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Design and Simulation of Solar Photovoltaic Powered Cathodic Protection Systems

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This Thesis was defended successfully on 15/12 /2015, and approved by

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Dedication

إلى والدي العزيزين اللذين هما نور حياتي ودربي ... بكل الحب والإحترام أهديكم هذا العمل

To the candles that burnt to light the road for me, my Father and my Mother

To my brothers and my sister

To those who enlightened my way with their glitter words

I dedicate this work

Acknowledgments

الحمد لله الذي بنعمته تتم الصالحات، والصلاة والسلام على سيدنا محمد وعلى ألُه وصحبه أجمعين.

Praise is to Allah who gave me the ability and patience to complete this thesis. Peace and blessings be upon His Prophet and his truthful companions.

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A great thankful to my eye sight my loving father and loving mother, who implemented me in loving science and success, may Allah gives them long and healthy life.

Also special thanks to my brothers, my sister, her husband, my uncle Hasan and his family, in them I see big hope and help.

الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل عنوان:

Design and Simulation of Solar Photovoltaic Powered Cathodic Protection Systems

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Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name: عبد الرحمن جمال خالد سلودي **:اسم الطالب**

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Date: 15/12/2015 **:التاريخ**

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List of Abbreviations and Symbols

API	American Petroleum Institute
CP	Cathodic Protection
ICCP	Impressed Current Cathodic Protection
SACP	Sacrificial Anode Cathodic Protection
GACP	Galvanic Anode Cathodic Protection
Alternative A	The case of design where the coating efficiency is 90%
Alternative B	The case of design where the coating efficiency is 95%
Alternative C	The case of design where the coating efficiency is 98%
USA	United States of America
PV	Photovoltaic
USD	United States of America Currency [$]
$\boldsymbol{W}$	Watt (Unit of Electrical Power)
MW	Mega Watt ($1x10^6\ W$)
GDP	Gross Domestic Product
$\boldsymbol{km}$	Kilo Meter ($1x10^3\ m$)
Ω	Ohm (Unit of Electrical Resistance)
V	Volt (Unit of Electrical Potential)
A	Ampere (Unit of Electrical Current)
$\boldsymbol{mm}$	Mille Meter ($1x10^{-3}\ m$)
MMO	Mixed Metal Oxide
$\boldsymbol{Ah}$	Ampere Hour (Unit of Battery Current Capacity)
$\boldsymbol{Wh}$	Watt Hour (Unit of Electrical Energy)
GNP	Gross National Products
DC	Direct Current
AC	Alternating Current
$\boldsymbol{Fe}$	Iron Atomic Symbol
$\boldsymbol{H}$	Hydrogen Atomic Symbol
$\boldsymbol{O_2}$	Oxygen Atomic Symbol
$\boldsymbol{+ve}$	Positive
$\boldsymbol{-ve}$	Negative
$\boldsymbol{e^-}$	Electron Symbol
$\boldsymbol{pH}$	Power of Hydrogen

E	Magnetic Field
q	Electrical Charge
F	Electrical Force
Al	Aluminum
Mg	Magnesium
Zn	Zinc
g	Unit of Mass ($1x10^{-3}kg$)
cm	Centimeter (Unit of Length ($1x10^{-2}m$))
LCOE	Leveled Cost of Electricity
STC	Standard Temperature Condition
CIGS	Copper Indium/Gallium Selenide
CIS	Copper Indium Selenide
SOC	State of Charge
HVD	High Voltage Disconnects
LVD	Low Voltage Disconnect
DOD	Depth of Discharge
PDN	Pipeline Distribution Network
C	Carbon
Mn	Manganese
P	Phosphorus
S	Sulfur
Cr	Chromium
Ni	Nickel
Mo	Molybdenum
V	Vanadium
Cu	Copper
FBE	Fusion Bonded Epoxy
μA	Micro Ampere ($1x10^{-6}A$)
SCC	Stress Corrosion Cracking

Design and Simulation of Solar Photovoltaic Powered Cathodic Protection System

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Abstract

This thesis discusses the using of cathodic protection (CP) technology for providing protection against corrosion of Submarines and underground pipeline distribution networks (PDN) in Palestine. Solar photovoltaic (PV) energy is used to supply an impressed current cathodic protection (ICCP) system. The design deals with three alternatives depending on the percentage of protected surface area from the total area of the pipelines, the alternative A, B and C represent 90%, 95% and 98% respectively. A simple model has been built through Simulink/MATLAB software in this thesis.

Economic analysis is applied to compare between rehabilitation of the damaged pipelines and using the PV powered ICCP system for each alternative. The economic analysis shows that the saving through using PV powered ICCP system instead of rehabilitation of the pipelines is very large. The saving for the alternatives presented as: (A) is $3,985,440 from $5,371,493, (B) is $1,840,670 from $2,688,311 and (C) is $1,015,603 from $1,075,350. These savings represent percentages of 74.2%, 68.47% and 94.44% of the rehabilitation cost for the alternatives A, B and C respectively.

Chapter One

Introduction

Pipelines play an extremely important role throughout the world as a means of transporting gases and liquids over long distances from their sources to the ultimate consumers [1.1].

For natural gas transportation pipeline accidents, 36% were caused by external corrosion and 63% were caused by internal corrosion. For natural gas distribution pipeline accidents, only approximately 4% of the total accidents were caused by corrosion, and the majority of those were caused by external corrosion [1.2].

In a summary report for incidents between 1985 and 1994, corrosion accounted for 28.5% of pipeline incidents on natural gas transmission and gathering pipelines [1.4]. In a summary report for incidents between 1986 and 1996, corrosion accounted for 25.1% of pipeline incidents on hazardous liquid pipelines [1.4].

The vast majority of underground pipelines are made of carbon steel, based on American Petroleum Institute API 5L specifications [1.5]. Typically, maximum composition limits are specified for carbon, manganese, phosphorous, and sulfur. In some cases, other alloying elements are added to improve mechanical properties.

Most of the corrosion of underground metal is as a result of an electrochemical reaction. Corrosion occurs through the loss of the metal ions at anodic area to the electrolyte. Cathodic areas are protected from corrosion because of the deposition of hydrogen or other ions that carry current [1.4].

Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte. In practice its main use is to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion.

The most rapid development of cathodic-protection systems was made in the United States of America to meet the requirements of the rapidly expanding oil and natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. For that purpose the method was well established in the United States in 1945. [1.4]

In the United Kingdom, where low-pressure thicker-walled cast-iron pipes were extensively used, very little cathodic protection was applied until the early 1950s. The increasing use of cathodic protection has arisen from the success of the method used from 1952 onwards to protect about 1000 miles of wartime fuel-line network that had been laid between 1940 and 1944. The method is now well established. [1.4]

There are two primary types of CP systems: sacrificial anode (galvanic anode) cathodic protection (SACP) and impressed current cathodic protection (ICCP). SACP utilizes an anode material that is electronegative to the pipe steel. When connected to the pipe, the pipe becomes the cathode in the circuit and corrosion is mitigated. Typical sacrificial anode materials for underground pipelines are zinc and magnesium. ICCP utilizes an outside power supply (rectifier) to control the voltage between the pipe and an anode (cast iron, graphite, platinum clad, mixed metal oxide, etc.) in such a manner that the pipe becomes the cathode in the circuit and corrosion is mitigated. [1.1]

The solar energy especially the Photovoltaic (PV) is used as power supply to feed the ICCP system. PV powered ICCP systems are used in different applications around the world. Solar panels generate electricity only when they are subjected to solar radiations.

During the first decade of the 21st century, the worldwide photovoltaic (PV) markets have experienced a tremendous expansion. The installed PV power increased from below 1000 MW to almost 8000 MW between years 2000 and 2007. The most rapid development of CP systems was made in the United States of America (USA) to meet the requirements of the rapidly expanding oil and the natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. For that purpose the method was well established in USA in 1945. [1.1]

The industry sectors for corrosion cost analyses represented approximately 27% of the USA economy gross domestic product (GDP), and were divided among five sector categories: infrastructure, utilities, transportation, production, manufacturing, and government. [1.2]

1.1 Literature Survey

Krause [1.6] identified corrosion as the deterioration of a material (usually a metal) as a result of its reaction with its environment. Corrosion is inevitable in our ambient environment and constitutes a major problem for the crude-oil and natural-gas industry and pipeline operators. The rate of corrosion can be controlled by the use of protective coatings, CP as well as the choice of appropriate materials for the pipeline and/or corrosion inhibitors. Installing an effective protection system is seemed to be highly economic and constitutes only about 1% of total project cost for the pipeline.

Lilly [1.7], using the Saudi Arabian Oil-Company experience, reviewed the external corrosion of two 22-year old commissioned pipelines crossing the Arabian Desert. External corrosion protection was an applied tape-wrap, supplemented by an ICCP system, which was implemented after both pipelines were commissioned. No mention was made of maintaining the technical integrity of the new pipeline against external corrosion during the construction period.

Anene [1.8] concluded that increasing the wall thickness is not a recommended solution for an integrity problem as the pipeline will continue to corrode until a CP system is installed. Operating a commissioned pipeline with effective external CP, will result in considerable cost savings in life-time maintenance. Also an overall reduction in environmental and health hazards associated with leaks that would have occurred resulting of external corrosion of the pipeline. The use of an expensive alloy as the material of a pipeline (in order to inhibit its corrosion) is uneconomic [1.9].

Eliassen and Hesjerik [1.10] concluded that, for most pipelines buried in high-resistivity soil, the CP current demand is high. However the pipeline's integrity can be threatened by severe interference problems, e.g. arising from the presence locally of a direct current for a local electric railway. (For operational pipelines, the external corrosion risks are generally dependent on the anodic-current densities). Also, alternating current interference from near-by high-power transmission lines can be a major source of a pipeline's external corrosion. Hence, careful pipeline-route selection is important.

Pipelines are generally designed with an expected minimum service life of 25 years [1.11]. So in order to survive the harsh underground surroundings in which these pipelines are laid, they should be protected from external corrosion by appropriate coatings and supplemented with CP systems [1.12].

However, little or no consideration is at present given to the deteriorating integrity of pipelines during assembly in Nigeria, despite the often long unexpected delays during this construction period. The provision of a protective system for a pipeline throughout this construction stage is desirable. [1.12]

1.1.1 Previous Work

In 2009, a study in Algeria applied on gas transportation pipelines was performed. The object of the study is to provide corrosion prevention to the pipelines by design an ICCP system supplied with solar energy. The ICCP system is implemented for a pipeline mainly described by some characteristics which are summarized in table (1.1). [1.13]

Table (1. 1): Pipeline Characteristics [1.13]

Characteristics of the Pipeline
Material: Carbon Steel API – 5L, Grade, X60
Length: 292 km
External Diameter: 0.762 m
Surface Area to Protect: $699{,}020\ m^2$
Resistivity: $8{,}000\ \Omega.m$

The results of study show that the impressed current configuration by the solar photovoltaic modules ensures the protection of the pipeline. The results of study are listed as follows [1.13]:

- The mass of the backfill is 14.4 tons and the numbers of anodes is 5
- The number of modules is acceptable; 10 modules with 14 batteries
- The output voltage is 24 V
- The output current is 3.65 A which is high enough to protect the pipeline

In 2013, a research in Iran for designing an ICCP system powered by PV system to provide protection from corrosion to the buried pipeline network of Ahwaz region in Iran, which is owned by National Iranian South Oil Company, was carried out.

The design of ICCP system depends on the parameters of the soil and the pipeline structure. The parameters are represented in tables (1.2) and (1.3) respectively. [1.14]

Table (1. 2): Soil Parameters [1.14]

Parameter	Quantity
Soil Moisture	70%
Soil Temperature [℃]	35
Average Soil Resistivity [$\Omega.cm$]	1200
Soil pH	7.5

Table (1. 3): Pipeline Parameters [1.14]

Parameter	Quantity		
Pipe Material	Carbon Steel API – 5L		
Nominal Diameter [mm]	50.08	152.4	203.2
Length [m]	52	6,000	7,000
Total Surface Area to be Protected [m^2]	8000.47		

A selection of mixed metal oxide (MMO) coated titanium (150, 2.5×50) and a 4A nominal output according to the specifications of standard anodes. The used type of PV modules is AT250 with nominal output voltage, current and power of 17.5V, 2.86A and 250W respectively. The battery is sealed lead acid with nominal voltage and capacity of 12V and 250Ah. The results of ICCP System design are represented in table (1.4). [1.14]

Table (1. 4): ICCP Design Results [1.14]

Subject	Quantity
Minimum Required Current by System [A]	7.867
Number of Required Anodes	5
Pipe Resistance [Ω]	0.765
Coating Resistance [Ω]	0.51
Cable Resistance [Ω]	0.17
Ground-bed Resistance [Ω]	1.52
Voltage Required by System [V]	48
Power Required by System [W]	755
System Lifetime [years]	32
Number of PV Modules	42
Output Voltage [V]	52.2
Output Current [A]	40.04
Output Power [W]	2102
Number of Batteries	4 in Series

1.2 Thesis Objectives

Previous studies (previous section) in Algeria and Iran about the use of PV system as an energy source to the ICCP system are feasible according to their studies. So as in this thesis, a PV powered ICCP system is designed for Palestine and a mathematical and economic study is done to ensure that this technology of corrosion prevention is feasible in Palestine.

The pipelines used to transport natural gas from Gaza Marine Natural Gas Station in the Mediterranean Sea to different distribution stations in Gaza Strip and West Bank. The case study of the thesis is a suggested situation, it does not exist at the present time, and the mathematical, economical studies are depending on this suggested case study.

There many important objectives that are reached in the study, design and simulation of the PV powered ICCP system. The objectives are listed as follows:

1. Building a scientific basis about the cathodic protection (CP) technology using in preventing corrosion damage
2. Investigating the electrical and chemical behavior of environment and the structure to be protected by CP
3. Investigating the possibility of using solar photovoltaic (PV) power to supply the cathodic protection systems
4. Investigating the techno-economic feasibility of using PV powered CP in the Palestinian environment considering the natural gas pipeline distribution network from Gaza Marine Natural Gas Station to Gaza Strip and to West Bank
5. Design and simulation of solar electric powered CP systems to be used in Palestine

Chapter Two

Literature Review

2.1 Background of Cathodic Protection

2.1.1 Definition and Principal of Cathodic Protection (CP)

CP is a method of corrosion control and prevention that can be applied to the buried and submerged metallic structures. CP used in conjunction with coating and can be considered as a secondary corrosion control technique, where the coating system can be efficient with percentage between (50% - 99%). The percentage depends on type, age and a method of installation. So, the properly designed corrosion control or prevention is the combination between coating and CP system. [2.1]

CP works by preventing the anodic reactions of metal dissolution occurring on the structure under protection. CP prevents corrosion by allowing the anodic reactions to occur on specially designed and installed anodes. Also, CP can be defined as electrochemical means of corrosion control in which the oxidation reaction in a galvanic cell is constructed at the anode and suppresses corrosion of the cathode in the same cell [2.2].

In principal, CP can be applied to any metal, but in practice it's primarily used in carbon steel due to its little natural corrosion resistance when it used in corrosive environments as seawater, acid soils, salt-laden concrete, and many other corrosive environments.

CP has two forms of mechanisms; the first mechanism is the sacrificial anode CP, and the second mechanism is the impressed current

CP. The two forms differ in the source of current and type or operation of the anode.

In both techniques of CP, the current flows from the auxiliary anode through the soil to structure to be protected, where this current flow onto a structure from the surrounding electrolyte (soil or seawater), the potential of the structure is made more negative. CP can be achieved by the application of current of sufficient magnitude. Although, this statement is true, it is deceptively simple because there are very large differences in the design of CP systems. These differences result from the infinite variety of structures that are to be protected and from the large assortment of environments in which those structures that are located. [2.2]

If a portion of the structure does not receive current, the normal corrosion activity will continue at that point. If any of CP current picked up by the structure leaves that structure to flow back into the electrolyte, corrosion will be accelerated at the location where the current is discharged.

The need of CP can be summarized in the following points [2.3]:

- 3% to 5% of Gross National Products (GNP) is attributed to corrosion damage
- USA spend about $300 Billion per year due to corrosion
- CP saved about one third of the money that spent on corrosion

CP can protect all types of buried and submerged metallic structures including the following:

- Cross country pipelines

- In plant pipelines
- Aboveground storage tank basis
- Buried tanks and vessels
- Internal surfaces of tanks, vessels, condensers, pipelines, and platforms ships
- Reinforced steel in concrete

2.1.2 CP History

In the 18th century, Galvani and Volta, investigate the potential differences between different metals in an electrolyte and the technical basis for batteries and galvanized steel. In addition, Volta's galvanic cells were described in a paper to the Royal Society in 1799. Galvanizing starts in 1742 by French chemist P.J. Malouin, who describe a method of coating iron by dipping it in molten zinc to French Royal Academy. [2.1]

In 1820s, Sir Humphrey Davey the first suggestion of using CP as a corrosion control on British Naval Ships. In 1836, Stanilaus Sorel who is French chemist obtained a patent for a means of coating iron with zinc. In 1850, Galvanizing industry was using 10,000 tons of zinc per year. [2.2]

In 1950, Applied of extensive use of low-pressure, thicker-walled cast iron pipe meant little CP. In the second half of 20th century, in part, from initial success of a method as used from 1952 onwards to protect 1,000 miles of wartime fuel-line network, also a wide use of CP expanded through North America, due to expanding use of oil and gas industry using steel pipes for underground product transmission, and steel drilling platforms and pipes in the ocean. [2.1]

2.1.3 Advantage and Uses of CP

A substantial advantage of CP over other forms of corrosion mitigation is that it is achieved simply by maintaining a direct current (DC) electrical circuit, the effectiveness of which can be continuously monitored. CP commonly is applied to a coated structure to control corrosion at surfaces where the coating fails or is damaged.

Specifying the use of CP initially will avoid the need to provide a “corrosion allowance” to thin sections of structures that may be costly to fabricate. CP may be used to afford security where even a small leak cannot be tolerated for reasons of safety or environment. CP can, in principle, be applied to any metallic structure in contact with a bulk electrolyte (including concrete). In practice, its main use is to protect steel structures buried in soil or immersed in water. CP cannot be used to prevent atmospheric corrosion on metals. However, CP can be used to protect atmospherically exposed and buried reinforced concrete from corrosion, as the concrete itself contains sufficient moisture to act as electrolyte. [2.3]

CP is also used to protect the internal surfaces of [2.3]:

- Large diameter pipelines
- Ship’s tanks (oil and water)
- Water-circulating systems

CP is applied to control the corrosion of steel embedded in reinforced concrete structures; bridges, buildings, ports and harbors structures, etc.

CP can be applied to copper-based alloys in water systems, and exceptionally to lead-sheathed cables and to aluminum alloys, where cathodic potentials have to be very carefully controlled.

2.1.4 Types of CP Systems

2.1.4.1 Sacrificial Anode Cathodic Protection (SACP) System

In SACP, the naturally occurring electrochemical potentials of different metals are used to provide protection. The sacrificial anodes are coupled to the structure under protection and conventional current flows from the anode to the structure as long as the anode is more active than the structure. As the current flows, all corrosion reactions occur on the auxiliary anode which is sacrifices itself in order to offer protection from corrosion to the structure. [2.4]

SACP use galvanic anodes which have a higher energy level or potential with respect to the structure to be protected. The anodes made of materials such as magnesium or zinc, which are naturally anodic with respect to steel structure [2.4]. See figure (2.1).

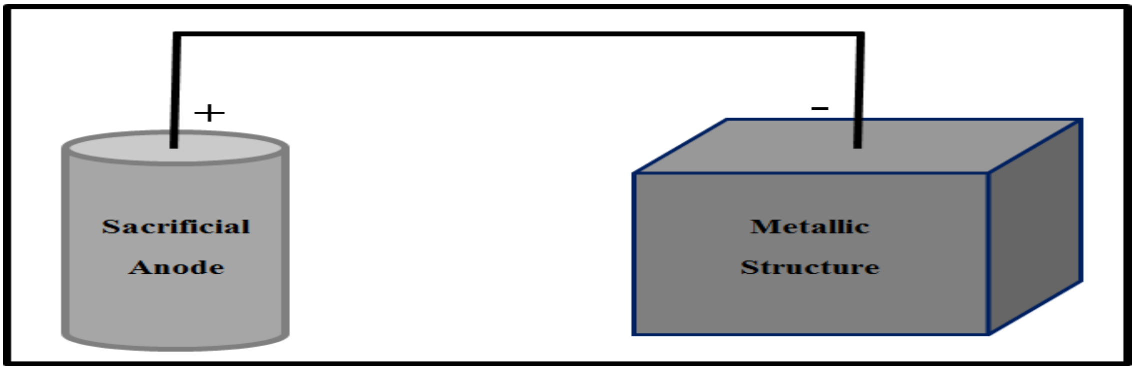

Figure (2. 1): SACP Anode Connected to the Structure

2.1.4.2 Impressed Current Cathodic Protection (ICCP) System

In ICCP system, the current is impressed (forced) by an external power supply to the rest components of the protection system. The anodes are either inert or have low consumption rates and can be surrounded by carbonaceous backfill to increase the efficiency and decrease cost. Typical anodes are titanium coated with Mixed Metal Oxide (MMO) or platinum, silicon iron, graphite and magnetite. [2.4]

As ICCP needs an external power source (DC), it can be obtained using a rectifier with an AC power source or from a Solar Photovoltaic (PV) System which can provide DC power directly.

ICCP use anodes which are energized by an external DC power source. The anodes are installed in the electrolyte (corrosive environment) and are connected to the positive terminal of the power source and the structure to be protected is connected to the negative terminal of the power source. See figure (2.2).

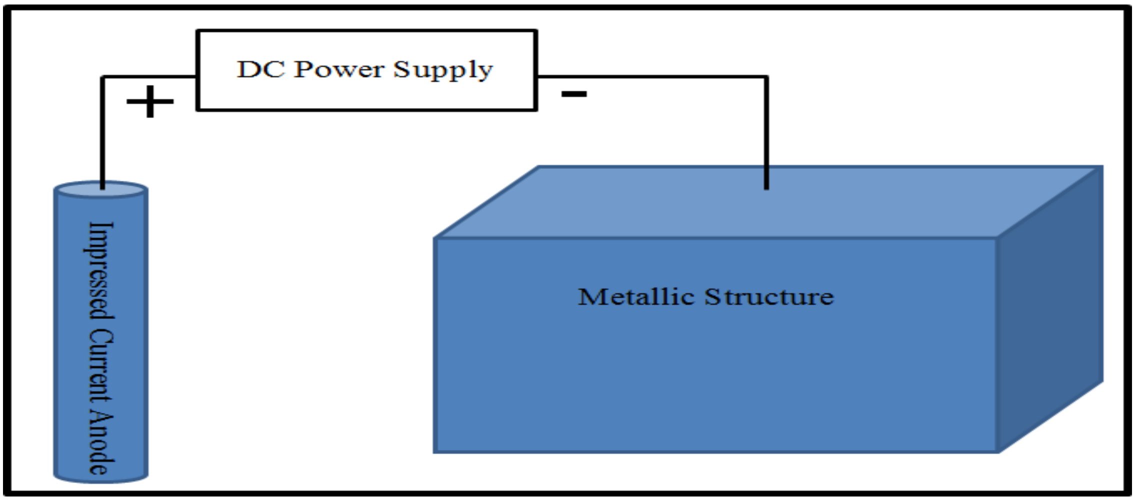

Figure (2. 2): ICCP System

2.1.4.3 Comparison between ICCP and SACP

The following table represents a comparison between the two types of CP Systems.

Table (2. 1) [2.4]

SACP	ICCP
Uses - For protection of well coated areas - Where the surface area of protected structure is small due to economic restrictions	**Uses** - Where the protective current and life requirements are high - Over a wide range of soil and water resistivity quantities - For protection of large uncoated areas
Benefits and Features - No independent current source - Limited effects on neighbor structures - Self-adjusting - Simple to install - No damage due to wrong installation	**Benefits and Features** - Need external power source - Adjusted manually or automatically - Anodes are very compact - Can effects other structures - Damage possibility due to wrong installation - Need small number of Anodes

2.2 Electrochemical Analysis of Corrosion and Cathodic Protection

2.2.1 Corrosion Definition

Corrosion can be defined as electrochemical changes occur on the surface of metallic structure due to magnitude of potential difference when electrons move from the anodic site (where the oxidation reactions occur) to the cathodic site (where the reduction reactions occur). [2.5]

The electrochemical changes that lead to the oxidation and reduction reactions need a corrosive medium (electrolyte). In the electrolyte, the positive and negative ions move between the anodic and cathodic sites due to their charges as; the negative ions move from cathodic site to anodic site, and the positive ions move from the anodic site to the cathodic site. Corrosion causes a mechanical damage in the metallic structure due to corrosion products which are called rust (produced from reduction reactions). [2.5]

2.2.2 Corrosion Parameters

Corrosion cell is a circuit consisting of an anode, cathode, electrolyte and an electrical contact between the anode and cathode.

2.2.2.1 Anode

Anode is the metal surface where the corrosion reaction (oxidation) occurs as the metal atoms dissolve to produce electrons and ions, where electrons leave the anode through an electrical connection to the cathode and ions leave the anode to the electrolyte. The following equation represents the oxidation reaction of Iron atom [2.6]:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.1)}$$

2.2.2.2 Cathode

Cathode is the metal surface where the reduction reactions occur as a consumption of arriving electrons from anode through the electrical connection by the dissolved hydrogen and oxygen in the cathode's surrounding area of electrolyte. The following equations represent the reduction of hydrogen and oxygen [2.6]:

$$2H^{+} + 2e^{-} \rightarrow H_2 \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

$$2O^{2-} + 4e^{-} \rightarrow O_2 \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

2.2.2.3 Electrolyte

Electrolyte is the medium -which can be soil, water or any corrosive solution- where the dissolved negative and positive ions move from anode and cathode as to positive ions or from cathode to anode as to negative ions. The changes that occur in the electrolyte as a result of corrosion process are called electrolysis. [2.6]

- **Soil**

Chemical analysis of soils is usually limited to determination of constitutes that are soluble in water under standardized conditions. The elements that are usually determined are; the base-forming elements, such as sodium, potassium, calcium and magnesium; and the, or acid-forming elements, such as carbonate, bicarbonate, chloride, nitrate and sulfate. The nature and amount of soluble salts, together with the moisture content of the soil, largely determine the ability of the soil to conduct an electric current.

