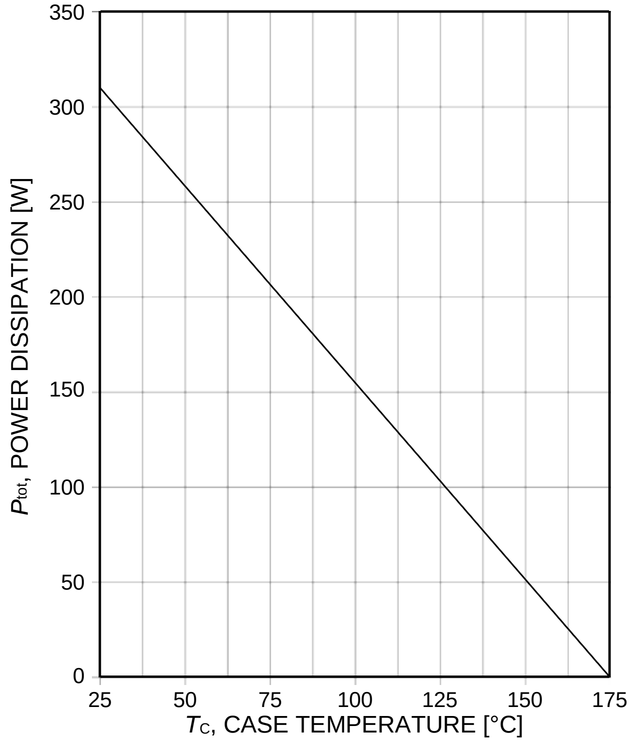


Figure 3. **Power dissipation as a function of case temperature**
(T_j≤175°C)

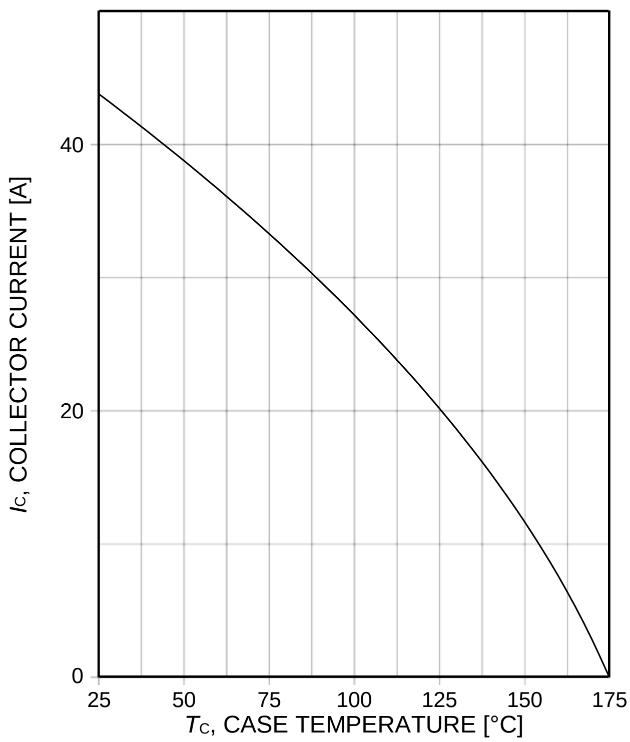


Figure 4. **Collector current as a function of case temperature**
(V_{GE}≥15V, T_j≤175°C)

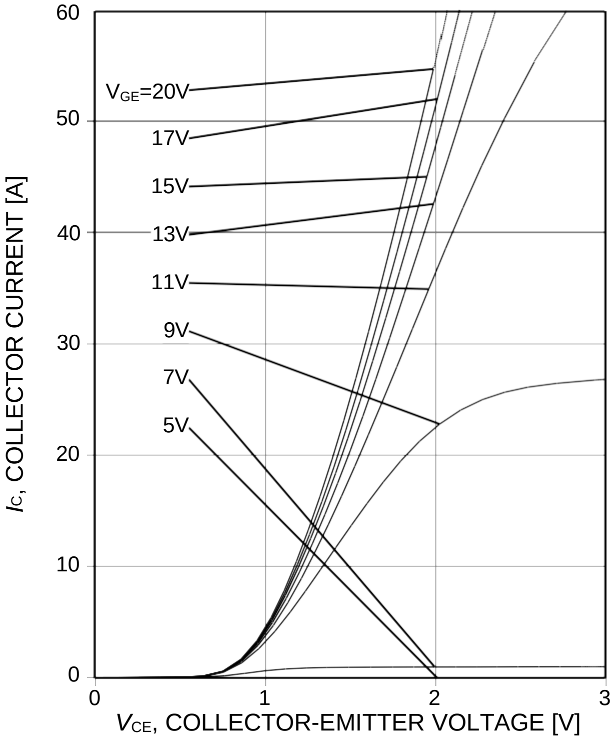


Figure 5. **Typical output characteristic**
(T_j=25°C)

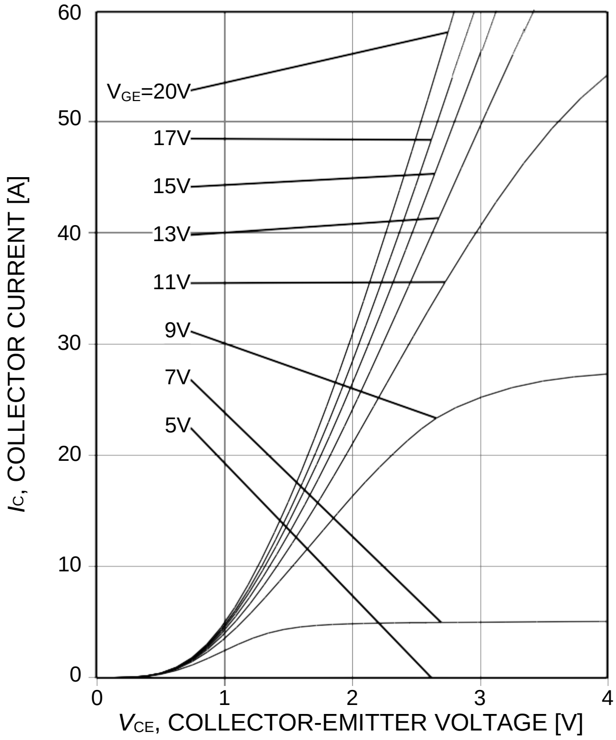


Figure 6. **Typical output characteristic**
(T_j=175°C)

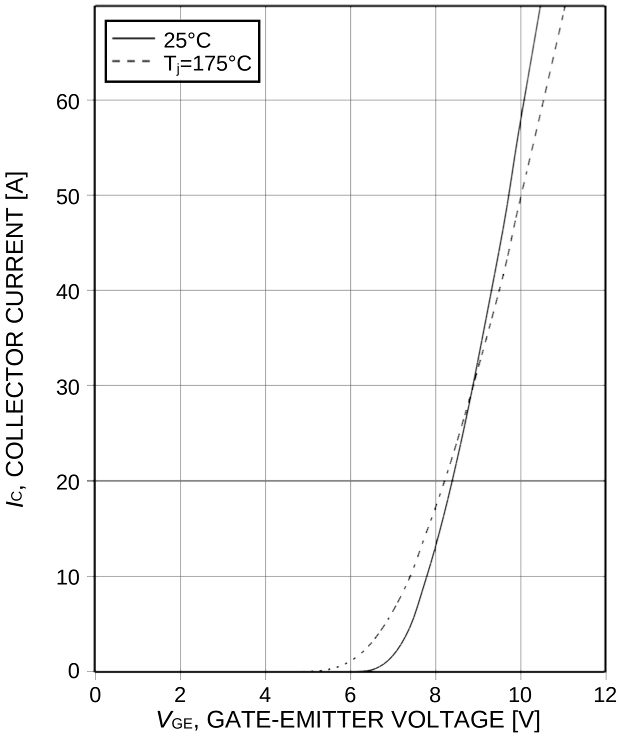


Figure 7. **Typical transfer characteristic**
(V_{CE}=20V)

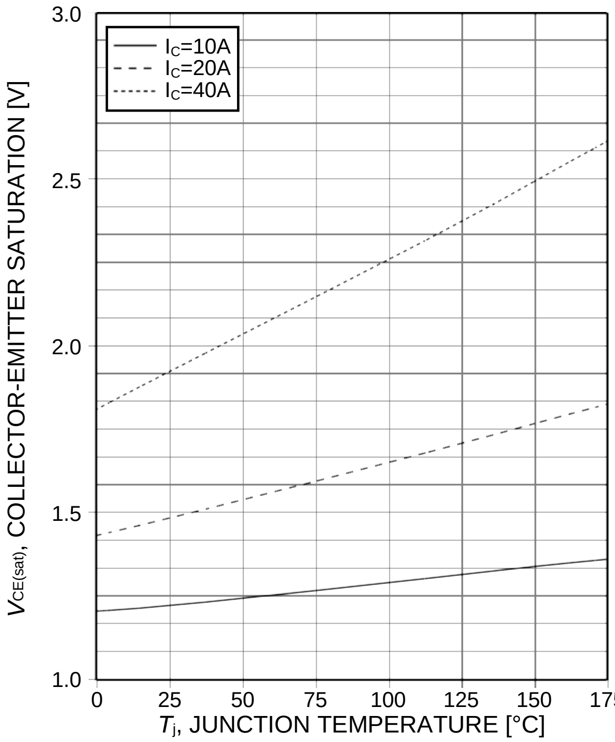


Figure 8. **Typical collector-emitter saturation voltage as a function of junction temperature**
(V_{GE}=15V)

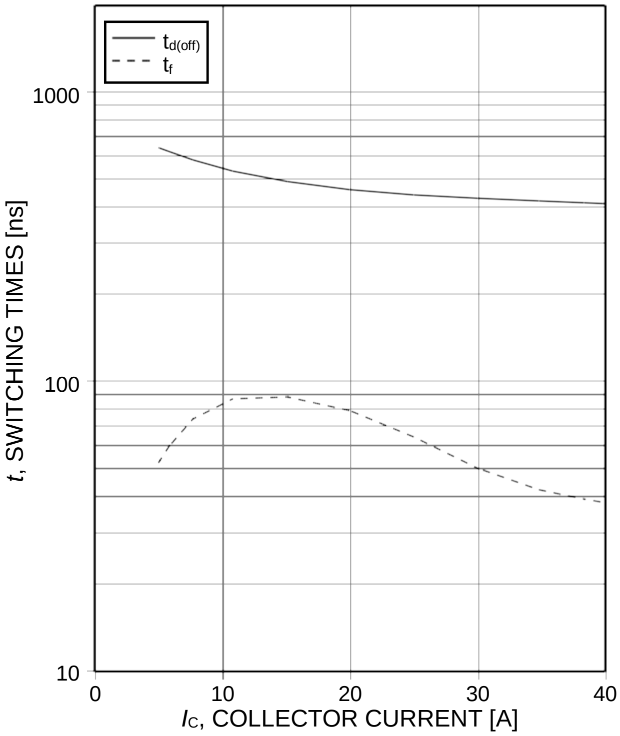


Figure 9. **Typical switching times as a function of collector current**
(ind. load, T_j=175°C, V_{CE}=600V, V_{GE}=0/15V, $R_{G(on)}$=15Ω, $R_{G(off)}$=15Ω, test circuit in Fig. E)

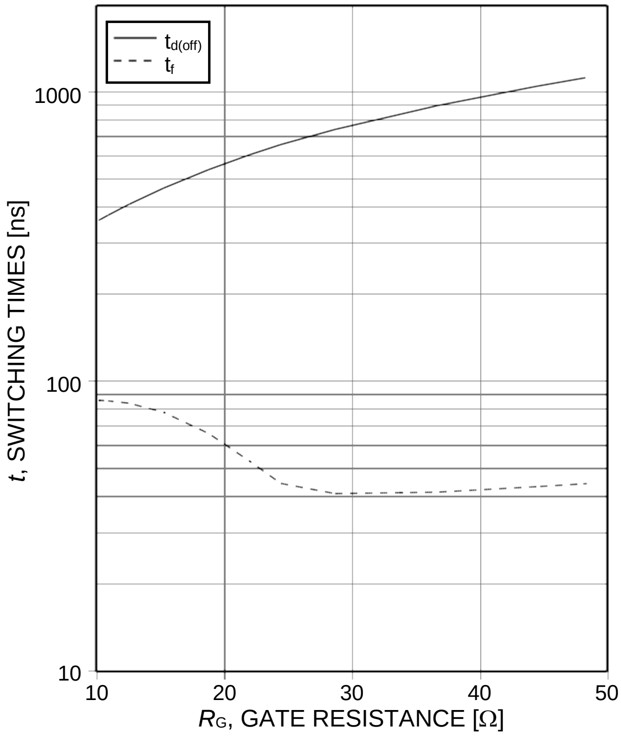


Figure 10. **Typical switching times as a function of gate resistance**
(ind. load, T_j=175°C, V_{CE}=600V, V_{GE}=0/15V, I_C=20A, test circuit in Fig. E)

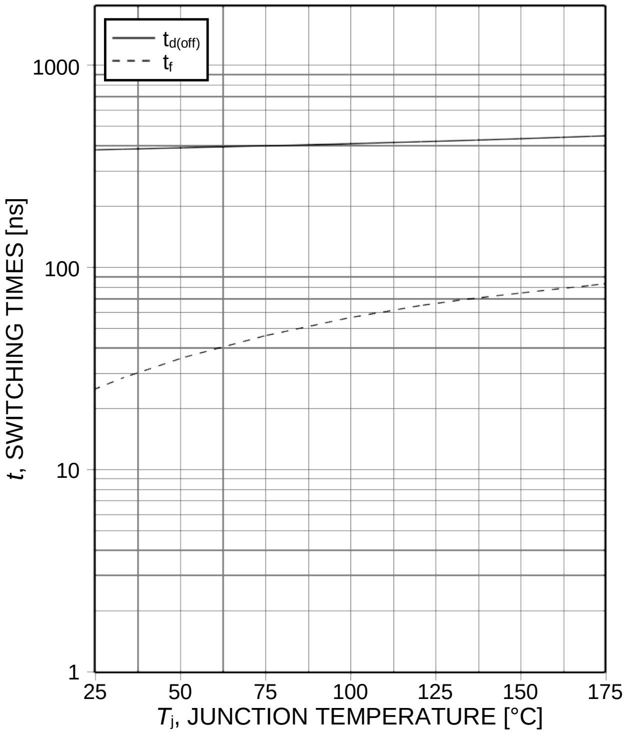


Figure 11. **Typical switching times as a function of junction temperature**
(ind. load, V_{CE}=600V, V_{GE}=0/15V, I_C=20A, $R_{G(on)}$=15Ω, $R_{G(off)}$=15Ω, test circuit in Fig. E)

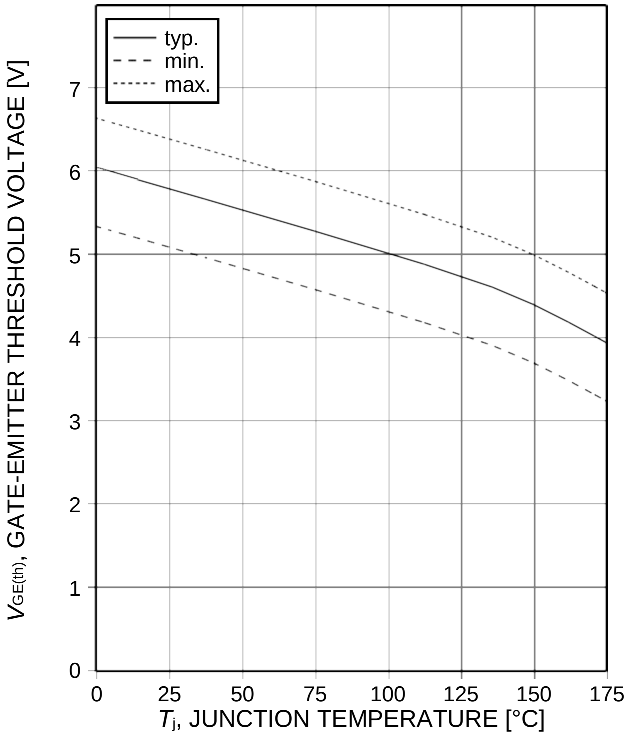


Figure 12. **Gate-emitter threshold voltage as a function of junction temperature**
(I_C=0.5mA)

