

**DEVELOPMENT OF POTENTIOSTAT AND DETERMINATION OF  
CORROSION RATE OF LOW CARBON STEEL IN SEA WATER  
EQUIVALENT IN CHLORIDE WATER**

**A DISSERTATION SUBMITTED IN PARTIAL  
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OF THE**

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## **CERTIFICATE OF APPROVAL**

This is certify that the thesis entitled “**DEVELOPMENT OF POTENTIOSTAT AND DETERMINATION OF CORROSION RATE OF LOW CARBON STEEL IN SEA EQUIVALENT IN CHLORIDE WATER**”, IS A BONAFIDE RECORD OF WORK CARRIED OUT UNDER MY GUIDNANCE BY **MAHENDRA KUMAR VISHWAKARMA** DURING THE AACDEMIC SESSION 2020-2022 FOR THE PARTIAL FULLFILLMENT OF DEGREE OF **MASTER OF ENGINEERING IN METALLURGICAL ENGINEERING** FROM **JADAVPUR UNIVERSITY** .IN MY OPINION THE WORK FUFILS THE REQUIREMENT FOR WHICH IT IS GOING TO BE SUBMITTED.

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## **DECLARATION**

I do hereby solemnly declare that the work embodies in this entitled “**DEVELOPMENT OF POTENTIOSTAT AND DETERMINATION OF CORROSION RATE OF LOW CARBON STEEL IN SEA WATER EQUIVALENT IN CHLORIDE WATER**”, is the original investigation carried out independently by me under the supervision of Prof. SUBIR PAUL Department of Metallurgy and Material Engineering, Jadavpur University, Kolkata, India for the award of the degree of Master Of Engineering (Metallurgy Engineering) of Jadavpur University. To the best of my knowledge and belief, this work has not been presented for any degree or distinction under any other university.

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**MAHENDRA KUMAR VISHWAKARMA**

**DATE: -**

**07/07/2022**

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## **ABSTRACT**

For design and corrosion experts, predicting the life of steel structures in a marine environment and aqueous environment is a difficult task for both existing and new structures. The rate of marine/aqueous corrosion is a complicated function of various fluid characteristics and saltwater chemistry parameters. Salinity, sulphate, bicarbonates, pH, temperature, and dissolved oxygen are the main factors that influence the rate. These factors vary greatly based on the structure's geographical location as well as the depth of seawater in which parts of the structure are submerged. The interdependence of the parameters makes formulating a mathematical equation extremely challenging. It's also fascinating to discover a location where the pace of structure degradation is the slowest. By doing a few laboratory tests, the current study attempted to estimate the corrosion rate for a specific geographical position in an ocean with any combination of these variables. Using a combination of five genes: chloride, sulphate, dissolved oxygen, pH, and temperature, genetic algorithms were used to find the best combination of these five parameters that would reduce steel corrosion to a minimum

Potentiostat is an important instrument in material science for environmental degradation studies in for metals and alloy in sea water, river water, petroleum oil production unit of material like steel pipe, hull of ship submarine material underground soil, tank pipe etc.....

Potentiostat electrochemical instruments, basically it consists of source of DC potential applied to the working electrode against a counter electrode and Applied potential are measured with respect to reference electrode.

That is with consist of three electrode system WE(Working Electrode), CE(Counter Electrode) and RE(Reference Electrode).

The potential are measured varied from negative (Cathodic Region) to the positive current (Anodic region).

# **CHAPTER-1**

## **INTRODUCTION**

### **1.1 BACKGROUND AND MOTIVATION**

Potentiostat is an important instrument in material science for environmental degradation studies in for metals and alloy in sea water river water, petroleum oil production unit of material like steel pipe hull of ship submarine material underground soil, tank pipe etc.....

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The potential are measured varied from negative (Cathodic Region) to the positive current (Anodic region).

The data, all potentials current are measured by digital voltmeter and Ammeter respectively.

The data are plotted in Excel to generate cathodic and anodic polarization where  $i_{corr}$  (corrosion current ) and  $E_{corr}$  are obtained by Tafel's Extrapolation method.

Todays Potentiostat are computerized changes in potential and current are measured digitally and current generate directly to monitor to the computer  $E_{corr}$  and  $i_{corr}$  are displayed after the experiment is over.

This automatic Potentiostat machine are expensive mostly manufactured from Europe and America.

An attempt to made myself to manufactured portable mini Potentiostat using resistance, electronics chip, diode and operation amplifier with a Robotic Circuit Using Arduino UNO.

THE Hardware Arduino UNO can be programmed by C-program language to supply and vary the applied potential with a control Scan rate that can user decide.

THIS developed microprocessor mini Potentiostat can generate anodic and cathodic polarization automatically, no need plotting and  $E_{corr}$  and  $I_{corr}$  are measured directly



The size of Potentiostat develop myself is like Pencil box which Corrosion Engineer take in its pocket go to actual sites of material corrosion and Directly Monitor corrosion rate at sites itself (No need of bringing material in corrosion sites).

THE corrosion rate by developed mini potentiostat has been verified by the manual potentiostat in The Department of Metallurgy and Material Engineering (In Electrochemistry and Corrosion Lab) OF JADAVPUR UNIVERSITY, KOLKATA

THE RESULT of polarization curve and corrosion rate can also be displayed in MOBILE PHONE so that a man can keep its pocket sites and possible a smart phone can be easily measured Degradation of any material whether at home or at Industrial areas.

## **CHAPTER-2**

### **LITRATURE REVIEW**

#### **2.1INTRODUCTION**

##### **HOW IS AFFECTING IN CORROSION IN SEA WATER?**

Aqueous water or Seawater is one of the most complex and aggressive media. Marine/aqueous corrosion depends on numerous interdependent parameters and combines chemical, biological and mechanical factors. The understanding of the influence of each of these parameters and factors is the key to the optimization of the design of metal structures and devices used in aqueous environments. It is also the key to the optimization of anticorrosion methods and materials performance. Localized corrosion is a particularly insidious degradation phenomenon and thus a hazard for metal structures integrity. Severe localized degradations may induce major industrial failures while consuming a very small number of materials. In aqueous water, owing to various combined factors such as materials heterogeneity (grain boundaries, inclusions, welds), differential aeration, and biological activity, the corrosion processes of carbon steels, though commonly acknowledged as being mainly uniform, are often localized. The well-known ALWC (Accelerated Low Water Corrosion) phenomenon, which combines differential aeration and bacteria consortium activity, perfectly illustrates this point.

The geographical variation in the corrosivity of natural aqueous water results from the variation of salinity, temperature, dissolved oxygen and the presence of various other salts. Chloride ion ( $\text{Cl}^-$ ) has a strong influence on the corrosivity of structural steel. The chloride ( $\text{Cl}^-$ ) concentration of sea water varies from about 5.8 g/Kg to about 24 g/Kg, sulphate ( $\text{SO}_4^{2-}$ ) concentration varies from 0.8 g/Kg to 3.4 g/Kg and the bicarbonate ( $\text{HCO}_3^-$ ) concentration varies from 0.01 g/Kg to 0.2 g/Kg across different oceans and seas. An increase of temperature and dissolved oxygen [O] concentration is known to aggravate the degradation rate of the structural material. Though the pH of seawater is in the range of neutral to slightly alkaline, local acidity is developed due to corrosion products as well as crude petroleum products, which results in a lowering of pH to around pH 4. It is interesting to find the effect sulphate ( $\text{SO}_4^{2-}$ ), which also influences corrosion rate of steel.

## **2.2 Types of Corrosion**

Following are the 9 different types of corrosions that commonly occur in metals.

1. Atmospheric Corrosion
2. Erosion Corrosion
3. Selective Corrosion
4. Uniform Corrosion
5. Pitting Corrosion
6. Fretting Corrosion
7. Stress Corrosion
8. Inter-granular Corrosion
9. Corrosion Fatigue

### **2.2.1 Atmospheric Corrosion**

Atmospheric corrosion is a type of wet corrosion caused by the action of electrolytes. In this case, moisture present in the atmosphere, rainwater, etc. acts as electrolytes triggering corrosion of the exposed metal surface.



Fig 1: Atmospheric Corrosion

### **2.2.2 Erosion Corrosion**

Erosion corrosion is caused by mechanical abrasion due to the relative movement between metal surfaces and corrosive fluids. In this case, the surface of metal gets deteriorated gradually by the abrasion

of fast-moving fluids and cavities are also formed. This type of corrosion commonly seen in metal tubes carrying moving fluids in it.



Fig 2: Erosion Corrosion

### **2.2.3 Selective Corrosion**

Selective corrosion occurs in alloys where one of the component metals is de-alloyed by the corrosive environment. This type of corrosion can be seen in brass alloy pipes where zinc is commonly used as another component and here zinc is de-alloyed. Similarly, in the case of copper-nickel alloy tubes where nickel is de-alloyed by selective corrosion.



Fig 3: Selective Corrosion of Brass Pipe

### **2.2.4 Uniform Corrosion**

In case of uniform corrosion, a uniform layer of rust is formed on the surface of metals and it is extended over the whole surface area of metal. This type of corrosion can be seen in metals which are not protected by surface coating. Aluminum, zinc, lead, etc. are some metals commonly affected by uniform corrosion.



Fig 4: Uniform Corrosion

### **2.2.4 Pitting Corrosion**

Pitting is the formation of rust pits or holes on the surface. Pitting corrosion is a localized form of corrosion where the corrosion is limited to small areas. The shapes of rust pits may not be similar but in most of the cases, they are hemispherical in shape.

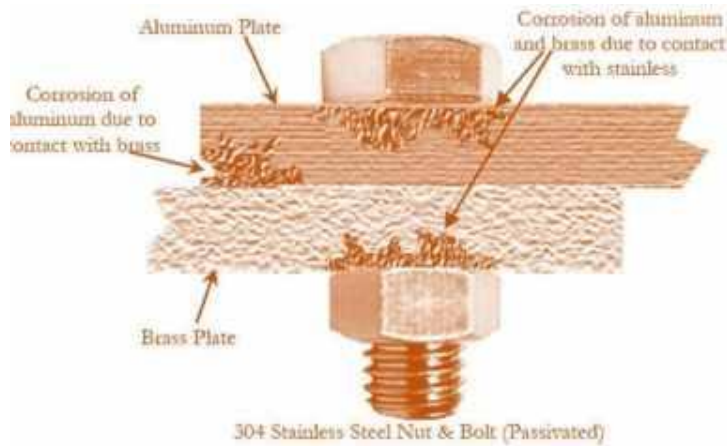
Pitting corrosion occurs when the protective oxide layer of the surface gets damaged or due to structural defects in metal. It is considered more dangerous because it causes the failure of structure with a relatively low overall loss of material. It can be observed in steel, aluminium, nickel alloys, etc.



Fig 5: Pitting Corrosion

### **2.2.5 Fretting Corrosion**

Fretting corrosion occurs at the contact area of the two materials which are joined together. This is developed when the contact area is subjected to slips and vibrations. This type of corrosion can be seen in bolted and riveted joints, clamped surface, etc.



F

Fig 6: Fretting Corrosion

### 2.2.6- Stress Corrosion

Stress corrosion caused by the combined action of a corrosive environment and mechanical stress on the surface of the material. In its initial stage, small cracks are developed and these finally leads to failure of the whole structure. This type of corrosion can be seen in stainless steel when they are stressed in chloride environments, in brass materials when they are stressed in the presence of ammonia, etc.



Fig 7: Stress Corrosion

### 2.2.7 Inter-granular Corrosion

Inter-granular corrosion is the corrosion occurs along the grain boundaries and the grains are not affected in this case. It is caused when there is a noticeable difference in reactivity against impurities exists

between grain boundaries and grains. This difference in reactivity occurs due to defective welding, heat treatment stainless steels, copper, etc.



Fig 8: Inter-granular Corrosion

### **2.2.8 Corrosion Fatigue**

Fatigue of materials is defined as the failure of a material due to repeated application of stress. When the fatigue of metal is developed in the corrosive environment then it called corrosion fatigue. This can be prevented by improving the fatigue resistance of a material.



Fig 9 corrosion fatigue

### **2.2.9 HOW IS AFFECT CORROSION ON MILD STEEL???**

Mild steel does not have a high resistance to corrosion in its untreated form, however, the corrosion resistance can be greatly improved by applying an appropriate surface protection product to the exposed parts of any project. If mild steel is exposed to an aerated neutral aqueous solution, such as a dilute solution of sodium chloride in water, a corrosive attack will begin at defects in the oxide film on the steel. Effects of heat treatment on corrosion of mild

steel have also gained attention of some authors. Stephen et al. investigated the effects of heat treatment on corrosion rates of mild steel pipe weldments and pipe whip restraint devices in saltwater. The results showed that corrosion rate decreases with increase in pipe preheat temperatures but increases with increase in welding pass. Corrosion rate of mild steel was also found to depend on immersion time and tempering temperature. They concluded that appropriate heat treatment could be used to minimize the corrosion rates of metallic structures in a corrosive medium. Studied corrosion behaviour of commercial mild steel in municipal tap water. The mild steel was subjected to various heat treatments (annealing, hardening, normalizing and tempering) and the result revealed the heat-treated samples had better corrosion resistivity than untreated sample, most especially the annealed and normalized samples. Agnesis and

Ovary studied the effects of

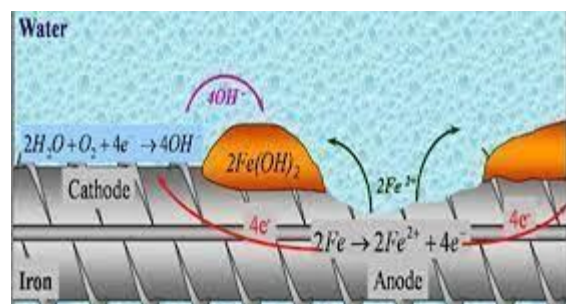
microstructural change and corrosion susceptibility of heat-treated medium carbon steel in different corrosive media. The study showed that microstructures obtained by different heat treatment processes are sensitive to the environment and corrosion as a



result of ferrite precipitation and carbide phases.

By conducting a few laboratory experiments in artificially created aqueous water, the current inquiry attempted to determine the corrosion rate of mild steel for a given geographical position in an ocean with any combination of those variables. For a series of studies, the whole range of salt components, temperature, pH, and dissolved oxygen were chosen using a  $2^k$  factorial design of trials. To get the combination of these five parameters causing the lowest corrosion rate of steel, a genetic algorithm was used with combinations of five genes: chloride, sulphate, dissolved oxygen, pH, and temperature.

Mild steel is used in several Engineering applications for the production of some automobile components, structural shapes (I beam and angle iron) and sheets





that are used in pipelines, buildings, plants, bridges and tin cans. It is majorly used as construction materials. However, mild steel is known for its high carbon content of about 0.2% to 2.1%, manganese (1.65%), copper (0.6%), silicon (0.6%). It is produced from steel which is been extracted from pig iron and also less expensive to produce and it is readily available. It has outstanding ductility and toughness

high machinability and weldability which make its applications possible in the engineering fields. The application for which mild steel was developed generally did not involve corrosion resistance as a primary consideration; corrosion resistance of metals and alloys is a basic property related to the ease with which these metals react with a given environment. With the increased utilization of this metal in the manufacturing and construction firms, one of the major problems encountered is the control of corrosion rate when exposed to different corrosive environments. Corrosion is a natural process that reduces the binding energy in metals with the end result involving a metal being oxidized as the bulk metal loses one or more electrons.

### **2.10 Electrochemical Techniques:**

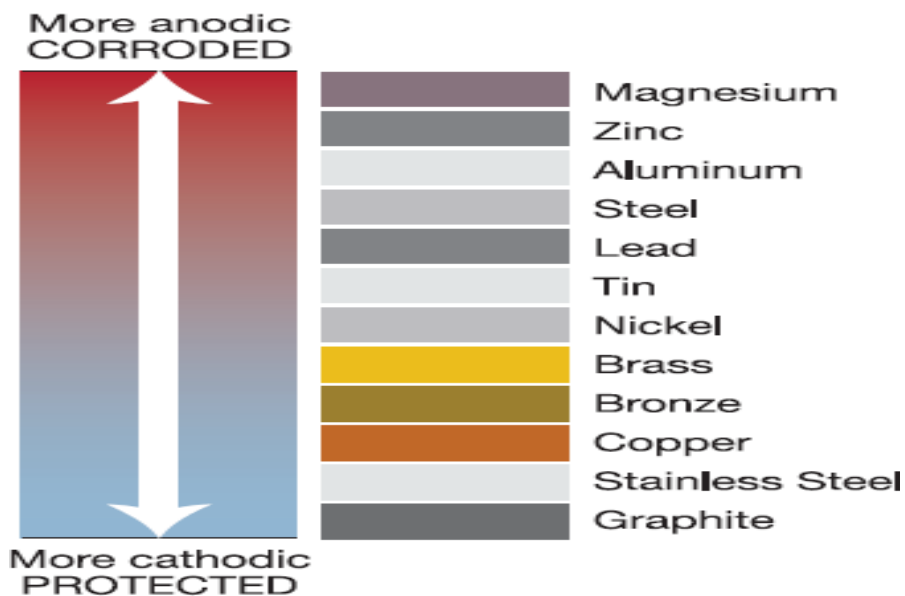
Corrosion is an electrochemical, or “Redox”, process involving electron transfer



redox = reduction-oxidation

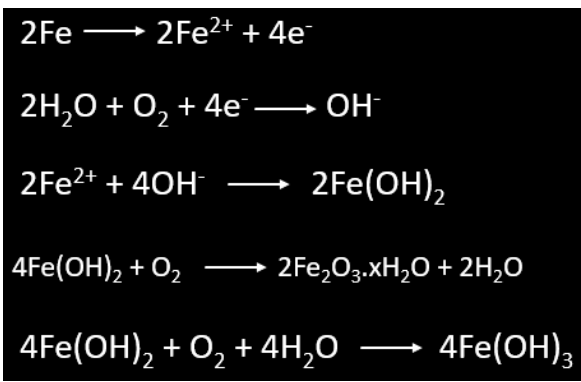
A broad range of electrochemical techniques have been developed specifically for corrosion measurement. Electrochemical techniques are fast. Electrochemical techniques are sensitive. Can be used in the lab or in the field. Corrosion is an inherently slow process. A typical corrosion rate is 10 mills per year (mpy) or 0.254 millimeters per year (mpy) or 254 microns per year. The “best” corrosion tests are weight loss measurements after exposure. However, they are very slow (weeks, months, or years). Electrochemical

instruments polarize the sample to accelerate the corrosion process and make the measurement in minutes or hours.



Electrochemical techniques can measure very low corrosion rates. A sample with a low corrosion rate will exhibit a low current during the electrochemical experiment. Corrosion scientists often use “rate” and “current” interchangeably. Electrochemical instruments can be designed to measure low currents very accurately. A 1 cm<sup>2</sup> iron sample with a corrosion rate of 1 mpy (mills per year) will exhibit a current in the range of 2-5 μA, which can be measured very

accurately by a modern potentiostat. 4 milli-inches corresponds roughly to the diameter of a human hair.



## 2.11 Electrochemistry

The study of chemical reactions accompanied by the exchange of electrons. Electron-transfer is always a factor in electrochemistry. Additional chemistry is sometimes a factor in electrochemistry.

**Oxidation:** Loss of electrons       $\text{Fe} \longrightarrow \text{Fe}^{2+} + 2\text{e}^-$

**Reduction:** Gain of electrons       $2\text{H}^+ + 2\text{e}^- \longrightarrow \text{H}_2$   
 (Remember that LEO (the lion) says GER!)

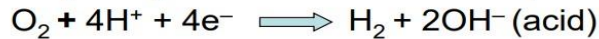
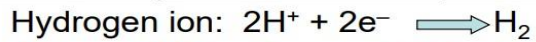
General Echem Reaction:  $\text{Ox} + \text{ne}^- \longrightarrow \text{Red}$

The Oxidized species accepts an electron to form the Reduced species.

### Oxidation: The Metal Being Tested



### Reduction: Usually Some Solution Species



- Oxidation is *always* accompanied by Reduction in both the Real World and the electrochemical experiment.

