Resonant-Enhanced Full-Bridge Onboard Charger LLC Tank and Synchronous Rectification Design

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ABSTRACT

This paper presents the redesign of a phase-shifted full-bridge onboard DC–DC converter for electric-vehicle charging by integrating an LLC resonant tank on the primary side and synchronous rectification on the secondary. The resonant tank (Lr–Cr with transformer magnetizing inductance Lm) enables soft switching over a wide load range, substantially reducing switching and reverse-recovery losses while permitting higher effective switching frequencies and a smaller magnetic footprint. A frequency-control strategy is used to regulate the output voltage while maintaining Zero-Voltage Switching (ZVS) margins across nominal input/output conditions. Detailed magnetics design, tank tuning, and control implementation are described to manage resonant currents, limit RMS stress, and ensure robust transient and startup behavior. Comparative loss breakdowns from simulations and hardware prototyping show a marked reduction in switching energy and improved thermal distribution versus the original phase-shifted topology, leading to higher overall efficiency and reduced EMI generation. The proposed LLC approach offers a practical pathway for increasing power density and efficiency in onboard chargers while maintaining reliability and controllability required for automotive applications.

CHAPTER 1

INTRODUCTION

The rapid growth of electric vehicles (EVs) has intensified the demand for compact, efficient, and reliable power conversion systems capable of delivering high-quality energy from the utility grid to the vehicle battery pack. Among these, the Onboard Charger (OBC) serves as a vital component that performs AC-to-DC conversion, ensuring safe and efficient battery charging. As the penetration of EVs increases, the design of OBCs must meet multiple challenges—high efficiency, wide output voltage range, reduced volume, high power density, and low electromagnetic interference (EMI).

Traditional hard-switched converters, though simple, suffer from high switching losses, thermal stress, and limited efficiency, especially at high switching frequencies. To overcome these limitations, resonant converters, particularly the LLC resonant topology, have gained significant attention due to their soft-switching capability, reduced switching losses, and improved thermal management. The LLC resonant tank, composed of a resonant inductor, a magnetizing inductor, and a resonant capacitor, enables Zero Voltage Switching (ZVS) for primary switches and Zero Current Switching (ZCS) for secondary devices. This minimizes switching transitions, thereby improving conversion efficiency and extending device life.

In high-power EV OBC applications, the Full-Bridge LLC resonant converter is especially attractive because it supports bidirectional energy flow, accommodates a wide output voltage range, and efficiently delivers power levels exceeding 3.3 kW. The integration of Synchronous Rectification (SR) on the secondary side further enhances efficiency by replacing traditional diodes with actively controlled MOSFETs. This approach significantly reduces conduction losses, especially under low-output-voltage or high-current conditions, and ensures superior thermal performance.

The Resonant-Enhanced Full-Bridge LLC OBC with Synchronous Rectification thus represents a state-of-the-art solution for modern EV charging systems. It combines soft- switching techniques, digital frequency modulation control, and advanced semiconductor technologies (such as SiC and GaN devices) to achieve efficiency levels above 96%, power density beyond 3 kW/L, and superior reliability under varying load and grid conditions. By carefully designing the resonant tank and optimizing SR timing, the proposed configuration ensures minimal switching stress, reduced electromagnetic noise, and highly stable DC output suitable for a wide range of battery chemistries.

In summary, this study focuses on the design, analysis, and performance optimization of a Full-Bridge LLC Resonant Onboard Charger incorporating Synchronous Rectification, aiming to achieve high efficiency, compactness, and improved thermal and electrical performance for next-generation electric vehicle power systems.

1.2 BACKGROUND

The increasing global emphasis on reducing greenhouse gas emissions and dependence on fossil fuels has accelerated the adoption of electric vehicles (EVs). As EVs become more prevalent, the efficiency, size, and cost of their onboard chargers (OBCs) have become crucial factors influencing vehicle performance and user convenience. The OBC is responsible for converting alternating current (AC) from the power grid into direct current (DC) suitable for charging the EV battery. Achieving high efficiency and power density in this conversion process is essential to minimize heat losses, reduce charging time, and improve overall vehicle energy utilization.

Traditional hard-switched converters suffer from high switching losses, large electromagnetic interference (EMI), and bulky heat sinks due to high-frequency operation. These limitations hinder the design of compact and lightweight OBC systems. To overcome these drawbacks, resonant converter topologies, particularly the LLC resonant converter, have gained significant attention due to their soft-switching characteristics. By operating under Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) conditions, the LLC converter minimizes switching losses, enhances efficiency, and enables higher switching frequencies, thereby reducing the size of magnetic components and filters.

In an LLC resonant full-bridge converter, a resonant tank—comprising a resonant inductor (Lr), magnetizing inductor (Lm), and resonant capacitor (Cr)—is designed to shape the voltage and current waveforms for efficient energy transfer. The full-bridge configuration allows higher power levels, improved load regulation, and reduced stress on the power switches compared to half-bridge topologies. This makes it ideal for medium-to-high power applications, such as EV chargers in the 3.3 kW to 11 kW range.

Another key enhancement in modern OBC systems is synchronous rectification (SR). In conventional rectifiers, diode forward voltage drops cause significant conduction losses,

especially in low-voltage, high-current outputs. By replacing diodes with MOSFET-based synchronous rectifiers, conduction losses are drastically reduced, boosting efficiency and enabling compact thermal design. The SR MOSFETs are controlled in synchronization with the resonant current, ensuring ZCS operation and further minimizing losses.

Combining LLC resonant conversion with synchronous rectification results in a highly efficient, compact, and reliable onboard charger architecture. This resonant-enhanced full- bridge OBC achieves peak efficiencies above 96%, maintains low total harmonic distortion (THD), and offers superior thermal and electromagnetic performance. Such advancements are essential for supporting the next generation of EVs with fast-charging capabilities**,** vehicle-to- grid (V2G) integration, and high reliability under diverse grid conditions**.**

1.3 OVERVIEW

The Resonant-Enhanced Full-Bridge Onboard Charger (OBC) based on an LLC resonant tank and synchronous rectification is a high-efficiency power conversion system designed for modern electric vehicles. The system is engineered to convert single-phase AC power from the grid into a regulated DC output suitable for charging the vehicle's high-voltage battery pack. The design focuses on achieving soft-switching operation, low conduction losses, and compactness, while maintaining high reliability and power density.

The overall architecture of the charger consists of two major stages:

1. **AC-DC Front-End (PFC Stage):**

The first stage uses a Power Factor Correction (PFC) circuit, typically a boost converter, to shape the input current in phase with the input voltage. This ensures a unity power factor, reduces harmonic distortion, and stabilizes the intermediate DC bus voltage. The PFC stage provides a regulated DC link (usually around 380–400 V) to feed the subsequent DC-DC converter.

2. **DC-DC Full-Bridge LLC Resonant Converter:**

The second stage is the core of the OBC, responsible for galvanic isolation and efficient energy transfer to the battery. The LLC resonant tank—comprising a resonant inductor (Lr), a magnetizing inductor (Lm), and a resonant capacitor (Cr)— enables soft-switching through resonance. The full-bridge inverter on the primary side converts the DC link voltage into a high-frequency AC waveform, exciting the resonant tank and transformer. On the secondary side, a synchronous rectifier (SR) converts the high-frequency AC back to DC, supplying the battery with controlled voltage and current.

The LLC resonant topology operates at variable frequency to regulate the output. When the load increases or the battery voltage decreases, the switching frequency is reduced below the resonant frequency to increase the voltage gain. Conversely, under light loads or higher battery voltages, the frequency rises above resonance to decrease the gain. This frequency modulation approach ensures Zero Voltage Switching (ZVS) for the primary switches and Zero Current Switching (ZCS) for the secondary rectifiers, drastically minimizing losses and enhancing system efficiency.

The synchronous rectification circuit replaces traditional diodes with MOSFETs, driven in synchronization with the resonant current, effectively reducing conduction losses and improving overall efficiency. Advanced digital controllers such as DSPs or microcontrollers are employed to manage switching frequency, SR timing, and system protection functions like overvoltage (OVP), overcurrent (OCP), and overtemperature (OTP).

The key advantages of this system architecture include:

- High efficiency (> 96%) due to soft-switching and SR techniques.
- Compact design with reduced magnetic and filter component size.
- High power density suitable for vehicle integration.
- Low electromagnetic interference (EMI) and improved thermal performance.
- Scalability for various battery voltage levels (200 V–450 V).

In operation, the system maintains stable DC output across wide load conditions, ensuring safe and efficient charging of the EV battery. The resonant-enhanced full-bridge LLC converter with synchronous rectification represents a major step forward in the evolution of onboard chargers, aligning with the industry’s goals of faster charging, energy efficiency, and enhanced vehicle-grid integration.

1.4 Objective

➢ To design and model a Full-Bridge LLC Resonant Converter suitable for medium-to- high-power EV onboard charging systems, ensuring optimal power transfer and minimal energy loss.

➢ To develop an accurate LLC resonant tank configuration by selecting appropriate resonant and magnetizing inductances and capacitances to achieve Zero Voltage Switching (ZVS) on the primary side and Zero Current Switching (ZCS) on the secondary side.

➢ To integrate Synchronous Rectification (SR) in the secondary stage to minimize diode forward voltage drop, enhance conversion efficiency, and improve thermal performance under varying load conditions.

➢ To implement and analyze frequency modulation control for regulating output voltage and ensuring stable performance across a wide load and input range.

➢ To evaluate the performance parameters such as efficiency, output voltage regulation, switching stress, and thermal behavior through simulation and hardware validation.

➢ To achieve an overall system efficiency greater than 96%, ensuring compactness, lower EMI, and superior reliability suitable for next-generation EV charging platforms.

CHAPTER 2

LITERATURE SURVEY

1) **On-Board Chargers for Electric Vehicles: A Comprehensive Performance and Efficiency Review** — A. R. Dar — *2024*

A broad review of OBC topologies, components, and trends; compares PFC front- ends and DC-DC stages, highlights the rise of LLC resonant converters and synchronous rectification, and discusses bidirectional (V2G/V2L) requirements and efficiency benchmarks for modern EV chargers.

2) **A High-Efficiency Design Method of LLC Resonant Converter for PHEV Battery Chargers Based on Time-Domain Model** — C. Shen (and coauthors) — *2020*

Presents a time-domain design methodology for LLC resonant converters applied to PHEV/OBC use; provides element-sizing steps and demonstrates a lab prototype (multi-voltage range) with experimentally validated high efficiency and ZVS operation.

3) **Analysis and Design of LLC Resonant Converter with PFM Control for Wide Gain Range** — Y. Wei et al. — *2020*

Examines pulse-frequency modulation (PFM) control for LLC converters to achieve a wide regulation range; develops small-signal models and design guidance for maintaining ZVS and stable regulation across battery voltage extremes.

4) **Synchronous Rectification of LLC Resonant Converters Based on Resonant- Inductor Voltage (RLV-SR)** — Z. Luo (Luo & Wu) — *2023*

Proposes an RLV-based synchronous-rectifier driving method that is sensorless (no current sensors), robust to rectifier parasitics, and improves light-load and full-load SR timing — demonstrated with simulations and experimental validation.

5) **LLC DC-DC Converter Performances Improvement for Bidirectional Electric Vehicle Charger Application** — H. Al Attar — *2021*

Studies isolated bidirectional LLC DC-DC converters for EV chargers, proposing control and design modifications to preserve soft-switching in both directions and to improve efficiency across battery voltage/power ranges (supporting V2G/V2L scenarios).

CHAPTER 3

3.1 EXISTING SYSTEM:

Simplified MOSFET loss models often neglect parasitic inductances, assuming ideal switching with perfect zero-voltage switching (ZVS) or zero-current switching (ZCS) and no stray effects. However, in practical power electronic systems, every current path and device package inherently contains small inductances that resist rapid current variations. During switching transitions, these parasitic inductances generate voltage overshoots following the relation

$\vartheta = L\frac{di}{dt}$. The energy stored in these inductances interacts with circuit capacitances, producing oscillations or ringing in the voltage and current waveforms. This ringing increases switching losses, device stress, and electromagnetic interference (EMI). In severe cases, voltage overshoots can exceed the MOSFET's rated limits, causing avalanche breakdown and compromising long-term reliability. Additionally, the oscillatory energy disturbs ideal soft- switching conditions, interrupting ZVS or ZCS operation and leading to performance degradation. Consequently, the actual efficiency, thermal performance, and reliability of the converter deviate from simplified analytical predictions. To ensure accurate design and analysis, parasitic inductances—arising from component layout, device packaging, and transformer leakage—must be carefully modeled and minimized in high-frequency resonant converter systems.

3.2 DISADVANTAGE OF EXISTING SYSTEM

- **Underestimated Switching Losses** – Ignoring parasitic inductances leads to lower predicted energy dissipation during transitions than actually occurs.
- **Voltage Overshoot Risk** – Parasitic-induced overshoot can exceed the MOSFET's voltage rating, risking device failure.
- **Invalid ZVS/ZCS Assumptions** – Extra energy from parasitics can prevent zero- voltage or zero-current switching, defeating soft-switching benefits.
- **Increased Electromagnetic Interference (EMI)** – Ringing caused by L–C resonances generates high-frequency noise that is not predicted by simplified models.
- **Thermal Stress Misestimation** – Overlooked losses and ringing can raise device temperature, reducing reliability and lifespan.
- **Poor Layout Guidance** – Simplified models ignore loop inductances, leading to design decisions that may exacerbate overshoot, ringing, and switching stress in hardware.

3.3 ROPOSED SYSTEM

The proposed Resonant-Enhanced Full-Bridge LLC Onboard Charger with Synchronous Rectification offers multiple performance advantages over traditional hard-switched topologies. The resonant tank enables zero-voltage or zero-current switching (ZVS/ZCS) during MOSFET transitions, drastically reducing switching energy and reverse-recovery stress compared with conventional phase-shifted full-bridge converters. This, combined with synchronous rectification at the secondary, leads to higher overall efficiency, typically improving system efficiency by 1–3% or more depending on device selection, as switching losses are minimized and energy from clamp/snubber circuits is partially recovered.

Additionally, the reduced switching penalties allow operation at higher effective switching frequencies, enabling smaller magnetics with fewer transformer turns and smaller filter components, which increases power density and reduces system volume and weight. The gentler resonant transitions lower dv/dt and di/dt, reducing both conducted and radiated electromagnetic interference (EMI) and simplifying filter design and EMC compliance.

Finally, the softer switching profile reduces device stress, voltage/current spikes, and thermal cycling, improving the reliability and lifetime of both power semiconductors and magnetic components, making the system well-suited for demanding automotive environments.

3.4 ADVANTAGE OF PROPOSED SYSTEM

- **Much lower switching losses (ZVS/ZCS)**

The resonant tank enables zero-voltage or zero-current switching during MOSFET transitions, drastically reducing switching energy (E_sw) and reverse-recovery stress compared with hard-switching PSFB.

- **Higher overall efficiency (especially at nominal load)**

Reduced switching + recovered clamp/snubber energy and lower diode conduction losses at the secondary (with synchronous rectification) translate into measurable efficiency gains (typical +1–3% or more depending on device choices).

- **Smaller magnetics / higher power density**

By allowing operation at higher effective switching frequencies without large switching loss penalties, you can reduce transformer and filter sizes (fewer turns, smaller core), shrinking volume and weight.

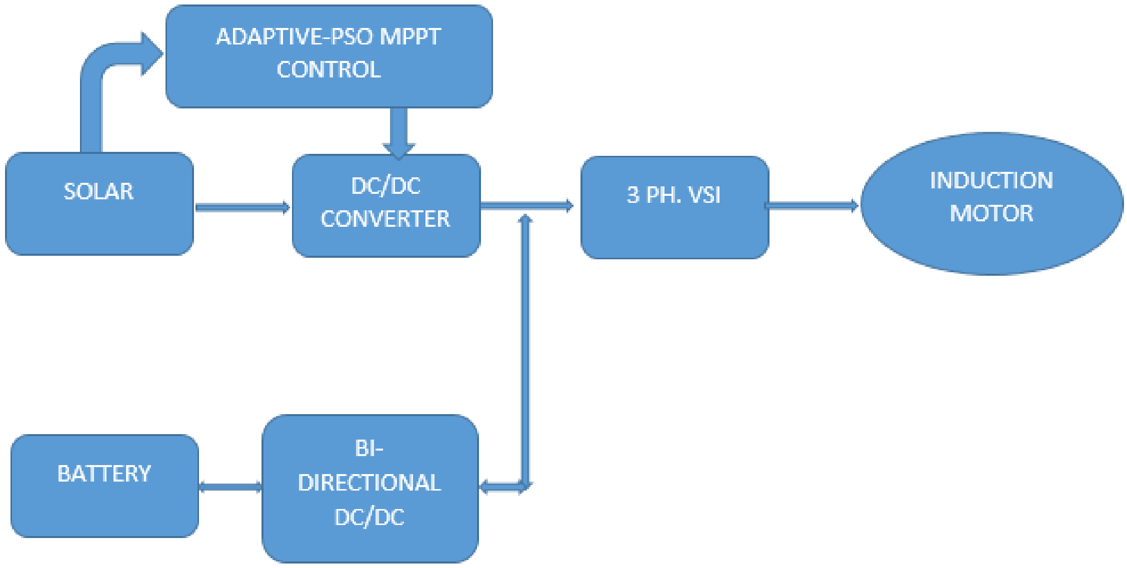
- Reduced **EMI and softer voltage/current transitions**

Resonant transitions are gentler (lower dv/dt and di/dt), which lowers conducted and radiated EMI and eases filter design and EMC compliance.