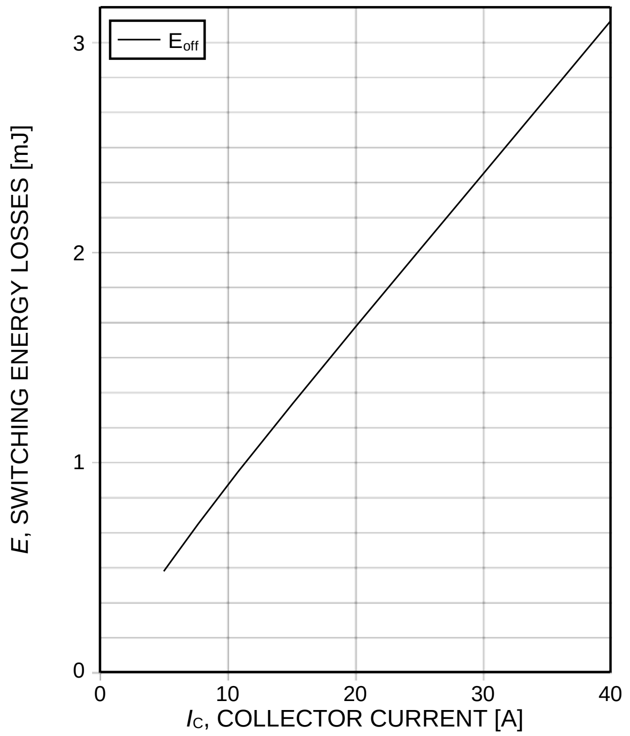


Figure 13. **Typical switching energy losses as a function of collector current**
(ind. load, T_j=175°C, V_{CE}=600V, V_{GE}=0/15V, $R_{G(on)}$=15, $R_{G(off)}$=15Ω, test circuit in Fig. E)

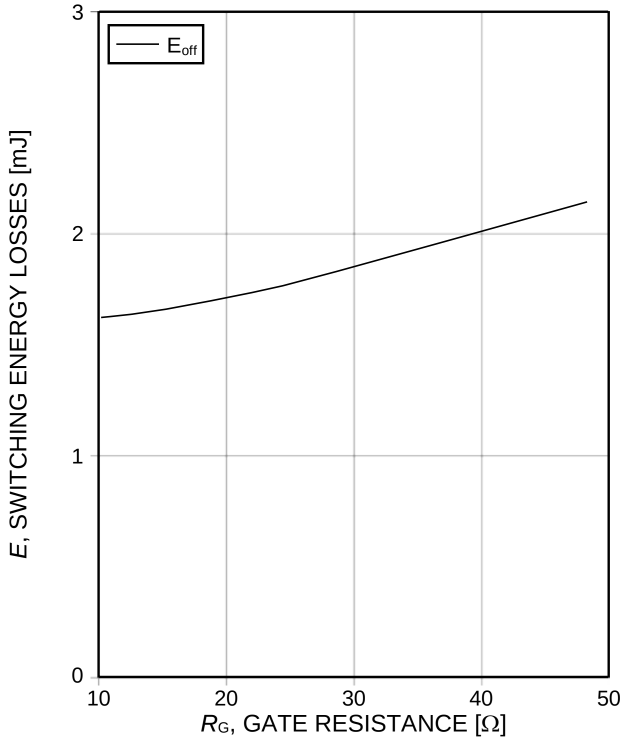


Figure 14. **Typical switching energy losses as a function of gate resistance**
(ind. load, T_j=175°C, V_{CE}=600V, V_{GE}=15/0V, test circuit in Fig. E)

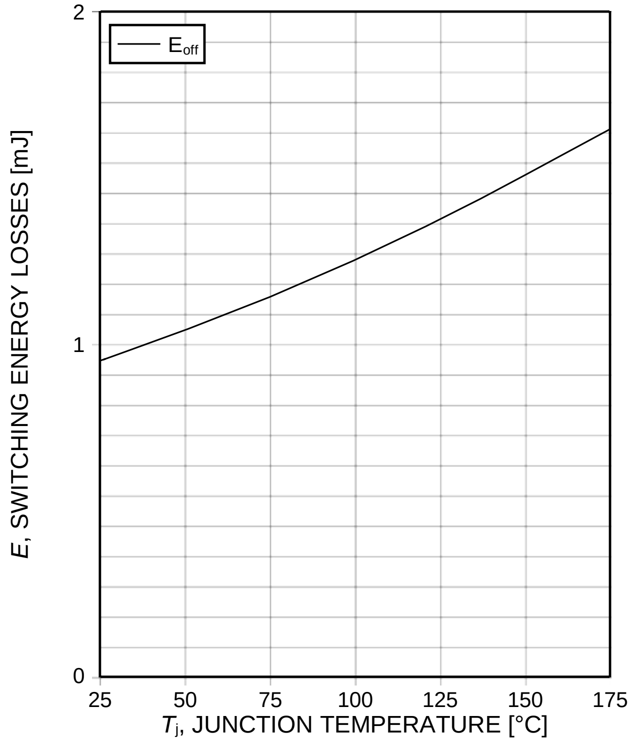


Figure 15. **Typical switching energy losses as a function of junction temperature**
(ind load, V_{CE}=600V, V_{GE}=0/15V, I_C=20A, $R_{G(on)}$=15Ω, $R_{G(off)}$=15Ω, test circuit in Fig. E)

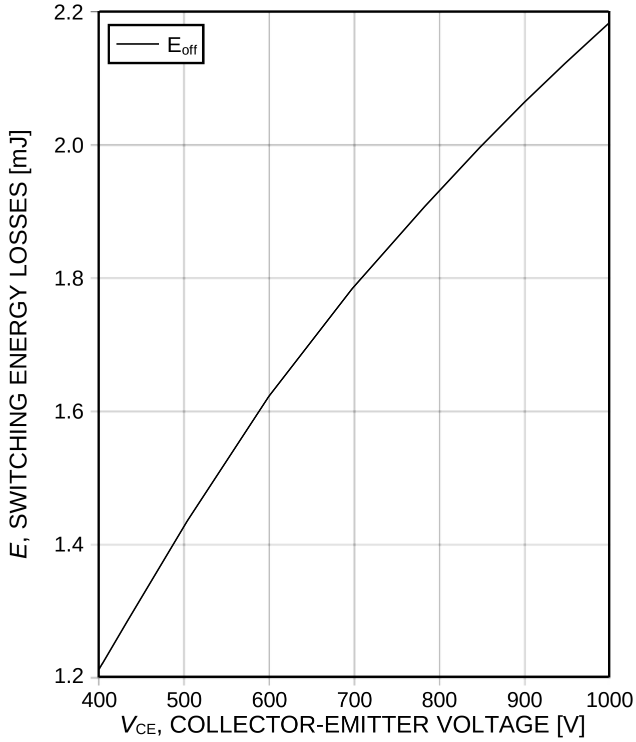


Figure 16. **Typical switching energy losses as a function of collector emitter voltage**
(ind. load, T_j=175°C, V_{GE}=150/V, I_C=20A, $R_{G(on)}$=15Ω, $R_{G(off)}$=15Ω, test circuit in Fig. E)

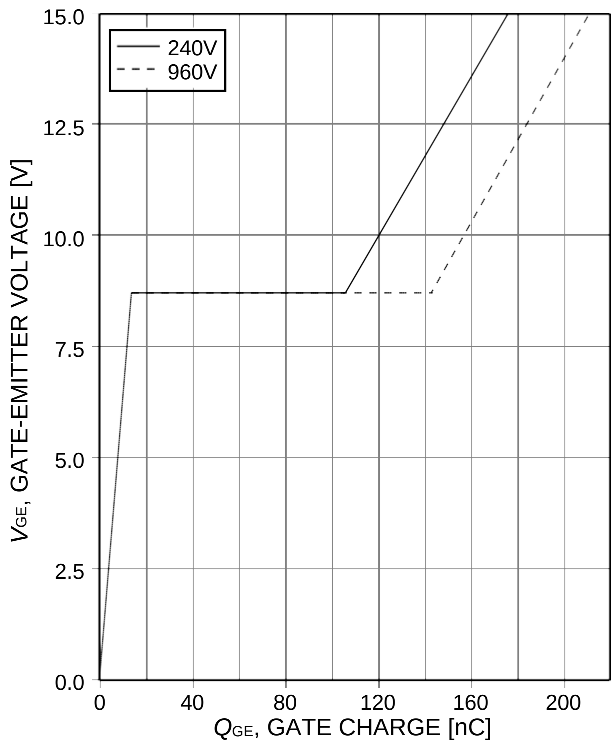


Figure 17. **Typical gate charge**
(I_C=20A)

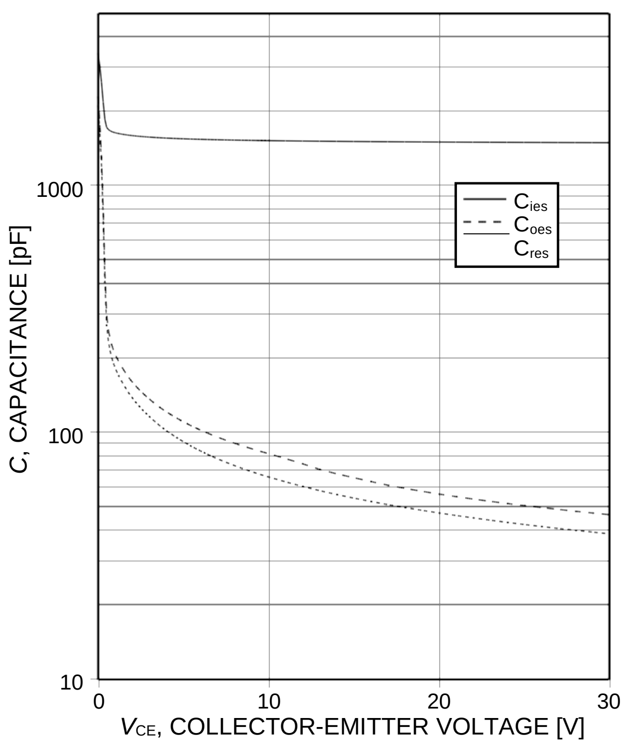


Figure 18. **Typical capacitance as a function of collector-emitter voltage**
(V_{GE}=0V, f=1MHz)

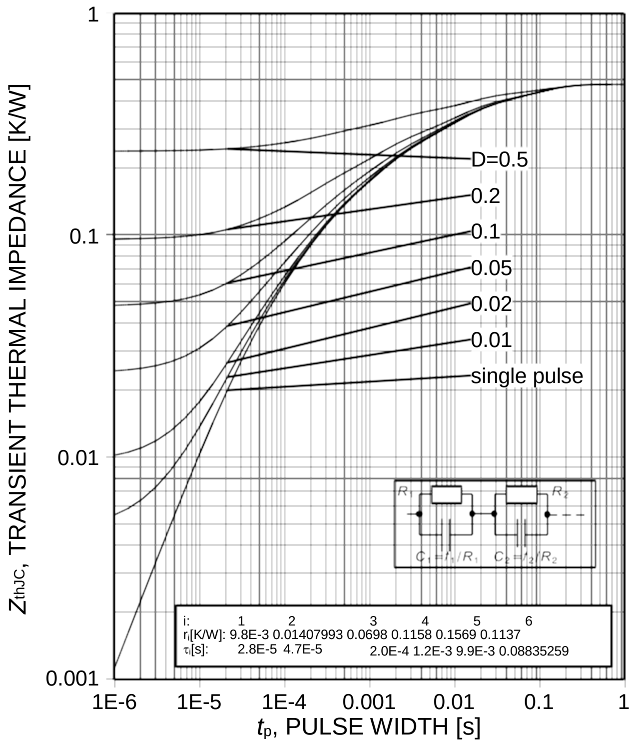


Figure 19. **IGBT transient thermal impedance**
(D=t_p/T)

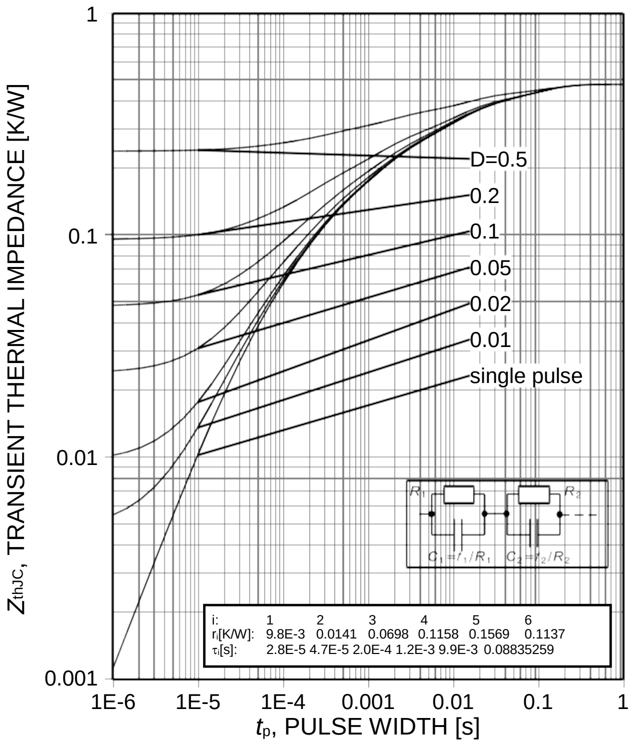


Figure 20. **Diode transient thermal impedance as a function of pulse width**
(D=t_p/T)