## 2.3 MECHANISM OF CORROSION INSIDE THE MATERIAL

### 2.3.1 MECHANISM OF UNIFORM CORROSION

Corrosion mechanism in aqueous solution has been amply demonstrated. In atmospheric corrosion which also exemplifies uniform corrosion, a very thin layer of electrolyte is present. It is probably best demonstrated by putting a small drop of seawater on a piece of steel. On comparing the atmospheric corrosion with aqueous corrosion, the following differences are observed:

On a metal surface exposed to atmosphere, only a limited quantity of water and dissolved ions are present, whereas the access to oxygen present in the air is unlimited. Corrosion products are formed close to the metal surface, unlike the case in aqueous corrosion, and they may prevent further corrosion by acting as a physical barrier between the metal surface and environment, particularly if they are insoluble as in the case of copper or lead. The following is a simplified mechanism of aqueous corrosion of iron (Fig. 10):

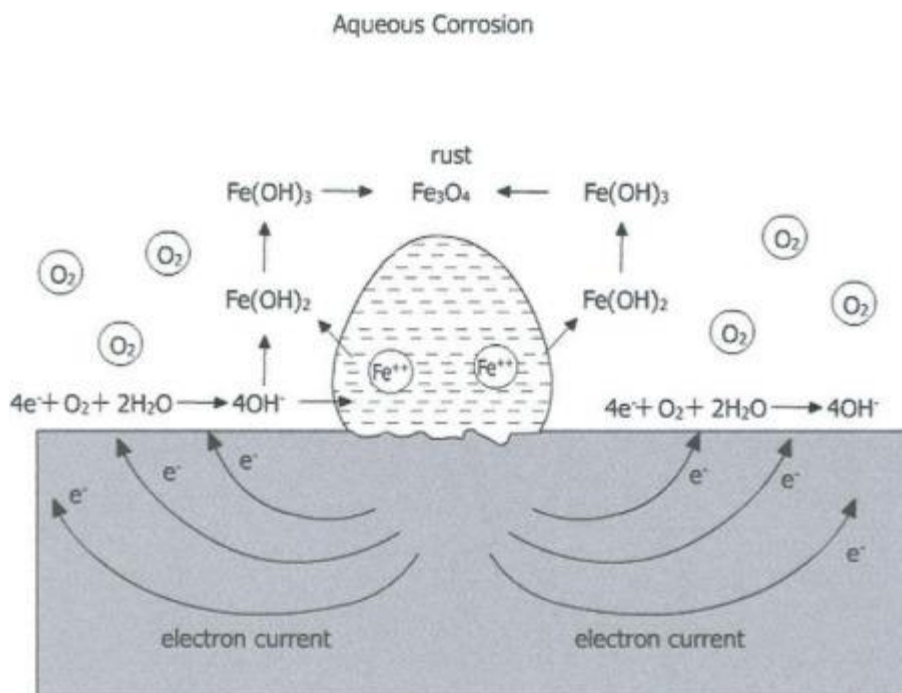
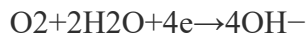


Figure 10 Aqueous corrosion of iron

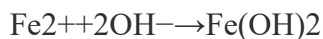
At the anodic areas, anodic reaction takes place:



At the cathodic areas, reduction of oxygen takes place:



The OH ions react with the Fe<sup>++</sup> ions produced at the anode:



With more access to oxygen in the air, Fe(OH)<sub>2</sub> oxidizes to Fe(OH)<sub>3</sub> and later it loses its water:



Ferrous hydroxide is converted to hydrated ferric oxide or rust by oxygen:



Rust (Fe<sub>2</sub>O<sub>3</sub>·H<sub>2</sub>O) is formed halfway between the drop center and the periphery which is alkaline.

The electrons flow from the anode (drop center) to cathode (periphery) in the metallic circuit. The current flow is shown in Fig. 10. The ferrous ions on the surface of iron are soluble whereas those in solution are oxidized by oxygen to insoluble hydrated oxides of ferric called *rust*. The rust is formed away from the corroding site.

The corrosion rate is very high if the ferrous ion is oxidized to ferric oxide rapidly. Fe(OH)<sub>3</sub> is insoluble and if it forms away from a metal surface, the corrosion reaction speeds up as equilibrium is to be

maintained by supplying more ferrous ions ( $\text{Fe}^{++}$ ) from the surface. If, however,  $\text{Fe}(\text{OH})_3$  is formed on the surface of a metal very rapidly, the corrosion is prevented (a passive film).

If  $\text{SO}_2$  is present as a pollutant, in air,  $\text{FeSO}_4$  is produced from equations . The corrosion of iron is significantly affected by the presence of soluble sulfate ion in solution. The sulfate ion continues to attack iron and the surface becomes uneven and even pitted. In this case, layers of porous rust are formed. As no protection is provided by the porous rust to the metal, corrosion continues to take place. The effect of  $\text{SO}_2$ ,  $\text{SO}_3$  and  $\text{Cl}^-$  ions is illustrated in Fig. 11.

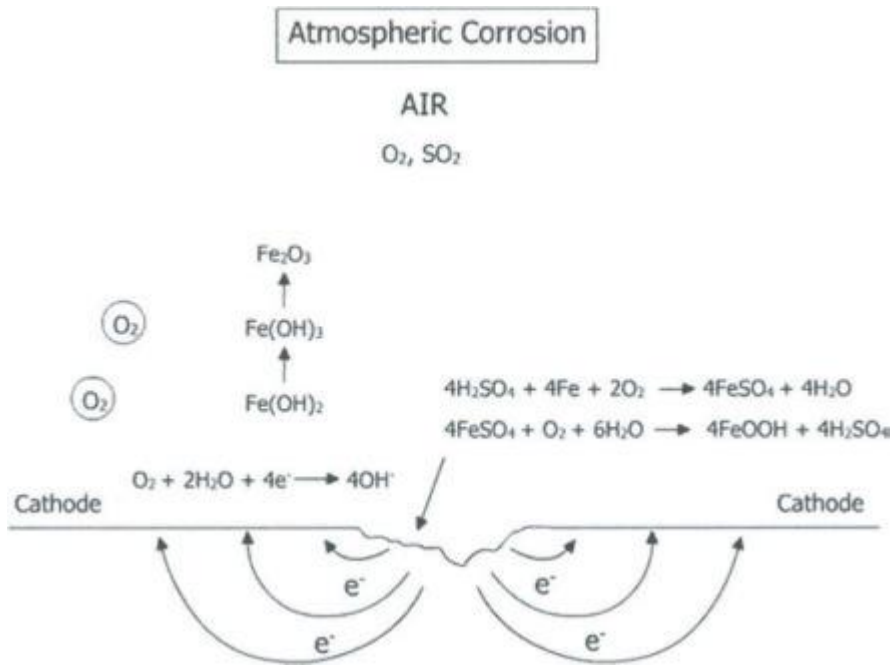


Fig 11

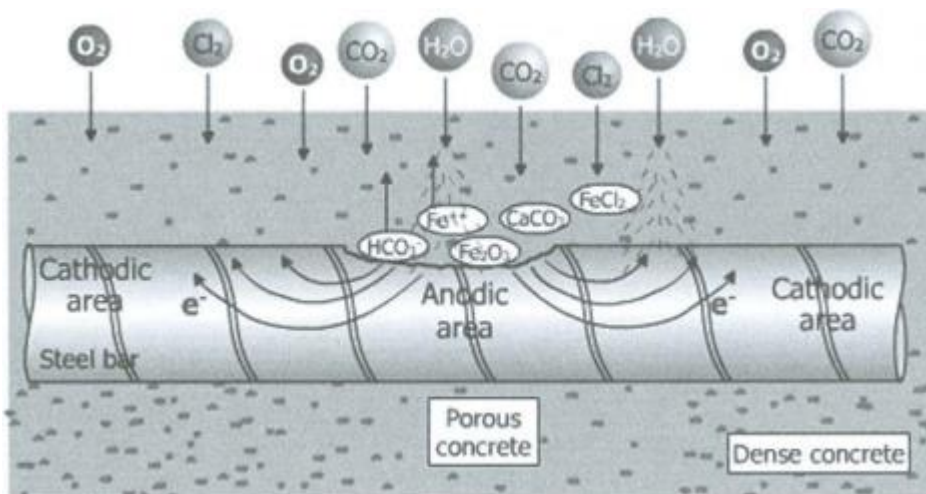


Fig 12

### 2.3.2 ELECTROCHEMICAL PRINCIPLE

When a steel structure is in contact with an open aqueous environment or in underground soil , an electrochemical cell is formed with following anodic and cathodic reactions.

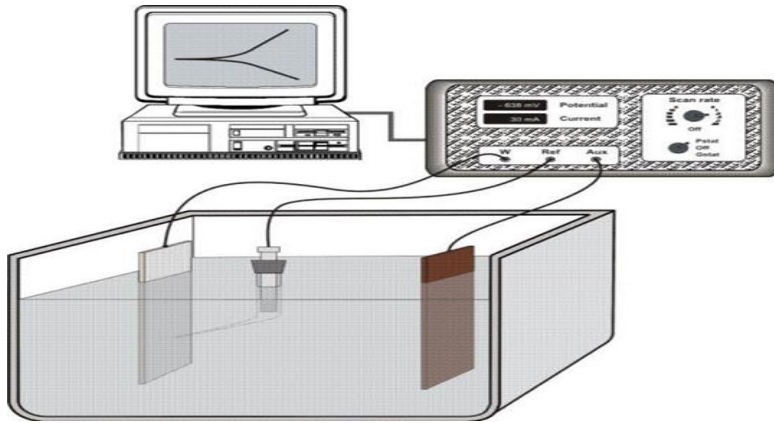
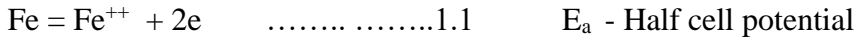
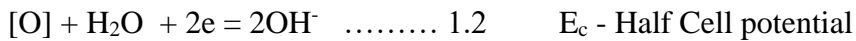


Fig 13



$$\text{The cell potential } E = E_a - E_c \quad \dots\dots\dots 1.3$$

The free energy change associated with it

$$\text{DG} = -nFE , \dots\dots\dots 1.4$$

where n is the no of charge e or electron involved and F is Faraday. The half cell potentials  $E_a$  and  $E_c$  are related to activities and standard potential by Nernst equation as follows.

$$E_a = E_a^0 - \frac{RT}{nF} \ln (a_{\text{Fe}^{++}}) \quad \dots\dots\dots 1.5$$

$$E_c = E_c^0 - \frac{RT}{nF} \ln ( \text{OH}^-)^2 / (\text{O}) \quad \dots\dots\dots 1.6$$

( Assuming the solution behave ideally and activity equals to concentration )

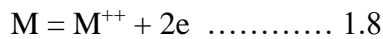
If the resistance of the aqueous electrolyte path in between the anode and cathode be R , then electrochemical corrosion current  $I_0$  can be written as

$$I_0 = (E_a - E_c) / R \quad \dots\dots\dots 1.7$$

Thus corrosion of steel depends on electrode potential  $E_a$  and  $E_c$  , which in turn are related to concentration  $\text{Fe}^{++}$  and  $\text{OH}^-$  ions (pH) , dissolved oxygen concentration , temperature and resistivity of the electrolyte. It has been illustrated how on a same steel piece some regions act as anodic sites and others as cathodic sites.

This is a case of inseparable electrodes. The equivalent electrical circuit shows a cell and current flowing through the resistance offered by the electrolyte. Unlike the normal electrical circuit, here the current is the carrier of the charge through the electrolyte.

Electron flows from anodic sites to cathodic site through steel which also acts as external conductor. If a second metal M with electrode potential  $E_M$  is present in the system, it ionizes as follows



Depending on its position in the EMF series, it may suppress or aggravate corrosion reaction 1.1. In this case, two electrochemical cells will be formed and from the sign and magnitude of free energy change eqn. 1.4, one can find out which metal will preferentially corrode

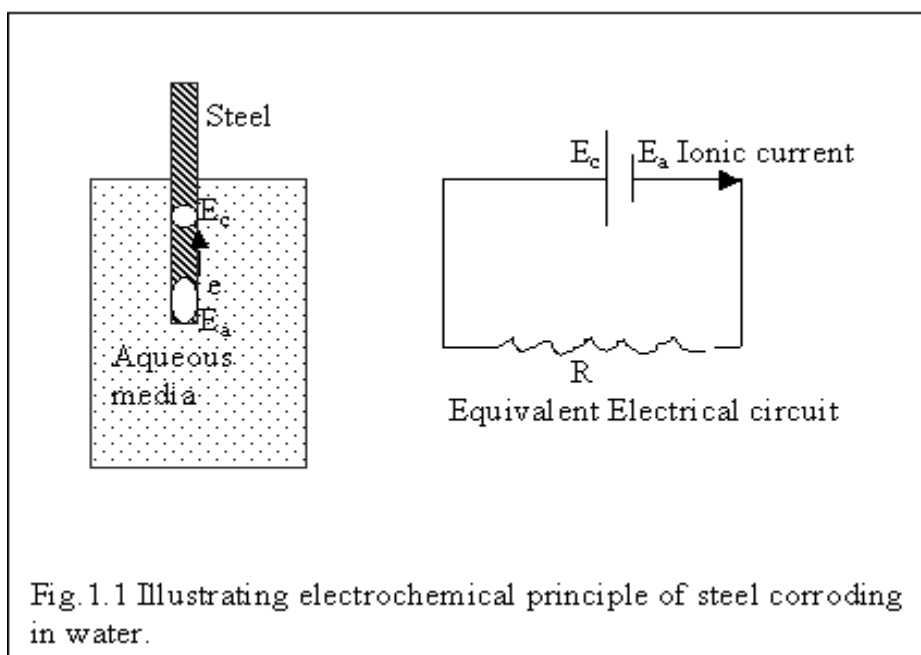


Fig. 1.1 Illustrating electrochemical principle of steel corroding in water.

For example for iron corroding in neutral aerated water, the cell potential is determined from under standard half cell electrode potential

$$E = (0.82)/2 - (-0.440) = 0.85 \text{ volt}$$

From equation 1.4

$$DG = -2 \times 23061 \times 0.85 = -39203.70 \text{ cal}$$

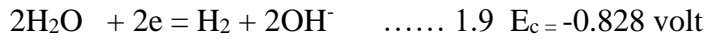
(F= 96500 coulombs converted to 23061 cal/g equivalent/volt)

$$\text{With Zn into the system } \Delta G = -2 \times 23061 \times ((0.82)/2 - (-0.763)) = -54101.106 \text{ Cal}$$

Higher negative free energy value for Zn indicates that zinc will preferentially corrode, protecting steel. Cathodic reaction 1.2 generates  $\text{OH}^-$  ions and so region in the vicinity of steel surface becomes alkaline with increase in pH.

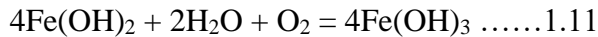
If the electrolyte here is stagnant, such as in under ground soil, soon a different cathodic reaction takes place as follows with higher electrode potential.



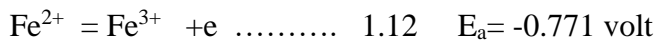


The evolution of hydrogen in the above reaction leads to embitterment of steel hydrogen. The free energy change  $\Delta G$  calculated for the cell using this cathodic reaction will have higher negative value.

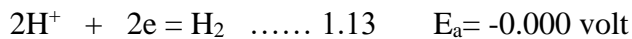
The corrosion product of reactions 1.1 and 1.2 is hydrated ferrous oxide which is not thermodynamically stable and in presence of aerated aqueous media is converted to ferric form.



So another electrochemical reaction with a half cell potential becomes active into the system.



Instead of water or soil, if corrosion takes place in acid the cathodic reaction will be of hydrogen evolution reaction as follows.



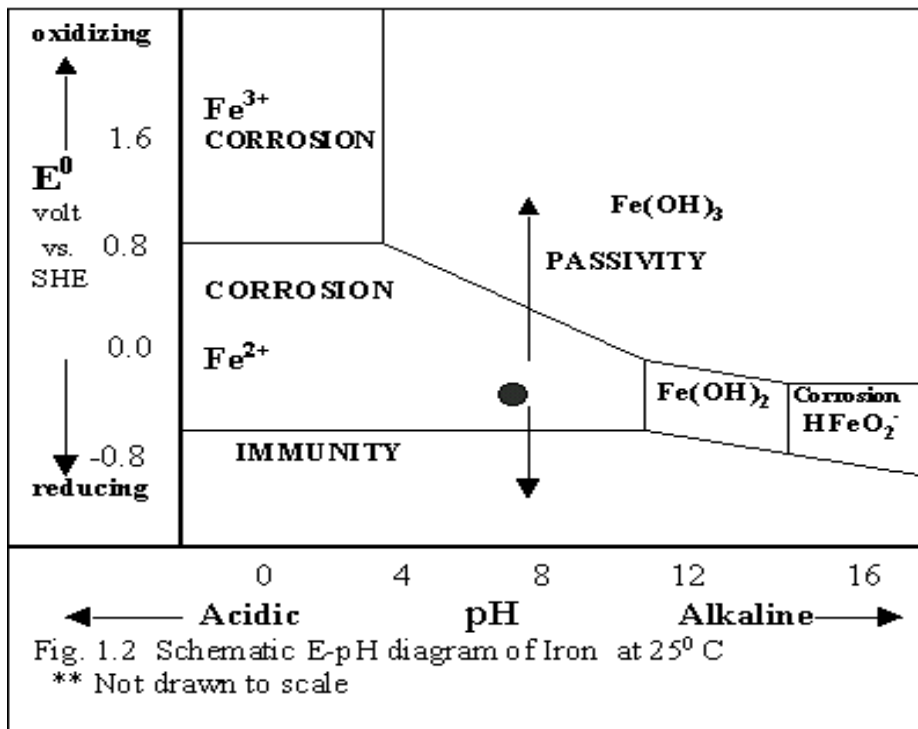
From above discussion it is clear that depending on constituents, concentration and temperature of environment, various electrochemical cells may be formed with different free energy changes and accordingly corrosion of steel would take place

### 2.3.3 E-PH Diagram

It is seen from Nernst equation that electrode potential of steel in aqueous media are influenced by concentration of reacting ions associated with electrochemical reaction.

Depending on the type of environment acidic, neutral, alkaline, oxidizing or reducing, various ions viz.  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{OH}^-$ ,  $\text{H}^+$  as well oxides may be present.

A graphical representation of electrode potential of a metal at different pH values with or without presence of these ions is called a E-PH diagram or Pourbaix diagram after M. Pourbaix who first obtained for different metal-water systems. Detail E-PH diagram of iron with various reactions can be found in any corrosion text. Only utility of the diagram as far as corrosion control is concerned is discussed with a simplified form of it in fig. 1.2



Various environmental conditions such as acidic, alkaline, oxidizing and reducing are indicated by arrows. So for a highly acidic and oxidizing aqueous environment, one has to concentrate near top left portion of the diagram. The diagram maps three major zones of corrosion, passivity and immunity with respective ions or compounds present. Corrosion of steel would take place into the corrosion zones in the acidic regions with formation of  $\text{Fe}^{3+}$  or  $\text{Fe}^{2+}$  ions as well under alkaline condition with formation of hypo ferrite ion (caustic embrittlement of steel). Steel corroding neutral aerated water is indicated by black circle as shown in fig. 1.2

Immunity is the zone where corrosion never occurs. Thermodynamically corrosion is not favourable here and  $\Delta G$  comes out positive. In the passivity zone, on the other hand, corrosion does take place initially, but soon adherent, compact hydrated oxide layer forms over the surface. This oxide layer is passive to corrosive media and acts as a barrier between the metal surface and electrolyte. So the rate of corrosion becomes negligibly small. So in this zone corrosion is thermodynamically favourable but not kinetically. To control corrosion of steel from, one can either move into passivity region shown by arrow from black circle by oxidizing the system that is dragging electron from the steel, known as Anodic protection or into the immunity region by reducing it that is pumping electron into the steel known as cathodic protection to be covered in later chapters

### 2.3.4 Rate of corrosion

The rate of any chemical reaction  $r$  is amount reacted in unit time per unit area. So the amount reacted  $w$  on surface area  $s$  in  $t$  time can be represented as

$$r = w/st \quad 1.14$$

From above equation unit of rate of corrosion is expressed in **mdd ,which in mg per dm<sup>2</sup> per day**. But often change in weight is not a true representation of degree of representation. For example if very small holes develops into the hull of ship, the amount degraded is not much, but it may lean to entry of sea water into the hull ,making it

accident prone. So it is felt thickness of penetration per unit time is more appropriate and unit of corrosion is also expressed **in mils per year in short mpy**. One mil is thousand of an inch.

Since corrosion is an electrochemical reaction with consumption or production of electrons, the rate of corrosion is a measure of rate of electron flow or current I. By Faraday's law I can be related with the amount reacted w on surface area s in t time.

$$w = Ita/nF \quad 1.15$$

Where a is the atomic weight

$$r = w/s = (a/nF).(I/s)$$

$$\text{Or } r = (a/nF). i \quad 1.16$$

where i is current density that is current per unit area.

Now all the terms within bracket in equation 1.15 is constant for a particular corrosion reaction , **the current density i is proportional to the rate of corrosion**. It is expressed in mA/dm<sup>2</sup> or mA/cm<sup>2</sup>. Electrochemical determination of corrosion rate by i is more accurate and precious than by weight change method mdd or thickness measurement mpy, since very small current in terms of fraction of  $\square A$  can be measured. Corrosion rate i can be converted to mpy , knowing density and atomic weight of the metal from the equation

$$\text{mpy} = 0.129 \text{ ai/nd} \quad 1.17 \quad (i \text{ is in mA/cm}^2, d \text{ gm/cc})$$

### Faraday's Law

$$Q = nFm/A = it$$

Q = coulombs (A-s/eq), n = number of electrons, F = the Faraday (96,487 coulombs/equivalent), m = mass (g), A = atomic weight, i = current (A), t = time (s).