- Lower **device stress and improved reliability**

Softer switching reduces voltage/current spikes, dV/dt/dI/dt stress and thermal cycling on switches and magnetics — improving lifetime and reliability in automotive environments.

3.5 Block diagram


ADAPTIVE-PSO MPPT CONTROL
SOLAR
DC/DC CONVERTER
3 PH. VSI
INDUCTION MOTOR
BATTERY
BI-DIRECTIONAL DC/DC

CHAPTER 4

HARDWARE DETAILS

4.1 PIC CONTROLLER

High-Performance RISC CPU:

- Only 35 single-word instructions to learn
- All single-cycle instructions except for program branches, which are two-cycle
- Operating speed: DC – 20 MHz clock input DC – 200 ns instruction cycle
- Up to 8K x 14 words of Flash Program Memory, Up to 368 x 8 bytes of Data Memory (RAM), Up to 256 x 8 bytes of EEPROM Data Memory
- Pin out compatible to other 28-pin or 40/44-pin
- PIC16CXXX and PIC16FXXX microcontrollers

Peripheral Features:

- Timer0: 8-bit timer/counter with 8-bit prescaler
- Timer1: 16-bit timer/counter with prescaler, can be incremented during Sleep via external crystal/clock
- Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler
  - Two Capture, Compare, PWM modules
  - Capture is 16-bit, max. resolution is 12.5 ns
  - Compare is 16-bit, max. resolution is 200 ns
- PWM max. resolution is 10-bit
- Synchronous Serial Port (SSP) with SPI™ (Master mode) and I2C™ (Master/Slave)
- Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) with 9-bit address detection
- Parallel Slave Port (PSP) – 8 bits wide with external RD, WR and CS controls (40/44- pin only)
- Brown-out detection circuitry for Brown-out Reset (BOR)

Analog Features:

- 10-bit, up to 8-channel Analog-to-Digital Converter (A/D)
- Brown-out Reset (BOR)
- Analog Comparator module with:

- Two analog comparators
- Programmable on-chip voltage reference (VREF) module
- Programmable input multiplexing from device inputs and internal voltage reference
- Comparator outputs are externally accessible

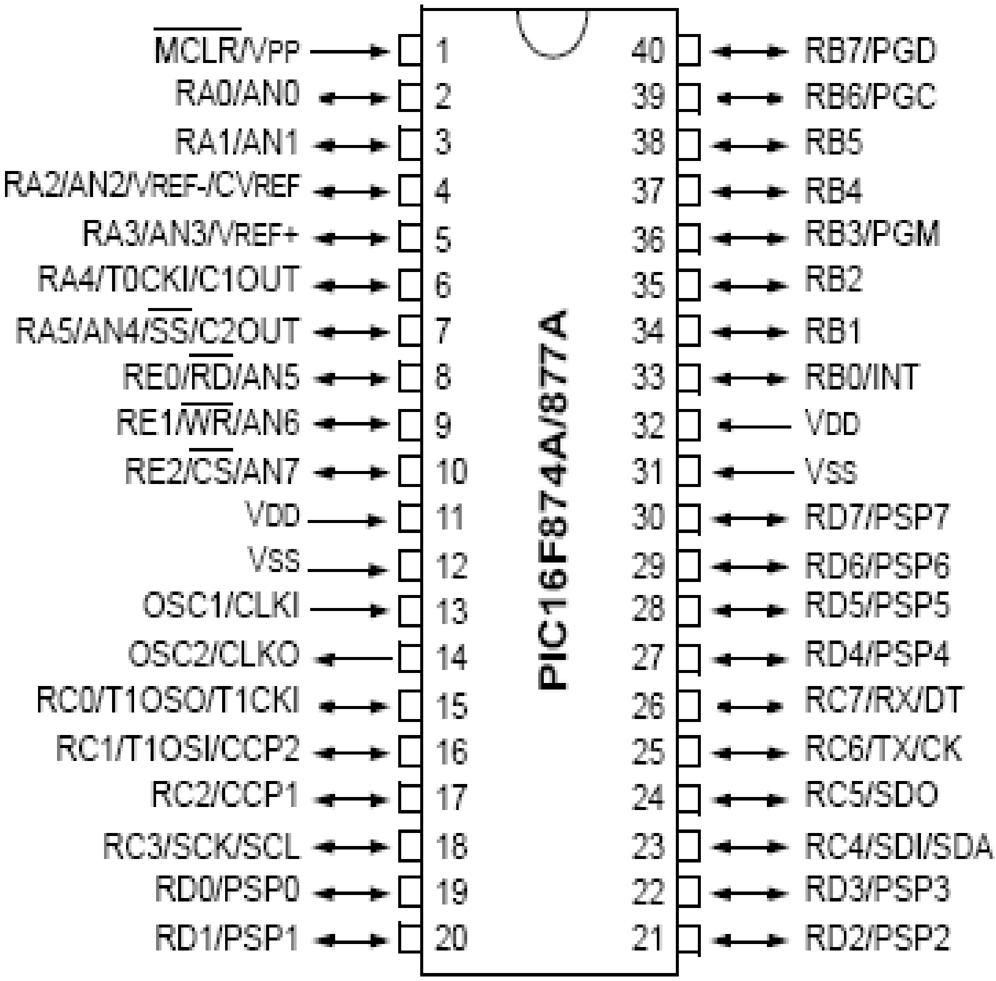
Special Microcontroller Features:

- 100,000 erase/write cycle Enhanced Flash program memory typical
- 1,000,000 erase/write cycle Data EEPROM memory typical
- Data EEPROM Retention > 40 years
- Self-reprogrammable under software control
- In-Circuit Serial Programming™ (ICSP™) via two pins
- Single-supply 5V In-Circuit Serial Programming
- Watchdog Timer (WDT) with its own on-chip RC oscillator for reliable operation
- Programmable code protection
- Power saving Sleep mode
- Selectable oscillator options
- In-Circuit Debug (ICD) via two pins

CMOS Technology:

- Low-power, high-speed Flash/EEPROM technology
- Fully static design
- Wide operating voltage range (2.0V to 5.5V)
- Commercial and Industrial temperature ranges
- Low-power consumption

Pin Digram:



DEVICE OVERVIEW:

This document contains device specific information about the following devices:

- PIC16F873A
- PIC16F874A
- PIC16F876A
- PIC16F877A

PIC16F873A/876A devices are available only in 28-pin packages, while PIC16F874A/877A devices are available in 40-pin and 44-pin packages. All devices in the PIC16F87XA family share common architecture with the following differences:

- The PIC16F873A and PIC16F874A have one-half of the total on-chip memory of the PIC16F876A and

PIC16F877A

- The 28-pin devices have three I/O ports, while the 40/44-pin devices have five
- The 28-pin devices have fourteen interrupts, while the 40/44-pin devices have fifteen
- The 28-pin devices have five A/D input channels, while the 40/44-pin devices have eight
- The Parallel Slave Port is implemented only on the 40/44-pin devices

The available features are summarized in Table 1-1. Block diagrams of the PIC16F873A/876A and PIC16F874A/877A devices are provided in Figure 1-1 and Figure 1- 2, respectively. The pin outs for these device families are listed in Table 1-2 and Table 1-3. Additional information may be found in the PICmicro® Mid-Range Reference Manual (DS33023), which may be obtained from your local Microchip Sales Representative or downloaded from the Microchip web site. The Reference Manual should be considered a complementary document to this data sheet and is highly recommended reading for a better understanding of the device architecture and operation of the peripheral modules.

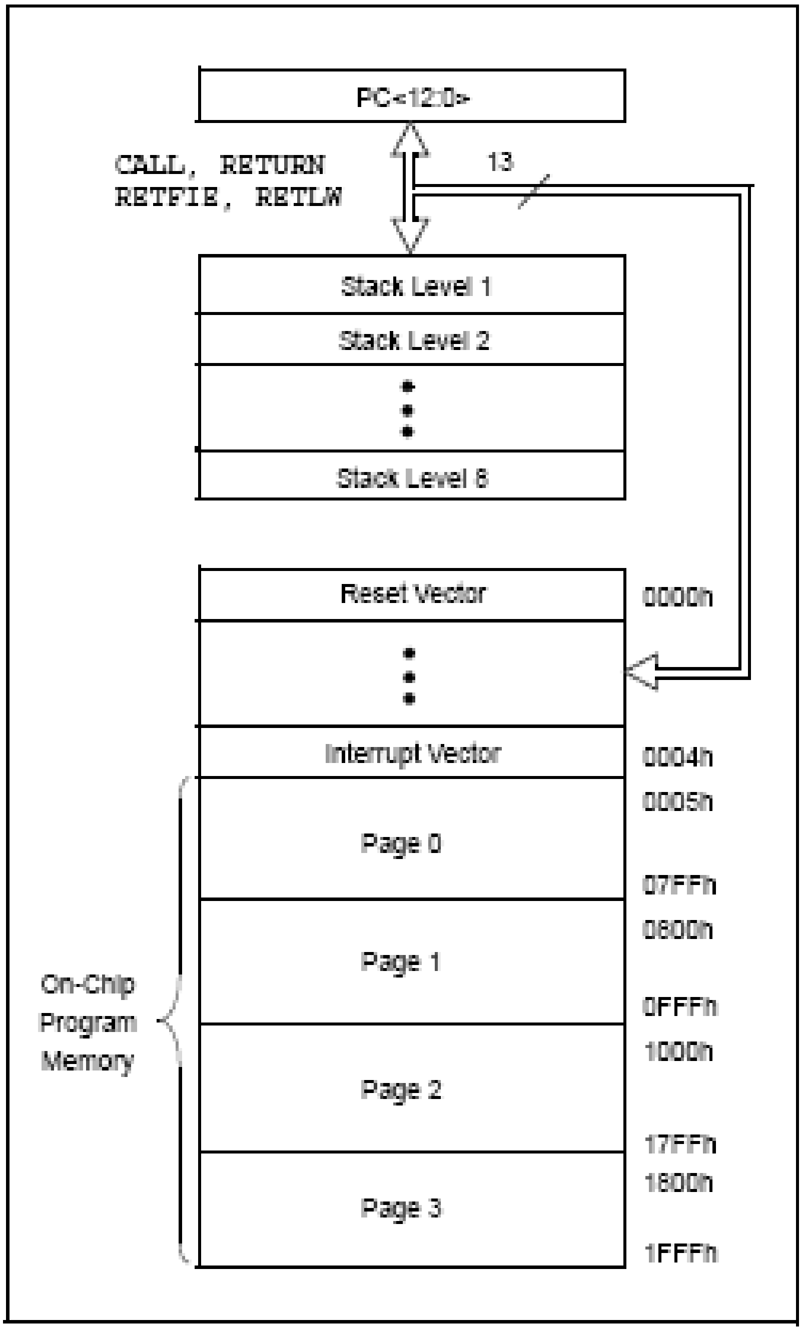
Memory Organization:

There are three memory blocks in each of the PIC16F87XA devices. The program memory and data memory have separate buses so that concurrent access can occur and is detailed in this section. The EEPROM data memory block is detailed in **Section 3.0 "Data EEPROM and Flash Program Memory"**. Additional information on device memory may be found in the PICmicro® Mid-Range MCU Family Reference Manual (DS33023).

Program Memory Organization:

The PIC16F87XA devices have a 13-bit program counter capable of addressing an 8K word x 14 bit program memory space. The PIC16F876A/877A devices have 8K words x 14 bits of Flash program memory, while PIC16F873A/874A devices have 4K words x 14 bits. Accessing a location above the physically implemented address will cause a wraparound. The Reset vector is at 0000h and the interrupt vector is at 0004h.

PROGRAM MEMORY MAP
AND STACK



Data Memory Organization:

The data memory is partitioned into multiple banks which contain the General Purpose Registers and the Special Function Registers. Bits RP1 (Status<6>) and RP0 (Status<5>) are the bank select bits. Each bank extends up to 7Fh (128 bytes). The lower locations of each bank are reserved for the Special Function Registers. Above the Special Function Registers are General Purpose Registers, implemented as static RAM. All implemented banks contain Special Function Registers. Some frequently used Special Function Registers from one bank may be mirrored in another bank for code reduction and quicker access.

I/O PORTS:

Some pins for these I/O ports are multiplexed with an alternate function for the peripheral features on the device. In general, when a peripheral is enabled, that pin may not be used as a general purpose I/O pin. Additional information on I/O ports may be found in the PICmicro™ Mid-Range Reference Manual (DS33023).

PORTA and the TRISA Register:

PORTA is a 6-bit wide, bidirectional port. The corresponding data direction register is TRISA. Setting a TRISA bit (= 1) will make the corresponding PORTA pin an input (i.e., put the corresponding output driver in a High-Impedance mode). Clearing a TRISA bit (= 0) will make the corresponding PORTA pin an output (i.e., put the contents of the output latch on the selected pin). Reading the PORTA register reads the status of the pins, whereas writing to it will write to the port latch. All write operations are read-modify-write operations. Therefore, a write to a port implies that the port pins are read; the value is modified and then written to the port data latch. Pin RA4 is multiplexed with the Timer0 module clock input to become the RA4/T0CKI pin. The RA4/T0CKI pin is a Schmitt Trigger input and an open-drain output. All other PORTA pins have TTL input levels and full CMOS output drivers. Other PORTA pins are multiplexed with analog inputs and the analog VREF input for both the A/D converters and the comparators. The operation of each pin is selected by clearing/setting the appropriate control bits in the ADCON1 and/or CMCON registers. The TRISA register controls the direction of the port pins even when they are being used as analog inputs. The user must ensure the bits in the TRISA register are maintained set when using them as analog inputs.

PORTB and the TRISB Register:

PORTB is an 8-bit wide, bidirectional port. The corresponding data direction register is TRISB. Setting a TRISB bit (= 1) will make the corresponding PORTB pin an input (i.e., put the corresponding output driver in a High-Impedance mode). Clearing a TRISB bit (= 0) will make the corresponding PORTB pin an output (i.e., put the contents of the output latch on the selected pin). Three pins of PORTB are multiplexed with the In-Circuit Debugger and Low- Voltage Programming function: RB3/PGM, RB6/PGC and RB7/PGD. The alternate functions of these pins are described in **"Special Features of the CPU"**. Each of the PORTB pins has a weak internal pull-up. A single control bit can turn on all the pull-ups. This is performed by clearing bit RBPU (OPTION_REG<7>). The weak pull-up is automatically turned off when the port pin is configured as an output. The pull-ups are disabled on a Power-on Reset.

This interrupt can wake the device from Sleep. The user, in the Interrupt Service Routine, can clear the interrupt in the following manner:

a) Any read or write of PORTB. This will end the mismatch condition.

b) Clear flag bit RBIF.

A mismatch condition will continue to set flag bit RBIF. Reading PORTB will end the mismatch condition and allow flag bit RBIF to be cleared. The interrupt-on-change feature is recommended for wake-up on key depression operation and operations where PORTB is only used for the interrupt-on-change feature. Polling of PORTB is not recommended while using the interrupt-on-change feature. This interrupt-on-mismatch feature, together with software configurable pull-ups on these four pins, allow easy interface to a keypad and make it possible for wake-up on key depression.

PORTC and the TRISC Register:

PORTC is an 8-bit wide, bidirectional port. The corresponding data direction register is TRISC. Setting a TRISC bit (= 1) will make the corresponding PORTC pin an input (i.e., put the corresponding output driver in a High-Impedance mode). Clearing a TRISC bit (= 0) will make the corresponding PORTC pin an output (i.e., put the contents of the output latch on the selected pin). PORTC is multiplexed with several peripheral functions (Table 4-5). PORTC pins have Schmitt Trigger input buffers. When the I2C module is enabled, the PORTC<4:3> pins can be configured with normal I2C levels, or with SMBus levels, by using the CKE bit (SSPSTAT<6>).

When enabling peripheral functions, care should be taken in defining TRIS bits for each PORTC pin. Some peripherals override the TRIS bit to make a pin an output, while other peripherals override the TRIS bit to make a pin an input. Since the TRIS bit override is in effect while the peripheral is enabled, read-modify write instructions (BSF, BCF, and XORWF) with TRISC as the destination, should be avoided. The user should refer to the corresponding peripheral section for the correct TRIS bit settings.

PORTD and TRISD Registers:

PORTD is an 8-bit port with Schmitt Trigger input buffers. Each pin is individually configurable as an input or output. PORTD can be configured as an 8-bit wide microprocessor port (Parallel Slave Port) by setting control bit, PSPMODE (TRISE<4>). In this mode, the input buffers are TTL.

PORTD Functions:

Name	Bit#	Buffer Type	Function
RD0/PSP0	bit 0	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 0.
RD1/PSP1	bit 1	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 1.
RD2/PSP2	bit2	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 2.
RD3/PSP3	bit 3	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 3.
RD4/PSP4	bit 4	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 4.
RD5/PSP5	bit 5	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 5.
RD6/PSP6	bit 6	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 6.
RD7/PSP7	bit 7	ST/TTL(1)	Input/output port pin or Parallel Slave Port bit 7.

PORTE and TRISE Register:

PORTE has three pins (RE0/RD/AN5, RE1/WR/AN6 and RE2/CS/AN7) which are individually configurable as inputs or outputs. These pins have Schmitt Trigger input buffers. The PORTE pins become the I/O control inputs for the microprocessor port when bit PSPMODE (TRISE<4>) is set. In this mode, the user must make certain that the TRISE<2:0> bits are set and that the pins are configured as digital inputs. Also, ensure that ADCON1 is configured for digital I/O. In this mode, the input buffers are TTL.