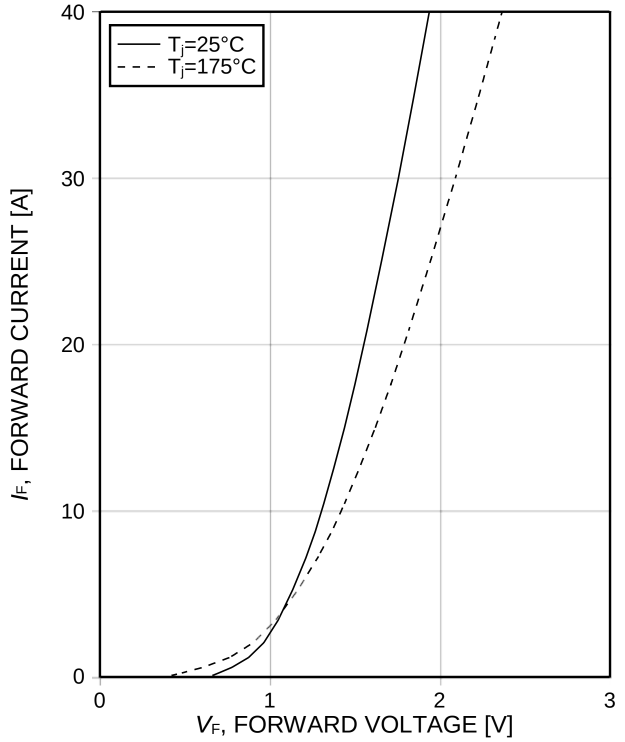


Figure 21. **Typical diode forward current as a function of forward voltage**

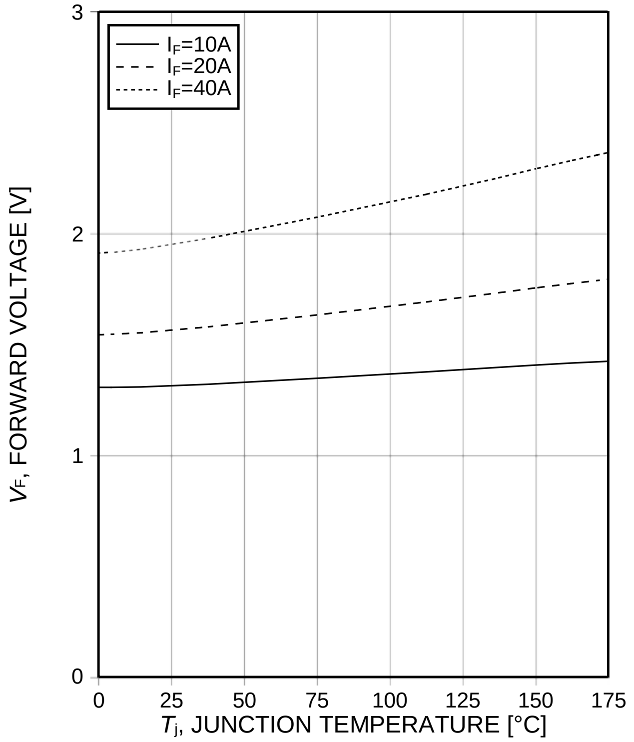
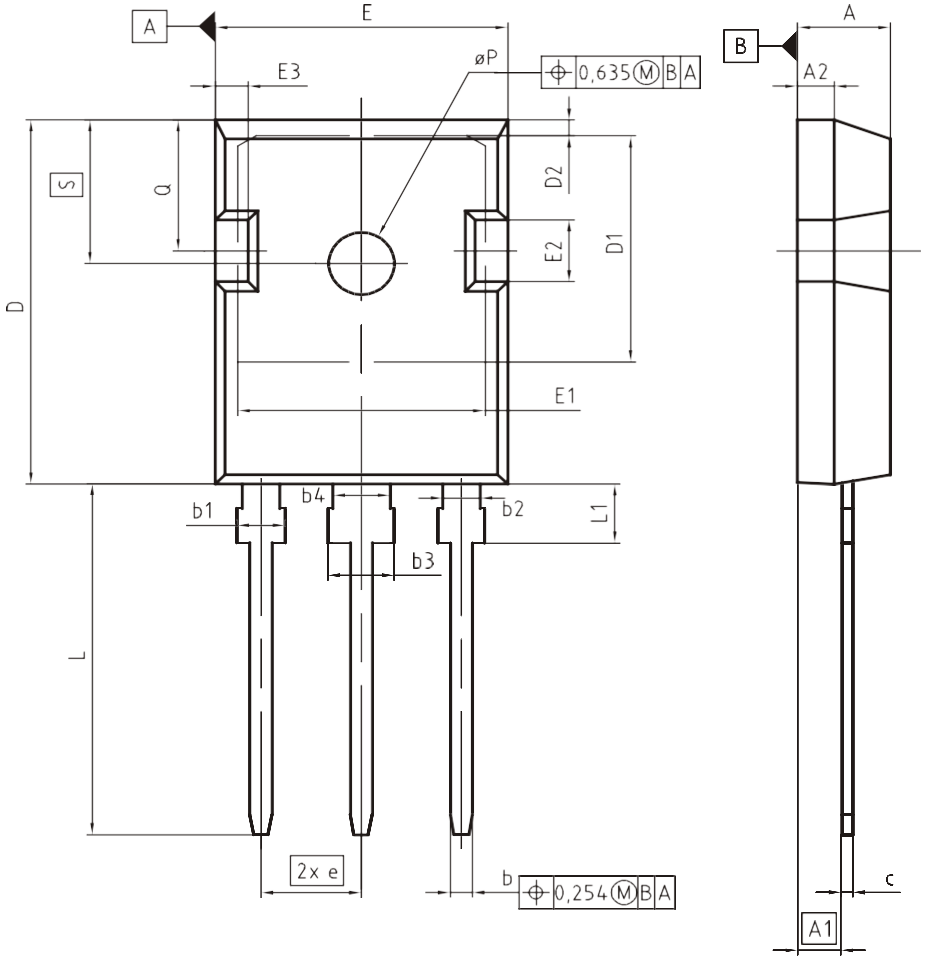


Figure 22. **Typical diode forward voltage as a function of junction temperature**

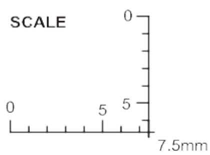
PG-TO247-3



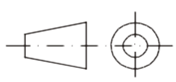
DIM	MILLIMETERS		INCHES	
	MIN	MAX	MIN	MAX
A	4.83	5.21	0.190	0.205
A1	2.27	2.54	0.089	0.100
A2	1.85	2.16	0.073	0.085
b	1.07	1.33	0.042	0.052
b1	1.90	2.41	0.075	0.095
b2	1.90	2.16	0.075	0.085
b3	2.87	3.38	0.113	0.133
b4	2.87	3.13	0.113	0.123
c	0.55	0.68	0.022	0.027
D	20.80	21.10	0.819	0.831
D1	16.25	17.65	0.640	0.695
D2	0.95	1.35	0.037	0.053
E	15.70	16.13	0.618	0.635
E1	13.10	14.15	0.516	0.557
E2	3.68	5.10	0.145	0.201
E3	1.00	2.60	0.039	0.102
e	5.44 (BSC)		0.214 (BSC)	
N	3		3	
L	19.80	20.32	0.780	0.800
L1	4.10	4.47	0.161	0.176
øP	3.50	3.70	0.138	0.146
Q	5.49	6.00	0.216	0.236
S	6.04	6.30	0.238	0.248

DOCUMENT NO.
Z8B00003327

SCALE



EUROPEAN PROJECTION



ISSUE DATE
09-07-2010

REVISION
05

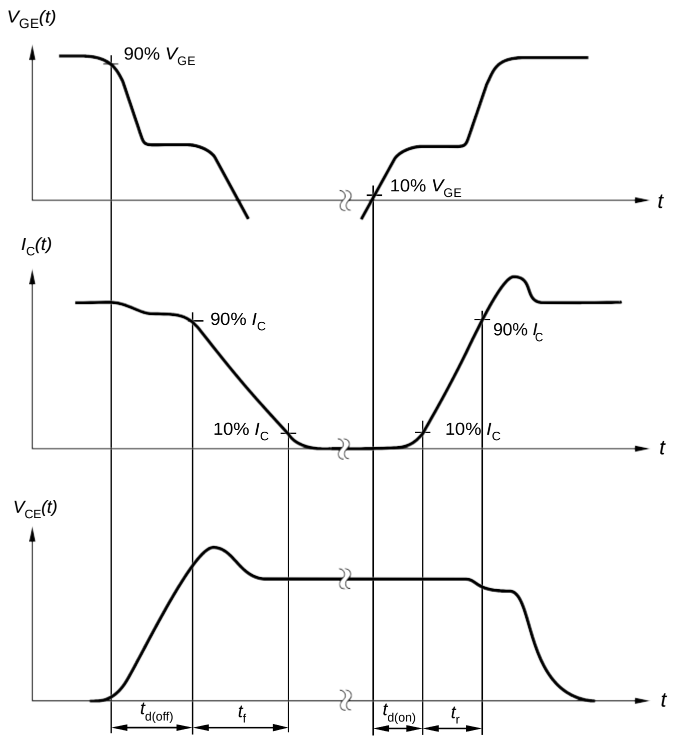
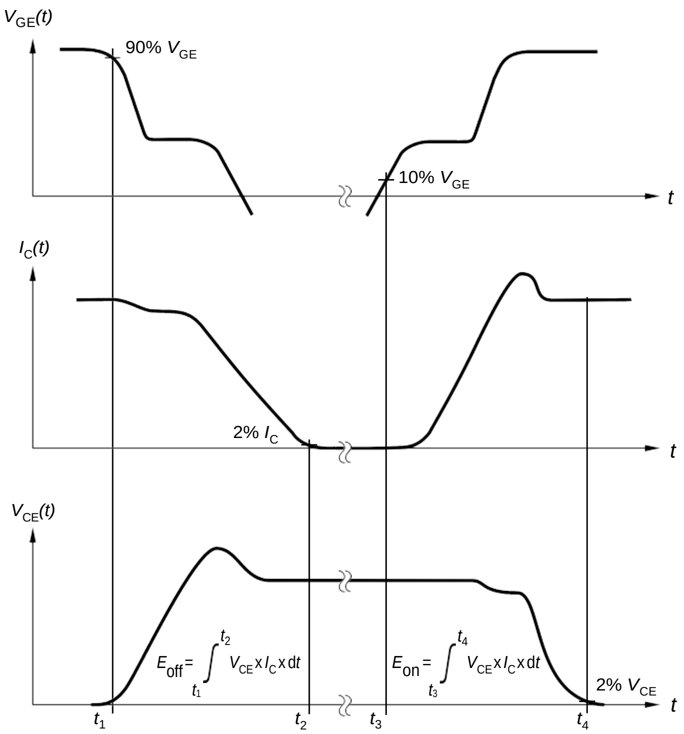


Figure A. **Definition of switching times**



$$E_{off} = \int_{t_1}^{t_2} V_{CE} \times I_C \times dt$$

$$E_{on} = \int_{t_3}^{t_4} V_{CE} \times I_C \times dt$$

Figure B. **Definition of switching losses**

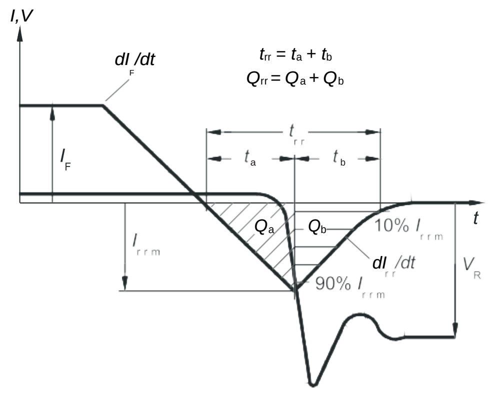


Figure C. **Definition of diode switching characteristics**

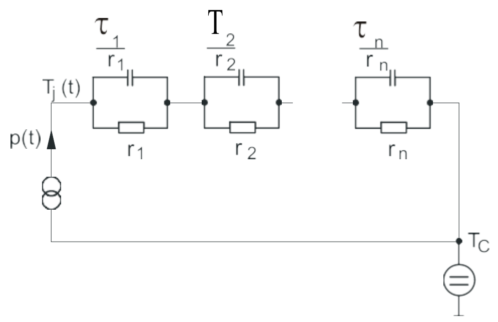


Figure D. **Thermal equivalent circuit**

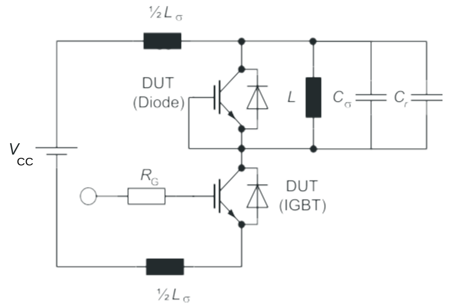


Figure E. **Dynamic test circuit**

Parasitic inductance L_{α},
parasitic capacitor C_{α},
relief capacitor C_r,
(only for ZVT switching)

Revision History

IHW20N120R3

Revision: 2015-01-26, Rev. 2.6

Previous Revision

Revision	Date	Subjects (major changes since last revision)
1.1	2008-05-06	-
1.2	2008-07-11	-
2.3	2008-07-29	-
2.4	2009-04-01	-
2.5	2013-02-12	Layout change
2.6	2015-01-26	Minor changes

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APPENDIX D

LM340, LM340A and LM7805 Family Wide V_{IN} 1.5-A Fixed Voltage Regulators

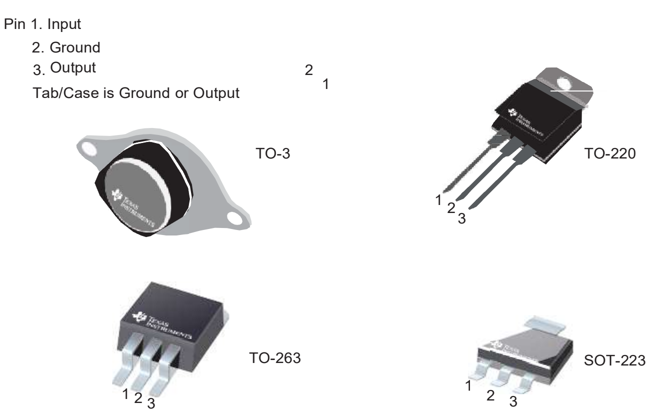
1 Features

- Output Current up to 1.5 A
- Available in Fixed 5-V, 12-V, and 15-V Options
- Output Voltage Tolerances of ±2% at T_J = 25°C (LM340A)
- Line Regulation of 0.01% / V of at 1-A Load (LM340A)
- Load Regulation of 0.3% / A (LM340A)
- Internal Thermal Overload, Short-Circuit and SOA Protection
- Available in Space-Saving SOT-223 Package
- Output Capacitance Not Required for Stability

2 Applications

- Industrial Power Supplies
- SMPS Post Regulation
- HVAC Systems
- AC Inventors
- Test and Measurement Equipment
- Brushed and Brushless DC Motor Drivers
- Solar Energy String Invertors

Available Packages



3 Description

The LM340 and LM7805 Family monolithic 3-terminal positive voltage regulators employ internal current-limiting, thermal shutdown and safe-area compensation, making them essentially indestructible. If adequate heat sinking is provided, they can deliver over 1.5-A output current. They are intended as fixed voltage regulators in a wide range of applications including local (on-card) regulation for elimination of noise and distribution problems associated with single-point regulation. In addition to use as fixed voltage regulators, these devices can be used with external components to obtain adjustable output voltages and currents.

Considerable effort was expended to make the entire series of regulators easy to use and minimize the number of external components. It is not necessary to bypass the output, although this does improve transient response. Input bypassing is needed only if the regulator is located far from the filter capacitor of the power supply.

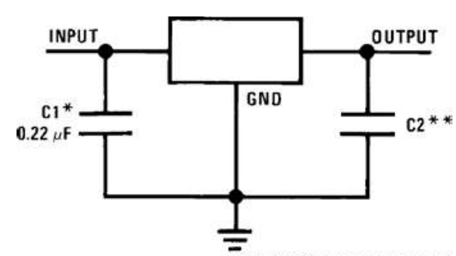
LM7805 is also available in a higher accuracy and better performance version (LM340A). Refer to LM340A specifications in the *LM340A Electrical Characterisitcs* table.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
LM340x LM7805 Family	DDPAK/TO-263 (3)	10.18 mm × 8.41 mm
	SOT-23 (4)	6.50 mm × 3.50 mm
	TO-220 (3)	14.986 mm × 10.16 mm
	TO-3 (2)	38.94 mm x 25.40 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Fixed Output Voltage Regulator



*Required if the regulator is located far from the power supply filter.
**Although no output capacitor is needed for stability, it does help transient response. (If needed, use 0.1-μF, ceramic disc).

Table of Contents

4 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

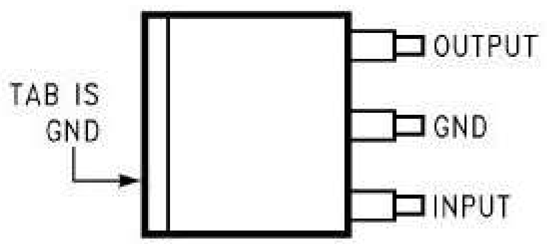
Changes from Revision K (November 2015) to Revision L	Page
• Changed pinout number order for the TO-220 and SOT-223 packages from: 2, 3, 1 to: 1, 2, 3	1

Changes from Revision J (December 2013) to Revision K	Page
• Added *ESD Ratings* table, *Thermal Information* table, *Feature Description* section, *Device Functional Modes*, *Application and Implementation* section, *Power Supply Recommendations* section, *Layout* section, *Device and Documentation Support* section, and *Mechanical, Packaging, and Orderable Information* section.	1
• Deleted obsolete LM140 and LM7808C devices from the data sheet	1
• Changed Figure 13 caption from *Line Regulation 140AK-5.0* to *Line Regulation LM340,*	11
• Changed Figure 14 caption from *Line Regulation 140AK-5.0* to *Line Regulation LM340,*	11

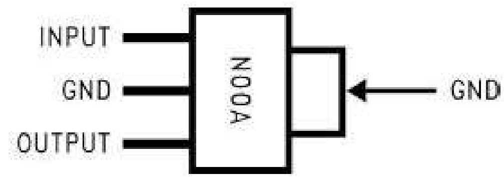
Changes from Revision I (March 2013) to Revision J	Page
• Changed 0.5 from typ to max	5

5 Pin Configuration and Functions

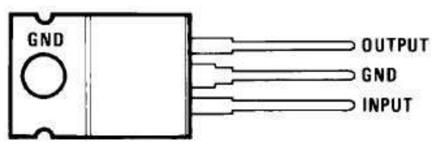
LM7805 and LM7812 KTT Package
3-Pin DDPAK/TO-263
Top View



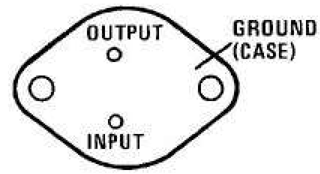
LM7805 DCY Package
4-Pin SOT-223
Side View



LM7805, LM7812, and LM7815 NDE Package
3-Pin TO-220
Top View



LM340K-5.0 NDS Package
2-Pin TO-3
Top View



Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
INPUT	1	I	Input voltage pin
GND	2	I/O	Ground pin
OUTPUT	3	O	Output voltage pin