Since Equivalent Weight (EW) = A/n,

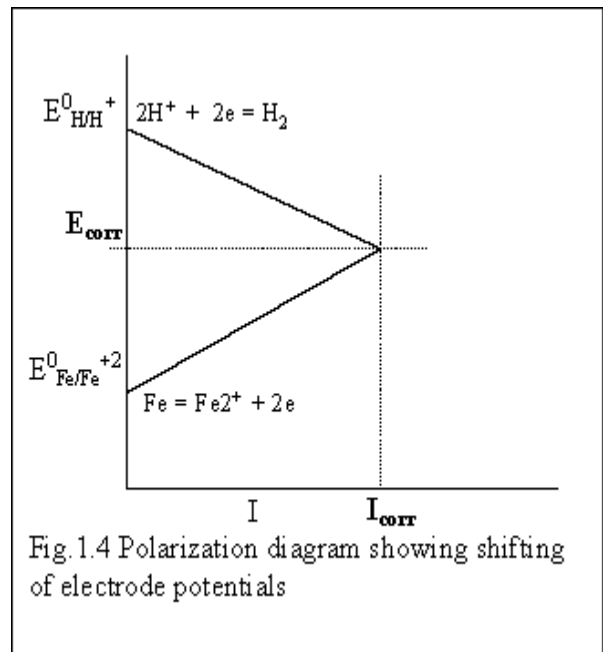
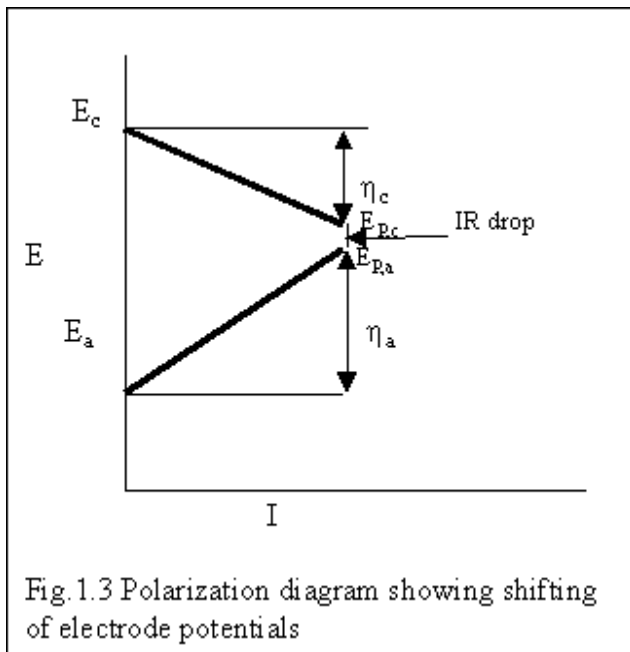
$$m = it(EW)/F$$

Corrosion Rate (g/s) = m/t = i(EW)/F

### 2.3.4 Polarization

It is seen from equation 1.7 that the electrochemical current  $I_0$  flowing through the cell is proportional to  $(E_a - E_c)$ . But as soon as current flows, the electrodes get polarized. Anode potential no more remains at  $E_a$  but increases in the positive direction as  $E_{P,a}$  and cathode potential  $E_c$  shifts in the negative direction to  $E_{P,c}$  as shown in fig.1.3. This phenomenon of shifting of electrode potentials from equilibrium values to polarized potentials is known as Polarization and magnitude of change is called overvoltage, designated by  $\eta$ .

After polarization electrode potentials of anode and cathode come to very close to each other (within about 1-2 mV) and a much smaller current  $I$  indicated by following equation 1.14 flows.



$$I = (E_{P,c} - E_{P,a}) / R \quad 1.18$$

Where resistive part  $R$  consists of electrolyte resistance  $R_{el}$  and external resistance  $R_{ext}$  which is conductive resistance from cathode to anode outside electrolyte so that equation can be written as

$$I R_{el} + I R_{ext} = (E_{P,c} - E_{P,a}) \quad 1.19$$

If the two electrodes are externally short circuited which is the case for inseparable electrodes,  $R_{ext} = 0$ . then,

$$I R_{el} = (E_{P,c} - E_{P,a}) \quad 1.20$$

If the electrolyte is of high conductivity such as acid or sea water,  $R_{el}$  will be negligibly small and may be approximated to very close to zero. Then right hand part of the above equation is close to zero.

$$0 = \eta ( E_{P,c} - E_{P,a} )$$

$$\text{or } E_{P,c} = E_{P,a} = E_{\text{corr}} \quad 1.21$$

Under such conditions cathode potential becomes equal to anode potential and both of them are equal to **corrosion potential**  $E_{\text{corr}}$ . At **corrosion potential** anodic reaction takes place with rate  $I_a$  known as anodic current which is equal and opposite in direction to  $I_c$  cathodic and both of them are equal to  $I_{\text{corr}}$ , **corrosion current** or rate of corrosion. This is illustrated in fig.1.4., with an example of iron corroding in acid. At  $E_{\text{corr}}$  and  $I_{\text{corr}}$ , dissolution of iron takes place in acid at a rate which is equal to the rate of reduction of hydrogen ions so that there is no net accumulation of electron.

$E_{\text{corr}}$  is the mixed potential of the two electrode potential. It will be seen later that both  $E_{\text{corr}}$  and  $I_{\text{corr}}$  have huge implication in combating corrosion of materials

### 2.3.5 Activation Polarization

#### 2.3.6 Why does polarization takes place ?

Before reactants start reacting, they need to achieve the activation energy to surmount to activated state. This energy requirement is proportional to the change in the electrode potential or overvoltage.

$$\Delta G_a^\# = nF\eta_a \quad 1.22 \quad \text{and}$$

$$\Delta G_c^\# = nF\eta_c \quad 1.23$$

Where  $\Delta G_a^\#$  and  $\Delta G_c^\#$  are the activation energies for anodic and Cathodic electrode reactions respectively with corresponding over voltages  $\eta_a$  and  $\eta_c$

For a solid iron surface to react with liquid acid containing  $H^+$  ions following steps need to occur.

- i.  $H^+$  ions must be available in the vicinity of solid surface
- ii. Formation of hydrogen atom by  $H^+ + e = H$
- iii. Adsorption of H to the metal surface as  $H_{ad}$
- iv. Molecular hydrogen by  $H_{ad} + H_{ad} = H_2$
- v. Formation of gas bubble and its detachment.
- vi. Availability of iron surface in contact with acid
- vii. Ionization  $Fe = Fe^{+2} + 2e$

Of all steps of Cathodic reduction reaction ( i- iv), one which will need maximum energy will control the electrode reaction rate and contribute for activation polarization. In general reaction (ii ) and (vii) account for activation polarization for cathodic and anodic reactions respectively.

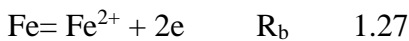
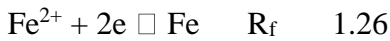
The activation polarization or overvoltage  $\eta$  is related to current density  $i_a$  or  $i_c$  by Tafel 's equation.

$$\eta_a = +\beta_a \log(i_a/i_0) \quad 1.24$$

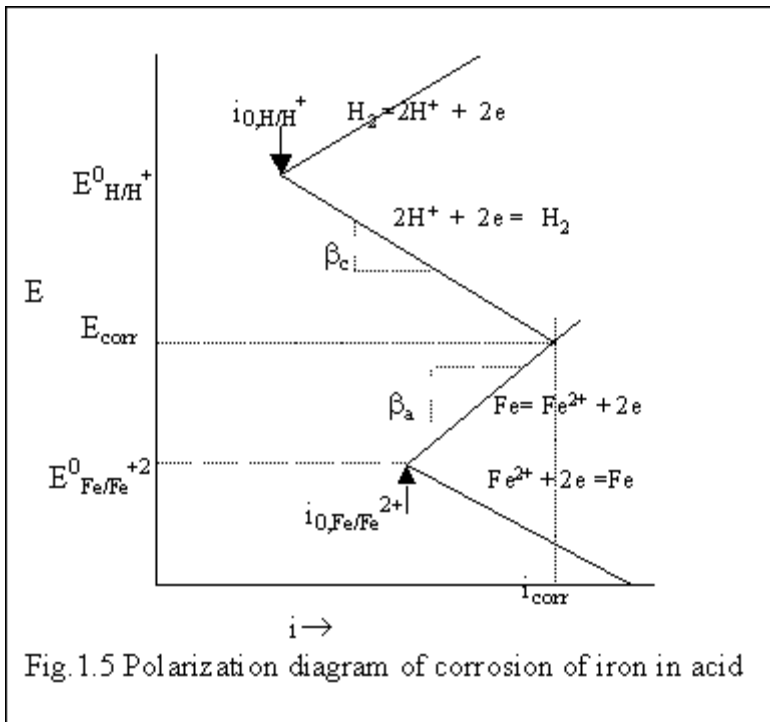
$$\eta_c = -\beta_c \log(i_c/i_0) \quad 1.25$$

where  $i_0$  is the exchange current density.

For any single electrode at equilibrium say Fe/Fe<sup>2+</sup>, rate of forward reaction  $R_f$  is equal to the rate of backward reaction  $R_b$ .



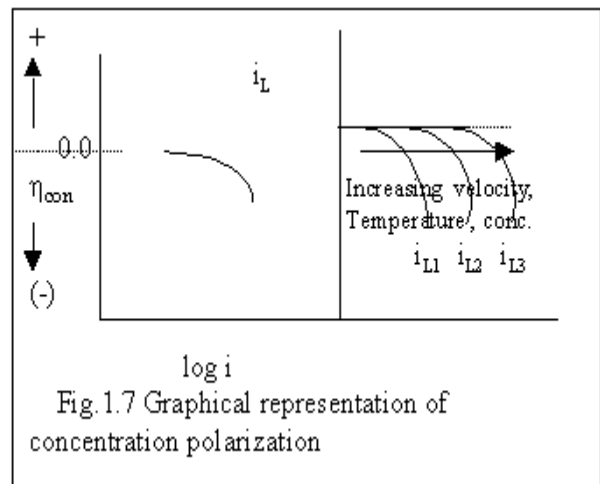
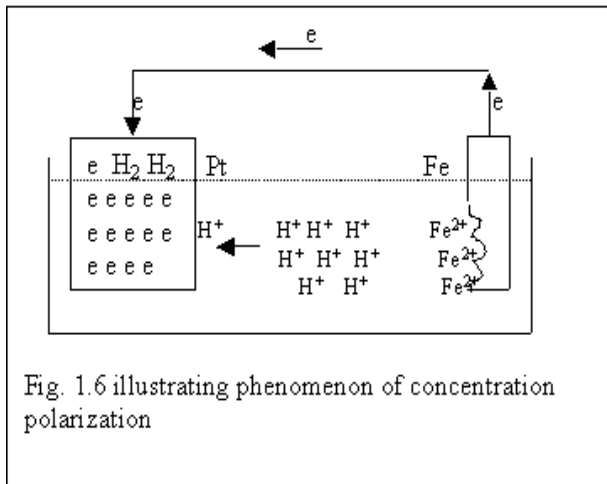
$$R_f = R_b = i_0 a/nF \quad 1.28$$



The exchange current is related to rate of forward reaction and backward reaction by the equation 1.28. Though the rate of forward 1.26 and backward reaction 1.27 are equal, there is no net accumulation Fe<sup>2+</sup> or Fe, still there is a rate which is represented by  $i_0$

### 2.2.18 Concentration polarization

Consider iron two electrodes iron and platinum dipped in acid as shown in fig.1.6.



At anode iron ionizes releasing electrons that pass through the external conductor to other electrode platinum and these electrons discharge hydrogen ions, when they are available in the vicinity of the platinum electrode surface. Once hydrogen ions adjacent to the platinum electrode have been consumed by electron, ions from the bulk of the solution need to diffuse through the solution towards the electrode surface for further reaction. Now the speed of electron movement through the external conductor from anode to cathode is much faster than the diffusional ionic speed of ions through the bulk solution towards the cathode surface. There is concentration deficiency of  $H^+$  ions near cathode surface and build up of negative charge electron, when the electrode potential of the cathode decreases or moves in the negative direction. This phenomenon is known as concentration polarization or Diffusion polarization. At times situation may arise, no  $H^+$  ions are available near cathode surface, no cathodic reaction takes place and overvoltage

approaches to negative infinity( see Fig.1.7). The rate at which it occurs is called limiting current density  $i_L$ . The concentration overvoltage can be given by the equation.

$$h_{con} = 2.3RT/nF \log ( 1- i/i_L) \quad 1.29$$

$$i_L = DnFC/\delta \quad 1.30$$

where  $D$  is the diffusivity of the reaction ion of concentration  $C$ ,  $\delta$  is the thickness of the concentration gradient. Thus  $i_L$  increases (fig.1.7) with higher concentration, higher temperature and solution agitation due to increase in  $D$ .

### 2.2.19 Combined Polarization

The total polarization  $\eta$  is the combined effect of activation and concentration polarization. Concentration polarization is normally absent at anode, since there is unlimited supply of the metal for ionization at anode, Thus total polarization for cathode and anode can be written as ;

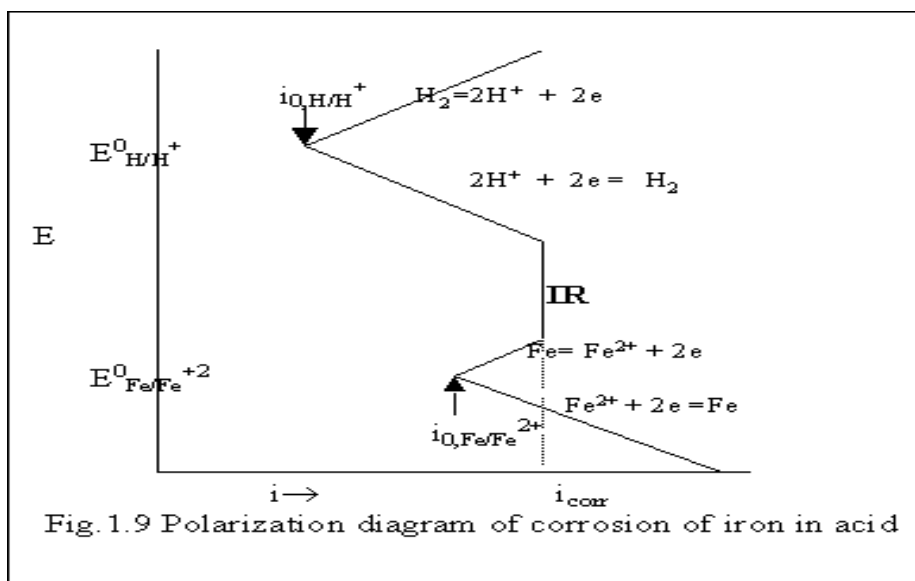
$$h_a = +\eta_a \log(i_a/i_0) \quad 1.31$$

$$\eta_c = -\eta_c \log(i_c/i_0) + 2.3RT/nF \log ( 1- i_c/i_L) \quad 1.32$$

From the above equations, it is seen that for a particular system of a metal corroding in an environment, the parameters  $\eta_a$ ,  $\eta_c$ ,  $i_0$  and  $i_L$  define the system and rate of corrosion is decided by them. In practice there may be more than one anodic reactions and cathodic reactions and each of the equation must follow either of the above two equation

### 2.3.7 Resistance Polarization

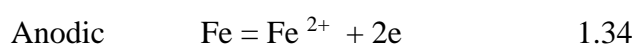
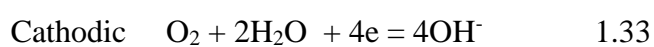
This polarization arises in cases where electrolyte resistance is very high. For example if an insulating coating which separates anodic and cathodic areas, is applied to steel structure. In this case the anodic line and cathodic line instead of intersecting, is separated by resistance polarization IR (fig.1.9).



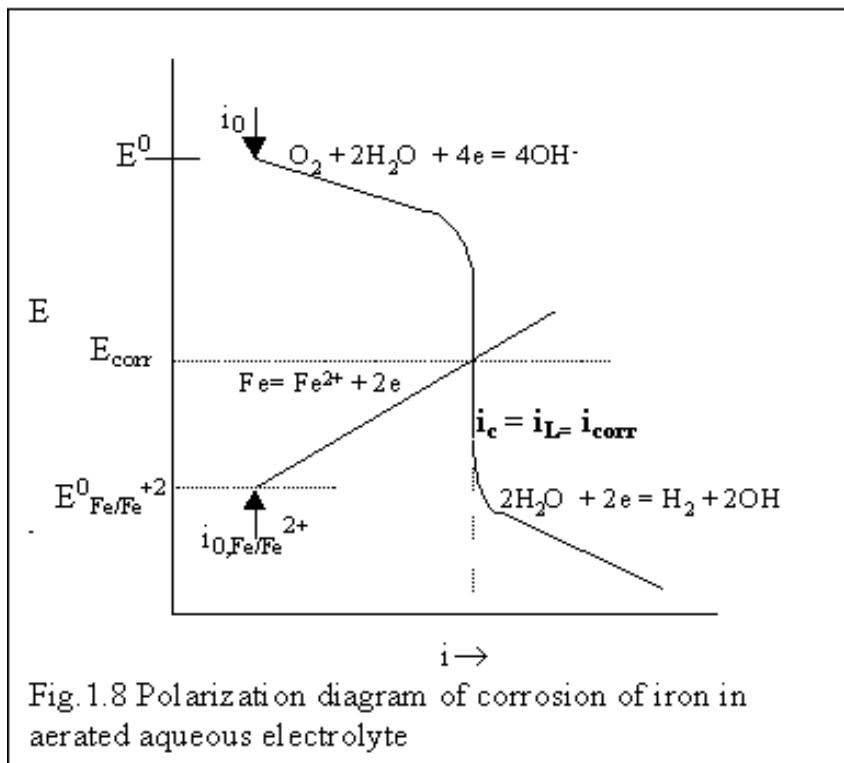
### 2.3.8 Mixed potential theory

According to Mixed potential theory, the total rate of oxidation or sum of anodic currents must be equal to total rate of cathodic current or the sum of cathodic currents and this would occur at the potential,  $E_{corr}$  and current,  $i_{corr}$ .

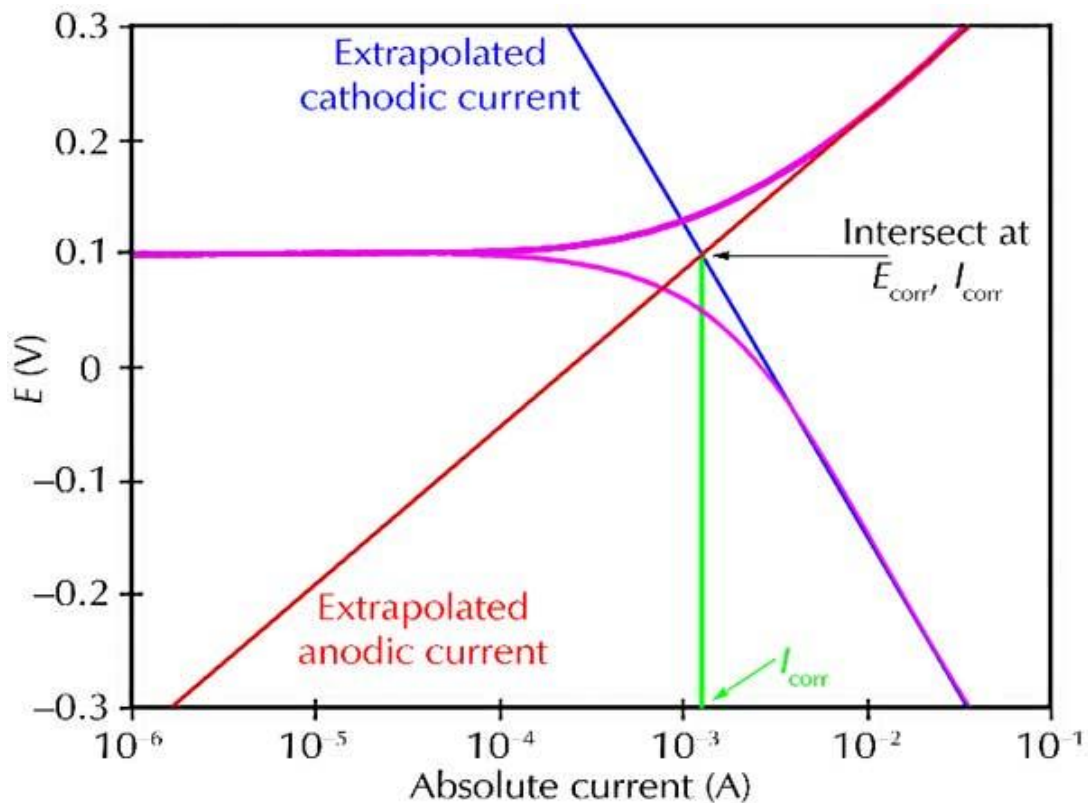
Activation polarization normally occurs in the initial stage of any reaction that is when current or rate is not very high, whereas concentration polarization generally occurs when at a later stage when the current is high. For most cases the point  $E_{corr}$  and  $i_{corr}$  in the region of activation polarization. Hence concentration polarization is normally not considered for determination of corrosion rate. However for corrosion of steel in aerated aqueous media or soil represented by following equations, concentration







Polarization occurs at very early stage. Since the cathodic reduction reaction is controlled by concentration of dissolved oxygen and rate controlling step is the diffusion of dissolved oxygen. So the point of  $E_{\text{corr}}$  and  $i_{\text{corr}}$  is on the concentration polarization line of cathodic reaction.