Register 4-1 shows the TRISE register which also controls the Parallel Slave Port operation. PORTE pins are multiplexed with analog inputs. When selected for analog input, these pins will read as '0's. TRISE controls the direction of the RE pins, even when they are being used as analog inputs. The user must make sure to keep the pins configured as inputs when using them as analog inputs.

4.2 Crystal Oscillator

Crystal Oscillator is an Electronics Oscillator circuit which uses the mechanical resonance of a vibrating crystal of piezoelectric material to generate an electrical signal with an accurate frequency. It also has automatic amplitude control and frequency drift is also very low due to change in temperature. Crystal Oscillators are only suitable for high-frequency application.

Every microcontroller needs a **crystal oscillator**, whenever selecting a crystal oscillator try to purchase silicon oscillator if the accuracy is adequate and the cost is also acceptable, otherwise choose quartz crystal.

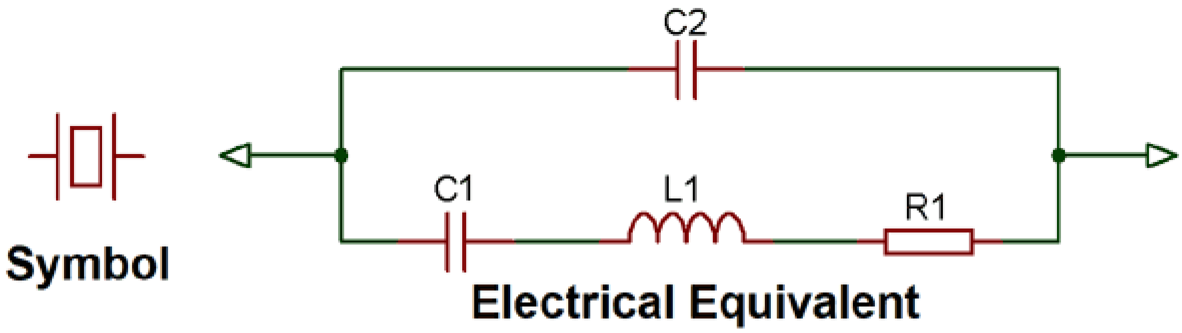
Popular Crystal Oscillators

8MHz, 11.0592MHz, 12MHz, 16MHz, 20MHz, 32MHz

There are many other crystal oscillators available in the market with a different frequency.

lectrical Equivalents

A crystal oscillator is a piezoelectric device used to convert electrical energy to mechanical energy. The conversion occurs at resonant frequency. The simplified electrical equivalent of crystal oscillator is given below:



Crystal oscillator works on the principle of the Inverse Piezoelectric Effect, the applied electrical field will generate a mechanical distortion across some material. Therefore, it utilizes the vibrating crystal's mechanical resonance, which is made through a piezoelectric material for generating an electrical signal of a certain frequency.

Series Resonant Frequency

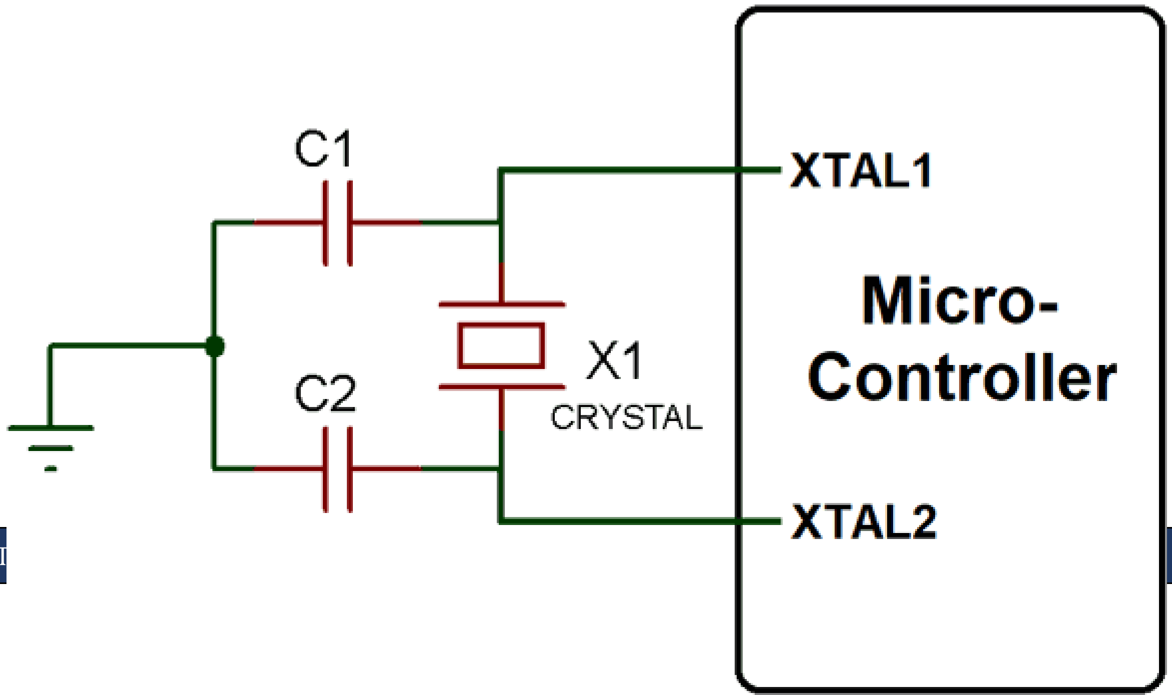
fs=1 / 2π√(L1C1)

Parallel Resonant Frequency

fp=1/ 2π√(C1C2 / C1+C2)

Crystal Oscillator with Micro-controller

The clock source used for microcontrollers are based on mechanical resonant devices such as crystal oscillator.



All microcontrollers have particular pins for connecting crystal oscillator. The pins generally named as XTAL1 and XTAL2, here the connection of crystal oscillator with micro-controller is given below:

The reason for using two capacitors in series with crystal oscillator is to resonate with the crystal inductance which cause the crystal to oscillate on its fundamental parallel resonant mode.

There are some factors which affect the frequency stability of an oscillator like variation in temperature, load and supply.

Applications

- Used in frequency synthesizers
- Used in special types of receivers
- Used as crystal clock in microprocessors
- Colpitts Crystal Oscillator Application
- Armstrong Crystal Oscillator
- Military and Aerospace
- Radio and TV transmitters

4.3 Regulator

For every electronic device, the regulated power supply is essential because these devices use semiconductor material with a fixed rate of voltage and current. If there is any difference in the fixed rate of voltage and current, then the device will get damage. Batteries are one of the main DC supply sources but we cannot use battery over time in sensitive electronic circuits as they lose their potential & drain out ultimately. The batteries provide different voltage ranges like 1.2 Volts, 3.7 Volts, 9 Volts, and 12 Volts. Most of the integrated circuits work with 5V supply therefore we require a device to supply a reliable 5V Supply called voltage regulator. Here, a 7805 voltage regulator comes from 78XX series of the linear voltage regulators. This regulator generates 5V regulated output.

What is a Voltage Regulator?

The voltage regulator is one kind of electrical component used to maintain a stable voltage across any electronic device. The fluctuations in the voltage can cause an undesirable cause in an electronic system. For that, maintaining a stable voltage is compulsory based on the system voltage requirement.

For instance, a simple LED uses a maximum of 3V. Once the voltage increases than this voltage, then the diode will get damage. Similarly, in all the electrical and electronic components, it is common. Once the voltage increases, all the components in the system will get damaged. To overcome this situation, a voltage regulator is used to provide a regulated power supply.

What is the 7805 Voltage Regulator?

Definition: IC 7805 is a linear voltage regulator and it includes three terminals including 5V of the fixed output voltage. This voltage is used in a variety of applications. At present, the manufacturing of this voltage regulator can be done by different manufacturing companies like STMicroelectronics, ON Semiconductor, Texas Instruments, Infineon Technologies, Diodes incorporated, etc. These ICs are available in different packages namely TO-3, TO- 220, TO-263, and SOT-223. But the most frequently used package is TO-220.

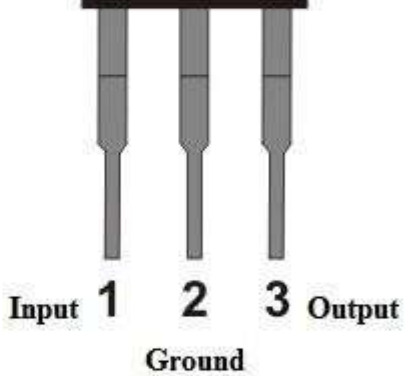
The equivalent ICs of this voltage regulator are IC LM7809, IC LM7806, IC LM317, IC LM7905, IC XC6206P332MR & IC LM117V33.

Features

The main features of the IC 7805 voltage regulator include t following.

- It uses fewer components to work properly.
- It delivers the current up to 1.5 A.
- Thermal shut down & internal current limiting.
- Minimum & maximum input voltages are 7V & 25V.
- The operating current is 5mA.
- Protection of short circuit and thermal overload.
- The highest junction temperature is 125 degrees Celsius.
- It is available in KTE and TO-220 package. Pin Diagram

The **pin diagram of the 7805 voltage regulator** is discussed below. This voltage regulator includes three pins namely input pin, ground pin, and output pin. Each pin and its function can be discussed below.

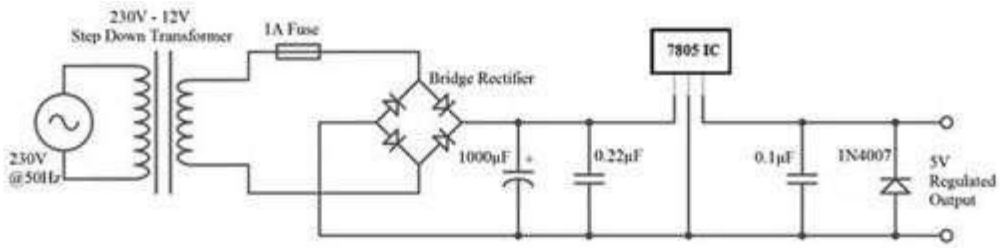


7805 Voltage Regulator Pin Diagram

- Pin1 (Input): This is an input pin, where a positive unregulated voltage can be given like an input toward this pin.
- Pin2 (Ground): This is the GND pin where this pin is common to both input & output.
- Pin3 (Output): This is the output pin where the 5V of regulated voltage can be taken at this pin.

7805 Voltage Regulator Circuit

The circuit diagram of the 7805 voltage regulator is shown below. This circuit generates a 5V regulated supply from AC mains. This circuit can built with a step-down transformer (230V-12V), bridge rectifier, Fuse 1A, Capacitor-1000µF, IC 7805-voltage regulator, capacitors- 0.22µF & 0.1µF, diode 1N4007.



7805 Voltage

Regulator Circuit

IC 7805 Voltage Regulator Working

In the above circuit, the AC power supply is converted into DC. This circuit is designed with a transformer, a bridge rectifier, IC 7805linear voltage regulator otherwise capacitors. This circuit is divided into two portions wherein the first portion of the circuit, the AC mains can be changed into DC. In the second portion, this DC can be changed into regulated 5V DC. At first, a step-down transformer is used to step down the voltage from 230V to 12V by connecting its primary winding to the mains supply. The secondary winding of the transformer can be connected to bridge rectifier

A 1A fuse is arranged in between the bridge rectifier and the transformer to stop the flow of current that is drawn through the 1A circuit. The bridge rectifier generates a rectified DC that is smoothened using 1000µF Capacitor. So, the output of the 1000µF capacitor is 12V unregulated DC. This DC can be given used like an input to the IC 7805 voltage regulator.

After that, this regulator changes regulated 5V DC & the o/p is attained at its o/p terminals. In the above circuit, the input voltage must be higher compare with the o/p voltage. The I/O currents are nearly the same. Once the 7.5V 1A supply can be given at i/p, then the o/p will be 5V 1A. The residual power can be dissipated like heat using the 7805 IC.

Heat Dissipation in IC 7805

In this kind of regulator, huge energy can be exhausted in heat form. The disparity in the input & output voltage will generate heat. So, if the difference in the voltage is high, then there will be a high generation of heat. So a heat sink is used with IC 7805 otherwise surplus heat will be the reason for malfunction.

Advantages

The **advantages of the IC 7805 voltage regulator** include the following.

- This does not need any component to handle its output voltage.
- In includes built-in protection to protect from the overvoltage.
- A heat sink can be used through the GND terminal to protect the IC from high current or short circuits.

7805 Voltage Regulator Applications

The applications of 7805IC include in a wide range of electrical and electronic circuits like the following.Changeable Output Regulator

- Permanent O/P Regulator
- Current Regulator
- DC Voltage Regulator
- Reverse Bias based Projection Circuit
- Inductance Meter
- Phone Charger
- Portable CD Player
- Extension of IR remote control
- UPS power supply circuits.
- Used as +5V voltage regulator

Thus, this is all about an overview of the 7805 voltage regulator. These are used in various electronic circuits to provide a stable o/p voltage for a different i/p voltage. So this IC can be used in most of the electronic projects. In this IC, 78 signifies a +ve voltage regulator whereas 05 signifies 5V output voltage. So this IC will provide +5V as an output voltage.

Here is a question for you, what are the different types of voltage regulators?

4.3 Rectifier

The W10 is a bridge rectifier diode commonly used for single-phase applications. The maximum input AC RMS voltage of this IC is 700V hence can be used for a broad range of applications. The maximum DC current that this IC can handle is 1.5A. This IC has a reverse breakdown voltage of 1000V and a low forward voltage drop. It has high efficiency and a high surge current capability of 40A. If you are looking for a compact IC for rectification application this can be a good choice.

PINOUT

Pin Number	Pin Name	Pin Description
1	Positive	Positive of Rectified Output
2	AC Input	AC Input
3	Negative	Negative of Rectified Output
4	AC Input	AC Input

FEATURES

- UL Recognized File # E-96005
- Surge overload ratings to 30 amperes peak
- Ideal for printed circuit board
- Reliable low-cost construction technique results in inexpensive product
- High temperature soldering guaranteed: 250°C/10 seconds / 0.375" (9.5mm) lead length at 5 lbs., (2.3 kg) tension

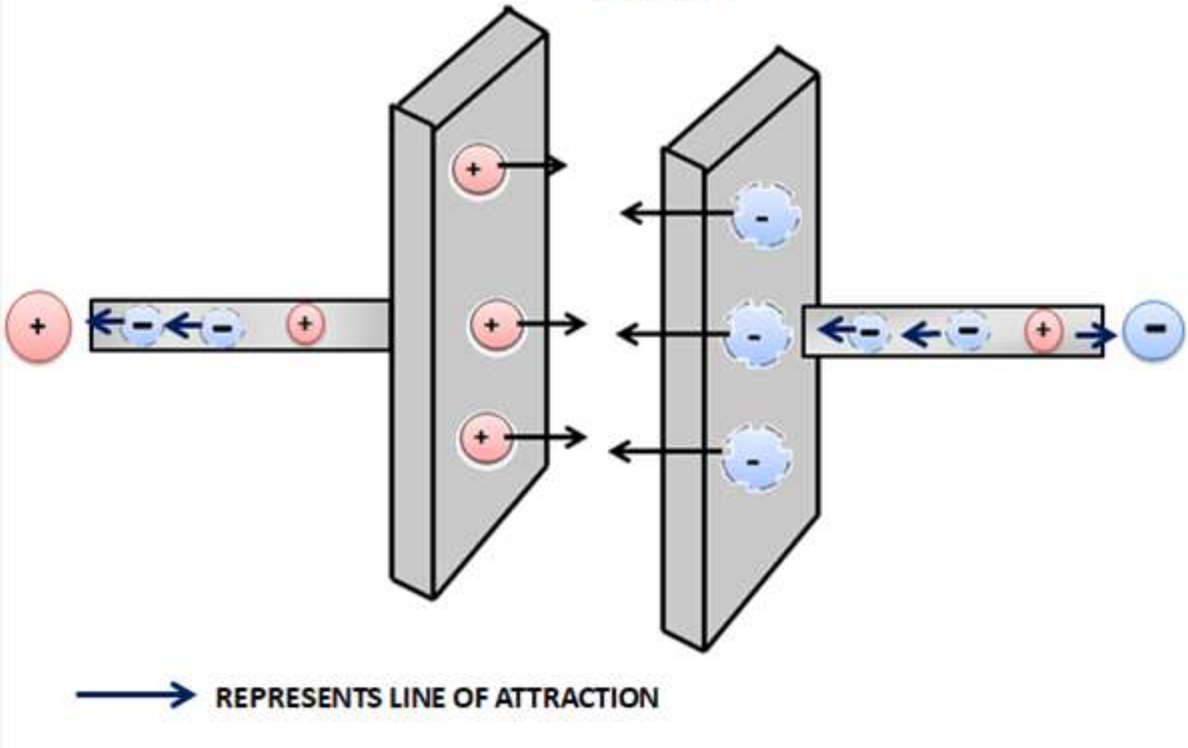
4.4 Capacitors

The word seems to suggest the idea of ***capacity***, which according to the dictionary means ‘the ability to hold something’. That is exactly **what a capacitor does** – it holds electric charge. But what makes it a common component in almost all electronic circuits? Let us break down the stuff behind capacitors to understand what it does and how one could use them in this article.

What is a capacitor?