6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)(2)

		MIN	MAX	UNIT
DC input voltage			35	V
Internal power dissipation(3)		Internally Limited		
Maximum junction temperature			150	°C
Lead temperature (soldering, 10 sec.)	TO-3 package (NDS)		300	°C
	Lead temperature 1,6 mm (1/16 in) from case for 10 s		230	°C
Storage temperature		−65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) If Military/Aerospace specified devices are required, please contact the Texas Instruments Sales Office/Distributors for availability and specifications.
(3) The maximum allowable power dissipation at any ambient temperature is a function of the maximum junction temperature for operation (T_{JMAX} = 125°C or 150°C), the junction-to-ambient thermal resistance (θ_{JA}), and the ambient temperature (T_A). $P_{DMAX} = (T_{JMAX} - T_A)/\theta_{JA}$. If this dissipation is exceeded, the die temperature rises above T_{JMAX} and the electrical specifications do not apply. If the die temperature rises above 150°C, the device goes into thermal shutdown. For the TO-3 package (NDS), the junction-to-ambient thermal resistance (θ_{JA}) is 39°C/W. When using a heat sink, θ_{JA} is the sum of the 4°C/W junction-to-case thermal resistance (θ_{JC}) of the TO-3 package and the case-to-ambient thermal resistance of the heat sink. For the TO-220 package (NDE), θ_{JA} is 54°C/W and θ_{JC} is 4°C/W. If SOT-223 is used, the junction-to-ambient thermal resistance is 174°C/W and can be reduced by a heat sink (see Applications Hints on heat sinking).If the DDPAK\TO-263 package is used, the thermal resistance can be reduced by increasing the PCB copper area thermally connected to the package: Using 0.5 square inches of copper area, θ_{JA} is 50°C/W; with 1 square inch of copper area, θ_{JA} is 37°C/W; and with 1.6 or more inches of copper area, θ_{JA} is 32°C/W.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM)(1)	±2000	V

(1) ESD rating is based on the human-body model, 100 pF discharged through 1.5 kΩ.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	MAX	UNIT
Temperature (T_A)	LM340A, LM340	0	125	°C

6.4 Thermal Information

THERMAL METRIC(1)		LM340, LM7805 Family				UNIT
		NDE (TO-220)	KTT (DDPAK/TO-263)	DCY (SOT-223)	NDS (TO-3)	
		3 PINS	3 PINS	4 PINS	2 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	23.9	44.8	62.1	39	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	16.7	45.6	44	2	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	5.3	24.4	10.7	—	°C/W
ψ_{JT}	Junction-to-top characterization parameter	3.2	11.2	2.7	—	°C/W
ψ_{JB}	Junction-to-board characterization parameter	5.3	23.4	10.6	—	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	1.7	1.5	—	—	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

6.5 LM340A Electrical Characteristics, V_O = 5 V, V_I = 10 V

I_{OUT} = 1 A, 0°C ≤ T_J ≤ 125°C (LM340A) unless otherwise specified(1)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_O	Output voltage	T_J = 25°C		4.9	5	5.1	V
		P_D ≤ 15 W, 5 mA ≤ I_O ≤ 1 A 7.5 V ≤ V_{IN} ≤ 20 V		4.8		5.2	V
ΔV_O	Line regulation	7.5 V ≤ V_{IN} ≤ 20 V	T_J = 25°C		3	10	mV
			Over temperature, I_O = 500 mA			10	mV
		8 V ≤ V_{IN} ≤ 12 V	T_J = 25°C			4	mV
			Over temperature			12	mV
ΔV_O	Load regulation	T_J = 25°C	5 mA ≤ I_O ≤ 1.5 A		10	25	mV
			250 mA ≤ I_O ≤ 750 mA			15	mV
		Over temperature, 5 mA ≤ I_O ≤ 1 A				25	mV
I_Q	Quiescent current	T_J = 25°C				6	mA
		Over temperature				6.5	mA
ΔI_Q	Quiescent current change	T_J = 25°C, I_O = 1 A 7.5 V ≤ V_{IN} ≤ 20 V				0.8	mA
		Over temperature, 5 mA ≤ I_O ≤ 1 A				0.5	mA
		Over temperature, I_O = 500 mA 8 V ≤ V_{IN} ≤ 25 V				0.8	mA
V_N	Output noise voltage	T_A = 25°C, 10 Hz ≤ f ≤ 100 kHz			40		µV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple rejection	f = 120 Hz 8 V ≤ V_{IN} ≤ 18 V	T_J = 25°C, , I_O = 1 A	68	80		dB
			Over temperature, I_O = 500 mA	68			dB
R_O	Dropout voltage	T_J = 25°C, I_O = 1 A			2		V
	Output resistance	f = 1 kHz			8		mΩ
	Short-circuit current	T_J = 25°C			2.1		A
	Peak output current	T_J = 25°C			2.4		A
	Average TC of V_O	Min, T_J = 0°C, I_O = 5 mA			−0.6		mV/°C
V_{IN}	Input voltage required to maintain line regulation	T_J = 25°C		7.5			V

(1) All characteristics are measured with a 0.22-µF capacitor from input to ground and a 0.1-µF capacitor from output to ground. All characteristics except noise voltage and ripple rejection ratio are measured using pulse techniques (t_w ≤ 10 ms, duty cycle ≤ 5%). Output voltage changes due to changes in internal temperature must be taken into account separately.

6.6 LM340 / LM7805 Electrical Characteristics, V_O = 5 V, V_I = 10 V

0°C ≤ T_J ≤ 125°C unless otherwise specified(1)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_O	Output voltage	T_J = 25°C, 5 mA ≤ I_O ≤ 1 A		4.8	5	5.2	V
		P_D ≤ 15 W, 5 mA ≤ I_O ≤ 1 A 7.5 V ≤ V_{IN} ≤ 20 V		4.75		5.25	V
ΔV_O	Line regulation	I_O = 500 mA	T_J = 25°C 7V ≤ V_{IN} ≤ 25V		3	50	mV
			Over temperature 8V ≤ V_{IN} ≤ 20V			50	mV
		I_O ≤ 1 A	T_J = 25°C 7.5V ≤ V_{IN} ≤ 20V			50	mV
			Over temperature 8V ≤ V_{IN} ≤ 12V			25	mV
ΔV_O	Load regulation	T_J = 25°C	5 mA ≤ I_O ≤ 1.5 A		10	50	mV
			250 mA ≤ I_O ≤ 750 mA			25	mV
		Over temperature, 5 mA ≤ I_O ≤ 1 A				50	mV
I_Q	Quiescent current	I_O ≤ 1 A	T_J = 25°C			8	mA
			Over temperature			8.5	mA
ΔI_Q	Quiescent current change	0°C ≤ T_J ≤ 125°C, 5 mA ≤ I_O ≤ 1 A			0.5		mA
		7 V ≤ V_{IN} ≤ 20 V	T_J = 25°C, I_O ≤ 1 A			1	mA
			Over temperature, I_O ≤ 500 mA			1	mA
V_N	Output noise voltage	T_A = 25°C, 10 Hz ≤ f ≤ 100 kHz			40		µV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple rejection	f = 120 Hz 8 V ≤ V_{IN} ≤ 18 V	T_J = 25°C, I_O ≤ 1 A	62	80		dB
			Over temperature, I_O ≤ 500 mA	62			dB
R_O	Dropout voltage	T_J = 25°C, I_O = 1 A			2		V
	Output resistance	f = 1 kHz			8		mΩ
	Short-circuit current	T_J = 25°C			2.1		A
	Peak output current	T_J = 25°C			2.4		A
	Average TC of V_{OUT}	Over temperature, I_O = 5 mA			−0.6		mV/°C
V_{IN}	Input voltage required to maintain line regulation	T_J = 25°C, I_O ≤ 1 A		7.5			V

(1) All characteristics are measured with a 0.22-µF capacitor from input to ground and a 0.1-µF capacitor from output to ground. All characteristics except noise voltage and ripple rejection ratio are measured using pulse techniques (t_w ≤ 10 ms, duty cycle ≤ 5%). Output voltage changes due to changes in internal temperature must be taken into account separately.

6.7 LM340 / LM7812 Electrical Characteristics, V_O = 12 V, V_I = 19 V

0°C ≤ T_J ≤ 125°C unless otherwise specified(1)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_O	Output voltage	T_J = 25°C, 5 mA ≤ I_O ≤ 1 A		11.5	12	12.5	V
		P_D ≤ 15 W, 5 mA ≤ I_O ≤ 1 A 14.5 V ≤ V_{IN} ≤ 27 V		11.4		12.6	V
ΔV_O	Line regulation	I_O = 500 mA	T_J = 25°C 14.5V ≤ V_{IN} ≤ 30V		4	120	mV
			Over temperature 15V ≤ V_{IN} ≤ 27V			120	mV
		I_O ≤ 1 A	T_J = 25°C 14.6V ≤ V_{IN} ≤ 27V			120	mV
			Over temperature 16V ≤ V_{IN} ≤ 22V			60	mV
ΔV_O	Load regulation	T_J = 25°C	5 mA ≤ I_O ≤ 1.5 A		12	120	mV
			250 mA ≤ I_O ≤ 750 mA			60	mV
		Over temperature, 5 mA ≤ I_O ≤ 1 A				120	mV
I_Q	Quiescent current	I_O ≤ 1 A	T_J = 25°C			8	mA
			Over temperature			8.5	mA
ΔI_Q	Quiescent current change	5 mA ≤ I_O ≤ 1 A				0.5	mA
		T_J = 25°C, I_O ≤ 1 A 14.8 V ≤ V_{IN} ≤ 27 V				1	mA
		Over temperature, I_O ≤ 500 mA 14.5 V ≤ V_{IN} ≤ 30 V				1	mA
V_N	Output noise voltage	T_A = 25°C, 10 Hz ≤ f ≤ 100 kHz			75		µV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple rejection	f = 120 Hz 15 V ≤ V_{IN} ≤ 25 V	T_J = 25°C, I_O ≤ 1 A	55	72		dB
			Over temperature, I_O ≤ 500 mA,	55			dB
R_O	Dropout voltage	T_J = 25°C, I_O = 1 A			2		V
	Output resistance	f = 1 kHz			18		mΩ
	Short-circuit current	T_J = 25°C			1.5		A
	Peak output current	T_J = 25°C			2.4		A
	Average TC of V_{OUT}	Over temperature, I_O = 5 mA			−1.5		mV/°C
V_{IN}	Input voltage required to maintain line regulation	T_J = 25°C, I_O ≤ 1 A		14.6			V

(1) All characteristics are measured with a 0.22-µF capacitor from input to ground and a 0.1-µF capacitor from output to ground. All characteristics except noise voltage and ripple rejection ratio are measured using pulse techniques (t_w ≤ 10 ms, duty cycle ≤ 5%). Output voltage changes due to changes in internal temperature must be taken into account separately.

6.8 LM340 / LM7815 Electrical Characteristics, V_O = 15 V, V_I = 23 V

0°C ≤ T_J ≤ 125°C unless otherwise specified(1)

PARAMETER			TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_O	Output voltage		T_J = 25°C, 5 mA ≤ I_O ≤ 1 A		14.4	15	15.6	V
			P_D ≤ 15 W, 5 mA ≤ I_O ≤ 1 A 17.5 V ≤ V_{IN} ≤ 30 V		14.25		15.75	V
ΔV_O	Line regulation		I_O = 500 mA	T_J = 25°C 17.5 V ≤ V_{IN} ≤ 30 V		4	150	mV
				Over temperature 18.5 V ≤ V_{IN} ≤ 30 V			150	mV
			I_O ≤ 1 A	T_J = 25°C 17.7 V ≤ V_{IN} ≤ 30 V			150	mV
				Over temperature 20 V ≤ V_{IN} ≤ 26 V			75	mV
ΔV_O	Load regulation		T_J = 25°C	5 mA ≤ I_O ≤ 1.5 A		12	150	mV
				250 mA ≤ I_O ≤ 750 mA			75	mV
			Over temperature, 5 mA ≤ I_O ≤ 1 A,				150	mV
I_Q	Quiescent current		I_O ≤ 1 A	T_J = 25°C			8	mA
				Over temperature			8.5	mA
ΔI_Q	Quiescent current change		5 mA ≤ I_O ≤ 1 A			0.5		mA
			T_J = 25°C, I_O ≤ 1 A 17.9 V ≤ V_{IN} ≤ 30 V				1	mA
			Over temperature, I_O ≤ 500 mA 17.5 V ≤ V_{IN} ≤ 30 V				1	mA
V_N	Output noise voltage		T_A = 25°C, 10 Hz ≤ f ≤ 100 kHz			90		µV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple rejection		f = 120 Hz 18.5 V ≤ V_{IN} ≤ 28.5 V	T_J = 25°C, I_O ≤ 1 A	54	70		dB
				Over temperature, I_O ≤ 500 mA,	54			dB
R_O		Dropout voltage	T_J = 25°C, I_O = 1 A			2		V
		Output resistance	f = 1 kHz			19		mΩ
		Short-circuit current	T_J = 25°C			1.2		A
		Peak output current	T_J = 25°C			2.4		A
		Average TC of V_{OUT}	Over temperature, I_O = 5 mA			−1.8		mV/°C
V_{IN}	Input voltage required to maintain line regulation		T_J = 25°C, I_O ≤ 1 A		17.7			V

(1) All characteristics are measured with a 0.22-µF capacitor from input to ground and a 0.1-µF capacitor from output to ground. All characteristics except noise voltage and ripple rejection ratio are measured using pulse techniques (t_w ≤ 10 ms, duty cycle ≤ 5%). Output voltage changes due to changes in internal temperature must be taken into account separately.

6.9 Typical Characteristics

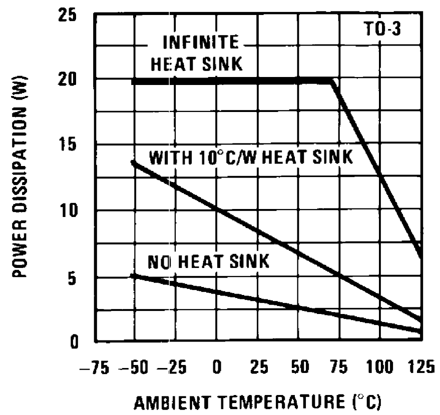


Figure 1. Maximum Average Power Dissipation

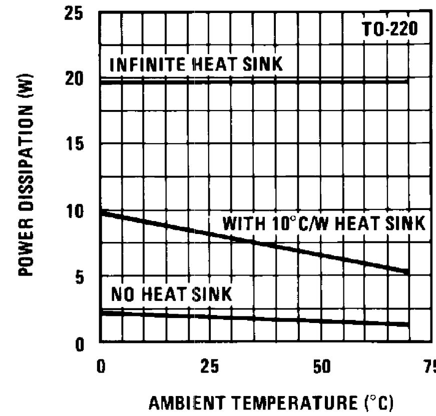


Figure 2. Maximum Average Power Dissipation

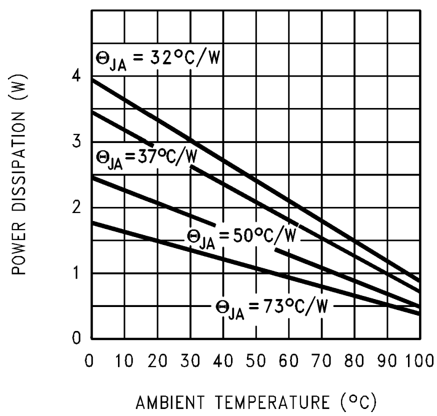
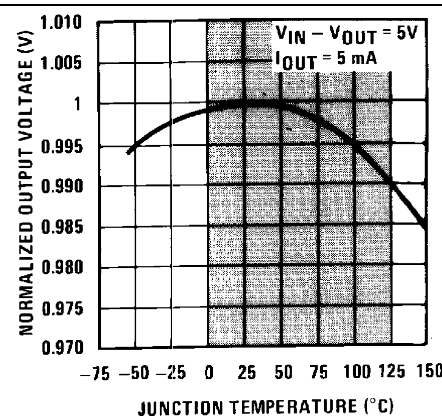


Figure 3. Maximum Power Dissipation (DDPAK/TO-263)



Shaded area refers to LM340A/LM340, LM7805, LM7812 and LM7815.