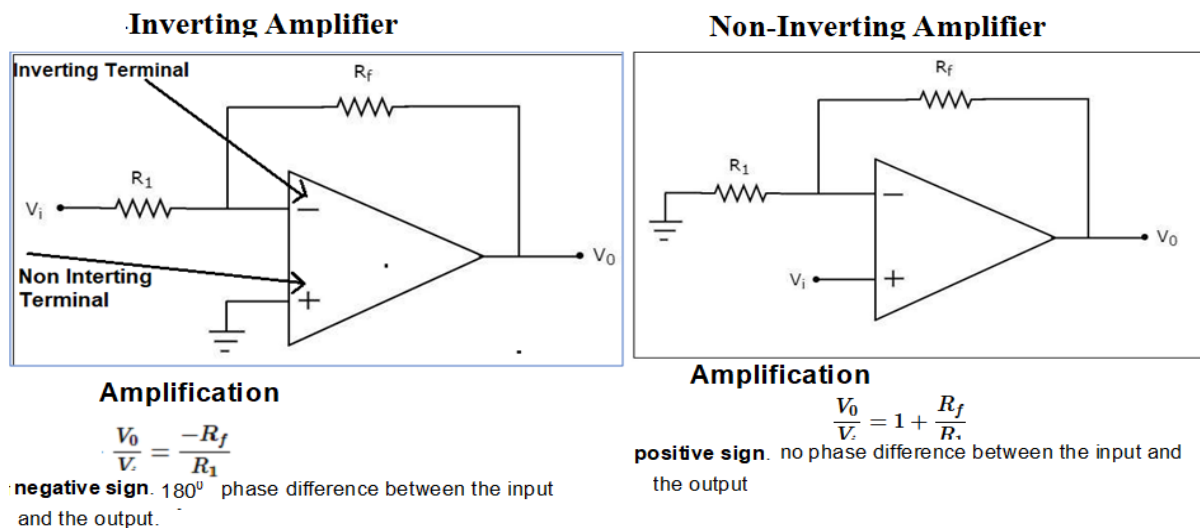


## 2.4 LITERATURE REVIEW FOR ROBOTIC CIERCUIT

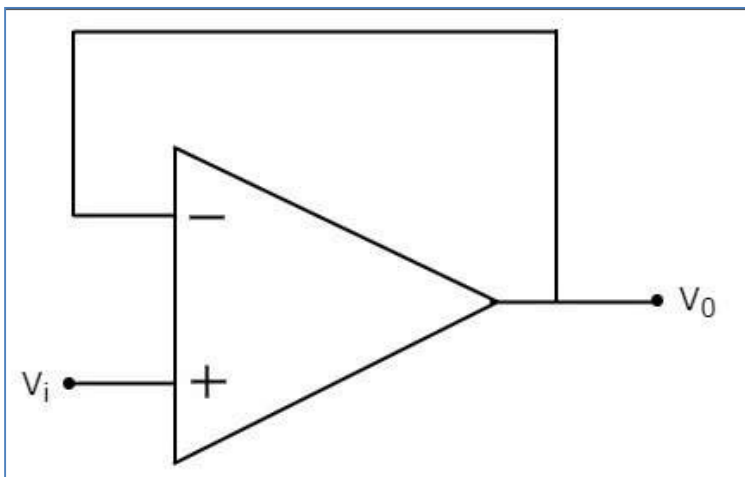
## Arduino Potentiostat Basics Electronics OP Amplifier

### 2.4.1 Inverting Amplifier and Non-Inverting Amplifier

An inverting amplifier takes the input through its inverting terminal through a resistor  $R_1$ , and produces its amplified version as the output. This amplifier not only **amplifies the input** but also **inverts it (changes its sign)**. A non-inverting amplifier is having a **positive sign**. It indicates that there is no phase difference between the input and the output.



### 2.4.2 Voltage follower

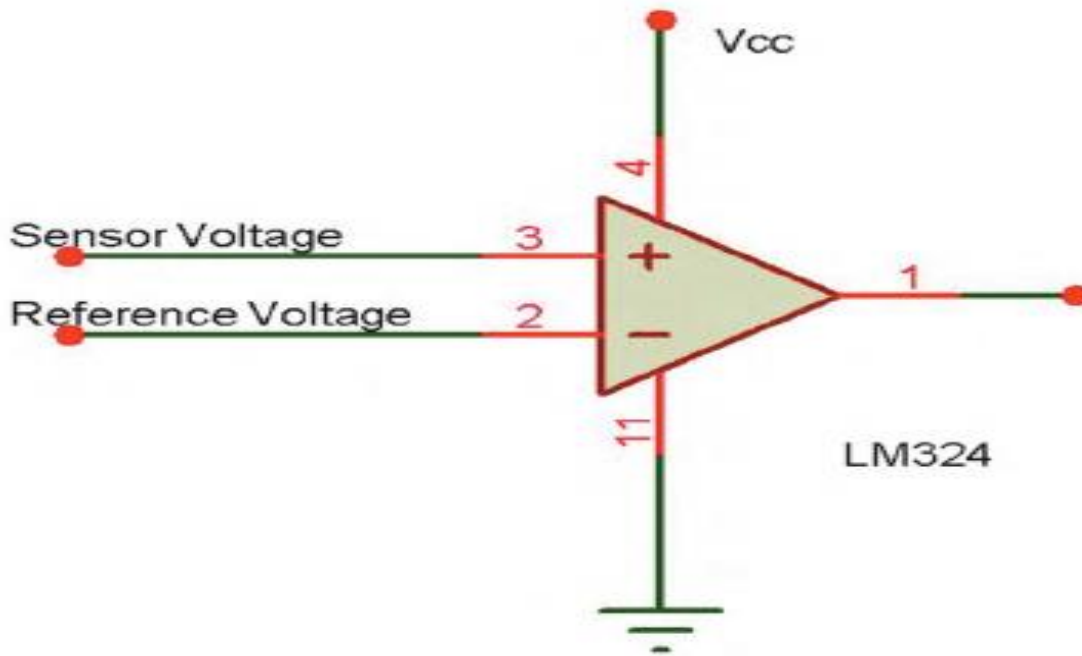


A **voltage follower** produces an output that follows the input voltage. It is a special case of non-inverting

amplifier. when  $R_f = 0$  and  $R_1 = \text{infinity}$ , then a non-inverting amplifier becomes a voltage follower.

$$V_0 = V_i$$

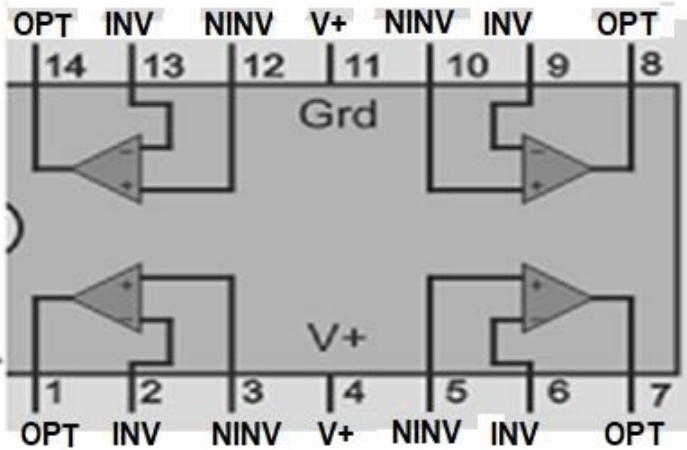
### 2.4.3 Comparator



A **comparator** is an electronic circuit, which compares the two inputs that are applied to it and produces an output. An op-amp consists of two input terminals and hence an op-amp based comparator compares the two inputs that are applied to it and produces the result of comparison as the output.

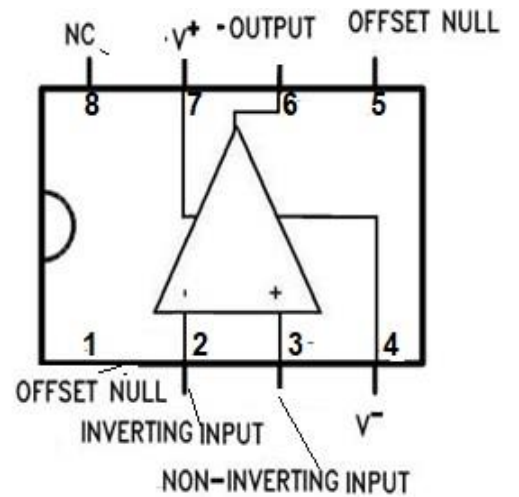
**Types of Comparators** Comparators are of two types : Inverting **and** Non-inverting

### 2.4.4- Two operational amplifier LM 324 LM 741

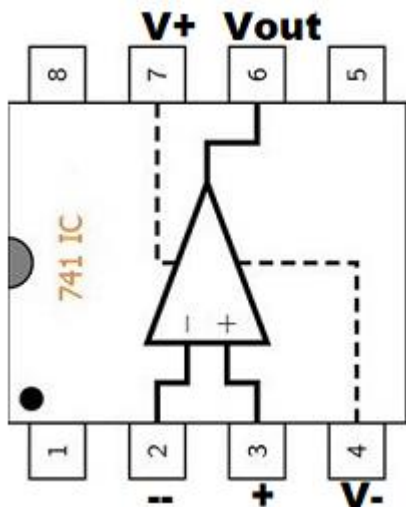


OPT: output INV: Inverting Input NINV: Non Inverting Input

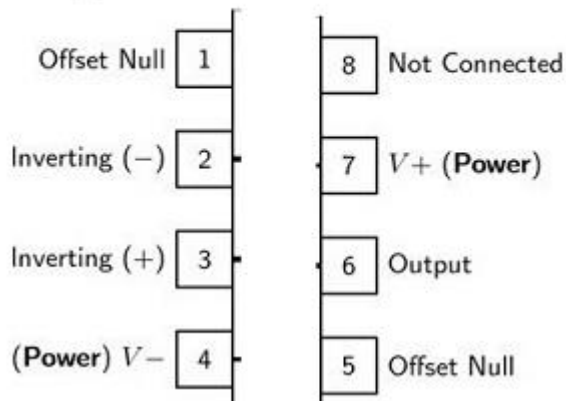
LM324 pin diagram



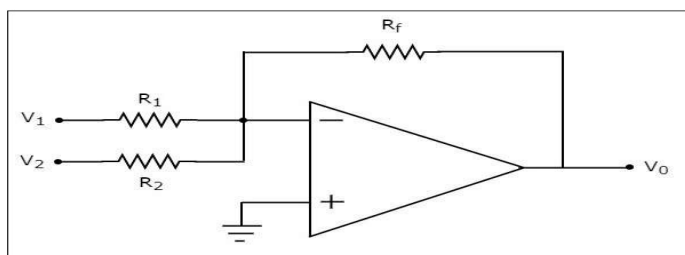
LM741 Pinout Diagram



LM 741



### 2.4.5-Summing Amplifier (Adder)



An op-amp based adder produces an output equal to the sum of the input voltages applied at its inverting terminal. It is also called as a **summing amplifier**, since the output is an amplified one

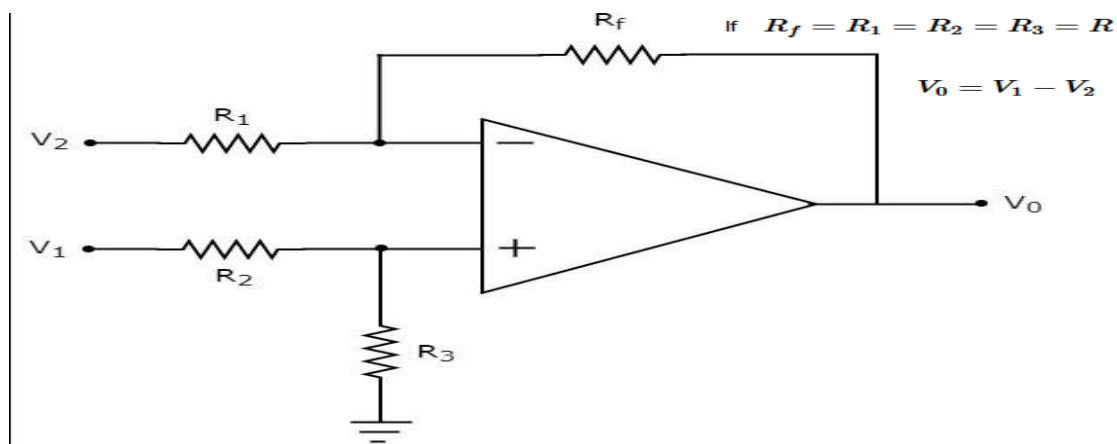
$$V_0 = R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} \right)$$

if  $R_f = R_1 = R_2 = R$ , then the output voltage  $V_0$  will be

$$V_0 = -R \left( \frac{V_1}{R} + \frac{V_2}{R} \right) \Rightarrow V_0 = -(V_1 + V_2)$$

Therefore, the op-amp based adder circuit discussed above will produce the sum of the two input voltages  $v_1$  and  $v_1$ , as the output, when all the resistors present in the circuit are of same value. Note that the output voltage  $V_0$  of an adder circuit is having a **negative sign**, which indicates that there exists a  $180^\circ$  phase difference between the input and the output..

#### 2.4.6-Difference amplifier (subtractor)



It produces an output, which is equal to the difference of the applied input

$$V_0 = V_1 \left( \frac{R_3}{R_2 + R_3} \right) \left( 1 + \frac{R_f}{R_1} \right) - \left( \frac{R_f}{R_1} \right) V_2$$

if  $R_f = R_1 = R_2 = R_3 = R$ , then the output voltage  $V_0$  will be

$$V_0 = V_1 \left( \frac{R}{R + R} \right) \left( 1 + \frac{R}{R} \right) - \left( \frac{R}{R} \right) V_2$$

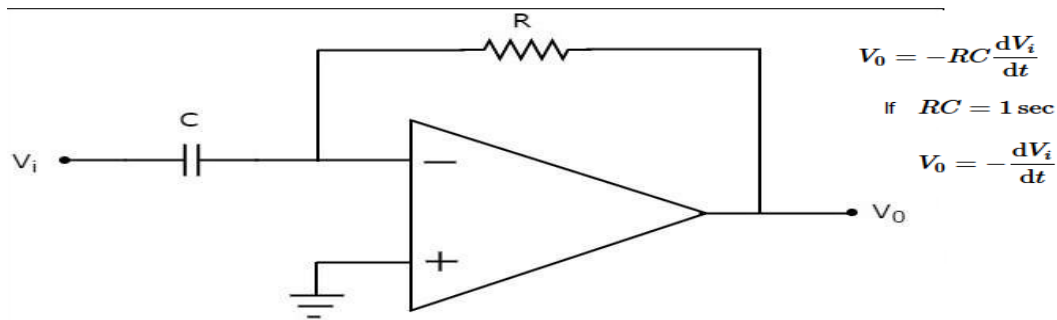
$$\Rightarrow V_0 = V_1 \left( \frac{R}{2R} \right) (2) - (1)V_2$$

$$V_0 = V_1 - V_2$$

### 2.5 RC CIRCUIT

#### 2.5.1-DIFFERENTIATOR

A **differentiator** produces an output equal to the first derivative of its input.



In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal. According to the **virtual short concept**, the voltage at the inverting input terminal of opamp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts.

The nodal equation at the inverting input terminal's node is -

$$C \frac{d(0 - V_i)}{dt} + \frac{0 - V_0}{R} = 0 \Rightarrow -C \frac{dV_i}{dt} = \frac{V_0}{R}$$

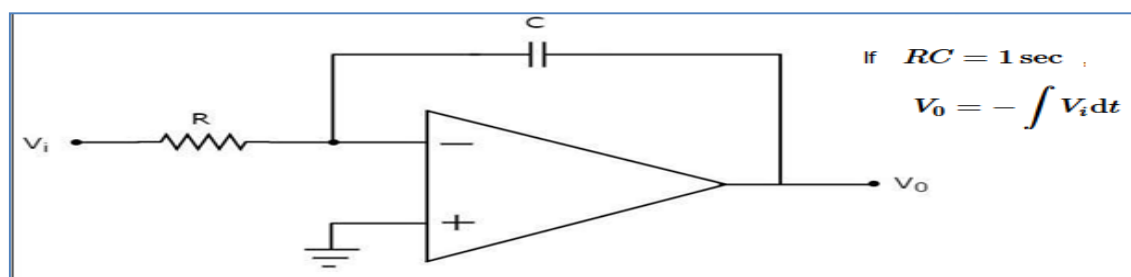
$$\Rightarrow V_0 = -RC \frac{dV_i}{dt}$$

$$\text{if } RC = 1 \text{ sec} \quad V_0 = -\frac{dV_i}{dt}$$

Note that the output voltage  $V_0$  is having a **negative sign**, which indicates that there exists a  $180^\circ$  phase difference between the input and the output.

### 2.5.2 -INTEGRATOR

An **integrator** is an electronic circuit that produces an output that is the integration of the applied input.



An op-amp based integrator produces an output, which is an integral of the input voltage applied to its inverting terminal. In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

According to **virtual short concept**, the voltage at the inverting input terminal of op-amp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts.

So, the op-amp based integrator circuit discussed above will produce an output, which is the integral of input voltage  $V_i$ , when the magnitude of impedances of resistor and capacitor are reciprocal to each other.

**Note** – The output voltage,  $V_0$  is having a **negative sign**, which indicates that there exists  $180^\circ$  phase difference between the input and the output.

$$\frac{0 - V_i}{R} + C \frac{d(0 - V_0)}{dt} = 0 \quad \Rightarrow \quad \frac{-V_i}{R} = C \frac{dV_0}{dt}$$

$$\Rightarrow \frac{dV_0}{dt} = -\frac{V_i}{RC} \quad \Rightarrow \quad dV_0 = \left(-\frac{V_i}{RC}\right) dt$$

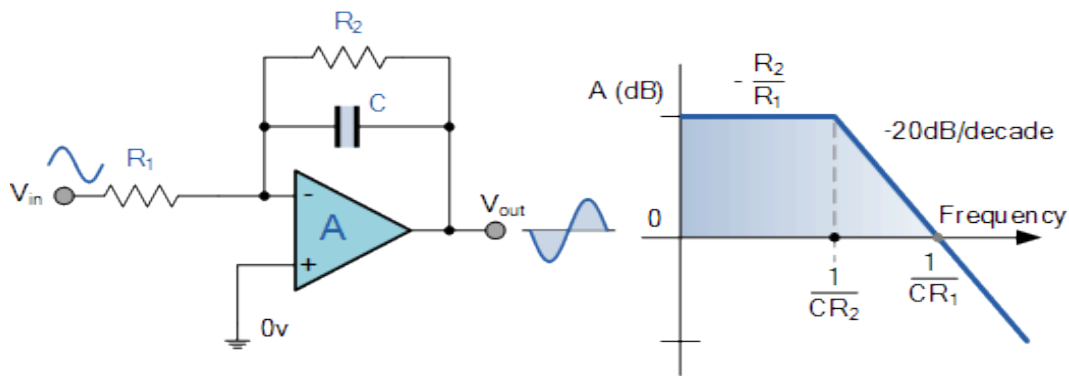
Integrating both sides of the equation shown above, we get –

$$\int dV_0 = \int \left(-\frac{V_i}{RC}\right) dt \quad \Rightarrow \quad V_0 = -\frac{1}{RC} \int V_i dt$$

If  $RC = 1 \text{ sec}$ , then the output voltage,  $V_0$  will be –

$$V_0 = -\int V_i dt$$

### 2.5.3-The AC Op-amp Integrator with DC Gain Control



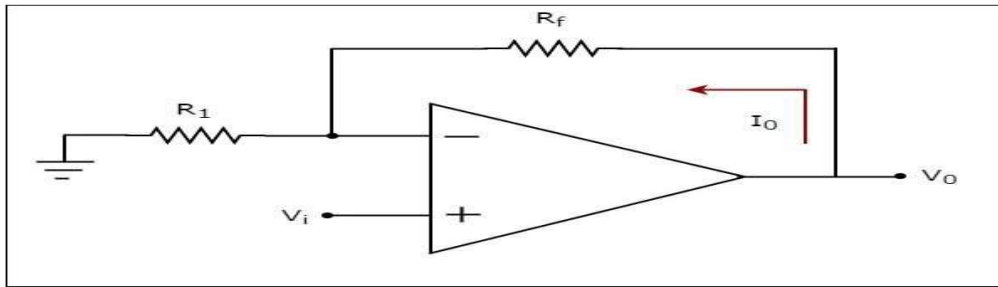
$$\text{D.C. Voltage Gain, } (A_{V_0}) = -\frac{R_2}{R_1}$$

$$\text{A.C. Voltage Gain, } (A_V) = -\frac{R_2}{R_1} \times \frac{1}{(1 + 2\pi f C R_2)}$$

$$\text{Corner Frequency, } (f_0) = \frac{1}{2\pi C R_2}$$

### 2.5.4-Voltage to Current Converter

A **voltage to current converter** or **V to I converter**, is an electronic circuit that takes current as the input and produces voltage as the output. An op-amp based voltage to current converter produces an output current when a voltage is applied to its non-inverting terminal.



The **nodal equation** at the inverting input terminal's node is -

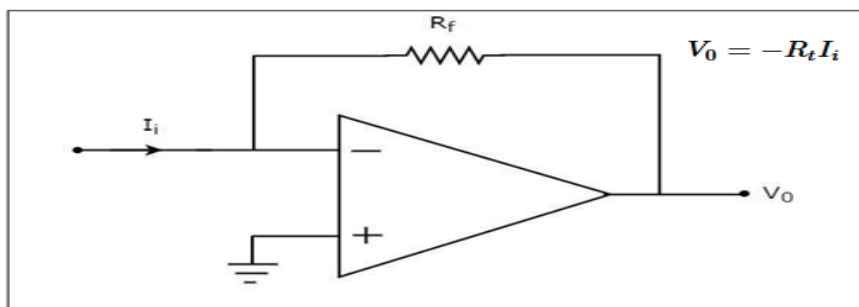
$$\frac{V_i}{R_1} - I_0 = 0 \quad \Rightarrow \quad I_0 = \frac{V_i}{R_1}$$

Thus, the **output current**  $I_0$  of a voltage to current converter is the ratio of its input voltage  $V_i$  and resistance  $R_1$

$$\frac{I_0}{V_i} = \frac{1}{R_1}$$

### 2.5.5-Current to Voltage Converter

A **current to voltage converter** or **I to V converter** is an electronic circuit that takes current as the input and produces voltage as the output. An op-amp based current to voltage converter produces an output voltage when current is applied to its inverting terminal.