Moisture content in soil will probably have the most profound effect when considering corrosion potential than any other variable. No corrosion will occur in environments that are completely dry. When the soil is nearly dry, its resistivity is very high. However, the resistivity decreases rapidly with increases of moisture content until the saturation point is reached, after which further additions of moisture have little or no effect on the resistivity. [2.6]

- **Water**

The corrosion of metals in water depends on occurrence of base-forming and acid-forming element such as in soil. No corrosion will occur in completely fresh water. The corrosion in seawater or salt water depends on the concentration of corrosion inhibitors. [2.6]

- **Effect of pH Value**

A high pH value means there are fewer free hydrogen ions, and that a change of one pH unit reflects a tenfold change in the concentrations of the hydrogen ions. For example, there are 10 times as many hydrogen ions available at pH 7 than at pH 8. The pH scale commonly quoted ranges from 0 to 14 with a pH of 7 is considered to be neutral. [2.6]

Low pH acid waters accelerate corrosion by supplying hydrogen ions to the corrosion process. Although even absolutely pure water contains some free hydrogen ions, dissolved carbon dioxide in water can increase the corrosion chemistry hydrogen ion concentration. At pH of 4 or below, direct reduction of H^+ ions, is important particularly at lower partial pressure of carbon dioxide and the pH has a direct effect on the corrosion rate. [2.6]

2.2.3 Underground Pipeline Corrosion

There are many metals (such as iron) used in underground construction applications. The metallic materials used in underground construction are subjected to very complex corrosion types, because of the presence of many corrosiveness factors that may individual or in combination affect the corrosion reactions. These factors determine the rate and the type of electrochemical corrosion, such as uniform and pitting corrosion [2.7]. The following sections are the summary for commonly observed forms of corrosion.

The corrosion and CP of the underground pipelines is the main object in this thesis, especially in the design and simulation. It’s important to have a good knowledge about these types of corrosion in order to get proper design of CP system to protect the underground pipelines.

2.2.3.1 Uniform Corrosion

Uniform corrosion or general corrosion process is exhibiting uniform thinning that proceeds without appreciable localized attack. It is the most common form of corrosion and may appear initially as a single penetration, but with thorough examination of the cross section it becomes apparent that the base material has uniformly thinned [2.8].

2.2.3.2 Pitting Corrosion

Pitting corrosion is a localized form of corrosion by which cavities (holes) are produced in the material. Pitting is considered to be more dangerous than uniform corrosion because it is more difficult to detect, predict, and design against. Corrosion products often cover the pits. The small narrow pit with minimal overall metal loss can lead to the failure of an entire engineering system. [2.8]

2.2.3.3 Corrosion Due to Dissimilar Metals

This form of corrosion occurs when dissimilar metals are in contact in the presence of an electrolyte, such as water (moisture) containing very small amounts of acid. The dissimilar metals produce a galvanic reaction which is resulted in deterioration of one of them [2.8].

2.2.4 Corrosion Circuit

Corrosion of iron in salt water is a good example to explain the process of corrosion. This section will discuss it in details.

2.2.4.1 Parameters of Corrosion Circuit

The corrosion circuit consists of two iron electrodes; one of them is unprotected so it’s more active (has a higher ability to corrosion) than the other. Both of the electrodes are immersed in salt water solution with an electrical connection between them. Figure (2.3) shows the corrosion circuit diagram. The parameters of corrosion circuit are:

- Anode (Iron electrode with higher activity)

- Cathode (Iron electrode with lower activity)
- Electrolyte (salt water)
- Electrical connection

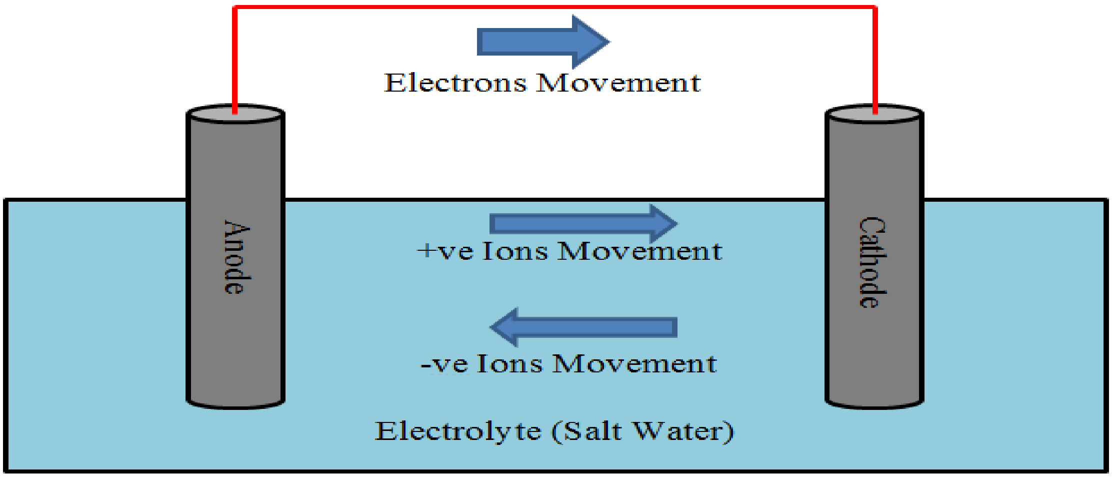

Figure (2. 3): Corrosion Circuit Diagram

2.2.4.2 Anodic Reaction

At the anode, the high concentration of salts, acidity, lower pH value in salt water and other solutions around the anode electrode, these factors lead the iron atoms at the surface of electrode to dissolve (oxidize/loose electrons), the electrons transferred along the surface of anode electrode surface, the transferred to the cathode electrode through the electrical connection. Due to iron conductivity, oxidation reactions happen as in equation (2.1) [2.5].

The electrons movements from anode to cathode are due to potential difference occur as a result of oxidation reaction of iron. As the potential increases some water molecules dissolve to the electrolyte as in equation

(3.4). Figure (2.4) represents the oxidation of iron and water molecules at the anode/electrolyte interface. [2.5]

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \text{.................... (2.4)}$$

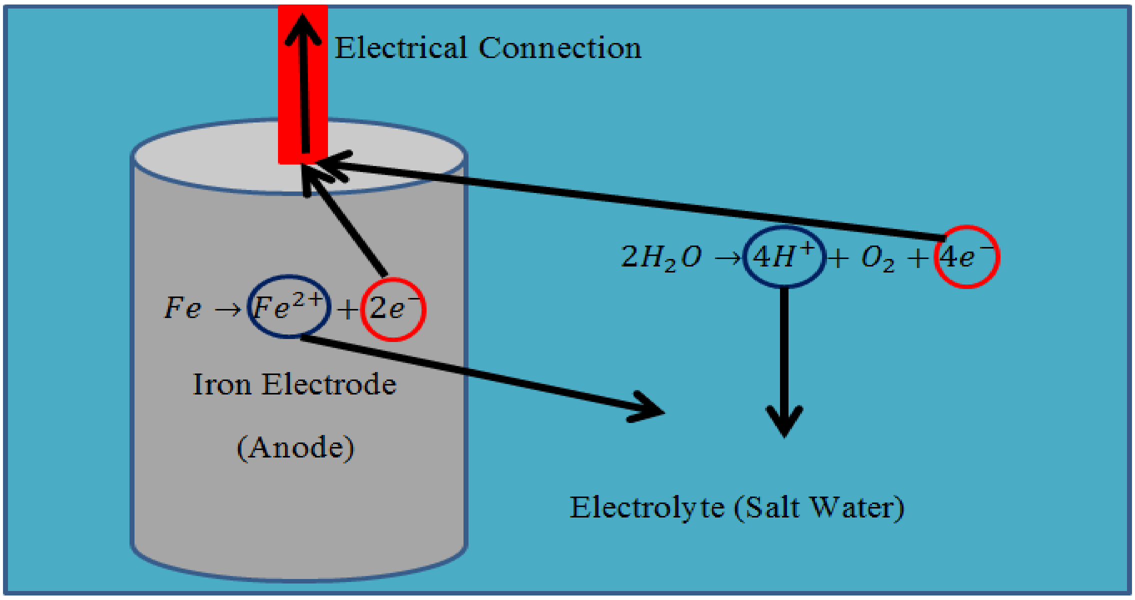

Figure (2. 4): Oxidation of Iron and Water Molecules at the Anode/Electrolyte Interface

2.2.4.3 Cathodic Reaction

At the cathode, the released electrons from anode which are transferred to the cathode through the electrical connection, these electrons will be consumed by the reduction reaction. The reduction happens as in reduction of oxygen and water with released electrons to form the hydroxide, see equation (2.5). Figure (2.5) represent the reduction reaction at the cathode/electrolyte interface. [2.5]

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \text{.................... (2.5)}$$

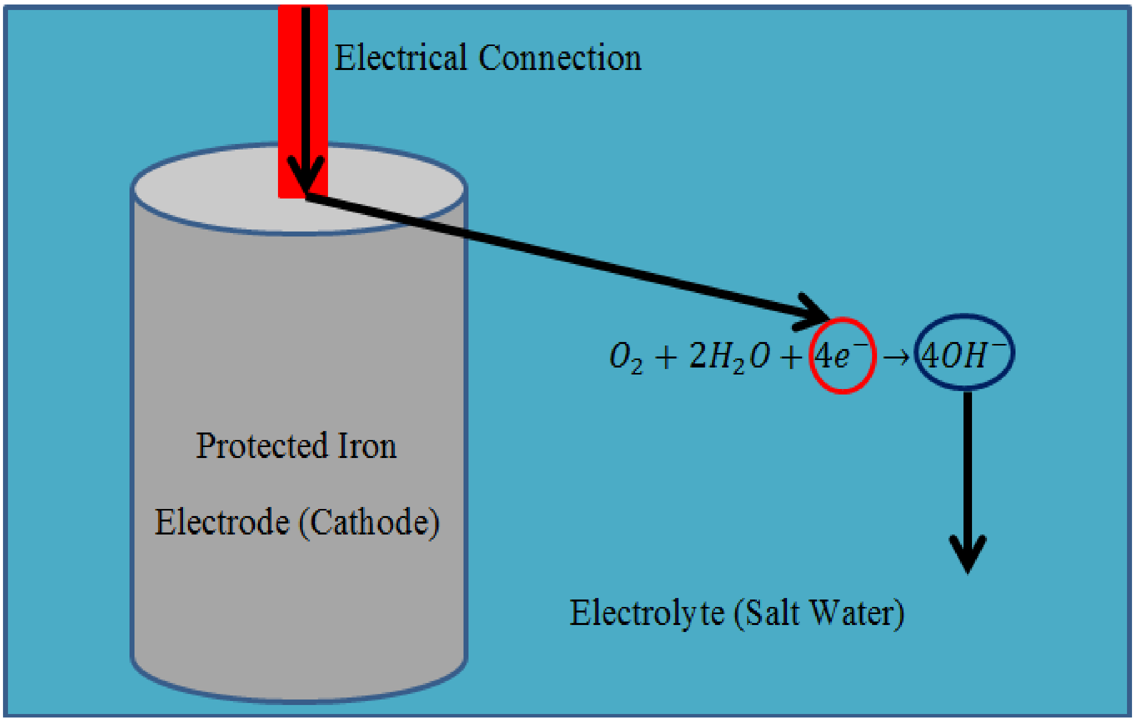

Figure (2. 5): Reduction Reaction at the Cathode/Electrolyte Interface

2.2.4.4 Electrons and Ions Movement

Water temperature, pH value or concentration of salts and different corrosive materials are coefficients that provide energy to the metal surface atoms. The provided energy will result of potential difference in the electrolyte.

At specific quantity of energy, two electrons will free out of the iron atom outer band. As electrons free out as the iron atom become a positive ion and dissolves into the electrolyte. The free electrons travel through the metal path to the less active site and consumed through reduction reaction as in equation (2.5). Water molecules can dissolve like iron atoms as in equation (2.4).

The potential difference between the positive (active) part which is the anode and the negative part which is the cathode will polarize the electrolyte ions; the positive ions (like:H^{+}, Fe^{2+}) goes from the anodic side to the cathodic side, and negative ions (hydroxide ions which produced from reduction of water, oxygen and free electrons that received from the anode) goes from the cathode side to the anode side.

The potential difference of the corrosion cell will produce an electric field (E) between anode and cathode. E lines are transmitted from the cathode to the anode. As charges move due to E, an electric force (F) produces. The direction of F is depending on the electric charge (q) polarity as in equations (2.6, 2.7, 2.8, and 2.9). [2.5]

Both F and E are vector quantities; they have both magnitude and direction. The magnitude of F is equal to (qE) and the direction of F is equal to the direction of E if q is positive, and the direction of F is in the opposite direction of E if q is negative. E is uniform when neither its magnitude nor its direction changes from one point to another. The unit of E is $(V.m^{-1})$. Figure (2.6) represents the movement of electrons and ions in the electrolyte. [2.9]

$$E = \frac{1}{4\pi\epsilon} x \frac{q}{r^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

Where:ϵ the permittivity is r is the distance from charge (or the center of sphere) and the electric field is in a radial direction, and q is the electric charge. [2.9]

$$F = qE \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

For positive ions [3.3]:

$$F = +1.6x10^{-19}xE \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

For negative ions [3.3]:

$$F = -1.6x10^{-19}xE \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

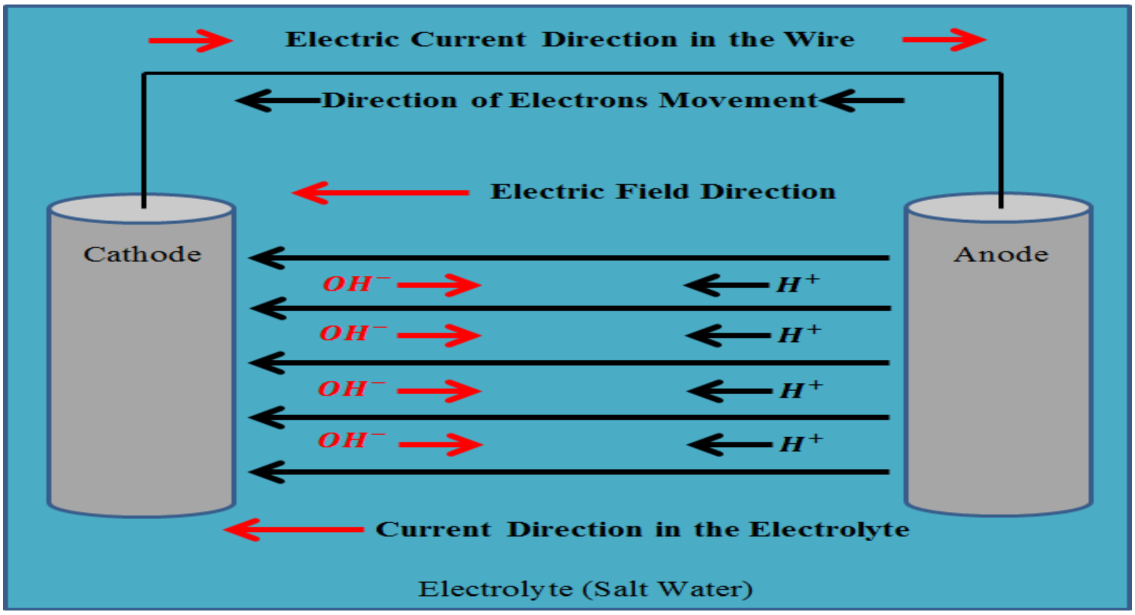

Figure (2. 6): Movement of Electrons and Ions in the Corrosion Cell

2.2.4.5 Rust Formation

Hydroxide ions (OH^-) appear in water as the hydrogen ion concentration falls. They react with the iron (II) ions to produce insoluble iron (II) hydroxide, $(Fe(OH)_2)$, as in the following equation [2.3]:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

Iron (II) ions also react with hydrogen ions and oxygen to produce iron (III) ions, as in the following equation [2.3]:

$$Fe^{2+} + 4H^+ + O_2 \rightarrow 4Fe^{3+} + H_2O \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.11)$$

Iron (III) ions react with hydroxide ions to produce hydrated iron (III) oxide (also known as iron (III) hydroxide), as in the following equation [2.3]:

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.12)$$

Iron (III) hydroxide dried to make plain (III) oxide (Fe_2O_3), this red-brown, powdery stuff and easily crumbles off to continually expose fresh metal for reaction, which is called "Rust". Figure (2.7) represents the formation of rust on the iron metallic structure in salt water.

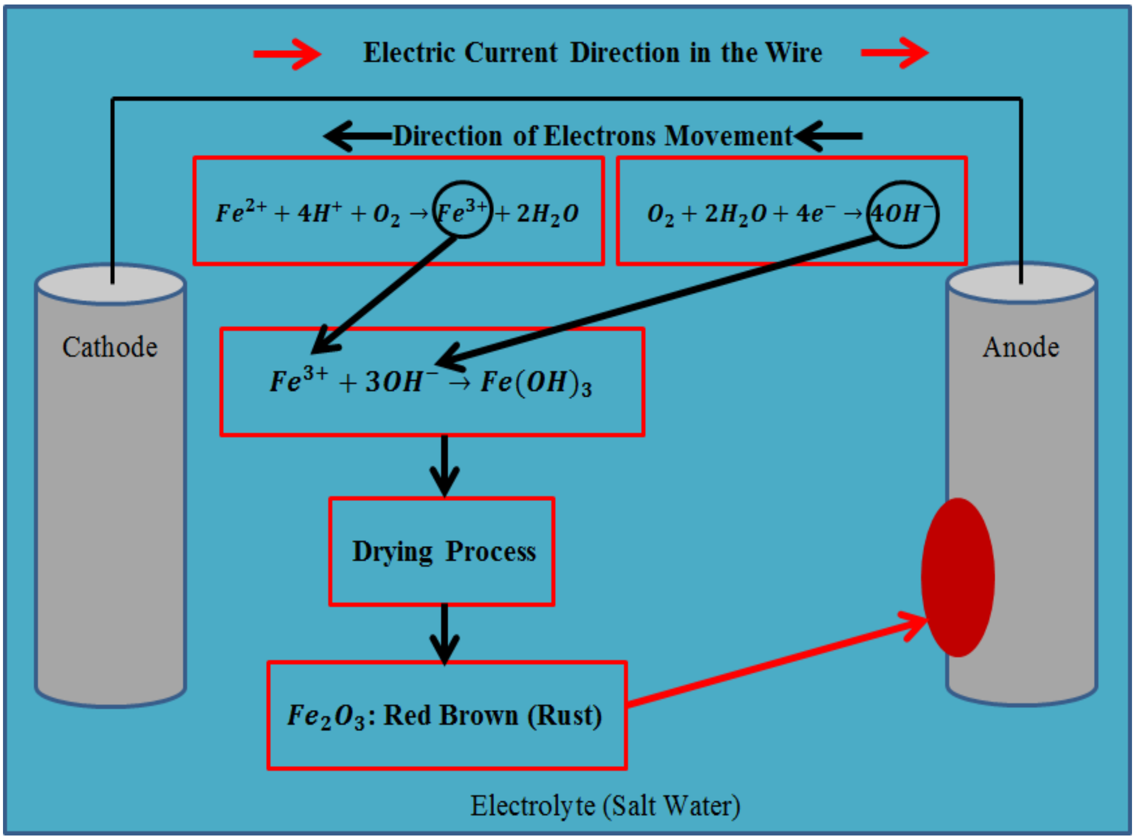

Figure (2. 7): Rust Formation

2.2.5 Cathodic Protection Circuit

2.2.5.1 Corrosion Circuit of Pipeline

The corrosion process can be described as in figure (2.8).

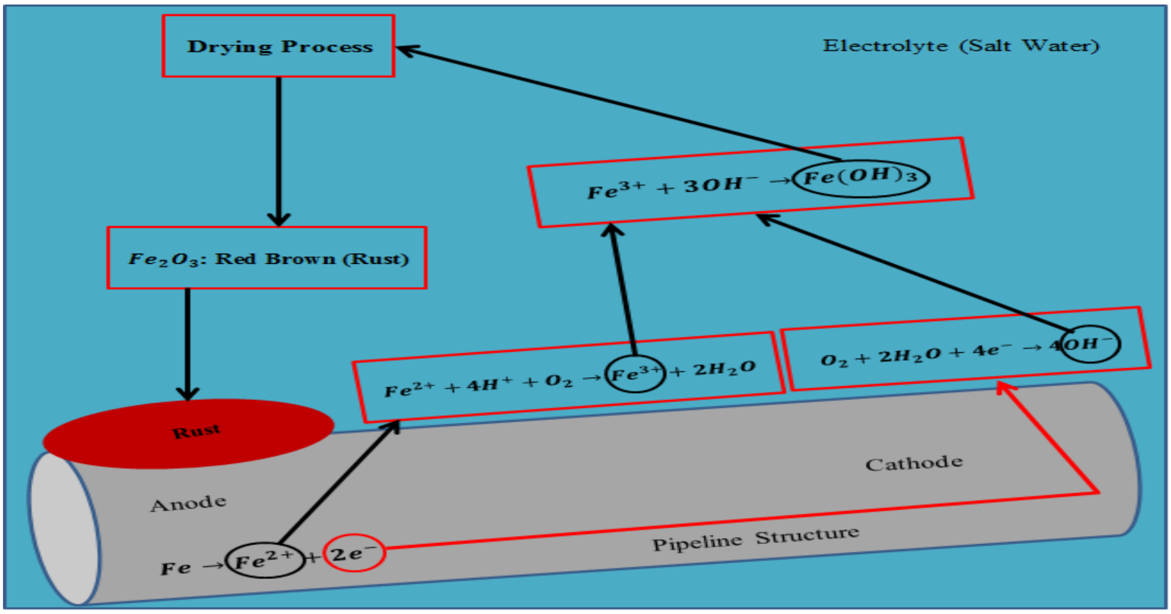

Figure (2. 8): Pipeline Corrosion Circuit

2.2.5.2 Sacrificial (Galvanic) Anode Cathodic Protection (SACP)

- **Sacrificial Anodes**

Sacrificial anodes are commonly made of alloys of zinc (Zn), aluminum (Al) or magnesium (Mg), which are used to form a galvanic cell. Due to the potential differences that existing between sacrificial anode alloys and the cathodic area (steel), positively charged metal ions leave the anode surface while electrons leave the surface at the cathode. In the case of aluminum alloy anodes, the reaction at the aluminum anode surface is as in the following equation [2.5, 2.6]:

$$Al \rightarrow Al^{3+} + 3e^- \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.13)$$

In underground applications, aluminum anodes are normally surrounded with a special backfill. The backfill is usually a mixture of Gypsum, Mennonite and sodium sulfate, this special backfill serves a number of purposes. First, it provides a uniform environment for the anode, thereby making the corrosion of the anode uniform. Second, the backfill decreases the anode to earth resistance. Third, it retains moisture and thereby maintains a lower resistance. Fourth, it acts as a depolarizing agent [2.6].

The most common alloys used for SACP with their specifications are explained in table (2.2).

Table (2. 2): Sacrificial Anodes Specifications [2.5]

Metal	Potential (Volts)	Density (g/cm^3)
Magnesium (Mg)	-1.55	1.70
Aluminum (Al)	-1.15	2.70
Zinc (Zn)	-1.10	7.10

- **Protection Circuit**

In explanation of sacrificial anode circuit, a magnesium anode is used. By using magnesium anode, the structure to be protected will be as cathode, and as the structure is more cathodic as it is more protective from corrosion. The anodic (oxidation) reactions will occur on the magnesium anode.

When electrons move from the sacrificial anode to the pipe structure, it consumed by the reduction reaction of water and oxygen to form hydroxide molecules. As electrons transferred to the pipeline structure as the pipeline is protected from corrosion.

The magnesium anode sacrifices itself (waste away) as long as occurrence of anodic and cathodic reaction, as in figures (2.9).

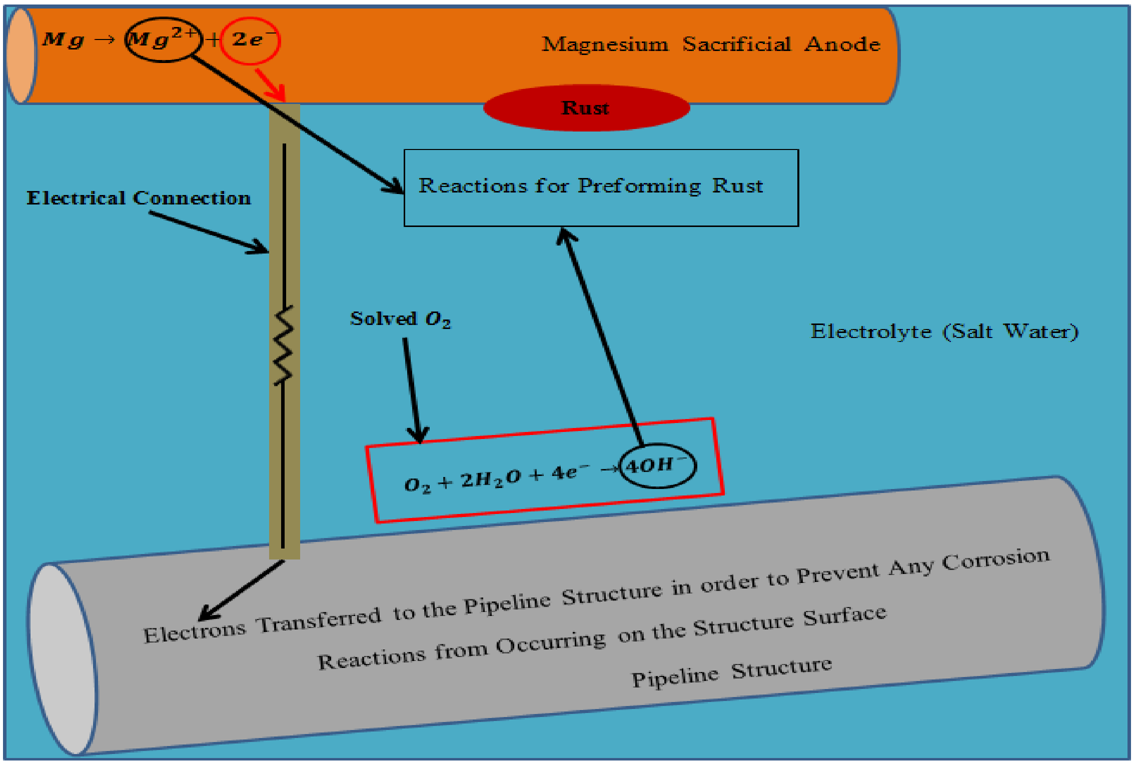

Figure (2. 9): Sacrificial Anode Cathodic Protection Circuit

2.2.5.2 Impressed Current Cathodic Protection (ICCP)

- **Impressed Current Anodes**

When external power source is used, the current is derived from an outside source and is not generated by the corrosion of particular metal as in the case with galvanic anodes. However, materials used as energized anodes do corrode.

The materials that are commonly used are graphite, high silicon cast iron and mixed metal oxide coated titanium. In underground work, special coke breeze backfills are usually used for the purpose of providing a uniform environment around the anode and for lowering the anode to earth resistance. [2.5, 2.6]

The impressed current anode material is ideally non-consumed by the passage of current from it into the electrolyte, in practice the materials used are a compromise between this ideal and the cost and physical properties of available materials. Impressed current anodes specifications are represented in table (2.3).