Figure 4. Output Voltage (Normalized to 1 V at T_J = 25°C)

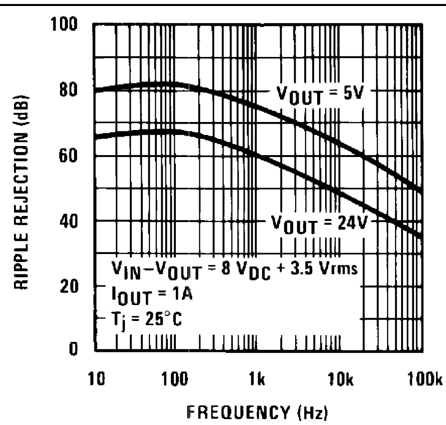


Figure 5. Ripple Rejection

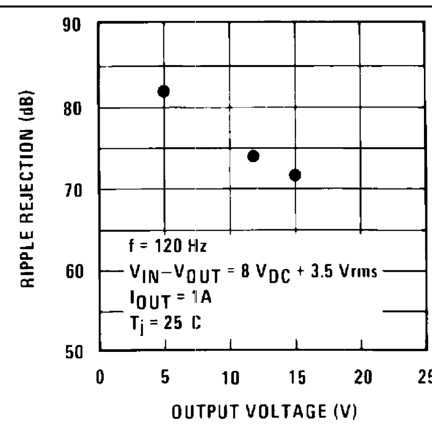


Figure 6. Ripple Rejection

Typical Characteristics (continued)

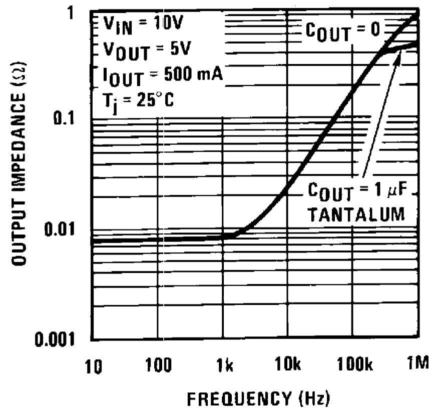


Figure 7. Output Impedance

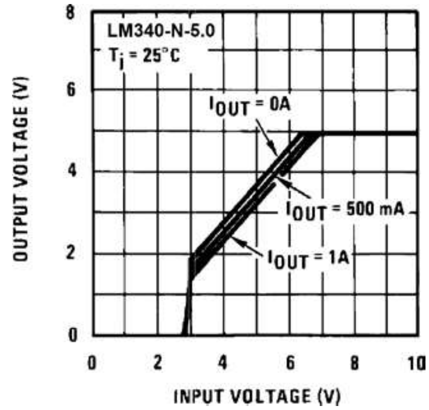
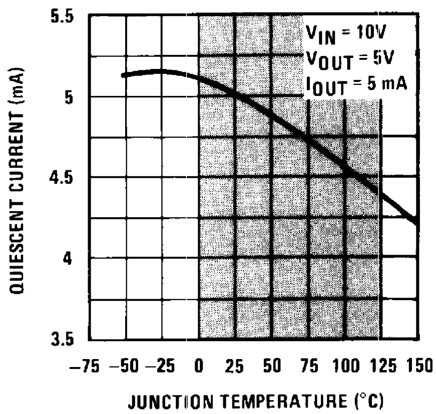


Figure 8. Dropout Characteristics



Shaded area refers to LM340A/LM340, LM7805, LM7812, and LM7815.

Figure 9. Quiescent Current

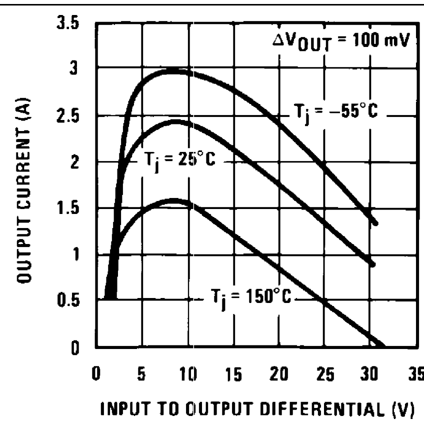
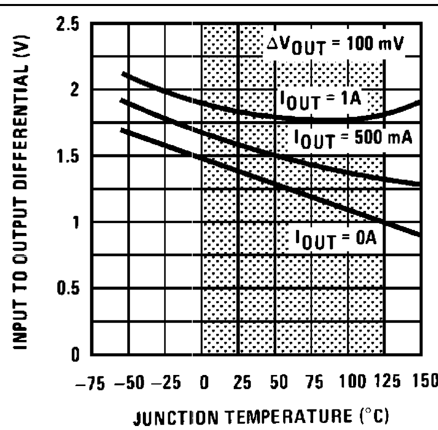


Figure 10. Peak Output Current



Shaded area refers to LM340A/LM340, LM7805, LM7812, and LM7815.

Figure 11. Dropout Voltage

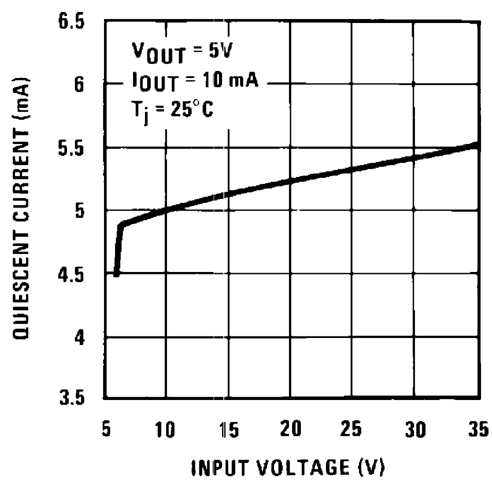
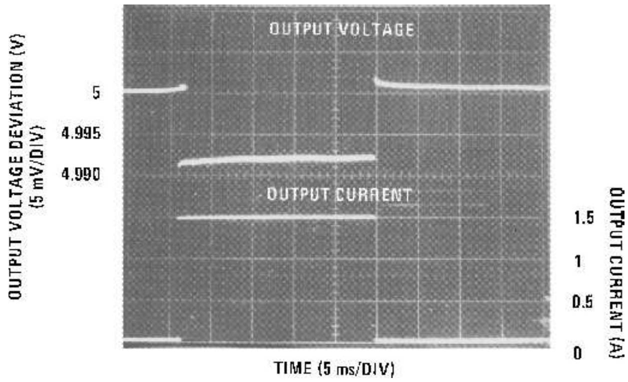


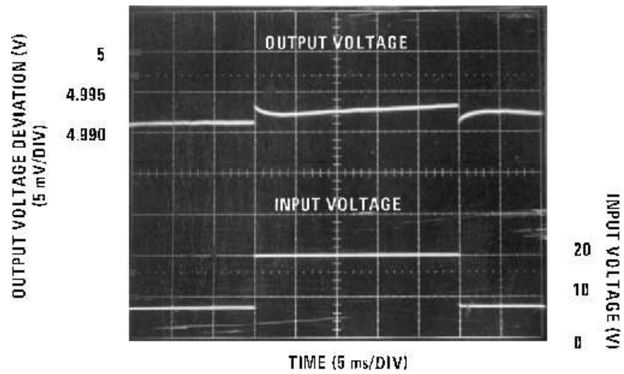
Figure 12. Quiescent Current

Typical Characteristics (continued)



I_{OUT} = 1 A, T_A = 25°C

Figure 13. Line Regulation LM340



V_{IN} = 10 V, T_A = 25°C

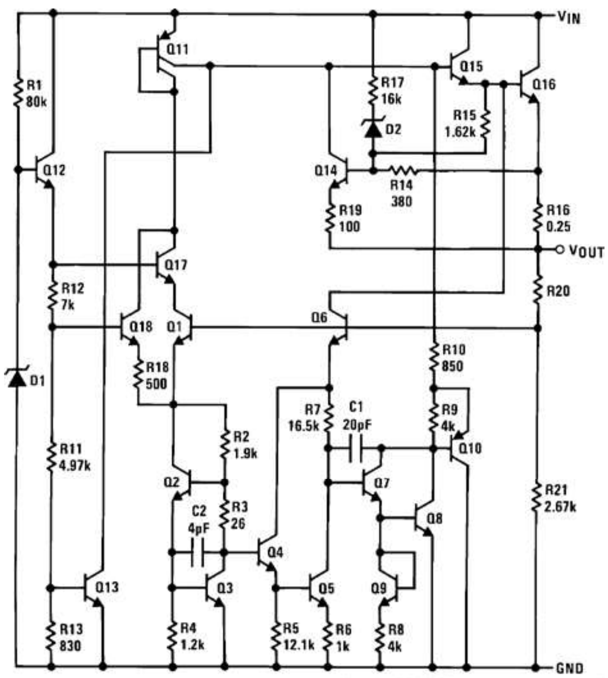
Figure 14. Line Regulation LM340

7 Detailed Description

7.1 Overview

The LM340 and LM7805 devices are a family of fixed output positive voltage regulators with outputs ranging from 3 V to 15 V. They accept up to 35 V of input voltage and with proper heat dissipation can provide over 1.5 A of current. With a combination of current limiting, thermal shutdown, and safe area protection, these regulators eliminate any concern of damage. These features paired with excellent line and load regulation make the LM340 and LM7805 Family versatile solutions to a wide range of power management designs. Although the LM340 and LM7805 Family were designed primarily as fixed-voltage regulators, these devices can be used with external component for adjustable voltage and current.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Output Current

With proper considerations, the LM340 and LM7805 Family can exceed 1.5-A output current. Depending on the desired package option, the effective junction-to-ambient thermal resistance can be reduced through heat sinking, allowing more power to be dissipated in the device.

7.3.2 Current Limiting Feature

In the event of a short circuit at the output of the regulator, each device has an internal current limit to protect it from damage. The typical current limits for the LM340 and LM7805 Family is 2.4 A.

7.3.3 Thermal Shutdown

Each package type employs internal current limiting and thermal shutdown to provide safe operation area protection. If the junction temperature is allowed to rise to 150°C, the device will go into thermal shutdown.

7.4 Device Functional Modes

There are no functional modes for this device.

8 Application and Implementation

NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

8.1 Application Information

The LM340x and LM7805 series is designed with thermal protection, output short-circuit protection, and output transistor safe area protection. However, as with any IC regulator, it becomes necessary to take precautions to assure that the regulator is not inadvertently damaged. The following describes possible misapplications and methods to prevent damage to the regulator.

8.1.1 Shorting the Regulator Input

When using large capacitors at the output of these regulators, a protection diode connected input to output (Figure 15) may be required if the input is shorted to ground. Without the protection diode, an input short causes the input to rapidly approach ground potential, while the output remains near the initial V_{OUT} because of the stored charge in the large output capacitor. The capacitor will then discharge through a large internal input to output diode and parasitic transistors. If the energy released by the capacitor is large enough, this diode, low current metal, and the regulator are destroyed. The fast diode in Figure 15 shunts most of the capacitors discharge current around the regulator. Generally no protection diode is required for values of output capacitance ≤ 10 µF.

8.1.2 Raising the Output Voltage Above the Input Voltage

Because the output of the device does not sink current, forcing the output high can cause damage to internal low current paths in a manner similar to that just described in *Shorting the Regulator Input*.

8.1.3 Regulator Floating Ground

When the ground pin alone becomes disconnected, the output approaches the unregulated input, causing possible damage to other circuits connected to V_{OUT}. If ground is reconnected with power ON, damage may also occur to the regulator. This fault is most likely to occur when plugging in regulators or modules with on card regulators into powered up sockets. The power must be turned off first, the thermal limit ceases operating, or the ground must be connected first if power must be left on. See Figure 16.

8.1.4 Transient Voltages

If transients exceed the maximum rated input voltage of the device, or reach more than 0.8 V below ground and have sufficient energy, they will damage the regulator. The solution is to use a large input capacitor, a series input breakdown diode, a choke, a transient suppressor or a combination of these.

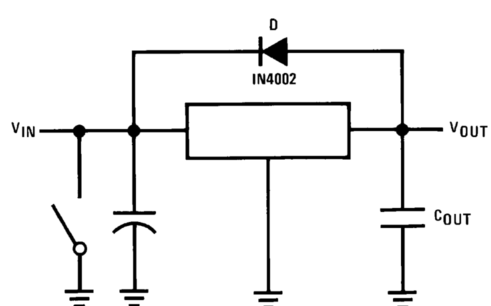


Figure 15. Input Short

Application Information (continued)

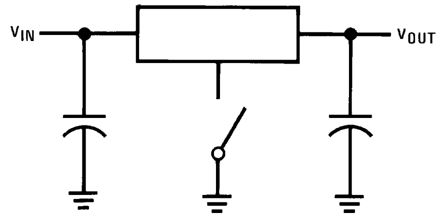


Figure 16. Regulator Floating Ground

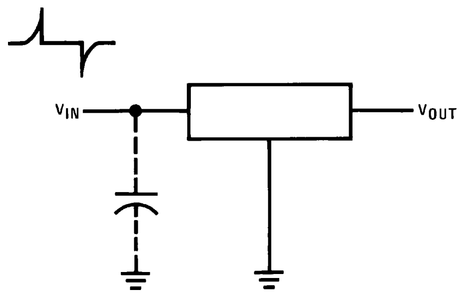


Figure 17. Transients

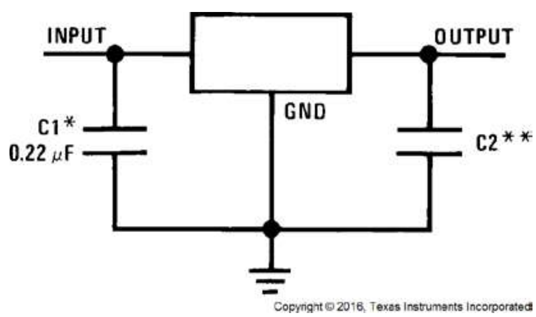
When a value for $\theta_{(H–A)}$ is found, a heat sink must be selected that has *a value that is less than or equal to this number.*

$\theta_{(H–A)}$ is specified numerically by the heat sink manufacturer in this catalog or shown in a curve that plots temperature rise vs power dissipation for the heat sink.

8.2 Typical Applications

8.2.1 Fixed Output Voltage Regulator

The LM340x and LM7805 Family devices are primarily designed to provide fixed output voltage regulation. The simplest implementation of LM340x and LM7805 Family is shown in Figure 18.



*Required if the regulator is located far from the power supply filter.
**Although no output capacitor is needed for stability, it does help transient response. (If needed, use 0.1-µF, ceramic disc).

Figure 18. Fixed Output Voltage Regulator

8.2.1.1 Design Requirements

The device component count is very minimal. Although not required, TI recommends employing bypass capacitors at the output for optimum stability and transient response. These capacitors must be placed as close as possible to the regulator. If the device is located more than 6 inches from the power supply filter, it is required to employ input capacitor.

Typical Applications (continued)

8.2.1.2 Detailed Design Procedure

The output voltage is set based on the device variant. LM340x and LM7805 Family are available in 5-V, 12-V and 15-V regulator options.

8.2.1.3 Application Curve

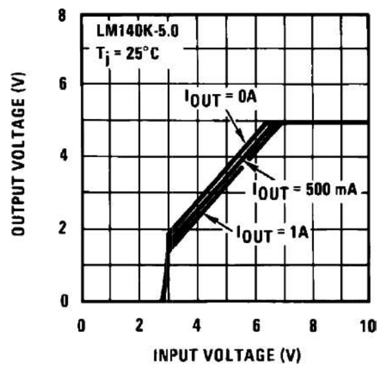
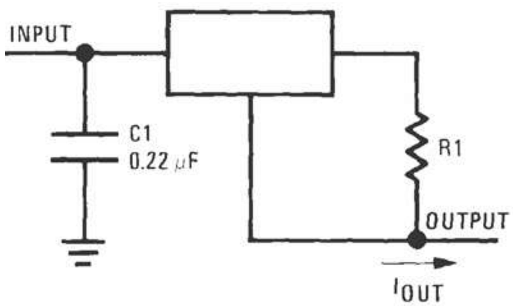


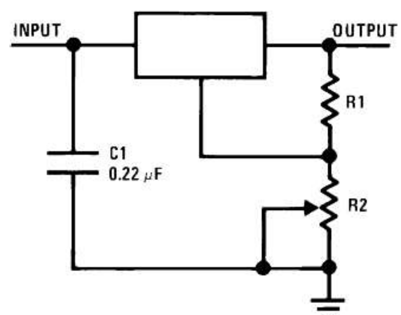
Figure 19. V_{OUT} vs V_{IN}, V_{OUT} = 5 V

8.3 System Examples



I_{OUT} = V2–3 / R1 + I_Q
ΔI_Q = 1.3 mA over line and load changes.