A capacitor in its most primitive form consists of two conductive plates separated by a dielectric medium. The term dielectric is just a fancy word for an insulator that can be polarized, i.e. form negative and positive charges on opposite faces. When voltage is applied across these two plates, current flows through the conductive plates. One side gets positively charged (lack of electrons) and the other side gets negatively charged (excess electrons). We’re all familiar with the fact that unlike charges attract, so since the plates are oppositely charged, the charges on the plates attract.

Figure 1

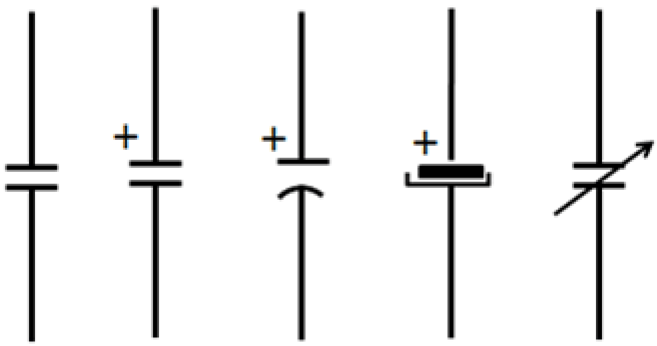


Remember that there's an **insulator** between the plates, so the charges cannot 'flow' to equalize each other and are (ideally) stuck in a state of mutual attraction and stay put. And that is how capacitors carry out their most basic function – retention or storage of charge.

Symbol of Capacitors

Since the capacitors have two parallel metal plates as discussed above, their symbol kind of represents the same. At least it's easy to draw

Figure 2



In a practical case, Capacitors are no longer just two plates with a gap between them, in the case of aluminium electrolytics the two plates take the form of metal foil rolled up with a spacer between them in a tube.

The second set of symbols stand for polarized capacitors, meaning ones which have defined positive and negative terminals by internal design. Accidentally reversing these terminals will almost certainly result in a spectacular failure (especially for larger specimens), ejecting bits of foil and paper meters from the site of failure and most of the time smelling very bad.

Capacitance and Voltage Rating for a Capacitor

Capacitors are measured in **Farads**; it is named after the famous British electrochemist, Michael Faraday. The unit of capacitance, standing in for Coulomb per Volt. The Coulomb (pronounced 'koo-lom') is the S.I. unit for charge, and a Volt, as we know, is the unit for voltage or potential difference. That makes the Farad the amount of charge stored per Volt of potential difference. This simple way of looking mathematically at a capacitor lends itself to a wide range of interpretation, manifested by a lot of deadly complex math equations stuff like integrals and exponents and vectors which we engineers will use while working with capacitors, that is something way beyond the scope of this article. However, we'll get into a little interesting math that'll help us design circuits with capacitors later in the article

Of course, the Farad (one Coulomb per Volt) is a very large unit for most practical purposes (since the Coulomb itself is a rather large amount of charge, as you might already know), so most capacitors (except for very large ones) are measured in microfarads, or one-millionth (0.000001) of a Farad. Suppose you have a capacitor that reads 25V 10uF (the 'u' prefix stands for micro, it's a corruption of the Greek symbol μ ('mu') meaning 'micro') on the plastic outer cover. Since the cap (short in the electronic world for capacitors) is rated for 10uF, it can hold a charge of ten micro coulombs (that is, ten millionths of a Coulomb, 0.000010 C) per volt of voltage across its terminals. That means, at the maximum voltage of 25V, the capacitor can hold a charge of 25V x 10uF, which works out to be 0.000250 Coulombs.

Remember I said 'maximum' voltage. Max voltage is probably the most important rating on the capacitor. It tells you how much voltage a capacitor can handle across its terminals before it goes KABOOM.

Working of a Capacitor

Basically what is happening inside a capacitor is that the insulator between those plates is undergoing a process called 'dielectric breakdown', meaning the insulator can no longer insulate since the voltage across the insulator is too high for it to be able to remain an insulator. The underlying physics is somewhat off scope, but all you need to know to understand why this happens is that no insulator is prefect, that is, up to a certain point. Even the strongest bridge collapses if it is overloaded. What happens here is similar. To reduce breakdown, you might increase the gap between the two plates, but that comes with a trade-off – reduced capacitance, since the plates are further apart and charges do not attract as much as they do when they are closer – much like the way magnets behave.

A good rule of thumb would be to use caps rated for a 50% greater voltage than what your circuit might be expected to see. This leaves a wide safety margin. For example, if you need a cap to decouple (worry not, decoupling is explained later in the article) a 12V power supply rail, you could get away with using a 16V capacitor, but using a 25V capacitor is recommended since it gives you a wide safety margin. Okay you found it out!! Yes 25V is, of course, not 25% greater than 12V, but 18V is not a standard capacitor value - you won't find any with that voltage rating. The nearest is 25V.

Different Types of Capacitors

The reason for the breakdown voltage ranges is because of the material used as a dielectric, which is also the basis on which capacitors are classified:

Aluminium Electrolytic Capacitors

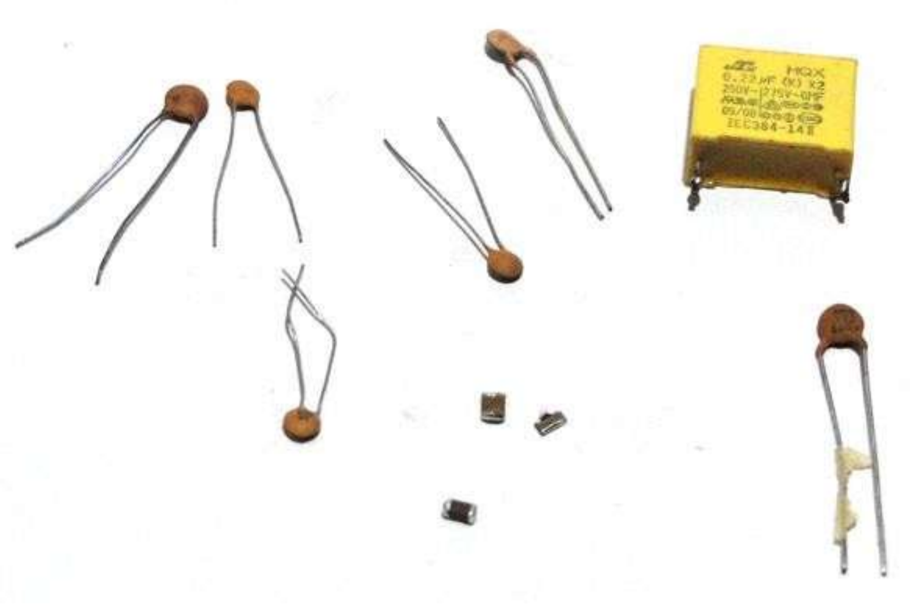
These are probably the most recognizable **types of capacitors**. They come in distinctive metal cans with a plastic sheath, with clearly stated voltage and capacitance ratings and a white band to indicate the cathode. The name comes from the fact that, like mentioned above, the 'plates' are made of chemically etched aluminum foil. The etching process makes the aluminium porous (much like a sponge) and increases its surface area greatly, hence increasing capacitance. The dielectric is a thin layer of aluminium oxide. These capacitors are filled with oil that acts like an electrolyte, hence the name. Electrolytic capacitors are polarized because of their internal construction. They have large capacitance compared to other members of the capacitor family, but much lower voltages. You can expect to see electrolytics between 0.1uF

to monsters like 100mF and with rated voltages of a few volts to around 500V. Their internal resistances, however, tend to be high.

SIDE NOTE: Internal resistance in capacitors is due to the materials which the cap is made of – for example the resistance of the aluminium foil or the resistance of the leads.

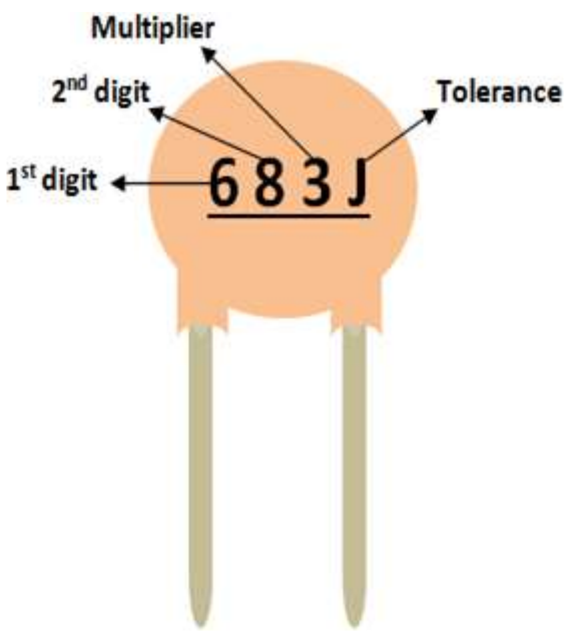
Ceramic Capacitors

These are caps with a ceramic dielectric. Since the breakdown limit for the ceramic dielectric is quite high, you can expect to see ceramic caps with crazy breakdown voltages like 10kV. However, capacitance tend to be low, in the range of picofarads (0.000000000001F) to a few tens of microfarads. They are generally a lot smaller than **other types of capacitors**, as shown in the picture. They also have very small internal resistances.



Identifying Ceramic Capacitors

The value of a ceramic capacitance will not be directly mentioned on the ceramic capacitor. There will always be a three digit number followed by a variable; let's learn how to identify the value using these numbers. Consider the following capacitor.



As you can notice, these three digits are split into two digits and the third one is the multiplier. In this case 68 is the digit and 3 is the multiplier. So 68 should be multiplied with 10^3. Simple put it is 68 followed by 3 zeros. Hence the value of this capacitor will be 68000 pF. Notice the unit should always be pF. Similarly a capacitor with 220 code means it is 22 Pico farad, since 10^0 is 0.

The voltage rating of the capacitor can be found by using the line under this code. If there is a line then the voltage value is 50/100V if there is no line then it is 500V.

The most commonly used capacitor values along with their conversion in Pico Farad, Nano Farad and microfarad is given below.

Code	**Picofarad (pF)**	**Nanofarad (nF)**	**Microfarad (uF)**
100	10	0.01	0.00001
150	15	0.015	0.000015
220	22	0.022	0.000022
330	33	0.033	0.000033
470	47	0.047	0.000047
331	330	0.33	0.00033
821	820	0.82	0.00082
102	1000	1.0	0.001
152	1500	1.5	0.0015
202	2000	2.0	0.002
502	5000	5.0	0.005
103	10000	10	0.01
683	68000	68	0.068

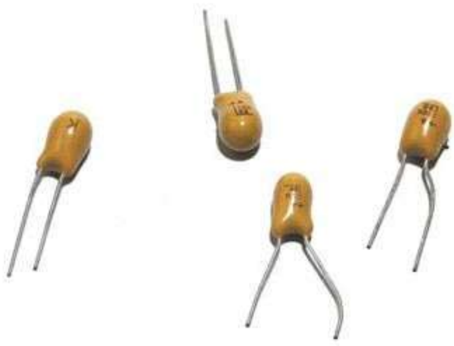
104	100000	100	0.1
154	150000	150	0.15
334	330000	330	0.33
684	680000	680	0.68
105	1000000	1000	1.0
335	3300000	3300	3.3

Film capacitors

As the name suggests, the dielectric in these capacitors is a plastic film, often familiar plastics such as mylar and polyester. They have the same properties as ceramic caps, high breakdown voltages (because of the way the plastic polymers behave) and low capacitances. The only difference is that they tend to be slightly larger though they look superficially like ceramic caps. Internal resistance is comparable to ceramic caps.

Tantalum and Niobium capacitors

These caps technically fall under the electrolytic category of capacitors. Here, the electrolyte is a solid material made of tantalum or niobium oxides. They have very low internal resistance for a given capacitance, however they are less immune to overvoltage compared to other types (ceramic has the best) and tend to go kaput without much warning and with a lot of nasty black smoke.

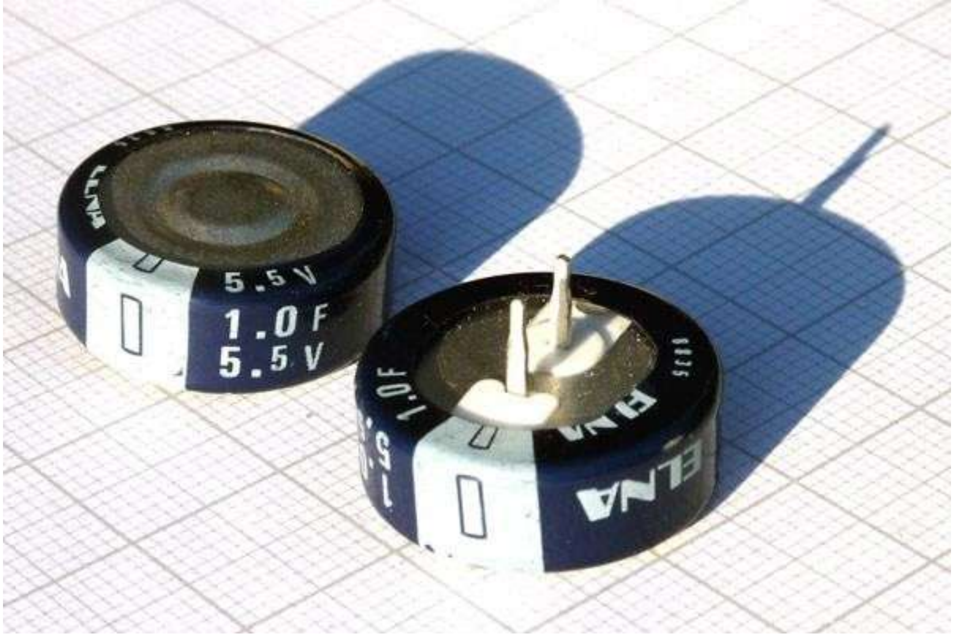


Special purpose capacitors

These include silver – mica caps, X and Y rated caps, etc. X and Y rated capacitors, for example, are built for line filtering – more robust construction and higher voltage ratings, also low capacitances, to reduce the current passing through it if AC voltage is applied and to limit the energy stored in the cap if DC voltage is applied.

Supercapacitors and ultracapacitors

They take capacitors to a whole new level, with largely increased capacitances, sometimes in the range of hundreds of Farads! This is possible because of some clever chemistry. Supercapacitors and ultracapacitors bridge the gap between capacitors and chemical batteries. They come in very low voltages, however.



And those are pretty much all the **common types of capacitors** you might commonly encounter in the world of electronics.

How Capacitors Behave in Circuits

A useful first task would be to learn how to calculate the energy stores in a capacitor, which is given by the formula,

$E = 1/2CV^2$

Where E is the energy stored in Joules, C is the capacitance in Farads and V is the voltage in Volts. Note that this equation takes the form of many other Newtonian equations for energy, a neat easter egg!

Supposing you have a cap rated for a voltage of 50V and with a capacitance of 1000uF, the stored energy at the full 50V would be:

1/2 * 0.001000F * 50V * 50V

Which works out to be a measly 1.25J of stored energy.

This reveals a major **disadvantage of capacitors as energy storage devices** – the stored energy for a given size is very low, a battery of the same size would have at least a thousand times more stored energy! However, caps have greatly lower internal resistances than chemical batteries, which enable them to dump all their stored energy quickly. Shorting a battery would only cause it to heat up because of the power dissipated by the internal resistance, but shorting a capacitor would only create a few sparks since all the charge is dumped at once without damage to the capacitor.

Second, there is another neat formula that relates voltage, current and capacitance: $I/C = dV/dt$

Where I is the current supplied to the capacitor in amps, C is the capacitance in Farads and dV/dt is the rate of change of voltage across the capacitor terminals. Think of this in terms of its unit – volts per second for a given current and capacitance. Don't worry about the little 'd', it's just a mathematical way of saying 'to the limit zero'.

Let's say you have a power supply that spits out a constant voltage of 5V at a constant current of 1mA, then on rearranging the equation we can find the time taken to charge a 100uF capacitor to 5V:

dt = CdV/I

dt = (0.000100F * 5V)/0.001A

dt = 0.5 seconds

So the capacitor would charge up to 5V in 0.5 seconds. (Remember that a capacitor can only charge up to the maximum voltage supplied to it, never more, they cannot magically 'create' voltage.)

This predictable behavior of a capacitor makes it very useful for generating time delays, for example, with a little additional circuitry. You can rearrange the equation to obtain time.

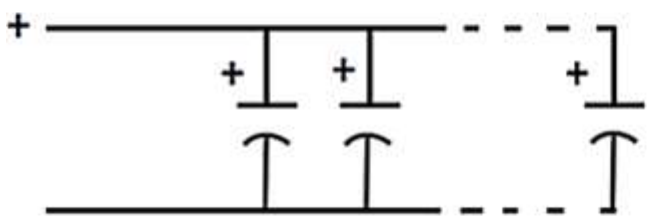
Now for the good stuff – actual capacitor circuits!

Capacitor Behavior in Circuits

Let's begin simple – the different ways capacitors can be connected together. It's much the same as connecting two resistors – you can either connect them in series or parallel.

Capacitors in Parallel

The figure below shows three capacitors connected in parallel, with all the respective positive and negative terminals connected together (assuming the caps are polarized). The total capacitance of this arrangement is simply the sum of all the capacitances of all the capacitors in the circuit. This makes sense, since connecting the capacitor plates in parallel increases the surface area, increasing the capacitance.



The maximum voltage this sort of arrangement can handle is the voltage of the smallest capacitor, since in the voltage is common to all the caps.