The **nodal equation** at the inverting terminal's node is -

$$-I_i + \frac{0 - V_0}{R_f} = 0 \quad -I_i = \frac{V_0}{R_f}$$

$$V_0 = -R_f I_i$$

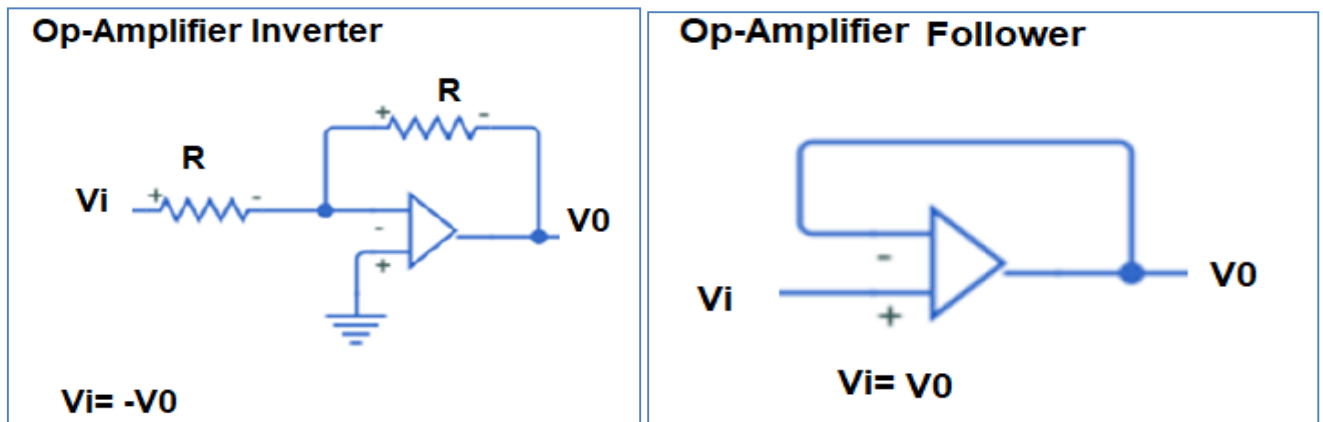
Thus, the **output voltage**,  $V_0$  of current to voltage converter is the (negative) product of the feedback resistance  $R_f$  and the input current,  $I_i$

$V_0$  is having a **negative sign**, which indicates that there exists a  $180^\circ$  phase difference

### 2.5.6-The Op-amp Inverter



The inverter does not amplify if both resistances are equal but does invert the input signal. The input impedance is equal to  $R$  and the gain is  $-1$  giving  $V_{out} = -V_{in}$



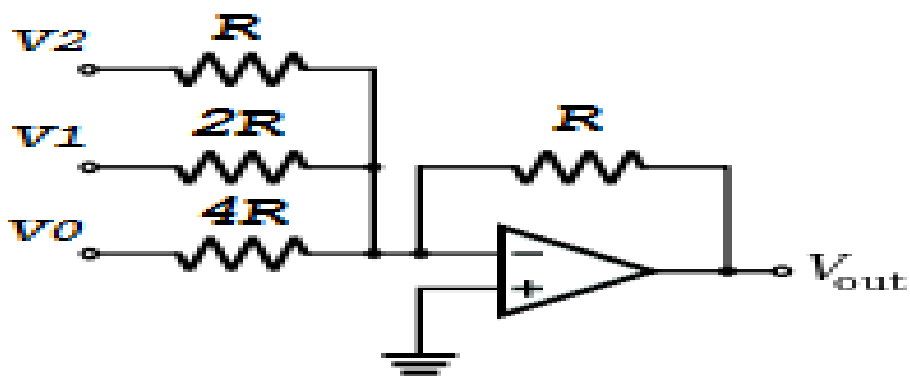
### 2.5.7-Digital to Analogue Converter ( DAC)

A digital-to-analog converter (DAC, D/A, D2A or D-to-A) is a circuit that converts digital data (usually binary) into an analog signal (current or voltage)

## 2.6-Types of DACs

### 2.6.1. Summing Amplifier

Since digital to analog conversion is simply a weighted sum of the binary input, a circuit called a summing amplifier is used. This is basically an op-amp amplifier with multiple resistors connected to one input.



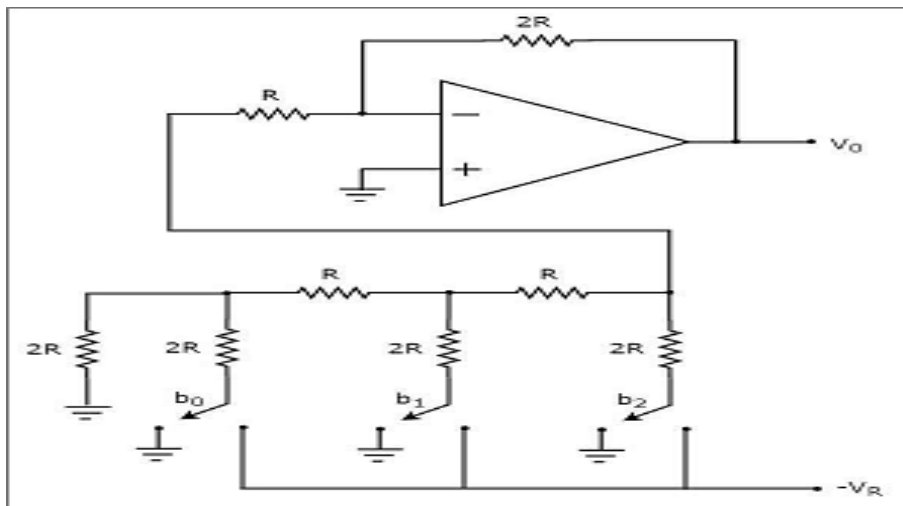
$$V_{out} = -R\left(\frac{V_2}{R} + \frac{V_1}{2R} + \frac{V_0}{4R}\right) \quad V_{out} = -\frac{1}{4}(4V_2 + 2V_1 + V_0)$$

Output Table				
V2	V1	V0	Digital Value	Vout
0	0	0	0	0
0	0	1	1	-0.25
0	1	0	2	-0.5
0	1	1	3	-0.75
1	0	0	4	-1.0
1	0	1	5	-1.25
1	1	0	6	-1.5
1	1	1	7	-1.75

### 2.6.2 R-2R Ladder

This is the simplest type of DAC and needs only two resistor values arranged in a ladder. You can think of this as a somewhat complex voltage divider, though the math is quite complex.

The binary input goes into the 2R resistors and the output is obtained at the bottom of the ladder.



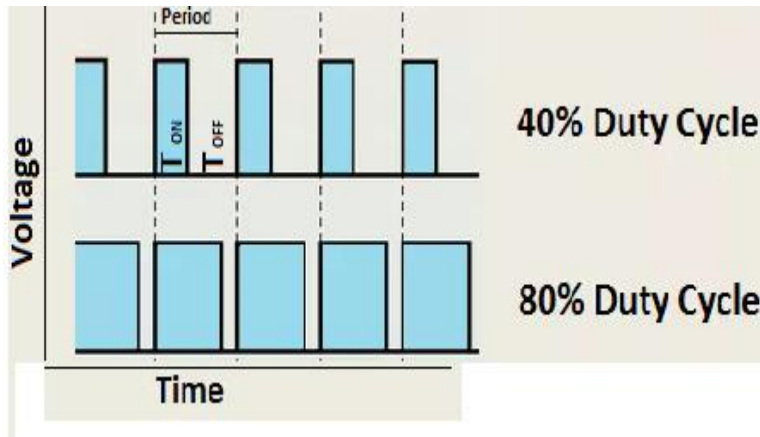
### 2.6.3 PWM DAC

The popular Arduino microcontroller has the capability to output analog signals using a PWM signal. On the outset the PWM signal looks like a binary waveform with only high and low peaks with a variable duty cycle (ratio of on time to time period). **frequency for 5,6 pins =980Hz, frequency for 3, 9, 10 and 11 = 490Hz**

**frequency for 5,6 pins =980Hz, frequency for 3, 9, 10 and 11 = 490Hz**

**analogWrite(0) 0% duty cycle.**

**analogWrite(127) 50% duty cycle.**



**TON (On Time):** It is the time when the signal is high.

**TOFF (Off Time):** It is the time when the signal is low.

**Period:** It is the sum of on time and off time.

**Duty Cycle:** It is the percentage of time when the signal was high during the time of period.

**analogWrite(0)** means a signal of 0% duty cycle.

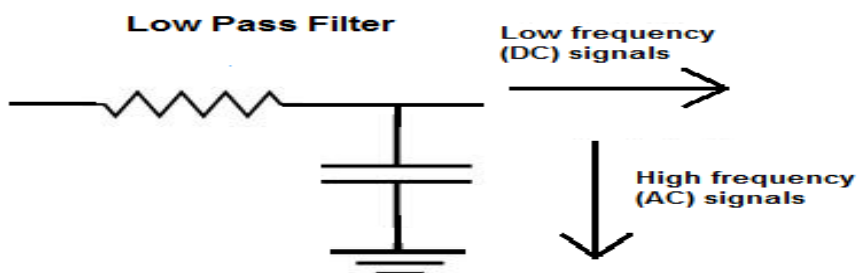
**analogWrite(127)** means a signal of 50% duty cycle.

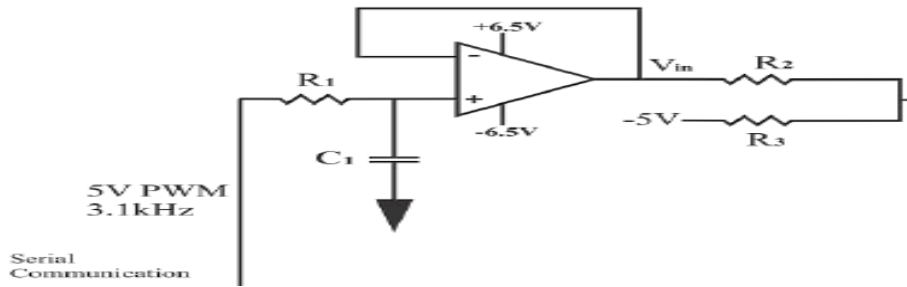
**analogWrite(255)** means a signal of 100% duty cycle.

**RC filter to convert the PWM signal into a voltage**

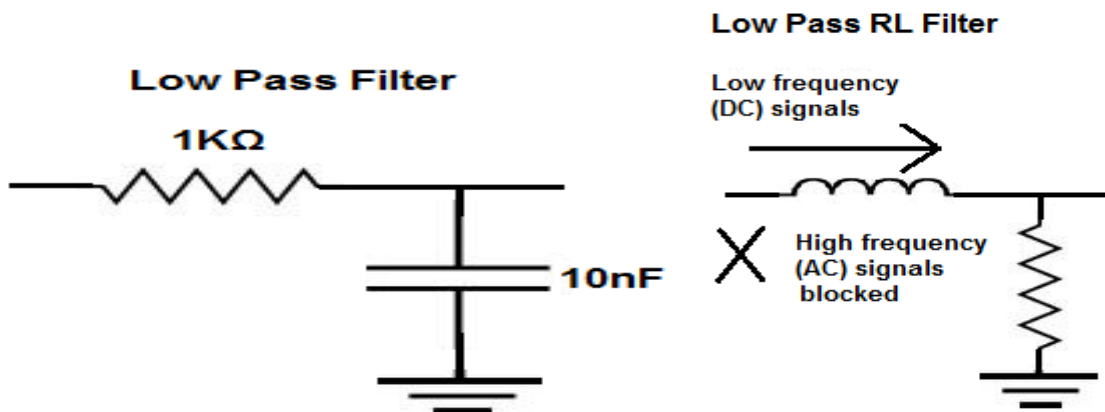
However, this is intended to be used with a **RC filter** to convert the PWM signal into a voltage value by filtering out the AC component and leaving behind the DC component. The voltage output is proportional to the duty cycle of the input – the higher the duty cycle the greater the output voltage of the filter.

## 2.7 Low Pass RC Filter





A Low pass RC filter, again, is a filter circuit composed of a resistor and capacitor which passes through low-frequency signals, while blocking high frequency signals. To create a low pass RC filter, the resistor is placed in series to the input signal and the capacitor is placed in parallel to the input signal, such as shown in the circuit below:

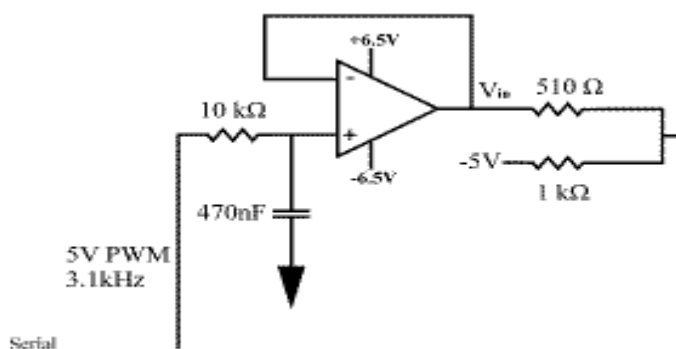


The formula to find the frequency cutoff point of an RC circuit is, **frequency=  $1/2\pi RC$** .

Doing the math, with the values shown above, we get a frequency of,

**frequency=  $1/2\pi RC = 1/(2(3.14)(1K\Omega)(10nF)= 15,923 \text{ Hz}$** , which is approximately 15.9KHz.

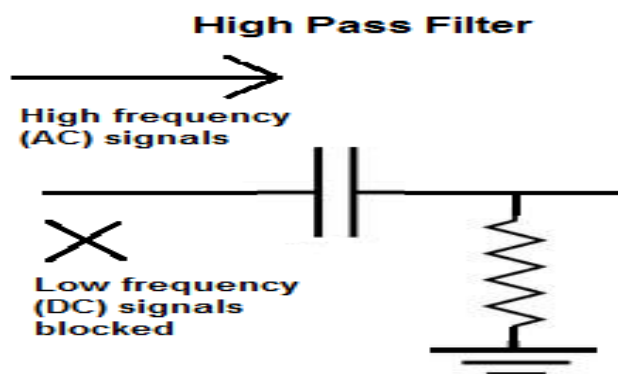
**This means that all frequencies above 15.9KHz are attenuated.** Frequencies below 15.9KHz are passed through without attenuation.



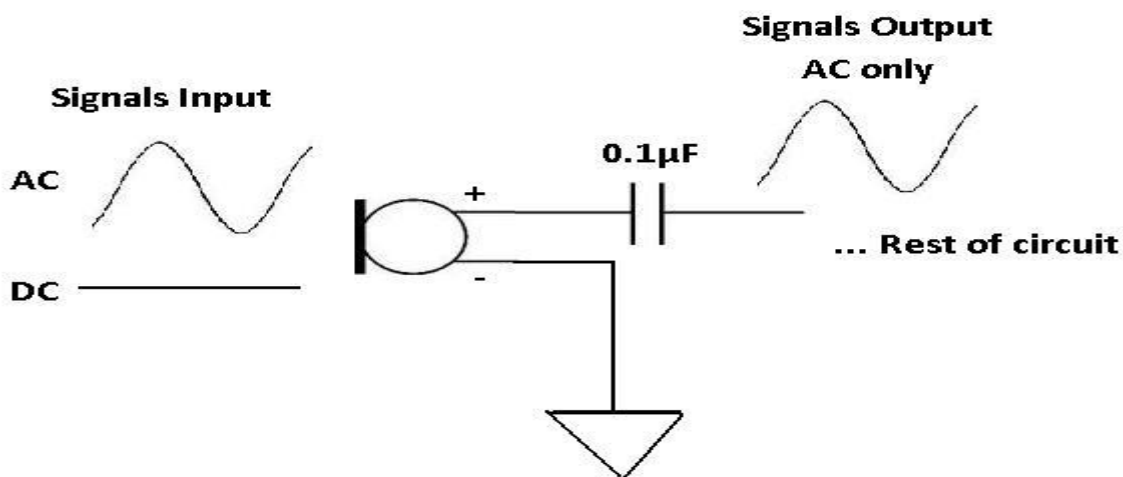
**frequency=  $1/2\pi RC = 1/(2(3.14)(10K\Omega)(470nF)=1/(2*3.14*10000*470*10^{-9})=33.88 \text{ Hz}$**

**This means that all frequencies above 33.88 Hz are attenuated.** Frequencies below 33.88 Hz are passed through without attenuation.

## High Pass RC Filter



A high pass RC filter, again, is a filter which passes through high-frequency signals, composed of a resistor and capacitor. To create a high pass RC filter, the capacitor is placed in series with the power signal entering the circuit, such as shown in the circuit below:



### 2.7.1 Analogue to Digital converter (ADC)

An analog to digital converter (ADC) is an electronic device which converts varying analog signals into digital signals so that they can easily be read by the digital devices.

The digital output varies from 0-255. ADC needs a clock to operate. The time taken to convert the analog to digital value depends on the clock source. An external clock can be given to CLK IN pin no.4. A suitable RC circuit is connected between the clock IN and clock R pins to use the internal clock

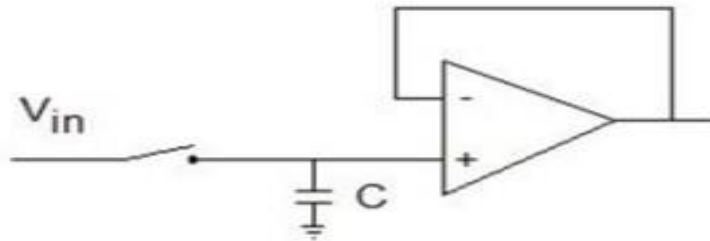
Basically the digital numbers used here are binary i.e '0' and '1'. The '0' indicates the 'off' state and '1' represents the 'on' state. Hence all the analog values are converted into digital binary values by an ADC

### 2.7.2 ADC PROCESS and How ADC works ?

Mainly there are two steps for the analog to digital conversion:

1. S/H: Sampling and holding
2. Q/E: Quantizing and Encoding

### Sampling and Holding

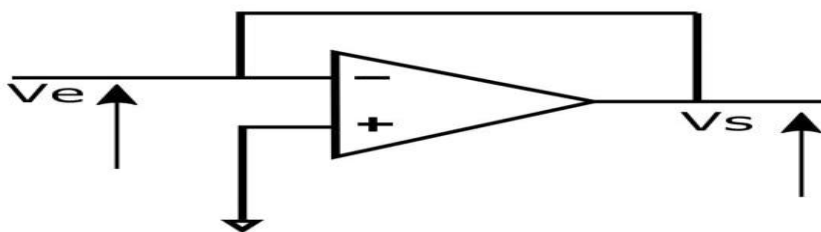


An analog signal continuously changes with time, in order to measure the signal we have to keep it steady for a short duration so that it can be sampled. We could measure the signal repeatedly and very fast, and then find out the right time scale. or we could measure the signal at different timings and then average it. Or preferably we can hold the signal for a specific duration and then digitize the signal and sample the value. This is done by a sample and hold circuit. For, at least the time required for digitization, it keeps the value stable. Figure shows the circuit for sampling and holding of a signal.

## 2.8 Fundamental OP

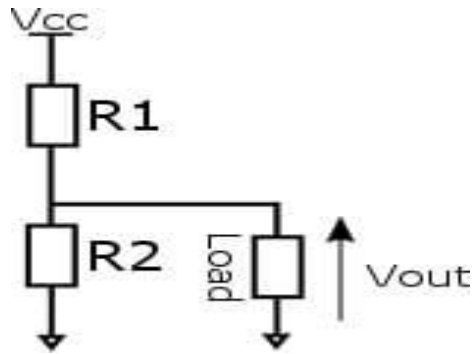
### 2.8.1 Voltage Follower

The most basic circuit is the voltage buffer, as it does not require any external components. As the voltage output is equal to the voltage input, students might become puzzled and wonder whether this kind of circuit has any practical application.

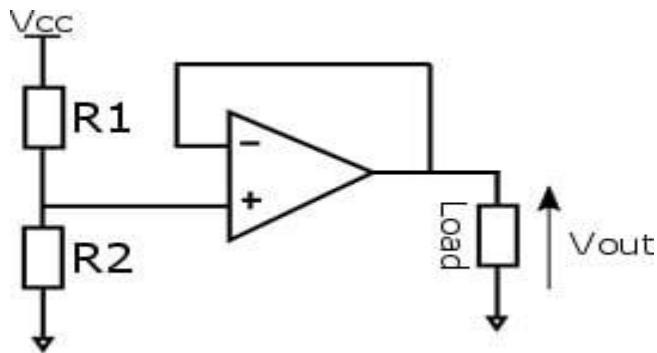


$$V_s = V_e$$

This circuit allows for the creation of a very high impedance input and low impedance output. This is useful to interface logic levels between two components or when a power supply is based on a voltage divider. The figure below is based on a voltage divider, and the circuit cannot function. Indeed, the load impedance can have large variations, so  $V_{out}$  voltage can change dramatically, mainly if the load impedance has a value of the same magnitude as  $R_2$ .



To solve this issue, an [amplifier](#) between the load and the voltage divider (see figure below) is inserted. Thus,  $V_{out}$  depends on  $R_1$  and  $R_2$  and not on load value.