Figure 20. Current Regulator



V_{OUT} = 5 V + (5 V/R1 + I_Q) R2 5 V/R1 > 3 I_Q,
load regulation (L_r) ≈ [(R1 + R2)/R1] (L_r of LM340-5).

Figure 21. Adjustable Output Regulator

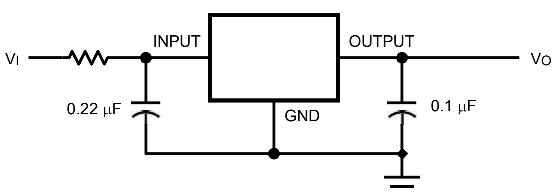


Figure 22. High Input Voltage Circuit With Series Resistor

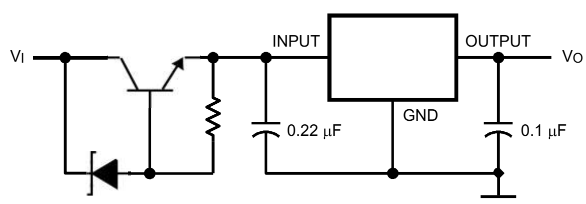
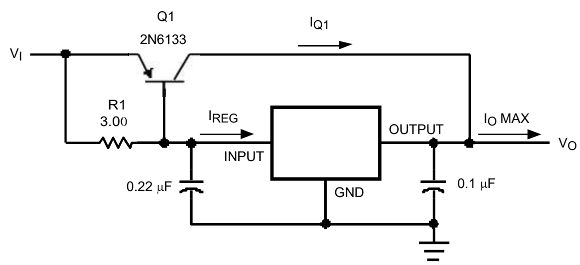


Figure 23. High Input Voltage Circuit implementation With Transistor

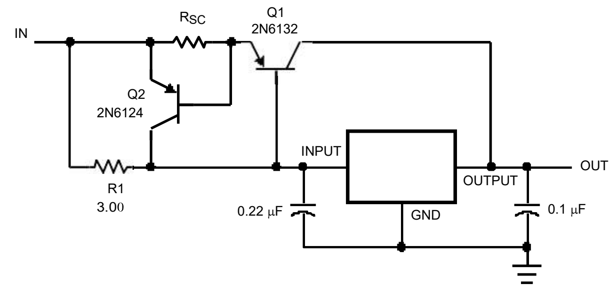
System Examples (continued)



$\beta(Q1) \geq I_{O\ Max} / I_{REG\ Max}$

$R1 = 0.9 / I_{REG} = \beta_{(Q1)} V_{BE(Q1)} / I_{REG\ Max\ (\beta+1)} - I_{O\ Max}$

Figure 24. High Current Voltage Regulator



$R_{SC} = 0.8 / I_{SC}$

$R1 = \beta V_{BE(Q1)} / I_{REG\ Max} (\beta + 1) - I_{O\ Max}$

Figure 25. High Output Current With Short-Circuit Protection

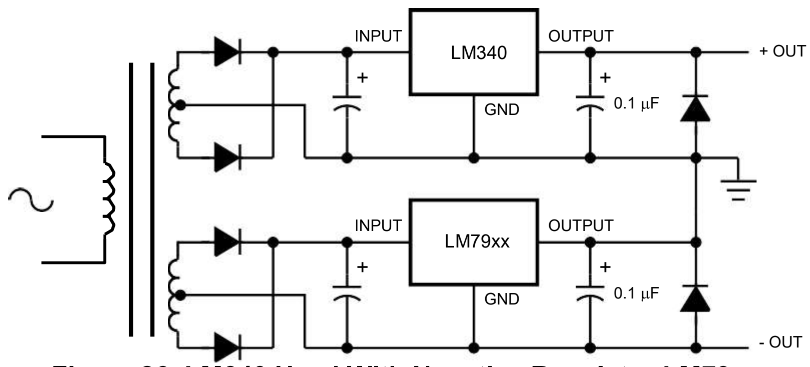


Figure 26. LM340 Used With Negative Regulator LM79xx

9 Power Supply Recommendations

The LM340 is designed to operate from a wide input voltage up to 35 V. Please refer to electrical characteristics tables for the minimum input voltage required for line/load regulation. If the device is more than six inches from the input filter capacitors, an input bypass capacitor, 0.1 µF or greater, of any type is needed for stability.

10 Layout

10.1 Layout Guidelines

Some layout guidelines must be followed to ensure proper regulation of the output voltage with minimum noise. Traces carrying the load current must be wide to reduce the amount of parasitic trace inductance. To improve PSRR, a bypass capacitor can be placed at the OUTPUT pin and must be placed as close as possible to the IC. All that is required for the typical fixed output regulator application circuit is the LM340x/LM7805 Family IC and a 0.22-µF input capacitor if the regulator is placed far from the power supply filter. A 0.1-µF output capacitor is recommended to help with transient response. In cases when VIN shorts to ground, an external diode must be placed from VOUT to VIN to divert the surge current from the output capacitor and protect the IC.

10.2 Layout Example

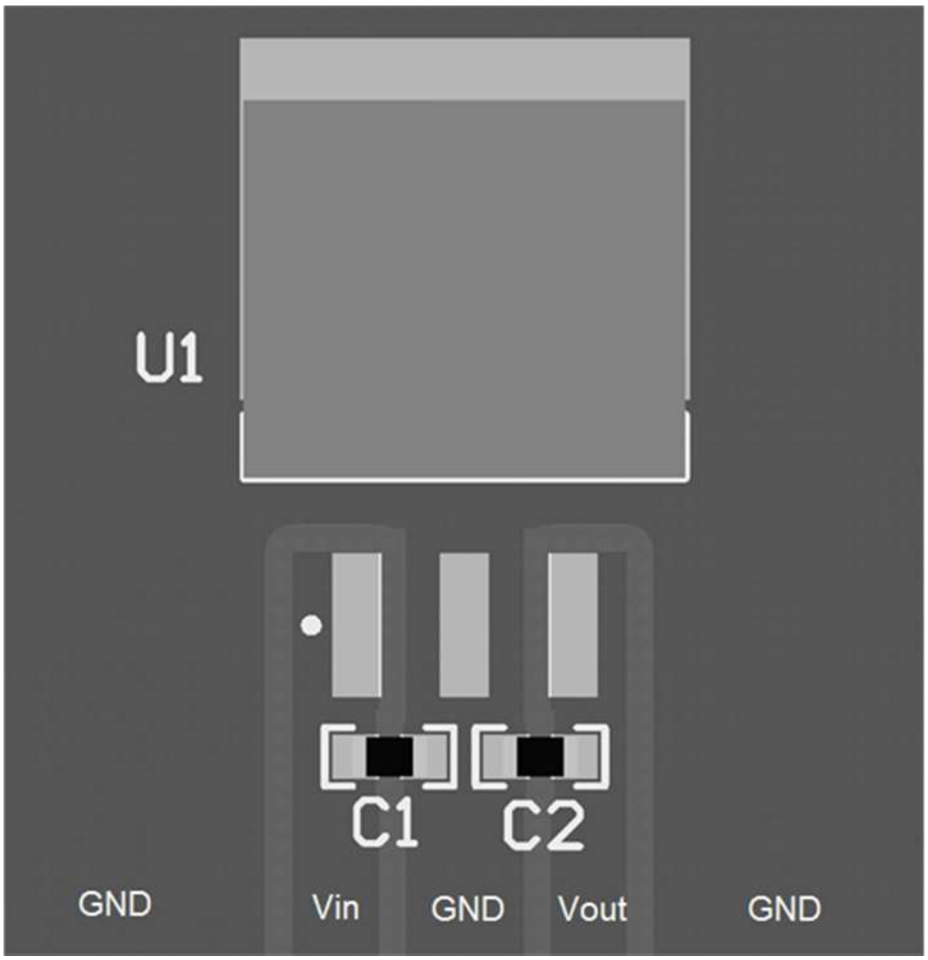


Figure 27. Layout Example DDPAK

Layout Example (continued)

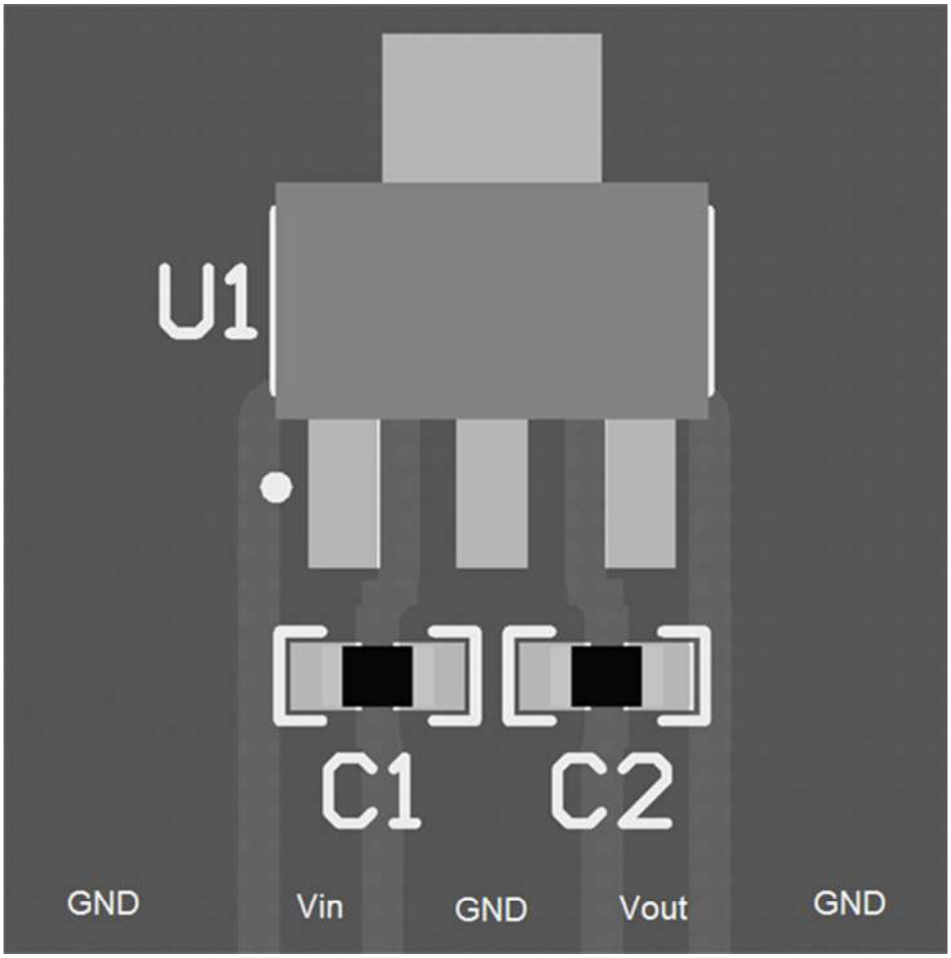


Figure 28. Layout Example SOT-223

10.3 Heat Sinking DDPAK/TO-263 and SOT-223 Package Parts

Both the DDPAK/TO-263 (KTT) and SOT-223 (DCY) packages use a copper plane on the PCB and the PCB itself as a heat sink. To optimize the heat sinking ability of the plane and PCB, solder the tab of the plane.

Figure 29 shows for the DDPAK/TO-263 the measured values of $\theta_{(J-A)}$ for different copper area sizes using a typical PCB with 1-oz copper *and no solder mask over the copper area used for heat sinking*.

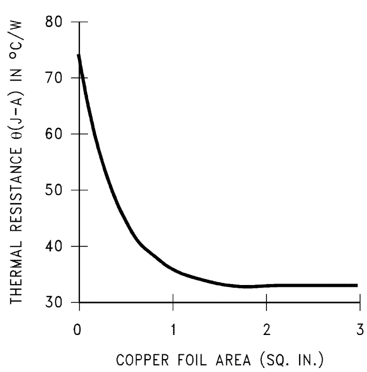


Figure 29. $\theta_{(J-A)}$ vs Copper (1 Ounce) Area for the DDPAK/TO-263 Package

Heat Sinking DDPAK/TO-263 and SOT-223 Package Parts (continued)

As shown in Figure 29, increasing the copper area beyond 1 square inch produces very little improvement. It should also be observed that the minimum value of $\theta_{(J-A)}$ for the DDPAK/TO-263 package mounted to a PCB is 32°C/W.

As a design aid, Figure 30 shows the maximum allowable power dissipation compared to ambient temperature for the DDPAK/TO-263 device (assuming $\theta_{(J-A)}$ is 35°C/W and the maximum junction temperature is 125°C).

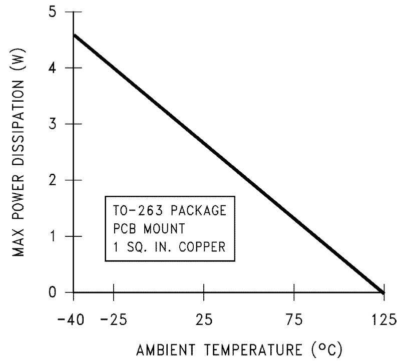


Figure 30. Maximum Power Dissipation vs T_{AMB} for the DDPAK/TO-263 Package

Figure 31 and Figure 32 show the information for the SOT-223 package. Figure 31 assumes a $\theta_{(J-A)}$ of 74°C/W for 1-oz. copper and 51°C/W for 2-oz. copper and a maximum junction temperature of 125°C.

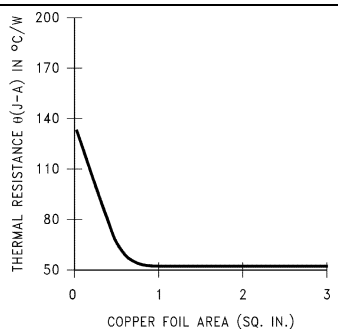


Figure 31. $\theta_{(J-A)}$ vs Copper (2 Ounce) Area for the SOT-223 Package

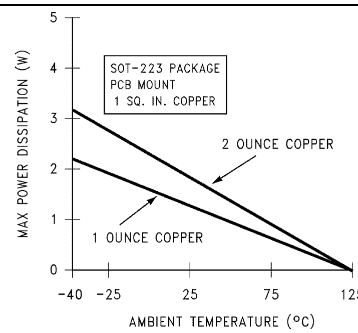


Figure 32. Maximum Power Dissipation vs T_{AMB} for the SOT-223 Package

See *AN-1028 LMX2370 PLLatinum Dual Freq Synth for RF Pers Comm LMX2370 2.5GHz/1.2GHz* (SNVA036) for power enhancement techniques to be used with the SOT-223 package.

11 Device and Documentation Support

11.1 Documentation Support

11.1.1 Related Documentation

For related documentation, see the following:
- *AN-1028 LMX2370 PLLatinum Dual Freq Synth for RF Pers Comm LMX2370 2.5GHz/1.2GHz* (SNVA036)
- *LM140K Series 3-Terminal Positive Regulators* (SNVS994)

11.2 Related Links

The table below lists quick access links. Categories include technical documents, support and community resources, tools and software, and quick access to sample or buy.

Table 1. Related Links

PARTS	PRODUCT FOLDER	SAMPLE & BUY	TECHNICAL DOCUMENTS	TOOLS & SOFTWARE	SUPPORT & COMMUNITY
LM340	Click here	Click here	Click here	Click here	Click here
LM340A	Click here	Click here	Click here	Click here	Click here
LM7805	Click here	Click here	Click here	Click here	Click here
LM7812	Click here	Click here	Click here	Click here	Click here
LM7815	Click here	Click here	Click here	Click here	Click here

11.3 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. In the upper right corner, click on *Alert me* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

11.4 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

TI E2E™ Online Community ***TI's Engineer-to-Engineer (E2E) Community.*** Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

Design Support ***TI's Design Support*** Quickly find helpful E2E forums along with design support tools and contact information for technical support.