Table (2. 3): Impressed current anodes specifications [2.5]

Type	Density ($g.cm^{-3}$)	Anode Current Density ($A.m^{-2}$)	
		Maximum	Average
Graphite	1.6 to 2.1	50 to 150	10 to 50
Magnetite	5.2	-	90 to 100
High-Silicon Iron	7.0 to 7.2	300	10 to 50
Lead Silver alloy	11.0 to 11.2	300	50 to 200
Lead-Platinum	11.0 to 11.2	300	100 to 250

- **Protection Circuit**

The DC power source drives electrons to the pipeline metallic structure through connection wire. The negative pole of the power source is connected with the pipeline structure. As the structure is at negative polarization as it’s protected from corrosion.

The only reactions which are permitted to occur are the cathodic (reduction) reactions because the external power source is delivering electrons, so there is no anodic reactions will occur at the anode. ICCP protection circuit for pipeline is represented in figure (2.10).

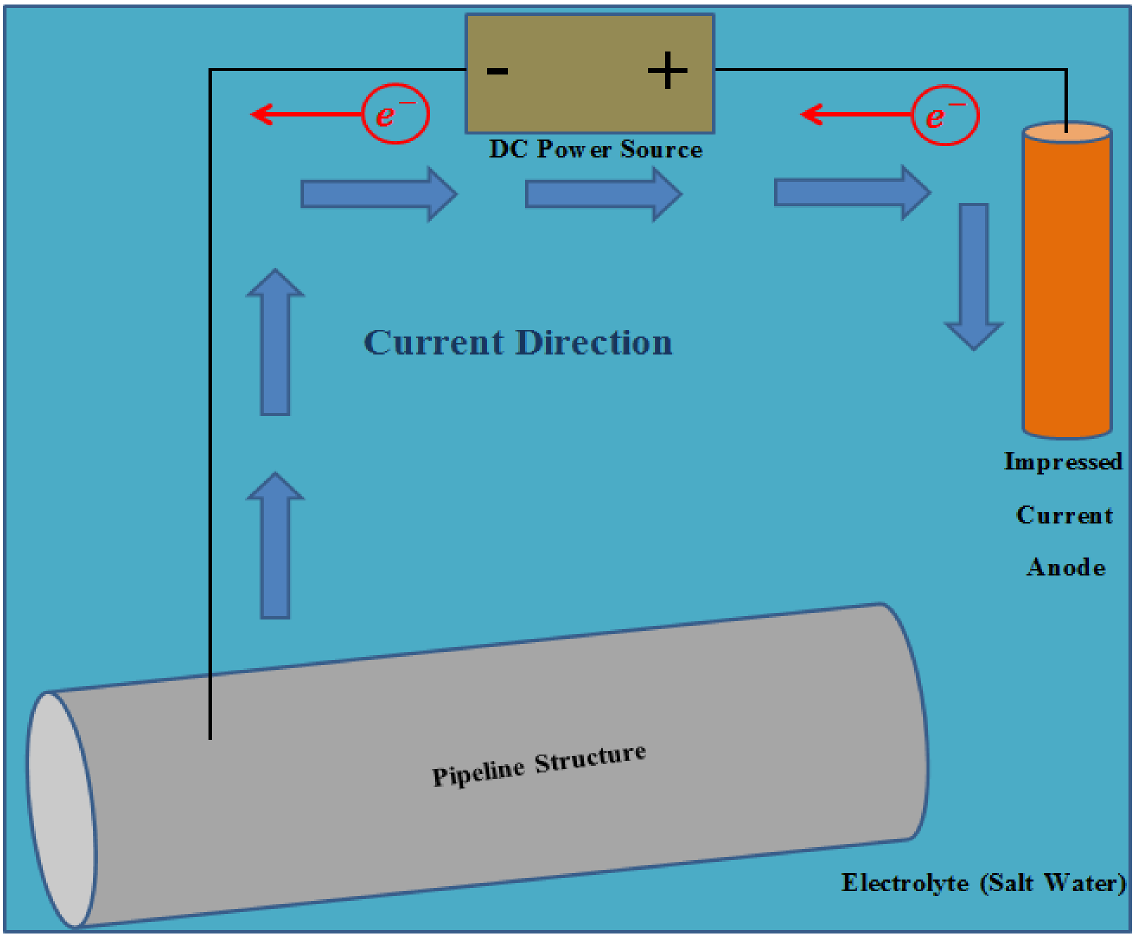

Figure (2. 10): ICCP Protection Diagram

2.3 Photovoltaic (PV) Technology

Renewable power generation can help countries to meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy. Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of Giga-Watts of wind, hydropower and solar PV capacity are installed worldwide every year in a renewable energy market that is worth more than Hundred Billion USD annually [2.10].

The rapid increase in the growth of the renewable energy sector can be traced to the decline in the stock of conventional energy source such as oil, gas and coal. With the rapid growth of renewable energy, the prices and the cost of renewable energy systems has decreased remarkably. Recent years have seen dramatic reductions in the cost of renewable energy technologies as a result of research and accelerated development. [2.11]

2.3.1 PV Technology

PV is a method of generating electrical power by converting sunlight into direct current electricity using semiconducting materials that exhibit the PV effect. A PV system employs solar modules composed of a number of solar cells to supply usable solar power. Power generation from solar PV has long been seen as a clean sustainable energy technology which draws upon the plant’s most plentiful and widely distributed renewable energy source – the sun. The direct conversion of sunlight to electricity occurs without any moving parts or environmental emissions during operation.

2.3.2 History

The PV effect was first experimentally demonstrated by French physicist Edmond Becquerel. In 1839, he built the world’s first PV cell in his father’s laboratory. Willoughby Smith first described the effect of light on Selenium during the passage of an electric current issue of nature, in February, 20, 1873. In 1883, Charles Frittz built the first solid state PV cell by coating the semiconductor selenium with a thin layer of gold to form the junctions. The device was only around 1% efficient. In 1888, Russian physicist Alexander Stoletov built the first cell based on the outer PV effect discovered by Heinrich in 1887 [2.10, 2.11].

Albert Einstein explained the underlying mechanism of light instigated carrier excitation – the PV effect – in 1905, for which he received the Noble Prize in physics in 1921. Russell Ohl patented the modern junction semiconductor solar cell in 1946, discovered while working on the series of advances that would lead to the transistor. [2.10]

The first practical PV cell was publicly demonstrated on April, 25 1954 at Bell Laboratories. The inventors were Daryl Chapin, Calvin Southern Fuller and Gerald Pearson. Solar cells gained prominence when they were proposed as an addition to the 1958 Vanguard 1^{st} Satellite. By adding cells to the outside of the body, the mission time could be extended with no major changes to the spacecraft or its power system. In 1959, United States launched Explorer 6^{th}, featuring large wing-shaped solar arrays, which became a common feature in satellites, these arrays consisted of 9600 Hoffman solar cells. [2.10, 2.11]

In 2013, the fast-growing capacity of worldwide installed solar PV increased by 38% to (139 Giga-Watts). This is sufficient to generate at least 160 Tera-Watts-Hours or about 0.35% of the electricity demand on the planet. China, followed by Japan and the United States, is now the fastest growing market, while Germany remains the world’s largest producer, contributing almost 6% to its national electricity demands. [2.12, 2.13 and 2.14]

2.3.3 PV Module

Figure (2.11) represents the PV module diagram and figure (2.12) represents the PV cell, module and array.

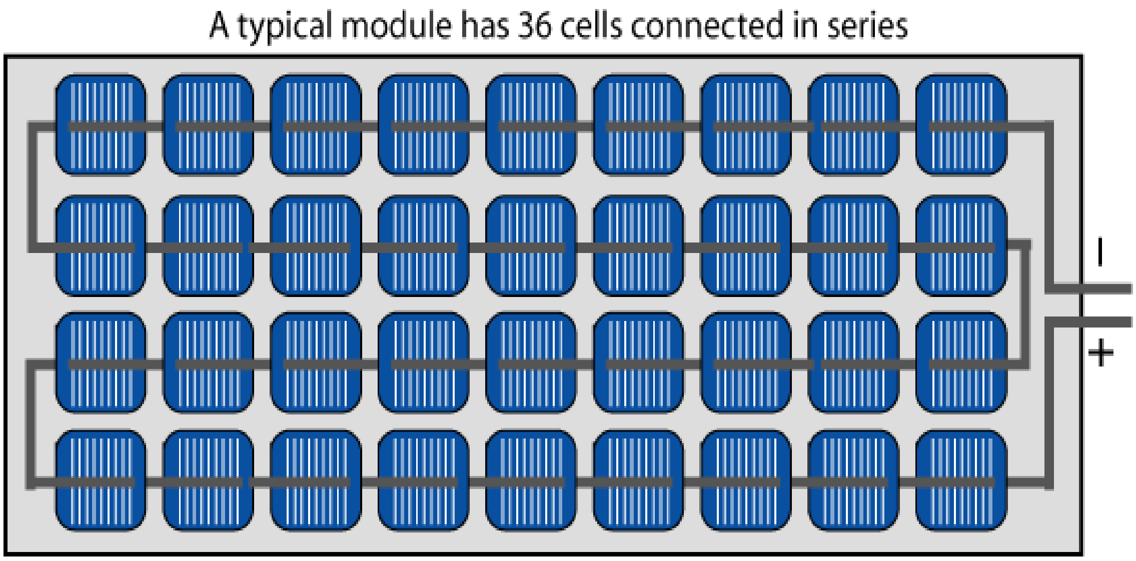

Figure (2. 11): PV Module Diagram [2.15]

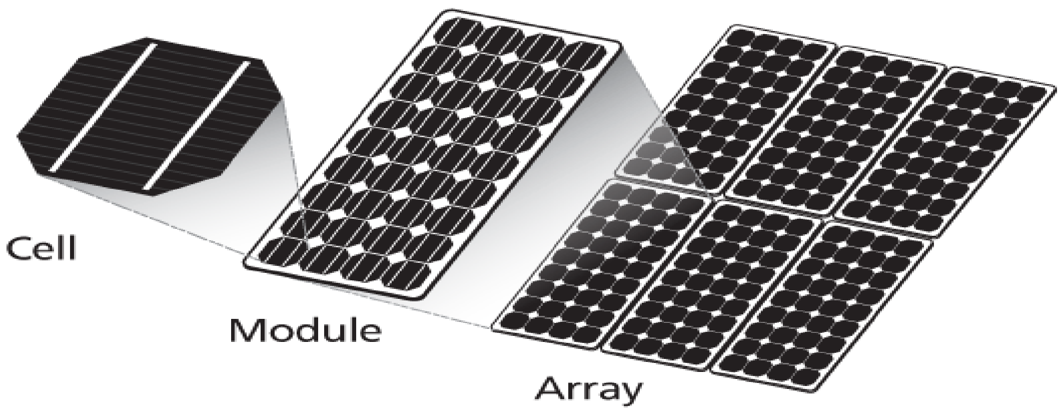

Figure (2. 12): PV Cell, Module and Array [2.15]

2.3.3.1 PV Module Characteristics and Equivalent Circuit

If a variable load is connected through the terminals of the PV module, the current and the voltage will be found to vary. The relationship between the current and the voltage will be found to vary. The relationship between the current and the voltage is known as the IV characteristic curve of the PV module.

To measure the IV characteristic of a PV module and to find the maximum power point, international standard conditions (STC) should be fulfilled. Standard conditions means: irradiance level equal to $(1000\ W/m^2)$, the reference air mass equal 1.5, and module junction temperature should be of $25℃$ [2.16].

2.3.3.2 PV Module Parameters

The main parameters that characterize a PV module are [2.17]:

1- Open Circuit Voltage (V_{OC}): The maximum voltage that the module provides when the terminals are not connected to any load (an open circuit). This value is about 22 V for modules dispend to work in 12 V systems. The output voltage of the module is directly proportional to the number of cells connected in series.

2- Short Circuit Current (I_{SC}): The maximum current provided by the module when the connectors are short circuited. The value of the output current of the module is proportional to the number of cells connected in parallel.

3- Maximum Power Point (P_{MPP}): The point where the power supplied by the module is at maximum value. The maximum power point of a module is measured in watts $[W]$ or peak watts $[W_p]$. Typical value of: $V_{max} and\ I_{max} are\ a\ bit\ smaller\ than\ V_{OC} and\ I_{SC}.$

4- STC:

$(T_{cell} = 25°C, G = 1000\,W/m^2\,, Airmass = 1.5\ and\ V_{wind} \leq 2\,m/s)$

Solar cells consist of a p-n junction fabricated in thin wafer or layer of semiconductors, whose electrical characteristics differ very little from a diode represented by the equation of Shockley. Thus the simplest equivalent circuit of a solar cell is a current source in parallel with a diode, see figure (2.13) [1.30]. The output of the current source is directly proportional to the light falling on the cell. So the process of deriving an equivalent circuit and IV characteristic curve can be developed based on the following equations [2.17].

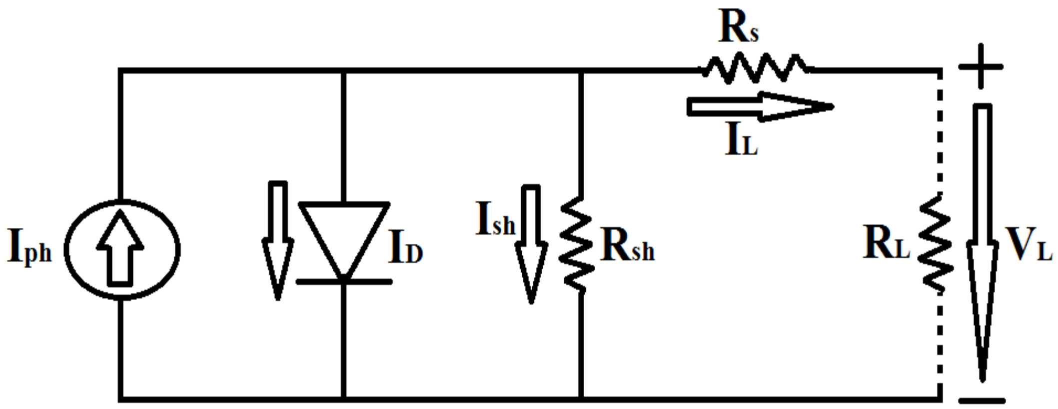

Figure (2. 13): PV Module Equivalent Circuit Diagram ; R_{sh}: Shunt Resistance, R_s: Series Resistance, I_{ph}: Photon Current, I_D: Diode Current, I_{sh}: Shunt Current, I_L: Load Current and V_L: Load Voltage [2.17]

$$I_L = I_{ph} - I_D - I_{sh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.14)}$$

$$I_L = I_{ph} - I_0 \left(e^{\left[\frac{q(V+R_S I_S)}{AKT}\right]} - 1 \right) - I_{sh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.15)}$$

Where:

- A: Ideality factor = 1 – 2
- K: Boltzmann Constant; $1.38x10^{-23}\frac{ws}{°K}$
- I_0: Saturation Current
- T: Cell Temperature in Kelvin

$$V_{R_s} = R_{sh}I_{sh} - V_L, R_{sh} \gg R_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.16)$$

When applying open and short circuit tests as follows [2.17]:

- At open circuit test of module: $I_L = 0$.

$$\ln\left(\frac{I_{ph}}{I_0}\right) = \frac{qV_{oc}}{AKT} \to V_{oc} = \frac{AKT}{q}\ln\left(\frac{I_{ph}}{I_0}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.17)$$

- At short circuit test of module; $V_L = 0, V_{R_s} = V_{R_{sh}}, I_L = I_{ph} = I_{sc}$

Then the IV characteristic curve will be as in figure (2.14):

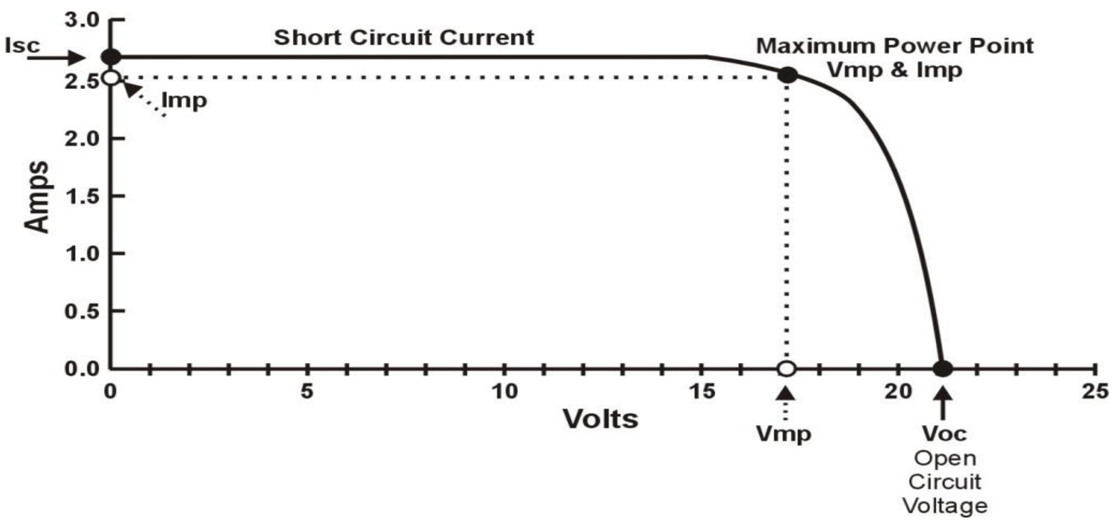

Figure (2. 14): IV-Characteristic Curve [2.18]

From IV characteristic curve some factors can be calculated as follows [2.17]:

$$\eta(Efficiency) = \frac{V_{mpp}I_{mpp}}{G_0A_{cell}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.18)$$

$$FF(Fill\ Factor) = \frac{V_{mpp}I_{mpp}}{V_{oc}I_{sc}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.19)$$

2.3.3.3 PV Module Types

- Mono Crystalline Silicon Cell: these are made using cells cut from single cylindrical crystal silicon. While mono crystalline cells offer the highest efficiency (approximately 18% conversion of incident sunlight), their complex manufacturing process makes them slightly more expensive. Mono crystalline cell specifications:
  - Open Circuit Voltage; $V_{oc} = 0.6 - 0.62\ Volts$
  - Short Circuit Current; $I_{sc} = 3.4\ A/100cm^2$
- Polycrystalline Silicon Cell: these are made by cutting micro-fine wafers from ingots of molten and recrystallized silicon. Polycrystalline cells are cheaper to produce, but there is a slight compromise on efficiency (approximately 14% conversion of incident sunlight). Polycrystalline cell specifications:
  - Open Circuit Voltage; $V_{oc} = 0.55 - 0.58\ Volts$
  - Short Circuit Current; $I_{sc} = 2.6 - 3.1\ \ A/100cm^2$

- Thin Film Silicon Cell: these are made by depositing an ultrathin layer of PV material onto a substrate. The most common type of thin film PV is made from the material a-Si (amorphous silicon), but numerous other materials such as Copper Indium/Gallium Selenide (CIGS), Copper Indium Selenide (CIS), Cadmium Telluride ($CdTe$) are produced. The efficiency of this type varies approximately in the range from $2\% - 10\%$
  - Open Circuit Voltage; $V_{oc} = 0.65 - 0.78\ Volts$

- Short Circuit Current; $I_{sc} = 1 - 2\,A/100cm^2$ [2.17]

2.3.3.4 Temperature and Solar Radiation Effects on PV Performance

The two most important effects that must be considered are due to the variable temperature and solar radiation. The effect of these two parameters must be taken into account while sizing the PV system, as in figure (2.15) and figure (2.16).

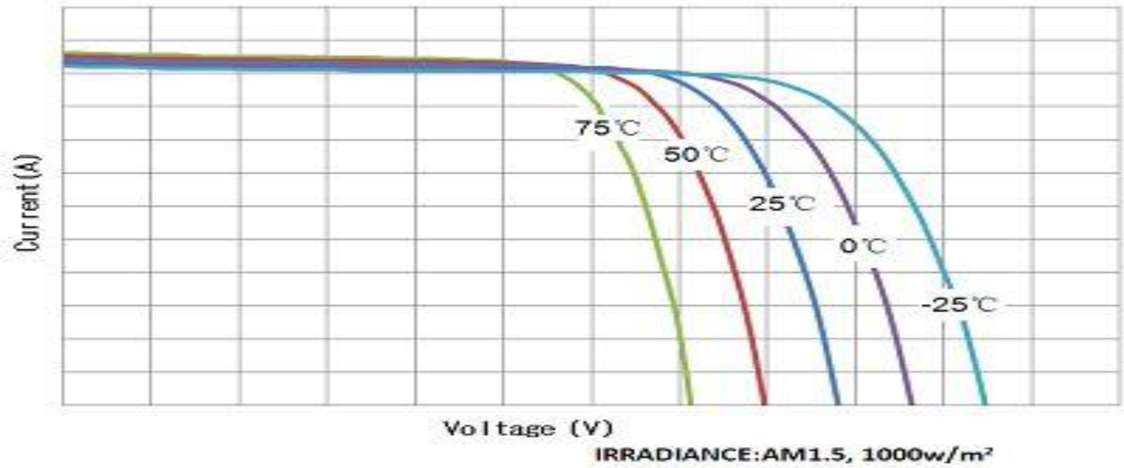

Figure (2. 15): Effect of Temperature on IV-Characteristic Curve [2.18]

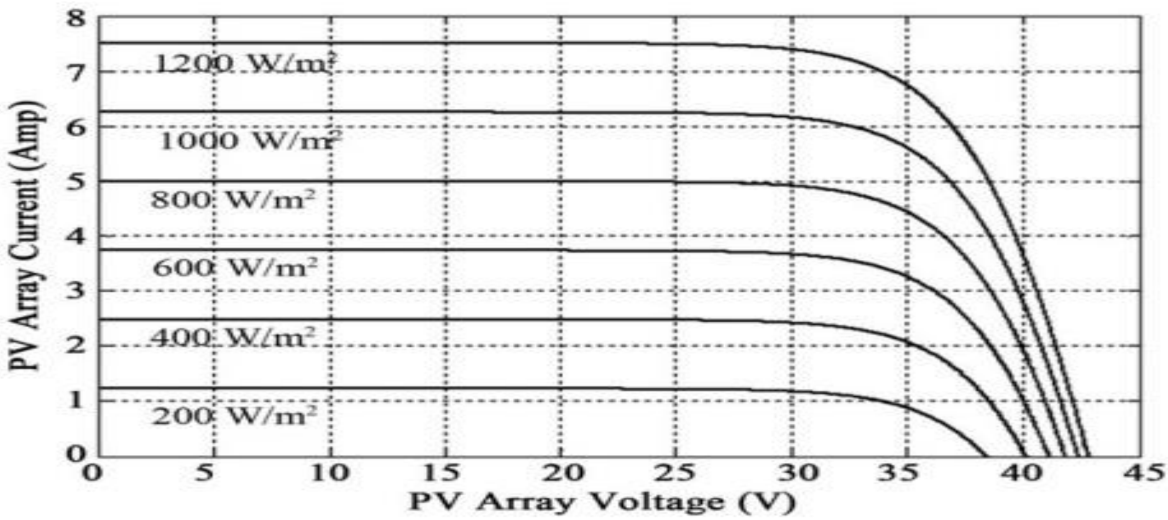

Figure (2. 16): Effect of Variable Solar Radiation Levels on IV-Characteristic [2.18]

Temperature effect: this has an important effect on the power output from the cell. The temperature effect appears on the output voltage of the cell, where the voltage decreases as temperature increases. The output voltage decrease for silicon cell is approximately $2.3\ mV\ per$ 1℃ increased in the solar cell temperature.

The solar cell temperature T_C can be found by the following equation [2.19]:

$$T_c = T_{amb} + \left(\frac{NOCT-20}{800}\right) * G \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.20)$$

Where:

T_{amb}: Ambient temperature in ℃

G: Solar radiation (W/m^2)

NOCT: Normal operating cell temperature at (solar radiation [$800\ W/m^2$], spectral distribution of AM1.5, ambient temperature 25℃ and wind speed [$> 1\ m/s$]) [2.17].

Solar radiation effect: the solar cell characteristics are affected by the variation of illumination. Increasing the solar radiation increases in the same proportion the short circuit current. The following equation illustrates the effect of variation of radiation on the short circuit current [2.19]:

$$I_{sc} = I_{sc}(at\ 1000\,W/m^2) * (G(in\ W/m^2)/1000) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.21)$$

The output power from the PV cell is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation [2.16]:

$$P_{out-PV} = P_{r-PV} * (G/G_{ref}) * [1 + K_T(T_C - T_{ref})] \ldots\ldots\ldots\ldots\ldots\ldots (2.22)$$

Where:

P_{out-PV}: Output power from the PV cell

P_{r-PV}: Rated power at reference conditions

G_{ref}: Solar radiation at reference conditions ($G_{ref} = 1000\ W/m^2$)

K_T: Temperature coefficient of maximum power ($K_T = -3.7x10^3/$°C) for mono and poly crystalline silicon

T_C: Cell temperature

T_{ref}: Cell temperature at reference conditions ($T_{ref} = 25$°C)

The following equation can be used to calculate the cell temperature approximately if the NOCT is not given by the manufacturer [2.17]:

$$T_C = T_{amb} + 0.0256 * G \ldots\ldots\ldots\ldots\ldots\ldots (2.23)$$

2.3.3.5 Effect of Tilting the PV Modules on the Total Solar Radiation

Measurements of solar radiation usually occur on a horizontal plane. PV modules are usually fixed making a tilt angle (β) with the horizontal. This is done to make the PV modules facing the sun to collect more solar radiation. The value of tilt angle depends mainly on latitude value of the location (L) and seasonal changes. PV modules may be fixed with a fixed tilt angle or may be changed seasonally to collect more solar radiation. These changes are as follows [2.17]:

- $\beta = L + 20°$ During winter season
- $\beta = L$ During spring and autumn season
- $\beta = L - 10°$ During summer season

If the tilt angle changes are made, a yearly increase in solar radiation by a value of 5.6% can be obtained. For Palestine (especially Ramallah & Nablus sites) latitude (L) is about ($32°$). [2.17]

2.3.3.6 Module Performance and Efficiency

In outdoor environment the magnitude of the current output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. The voltage of solar cell does not depend strongly on the solar irradiance but depends primarily on the cell temperature.