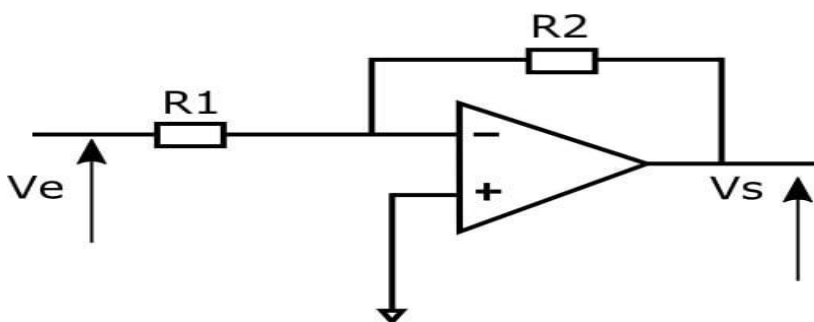


The primary goal of an operational amplifier, as its name states, is to amplify a signal. For instance, the output of a sensor must be amplified in order to have the ADC measure this signal.

### 2.8.1 Inverting Op Amp

In this configuration, the output is fed back to the negative or inverting input through a resistor ( $R_2$ ). The input signal is applied to this inverting pin through a resistor ( $R_1$ ).

The positive pin is connected to ground.



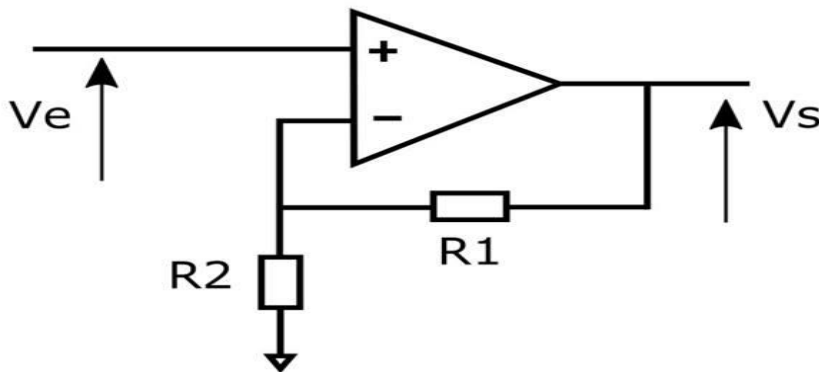
$$V_s = -V_e \frac{R_2}{R_1}$$

This is evident in the special case where  $R_1$  and  $R_2$  are equal. This configuration allows for the production of a signal that is complementary to the input, as the output is exactly the opposite of the input signal.

Due to the negative sign, the output and input signals are out of phase. If both signals must be in phase, a non-inverting amplifier is used.

### 2.8.2 Non-inverting Op Amp

This configuration is very similar to the inverting operation amplifier. For the non-inverting one, the input voltage is directly to the applied to the non-inverting pin and the end of feedback loop is connected to ground.

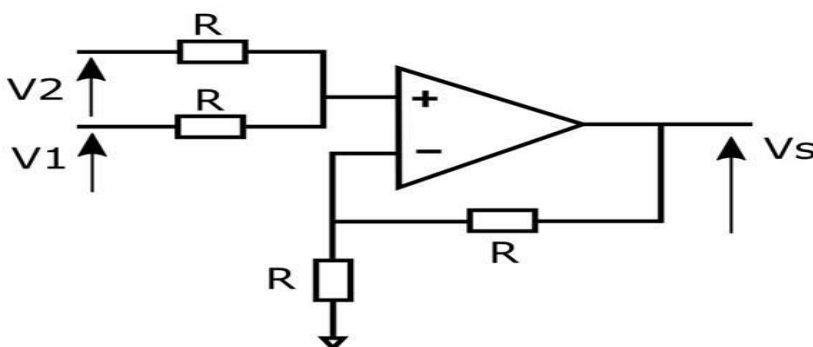


$$V_s = V_e \left( 1 + \frac{R_1}{R_2} \right)$$

These configurations allow amplification of one signal. It's possible to amplify several signals by using summing amplifiers.

### 2.9 Non-inverting Summing Amplifier

To add 2 voltages, only 2 resistors can be added on the positive pin to the non-inverting operational amplifier circuit.



$$V_s = V_1 + V_2$$

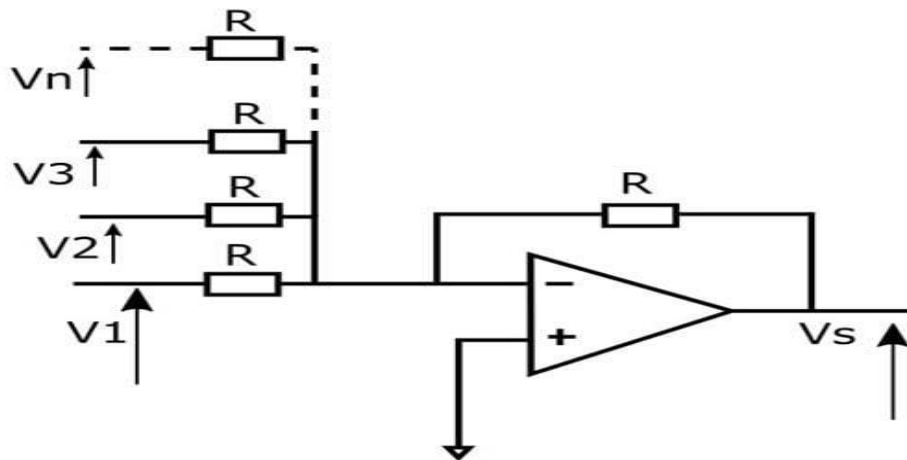


It is worth noticing that adding several voltages is not a very flexible solution. Indeed, if a 3<sup>rd</sup> voltage is added with exactly the same resistances, the formula would be  $V_s = 2/3 (V_1 + V_2 + V_3)$ .

The resistors would need to be changed to get  $V_s = V_1 + V_2 + V_3$ , or a 2<sup>nd</sup> option is to use an inverting summer amplifier.

### 2.9.1 Inverting Summing Amplifier

By adding resistors in parallel on the inverting input pin of the inverting operation amplifier circuit, all the voltages are summed.



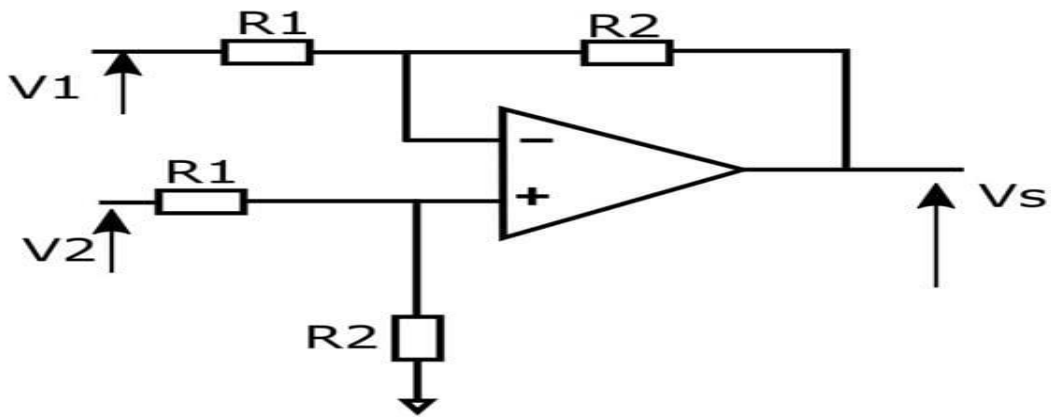
$$V_s = -(V_1 + V_2 + V_3 + \dots + V_n)$$

Unlike the non-inverting summing amplifier, any number of voltages can be added without changing resistor values.

### 2.9.2 Differential Amplifier

The inverting operational amplifier (see circuit number 2) amplified a voltage that was applied on the inverting pin, and the output voltage was out of phase. The non-inverting pin is connected to ground with this configuration.

If the above circuit is modified by applying a voltage through a voltage divider on the non-inverting, we end up with a differential amplifier as shown below.

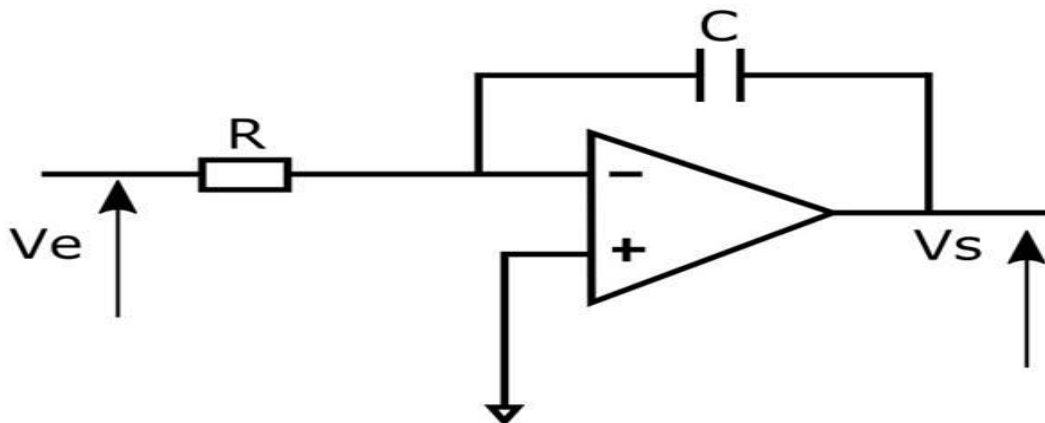


$$V_s = \frac{R_2}{R_1} (V_2 - V_1)$$

An amplifier is useful not just because it lets you add, subtract, or compare voltages. Many circuits allow you to modify signals. Let's see the most basic ones.

### 2.9.3 Integrator

A square wave is very easy to generate, by just toggling a GPIO of a microcontroller for example. If a circuit needs a triangle waveform, a good way to do it is just integrating the square wave signal. With an Operational Amplifier, a capacitor on the inverting feedback path, and a resistor on the input inverting pin as shown below, the input signal is integrated.



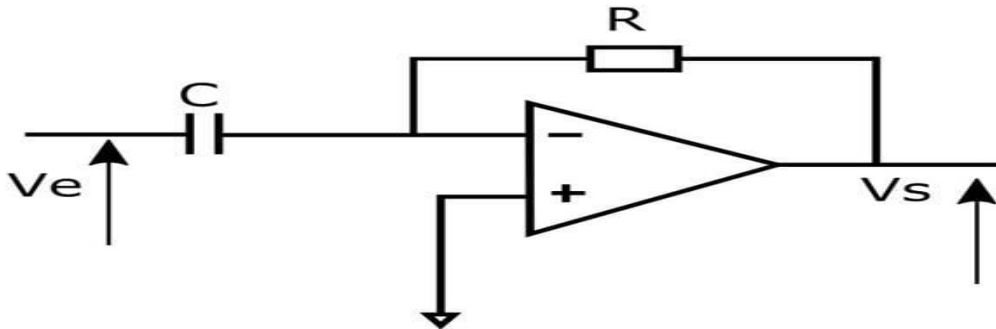
$$V_s = -\frac{1}{RC} \int V_e dt$$

Be aware that a resistor is often connected in parallel to the capacitor for saturation issues. Indeed, if the input signal is a very low frequency sine wave, the capacitor acts like an open circuit and blocks feedback voltage. The amplifier is then like a normal open-loop amplifier that has very high open-loop gain, and

the amplifier is saturated. Thanks to a resistor in parallel of the capacitor, the circuit behaves like an inverting amplifier with a low frequency, and saturation is avoided.

### 2.9.4 Op Amp Differentiator

The differentiator works similarly to the integrator by swapping the capacitor and the resistor.

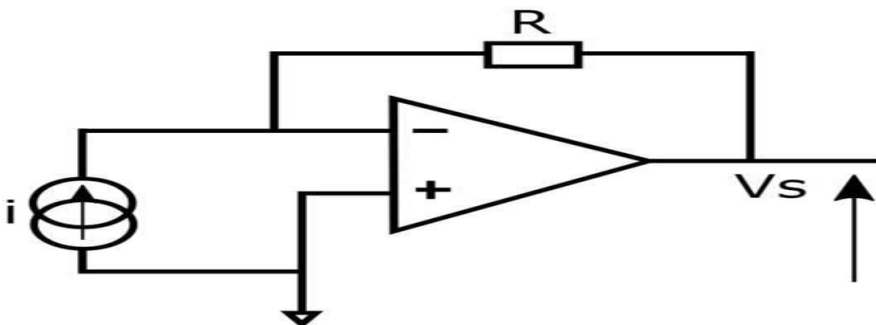


$$V_s = -RC \frac{dV_e}{dt}$$

All the configurations that were presented up to now.

### 2.9.5 Converter current – voltage

A [photodetector](#) converts light into current. To convert the current into voltage, a simple circuit with an operational amplifier, a feedback loop through a resistor on the non-inverting, and the diode connected between the two input pins allows you to get an output voltage proportional to current generated by the photodiode, which is evident by the light characteristics.

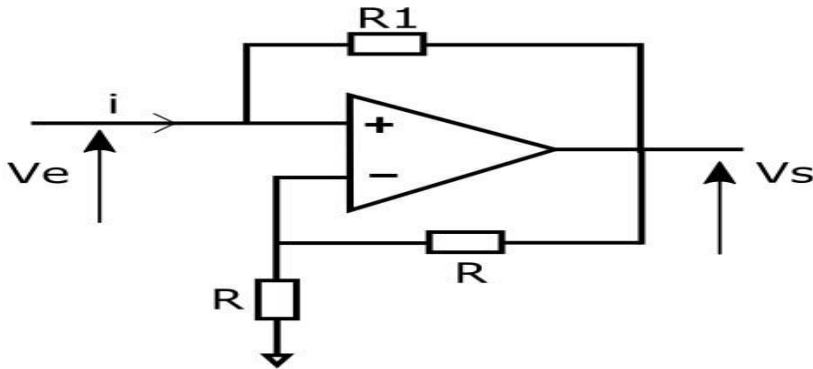


$$V_s = R I$$

The above circuit applies Ohm's law with the fundamental formula: voltage is equal to resistance multiplied by current. The resistance is in Ohms and is always positive. But thanks to operational amplifiers, a negative resistance can be designed!

## 2.9.6 Negative resistance

A feedback on the inverting pin forces the output voltage to be the double of the input voltage. As the output voltage is always higher than the input voltage, the positive feedback through the R1 resistor on the non-inverting pin simulates a negative resistance.

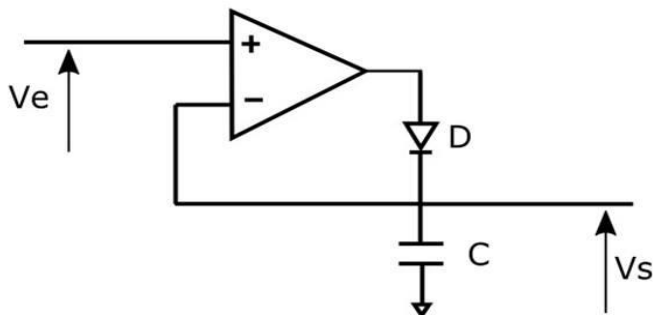


$$V_e = -R_1 I$$

Finally, a circuit with operational amplifier does not necessarily modify the input signal, but records it like the peak detector amplifier.

### Also: Peak Detector Operation Amplifier

The capacitor is used as a memory. When the input voltage on the non-inverting input is higher than the voltage on the inverting input that is also the voltage across the capacitor, the amplifier enters in saturation and the diode is forward and charges the capacitor. Assuming the capacitor does not have a quick self discharge, when the input voltage  $V_e$  is lower than voltage across the capacitor, the diode is blocked. Hence, the peak voltage is recorded thanks to the capacitor.





## **CHAPTER-3**

### **EXPERIMENT SET UP AND PROCEDURE**

### 3.1 EXPERIMENTAL PROCEDURE

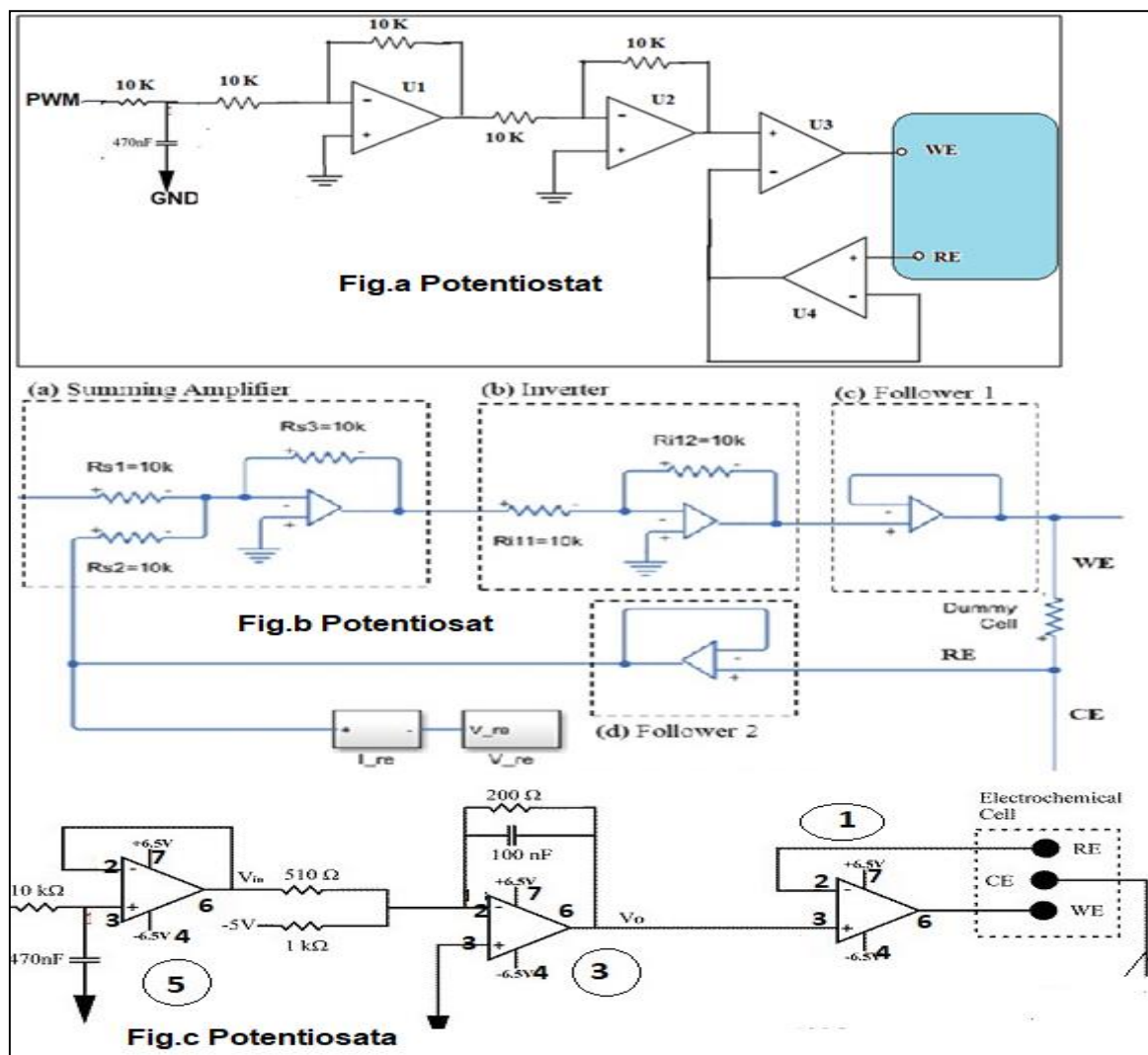
The present distinction was carried out by the following experimental method....