An example should clear this up. Supposing you have two capacitors, one with the ratings 25V 470uF and the other 35V 1000uF. The total capacitance would be 470uf + 1000uF = 1470uF. However, the maximum voltage you could put across this bank (a bunch of capacitors connected together can be called a capacitor 'bank') would be just 25V. If you put anything higher than that across this bank, sparks would fly, since you exceed the max. voltage of the 25V capacitor.

Capacitors in series

Connecting capacitors in parallel is particularly useful when you want a large capacitance and you have only small values. Putting together those smaller value caps in parallel will eventually get you the larger value and do the job, assuming you are mindful of voltage.

Now putting capacitors in series is a little more complicated. The capacitance is given by the formula:

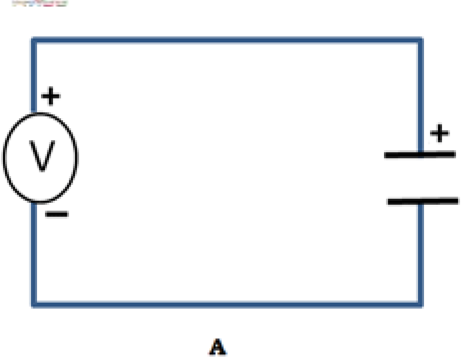
1/Ctotal = 1/C1 + 1/C2 + … + 1/Cn

Where C1, C2…Cn are the capacitances of each capacitor used in the circuit. The voltage the bank can now handle is the sum of all the rated voltages.

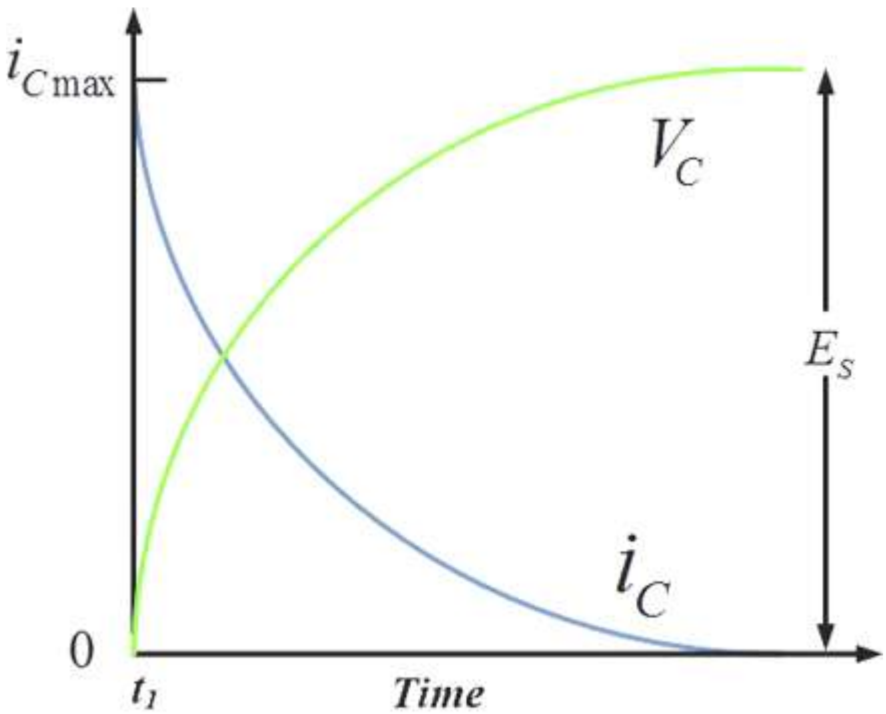
If you're given a cap rated for 10V 1uF and a cap rated for 50V 10uF, then the voltage the bank can handle in series is 10V + 50V = 60V. The capacitance works out to be 0.9091uF.

Capacitor Voltage vs Time

What if we want to charge a capacitor? We could just connect it across a voltage source, like in figure below. What would happen here is that the moment the voltage source is connected, assuming the cap is completely discharged, charges rush to accumulate on the plates, leading to a very large (in theory, infinite!) current spike limited only by the internal resistance of the capacitor. This is not desirable, of course, if your power supply happens to be something like a battery. A sensible idea would be to add a resistor in series with the capacitor and the voltage source to limit the current like in Figure, and voila! You have something engineers call an RC circuit, 'R' for resistor and 'C' for capacitor!



This circuit shows some interesting behavior. When the voltage is connected to the side of the resistor marked 'I', the voltage on the capacitor rises slowly since the current is limited. The graph looks something like this:



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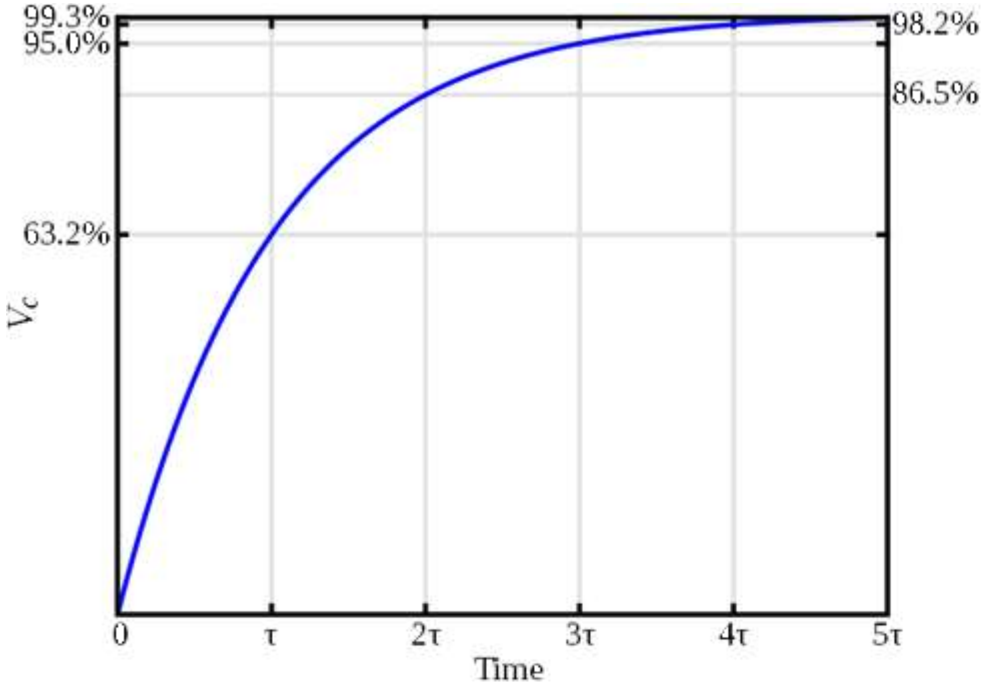
The more mathematically inclined of my viewers would recognize the shape of the slope – it resembles that of the exponential function!

Remember how I said caps could be used to generate time delays? This is one way of doing that without a constant current source (which needs some additional circuitry). Since the time

taken to reach a particular voltage is predictable if we know the capacitance, voltage and resistance, we can create time delay circuits.

The product of resistance and capacitance, RC, is known as the time constant of the circuit. This parameter becomes useful in actually determining the time to reach a given voltage accurately, as shown by the graph figure below.

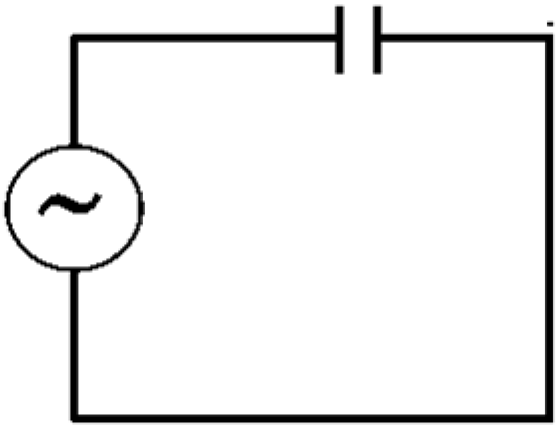


From the graph you can see that the capacitor reaches 63% of the applied voltage in one time constant, and so on.This is the principle the all-season 555 timer uses, though the design equations are a little different.

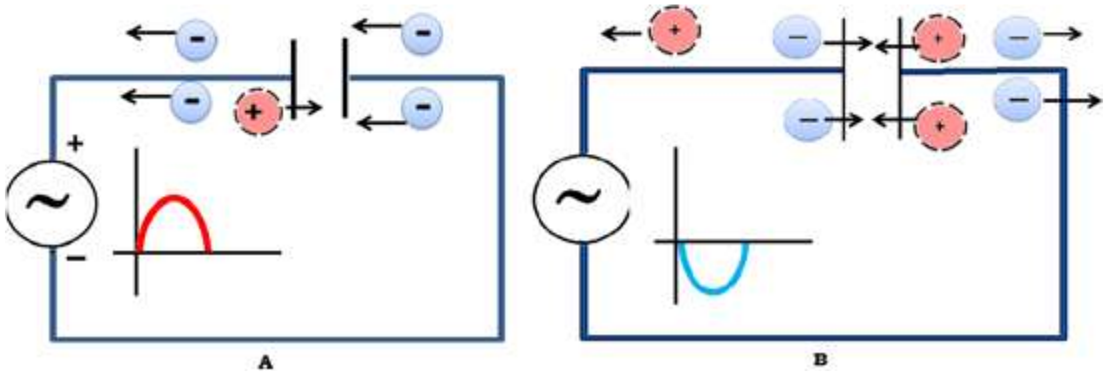
Another interesting application of **RC circuits** is signal filtering, i.e. removing an electrical signal of an unwanted frequency from a circuit. The RC circuit takes a given amount of time to charge and discharge from a source. If we apply a periodic wave with a time period greater than RC, then the same signal would appear on the output with very little distortion. However, on increasing the frequency, the signal keeps changing polarity faster than the circuit can charge and discharge, and eventually after a certain point, the signal vanishes, and all you are left with is clean DC! This is called signal attenuation. As you can see an RC circuit acts like a filter that blocks AC signals (even ones superimposed on DC, i.e. having a DC offset) beyond a certain frequency. This kind of filter is called a low-pass filter, that is, it lets low frequencies pass through but does not let high frequencies through.

Capacitors in Ac circuits

Capacitors behave in an interesting way when placed in AC circuits. They can be thought of as frequency dependent resistors, from the signal point of view. As seen above, the RC circuit blocks all AC from a signal, but what happens when a capacitor is connected in series with an AC voltage source? The exact opposite!



Since the capacitor is just two metal plates separated by an insulator, it does not let any DC current pass through it. However, an Ac signal has constantly changing voltages, so one plate sees a changing voltage and induces the opposite charge on the other plate, as shown in the figure:



This has the overall effect of letting current 'pass' through the capacitor at relatively high frequencies. The addition of a resistor in parallel with the output makes a high-pass filter, i.e. a filter which lets through only high frequencies and blocks all DC signals.

The 'AC resistance', or impedance, of a capacitor, is given by the formula: XC = 1/(2*π*f*C)

Where XC is the capacitive reactance or impedance, f is the frequency and C is the capacitance. You can use this formula to calculate the virtual 'resistance' a capacitor has in an AC circuit.

Where Capacitors are Found in the Wild

Okay, that was enough theory. Let's look into the many **uses of capacitors**.

The first place you might expect to see capacitors are in power supplies of all sorts as filters and for decoupling. They act as charge reservoirs – providing quick current when the load needs it.

Here are two oscilloscope shots that show the effect of not having and having a capacitor across the leads of a power supply. As you can see, having capacitors dramatically reduces the 'noise' on the power supply rails, thus protecting delicate parts from sudden voltage spikes.

They're also called **'decoupling' capacitors**, since they 'decouple' sections of the circuit across which they are mounted from the power supply. Sometimes the power leads on a circuit board might be quite long and have a high inductance and resistance. This can lead to them providing less current than usual. Having a capacitor at the end of the supply line is like having a smaller temporary 'battery' across the device, providing bursts of current when needed and charging up when the device consumes low power.

You can use the formula I/C = dV/dt to calculate the necessary capacitance to remove 'ripple' voltage from the power supply terminals.

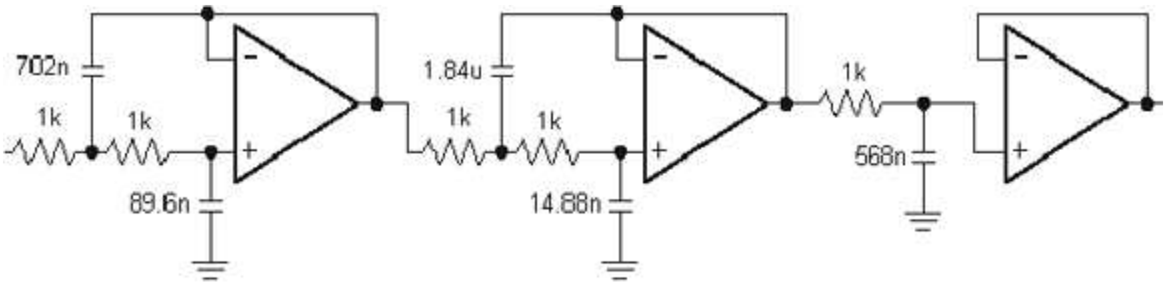
Suppose you have a **power supply** whose voltage varies from 11.5V to 12V (ripple) every 10ms, which is common in mains powered devices due to the 50Hz frequency, and you need to place a cap across the terminals to smooth out the voltage. If the load current in this case is 1A, then we can rearrange the formula this way to find out the capacitance:

(I * dt)/dV

Where I is the load current, dt is the time period of the noise, and dV is the ripple voltage. Substituting the values, we find that we need a capacitance of 20000uF. Now this may seem like a lot, but you could get away with much less. The value obtained only serves as a guideline.

In real life you might find multiple types and values of capacitors across power traces, this is to reduce the noise content across many frequencies and have the smoothest voltage possible.

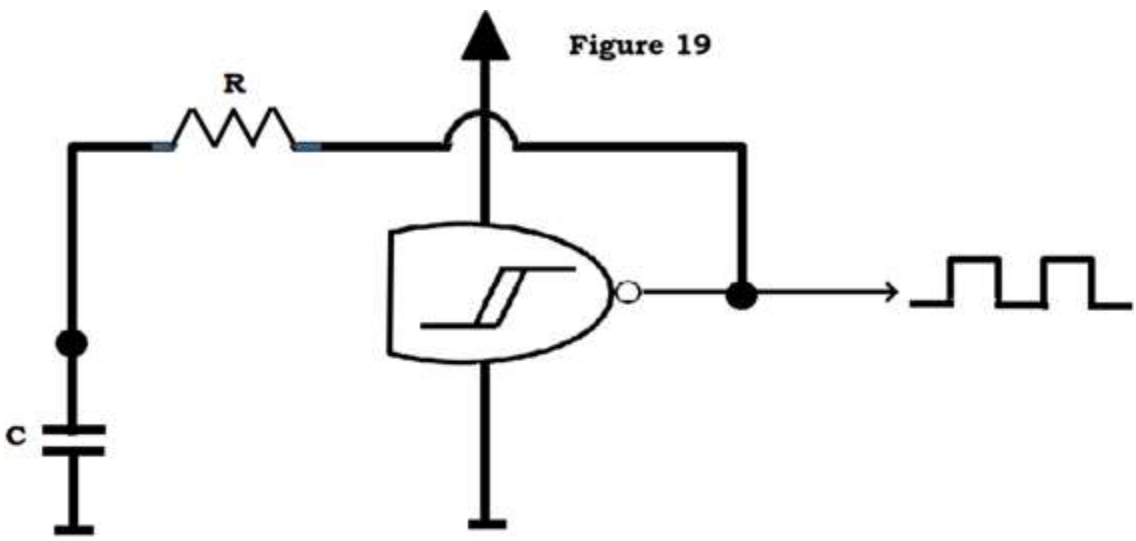
Another use of capacitors are in complicated filters like this one:



But a simpler filter would be the **RC filter**, one interesting filter is described here.

Everyone knows the Arduino microcontroller board. A versatile tool, but haven't you ever wondered why the analog outputs spit out a digital PWM signal? That's because they were designed to be used with an external filtering network to smooth out the PWM voltage to a truly analog voltage. This can be done with parts as simple as a 1K resistor and a 10uF capacitor. Try it!

Another use, like mentioned above, is timing. A simple oscillator can be built using a NAND gate (try figuring out why AND gates won't work), a resistor and a capacitor.



Assuming that there is initially no voltage across the capacitor, the NAND inputs (which are tied together) see close to 0V across them, and turn the output on. The cap now charges through the resistor. When it reaches the 'high' threshold of the gate, the output flips low and the cap now discharges. This cycle continues to produce a square wave output with a frequency dependent on the values of R and C.

Finally, another interesting use of capacitors is energy storage. Of course, capacitors are no match for batteries, but for some applications which need the energy quickly, caps are the best for the job.

Devices like **coilguns** (more can be found on the web) need a large pulse of current to accelerate the projectile, so high voltage capacitors are used for purposes like this, often with ratings such as 450V 1500uF, which can store significant amounts of energy.