Table (2.4) and table (2.5) contain typical parameters that are used in module specification sheets to characterize PV modules. Four examples of PV modules with comparable power output are included in table (2.4), such as a Shell module with Mono crystalline silicon solar cells, a Shell module based on copper indium dieseline (CIS) solar cells, a Kaneka's amorphous silicon ($a - Si: H$) module, and a module of First Solar based on cadmium telluride ($CdTe$) solar cells. Electrical parameters are determined at standard test conditions (STC). [2.11, 2.14]

Table (2. 4): Specifications of Different PV Modules [2.11, 2.14]

Module Type	Shell SM50-H	Shell ST40	Kaneka PLE	First Solar FS-50
Cell Type	Mono c-Si	CIS	$a - Si: H$	$CdTe$
$P_{max}[W_p]$	50	40	50	52
$V_{MPP}[V]$	15.9	16.6	16.5	63
$I_{MPP}[A]$	3.15	2.2	3.03	0.82
$V_{OC}[V]$	19.8	23.3	23	88
$I_{SC}[A]$	3.4	2.68	3.65	0.95
Cells/Module	33	40	36	96
Dimensions [mm]	1219x329	1293x328	952x920	1200x600

Table (2. 5): Different Cells Efficiencies [2.17]

PV Module Type	Efficiency
Mono Crystalline Silicon	12.5% to 15%
Poly Crystalline Silicon	11% to 14%
Copper Indium Gallium Selenide (CIGS)	10% to 13%
Cadmium Telluride ($CdTe$)	9% to 12%
Amorphous Silicon (a-Si)	5% to 7%

2.3.4 Battery Storage System for PV System

The simplest means of electricity storage is to use the electric rechargeable batteries, especially when PV modules produce the DC current required for charging the batteries. Most of batteries used in PV systems are lead acid batteries. In some applications, for example when used in locations with extreme climate conditions or where high reliability is essential, nickel-cadmium batteries are used. The major difficulty with this form of storage is the relative high cost of the batteries and a large amount required for large scale application [2.17]. The following factors should be considered when choosing a battery for a PV application:

- Operating temperature range (1.5℃ to 50℃)
- Self-discharge rate
- Permissible depth of discharge (DOD) up to 80%
- Capacity ampere hour (Ah) at 10 hour & 100 hour rates (C_{10}&C_{100})
- Resistance to over charging
- Cost

2.3.4.1 Lead Acid Batteries

The most commonly available lead acid battery is the car battery, but these are designed mainly to provide a high current for short periods to start engines, and they are not well suited for deep discharge cycles experienced by batteries in PV systems. Car batteries are sometimes used for small PV systems because they are cheap, but their operational life in PV applications is likely to be short.

The most attractive lead acid battery for use in most PV systems is the flooded tubular plate design, with low antimony plates. Good quality batteries of this type can normally be expected to have operational life of 5 – 7 years if they are properly maintained and used in a PV system with a suitable charge controller. Longer operational life may be achieved if the maximum depth of discharge is limited, but shorter lifetimes must be expected if the batteries are mistreated. [2.17]

2.3.4.2 Nickel Cadmium ($NiCd$) Batteries

There are two types of $NiCd$ batteries represented as follows:

- Sintered plate ($NiCd$) batteries suffer from the well-known memory effect, in which the useful capacity of the battery appears to drop after it has been discharged over many cycles or if it is discharged at low rates. Sintered plate $NiCd$ batteries are not therefore attractive for use in PV systems.
- Pocket plate $NiCd$ batteries can be used in PV systems, because they have additives in their plates to prolong their operational life and to

minimize the memory effect. In addition, they are highly resistant to extremes of temperature, and can safely be taken down to less than 10% state of charge. Their main disadvantage is their high cost compared with lead acid batteries, as in table (2.6). [2.17]

Table (2. 6): Lead Acid and NiCd Batteries Parameters [2.10]

Battery Parameter	Lead Acid	$NiCd$
Cycle Time	600 to 1500	1500 to 3500
Efficiency	83% to > 90%	71%
Self-discharge Rate	3% to 10%	6% to 20%
Range of Operation	-15℃ to 50℃	-40℃ to 45℃

2.3.5 Solar Radiation in Palestine

Palestine is located between ($[34°20' - 35°30']East\ and$ $[31°10' - 32°30']North$). Palestine elevations range from 350 m below sea level in Jordan Valley and exceed 1000 m above sea level at some location in West Bank. Climate conditions in Palestine vary widely. The daily average temperature and humidity in West Bank vary in the ranges of (8℃ to 25℃) and (51% to 83%) respectively. Palestine has about 3000 sun shine hours per year. The annual solar radiation on horizontal surface varies from ($2.63kWh/m^2$) daily in December to ($8.4kWh/m^2$) daily in June [RCA]. See figure (2.17). [2.17]

Palestine has an average solar radiation of ($5.4Wh/m^2$) daily, this average solar radiation can be used in several applications, specially the electrical applications either off grid or on grid. Table (2.7) presents the monthly average of daily solar radiation for different months for Nablus site.

Table (2. 7): Monthly Average of Daily Solar Radiation for Nablus Site [2.19]

Month	Monthly Average Radiation ($kWh/m^2.day$)
January	2.89
February	3.25
March	5.23
April	6.25
May	7.56
June	8.25
July	8.17
August	8.1
September	6.3
October	4.7
November	3.56
December	2.84

Chapter Three

Methodology for Designing a Cathodic Protection System for Pipeline Distribution Network (PDN)

3.1 Study Objective

There are many forms of corrosion occurring on different materials in different environments, and the CP has also many forms of protection techniques. In order to have a good understanding of corrosion prevention by CP, the main objective of this study is to deal with the corrosion of steel pipelines that transport natural gas under seawater surface and underground, and the protection is depending on the ICCP system which is powered by solar PV generation system with battery storage system.

The study is depending on the knowledge that represented in the literature review chapter and on the experiences and applied projects that represented in previous work section in the introduction chapter.

3.2 Case Study Preview

There is neither pipeline distribution network (PDN) nor existing large metallic structure that can be studied seriously in Palestinian Territories, so this thesis will depend on a suggested PDN under the Palestinian seawater and ground. The specifications of the pipelines depend on the USA steel pipelines properties that are represented in appendix (1), and the corrosion damage is measured by taking the properties of the seawater and soils in Palestine.

3.2.1 PDN Description

The suggested pipeline distribution network in Palestine transports the produced natural gas from Gaza Marine Natural Gas Station in the Mediterranean Sea to distribution stations in Gaza Strip and West Bank. The pipelines are installed under water in the sea area and buried underground in rest areas. Figure (3.1) shows the pipeline network distribution.

The Gaza Marine natural gas field is legally under the control of the Palestinian National Authority. It is located about 36 kilometers offshore at a depth of 610 m. It has around 1.4 trillion cubic feet of gas and an estimated value of 2.4 to 7 billion dollars.[2] In 1999, the leader of the Palestinian Authority, Yasser Arafat, made a deal with British Gas (BG), to have 25 years to exploit the oil fields. In 2000, BG discovered the Gaza Marine Gas Field. It has enough energy to supply Palestinian territories and still have a surplus for export, making the Palestinian territories more energy independent. See figure (3.2). [3.1]

The pipeline distribution network total length is 437 km, these lengths have been measured using Google Earth program, and they are distributed as:

- 50 km in Sea area
- 105 km in clay, well aerated soil
- 70 km in desert sand
- 85 km in dry soil
- 127 km in wet soil with stones

The material of pipeline is carbon steel, API Spec. 5L, Grade X-42, high strength and low alloy steel (which is widely used in the construction of natural gas and petroleum pipelines). The dimensions of carbon steel pipeline are represented in table (3.1) and the chemical composition is represented in table (3.2). See the carbon steel pipeline properties in appendix (1).

Table (3. 1): Dimensions of the Structure of Pipeline [2.9]

Item	Quantity
Diameter $[cm]$	30.5
Thickness $[cm]$	1.27
Mass per Unit Length $[kg/m]$	40.27

Figure (3. 1): Natural Gas Pipeline Distribution Network [2.18]

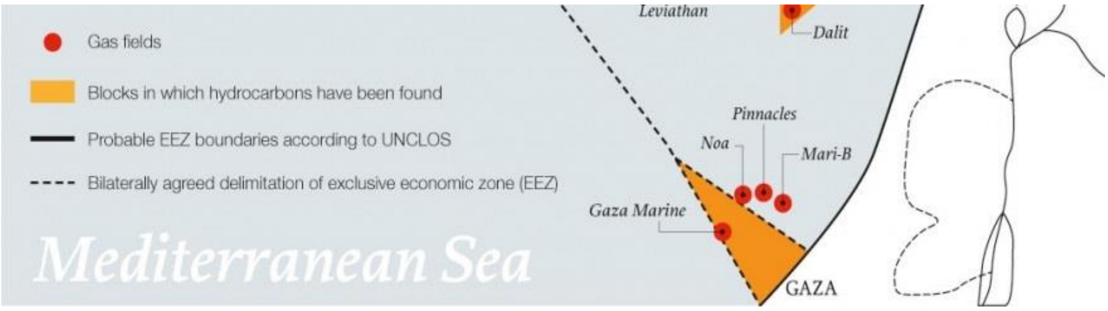

Figure (3. 2): Gaza Marine Gas Field [3.2]

Table (3. 2): Chemical Composition of the Pipeline [2.9]

Chemical Composition	Nominal	Analytical
$C(\%)$	0.199	0.191
$Mn(\%)$	1.95	1.95
$P(\%)$	0.016	0.014
$S(\%)$	0.018	0.015
$Cr(\%)$	0.015	0.015
$Ni(\%)$	0.007	0.003
$Mo(\%)$	0.008	0.008
$V(\%)$	0.004	0.003
$Cu(\%)$	0.024	0.028
$Fe\ (\%)$	Remaining	Remaining

- **Coating Type**

Fusion-bonded epoxy coatings are 100% solid, thermosetting materials in powder form that bond to the steel surface as a result of a heat-generated chemical reaction. Formulations consist of epoxy resins, hardeners, pigments, flow control additives, and stabilizers to provide ease of application and performance. [3.3]

The pipe must be preheated to remove moisture, and it must be cleaned with proper anchor pattern profile and to improve the adhesion properties. It is important to observe the powder manufacturer's pipe preheat temperature. Heating the pipe to be coated is typically done with induction or gas burners to temperatures in the range of ($215℃ \ to \ 245℃$). [3.3]

Fusion Bonded Epoxy (FBE) coating system is used for coating of underground and underwater pipelines. FBE offer corrosion protection to the pipeline structure by preventing interacts between the pipeline structure and the surrounding environment, so it plays as an isolation layer. Table (3.3) represents some specifications of FBE coating.

Table (3. 3): Specifications of FBE Coating [3.3]

Item	Quantity
Current Density [$\mu A/m^2$]	5
Thickness [mm]	1.5 to 2
High Temperature [℃]	+130 to +160
Low Temperature [℃]	-60
Life Time [Year]	20 to 25

There are a number of properties that make FBE coatings useful as pipe coatings. They exhibit: [3.3]

- Excellent adhesion to steel
- Good chemical resistance
- Non-shielding, work with cathodic protection (CP)
- No reported cases of stress-corrosion cracking (SCC) of pipe coated with FBE
- Toughness, frequently installed under the sea, through rolling plains, in rocky mountainous areas, in the desert, and in the arctic

3.2.2 PDN Surrounding Environment

There are four types of soil which the pipelines are immersed in it as mentioned above in addition to the sea water. Due to the differences in humidity, pH values, salts concentration, etc. in different sea water and soil types, the current density and resistivity will be different. The quantities of current density (J $[A/m^2]$) and resistivity (ρ $[\Omega.cm]$) are represented in the following table.

Table (3. 4): Electrical Parameters of the Pipeline Surrounding Environment [1.14, 3.4, 3.5, and 3.6]

Environment	J $[A/m^2]$	ρ $[\Omega.cm]$
Seawater	0.008	10
Clay, Well Aerated Soil	0.003	250
Dry Soil	0.0015	2000
Desert	0.0004	2500
Wet Soil with Stones	0.006	120

The current densities and soil resistivity quantities that are represented in table (3.4) are not been measured in Palestine, these quantities were matched with the similar types of seawater and soils that were measured by previous work in applied projects that represented in the introduction chapter.

The properties of seawater and soils in this study were matched with the properties of seawater and soils in the previous applied projects (taking in consideration all factors that affect these quantities due to differences in climate and ground properties) and publications from institutions that interested in this field of science, such as the department of transportation in USA, University of Khartoum, Islamic Azad University in Iran and corrosion society NACE in USA.

3.2.3 Case Study Alternatives

In this study there are three alternatives for ICCP system design depending on the coating efficiency (η_c) of the pipeline distribution network. The CE means the coating damaged (inactive) area to the coating active area, for example if the damaged coated area of pipeline is 10% from total pipeline surface area, so this means that the η_c is 90%.

The three alternatives are listed as follows:

- Alternative (A): η_c = 90%
- Alternative (B): η_c = 95%
- Alternative (C): η_c = 98%

3.3 Components of the ICCP System

An impressed current cathodic protection (ICCP) system consists of: the DC current source which is a PV generator, batteries storage system, DC – DC converter (not used in the design of the PV system), coated pipeline structure and impressed current anodes. All the mentioned ICCP system and PV system components are described in chapter three and chapter four respectively. Figure (3.3) shows a block diagram for the whole PV powered ICCP system.

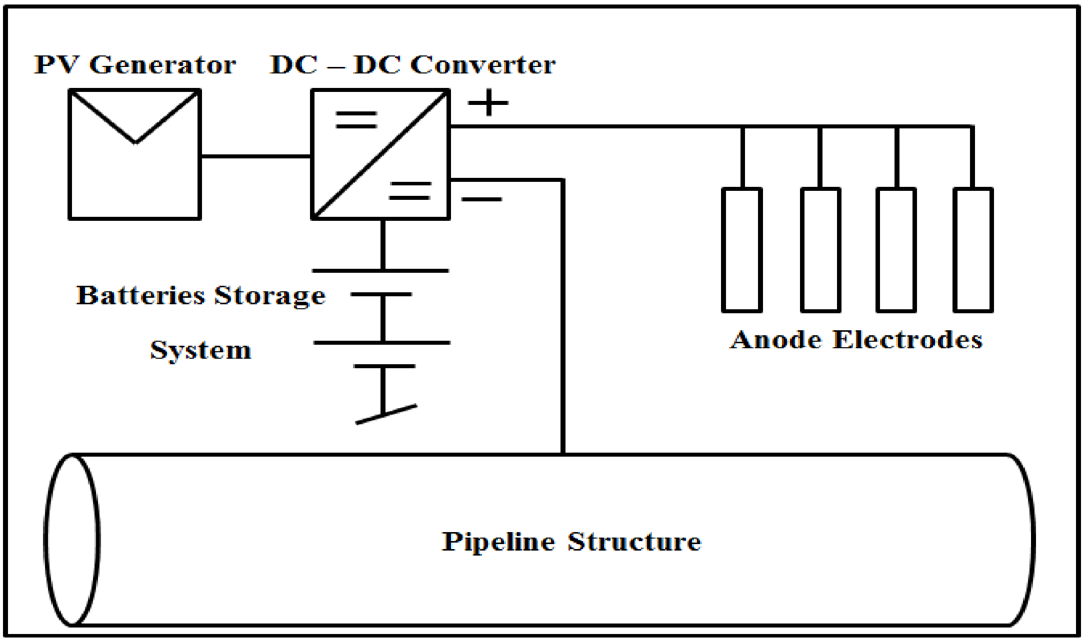

Figure (3. 3): Block Diagram of ICCP System

3.4 Simulation Model

The simulation of the ICCP system is done in the MATLAB program which is a short for (MATrix LABoratory) is a programming package specifically designed for quick and easy scientific calculations and I/O. It has literally hundreds of built-in functions for a wide variety of computations and many toolboxes designed for specific research disciplines, including statistics, optimization, solution of partial differential equations, data analysis. [3.7]

The modeling of the ICCP system is depending on the equations that used in the mathematical design and these equations is modeled in the Simulink application in matlab.

3.4.1 Simulink Application

Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi rate, i.e., have different parts that are sampled or updated at different rates. [3.8]

3.5 Economic Study

The economic study in this thesis concentrates on the comparison between the costs of the ICCP system at different alternatives and the cost of the rehabilitation of the pipelines. The data and costs that related to the rehabilitation of pipelines are taken from measurements done by the department of transportations in USA. The costs of the impressed current anodes, PV modules and Batteries are taken from the manufactures price lists.

Chapter Four

Mathematical Design and Simulation of PV Powered ICCP System for Pipeline Distribution Network

4.1 Corrosion Current Calculation

4.1.1 Pipeline Surface Area

The total surface area (A) of the pipeline in different media (environment) can be calculated using the following equation, which is applied on cylindrical shapes as the distribution pipelines depending on the length of the pipeline (L) and the diameter of the pipeline (D). Table (4.1) represents L, D and A of the pipeline in different media.

$$A = \pi x D x L \text{ ………………… (4.1)}$$

Table (4. 1): Pipeline Dimensions in Different Media

Environment	L [m]	D [m]	A [m^2]
Seawater	50,000	0.305	48,000
Clay, Well Aerated Soil	105,000	0.305	100,601
Dry Soil	85,000	0.305	79,466
Desert	70,000	0.305	67,073
Wet Soil with Stones	127,000	0.305	121,690

4.1.2 Unprotected Pipeline Surface Area

The unprotected surface area (A_{up}) of the pipeline depends on the coating efficiency (η_c) – as mentioned in chapter five – which represents the three alternatives of the design. The following equation is used to find A_{up} for each alternative in different media. Equation (4.2) is applied on the values of η_c= 90%, 95% and 98% for alternatives A, B and C are illustrated in Tables (4.2), (4.3) and (4.4) respectively. [1.14]

$$A_{up} = (1 - \eta_c)xA \text{ ....} (4.2)$$

Table (4. 2): Alternative A

Media	A $[m^2]$	A_{up} $[m^2]$
Seawater	48,000	4,800
Clay, Well Aerated Soil	100,601	10,060
Dry Soil	79,466	7,946.6
Desert	67,073	6,707.3
Wet Soil with Stones	121,690	12,169

Table (4. 3): Alternative B

Media	A (m^2)	A_{up} $[m^2]$
Seawater	48,000	2,400
Clay, Well Aerated Soil	100,601	5,030
Dry Soil	79,466	3,973.3
Desert	67,073	3,345
Wet Soil with Stones	121,690	6,084.5

Table (4. 4): Alternative C

Media	A $[m^2]$	A_{up} $[m^2]$
Seawater	48,000	960
Clay, Well Aerated Soil	100,601	2,012
Dry Soil	79,466	1,590
Desert	67,073	1,341
Wet Soil with Stones	121,690	2,434

4.1.3 Corrosion Current Calculation

The required current to prevent corrosion (I_R) is calculated for different media depending on the quantities of (J) which is the minimum quantity of electrical current required to prevent corrosion from occurring on the pipeline steel surface (from table (3.4)) and (A_{up}). (I_R) can be calculated as in the following equation.

$$I_R = \text{J}\text{x}A_{up} \text{ ………………… } (4.3)$$

The values of (I_R) which depend on the values of A_{up} for alternatives A, B and C are illustrated in tables (4.5), (4.6) and (4.7) respectively.

Table (4. 5): Alternative A

Media	A_{up} (m^2)	J (A/m^2)	I_R [A]
Seawater	4,800	0.008	38.4
Clay, Well Aerated Soil	10,060	0.003	30.2
Dry Soil	7,946.6	0.0015	11.92
Desert	6,707.3	0.0004	2.7
Wet Soil with Stones	12,169	0.006	73

Table (4. 6): Alternative B

Media	A_{up} (m^2)	J (A/m^2)	I_R [A]
Seawater	2,400	0.008	19.2
Clay, Well Aerated Soil	5,030	0.003	15.1
Dry Soil	3,973.3	0.0015	5.96
Desert	3,345	0.0004	1.35
Wet Soil with Stones	6,084.5	0.006	36.5

Table (4. 7): Alternative C

Media	A_{up} (m^2)	J (A/m^2)	I_R [A]
Seawater	960	0.008	7.7
Clay, Well Aerated Soil	2,012	0.003	6.04
Dry Soil	1,590	0.0015	2.4
Desert	1,341	0.0004	0.54
Wet Soil with Stones	2,434	0.006	14.6

4.2: Anodes Calculation and Anode Ground-bed Design

4.2.1 Anode Ground-bed

Impressed-current ground-beds in soils have traditionally consisted of high-silicon cast iron. However, mixed metal oxide (MMO) anodes are becoming increasingly popular for all environments because of their good mechanical and electrical characteristics and compact size. For seawater applications and areas where chlorides are present, MMO anodes work well as do high-silicon cast iron alloyed with chromium. Other anodes consist of lead alloy and platinum formed in a thin layer on a titanium or niobium base.

4.2.2 Carbonaceous Backfill

Impressed current anodes are usually surrounded by a carbonaceous backfill. Types of materials are used include metallurgical coke and petroleum coke. The dual purpose of the carbonaceous backfill is to reduce the ground-bed resistance by increasing the effective size of the anode and to provide a surface on which oxidation reactions could occur. The latter function prolongs anode life. To ensure good electrical contact, the backfill must be tamped around the anode. Resistivity of carbonaceous backfill is in the range of 10 - 50 Ωcm. Particle size and shape is also important when specifying a backfill. Both parameters determine the contact area between anode and surrounding soil whilst influencing the porosity of the column which is important for gas ventilation. [4.1]

A general purpose coke breeze is for use in shallow horizontal and vertical ground-beds. It has a resistivity of approx. ($35\ \Omega.cm$). For deep well applications a special calcined petroleum coke breeze is available, this coke specification is represented in table (4.8). It has a resistivity of approx. ($15\ \Omega.cm$) and can be pumped. Metallurgical coke of high quality that gives optimum performance at a low cost is available in various size ranges and its specification is represented in table (4.9). [4.1, 4.2]

Coke backfill, prepared from calcinated petroleum coke, has been properly developed to meet all the basic requirements for an earth contact backfill. The carbon content, very high in calcined coke assures a low consumption rate of the backfill material and therefore a longer system life. [4.1]

Table (4. 8): Specification Calcined Petroleum Coke [4.1]

Ash	0.1%	Max. 0.8%
Volatile	0.6%	Max. 0.8%
Moisture	0.1%	Max. 0.5%
Fixed Carbon	99.0%	Min. 98.0%
Grading: (2 – 8)mm		
Resistivity: $10\ \Omega.cm$		
Bulk Density: $approx. (800 - 900)\ kg/m^3\ (compacted)$		

Table (4. 9): Specifications Metallurgical Coke [4.1]

Ash	10.0%	Max. 12.0%
Volatile	1.4%	Max. 1.8%
Sulfur	0.6%	Max. 1.0%
Moisture	0.6%	Max. 1.0%
Fixed Carbon	89.0%	Min. 86.0%
Grading: (0 – 1)mm, (1 – 5)mm, (2 – 7)mm, (3 – 10)mm		
Resistivity: $50\ \Omega.cm$		

4.2.3 Anode Type and Properties

The most common anode type in underwater and underground applications is the mixed metal oxide (MMO) coated titanium, the tubular shape type. The dimensions and outputs of MMO anode are represented in table (4.10). See appendix (2) for some ICCP anodes specifications.

Table (4. 10): Dimensions and Specifications of MMO Anode [4.3]

Item	Quantity
D $[mm]$	25
L $[mm]$	500
A $[m^2]$	0.039
Mass [kg]	0.56
Typical I_A in Carbonaceous Backfill $[A]$	4
Typical I_A in Seawater $[A]$	25
Maximum Anode Current Density (J_A) $[A/m^2]$	50
Life Time [Years]	20
Anode Cable Cross Section Area (A_{cross}) $[mm^2]$	50

4.2.4 Number of Anodes for Different Media at different Alternative

The number of anodes (N_A) in ICCP system can be calculated according to the following equation. (N_A) depends on (I_A) which can be taken from the MMO anode in different media.

$$N_A = \frac{I_R}{I_A} \qquad (4.4)$$

(N_A) for alternatives A, B and C are illustrated in tables (4.11), (4.12) and (4.13) respectively.

Table (4. 11): Alternative A

Media	I_R [A]	I_A [A]	N_A
Seawater	38.4	25	2
Clay, Well Aerated Soil	30.2	4	8
Dry Soil	11.92	4	3
Desert	2.7	4	1
Wet Soil with Stones	73	4	19

Table (4. 12): Alternative B

Media	I_R [A]	I_A [A]	N_A
Seawater	19.2	25	1
Clay, Well Aerated Soil	15.1	4	4
Dry Soil	5.96	4	2
Desert	1.35	4	1
Wet Soil with Stones	36.5	4	10

Table (4. 13): Alternative C

Media	I_R [A]	I_A [A]	N_A
Seawater	7.7	25	1
Clay, Well Aerated Soil	6.04	4	2
Dry Soil	2.4	4	1
Desert	0.54	4	1
Wet Soil with Stones	14.6	4	4

4.3 Total Resistance Calculations

4.3.1 Total Resistance Diagram

Figure (4.1) represents the parameters of the circuit diagram. The symbols that are represented in figure (4.1) are described in the following list:

- R_{C1}: Resistance of cables from DC power source and the pipeline
- R_{C2}: Resistance of cables from DC power source and the anodes ground-bed
- R_{C3}: Resistance of cables between anodes
- R_P: Resistance of the pipeline metallic structure
- R_A: Resistance of anodes
- R_{GB}: Ground-bed to earth resistance

- The return back voltage: this voltage considered as (2 V) in the design of ICCP systems, it is the drop voltage from pipeline to the electrolyte between the pipeline and the anodes ground-bed [1.14, 3.4]

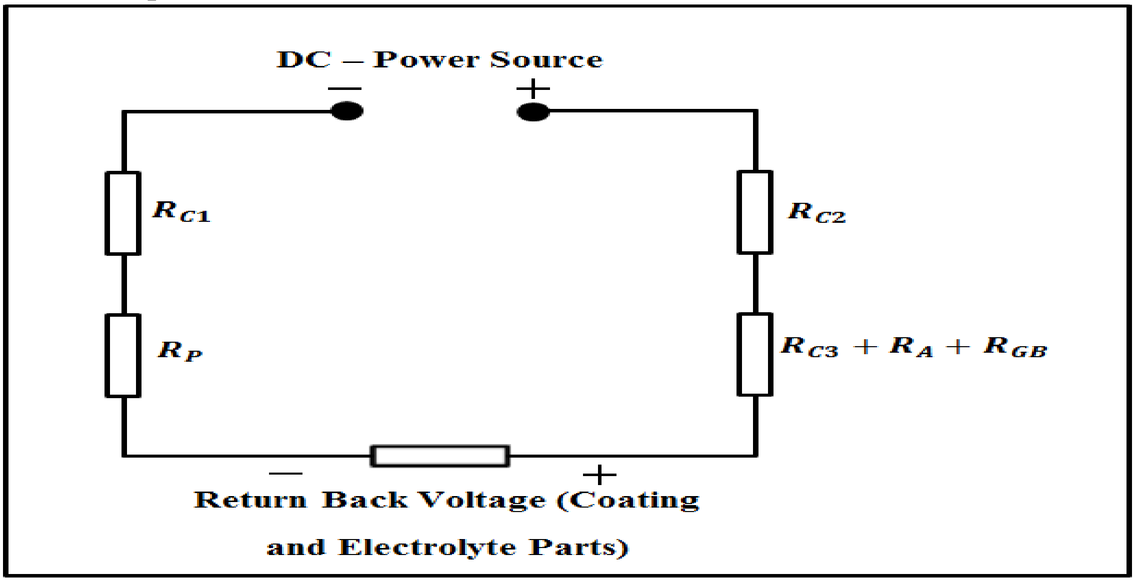

Figure (4. 1): Total Resistance of ICCP Circuit Diagram

4.3.2 Pipeline Metallic Structure Resistance

The resistance of the metallic structure of the pipeline distribution network (R_P) in different media is calculated using equation (4.5) [1.14, 3.4]. (R_P) is fixed for the different alternatives. (R_P) values are represented in table (4.14). [1.14]

$$R_P = (\frac{3.3}{4w})x10^{-3}xL \; .... \; (4.5)$$

Where: (w) is the mass of one meter length of the pipeline which is taken from chapter five as 40.27 kg/m and the quantity (3.3) represents the most common quantity in measurements of (R_P) in different researches and papers, this quantity is taken from the following reference [1.14].