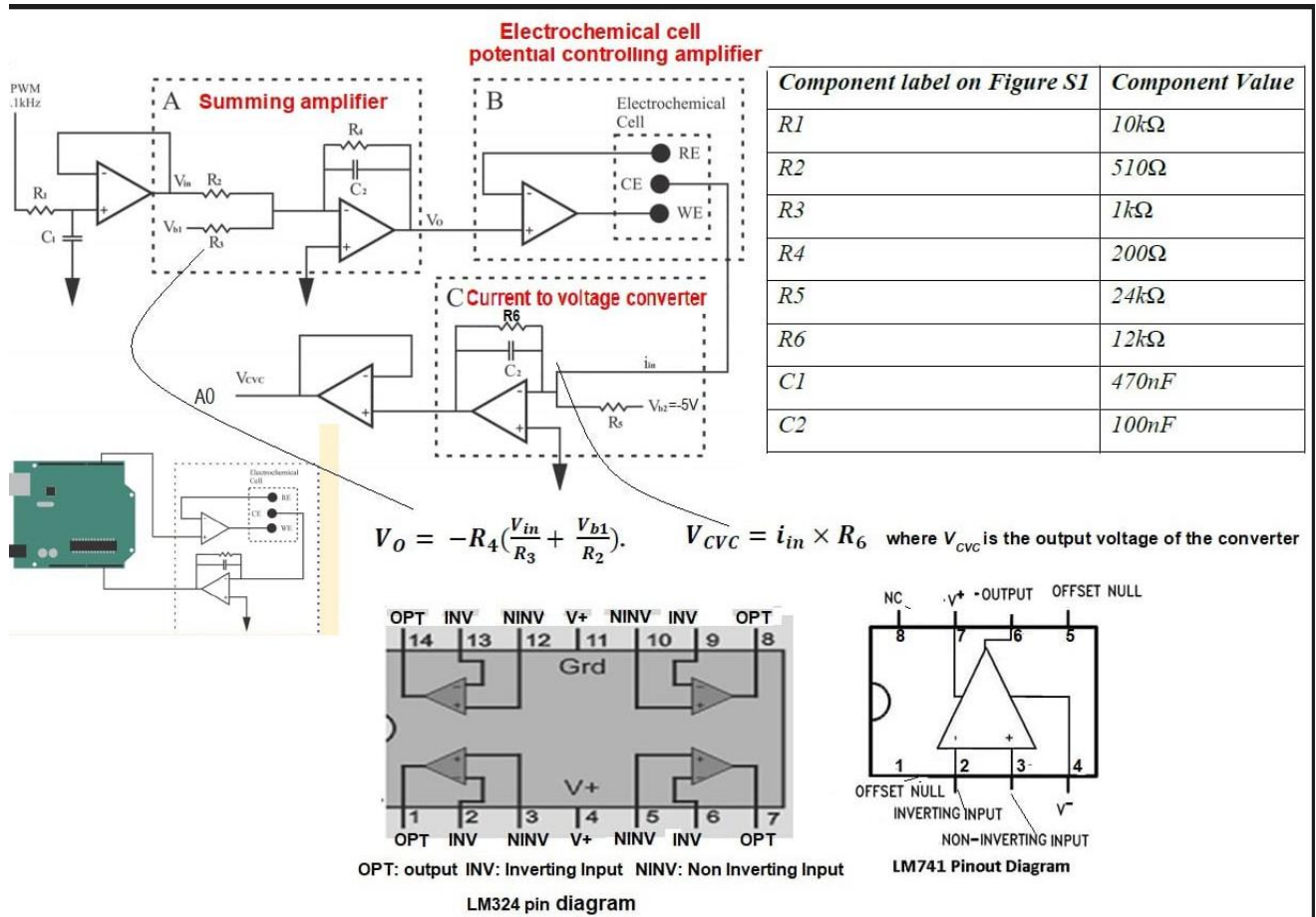
Electrochemical corrosion study was carried out in potentiostatic instruments as well as Potentiostat developed using microprocessor electronic chip with a Arduino robotic circuit. The material of corrosion study was low carbon steel which acted as a working electrode (WE), to complete the electrochemical cell graphite electrode (CE) was needed. The change of polarization potential was measured by with respect to saturated calomel electrode (SCE) acting as a reference electrode (RE).

The corrosion study was done in laboratory make sea water by dissolving 3.15 KCl in 100cc solution pH was maintained at above 8.5 which is normal pH sea water.

The mini potentiostat was developed using Arduino UNO robotic circuit with resistance, capacitor and operation amplifier LM324 as shown in figure.

Using following circuit, I made mini potentiostat





### 3.2 POTENTIOSTAT

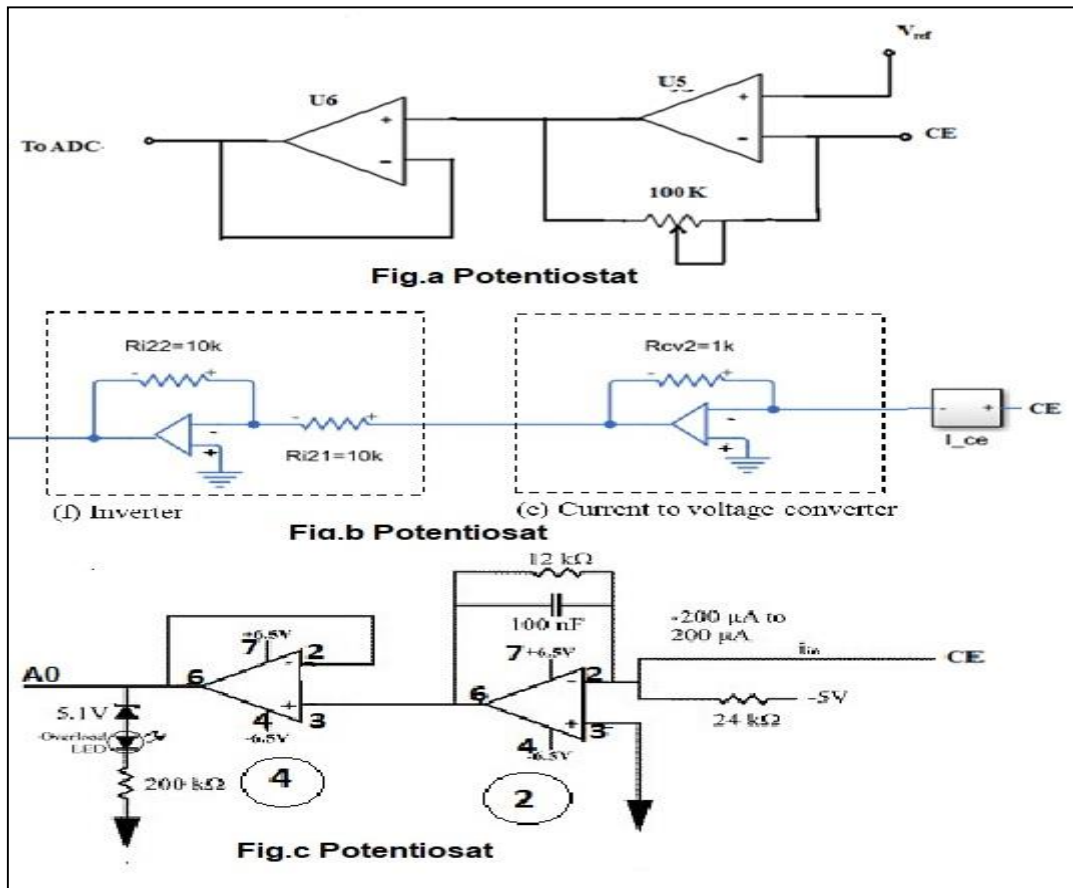
Potentiostat consists of operational amplifiers as shown in figure 14. The circuit has two parts.

First part provides the necessary power supply or potential to working electrode.

This is then fed back to the same through electrolyte and reference electrode.

The output of DAC is fed to inverting input of op-amp U1. Due to inverting amplifier configuration, this voltage is converted to negative equivalent voltage. This inverted voltage is then again inverted and initial voltage is obtained at the output of U2. In this way U1 and U2 forms a buffer amplifier. U3 and U4 are unity gain amplifiers. The feedback of this configuration is through the electrolyte, working electrode, reference electrode and U4. Due to unity gain configuration, the potential between working electrode and reference electrode is kept constant. For the purpose to avoid the loading effect, operational amplifier U4 is used Second part (CE) is Transimpedance amplifier. This stage converts the small amount of current through electrolyte into the voltage.





U5 is trans impedance amplifier which converts the current from counter electrode to the voltage. As the circuit generates bipolar voltages, a reference voltage is added at the trans impedance stage. This voltage shifter converts the bipolar voltage to unipolar voltage. The reference voltage is set to 2.5 V by adjusting POT. The operational amplifier U6 used is again in unity gain buffer configuration.

### 3.3 TYPES OF ELECTRODES

1. Working Electrode(WE)
2. Reference Electrode(RE)
3. Counter Electrode(CE)

### 3.4 FUNCTION OF ELECTRODE

#### A) WORKING ELECTRODE

We made a electrode which have a determined a corrosion rate of a material and applied potential to the working electrode against a counter electrode

#### B) COUNTER ELECTRODE

COUNTER ELECTRODE AS A GRAPHITE I AM USING what is happening naturally occurs corrosion inside material, at same time we plot cathodic sites and also besides their anodic sites

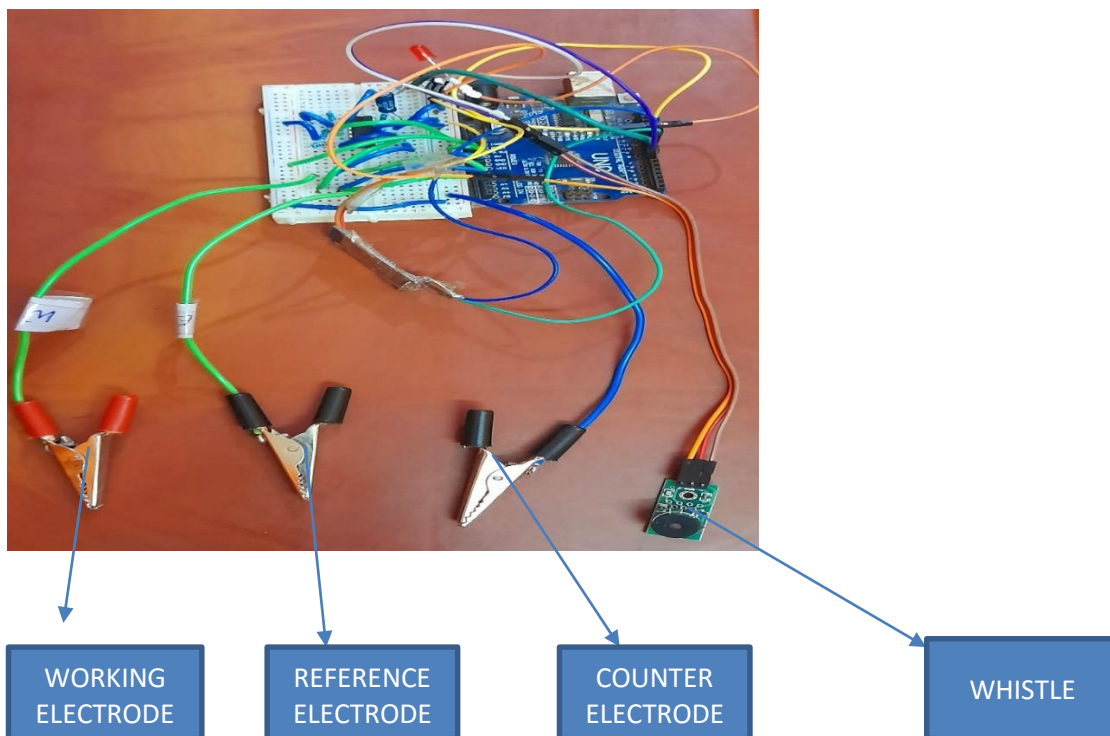
reaction takes place that means we easily plot cathodic polarization (cleaning the material) and anodic polarization (corrosion takes place)

### C) REFERENCE ELECTRODE

We require a scale to measure the corrosion potential ( $E_{corr}$ ) and corrosion current ( $I_{corr}$ ) so that to determine a corrosion rate.

I am using a saturated Calomel electrode using KCl solution and also we can use a hydrogen electrode but this is explosive in nature.

### 3.4 MINI POTENTIOSTAT LAYOUT



### 3.5 Equipment's Use in Experiment:

1. Mild Steel
2. Potentiostat/Galvanostat
3. Aqueous Environment
  - a) Chloride Solution
  - b) Acid Solution
  - c) Acids
4. Distilled Water
5. Multimeter
6. Electrode
  - a) Working Electrode (Mild Steel Sample)
  - b) Counter Electrode (Graphite)
  - c) Reference Electrode (Saturated Calomel Electrode)
7. Wire and Polishing paper

#### DISTILLED WATER SET UP



Mild steel material

### 3.6 PROCESS OF EXPERIMENT

A mild steel rod samples of 1.120cm<sup>2</sup> were cut from Mild steel. They were ground carefully in order to make the edges blunt and to give a near circular cross section. The samples were then further ground using a belt drive and polished up to 3/0 emery paper.

Polishing provides a uniform surface removing surface defects that could serve as pit sites.

Following this, the samples were washed with acetone and then left to be air-dried.

The samples were observed with a low magnification microscope to observe whether there were any pit or deep scratches on the polished surface. If any deep scratches or pits were observed, the samples were further polished. This procedure continued until the samples became pit free.

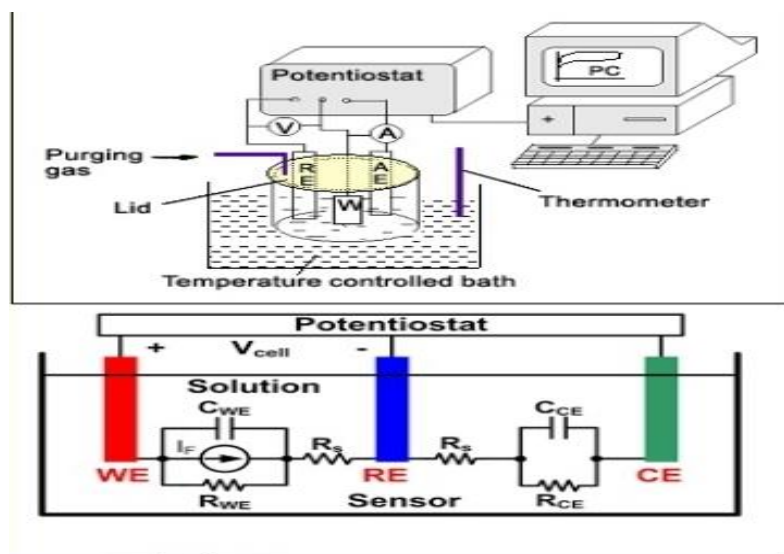
Fresh solutions were prepared before each experiment, using KCl, NaCl, H<sub>2</sub>SO<sub>4</sub> and H<sub>2</sub>SO<sub>4</sub> in double distilled water with various combinations of concentration of chloride, sulphate, dissolved oxygen contents, temperature and pH required for the experiments for factorial design and further experiments at other different combinations for validation of the model.

A standard corrosion cell was used to perform the electrochemical potentiostatic polarization tests on standard flat metal specimens.

Polarization experiments were carried out as per ASTM ST72 using Gamry Potentiostat. The software used was Gamry Echem Analyst.

The potentiodynamic experiment was done with the samples; the corrosion current and corrosion potential were determined by Tafel's extrapolation method as well as linear polarization method. A software was developed based on estimated equations and 3D mapping of corrosion with variables was generated by the software

Using this circuit diagram for -



# CHAPTER-4

## RESULTS AND DISCUSSION

Result and discussion of present investigation as described in introduction 1.0 and experiment set up 3.0 have been described in the following paragraph-

Polarization studies of steel in artificial sea water in laboratory using potentiostatic instrument

### 4.1 USING C-PROGRAMMING LANGUAGE TO COMPILE THE MINI POTENTIOSTAT

```
// This program has 2 loops, one for cyclic voltammetry, another for potential change
// use only one loop at a time
// 3 pins of arduino to be used one for potential supply to cell PWM digital pin 3,
// 2nd one A0 for potential reading of WE vs. RE & 3rd pin A2 for current reading of WE
#include <Wire.h>
#include <SoftwareSerial.h>
SoftwareSerial BTSerial(10, 11); // for Bluetooth TX | RX
char data = 0;
int AWM_pin = 9; // frequency for 3, 9, 10 and 11 = 490Hz, frequency for 5,6 pins = 980Hz
const int VoltagePin = A0; // no sensor direct for potential
const int CurrentPin = A1; // no sensor direct for current
const int PotentialPin = A2; // sensor potential pin
int Sensor_Potential;
float potentialValue=0.0 ;
float potentialValue2=0.0 ;
float R1 = 30000.0;
float R2 = 7500.0;
float cellPotential = 0.0;
int i=10;

const int CurrentPin2 = A3; // sensor current pin
```

```

int Sensor_Current=0;

float currentValue = 0;

float current =0;

float Samples=0.0;

float a=0.0;

void setup()

{

Serial.begin(9600);

BTSerial.begin(9600);

pinMode( AWM_pin, OUTPUT);

pinMode(VoltagePin,INPUT);

pinMode(CurrentPin,INPUT);

Serial.println("CLEARDATA");//clears up any data left from previous projects

//Serial.println( "Sensor_Potential  , potentialValue, potentialValue2 ,cellPotential");

Serial.println("LABEL,Time,Started Time,i,Potential,current,SensorV, SensorI, PotValue, CurrValue");

Serial.println("RESETTIMER");

//Serial.println("voltage  current");

}

// cyclic cyclic voltammetry function

void loop()

{

float SamplesV=0.0; float SamplesI=0.0;

int maxvoltage =200;

int voltage_scan=20;

delay(2000);

for(int i=0; i<maxvoltage; i=i+voltage_scan)

{

analogWrite( AWM_pin, i);

float voltage_avg=0;

float current_avg=0;

int steptime=85;

int y=0;

```

```

for( y=0; y<8; y=y+1)
{
  delay(stepTime/8);

  float Voltage =analogRead(VoltagePin);

  float Current=analogRead(CurrentPin);

  voltage_avg=(voltage_avg + Voltage)/2;

  current_avg=(current_avg +Current)/2;

  }

  voltage_avg=(voltage_avg*5/1023)*-1+3.3;

  current_avg=(current_avg*5/1023)-3.3;
for (int x = 0; x < 50; x++){ //Get 50 samples

  Sensor_Potential = analogRead(PotentialPin); //Read current sensor values

  SamplesV = SamplesV +  Sensor_Potential; //Add samples together

  delay (3); // let ADC settle before next sample 3ms

}

  potentialValue =SamplesV/50.0;//Taking Average of Samples
for (int x = 0; x < 50; x++){ //Get 50 samples

  Sensor_Current = analogRead(CurrentPin2); //Read current sensor values

  SamplesI = SamplesI +  Sensor_Current; //Add samples together

  delay (3); // let ADC settle before next sample 3ms

}

currentValue=SamplesI/50.0;//Taking Average of Samples

  Sensor_Potential = (analogRead(VoltagePin )*5/1023);

  Sensor_Current =( analogRead(CurrentPin)^5/1023);

  Serial.print("DATA,TIME,TIMER, ");

  Serial.print(i);

  Serial.print(",");

  Serial.print(voltage_avg);

  Serial.print(" , ");

  Serial.print(current_avg);

  Serial.print(",");

  Serial.print(Sensor_Potential);

```

```

Serial.print(",");

Serial.print( Sensor_Current);

Serial.print(",");

Serial.print(potentialValue);

Serial.print(",");

Serial.println( currentValue);

////////////////////////////////////

BTSerial.print("MV Met JU");

BTSerial.print(",");

BTSerial.print(i);

BTSerial.print(",");

BTSerial.print(voltage_avg);

BTSerial.print(",");

BTSerial.print(current_avg);

BTSerial.print(",");

BTSerial.print(potentialValue);

BTSerial.print(",");

BTSerial.print( currentValue);

BTSerial.print(";");

delay(1000);

}

for(int i=maxvoltage; i>0; i=i-voltage_scan)

{

analogWrite( AWM_pin, i);

float voltage_avg=0;

float current_avg=0;

int steptime=85;

int y=0;

for( y=0; y<8; y=y+1)

{

delay(steptime/8);

float Voltage =analogRead(VoltagePin);

```



```

float Current=analogRead(CurrentPin);

voltage_avg=(voltage_avg + Voltage)/2;

current_avg=(current_avg +Current)/2;

}

voltage_avg=(voltage_avg*5/1023)*-1+3.3;

current_avg=(current_avg*5/1023)-3.3;

for (int x = 0; x < 50; x++){ //Get 50 samples

    Sensor_Potential = analogRead(PotentialPin); //Read current sensor values

    SamplesV = SamplesV + Sensor_Potential; //Add samples together

    delay (3); // let ADC settle before next sample 3ms

}

    potentialValue =SamplesV/50.0;//Taking Average of Samples

for (int x = 0; x < 50; x++){ //Get 50 samples

    Sensor_Current = analogRead(CurrentPin2); //Read current sensor values

    SamplesI = SamplesI + Sensor_Current; //Add samples together

    delay (3); // let ADC settle before next sample 3ms

}

currentValue=SamplesI/50.0;//Taking Average of Samples

    Sensor_Potential = (analogRead(VoltagePin )*5/1023);

    Sensor_Current =( analogRead(CurrentPin)^5/1023);

    Serial.print("DATA,TIME,TIMER, ");

    Serial.print(i);

    Serial.print(",");

    Serial.print(voltage_avg);

    Serial.print(" , ");

    Serial.print(current_avg);

    Serial.print(",");

    Serial.print(Sensor_Potential);

    Serial.print(",");

    Serial.print( Sensor_Current);

    Serial.print(",");

    Serial.print(potentialValue);

```

```

Serial.print(",");

Serial.println( currentValue);

////////////////////////////////////

BTSerial.print("MV Met JU");

BTSerial.print(",");

BTSerial.print(i);

BTSerial.print(",");

BTSerial.print(voltage_avg);

BTSerial.print(",");

BTSerial.print(current_avg);

BTSerial.print(",");

BTSerial.print(potentialValue);

BTSerial.print(",");

BTSerial.print( currentValue);

BTSerial.print(";");

delay(1000);

}

}

```

Using this programming language we can easily plot cathodic polarization and anodic polarization indirectly but we can generate automatically anodic and cathodic current through a applied potential.

Also, we can detect through a android mobile phone by connecting a Bluetooth as a using above the programming language and also detect how rate corrosion rate occurs inside the material by connecting a sensor or whistle.