4.5 Resistor

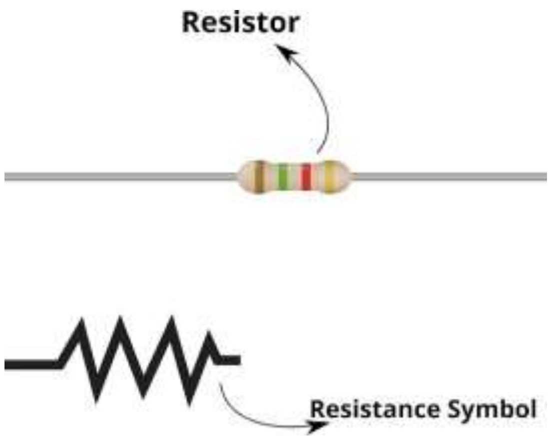
A resistor is a two-terminal passive electrical component that produces opposition in the flow of electric current. They can be found in almost electrical networks and electronic circuits.

- Resistors are electrical devices whose function is determined by their resistance.
- Resistance is the measure of the opposition to current flow in an electric circuit. It is defined as the ease with which electrons enable electricity to flow through them.
- Resistance is the electrical quantity utilized by the resistor to regulate the flow of electrons.
- An insulator has a higher resistance than a conductor.
- The SI unit of resistance is Ohm (Ω).
- The higher multiple and sub-multiple values of Ohm are known as kilo ohms (KΩ), mega ohms (MΩ), and so on.
- An Ohm is a resistance defined as a current flowing through a resistor whose terminals drop one volt when one ampere passes through them.
- The resistivity of a material is equal to the resistance of an object of that material of 1 m length and 1 m^2 area of cross-section.

According to **Ohm's law**, the voltage **V** across a resistor is precisely proportional to the current **I** flowing through it.

As a result, **V = IR**

Where R is the resistance of the resistor.

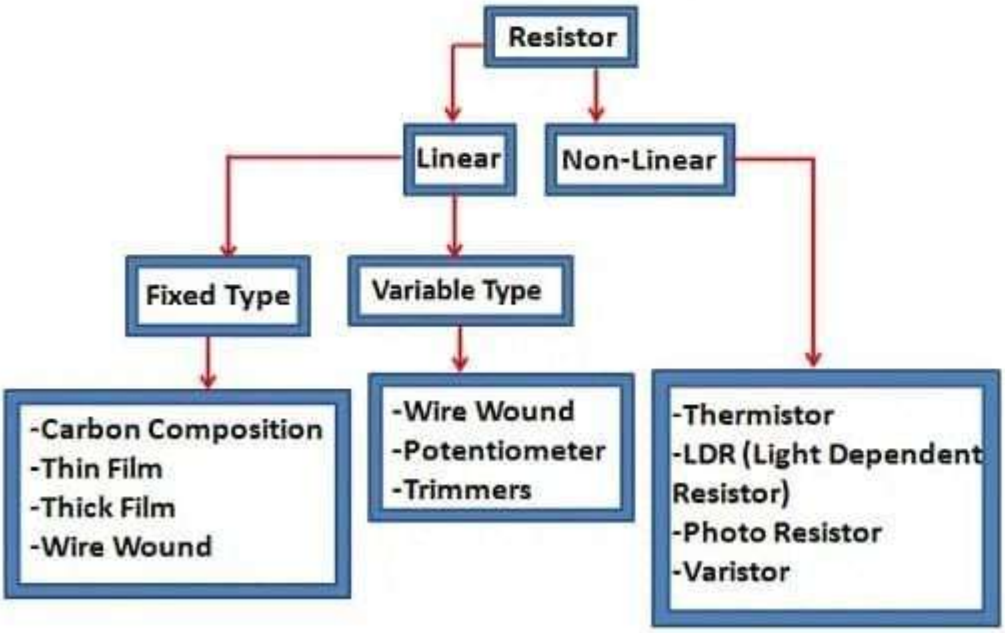


Symbols of Resistor

Types of Resistor

Many different types of resistors are used in electronic circuits. These resistors are classified depending on their manufacture and construction. Resistors are divided into two broad types:

- Linear Resistors
- Non-linear Resistors linear resistors and non-linear resistors.



Different Types of Resistors

Linear Resistors

Linear resistors are resistors whose values change when applied voltage and temperature change. Linear resistors are further classified as:

- **Fixed Resistors:** A Fixed resistor does not vary its resistance value. Its resistance changes slightly with temperature, time, or operating voltage. Carbon composition resistors, Thin film resistors (Carbon film resistors and Metal film resistors), Thick film resistors (Fusible resistors, Cermet film resistors, and Metal oxide resistors), and Wire wound resistors are examples of fixed resistors.
- **Variable Resistors:** A variable resistor is a resistor in which the electric resistance value can be adjusted. PotentiometerTrimmer, Rheostat Resistor, and Trimmer Resistor are the types of Variable Resistors.

Non-Linear Resistors

In non-linear resistors, the electric current flowing through them changes according to the temperature or voltage applied but does not follow Ohm's law. The most commonly used non- linear resistors are Thermistors, Light Dependent resistors (LDR), Photo Resistors, and Voltage-Dependent Resistors (also known as varistors).

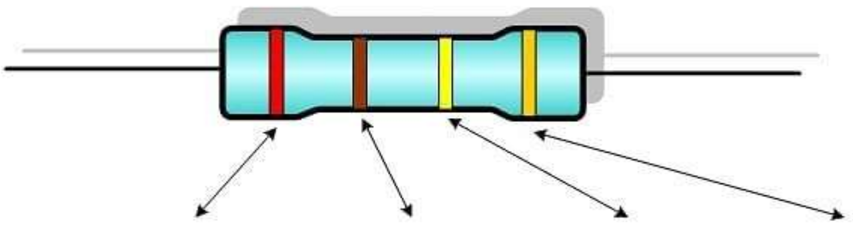
Color Coding of Resistors

[Click Here for Sample Questions]

The resistance value is indicated with several colored bands around the component body of the resistor. This technique of marking developed in the 1920s.

- The significant digit of the resistance value is determined by the first two bands.
- The third band is the multiplying factor
- And the fourth band gives the tolerance. Each color represents a different number and can be looked up in a resistor color code chart.

4-band Resistor



Color	1st band value	2nd band value	Multiplier	Tolerances
Black	0	0	× 1	
Brown	1	1	× 10	± 1%
Red	2	2	× 100	± 2%
Orange	3	3	× 1000	± 3%
Yellow	4	4	× 10,000	± 4%
Green	5	5	× 100,000	± 0.5%
Blue	6	6	× 1,000,000	± 0.25%
Violet	7	7	× 10,000,000	± 0.10%
Grey	8	8	× 100,000,000	± 0.05%
White	9	9	× 1,000,000,000	
Gold			× 0.1	± 5%
Silver			× 0.01	± 10%
No band				± 20%

Color Coding of Resistors

Example: **Brown, Red, Red, Silver**

Brown and Red represent 1 and 2, respectively. Those consist of the first and second digits, so it will be 12. The third band is Red. As a multiplier, it is × 100, therefore, it represents a 1200 ohm resistor. The fourth band, silver, represents the tolerance, so the final expression of the resistance is 1200 ± 10% Ω.

Working Principle of Resistor

he **electrical energy** is absorbed by the resistor in the process of acting as a barrier to the flow of electricity by lowering the voltage, and it is released as heat. Heat dissipation in today's modern circuits is generally a fraction of a **Watt**.

If **I** is the current flowing through the resistor in amperes and **R** is the resistance in ohms, then **V** is the voltage drop imposed by the resistor, **according to Ohm's law**:

$$\mathbf{V = IR}$$

Another way to put it is that when the capacity difference between the ends of the resistor is **1 volt**, the **1Ω** resistor will allow a current of **1 amp**.

In a **DC circuit**, if P is the power wasted by the resistor in watts:

$$\mathbf{V \times I = P}$$

We may represent **power (watts)** in terms of current and resistance by substituting in Ohm's law:

$$\mathbf{P = I^2 / R}$$

Power (watts) can also be expressed in terms of voltage and resistance:

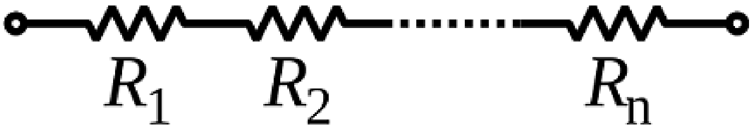
$$\mathbf{P = V^2 \times R}$$

Series and Parallel Circuits

An electrical circuit may have two or more resistors and they can be linked in both series and parallel configurations. A series connection occurs when two resistors are linked in a series path, and the current flowing through them is the same. The voltage across the resistors will be equal to the total voltage across each resistor.

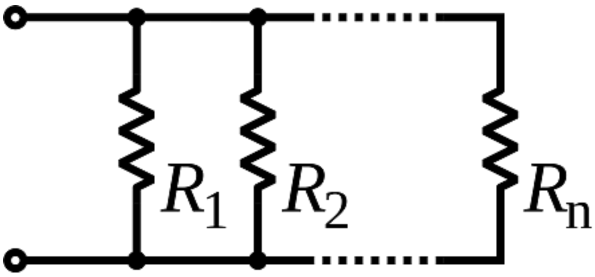
If three resistors $\mathbf{R_1}$, $\mathbf{R_2}$, and $\mathbf{R_3}$ are in a series connection, the overall resistance $\mathbf{R_{(total)}}$, will be:

$$\mathbf{R_{(total)} = R_1 + R_2 + R_3}$$



Resistors in Series

A parallel connection is a series in which the resistors are linked in parallel. The voltage applied across each component remains constant in this case. The sum of the currents flowing through each resistor equals the total current flowing through the series.



Resistors in Parallel If three resistors $\mathbf{R_1}$, $\mathbf{R_2}$, and $\mathbf{R_3}$ are linked in this circuit. The total resistance $\mathbf{R_{(total)}}$ will

be

$\mathbf{1/ R_{total} = (1/ R_1 + 1/ R_2 + 1/ R_3)}$ i.e.,

$\mathbf{R_{total} = (R_1 \times R_2 \times R_3)/ (R_1 + R_2 + R_3)}$

Power Dissipation

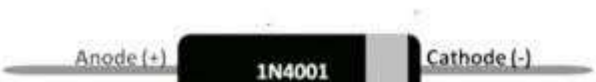
The power dissipation through a resistor is calculated using the equation below.

Power $\mathbf{P = I^2 \times R = V \times I = V^2/R}$

Joule's first law was used to generate the first equation, while Ohm's law was used to derive the other two.

1N4001

The 1N4001 diode belongs to the family of the 1N400x diode series, which are most commonly used in household electronic appliances. It allows the flow of current only in one direction, that is from anode terminal to cathode terminal just like a normal diode. It is referred to as a general-purpose rectifier diode used for rectification purposes. The **1N4001 diode is shown** in the figure below. The grey strike on the diode is used to



identify the cathode terminal.

1N4001 Diode

The current carrying capacity is of maximum 1 Ampere and can tolerate up to a peak value of 30 Amps. This type of silicon diode is mainly used in designing circuits with less than 1 Ampere. The negligible reverse current is 5 microAmps. The reverse peak voltage, where the diode can withstand is up to a maximum of 50 Volts.

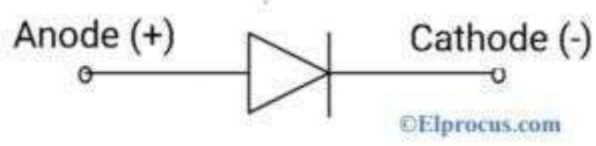
These diodes are mainly manufactured to perform general-purpose tasks and rectification in various electronic circuit applications. It is used in the conversion of AC voltage to DC voltage in the power supply circuits of electronic appliances and blocks the voltage in a particular location of the electronic circuit. It is available in the DO-41 package in small size at a very low cost with power dissipation of 3 Watts and 1 Ampere forward current.

1N4001 Diode Pin Configuration/Pin Diagram

The 1N4001 diode is a 2-terminal semiconductor device. It has an anode terminal, which is considered a positive terminal, and a cathode terminal, which is considered a negative

terminal. The 1N4001 diode pin configuration/pin diagram is explained below.

The **schematic symbol of the 1N4001 diode** is shown in the figure below. It allows the current only in one direction, that is from anode terminal to cathode terminal.



1N4001 Schematic Symbol

- **Anode (Positive Terminal):** The input current always flows through this terminal
- **Cathode (Negative Terminal):** The output current is obtained from this terminal Or exits through this terminal.

Features & Specifications

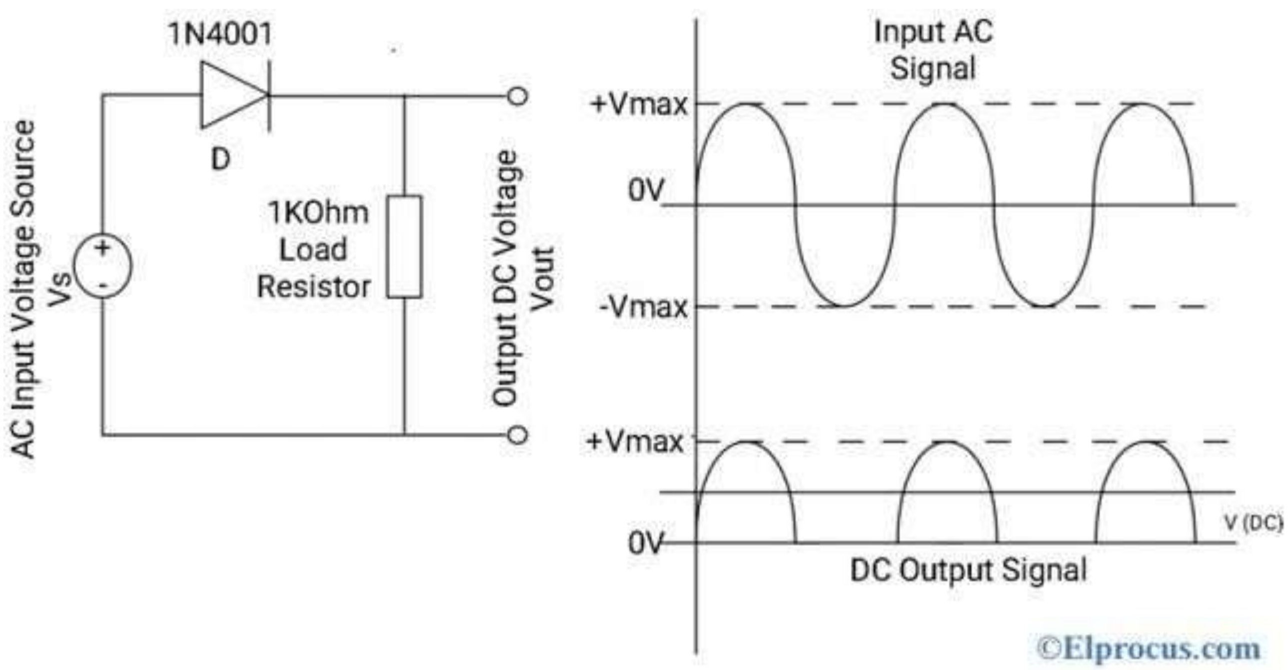
The **1N4001 diode specifications or the 1N4001 diode technical features** are given below.

- The 1N4001 diode is available in SMD and DO-41 package types.
- The average forward current of 1N4001 diode is 1 Ampere
- The peak current at non-repetitive is 30 Amps.
- The RMS reverse voltage is 35 Volts
- The reverse current is 5 microAmps
- The peak repetitive reverse DC voltage is 50 Volts
- The average rectified current is 1 Ampere.

- It belongs to ON semiconductor type in a single configuration with standard polarity
- The maximum forward voltage is 1.1 Volts.
- The maximum reverse current is 10 microAmps
- The maximum surge current is 30 Amps
- It operates at -55 to +175°C maximum temperature ranges
- The maximum output current will be 1 Amp.
- The maximum reverse voltage and DC voltage rating is 50 Volts
- The maximum power dissipation is 3 Watts.

The **alternative 1N4001 Diodes** or **equivalent 1N001 Diodes** are 1N4733A, 1N4148, 1N5822, 1N5408, Zener Diodes, 1N4002-T Diodes, 1N4002G-T ON Semiconductor Diode, 1N4002G-T Diodes, 1N4002-B Zetex Diodes, 1N4002-E3/54, 1N4002E-E3/54, 1N4002- E3/53, 1N4002E-E3/53 & 1N4002-E3/73 Circuit Diagram/How to Use

The 1N4001 diode is the most commonly used power diode used for rectification purposes and it belongs to the family of 1N400x series diodes. It is used in rectifier circuits like half- wave rectifiers, full-wave rectifiers, and diode clipper circuits to convert the applied AC voltage source to a certain DC voltage level.
Now let’s understand the circuit diagram/how to use the 1N4001 diode in a simple half-wave rectifier circuit. Here 1N4001 silicon diode is considered. So, it requires 0.7 Volts voltage drop across it to operate.



Half-Wave Rectifier Circuit with 1N4001 Diode

The circuit diagram and the output characteristics of the half-wave rectifier are illustrated below. The 1N4001 diode is connected in series with the load resistor R. The converted DC output voltage is taken across the load resistor.

The components required to design a half-wave rectifier circuit are

- One 1N4001 Diode
- 1 KOhm Load Resistor
- AC Voltage Source
- DC Voltage Source

Consider the AC sinusoidal input signal with two phases is applied. In the positive half cycle of the applied AC signal, the diode goes to forward biased condition and the current starts flowing through the diode at the constant voltage drop 0.7 Volts across it.