Table (4. 14): Pipeline Resistance

Media	(R_P) [Ω]
Seawater	1.024
Clay, Well Aerated Soil	2.143
Dry Soil	1.74
Desert	1.44
Wet Soil with Stones	2.603

4.3.3 Anodes and ground-beds Resistances

The resistance of the carbonaceous backfill ground-bed (R_{GB}) is fixed at the quantity of (1.5 [Ω]) and it used in the calculations of all medias except the seawater media. The resistance of anodes (R_A) that their numbers are calculated in (section 4.3.4) can be calculated as in the following equation [4.4].

$$R_A = \frac{\rho}{2x\pi x L_A} x[\ln(\frac{8xL_A}{D_A}) - 1] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

Where: (ρ) is the resistivity of seawater (10 $[\Omega.cm]$) and the carbonaceous backfill (50 $[\Omega.cm]$). (L_A) is the length of the anode (500) [mm], (D_A) is the diameter of the anode (0.025) [m]. The resistance of multiple anodes connected in parallel (R_{AT}) is calculated as: the general equation for calculating (R_{AT}) with different (R_A) values is equation (4.7). (R_{AT}) values for alternatives A, B and C are illustrated in tables (4.15), (4.16) and (4.17).

$$R_{AT} = \frac{1}{\frac{1}{R_{A1}}+\frac{1}{R_{A2}}+\cdots+\frac{1}{R_{AN}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.7)$$

Table (4. 15): Alternative A

Media	N_A	R_A [Ω]	R_{AT} [Ω]	R_{GB} [Ω]
Seawater	2	0.13	0.065	–
Clay, Well Aerated Soil	8	0.65	0.1	1.5
Dry Soil	3	0.65	0.22	1.5
Desert	1	0.65	0.65	1.5
Wet Soil with Stones	19	0.65	0.034	1.5

Table (4. 16): Alternative B

Media	N_A	R_A [Ω]	R_{AT} [Ω]	R_{GB} [Ω]
Seawater	1	0.13	0.13	–
Clay, Well Aerated Soil	4	0.65	0.2	1.5
Dry Soil	2	0.65	0.325	1.5
Desert	1	0.65	0.65	1.5
Wet Soil with Stones	10	0.65	0.07	1.5

Table (4. 17): Alternative C

Media	N_A	R_A [Ω]	R_{AT} [Ω]	R_{GB} [Ω]
Seawater	1	0.13	0.13	–
Clay, Well Aerated Soil	2	0.65	0.325	1.5
Dry Soil	1	0.65	0.65	1.5
Desert	1	0.65	0.65	1.5
Wet Soil with Stones	4	0.65	0.2	1.5

4.3.4 Cable Resistance

Connection cables have different cross sectional area and each of them has a resistance per meter depending on its material (cables material here is copper) and cross sectional area (A_{CS}). Table (4.18) represents each cross sectional area with its resistance of one meter length (R_m).

Table (4. 18): Cross Section Area and Its Resistivity [1.14]

A_{CS} (mm^2)	R_m [Ω/m]
16	0.00108
25	0.00069
35	0.000439
50	0.000345

The resistance of cable (R_C) can be calculated using the following equation, which is applied to find the values of: (R_{C1}) with cable length from DC power supply to the pipeline structure ($L_{SP} = 200m$), (R_{C2}) with cable length from DC power supply to the anode ground-bed ($L_{SA} = 20m$) and (R_{C3}) with cable length between anodes ($L_{AA} = 2m$). [1.14]

$$R_C = R_m x L_C \text{.................. (4.8)}$$

Where: (L_C) is the length of cable in meters. The values of (L_{SP}), (L_{SA}) and (L_{AA}) are applied in equation (4.8) instead of the value of (L_C). (L_{SP}) and (L_{SA}) are fixed with ($A_{CS} = 25mm^2$) for different alternatives. (R_{C1}) and (R_{C2}) they represented in tables (4.19) and (4.20) respectively.

Table (4. 19): R_{C1}

Media	R_{C1} [Ω]
Seawater	0.138
Clay, Well Aerated Soil	0.138
Dry Soil	0.138
Desert	0.138
Wet Soil with Stones	0.138

Table (4. 20): R_{C2}

Media	R_{C2} [Ω]
Seawater	0.0138
Clay, Well Aerated Soil	0.0138
Dry Soil	0.0138
Desert	0.0138
Wet Soil with Stones	0.0138

(R_{C3}) values with ($A_{CS} = 16mm^2$) for alternatives A, B and C are illustrated in tables (4.21), (4.22) and (4.23) respectively.

Table (4. 21): Alternative A

Media	N_A	R_{C3} [Ω]
Seawater	2	0.00216
Clay, Well Aerated Soil	8	0.01512
Dry Soil	3	0.00432
Desert	1	–
Wet Soil with Stones	19	0.03888

Table (4. 22): Alternative B

Media	N_A	R_{C3} [Ω]
Seawater	1	–
Clay, Well Aerated Soil	4	0.00648
Dry Soil	2	0.00216
Desert	1	–
Wet Soil with Stones	10	0.01944

Table (4. 23): Alternative C

Media	N_A	R_{C3} [Ω]
Seawater	1	–
Clay, Well Aerated Soil	2	0.00108
Dry Soil	1	–
Desert	1	–
Wet Soil with Stones	4	0.00648

4.3.5 Coating Current and Resistance

Coating current (I_{CO}) is a small quantity of current ($J_{CO} = 5\ \mu A/m^2$ for FBE coating type) which can improve more protection to the pipeline coating [1.14, 5.7 and 6.5]. (I_{CO}) can be calculated as in equation (4.10) depending on (J_{CO}) and the protected area of the pipeline (A_{Pr}) which can be calculated as in equation (4.9). [1.14, 5.7 and 6.4]

$$A_{Pr} = \eta_C x A \qquad (4.9)$$

$$I_{CO} = J_{CO} x A_{Pr} \qquad (4.10)$$

The values of (A_{Pr}) and (I_{CO}) for alternatives A, B and C are illustrated in tables (4.24), (4.25) and (4.26) respectively.

Table (4. 24): Alternative A

Media	A [m^2]	A_{Pr} [m^2]	I_{CO} [A]
Seawater	48,000	43,200	0.22
Clay, Well Aerated Soil	100,601	90,541	0.5
Dry Soil	79,466	71,520	0.36
Desert	67,073	60,366	0.302
Wet Soil with Stones	121,690	109,521	0.55

Table (4. 25): Alternative B

Media	A [m^2]	A_{Pr} [m^2]	I_{CO} [A]
Seawater	48,000	45,600	0.23
Clay, Well Aerated Soil	100,601	95,571	0.48
Dry Soil	79,466	75,493	0.38
Desert	67,073	63,720	0.32
Wet Soil with Stones	121,690	115,606	0.58

Table (4. 26): Alternative C

Media	A [m^2]	A_{Pr} [m^2]	I_{CO} [A]
Seawater	48,000	47,040	0.24
Clay, Well Aerated Soil	100,601	98,589	0.5
Dry Soil	79,466	77,877	0.4
Desert	67,073	65,732	0.33
Wet Soil with Stones	121,690	119,257	0.6

The coating resistance (R_{CO}) can be calculated as in the following equation depending on the return back voltage (V_{RB}) quantity which is equal to 2 V [1.14, 3.4 and 4.4].

$$R_{CO} = \frac{V_{RB}}{I_{CO}} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. (4.11)$$

(R_{CO}) values in different media for alternatives A, B and C are illustrated in tables (4.27), (4.28) and (4.29) respectively.

Table (4. 27): Alternative A

Media	I_{CO} [A]	R_{CO} [Ω]
Seawater	0.22	9.1
Clay, Well Aerated Soil	0.5	4
Dry Soil	0.36	5.56
Desert	0.302	6.623
Wet Soil with Stones	0.55	3.64

Table (4. 28): Alternative B

Media	I_{CO} [A]	R_{CO} [Ω]
Seawater	0.23	8.7
Clay, Well Aerated Soil	0.48	4.2
Dry Soil	0.38	5.3
Desert	0.32	6.25
Wet Soil with Stones	0.58	3.45

Table (4. 29): Alternative C

Media	I_{CO} [A]	R_{CO} [Ω]
Seawater	24	8.33
Clay, Well Aerated Soil	30.2	4
Dry Soil	11.92	5
Desert	2.7	6.1
Wet Soil with Stones	73	3.33

4.4 Total Required Voltage

The required voltage (V_R) from the DC power supply to deliver the ICCP system by energy to improve corrosion protection is calculated as in the following equation. Equation (4.12) depends on the previous calculated data in this chapter for resistances and current. (V_R) values in different media for alternatives A, B and C are illustrated in tables (4.30), (4.31) and (4.32) respectively. [1.14, 3.4 and 4.4]

$$V_R = I_R x (R_P + R_{AT+GB} + R_{CT}) + V_{RB} \quad \text{.................... (4.12)}$$

Where: (R_{AT+GB}) is the summation of (R_{AT}) and (R_{GB}), (R_{CT}) is the summation of (R_{C1}), (R_{C2}) and (R_{C3}).

Table (4. 30): Alternative A

Media	I_R [A]	R_P [Ω]	R_{AT+GB} [Ω]	R_{CT} [Ω]	V_R [V]
Seawater	38.4	1.024	0.13	0.2168	54.7
Clay, Well Aerated Soil	30.2	2.143	1.6	0.16	120
Dry Soil	11.92	1.74	1.72	0.154	45.1
Desert	2.7	1.44	2.15	0.152	12.1
Wet Soil with Stones	73	2.603	1.534	0.172	316.56

Table (4. 31): Alternative B

Media	I_R [A]	R_P [Ω]	R_{AT+GB} [Ω]	R_{CT} [Ω]	V_R [V]
Seawater	19.2	1.024	0.13	0.152	27
Clay, Well Aerated Soil	15.1	2.143	1.7	0.16	62.45
Dry Soil	5.96	1.74	1.825	0.153	24.16
Desert	1.35	1.44	2.15	0.152	7.052
Wet Soil with Stones	36.5	2.603	1.57	0.162	160.23

Table (4. 32): Alternative C

Media	I_R [A]	R_P [Ω]	R_{AT+GB} [Ω]	R_{CT} [Ω]	V_R [V]
Seawater	7.7	1.024	0.13	0.152	12
Clay, Well Aerated Soil	6.04	2.143	1.825	0.153	27
Dry Soil	2.4	1.74	2.15	0.152	12
Desert	0.54	1.44	2.15	0.152	4.02
Wet Soil with Stones	14.6	2.603	0.2	0.16	45.3

4.5 PV Generator Calculation

ICCP system needs an external current source, the PV generator is been used as a current source for the ICCP system. The PV station is constructed in one place per each section of PDN which means that each media has PV station and the station is including the anodes and batteries in the same place of PV station.

4.5.1 Required Power and Energy for ICCP System

The required power (P_R) for ICCP system can be calculated as in equation (4.13) and the required energy (E_R) for one day is calculated as in equation (4.14). (P_R) and (E_R) values in different media for alternatives A, B and C are illustrated in tables (4.33), (4.34) and (4.35) respectively. [2.17]

$$P_R = I_R x V_R \text{ .... (4.13)}$$

$$E_R = P_R x 24 \text{ .... (4.14)}$$

Table (4. 33): Alternative A

Media	I_R [A]	V_R [V]	P_R $[W]$	E_R $[Wh]$
Seawater	38.4	54.7	2,100	50,400
Clay, Well Aerated Soil	30.2	120	3,624	86,976
Dry Soil	11.92	45.1	537.592	12,902
Desert	2.7	12.1	32.67	784
Wet Soil with Stones	73	316.56	23,108.88	554,613

Table (4. 34): Alternative B

Media	I_R [A]	V_R [V]	P_R $[W]$	E_R $[Wh]$
Seawater	19.2	27	518	12,432
Clay, Well Aerated Soil	15.1	62.45	942.995	22,632
Dry Soil	5.96	24.16	143.9936	3,456
Desert	1.35	7.052	9.5202	228.5
Wet Soil with Stones	36.5	160.23	5,848.395	140,362

Table (4. 35): Alternative C

Media	I_R [A]	V_R [V]	P_R $[W]$	E_R $[Wh]$
Seawater	7.7	12	92	2,208
Clay, Well Aerated Soil	6.04	27	163.08	3,914
Dry Soil	2.4	12	28.8	691
Desert	0.54	4.02	2.1708	52.1
Wet Soil with Stones	14.6	45.3	661.38	15,873

4.5.2 Required Power from PV Generator

The required power from PV generator (P_{PV}) can be calculated as in the following equation. (P_{PV}) values in different media for alternatives A, B and C are illustrated in tables (4.36), (4.37) and (4.38) respectively. [2.17]

$$P_{PV} = \frac{E_R}{\eta_{Conv}} x1.15x \frac{1000\,W}{5400Wh/day} \ldots\ldots\ldots\ldots\ldots\ldots.. (4.15)$$

Where: (η_{Conv}) is the DC – DC converter efficiency which is (90%).

Table (4. 36): Alternative A

Media	E_R $[Wh]$	P_{PV} $[W]$
Seawater	50,400	11,926
Clay, Well Aerated Soil	86,976	20,581
Dry Soil	12,902	3,053
Desert	784	186
Wet Soil with Stones	554,613	131,236

Table (4. 37): Alternative B

Media	E_R $[Wh]$	P_{PV} $[W]$
Seawater	12,432	2,942
Clay, Well Aerated Soil	22,632	5,355
Dry Soil	3,456	818
Desert	228.5	54
Wet Soil with Stones	140,362	33,213

Table (4. 38): Alternative C

Media	$E_R\ [Wh]$	$P_{PV}\ [W]$
Seawater	2,208	523
Clay, Well Aerated Soil	3,914	926
Dry Soil	691	164
Desert	52.1	12
Wet Soil with Stones	15,873	3,756

4.5.3 Number of Modules

The number of modules (N_M) is calculated in equation (4.16) depending on the peak power of one module (P_M) which is taken here as ($240\,W$), this value referred to SCHOTT PV modules, the IV – Characteristic of SCHOTT module and module's specifications are represented in table (4.39). See appendix (3) for datasheet of 240 and 50 Watt PV modules. (N_M) values in different media for alternatives A, B and C are illustrated in tables (4.40), (4.41) and (4.42) respectively. [2.17]

$$N_M = \frac{P_{PV}}{P_M} \quad \text{………………..} \ (4.16)$$

Table (4. 39): SCHOTT Poly Crystalline Module Datasheet [4.5]

Item	Quantity
$P_{MPP}\ [W]$	240
$V_{MPP}\ [V]$	30.4
$I_{MPP}\ [A]$	7.9
$V_{OC}\ [V]$	37.3
$I_{OC}\ [A]$	8.52

Table (4. 40): Alternative A

Media	$P_{PV}\ [W]$	N_M
Seawater	11,926	50
Clay, Well Aerated Soil	20,581	86
Dry Soil	3,053	13
Desert	186	1
Wet Soil with Stones	131,236	547

Table (4. 41): Alternative B

Media	P_{PV} $[W]$	N_M
Seawater	2,942	14
Clay, Well Aerated Soil	5,355	23
Dry Soil	818	4
Desert	54	1
Wet Soil with Stones	33,213	139

Table (4. 42): Alternative C

Media	P_{PV} $[W]$	N_M
Seawater	523	3
Clay, Well Aerated Soil	926	4
Dry Soil	164	1
Desert	12	1 (50W)
Wet Soil with Stones	3,756	16

4.5.4 PV Modules Distribution

In order to distribute PV modules, it must be considered that the batteries design depends on the nominal (V_{BN}) for battery banks. The nominal open circuit voltage (V_{PV-OC}) necessary to charge the battery at STC can be considered as in the following equation. [2.17]

$$V_{PV-OC} = 1.8xV_{BN} \text{ ……………….. (4.17)}$$

The proper distribution of PV modules (the calculated number of PV modules could be edited in order to have the best design of PV system) for alternatives A, B and C are illustrated in tables (4.43), (4.44) and (4.45) respectively. The short name (N_{MP}) represent number of PV module strings and (N_{MS}) represents the number of modules in one string.

Table (4. 43): Alternative A

Media	N_M	N_{MP}	N_{MS}
Seawater	50	10	5
Clay, Well Aerated Soil	90	15	6
Dry Soil	15	5	3
Desert	1	1	1
Wet Soil with Stones	560	35	16

Table (4. 44): Alternative B

Media	N_M	N_{MP}	N_M
Seawater	14	7	2
Clay, Well Aerated Soil	24	8	3
Dry Soil	4	2	2
Desert	1	1	1
Wet Soil with Stones	144	18	8

Table (4. 45): Alternative C

Media	N_M	N_{MP}	N_M
Seawater	3	3	1
Clay, Well Aerated Soil	4	2	2
Dry Soil	1	1	1
Desert	1	1	1
Wet Soil with Stones	18	6	3

4.6 Battery Storage System Calculation

The required ampere hour capacity (C_{Ah}) of batteries can be calculated as in equation (4.18). (C_{Ah}) values depend on the DOD of the battery (0.85) and its average (Ah–efficiency = 78%). (C_{Ah}) values in different media for alternatives A, B and C are illustrated in tables (4.46), (4.47) and (4.48) respectively. [2.17]

$$C_{Ah} = \frac{E_R}{0.78x0.85xV_B} \quad \text{………………….. (4.18)}$$

Where: (V_B) is the battery bank voltage.

Table (4. 46): Alternative A

Media	E_R $[Wh]$	C_{Ah} $[Ah]$
Seawater	50,400	2,112
Clay, Well Aerated Soil	86,976	729
Dry Soil	12,902	406
Desert	784	99
Wet Soil with Stones	554,613	2,614

Table (4. 47): Alternative B

Media	E_R $[Wh]$	C_{Ah} $[Ah]$
Seawater	12,432	521
Clay, Well Aerated Soil	22,632	267
Dry Soil	3,456	109
Desert	228.5	29
Wet Soil with Stones	140,362	1,307

Table (4. 48): Alternative C

Media	E_R $[Wh]$	C_{Ah} $[Ah]$
Seawater	2,208	278
Clay, Well Aerated Soil	3,914	211
Dry Soil	691	22
Desert	52.1	7
Wet Soil with Stones	15,873	521

4.6.1 Batteries Number and Ratings

The number of batteries (N_B) in different media for alternatives A, B and C are calculated depending on the following equation – always correct (N_B) to nearest greater number– and they are illustrated in tables (4.49), (4.50) and (4.51). In the previous tables: (N_{St}) to (number of battery strings) and (N_{SB}) to (number of batteries in one string). [2.17]

$$N_B = \left(\frac{C_{Ah}}{B_{C10}}\right) x N_{SB} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.19)}$$

Where: (B_{C10}) is standard capacity that can be discharged in ten hours which is given from batteries datasheet. [4.6]

Table (4. 49): Alternative A

Media	C_{Ah} $[Ah]$	V_{BN}/B_{C10} $[V/Ah]$	N_{SB}	N_{St}	N_B
Seawater	2,112	2/3,415	18	1	18
Clay, Well Aerated Soil	729	2/3,415	60	2	120
Dry Soil	406	2/820	24	1	24
Desert	99	12/52	1	1	1
Wet Soil with Stones	2,614	2/3,415	160	10	1,600

Table (4. 50): Alternative B

Media	C_{Ah} $[Ah]$	V_{BN}/B_{C10} $[V/Ah]$	N_{SB}	N_{St}	N_B
Seawater	521	2/1,009	14	1	14
Clay, Well Aerated Soil	267	2/273	64	1	64
Dry Soil	109	2/220	24	1	24
Desert	29	12/52	1	1	1
Wet Soil with Stones	1,307	2/3,415	81	3	405

Table (4. 51): Alternative C

Media	C_{Ah} $[Ah]$	V_{BN}/B_{C10} $[V/Ah]$	N_{SB}	N_{St}	N_B
Seawater	278	2/325	6	1	6
Clay, Well Aerated Soil	211	2/273	14	1	14
Dry Soil	22	12/52	1	1	1
Desert	7	12/52	1	1	1
Wet Soil with Stones	521	2/1,009	23	1	23

4.7 PV System Diagram

The diagrams will be for the wet soil with stones environment. The diagrams for alternatives A, B and C are illustrated in figures (4.3), (4.4) and (4.5) respectively.

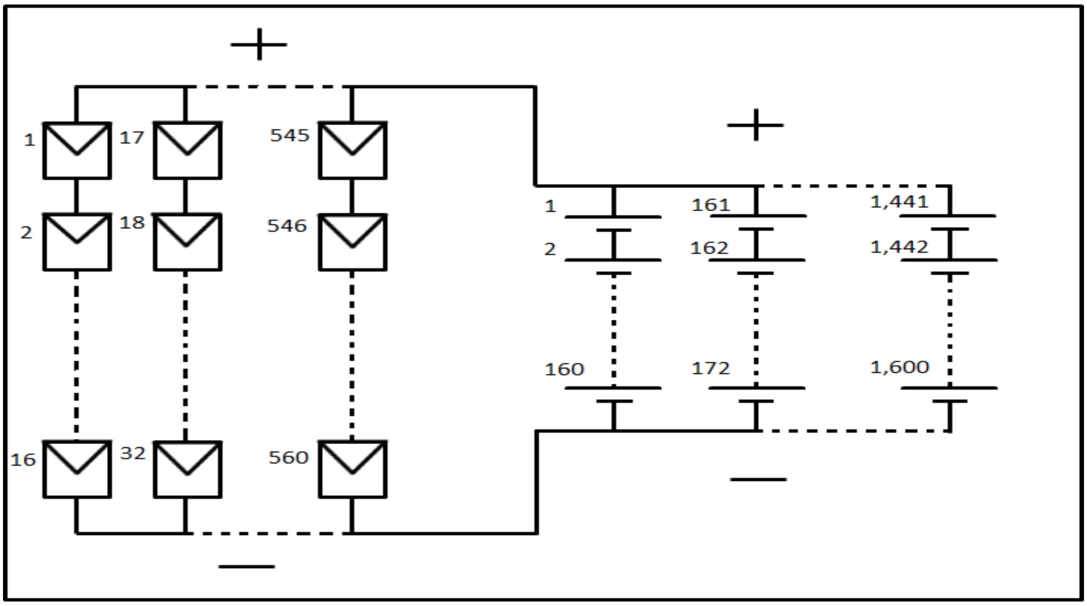

Figure (4. 2): PV System Diagram for Alternative A

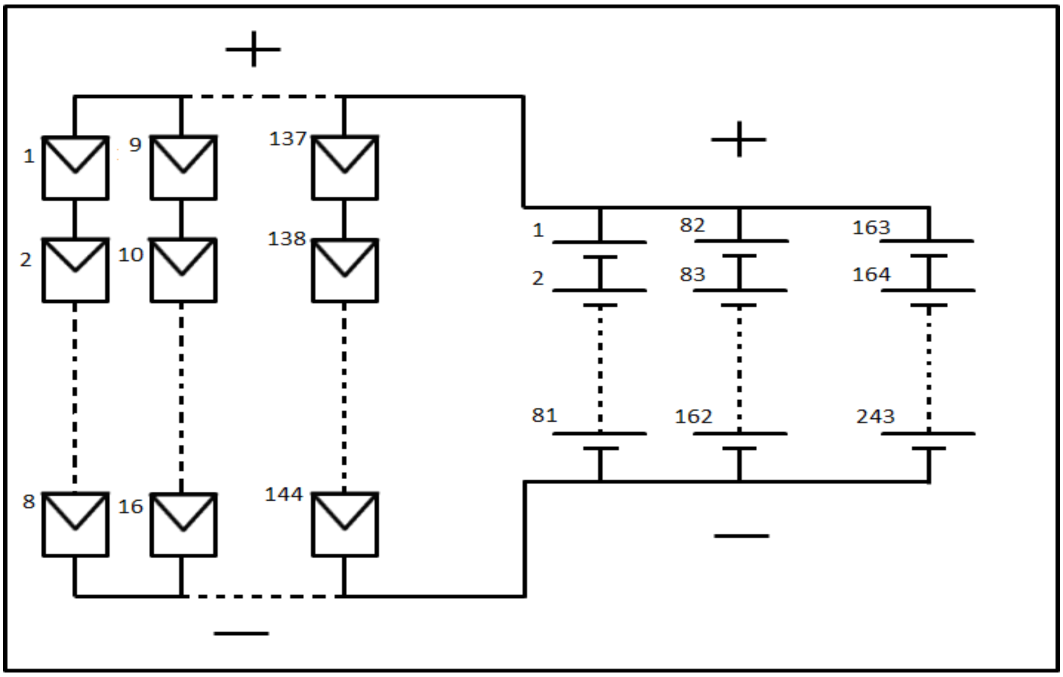

Figure (4. 3): PV System Diagram for Alternative B

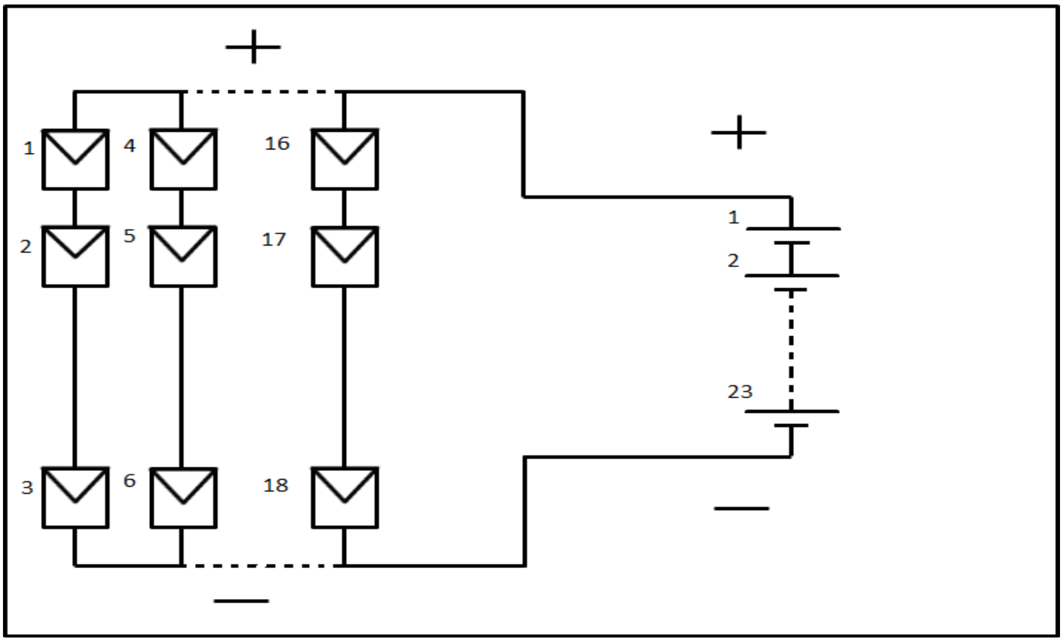

Figure (4. 4): PV System Diagram for Alternative C

4.8 Simulation of PV powered ICCP System for PDN

4.8.1 General System Description

In this section, the blocks are representing the equivalent of each part of the ICCP system depending on the equation and standards in previous sections. See the following figures (4.5) to (4.23).