11.5 Trademarks

E2E is a trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

11.6 Electrostatic Discharge Caution

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

11.7 Glossary

SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

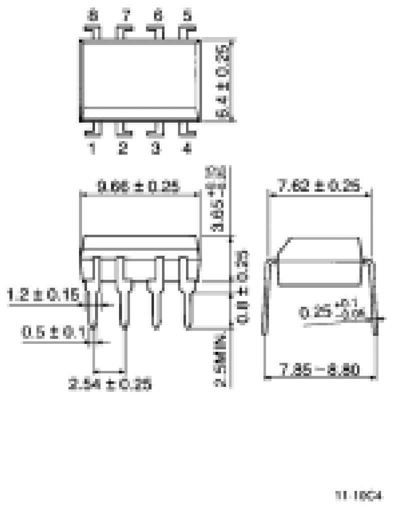
APPENDIX E

TOSHIBA Photocoupler GaAlAs Ired & Photo−IC

TLP250

Transistor Inverter
Inverter For Air Conditionor
IGBT Gate Drive
Power MOS FET Gate Drive

Unit in mm



TOSHIBA 11−10C4

Weight: 0.54 g

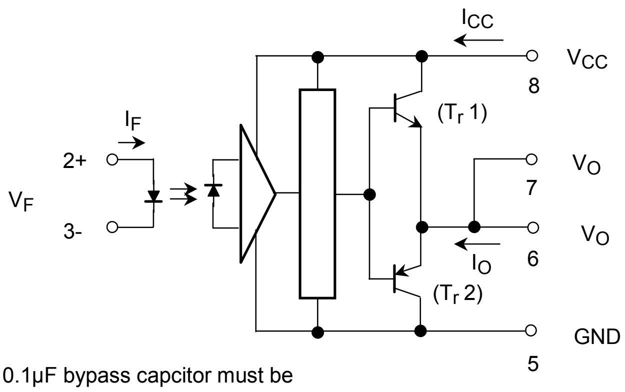
The TOSHIBA TLP250 consists of a GaAlAs light emitting diode and a integrated photodetector.
This unit is 8−lead DIP package.
TLP250 is suitable for gate driving circuit of IGBT or power MOS FET.

- Input threshold current: I_F=5mA(max.)
- Supply current (I_{CC}): 11mA(max.)
- Supply voltage (V_{CC}): 10−35V
- Output current (I_O): ±1.5A (max.)
- Switching time (t_{pLH}/t_{pHL}): 1.5μs(max.)
- Isolation voltage: 2500V_{rms}(min.)
- UL recognized: UL1577, file No.E67349
- Option (D4) type
  VDE approved: DIN VDE0884/06.92,certificate No.76823
  Maximum operating insulation voltage: 630V_{PK}
  Highest permissible over voltage: 4000V_{PK}

(Note) When a VDE0884 approved type is needed, please designate the "option (D4)"

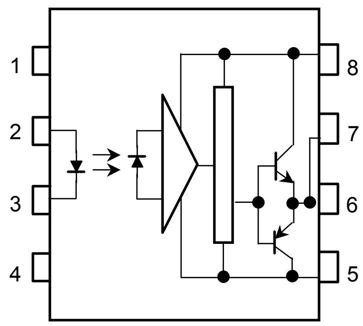
- Creepage distance: 6.4mm(min.)
  Clearance: 6.4mm(min.)

Schmatic



A 0.1μF bypass capcitor must be connected between pin 8 and 5 (See Note 5).

Pin Configuration (top view)



1 : N.C.
2 : Anode
3 : Cathode
4 : N.C.
5 : GND
6 : V_O (Output)
7 : V_O
8 : V_{CC}

Truth Table

		Tr1	Tr2
Input LED	On	On	Off
	Off	Off	On

Absolute Maximum Ratings (Ta = 25°C)

	Characteristic		Symbol	Rating	Unit
LED	Forward current		I_F	20	mA
	Forward current derating (Ta ≥ 70°C)		ΔI_F / ΔTa	−0.36	mA / °C
	Peak transient forward curent (Note 1)		I_{FPT}	1	A
	Reverse voltage		V_R	5	V
	Junction temperature		Tj	125	°C
Detector	"H"peak output current (P_W ≤ 2.5μs,f ≤ 15kHz) (Note 2)		I_{OPH}	−1.5	A
	"L"peak output current (P_W ≤ 2.5μs,f ≤ 15kHz) (Note 2)		I_{OPL}	+1.5	A
	Output voltage	(Ta ≤ 70°C)	V_O	35	V
		(Ta = 85°C)		24	
	Supply voltage	(Ta ≤ 70°C)	V_{CC}	35	V
		(Ta = 85°C)		24	
	Output voltage derating (Ta ≥ 70°C)		ΔV_O / ΔTa	−0.73	V / °C
	Supply voltage derating (Ta ≥ 70°C)		ΔV_{CC} / ΔTa	−0.73	V / °C
	Junction temperature		Tj	125	°C
Operating frequency (Note 3)			f	25	kHz
Operating temperature range			T_{opr}	−20~85	°C
Storage temperature range			T_{stg}	−55~125	°C
Lead soldering temperature (10 s) (Note 4)			T_{sol}	260	°C
Isolation voltage (AC, 1 min., R.H.≤ 60%) (Note 5)			BV_S	2500	Vrms

Note 1: Pulse width P_W ≤ 1μs, 300pps

Note 2: Exporenential wavefom

Note 3: Exporenential wavefom, I_{OPH} ≤ −1.0A(≤ 2.5μs), I_{OPL} ≤ +1.0A(≤ 2.5μs)

Note 4: It is 2 mm or more from a lead root.

Note 5: Device considerd a two terminal device: Pins 1, 2, 3 and 4 shorted together, and pins 5, 6, 7 and 8 shorted together.

Note 6: A ceramic capacitor(0.1μF) should be connected from pin 8 to pin 5 to stabilize the operation of the high gain linear amplifier. Failure to provide the bypassing may impair the switching proparty. The total lead length between capacitor and coupler should not exceed 1cm.

Recommended Operating Conditions

Characteristic	Symbol	Min.	Typ.	Max.		Unit
Input current, on (Note 7)	$I_{F(ON)}$	7	8	10		mA
Input voltage, off	$V_{F(OFF)}$	0	—	0.8		V
Supply voltage	V_{CC}	15	—	30	20	V
Peak output current	I_{OPH}/I_{OPL}	—	—	±0.5		A
Operating temperature	T_{opr}	−20	25	70	85	°C

Note 7: Input signal rise time (fall time) < 0.5 μs.

Electrical Characteristics (Ta = −20~70°C, unless otherwise specified)

Characteristic		Symbol	Test Circuit	Test Condition		Min.	Typ.*	Max.	Unit
Input forward voltage		V_F	—	I_F = 10 mA , Ta = 25°C			1.6	1.8	V
Temperature coefficient of forward voltage		$\Delta V_F / \Delta Ta$	—	I_F = 10 mA		—	−2.0	—	mV / °C
Input reverse current		I_R	—	V_R = 5V, Ta = 25°C			—	10	μA
Input capacitance		C_T	—	V = 0 , f = 1MHz , Ta = 25°C		—	45	250	pF
Output current	“H” level	I_{OPH}	3	V_{CC} = 30V (*1)	I_F = 10 mA V_{8-6} = 4V	−0.5	−1.5	—	A
	“L” level	I_{OPL}	2		I_F = 0 V_{6-5} = 2.5V	0.5	2	—	
Output voltage	“H” level	V_{OH}	4	V_{CC1} = +15V, V_{EE1} = −15V R_L = 200Ω, I_F = 5mA		11	12.8	—	V
	“L” level	V_{OL}	5	V_{CC1} = +15V, V_{EE1} = −15V R_L = 200Ω, V_F = 0.8V		—	−14.2	−12.5	
Supply current	“H” level	I_{CCH}	—	V_{CC} = 30V, I_F = 10mA Ta = 25°C		—	7	—	mA
				V_{CC} = 30V, I_F = 10mA		—	—	11	
	“L” level	I_{CCL}	—	V_{CC} = 30V, I_F = 0mA Ta = 25°C		—	7.5	—	
				V_{CC} = 30V, I_F = 0mA		—	—	11	
Threshold input current	“Output L→H”	I_{FLH}	—	V_{CC1} = +15V, V_{EE1} = −15V R_L = 200Ω, V_O > 0V		—	1.2	5	mA
Threshold input voltage	“Output H→L”	I_{FHL}	—	V_{CC1} = +15V, V_{EE1} = −15V R_L = 200Ω, V_O < 0V		0.8	—	—	V
Supply voltage		V_{CC}	—			10	—	35	V
Capacitance (input–output)		C_S	—	V_S = 0 , f = 1MHz Ta = 25°C		—	1.0	2.0	pF
Resistance(input–output)		R_S	—	V_S = 500V , Ta = 25°C R.H.≤ 60%		1×10^{12}	10^{14}	—	Ω

* All typical values are at Ta = 25°C (*1): Duration of I_O time ≤ 50μs

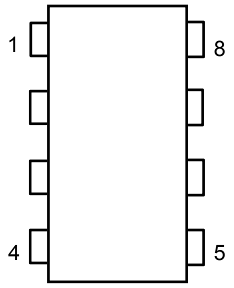
Switching Characteristics (Ta = −20~70°C , unless otherwise specified)

Characteristic		Symbol	Test Cir– cuit	Test Condition	Min.	Typ.*	Max.	Unit
Propagation delay time	L→H	t_{pLH}	6	I_F = 8mA (Note 7) V_{CC1} = +15V, V_{EE1} = −15V R_L = 200Ω	—	0.15	0.5	μs
	H→L	t_{pHL}			—	0.15	0.5	
Output rise time		t_r			—	—	—	
Output fall time		t_f			—	—	—	
Common mode transient immunity at high level output		C_{MH}	7	V_{CM} = 600V, I_F = 8mA V_{CC} = 30V, Ta = 25°C	−5000	—	—	V / μs
Common mode transient immunity at low level output		C_{ML}	7	V_{CM} = 600V, I_F = 0mA V_{CC} = 30V, Ta = 25°C	5000	—	—	V / μs

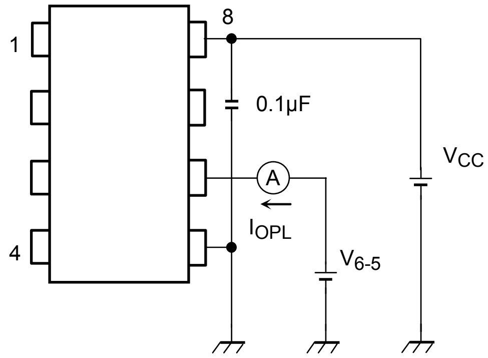
* All typical values are at Ta = 25°C

Note 7: Input signal rise time (fall time) $<$ 0.5 μs.

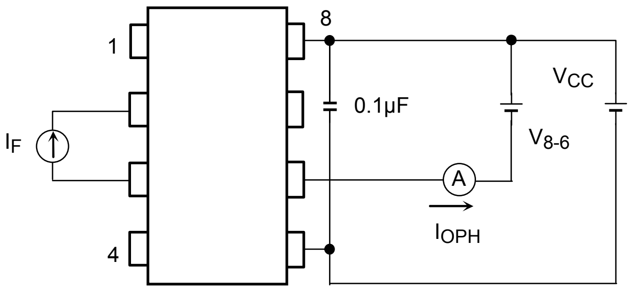
Test Circuit 1 :



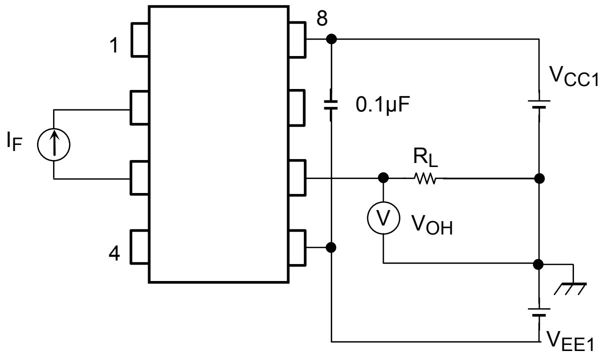
Test Circuit 2 : IOPL



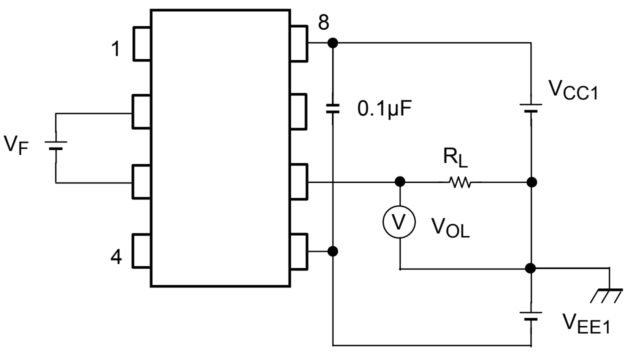
Test Circuit 3 : IOPH



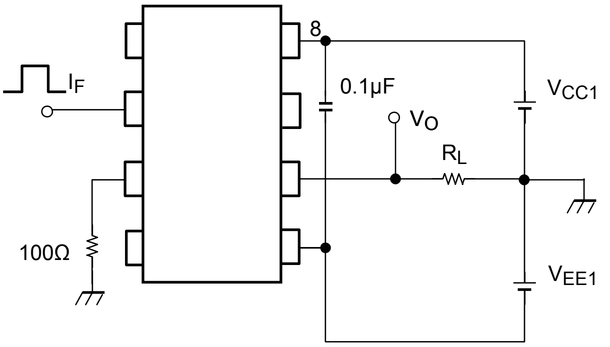
Test Circuit 4 : VOH

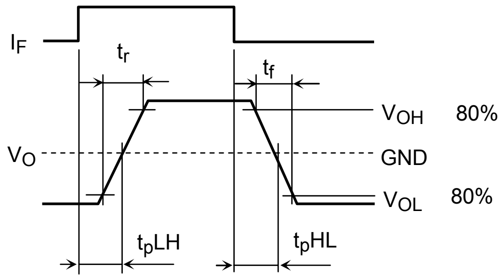


Test Circuit 5 : V_{OL}

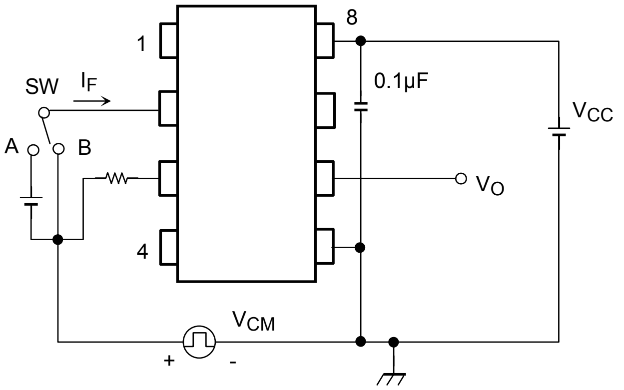


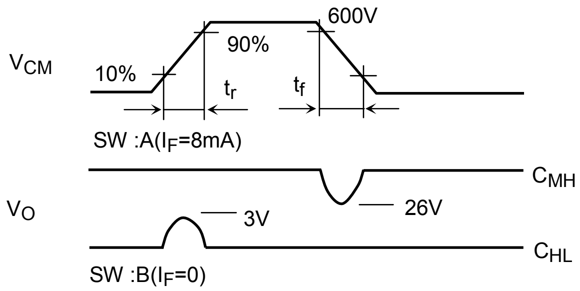
Test Circuit 6: t_{pLH}, t_{pHL}, t_r t_f