Here the anode terminal of the diode is positive with respect to the cathode terminal. Therefore the current flowing through the DC load resistor is directly proportional to the voltage and it is similar to the applied AC voltage. That means the output voltage Vout is equal to the supply voltage Vs. (Vout= Vs)

During the negative phase of the input signal (negative half cycle), the diode goes to reverse biased condition and it is open-circuited. The anode terminal of the diode is negative with respect to the cathode terminal and no current flows through the circuit or diode. As there is no current flow, the output voltage across the load resistor is zero.

As the current flows through the circuit only in the forward bias condition of the diode, this circuit is referred to as unidirectional. From the above output characteristics, the maximum AC voltage or peak to peak voltage is taken on X-axis and the output DC voltage is taken on Y-axis. It shows that the output across the load resistor is a positive half cycle, and the negative half cycle of the signal is zero. To calculate the DC voltage level at the output (across the resistor), use the following formula.

V (DC) = Vmax/π = 0.318 Vmax = 0.45 Vrms

Where Vmax is the aximum applied AC voltage V (DC) is the output DC voltage level

Vrms is the root mean square value of the applied voltage
n this way, the rectification of the signal is done using the 1N4001 diode. The output DC voltage and current are obtained during only the positive half cycle of the input signal. As it allows the only positive cycle of the signal, the output DC voltage across the load will be average. During the rectification of the AC signal, the steady stage DC voltage can be obtained continuously with ripple-free by connecting a capacitor parallel to the resistor called the smoothing capacitor.

here to Use/Applications

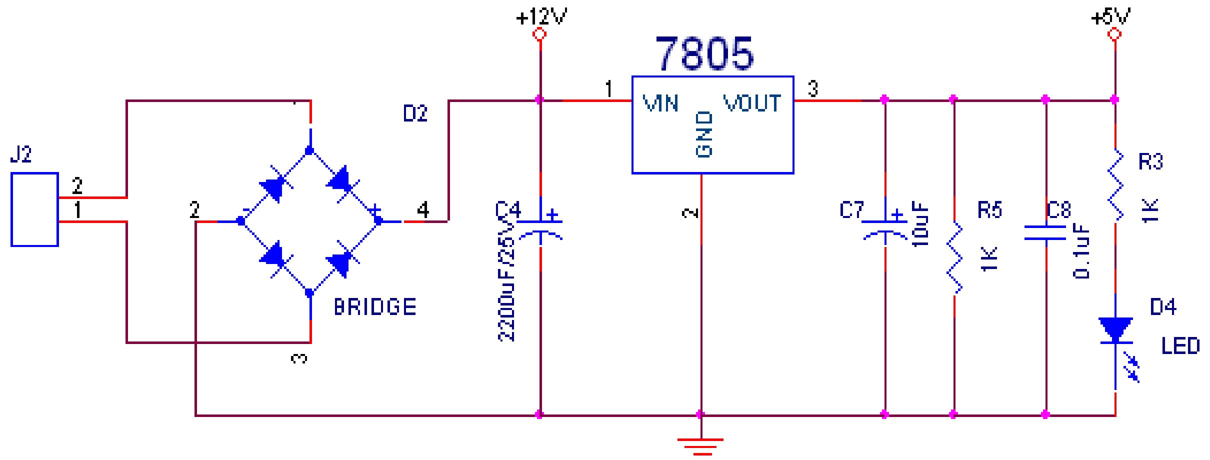
The following are the **applications of 1N4001 Diode**,

- These are used in the prevention of reverse polarity issue

- Used in full-wave and half-wave rectifiers
- Used in current flow regulators
- Can be used as a protection device.
- Used for rectification in battery chargers, power supply circuits, and other electronics appliances
- Used to block the current, block the voltage spikes, and boost the voltage, blocking unwanted incoming voltage, etc.
- Used in Voltage doublers
- Used in adapter circuits.

4.8 POWER SUPPLY:

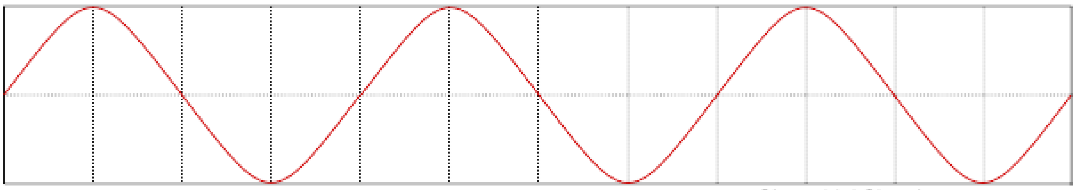
Power supply is a reference to a source of electrical power. A device or system that supplies electrical or other types of energy to an output load or group of loads is called a power supply unit or PSU. The term is most commonly applied to electrical energy supplies, less often to mechanical ones, and rarely to others.



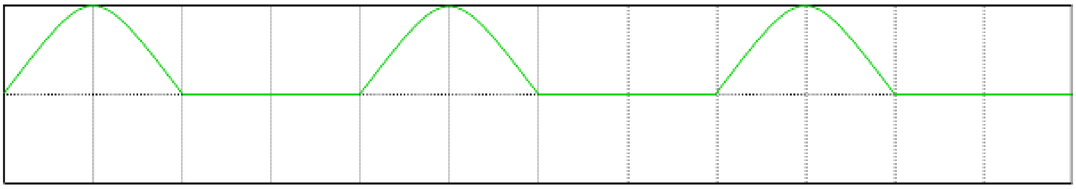
A 230v, 50Hz Single phase AC power supply is given to a step down transformer to get 12v supply. This voltage is converted to DC voltage using a Bridge Rectifier. The converted pulsating DC voltage is filtered by a 2200uf capacitor and then given to 7805 voltage regulator to obtain constant 5v supply. This 5v supply is given to all the components in the circuit. A RC time constant circuit is added to discharge all the capacitors quickly. To ensure the power supply a LED is connected for indication purpose.

RECTIFIER

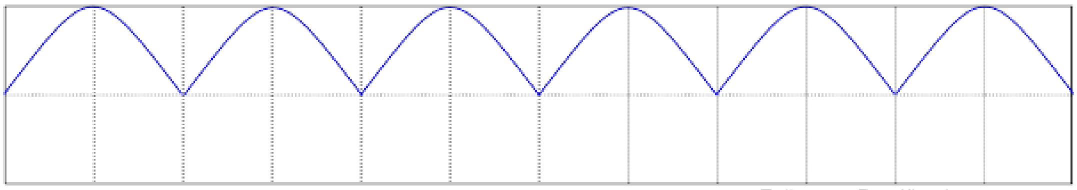
A **rectifier** is an electrical device that converts alternating current to direct current or at least to current with only positive value, a process known as **rectification**. Rectifiers are used as components of power supplies and as detectors of radio signals.



Sinusoidal Signal



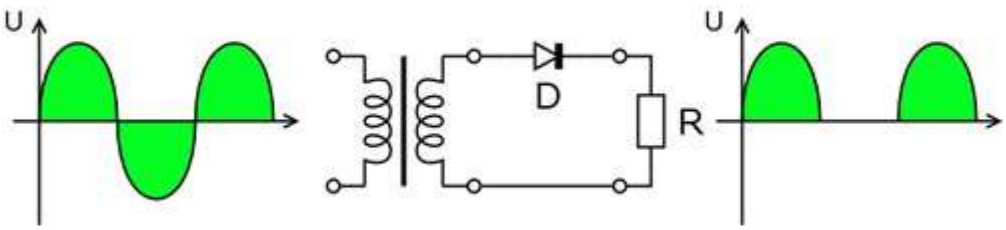
Half-wave Rectification



Full-wave Rectification

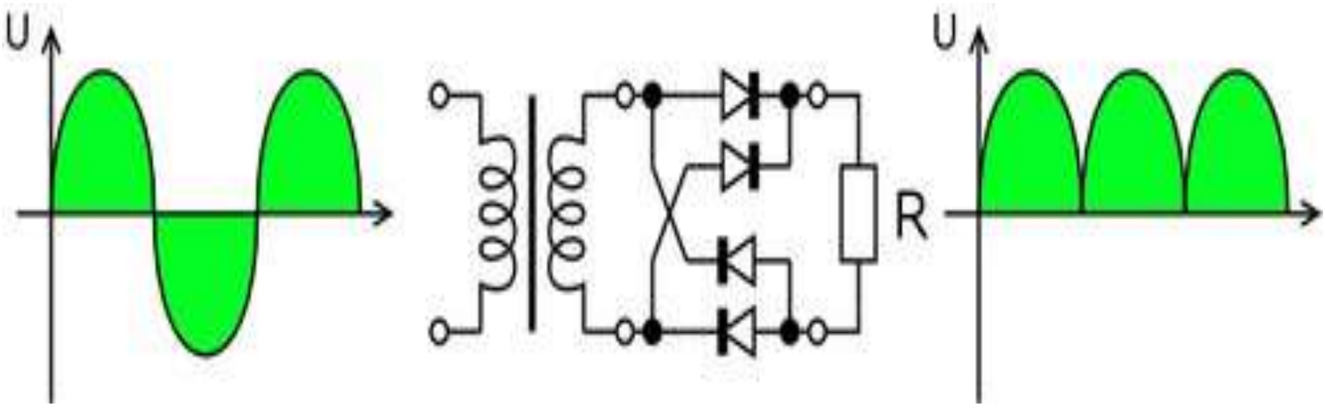
HALF-WAVE RECTIFICATION

A half wave rectifier is a special case of a clipper. In half wave rectification, either the positive or negative half of the AC wave is passed easily, while the other half is blocked, depending on the polarity of the rectifier. Because only one half of the input waveform reaches the output, it is very inefficient if used for power transfer. Half-wave rectification can be achieved with a single diode in a one phase supply.



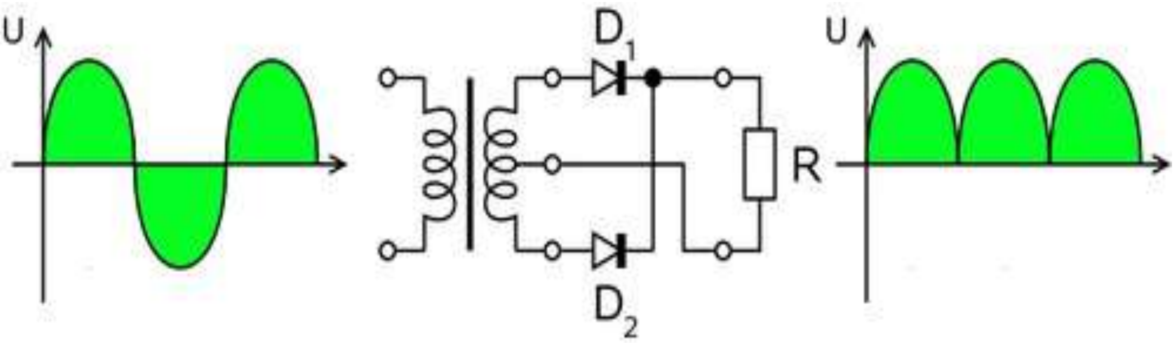
FULL-WAVE RECTIFICATION

Full-wave rectification converts both polarities of the input waveform to DC(direct current), and is more efficient. However, in a circuit with a non-center tapped transformer, four diodes are required instead of the one needed for half-wave rectification. This is due to each output polarity requiring two rectifiers each, for example, one for when AC terminal 'X' is positive and one for when AC terminal 'Y' is positive. The other DC output requires exactly the same, resulting in four individual junctions (See semiconductors, diode). Four rectifiers arranged this way are called a diode bridge or bridge rectifier:



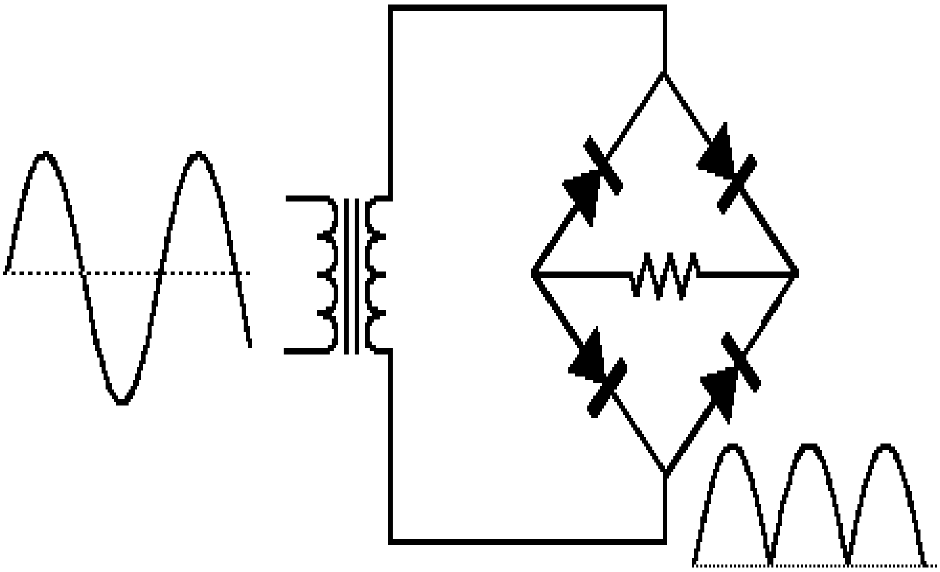
A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output by reversing the negative (or positive) portions of the alternating current waveform. The positive (or negative) portions thus combine with the reversed negative (or positive) portions to produce an entirely positive (or negative) voltage/current waveform.

For single-phase AC, if the transformer is center-tapped, then two diodes back-to-back (i.e. anodes-to-anode or cathode-to-cathode) form a full-wave rectifier.



BRIDGE RECTIFIER

A bridge rectifier makes use of four diodes in a bridge arrangement to achieve full- wave rectification. This is a widely used configuration, both with individual diodes wired as shown and with single component bridges where the diode bridge is wired internally.



CHAPTER 5

5.1 SOFTWARE REQUIREMENT EMBEDDED C

Embedded C is a set of language extensions for the C Programming language by the C Standards committee to address commonality issues that exist between C extensions for different embedded systems. Historically, embedded C programming requires nonstandard extensions to the C language in order to support exotic features such as fixed-point arithmetic, multiple distinct memory banks, and basic I/O operations.

In 2008, the C Standards Committee extended the C language to address these issues by providing a common standard for all implementations to adhere to. It includes a number of features not available in normal C, such as, fixed-point arithmetic, named address spaces, and basic I/O hardware addressing.

Embedded C uses most of the syntax and semantics of standard C, e.g., main() function, variable definition, datatype declaration, conditional statements (if, switch, case), loops (while, for), functions, arrays and strings, structures and union, bit operations, macros, etc.

A Technical Report was published in 2004 and a second revision in 2006.

NECESSITY

During infancy years of microprocessor based systems, programs were developed using assemblers and fused into the EPROMs. There used to be no mechanism to find what the program was doing.

LEDs, switches, etc. were used to check for correct execution of the program. Some ‘very fortunate’ developers had In-circuit Simulators (ICEs), but they were too costly and were not quite reliable as well. As time progressed, use of microprocessor-specific assembly-only as the programming language reduced and embedded systems moved onto C as the embedded programming language of choice.

C is the most widely used programming language for embedded processors/controllers. Assembly is also used but mainly to implement those portions of the code where very high timing accuracy, code size efficiency, etc. are prime requirements.

As assembly language programs are specific to a processor, assembly language didn't offer portability across systems. To overcome this disadvantage, several high level languages, including C, came up. Some other languages like PLM, Modula-2, Pascal, etc. also came but couldn't find wide acceptance. Amongst those, C got wide acceptance for not only embedded systems, but also for desktop applications. Even though C might have lost its sheen as mainstream language for general purpose applications, it still is having a strong-hold in embedded programming.

Due to the wide acceptance of C in the embedded systems, various kinds of support tools like compilers & cross-compilers, ICE, etc. came up and all this facilitated development of embedded systems using C. Assembly language seems to be an obvious choice for programming embedded devices. However, use of assembly language is restricted to developing efficient codes in terms of size and speed.

Also, assembly codes lead to higher software development costs and code portability is not there. Developing small codes are not much of a problem, but large programs/projects become increasingly difficult to manage in assembly language. Finding good assembly programmers has also become difficult nowadays. Hence high level languages are preferred for embedded systems programming.

ADVANTAGES

- It is small and simpler to learn, understand, program and debug.
- Compared to assembly language, C code written is more reliable and scalable, more portable between different platforms.
- C compilers are available for almost all embedded devices in use today, and there is a large pool of experienced C programmers.
- Unlike assembly, C has advantage of processor-independence and is not specific to any particular microprocessor/microcontroller or any system. This makes it convenient for a user to develop programs that can run on most of the systems.
- As C combines functionality of assembly language and features of high level languages, C is treated as a 'middle-level computer language' or 'high level assembly language'.
- It is fairly efficient.
- It supports access to I/O and provides ease of management of large embedded projects.
- Java is also used in many embedded systems but Java programs require the Java Virtual Machine (JVM), which consumes a lot of resources. Hence it is not used for smaller embedded devices.
- Other High-level programming language like Pascal, FORTRAN also provide some of the advantages.

EMBEDDED SYSTEMS PROGRAMMING

Embedded systems programming is different from developing applications on a desktop computers. Key characteristics of an embedded system, when compared to PCs, are as follows:

- Embedded devices have resource constraints(limited ROM, limited RAM, limited stack space, less processing power)
- Components used in embedded system and PCs are different; embedded systems typically uses smaller, less power consuming components. · Embedded systems are more tied to the hardware.

Two salient features of Embedded Programming are code speed and code size. Code speed is governed by the processing power, timing constraints, whereas code size is governed by available program memory and use of programming language. Goal of embedded system programming is to get maximum features in minimum space and minimum time.