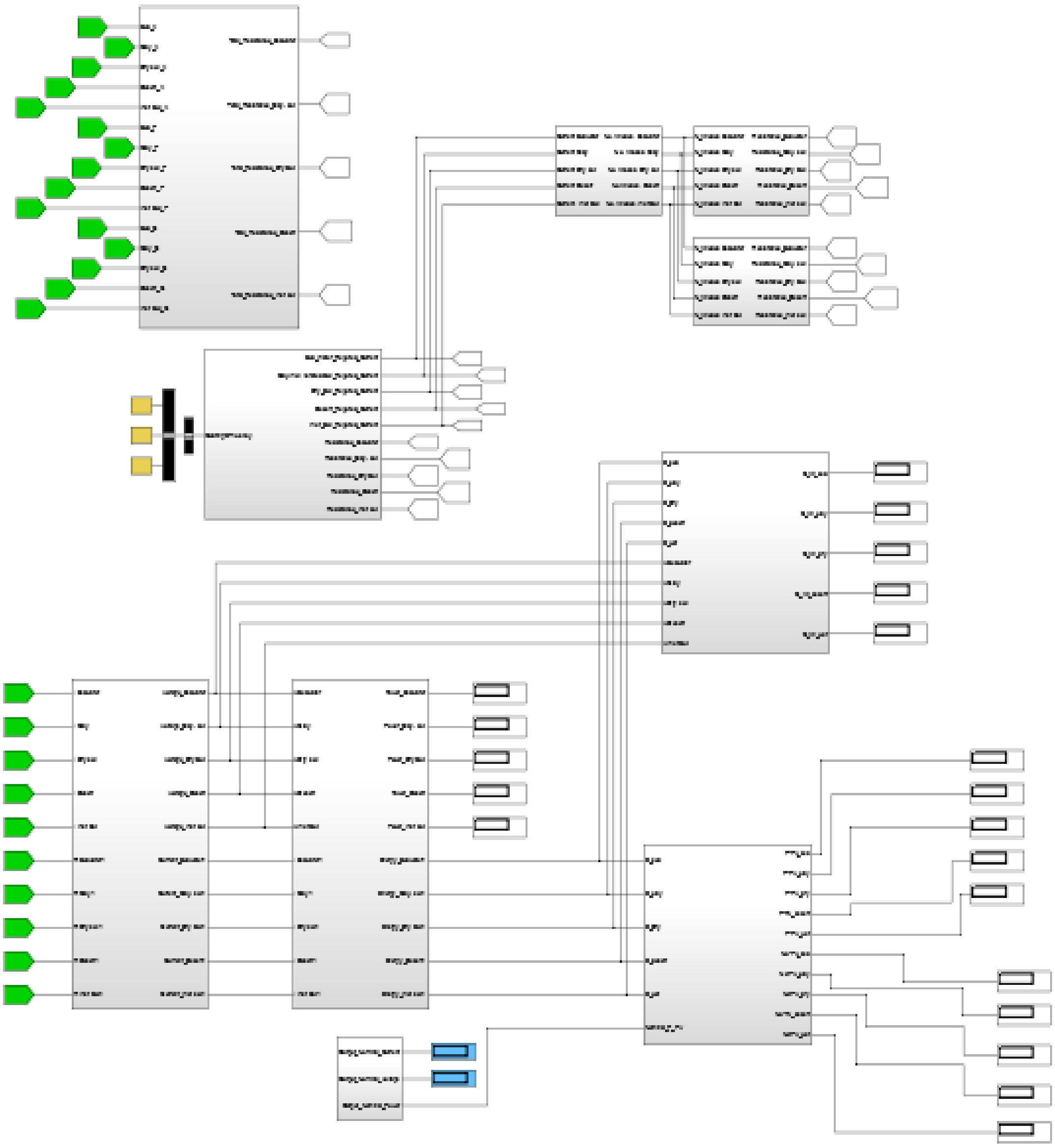

Figure (4. 5): General System Block

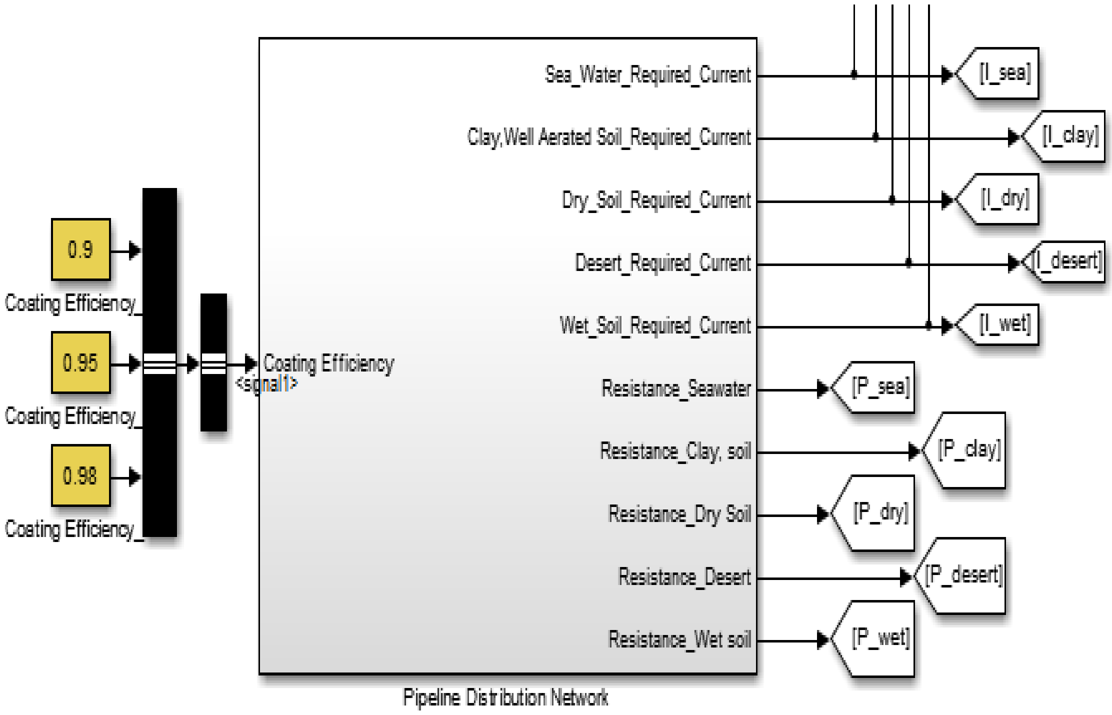

Figure (4. 6): Pipeline Distribution Network Block

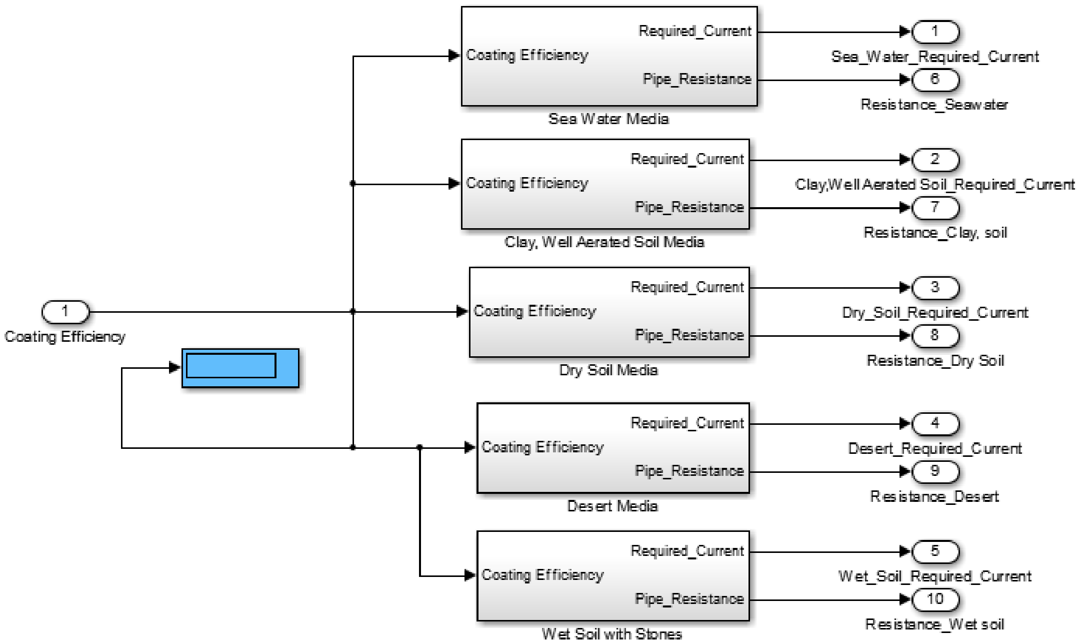

Figure (4. 7): Internal Blocks in Pipeline Distribution Network Block

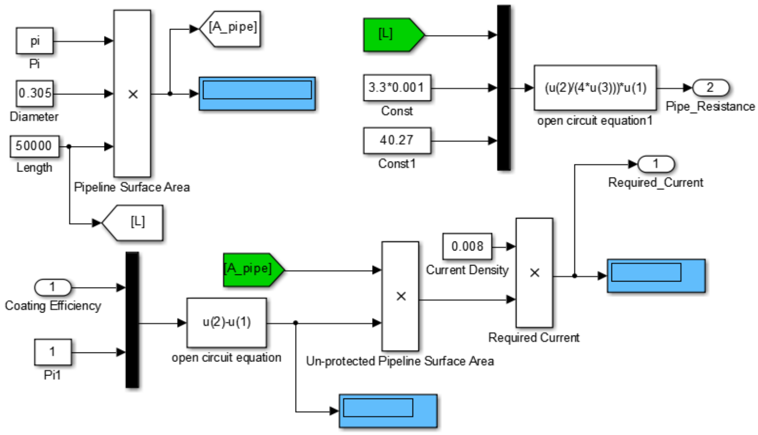

Figure (4. 8): Seawater Media Block

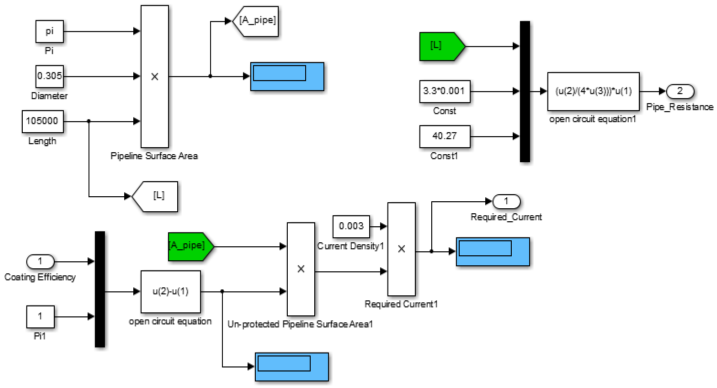

Figure (4. 9): Clay, Well Aerated Soil Media Block

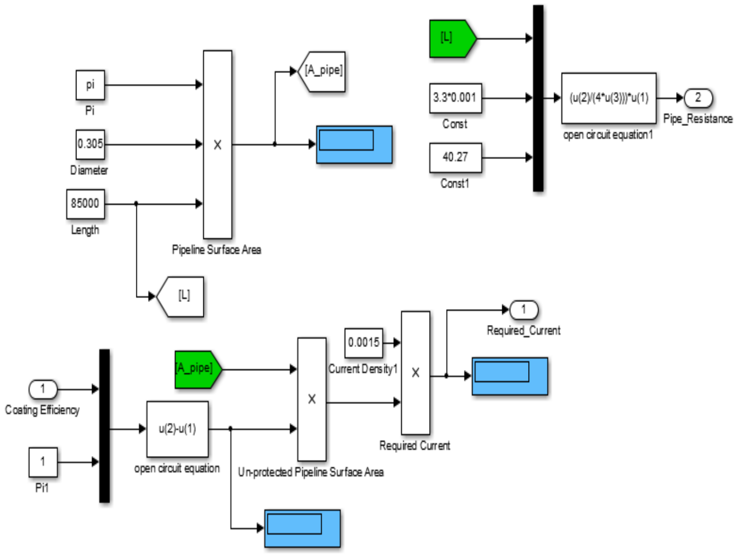

Figure (4. 10): Dry Soil Media Block

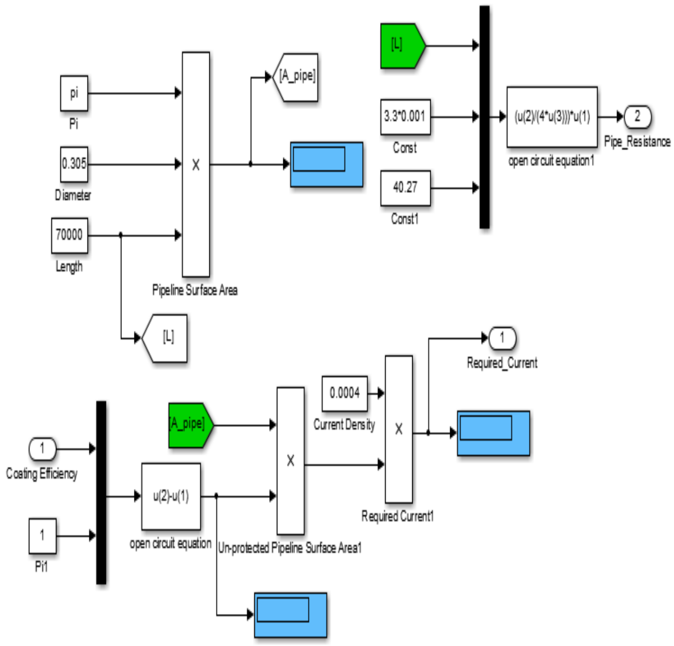

Figure (4. 11): Desert Media Block

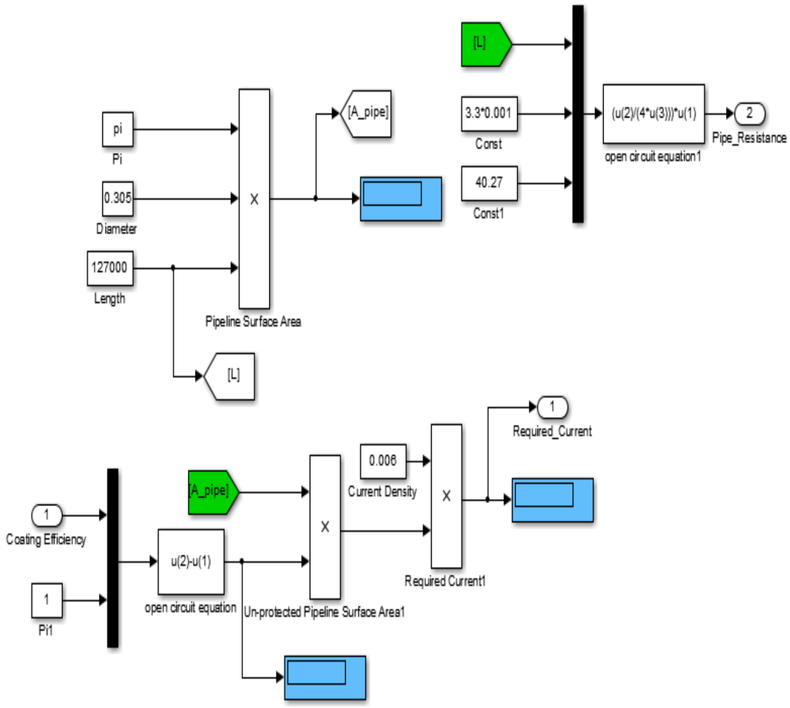

Figure (4. 12): Wet Soil with Stones Media Block

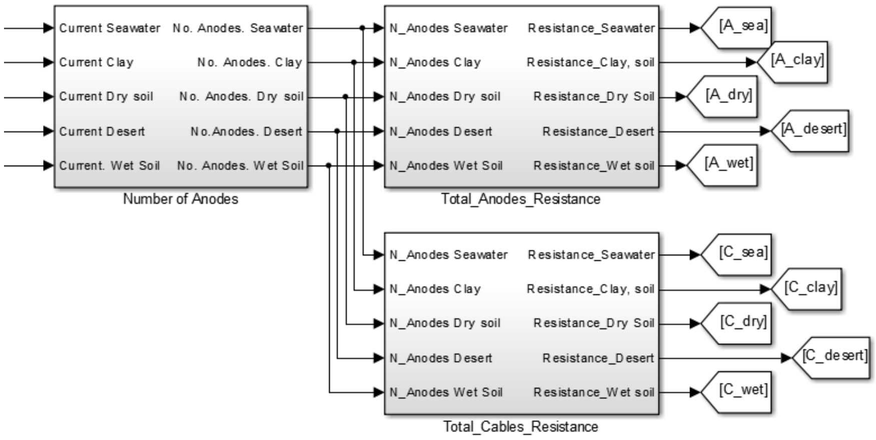

Figure (4. 13): General Anodes Blocks

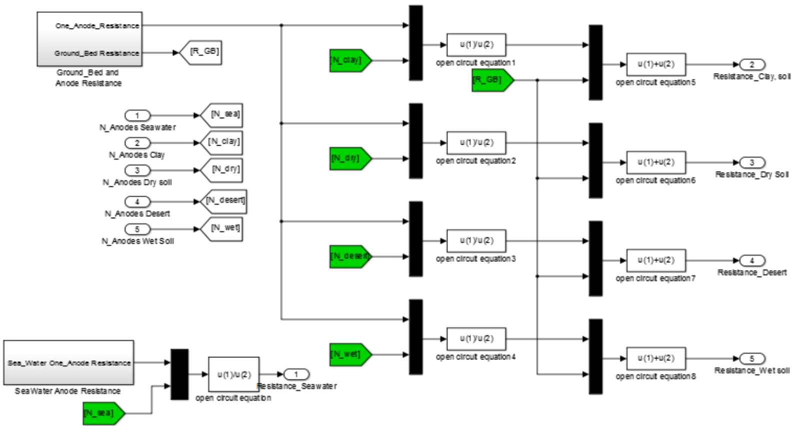

Figure (4. 14): Anode and Ground-bed Resistance Block

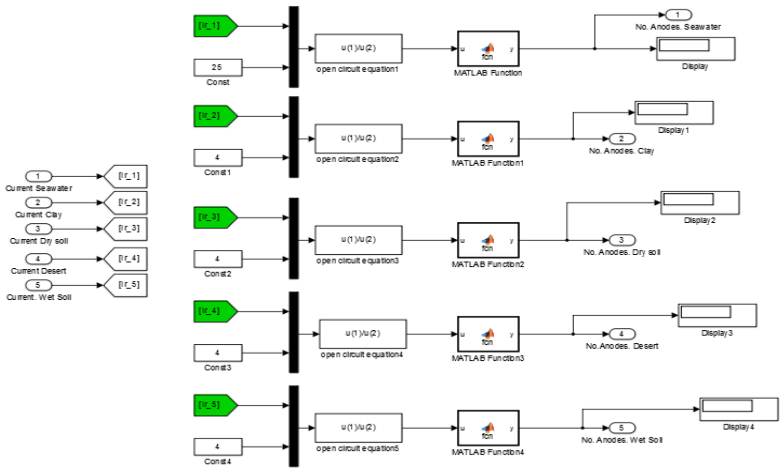

Figure (4. 15): Number of Anodes Block

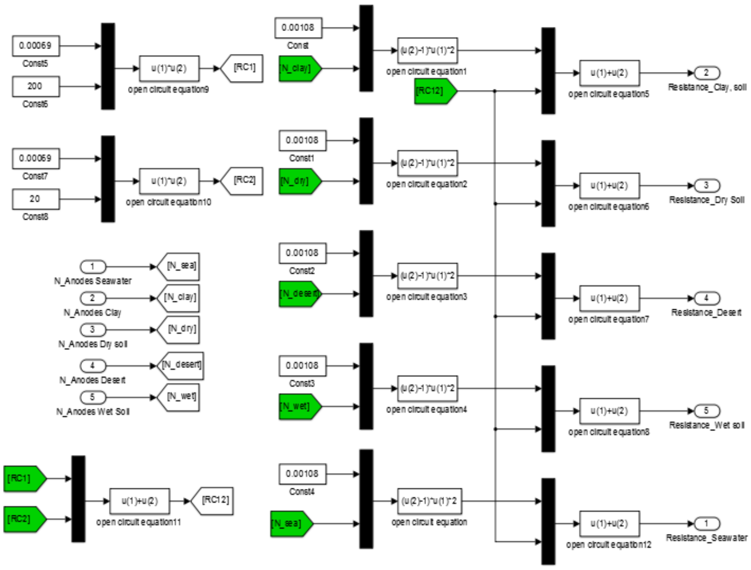

Figure (4. 16): Cables Resistance Block

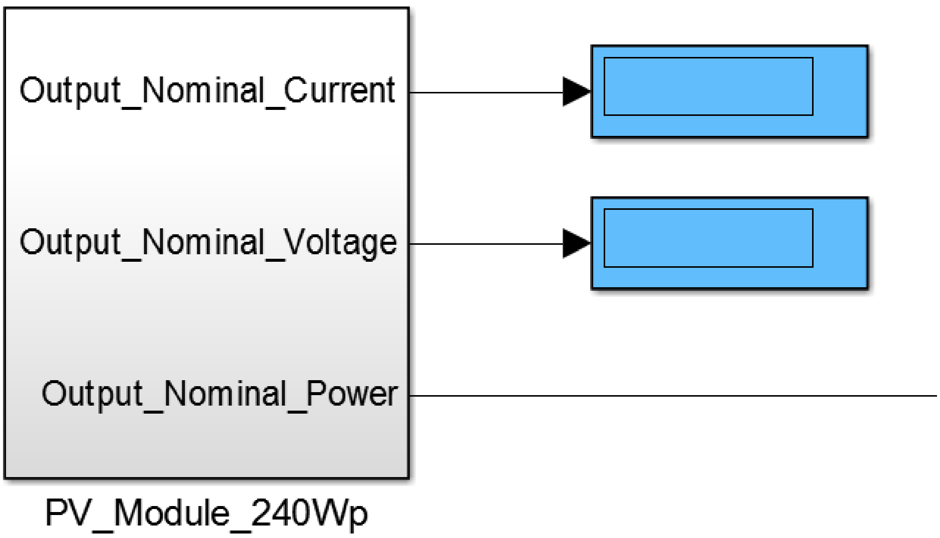

Figure (4. 17): PV Module Block

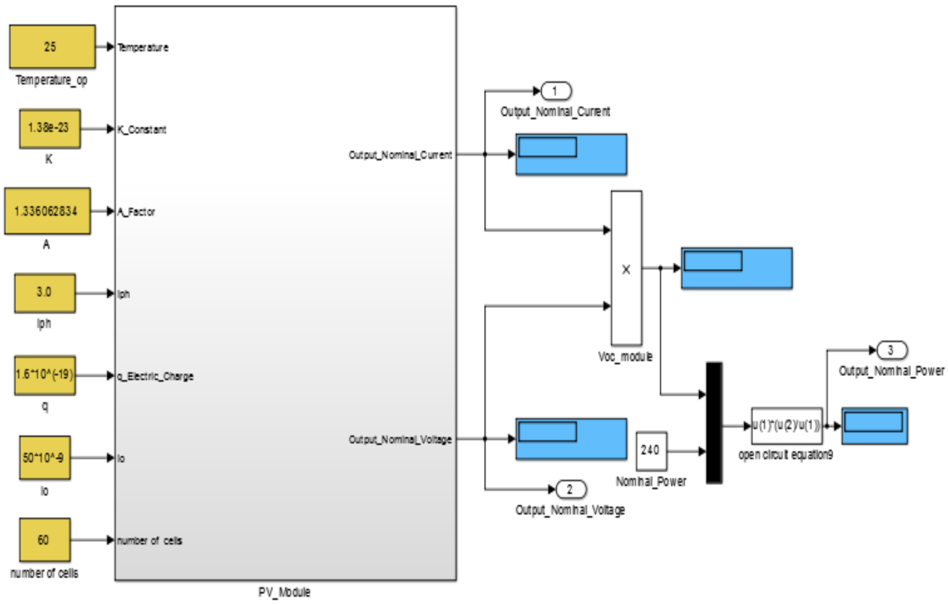

Figure (4. 18): Inside One PV Module Block

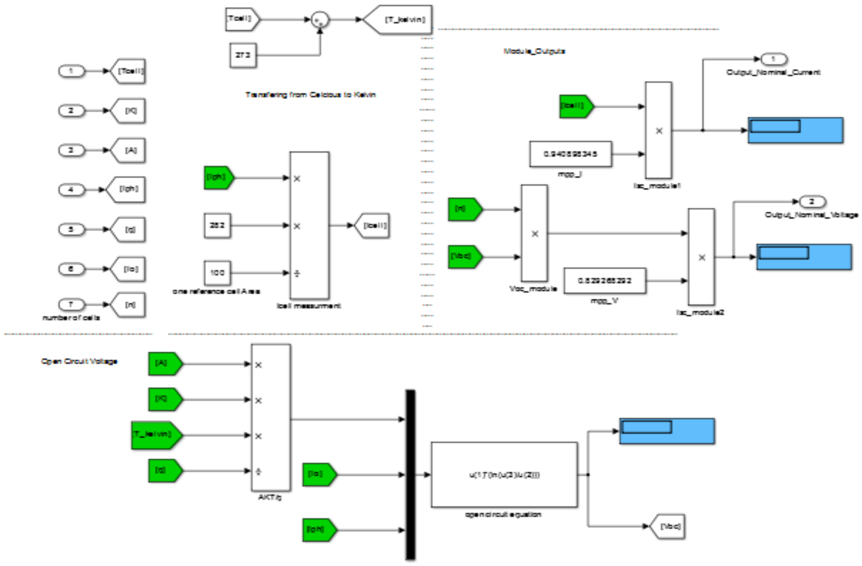

Figure (4. 19): Components of PV Module Block

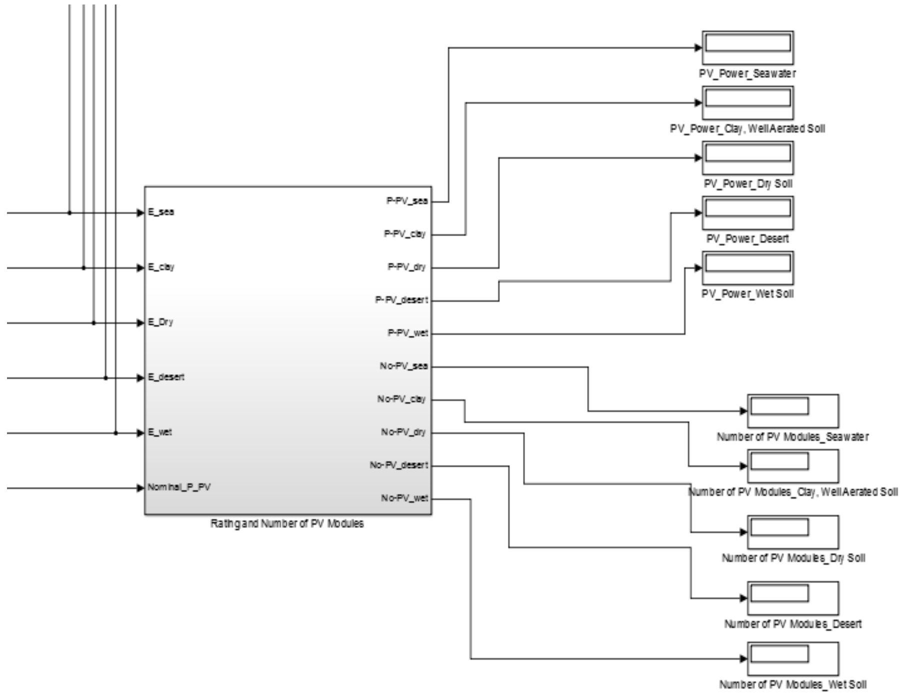

Figure (4. 20): Ratings and Number of PV Block

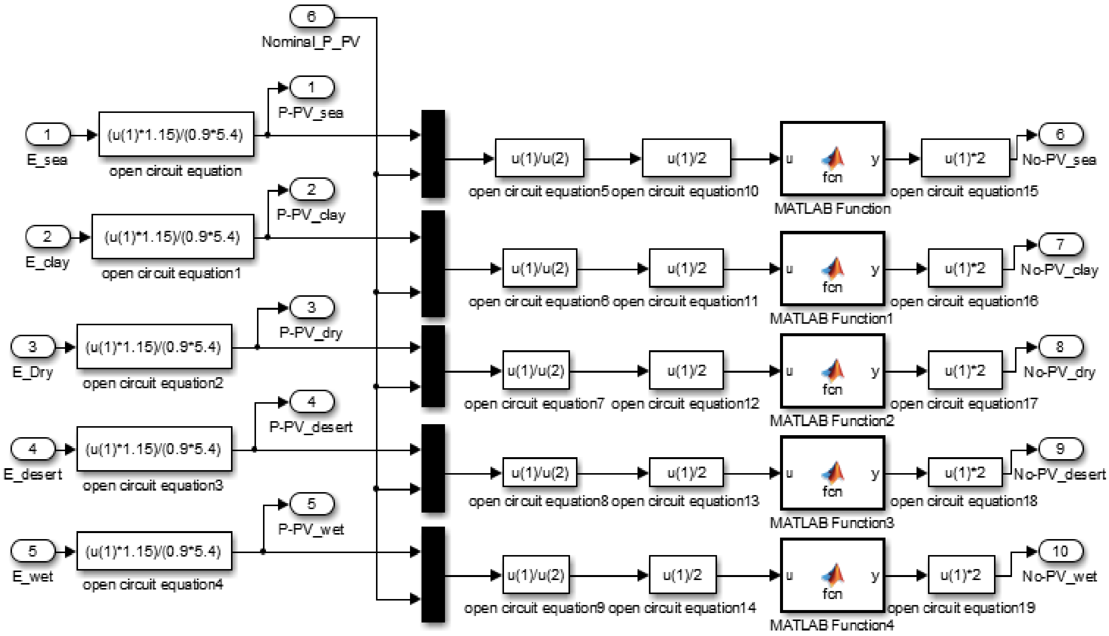

Figure (4. 21): Number of PV Modules Block

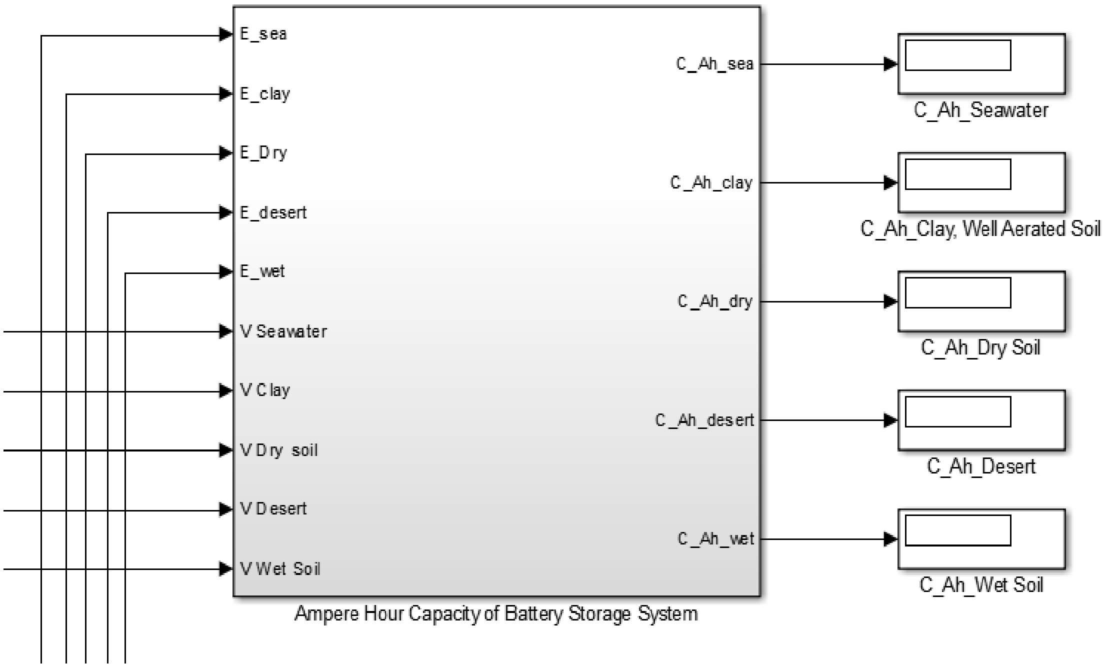

Figure (4. 22): Ampere Hour Capacity of Battery Block

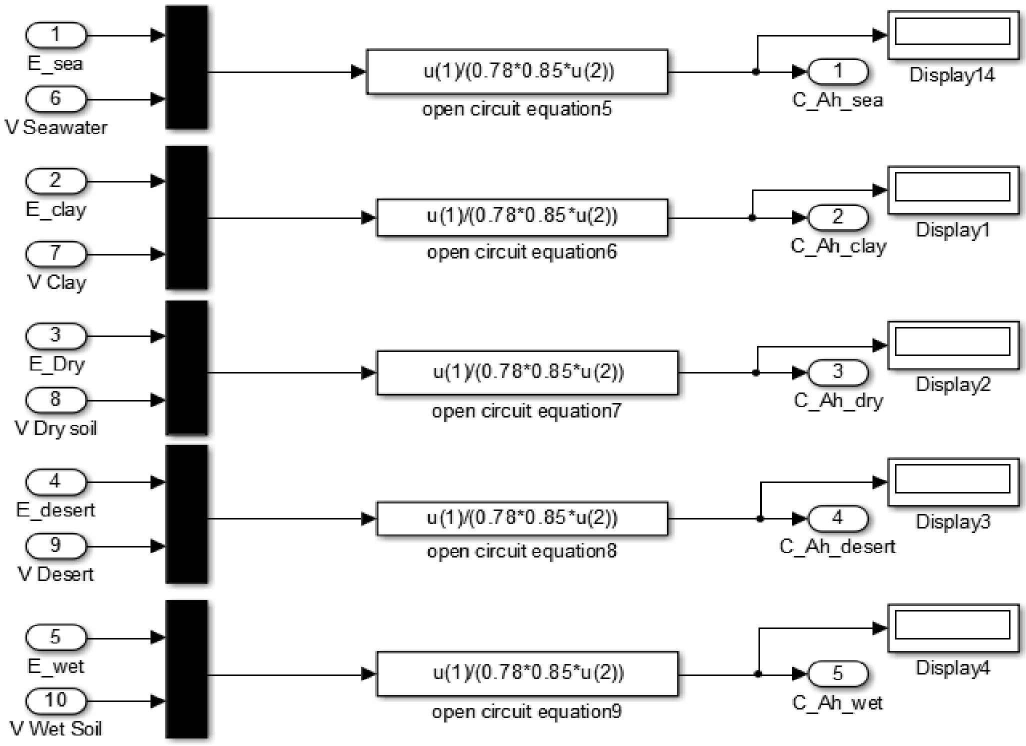

Figure (4. 23): Inside Ampere Hour Capacity Block

4.8.2 Current, Voltage, Power and Energy Measurement Blocks

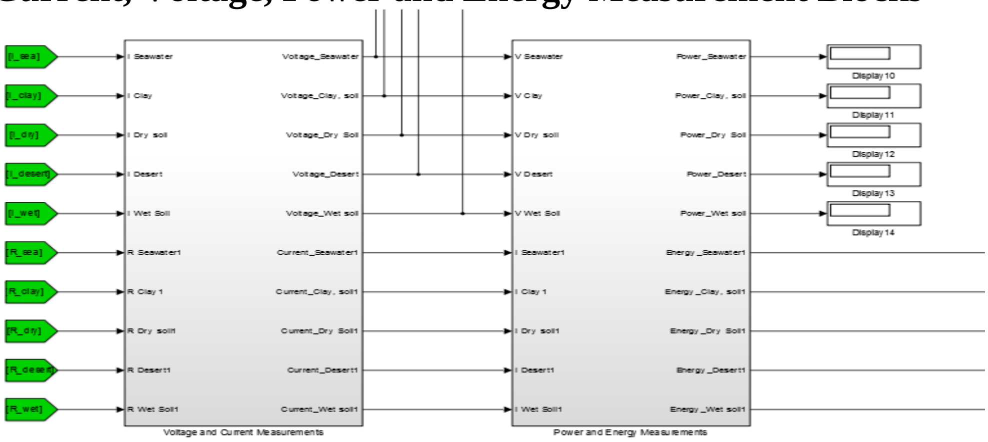

Figure (4. 24): General Measurement Blocks

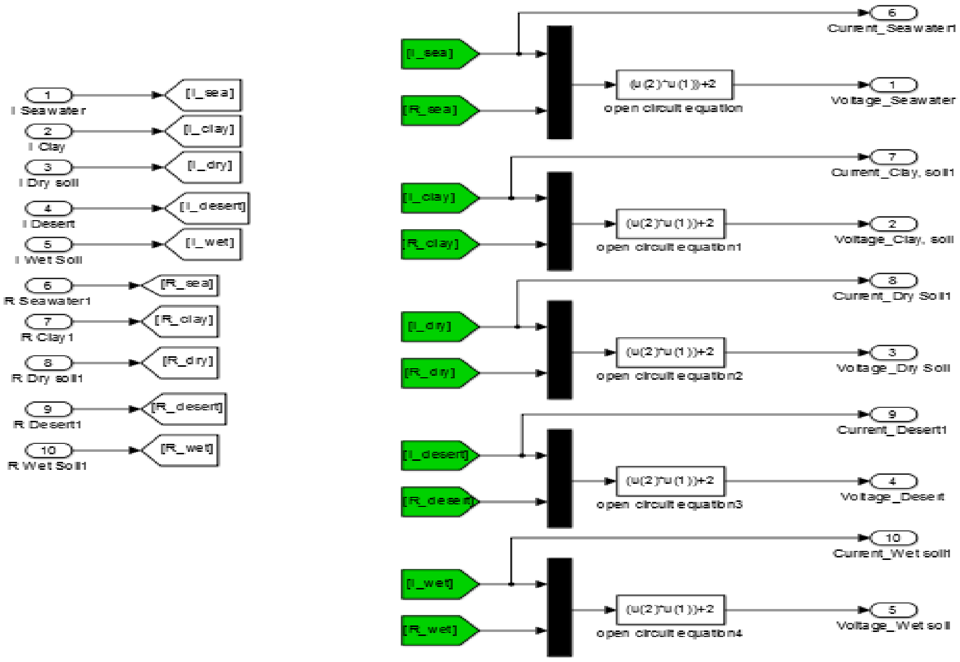

Figure (4. 25): Inside Current and Voltage Measurement Block

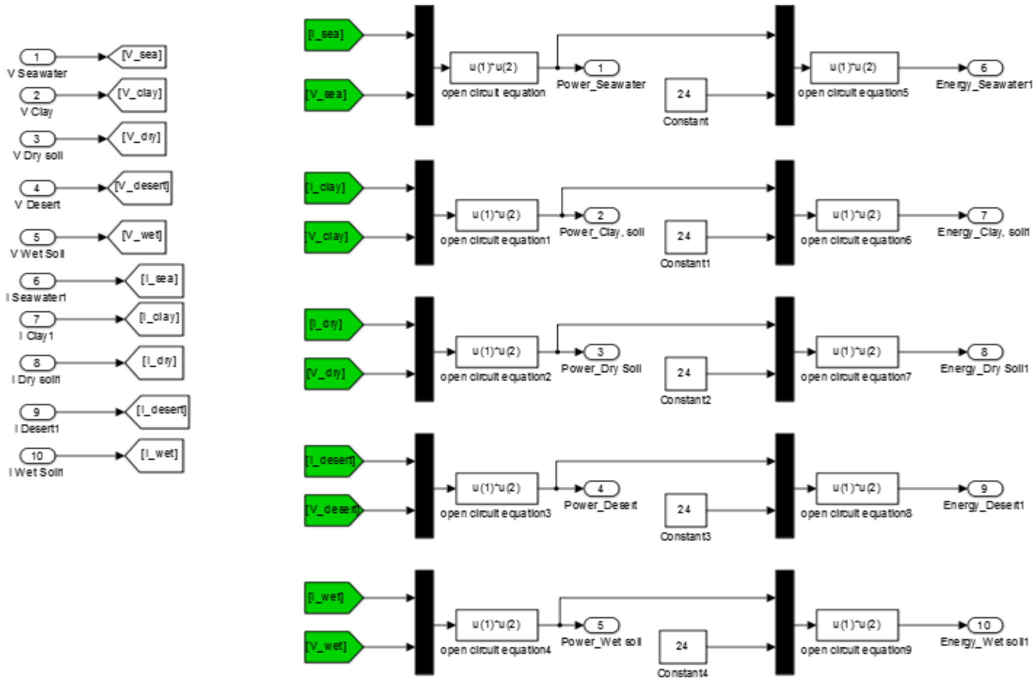

Figure (4. 26): Inside Power and Energy Block

4.8.3 Simulation Results

The results of the simulation are taken according to the first alternative which is at %90 coating efficiency.

4.8.3.1 Corrosion Current Quantities

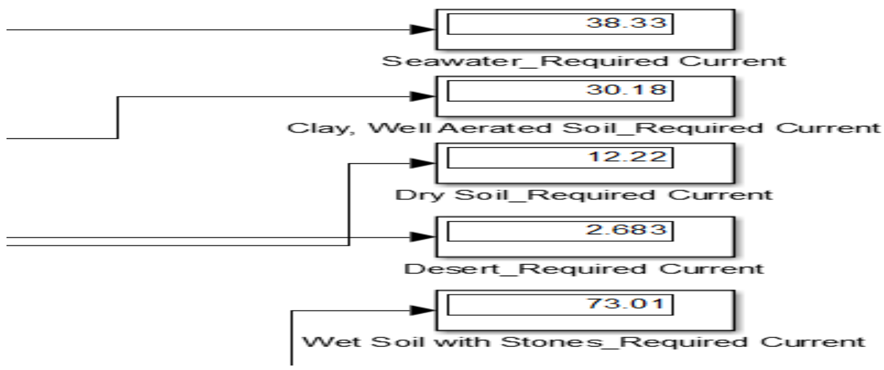

Figure (4. 27): Current Quantities in Amperes

4.8.3.2 Number of Anodes

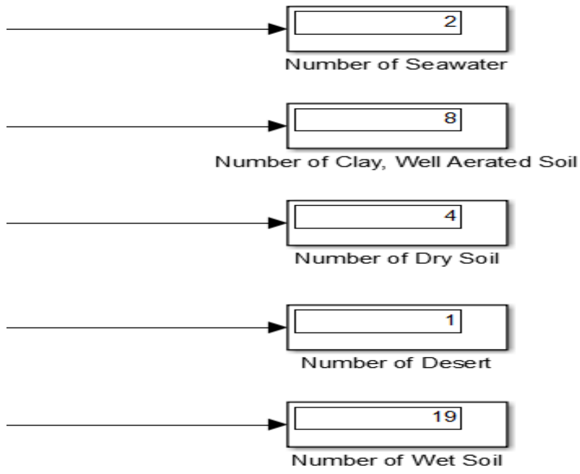

Figure (4. 28): Number of Anodes

4.8.3.3 Total Resistance Quantities

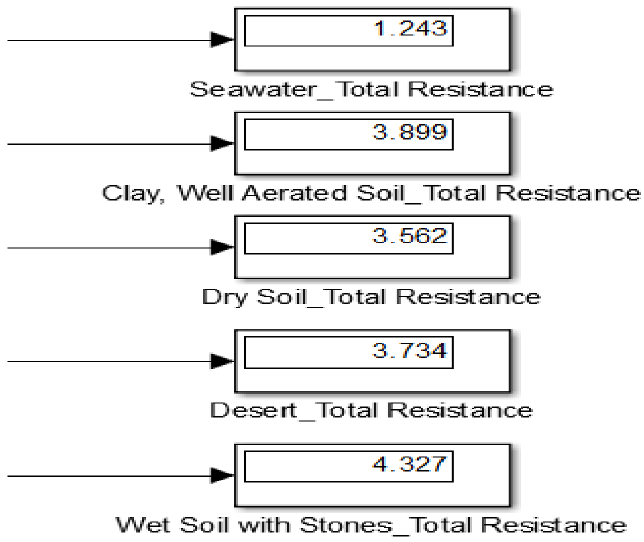

Figure (4. 29): Total Resistances Quantities in Ohms

4.8.3.4 Total Required Current, Voltage, Power and Energy Quantities

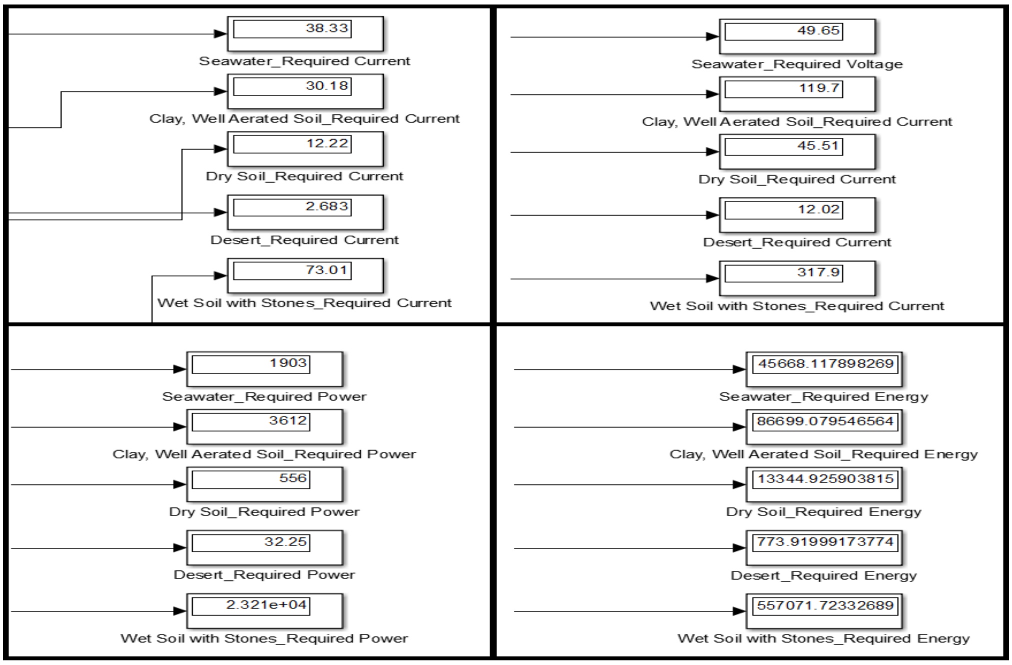

Figure (4. 30): The Required I, V, P and E Quantities in [A], [V], [W] and [Wh] respectively (Symbol e+04 represents 10000 in Matlab)

4.8.3.5 PV Modules Quantities

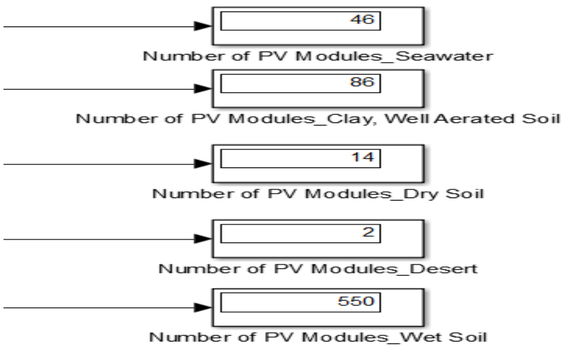

Figure (4. 31): Number of PV Modules

4.8.3.6 Batteries Ampere Hour Quantities

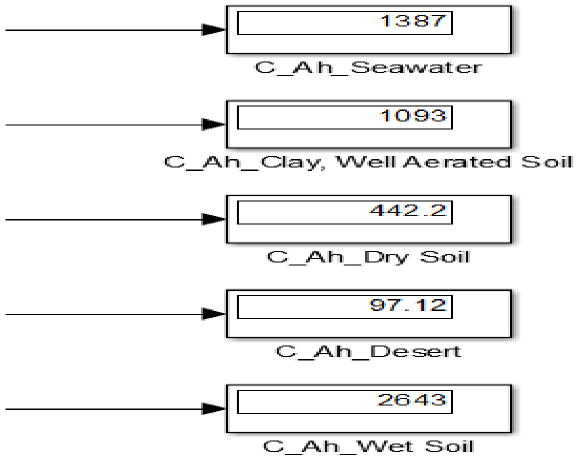

Figure (4. 32): Ampere Hour Capacity [Ah]

Chapter Five

Economic Study of PV powered ICCP System for Pipeline Distribution Network

The economic study in this chapter is depending on comparison between the costs of rehabilitation and the PV powered ICCP system. The rehabilitation cost is taken from different references from USA, Canada and Germany. The ICCP system components costs are taken from different selling websites and manufacturing companies.