Test Circuit 7: C_{MH}, C_{ML}

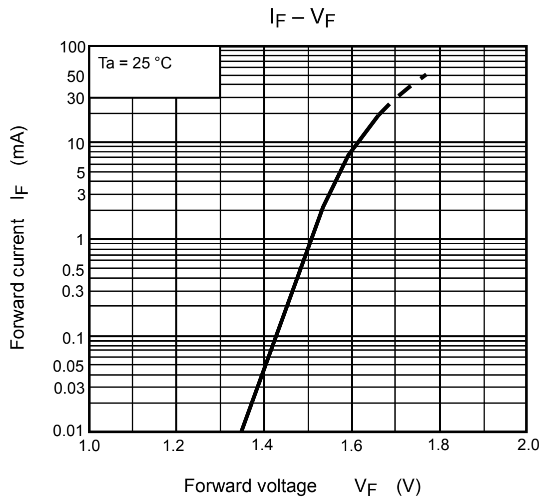


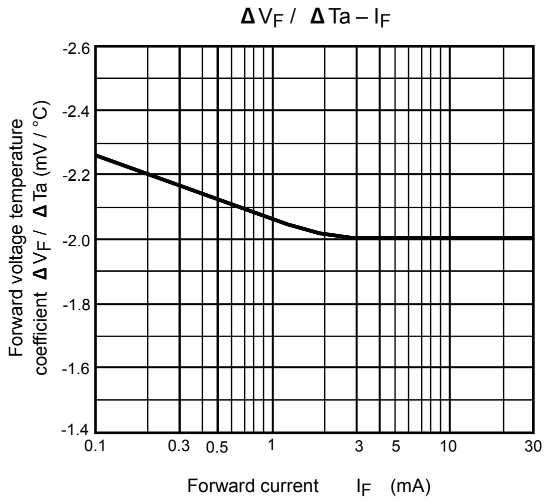


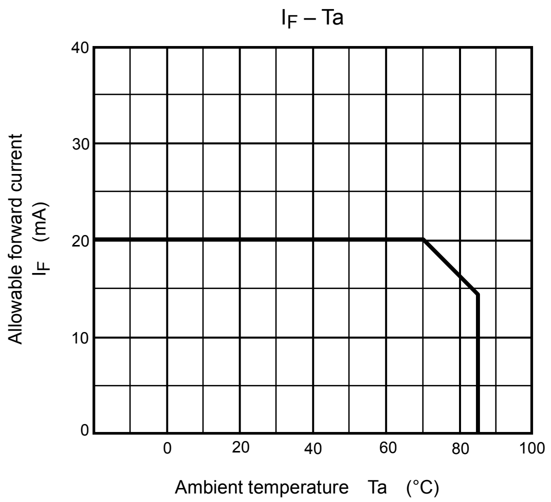
$$C_{ML} = \frac{480\ (V)}{t_{r\ (\mu s)}}$$

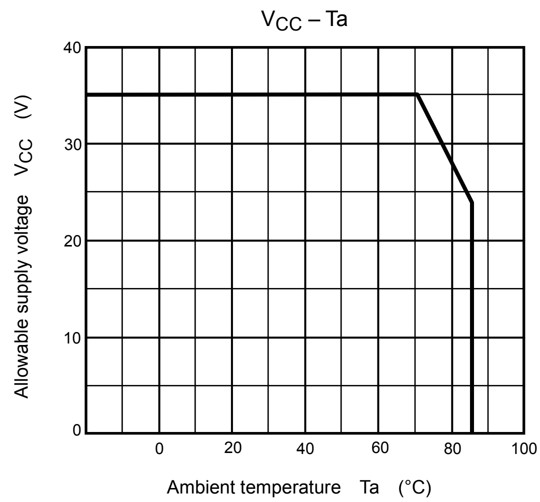
$$C_{MH} = \frac{480\ (V)}{t_{f\ (\mu s)}}$$

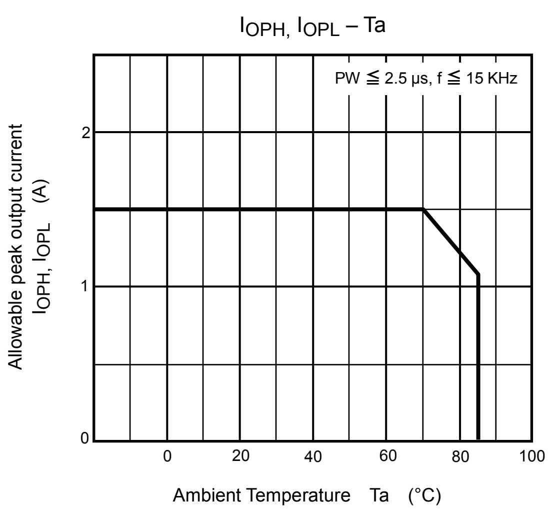
C_{ML}(C_{MH}) is the maximum rate of rise (fall) of the common mode voltage that can be sustained with the output voltage in the low (high) state.


$I_F – V_F$
Ta = 25 °C
Forward current I_F (mA)
100
50
30
10
5
3
1
0.5
0.3
0.1
0.05
0.03
0.01
1.0
1.2
1.4
1.6
1.8
2.0
Forward voltage V_F (V)


$\Delta V_F / \Delta Ta – I_F$
Forward voltage temperature coefficient $\Delta V_F / \Delta Ta$ (mV / °C)
-2.6
-2.4
-2.2
-2.0
-1.8
-1.6
-1.4
0.1
0.3
0.5
1
3
5
10
30
Forward current I_F (mA)


$I_F – Ta$
Allowable forward current I_F (mA)
40
30
20
10
0
0
20
40
60
80
100
Ambient temperature Ta (°C)


$V_{CC} – Ta$
Allowable supply voltage V_{CC} (V)
40
30
20
10
0
0
20
40
60
80
100
Ambient temperature Ta (°C)


$I_{OPH}, I_{OPL} – Ta$
PW ≦ 2.5 μs, f ≦ 15 KHz
Allowable peak output current I_{OPH}, I_{OPL} (A)
2
1
0
0
20
40
60
80
100
Ambient Temperature Ta (°C)

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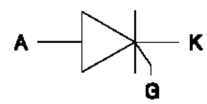
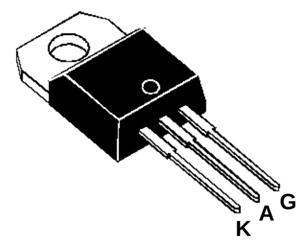
SGS-THOMSON MICROELECTRONICS TYN 204 ---> TYN 1004

SCR

FEATURES

- HIGH SURGE CAPABILITY
- HIGH ON-STATE CURRENT
- HIGH STABILITY AND RELIABILITY





TO220AB
(Plastic)

DESCRIPTION

The TYN 204 ---> TYN 1004 Family of Silicon Controlled Rectifiers uses a high performance glass passivated technology.
This general purpose Family of Silicon Controlled Rectifiers is designed for power supplies up to 400Hz on resistive or inductive load.

ABSOLUTE RATINGS (limiting values)

Symbol	Parameter		Value	Unit
$I_{T(RMS)}$	RMS on-state current (180° conduction angle)	Tc = 115 °C	4	A
$I_{T(AV)}$	Average on-state current (180° conduction angle, single phase circuit)	Tc = 115 °C	2.5	A
I_{TSM}	Non repetitive surge peak on-state current (Tj initial = 25°C)	tp = 8.3 ms	63	A
		tp = 10 ms	60	
I^2t	I^2t value	tp = 10 ms	18	A^2s
dI/dt	Critical rate of rise of on-state current Gate supply : I_G = 100 mA dI_G/dt = 1 A/µs		100	A/µs
Tstg Tj	Storage and operating junction temperature range		- 40 to + 150 - 40 to + 125	°C °C
Tl	Maximum lead temperature for soldering during 10 s at 4.5 mm from case		260	°C

Symbol	Parameter	TYN					Unit
		204	404	604	804	1004	
V_{DRM} V_{RRM}	Repetitive peak off-state voltage Tj = 125 °C	200	400	600	800	1000	V

THERMAL RESISTANCES

Symbol	Parameter	Value	Unit
Rth (j-a)	Junction to ambient	60	°C/W
Rth (j-c) DC	Junction to case for DC	2.5	°C/W

GATE CHARACTERISTICS (maximum values)

$P_{G\ (AV)}$ = 1W P_{GM} = 10W (tp = 20 µs) I_{FGM} = 4A (tp = 20 µs) V_{RGM} = 5 V.

ELECTRICAL CHARACTERISTICS

Symbol	Test Conditions			Value	Unit
I_{GT}	V_D=12V (DC) R_L=33Ω	Tj=25°C	MAX	15	mA
V_{GT}	V_D=12V (DC) R_L=33Ω	Tj=25°C	MAX	1.5	V
V_{GD}	V_D=V_{DRM} R_L=3.3kΩ	Tj= 110°C	MIN	0.2	V
tgt	V_D=V_{DRM} I_G = 40mA dI_G/dt = 0.5A/µs	Tj=25°C	TYP	2	µs
I_L	I_G= 1.2 I_{GT}	Tj=25°C	TYP	50	mA
I_H	I_T= 100mA gate open	Tj=25°C	MAX	30	mA
V_{TM}	ITM= 8A tp= 380µs	Tj=25°C	MAX	1.8	V
I_{DRM} I_{RRM}	V_{DRM} Rated V_{RRM} Rated	Tj=25°C	MAX	0.01	mA
		Tj= 110°C		2	
dV/dt	Linear slope up to V_D=67%V_{DRM} gate open	Tj= 110°C	MIN	200	V/µs
tq	V_D=67%V_{DRM} I_{TM}= 8A V_R= 25V dI_{TM}/dt=30 A/µs dV_D/dt= 50V/µs	Tj= 110°C	TYP	70	µs

Fig.1 : Maximum average power dissipation versus average on-state current.

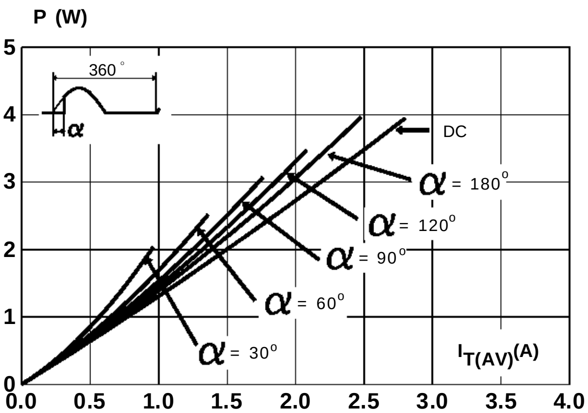


Fig.2 : Correlation between maximum average power dissipation and maximum allowable temperatures (T_{amb} and T_{case}) for different thermal resistances heatsink + contact.

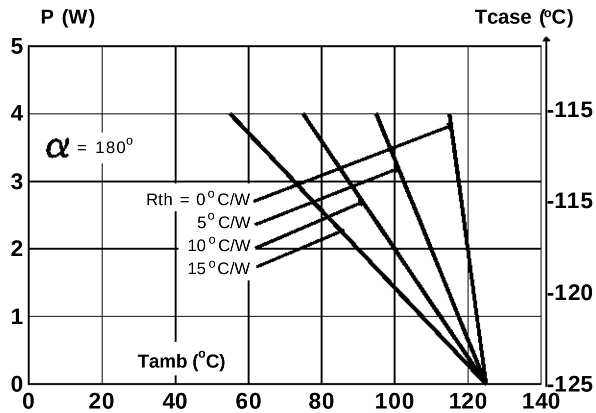


Fig.3 : Average on-state current versus case temperature.

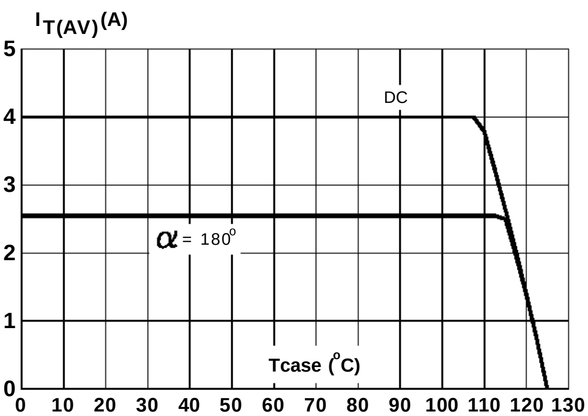


Fig.4 : Relativa variation of thermal impedance versus pulse duration.

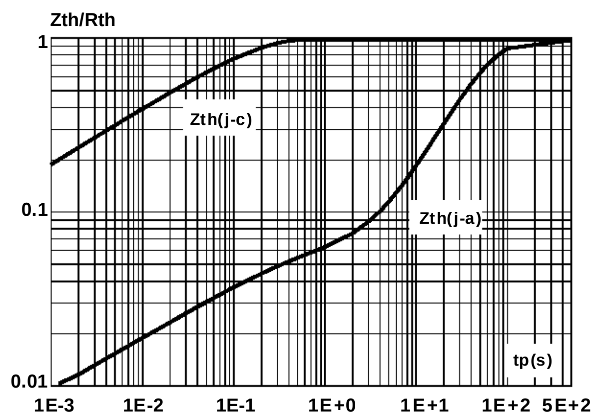


Fig.5 : Relative variation of gate trigger current versus junction temperature.

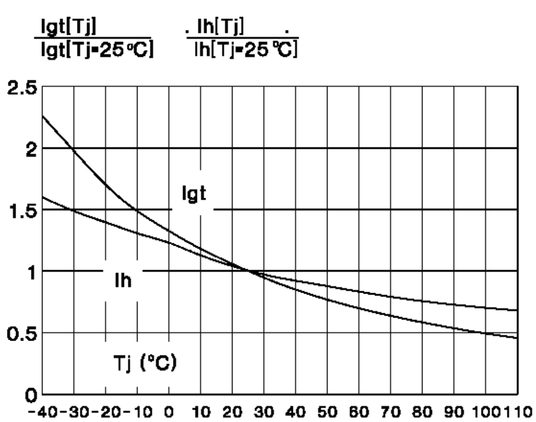


Fig.6 : Non repetitive surge peak on-state current versus number of cycles.

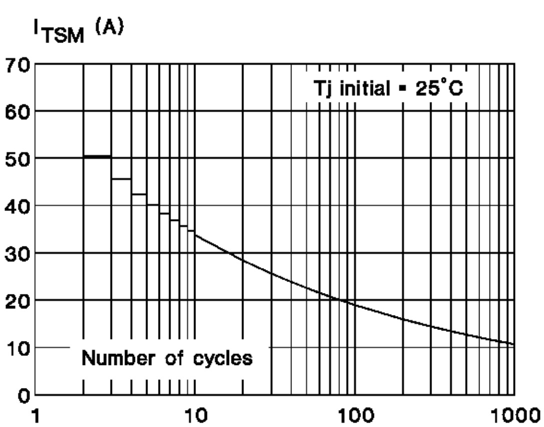


Fig.7 : Non repetitive surge peak on-state current for a sinusoidal pulse with width : t ≤ 10 ms, and corresponding value of I^2t.

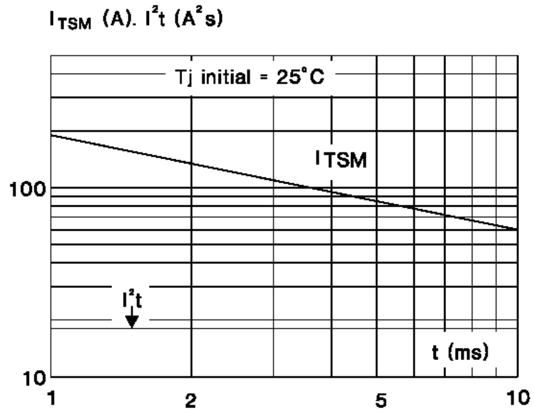
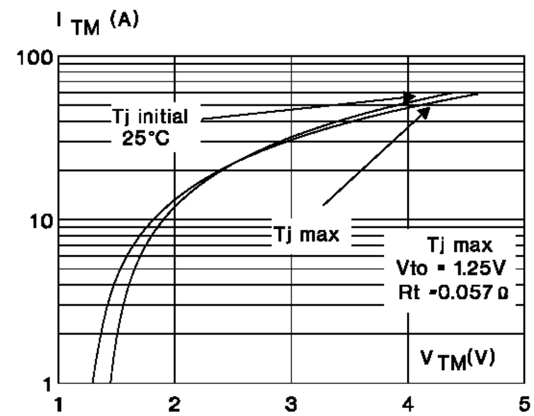
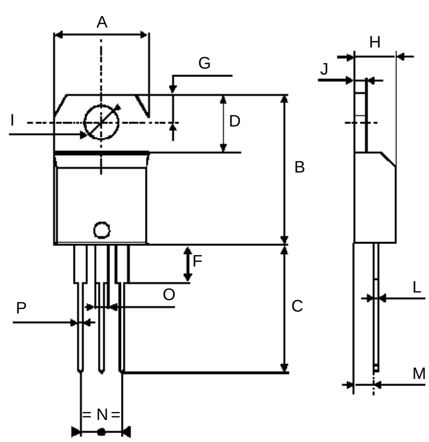


Fig.8 : On-state characteristics (maximum values).



PACKAGE MECHANICAL DATA

TO220AB Plastic



Cooling method : C
Marking : type number
Weight : 2.3 g

Recommended torque value : 0.8 m.N.
Maximum torque value : 1 m.N.