Embedded systems are programmed using different type of languages:

- Machine Code
- Low level language, i.e., assembly
- High level language like C, C++, Java, Ada, etc.
- Application level language like Visual Basic, scripts, Access, etc.

Assembly language maps mnemonic words with the binary machine codes that the processor uses to code the instructions. Assembly language seems to be an obvious choice for programming embedded devices. However, use of assembly language is restricted to developing efficient codes in terms of size and speed. Also, assembly codes lead to higher software development costs and code portability is not there. Developing small codes are not much of a problem, but large programs/projects become increasingly difficult to manage in assembly language. Finding good assembly programmers has also become difficult nowadays. Hence high level languages are preferred for embedded systems programming.

Use of C in embedded systems is driven by following advantages

- It is small and reasonably simpler to learn, understand, program and debug.
- C Compilers are available for almost all embedded devices in use today, and there is a large pool of experienced C programmers.
- Unlike assembly, C has advantage of processor-independence and is not specific to any particular microprocessor/ microcontroller or any system. This makes it convenient for a user to develop programs that can run on most of the systems.
- As C combines functionality of assembly language and features of high level languages, C is treated as a

'middle-level computer language' or 'high level assembly language'

- It is fairly efficient
- It supports access to I/O and provides ease of management of large embedded projects.

Many of these advantages are offered by other languages also, but what sets C apart from others like Pascal, FORTRAN, etc. is the fact that it is a middle level language; it provides direct hardware control without sacrificing benefits of high level languages.

Compared to other high level languages, C offers more flexibility because C is relatively small, structured language; it supports low-level bit-wise data manipulation.

Compared to assembly language, C Code written is more reliable and scalable, more portable between different platforms (with some changes). Moreover, programs developed in C are much easier to understand, maintain and debug. Also, as they can be developed more quickly, codes written in C offers better productivity. C is based on the philosophy 'programmers know what they are doing'; only the intentions are to be stated explicitly.

It is easier to write good code in C & convert it to an efficient assembly code (using high quality compilers) rather than writing an efficient code in assembly itself. Benefits of assembly language programming over C are negligible when we compare the ease with which C programs are developed by programmers.

Objected oriented language, C++ is not apt for developing efficient programs in resource constrained environments like embedded devices. Virtual functions & exception handling of C++ are some specific features that are not efficient in terms of space and speed in embedded systems. Sometimes C++ is used only with very few features, very much as C.

And, also an object-oriented language, is different than C++. Originally designed by the U.S. DOD, it didn't gain popularity despite being accepted as an international standard twice (Ada83 and Ada95). However, Ada language has many features that would simplify embedded software development.

Java is another language used for embedded systems programming. It primarily finds usage in high-end mobile phones as it offers portability across systems and is also useful for browsing applications. Java programs require Java Virtual Machine (JVM), which consume lot of resources. Hence it is not used for smaller embedded devices.

Dynamic C and B# are some proprietary languages which are also being used in embedded applications.

Efficient embedded C programs must be kept small and efficient; they must be optimized for code speed and code size. Good understanding of processor architecture embedded C programming and debugging tools facilitate this.

DIFFERENCE BETWEEN C AND EMBEDDED C

Though C and embedded C appear different and are used in different contexts, they have more similarities than the differences. Most of the constructs are same; the difference lies in their applications.

C is used for desktop computers, while embedded C is for microcontroller based applications. Accordingly, C has the luxury to use resources of a desktop PC like memory, OS, etc. While programming on desktop systems, we need not bother about memory.

However, embedded C has to use with the limited resources (RAM, ROM, I/Os) on an embedded processor. Thus, program code must fit into the available program memory. If code exceeds the limit, the system is likely to crash.
Compilers for C (ANSI C) typically generate OS dependant executables. Embedded
C requires compilers to create files to be downloaded to the microcontrollers/microprocessors where it needs to run. Embedded compilers give access to all resources which is not provided in compilers for desktop computer applications.
Embedded systems often have the real-time constraints, which is usually not there with desktop computer applications.
embedded systems often do not have a console, which is available in case of desktop applications.
So, what basically is different while programming with embedded C is the mindset; for embedded applications, we need to optimally use the resources, make the program code efficient, and satisfy real time constraints, if any. All this is done using the basic constructs, syntaxes, and function libraries of 'C'.

5.2 MATLAB

Matlab is a software program that allows you to do data manipulation and visualization, calculations, math and programming. It can be used to do very simple as well as very sophisticated tasks. We will start very simple.

Starting/quitting

To start Matlab, click on the 'Start' button on the left bottom of the screen, and then click on 'All Programs', then 'Math and Stats', then 'Matlab'. A window will pop up that will consist of three smaller windows. On the right there will be a big window entitled'Command Window'. On the left there will be two windows, one entitled 'Workspace' and

another one 'Command History'.

In addition, on the top there is a usual bar with 'File', 'Edit', etc. headings. You can use these as you would in any other software (Word for example). Click on 'File' and look at the available commands there. Do the same for all the other headings. Note that the last heading is 'Help' (very useful!). Therefore, if you are stuck you know where to look.

To use Matlab, you will mostly be typing in the 'Command window'. Click on the Command window. Its outline will become dark grey (that's how you know that you can type into that window). A cursor will start blinking on a line right after '>>' (this is called a prompt).

Let's start using Matlab by quitting it. In the Command window type quit (the letters should appear after the prompt) and hit enter. Matlab will close. Start Matlab again. Let's explore the Help bar. Look at the third option under the Help heading 'Using the Desktop'. Click on it. A Help window will come up with a list of topics describing the Desktop. Click on 'What Desktop Is'. On the bottom of the page that will come up you will find explanations of the buttons, windows and options available on the desktop. Scroll to the bottom. You will see text 'Drag the separator bar to resize window'.

Let's try that. Switch to the Matlab window. (To do this, look at the taskbar on the bottom of the screen and find an icon with a little orange and green hill on it that says 'MATLAB'.
Click on it.) Move your mouse to the space between the 'Command window' on the right and the windows on the left. The mouse should take a shape of an arrow with two points. Press the left mouse button down and move the mouse left and right. This should move the boundary between the windows.

If you have questions about the desktop in the future, you can go to Help/Using the Desktop for the answers. However, the most useful help option under the Help heading for you now is the second option called 'MATLAB Help'. Click on it. This will take you to the main page of Matlab help. The categories are on the left, the main text is on the right.

You can always go to this page if you have a question.

Two very useful features on this page are 'Index' and 'Search'. These are bars on top of the left window that contains the categories. In the 'Index' you can search for available functions in Matlab. In fact, the Index is like an index at the back of a Matlab manual book.For example, click on the Index bar. In the window under 'Search index for:' type logarithm. The text on the window below will jump to the entry under 'logarithm'. It has several subheadings. Double click on the subheading 'natural' in that window. On the right you will get the description of the log function in Matlab, with syntax and example.The Index bar is very useful to look up the syntax of a function or to see if a particular Matlab function exists. Another useful Help feature is the Search bar (located to the right of the Index bar).

That allows you to search Matlab documentation more thoroughly.

Therefore, if you cannot find something in the Index, you might want to try using Search.Close the Help window, and get back to the main Matlab window.Matlab as a super- calculator Click on the Command window. Type 2+3 at the prompt and then hit enter. The following will come up below the prompt:ans =5.As you can see, you can use Matlab as a basic calculator (although that's not the most efficient use for it).Notice that there is a new entry in the top left window entitled 'Workspace'. There is now an entry ans there of size 1x1. ans is a variable. This means that it's a string of text that

has a value (number) assigned to it. To see this, type ans at the prompt and then hit enter. As you can see Matlab again returns ans = 5, i.e. it remembers that ans holds a value of 5.ans is a special name for a variable in Matlab. It is assigned the value of the answer to the expression that you type at the prompt.

You can create your own variables. For example, type in x=10. Now Matlab has another entry in the 'Workspace' window called x. Now if you type x, Matlab will know that its value is 10. For example, type x+5. Matlab will give you the correct answer 15.Matlab has all the math functions that a calculator may have and many more. For example, you can find x2. Here, we need to learn a bit of notation. To raise x to the power of 2 in Matlab you type x.^2. You will get, predictably, 100 since you assigned a value of 10 to x. Among the most familiar functions, Matlab has sin, cos, exp, log functions. For

example, to find e2, you type exp(2). You should get 7.3891. As you can see, to use a function, you put the argument of the function in the parentheses after the function name (without a space between them).Matlab as a mathematical tool

So far we have used common mathematical functions. However, Matlab allows you to define (and evaluate) your own functions as well. For example, lets define a function f(x)=x2+1. To do this, simply type in f=x.^2+1. Since x has a value of 10, the answer is 101. You can now change the value of x. For example, type x=5 and enter, then type

f=x.^2+1 again. You should now get 26.

However, you don't want to type the expression for f(x) every time you want to change the value of x. You might want to define a function f(x) for a range of values of x. To do this in Matlab we need to make x be a range of values. For example, suppose we want to make x to go from 1 to 10. To do this in Matlab, you type x=1:10. You will get x =

1 2 3 4 5 6 7 8 9 10

as a result. Now, x is a list of values from 1 to 10. If we now type f=x.^2+1, we will get 10 values of f for each value of x. In other words, we have defined f as a function of x.

Right now the difference between two consecutive values of x is 1. To change this , we put the step between two consecutive values between the maximum and minimum values,

i.e. type x=1:0.5:10. You will get x =

Columns 1 through 8

1.0000 1.5000 2.0000 2.5000 3.0000 3.5000

4.0000 4.5000

Columns 9 through 16

5.0000 5.5000 6.0000 6.5000 7.0000 7.5000

8.0000 8.5000

Columns 17 through 19

9.0000 9.5000 10.0000

Now x still ranges from 1 to 10, but now it takes on 19 values with a step of 0.5. Since we redefined x, we now need to redefine f(x) as well. This means that we must again type f=x.^2+1. f(x) now has 19 values as well.

Plotting basics

One thing we want to do to with functions is plot them. Matlab is a very good tool for that. For example, to plot f as a function of x, type plot(x,f). A new window will come up with a plot of f(x) as a function of x. Matlab has many features for plotting. We will

now learn a few of them. First of all we want to define our axes. This is very simple to do. To define the x-axis, type xlabel('x') in the Command window. Now switch to the window with the figure. You will see a label on the x-axis. Let's do the same for the yaxis.

Predictably, to do this you need to type ylabel('f(x)'). Now, if we want to put a title on our graph the command it title('Function f'). As you can see, a lot of the commands are quite intuitive.

Matlab as a tool for data analysis

What about looking at data in Matlab? Usually, data comes in tables. For example, you could have some observation as a function of time, such as the average temperature as a function of a month. This data will have two columns, one for the month and another for the value of a temperature. Or you could have several replicates on an experiment where the average weight of some organisms was observed in environments with different food levels. This data can be recorded as a table with the number of rows equal to the number of replicate experiments and the number of columns equal to the food levels tested.

A mathematical term for a table is a matrix. (From now on you can understand the term matrix as table.) Matlab deals with matrices very well. Let's create a matrix of ones in Matlab. To do this, we need to know how many rows and columns we want in a matrix. Suppose we want to create a matrix of ones with 2 rows and 3 columns. To do this, type ones(2,3). The Matlab will return

ans = 1 1 1

1 1 1

Suppose we want to store this matrix in a variable. To do this, type M=ones(2,3). Now, M will appear in the Workspace window (notice that its size, 2 by 3, is also stated). The size of a matrix is often referred to as its dimensions. For example, M is 'a matrix of dimensions 2 by 3' or simply 'a 2 by 3 matrix'.

Whenever you want to change a variable or remove a variable, you can use command clear. If you type clear M, this will remove M from the Workspace. Try it. Anytime

that you have made a mistake defining a variable or a function, or when you reuse the same variable name, it is a very good practice to use the clear command. If you want to get rid of all the variables in your Workspace, you can simply type clear.

You can also construct your own matrix by typing it in. For example, if you type M=[2,5;9,7; 4,3], you will get a 3 by 2 matrix:

2 5

7

9 7

4 3

As you can see, to define a matrix in Matlab, you surround the entries by square brackets. Commas separate column entries and semicolons separate row entries. To look at the whole first row of the matrix M, you type M(1,:). Here, the colon means 'show me all the entries in the row(s) indicated'. To look at the whole second column, you type M(:,2). If you want to see only the second and third rows of M, you type M(2:3,:).

Let's work on an example. Suppose you have observations of average temperature as a function of month. Let's generate the data to represent that. As we do this, we will learn several more useful function of Matlab. First, we need to generate a column of months. We already generated a row of numbers from 1 to 10 in the previous section. Now, we need to make a column. Notice that a row is just a matrix of dimensions 1 by n (where n is the length of the row). Similarly, a column is a matrix of dimensions n by 1. These are called vectors. Since we know how to make a row, let's start with that. Type month=1:12. You will see

month =

1 2 3 4 5 6 7 8 9 10
11 12

To make this row into a column, we will transpose it. To transpose a matrix means to flip the values in the matrix so that the first row becomes the first column, the second row becomes the second column etc. Therefore, if you transpose a row, you will get a column. To do this type month=month'. The apostrophe tells Matlab to transpose month. You will get

month = 1

2

3

4

5

6

8

7

8

9

10

11

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This is what we wanted. Now, we need to generate values of average temperature for each month. For educational purposes, we will do this naively by picking random numbers between 0 and 80. Matlab provides a convenient function rand to generate random numbers between 0 and 1. Try it by typing rand at the prompt several times.

You will get a different number from 0 to 1 every time. To generate random values between 0 and 80, we can multiply a random number between 0 and 1 by 80. To do this type 80*rand. Now, we need to generate 12 of these numbers. There are several ways of doing this, we will learn two of them. (In fact, there are several ways of doing almost everything in Matlab. As long as you can do it any one way, it will suffice for most work that you will be doing in the course.)

We need to generate 12 random numbers between 0 and 80. We know how to generate one of them (the command is 80*rand). Now, we need to string them together. To do this, we will use a new variable called temp (for temperature). temp should be a column. A column is a matrix of dimensions n by 1. Therefore, the first entry in the variable temp will be located in the first row and first (and only) column. To express this in Matlab type temp(1,1)=80*rand. The second entry in the column will be located in the 2nd row

and 1st column, therefore type temp(2,1)=80*rand. You will get the answer giving

two random values stored in temp.MATLAB is started by clicking the mouse on the appropriate icon and is ended by typing exit or by using the menu option. After each MATLAB command, the "return" or "enter" key must be depressed.

A. Definition of Variables

Variables are assigned numerical values by typing the expression directly, for example, typing

a = 1+2

yields: **a = 3**

The answer will not be displayed when a semicolon is put at the end of an expression, for example type **a = 1+2;**.

MATLAB utilizes the following arithmetic operators:

+ addition

- subtraction

***** multiplication

/ division

^ power operator

' transpose

A variable can be assigned using a formula that utilizes these operators and either numbers or previously defined variables. For example, since a was defined previously, the following expression is valid

b = 2*a;

To determine the value of a previously defined quantity, type the quantity by itself:

b

yields: **b = 6**

If your expression does not fit on one line, use an ellipsis (three or more periods at the end of the line) and continue on the next line.

c = 1+2+3+...

5+6+7;

There are several predefined variables which can be used at any time, in the same manner as user-defined variables:

i **sqrt(-1)**

j **sqrt(-1)**
pi **3.1416...**

For example,

y= 2*(1+4*j)

yields: **y = 2.0000 + 8.0000i**

There are also a number of predefined functions that can be used when defining a variable. Some common functions that are used in this text are:

abs	magnitude of a number (absolute value for real numbers)
angle	angle of a complex number, in radians
cos	cosine function, assumes argument is in radians
sin	sine function, assumes argument is in radians
exp	exponential function

For example, with y defined as above,

c = abs(y)

yields: **c = 8.2462 c = angle(y)** yields: **c = 1.3258**

With a=3 as defined previously, c =cos(a)

yields: c = -0.9900 c = exp(a)

yields: c = 20.0855

Note that exp can be used on complex numbers. For example, with y = 2+8i as defined above,

c = exp(y)

yields: **c = -1.0751 + 7.3104i**

which can be verified by using Euler's formula:

c = exp(2)cos(8) + je(exp)2sin(8)

Conclusion

The design of a resonant-enhanced full-bridge onboard charger (OBC) with an LLC tank and synchronous rectification represents a highly efficient and compact solution for modern electric vehicle charging systems. By leveraging resonant power conversion, the system achieves soft-switching operation that minimizes switching losses, reduces electromagnetic interference (EMI), and improves overall converter reliability. The incorporation of synchronous rectification further enhances efficiency by lowering conduction losses compared to traditional diode rectifiers, making it especially beneficial for high-power, high- current EV applications.

However, real-world performance is influenced by parasitic inductances**,** leakage effects, and non-ideal switching behaviors that can lead to voltage overshoot, ringing, and partial loss of ZVS/ZCS operation.

Accurate modeling and optimization of these parameters are essential to ensure reliable operation and to maintain high efficiency under practical conditions.

In conclusion, the resonant-enhanced full-bridge OBC with an LLC tank offers a robust, high-efficiency, and power-dense charging solution suitable for next-generation electric vehicles. Its combination of soft-switching**,** synchronous rectification**,** and optimized magnetic design enables improved thermal management, reduced component stress, and enhanced system lifetime—addressing the growing demand for fast, reliable, and energy- efficient onboard charging technologies.

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