In this chapter, the economic study is started with calculating the cost of rehabilitation of the pipeline distribution network in different media. Then, the cost of ICCP anodes and ground-beds are calculated, in addition to the cost of PV system components. All of previous costs are calculated in different media for the three alternatives. After the calculations, cash flows are done and the net cost that represents the saving of using the PV powered ICCP system in protection of the pipeline distribution network is performed.

5.1 Life Time Analysis

The life time of each part of the pipeline rehabilitation, PV and ICCP systems is very important in the economic study in order to have a proper estimation of feasibility of rehabilitation and PV powered ICCP system. [5.1 – 5.7]

- Pipelines Recoating Life Cycle: the life time is 30 years. But for warranty the calculation will be on 20 years

- Anodes Life Cycle: the life time is 20 years
- PV Modules Life Cycle: the life time is from 20 to 25 years. But for warranty the calculation will be on 20 years
- Batteries Life Cycle: the life time is 10 years. But the calculation will depend on 20 years life time, so the batteries will be doubled

5.2 Interest Rate

There are many interest rates for cash flow analysis, but in this case study the interest rate that will be used is (8%). The interest rate table is represented in Appendix (5).

5.3 Capital Cost Analysis

5.3.1 Capital Cost of Rehabilitation of Pipeline Distribution Network

The rehabilitation process of pipeline includes; moving the pipelines out from sea and ground, removing the old coating layer, cleaning, recoating and re-installing the pipes into sea and ground. The average capital cost for rehabilitation of one meter length and 0.62 meter diameter of pipeline is \$100/m to \$250/m. [5.1 – 5.7]

In the case study situation the cost that will be taken is \$250/m with 0.62 meter diameter, but here the diameter is 0.305 meter, so the cost per meter (C_m) is \$123/m. The total capital cost (C_C) of rehabilitation for the total length (L) of the pipeline distribution network will be as in the following equation:

$$C_C = C_m x L = 123x437{,}000m = \$53{,}751{,}000 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Depending on the surface area of the pipeline distribution network (A), the cost of rehabilitation per square meter (C_{R-1m^2}) is calculated as in the following equation:

$$C_{R-1m^2} = \frac{C_C}{A} = \frac{53,751,000}{\pi x 0.305 x 437,000} = \$128.4/m^2 \quad \text{……………… (5.2)}$$

The rehabilitation costs (C_R) of the pipeline distribution network for alternatives A, B and C are (C_{R-A}), (C_{R-B}) and (C_{R-C}) respectively, they are illustrated in table (5.1). The rehabilitation costs of alternatives are calculated depending on the following equations [5.1 – 5.6]:

$$C_{R-A} = (1 - 0.9) x A x C_{R-1m^2} \quad \text{……………… (5.3)}$$

$$C_{R-B} = (1 - 0.95) x A x C_{R-1m^2} \quad \text{……………… (5.4)}$$

$$C_{R-C} = (1 - 0.98) x A x C_{R-1m^2} \quad \text{……………… (5.5)}$$

Table (5. 1): Rehabilitation Cost

Alternative	C_R [$]
A	5,376,493
B	2,688,311
C	1,075,350

5.3.2 Capital Cost of Impressed Current Anodes and Ground-bed

The cost of anode (C_{1-A}) and the cost of the ground-bed (C_{GB}) is taken from different sources, but they have very large difference in cost, so an average approximated cost is taken as follows:

- (C_A) = $300 for one anode. [5.10]
- (C_{GB}) = $2,400 for ground-bed. [5.10]

The costs of anodes and ground-beds in different media for alternatives A, B and C are illustrated in tables (5.2), (5.3) and (5.4).

The ground-bed is not used in seawater media. Where: (C_{AT}) is the anodes cost.