## **4.2 SOLUTIONS PREPARED BY USING DIFFERENT CONCENTRATION**

### **4.2.1 BY USING KCl 15gm/Lit and sodium sulphate 0.8gm/lit in a double distilled water**

1000cc of distilled water contains 15gm potassium chloride

Then if I take 100cc of distilled water contains a 1.5 gm KCl solution

Cl-(chloride concentration) present in KCl is=  $74.55/35.5$

Then 1.5gm of KCl in 100cc is how much Cl- chloride ions present

$$=(74.55/35.5)*1.5\text{gm}=3.15\text{gm}$$

$$= 3.15\text{gm}$$

Similarly, 1000cc of distilled water contains 0.8gm sodium sulphate( $\text{Na}_2\text{SO}_4$ ), then if I take 100cc of distilled water contains 0.08gm sodium sulphate solution

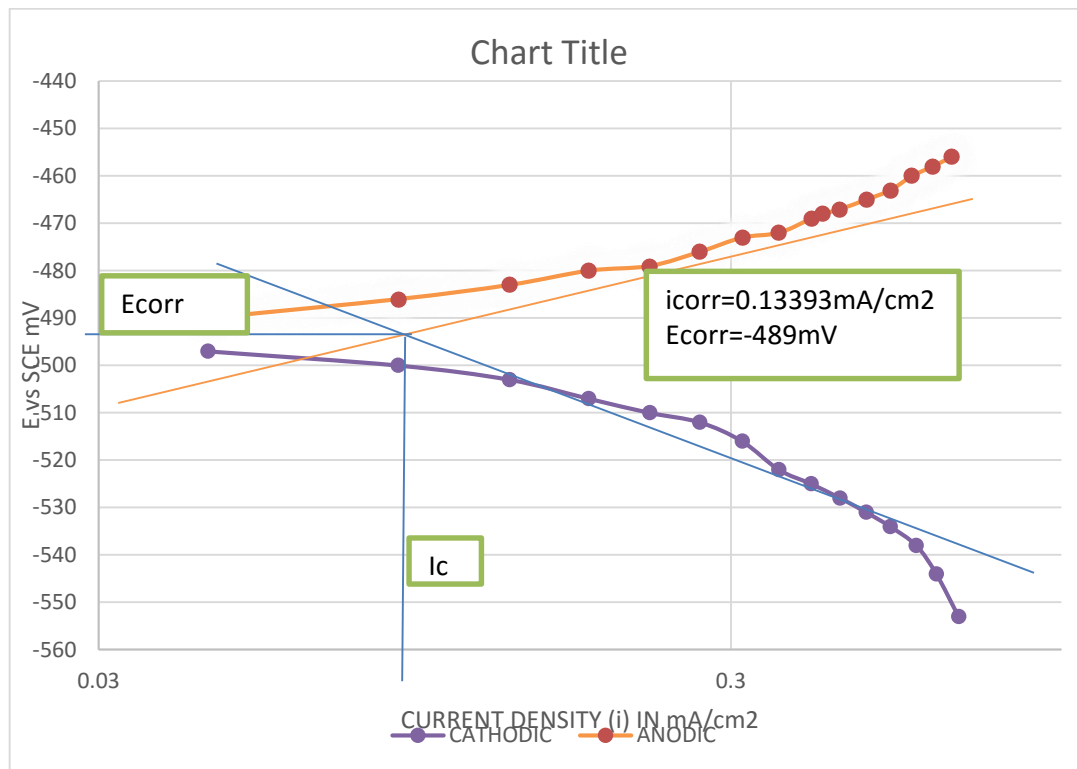
SULPHATE IONS in a sodium sulphate is  $=142.04/96.06$

Then 0.08gm of sodium sulphate in 100cc is how much sulphate ions present  $=(142.04/96.06)*0.08=0.1182\text{gm}$

#### 4.2.2 Sample Data For KCl Solution in 15gm/L From a Manual set up

CATHODIC SITES			ANODIC SITES		
I (current) (mA)	Electrode Potential (mV)	I (current density)	I (current) (mA)	Electrode Potential (mV)	I (current density)
-0.77	-553	0.6875	0.05	-490	0.044642857
-0.71	-544	0.633928571	0.1	-486	0.089285714
-0.66	-538	0.589285714	0.15	-483	0.133928571
-0.6	-534	0.535714286	0.2	-480	0.178571429
-0.55	-531	0.491071429	0.25	-479	0.223214286
-0.5	-528	0.446428571	0.3	-476	0.267857143
-0.45	-525	0.401785714	0.35	-473	0.3125
-0.4	-522	0.357142857	0.4	-472	0.357142857
-0.35	-516	0.3125	0.45	-469	0.401785714
-0.3	-512	0.267857143	0.47	-468	0.419642857
-0.25	-510	0.223214286	0.5	-467	0.446428571
-0.2	-507	0.178571429	0.55	-465	0.491071429
-0.15	-503	0.133928571	0.6	-463	0.535714286
-0.1	-500	0.089285714	0.65	-460	0.580357143
-0.05	-497	0.044642857	0.7	-458	0.625
			0.75	-456	0.669642857

### 4.2.3 GRAPH-POTENTIAL VS CURRENT DENSITY From A Manual Set Up



### 4.2.4 CORROSION RATE

$$\text{mpy} = 0.129 \frac{ai}{nd}$$

where  $I_{corr}$  = corrosion current in mA/cm<sup>2</sup>

$a$  = atomic weight in g/cc

$d$  = density in g/cc

$n$  = valency factor

From I get  $I_{corr} = 0.13393 \text{ mA/cm}^2$

$a = 55.84 \text{ g/cc}$

$d = 7.85 \text{ g/cc}$

$n = 2$

corrosion rate =  $(0.129 * 55.84 * 0.13393) / (2 * 7.85)$

= 0.06144 mpy

## 4.3 SAMPLE DATA USING A MINI POTENTIOSAT

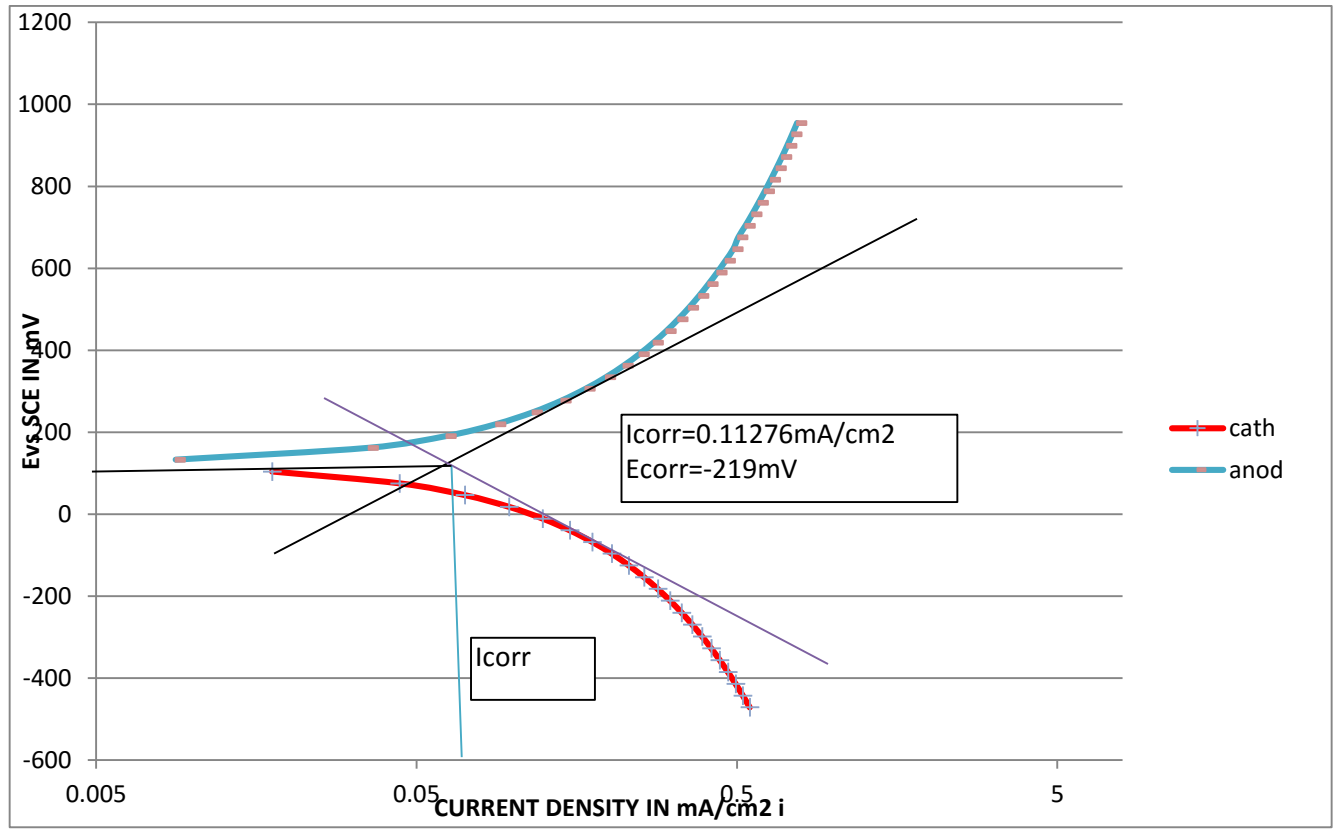
### 4.3.1 CATHODIC DATA IN 15gm/L KCl solution from a mini potentiostat

Time	Started Time	i	E mV	ImA		I current density mA/cm2
16:06:28	0.30	0	-471.16	-0.62	0.62	0.548673
16:06:29	1.61	5	-442.49	-0.59	0.59	0.522124
16:06:30	2.94	10	-413.75	-0.56	0.56	0.495575
16:06:32	4.27	15	-384.95	-0.53	0.53	0.469027
16:06:33	5.58	20	-356.08	-0.5	0.5	0.442478
16:06:34	6.91	25	-327.11	-0.47	0.47	0.415929
16:06:36	8.22	30	-298.14	-0.44	0.44	0.389381
16:06:37	9.55	35	-269.17	-0.41	0.41	0.362832
16:06:38	10.86	40	-240.2	-0.38	0.38	0.336283
16:06:40	12.19	45	-211.26	-0.35	0.35	0.309735
16:06:41	13.52	50	-182.32	-0.32	0.32	0.283186
16:06:42	14.83	55	-153.63	-0.29	0.29	0.256637
16:06:44	16.15	60	-125.06	-0.26	0.26	0.230088
16:06:45	17.47	65	-96.29	-0.23	0.23	0.20354
16:06:46	18.80	70	-67.79	-0.2	0.2	0.176991
16:06:48	20.13	75	-39.31	-0.17	0.17	0.150442
16:06:49	21.43	80	-10.83	-0.14	0.14	0.123894
16:06:50	22.73	85	17.85	-0.11	0.11	0.097345
16:06:52	24.06	90	46.52	-0.08	0.08	0.070796
16:06:53	25.37	95	75.29	-0.05	0.05	0.044248
16:06:54	26.73	100	104.17	-0.02	0.02	0.017699

### 4.3.2 ANODIC DATA IN 15gm/L KCl solution from a mini potentiostat

Time	Started Time	i	E mV	ImA		I current density mA/cm2
16:06:56	28.04	105	133.06	0.01	0.01	0.00885
16:06:57	29.37	110	161.94	0.04	0.04	0.035398
16:06:58	30.68	115	190.82	0.07	0.07	0.061947
16:07:00	32.01	120	219.66	0.1	0.1	0.088496
16:07:01	33.32	125	248.4	0.13	0.13	0.115044
16:07:02	34.65	130	277.06	0.16	0.16	0.141593
16:07:03	35.98	135	305.72	0.19	0.19	0.168142
16:07:05	37.29	140	334.04	0.22	0.22	0.19469
16:07:06	38.62	145	362.32	0.25	0.25	0.221239
16:07:07	39.93	150	390.58	0.28	0.28	0.247788
16:07:09	41.26	155	418.83	0.31	0.31	0.274336
16:07:10	42.57	160	447.02	0.34	0.34	0.300885
16:07:11	43.90	165	475.51	0.37	0.37	0.327434
16:07:13	45.23	170	503.93	0.4	0.4	0.353982
16:07:14	46.54	175	532.55	0.43	0.43	0.380531
16:07:15	47.87	180	561.23	0.46	0.46	0.40708
16:07:17	49.18	185	589.81	0.49	0.49	0.433628
16:07:18	50.51	190	618.41	0.52	0.52	0.460177
16:07:19	51.82	195	646.96	0.55	0.55	0.486726
16:07:21	53.15	200	675.4	0.57	0.57	0.504425
16:07:22	54.48	205	703.76	0.6	0.6	0.530973
16:07:23	55.79	210	732.07	0.63	0.63	0.557522
16:07:25	57.12	215	760.11	0.66	0.66	0.584071
16:07:26	58.43	220	788.11	0.69	0.69	0.610619
16:07:27	59.76	225	816.14	0.72	0.72	0.637168
16:07:29	61.09	230	843.98	0.75	0.75	0.663717
16:07:30	62.40	235	871.47	0.78	0.78	0.690265
16:07:31	63.73	240	899.06	0.81	0.81	0.716814
16:07:33	65.04	245	926.86	0.84	0.84	0.743363

### 4.3.3. GRAPH E VS SCE AND CURRENT DENSITY Generated From A Mini Potentiostat



### 4.3.4 CORROSION RATE

$$\text{mpy} = 0.129 \frac{ai}{nd}$$

where  $I_{corr}$  = corrosion current in mA/cm<sup>2</sup>

a = atomic weight in g/cc

d = density in g/cc

n = valency factor

From I get  $I_{corr} = 0.11276 \text{ mA/cm}^2$

a = 558.84 g/cc

d = 7.85 g/cc

n = 2

corrosion rate =  $(0.129 * 55.84 * 0.11276) / (2 * 7.85)$

= **0.051735 mpy**

## 4.4 BY USING KCl 20gm/Lit and sodium sulphate 0.8gm/lit in a double distilled water

1000cc of distilled water contains 20gm potassium chloride

Then if I take 100cc of distilled water contains a 2gm KCl solution

Cl-(chloride concentration) present in KCl is= 74.55/35.5

Then 2gm of KCl in 100cc is how much Cl- chloride ions present

$$= (74.55/35.5)*2\text{gm}=4.2\text{gm}$$

$$= 4\text{gm}$$

Similarly, 1000cc of distilled water contains 0.8gm sodium sulphate( $\text{Na}_2\text{SO}_4$ ), then if I take 100cc of distilled water contains 0.08gm sodium sulphate solution

SULPHATE IONS in a sodium sulphate is =142.04/96.06

Then 0.08gm of sodium sulphate in 100cc is how much sulphate ions present=  
 $(142.04/96.06)*0.08=0.1182\text{gm}$

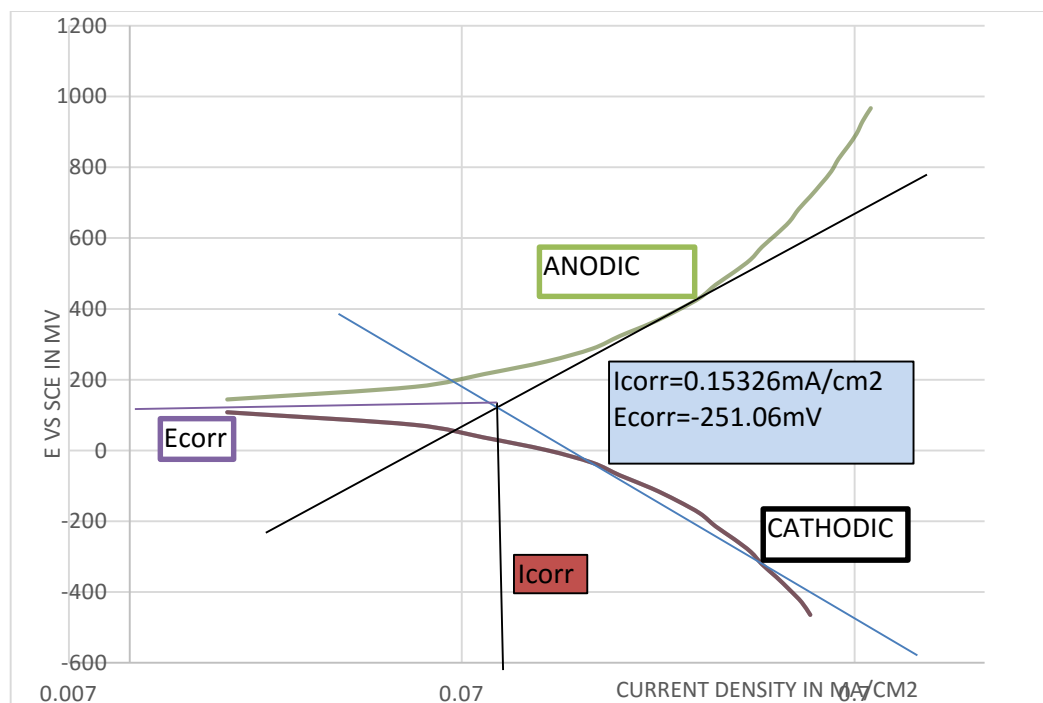
### 4.4.1 CATHODIC Sites 20gm/L KCl solution from a mini potentiostat

Time	Started Time	i	E mV	current		current density mA/cm <sup>2</sup>
15:13:02	0.22	0	-464.22	-0.61	0.61	0.539823
15:13:03	1.55	5	-428.64	-0.58	0.58	0.513274
15:13:04	2.86	10	-393.05	-0.54	0.54	0.477876
15:13:06	4.19	15	-357.38	-0.5	0.5	0.442478
15:13:07	5.52	20	-321.66	-0.46	0.46	0.40708
15:13:08	6.83	25	-285.8	-0.43	0.43	0.380531
15:13:10	8.16	30	-249.85	-0.39	0.39	0.345133
15:13:11	9.47	35	-213.92	-0.35	0.35	0.309735
15:13:12	10.80	40	-177.96	-0.32	0.32	0.283186
15:13:14	12.11	45	-142	-0.28	0.28	0.247788
15:13:15	13.44	50	-106.05	-0.24	0.24	0.212389
15:13:16	14.75	55	-70.18	-0.2	0.2	0.176991
15:13:18	16.08	60	-34.4	-0.17	0.17	0.150442
15:13:19	17.38	65	1.3	-0.13	0.13	0.115044
15:13:20	18.70	70	36.94	-0.09	0.09	0.079646
15:13:21	20.02	75	72.59	-0.06	0.06	0.053097
15:13:23	21.36	80	108.25	-0.02	0.02	0.017699

#### 4.4.2 Anodic Sites 20gm/L KCl solution from a mini potentiostat

Time	Started Time	i	E mV	current		current density mA/cm2
15:13:24	22.66	85	143.91	0.02	0.02	0.017699
15:13:25	23.98	90	179.63	0.06	0.06	0.053097
15:13:27	25.30	95	215.44	0.09	0.09	0.079646
15:13:28	26.66	100	251.31	0.13	0.13	0.115044
15:13:29	27.97	105	287.32	0.17	0.17	0.150442
15:13:31	29.30	110	323.37	0.2	0.2	0.176991
15:13:32	30.61	115	359.43	0.24	0.24	0.212389
15:13:33	31.94	120	395.5	0.28	0.28	0.247788
15:13:35	33.27	125	431.57	0.32	0.32	0.283186
15:13:36	34.58	130	467.59	0.35	0.35	0.309735
15:13:37	35.91	135	503.5	0.39	0.39	0.345133
15:13:39	37.22	140	539.29	0.43	0.43	0.380531
15:13:40	38.55	145	574.98	0.46	0.46	0.40708
15:13:41	39.86	150	610.61	0.5	0.5	0.442478
15:13:43	41.19	155	646.18	0.54	0.54	0.477876
15:13:44	42.52	160	681.73	0.57	0.57	0.504425
15:13:45	43.83	165	717.22	0.61	0.61	0.539823
15:13:47	45.16	170	752.71	0.65	0.65	0.575221
15:13:48	46.47	175	788.16	0.69	0.69	0.610619
15:13:49	47.80	180	823.45	0.72	0.72	0.637168
15:13:51	49.11	185	858.25	0.76	0.76	0.672566
15:13:52	50.43	190	894.46	0.8	0.8	0.707965
15:13:53	51.76	195	930.68	0.83	0.83	0.734513
15:13:55	53.08	200	966.9	0.87	0.87	0.769912

#### 4.4.3 GRAPH E VS SCE AND CURRENT DENSITY Generated From A Mini Potentiostat





#### 4.4.4 CORROSION RATE

$$\text{mpy} = 0.129 \text{ ai/nd}$$

where  $I_{\text{corr}}$ =corrosion current in mA/cm<sup>2</sup>

a=atomic weight in g/cc

d=density in g/cc

n=valency factor

From I get  $I_{\text{corr}} = 0.15326 \text{ mA/cm}^2$

a=558.84 gm/cc

d=7.85 gm/cc

n=2

corrosion rate=(0.129\*55.84\*0.15326)/(2\*7.85)

**=0.07031mpy**

## **5.0 CONCLUSION**

For the going result and discussion the following statement can be concluded –

- 1.) Corrosion rate of carbon steel is dependent on chloride concentration, pH, temperature and dissolved oxygen.
- 2.) The present investigation by developing a low cost, mini, portable potentiostat to determine corrosion rate of any material in any aqueous environment such as river water, sea water and soil water have been successful.
- 3.) The Mini Potentiostat developed can predict the life of material structure in corrosive environment.
- 4.) The present project assured that corrosion study can be performed by small and middle scale academic institution and industries with low budget

## 6.0 References:

1. [sptech.xyz](http://sptech.xyz)
2. [https://play.google.com/store/apps/details?id=com.sptech.sp\\_corrosion\\_protection](https://play.google.com/store/apps/details?id=com.sptech.sp_corrosion_protection)
3. <https://www.researchgate.net/publication/264084915> Estimation of Corrosion rate of Mild steel in seawater and Application of Genetic Algorithms
4. <https://www.corrosionpedia.com/definition/337/corrosion-rate#:~:text=Corrosion%20rate%20is%20best%20expressed,Weight%20loss%20g/m2>
5. <https://www.tandfonline.com/doi/abs/10.1179/cmq.2010.49.1.99>
6. <https://www.sciencedirect.com/topics/engineering/corrosion-rate>
- 7.