Table (5. 2): Alternative A

Environment	N_A	C_A [$]	C_{AT} [$]	C_{GB} [$]
Seawater	2	300	600	0
Clay, Well Aerated Soil	8	300	2,400	2,400
Dry Soil	3	300	900	2,400
Desert	1	300	300	2,400
Wet Soil with Stones	19	300	5,700	2,400
Total (C_{A+GB}) = $19,500				

Table (5. 3): Alternative B

Environment	N_A	C_A [$]	C_{AT} [$]	C_{GB} [$]
Seawater	1	300	300	0
Clay, Well Aerated Soil	4	300	1,200	2,400
Dry Soil	2	300	600	2,400
Desert	1	300	300	2,400
Wet Soil with Stones	10	300	3,000	2,400
Total (C_{A+GB}) = $15,000				

Table (5. 4): Alternative C

Environment	N_A	C_A [$]	C_{AT} [$]	C_{GB} [$]
Seawater	1	300	300	0
Clay, Well Aerated Soil	2	300	600	2,400
Dry Soil	1	300	300	2,400
Desert	1	300	300	2,400
Wet Soil with Stones	4	300	1,200	2,400
Total (C_{A+GB}) = $12,300				

5.3.3 Capital Cost of PV Generator

The capital cost of PV generator (C_{PV}) is calculated depending on the following equation which uses $1 per watt peak [2.17, 5.10]. (C_{PV}) for alternatives A, B and C are represented in tables (5.5), (5.6) and (5.7).

$$C_{PV} = P_{PV} x 1\$/W_p \ldots\ldots\ldots\ldots\ldots (5.6)$$

Table (5. 5): Alternative A

Environment	P_{PV} $[W]$	C_{PV} [$]
Seawater	12,000	12,000
Clay, Well Aerated Soil	21,600	21,600
Dry Soil	3,600	3,600
Desert	240	240
Wet Soil with Stones	134,400	134,400
Total (C_{PV})= $171,840		

Table (5. 6): Alternative B

Environment	P_{PV} $[W]$	C_{PV} [$]
Seawater	3,360	3,360
Clay, Well Aerated Soil	5,760	5,760
Dry Soil	960	960
Desert	240	240
Wet Soil with Stones	34,560	34,560
Total (C_{PV})= $44,880		

Table (5. 7): Alternative C

Environment	P_{PV} $[W]$	C_{PV} [$]
Seawater	720	720
Clay, Well Aerated Soil	960	960
Dry Soil	240	240
Desert	50	50
Wet Soil with Stones	4,320	4,320
Total (C_{PV})= $6,290		

5.3.4 Capital Cost of Batteries

The capital cost of one battery (C_{1-B}) for each capacity rating is represented in table (5.11). The life time of the battery is 10 years, but for life time of 20 years the cost of battery is doubled. The costs of batteries in different media for alternatives A, B and C are illustrated in tables (5.12), (5.13) and (5.14). See batteries ratings in appendix (4).

Table (5. 8): Battery Cost [5.9, 5.10]

B_{C10} $[Ah]$	C_{1-B} [$]
2/1,411	673
2/3,415	2,700
2/820	500
12/52	165
12/65	165
2/325	250
2/1,751	2,500
2/220	250
2/273	250
2/1,009	673

Table (5. 9): Alternative A

Environment	N_B	C_{1-B} $[V/Ah]$	C_{2-B} [$]	C_{BT} [$]
Seawater	18	2/3,415	5,400	97,200
Clay, Well Aerated Soil	60	2/3,415	5,400	234,000
Dry Soil	24	2/820	1,000	24,000
Desert	1	12/52	330	330
Wet Soil with Stones	160	2/3,415	5,400	864,000
Total (C_{BT}) = $1,201,530				

Table (5. 10): Alternative B

Environment	N_B	B_{1-B} $[V/Ah]$	C_{2-B} [$]	C_{BT} [$]
Seawater	14	2/1,009	1,346	18,844
Clay, Well Aerated Soil	64	2/1,751	5,000	320,000
Dry Soil	24	2/220	500	12,000
Desert	1	12/52	330	330
Wet Soil with Stones	81	2/3,415	5,400	437,400
Total (C_{BT}) = $788,574				

Table (5. 11): Alternative C

Environment	N_B	B_{1-B} $[V/Ah]$	C_{2-B} [$]	C_{BT} [$]
Seawater	6	2/325	500	3,000
Clay, Well Aerated Soil	14	2/273	500	7,000
Dry Soil	1	12/52	330	330
Desert	1	12/52	330	330
Wet Soil with Stones	23	2/1,009	1,346	30,958
Total (C_{BT}) = $41,618				

5.3.5 Capital Cost Conclusion

The conclusion of all capital costs are represented as ICCP system capital cost (C_{ICCP}) and rehabilitation capital cost (C_R) in the following table.

Table (5. 12): Capital Cost Conclusion

Alternative	C_R [$]	C_{ICCP} [$]
A	5,376,493	1,392,870
B	2,688,311	848,454
C	1,075,350	60,208

5.4 Annual Cost Analysis

The annual cost analysis is depending on 20 years life time and 8% interest rate. The annual cost of rehabilitation (C_{AR}) and the annual cost of ICCP System (C_{A-ICCP}) are calculated according to the following equations.

$$C_{AR} = (A/P)_{8\%} x C_R \quad \ldots\ldots\ldots\ldots\ldots.. (5.7)$$

$$C_{A-ICCP} = (A/P)_{8\%} x C_{ICCP} \quad \ldots\ldots\ldots\ldots\ldots.. (5.8)$$

Where: $((A/P)_{8\%})$ is taken from interest tables for 20 years life time and its equals (0.1019) [5.8]. (C_{AR}) and (C_{A-ICCP}) are represented in table (5.13). The costs of ICCP and rehabilitation are representing in cash flow diagrams in figures (5.1), (5.2), (5.3) for alternatives A, B and C respectively.

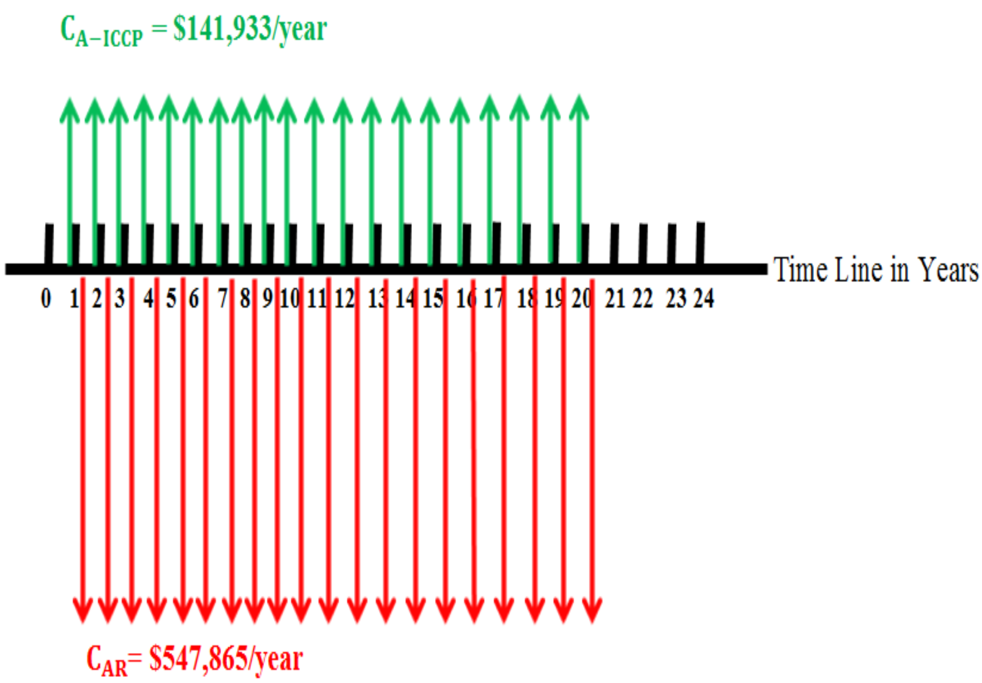

Figure (5. 1): Cost Cash Flow for Alternative (A)

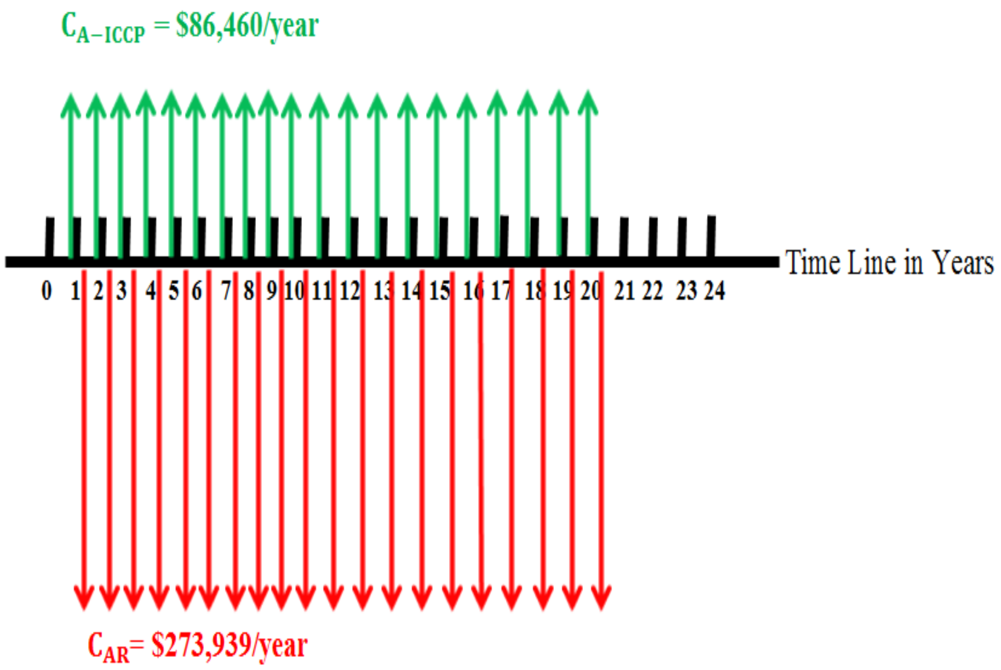

Figure (5. 2): Cost Cash Flow for Alternative (B)

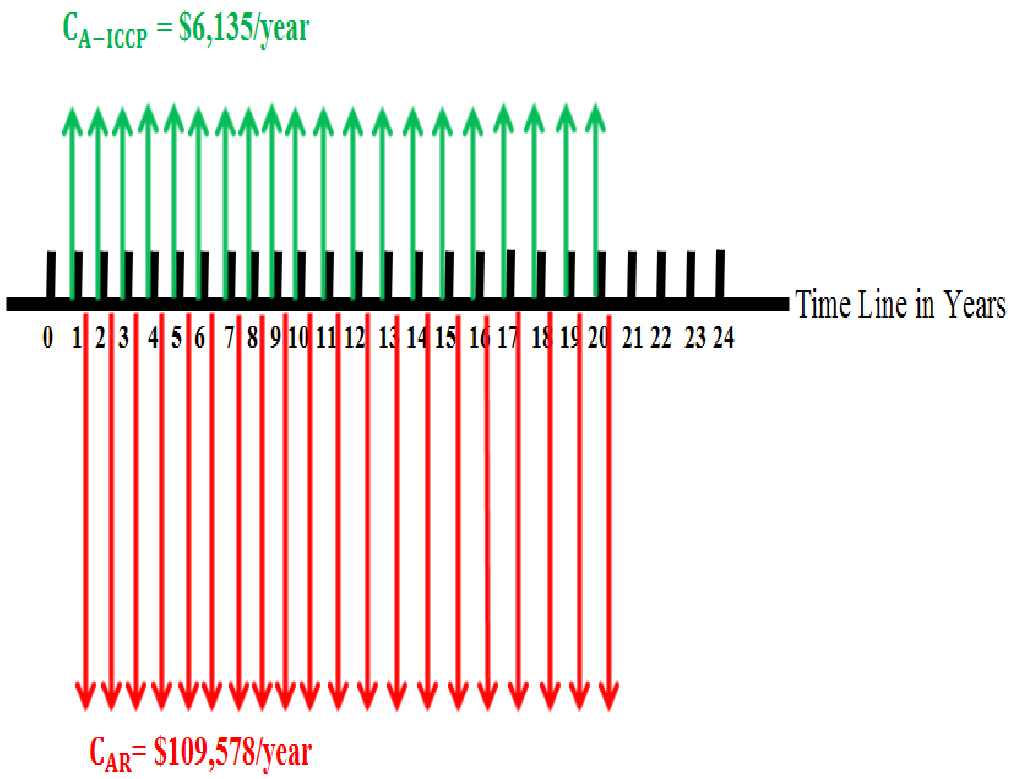

Figure (5. 3): Cost Cash Flow for Alternative (C)

Table (5. 13): Annual Cost

Alternative	C_R [$]	C_{ICCP} [$]	$(A/P)_{8\%}$	C_{AR} [$]/year	C_{A-ICCP} [$]/year
A	5,376,493	1,392,870	0.1019	547,865	141,933
B	2,688,311	848,454		273,939	86,460
C	1,075,350	60,208		109,578	6,135

5.5 Saving Calculation

The annual saving ($C_{A-saving}$) is calculated according to the following equation [5.8]:

$$C_{A-saving} = C_{AR} - C_{A-ICCP} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.9)$$

The present saving for 20 years ($C_{P-saving}$) is calculated according to the following equation [5.8]:

$$C_{P-saving} = C_{A-saving} x (P/A)_{8\%} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.10)$$

Where ($(P/A)_{8\%}$) is taken from interest table of 8% interest rate and its equals (9.818). ($C_{A-saving}$) and ($C_{P-saving}$) for each alternative are represented in table (5.14). The cash flow diagrams of annual and present saving for alternatives A, B and C are illustrated in figures (5.4), (5.5) and (5.6).

Table (5. 14): Cash Flow Data

Alternative	C_{AR} [$]	C_{A-ICCP} [$]/year	$C_{A-saving}$ [$]/year	$(P/A)_{8\%}$	$C_{P-saving}$
A	547,865	141,933	405,932	9.818	3,985,440
B	273,939	86,460	187,479		1,840,670
C	109,578	6,135	103,443		1,015,603

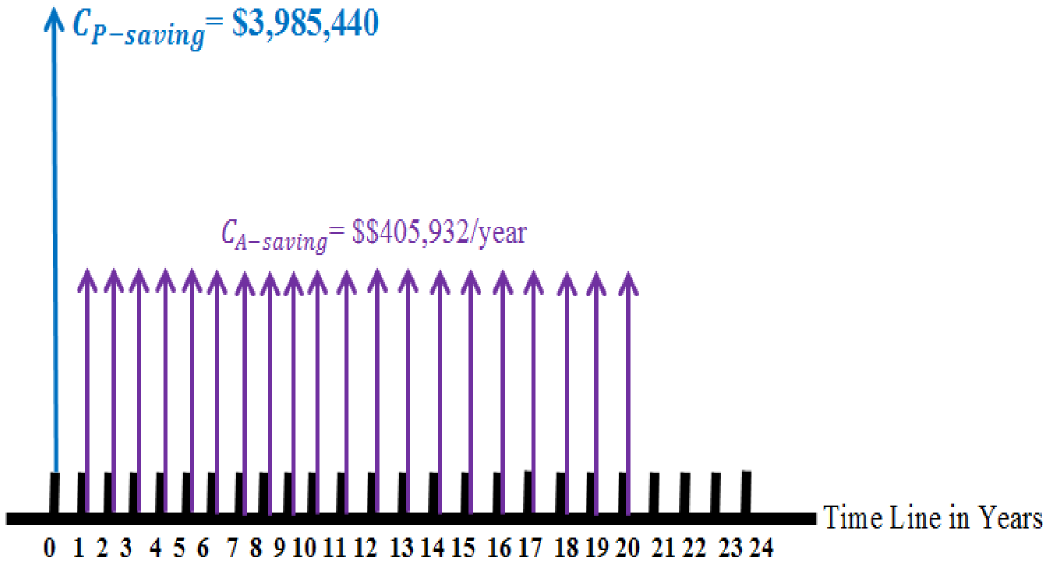

Figure (5. 4): Saving Cash Flow for Alternative (A)

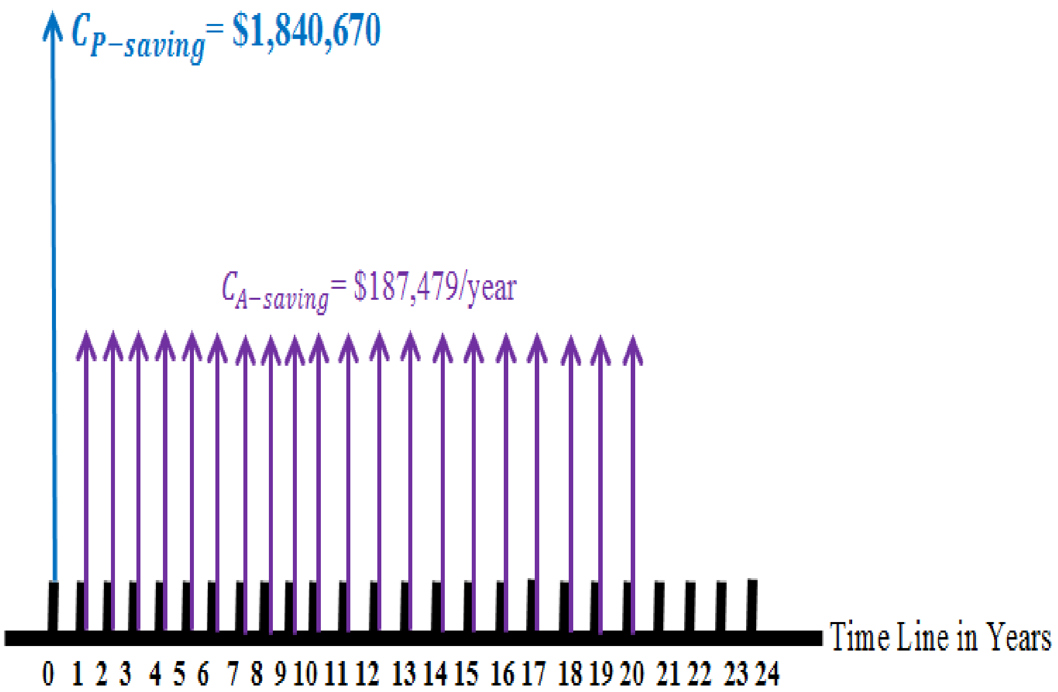

Figure (5. 5): Saving Cash Flow for Alternative (B)

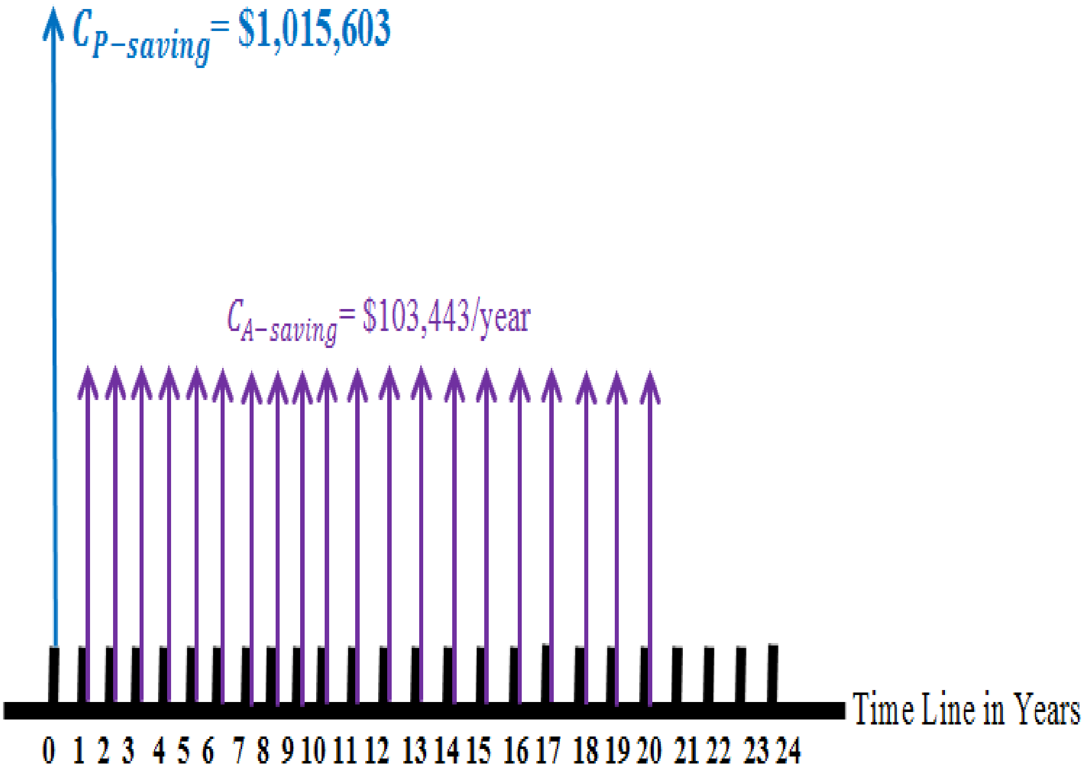

Figure (5. 6): Saving Cash Flow for Alternative (C)

Chapter Six

Discussion of the Results

The performed study and analysis have given the following results:

1. Using of cathodic protection technology is more appropriate for providing protection for the pipeline distribution network due to the difficulty of rehabilitation of the pipelines through digging, extracting, cleaning, recoating, re-piping and burying.
2. Using of solar PV electrical energy to supply the ICCP system is recommended due to the existing high solar energy potential in Palestine amounting to (5.4 $kWh/m^2 - day$).
3. The economic analysis shows that the saving from rehabilitation cost in alternative A is $3,985,440 from $5,371,493, for alternative B is $1,840,670 from $2,688,311 and for alternative C is $1,015,603 from $1,075,350

The economic analysis shows the savings are representing a percentage of 74.2%, 68.47% and 94.44% of the rehabilitation cost for alternatives A, B and C respectively. The high percentage of saving mean that using PV powered ICCP system instead of rehabilitation of the pipelines is more feasible.

Chapter Seven

Conclusion and Recommendations

7.1 Conclusion

Corrosion is very danger to the metallic structures (pipelines as a case study) due to its damage which destruct the metallic structure and make it out of service. Applying the cathodic protection (CP) technology for protection of pipeline distribution networks is recommended due to the cost and the difficulty of the rehabilitation of the pipelines.

The thesis shows that using solar photovoltaic (PV) energy to supply impressed current cathodic protection (ICCP) systems for Submarine and underground pipeline distribution network in Palestine is feasible. The design deals with three alternatives depending on the percentage of protected surface area, the alternative A, B and C represent 90%, 95% and 98% respectively.

The economic analysis shows that the saving for the three alternatives A, B and C are $3,985,440, $1,840,670, and $1,015,603 respectively and there percentages from the rehabilitation cost are 74.2%, 68.47% and 94.44% for alternatives A, B and C respectively.

7.2 Recommendations

1. Performing ICCP projects in Palestine (within B.sc graduation projects, M.Sc. thesis or Ph.D. thesis), where practical measurements of the current density and resistances of the different media have to be carried

out. Further mathematical analysis considering the obtained measuring results are required.

2. Implementation of studies about protection of different metallic structures as: storage tanks, bridges, ships, high voltage transmission line towers, etc...

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Appendices

Appendix (1): Carbon Steel Pipeline API Tables

The represented data in this section is taken from: "Standard Pipe and Line Pipe, USS Company, U. S. Steel Tubular Products".

Disclaimer

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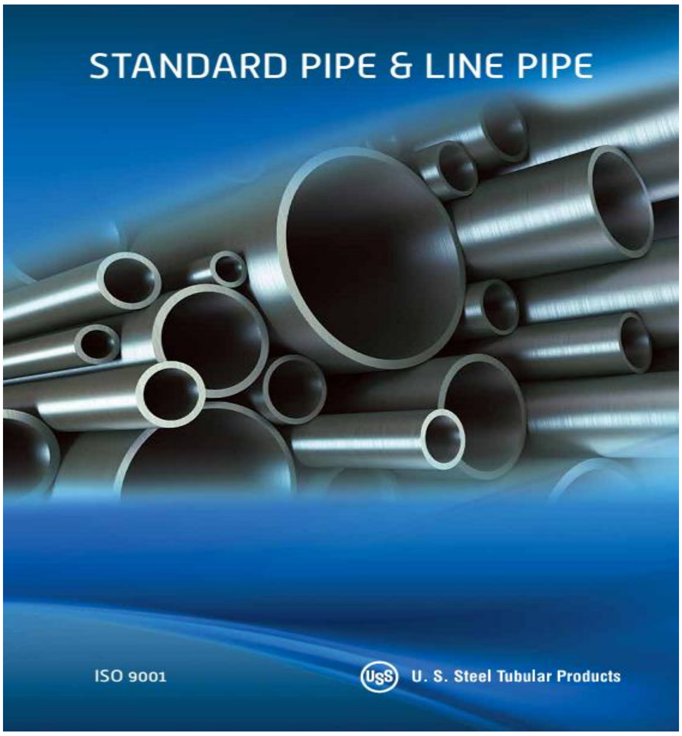

PRODUCT PROPERTIES

U. S. Steel Tubular Products manufactures both seamless and welded pipe to meet specific customer requirements. Advanced manufacturing techniques and controls ensure high quality, uniform, economical products. A complete range of ODs, end finishes and lengths are available.

Seamless Standard Pipe and Line Pipe

U. S. Steel Tubular Products manufactures its seamless pipe by piercing solid billets of fully killed steel. This "seamless" method of manufacture is a forging operation that only the soundest, toughest steel can tolerate.

Chemical and mechanical property requirements are as prescribed by current API, ASTM, ASME and applicable CSA standards. U. S. Steel Tubular Products is the only domestic producer of seamless pipe in the 11-3/4" to 26" OD size range.

U. S. Steel Tubular Products provides seamless Standard Pipe and Line Pipe for a wide range of applications. Our seamless pipe has an unsurpassed record of safety, and uniform strength and ductility, making it the product of choice for critical applications.

Standard Pipe is widely used primarily in the construction, refining, chemical and petrochemical industries. Line Pipe is used for the transmission of crude oil, natural gas and petroleum products as well as for water and slurry pipeline applications.

PRODUCT PROPERTIES

Availability – Standard Diameters and Walls

Size[1]		Wall Thickness,[2] Inches	
NPS	OD (Inches)	Lorain, OH	Fairfield, AL
1 1/2	1.900	0.140-0.281	–
2	2 3/8	0.154-0.436	–
2 1/2	2 7/8	0.160-0.552	–
3	3 1/2	0.170-0.600	–
3 1/2	4	0.180-0.650	–
4	4 1/2	0.188-0.674	0.205-0.750
5	5 9/16	–	0.250-0.750
6	6 5/8	–	0.250-0.870
8	8 5/8	–	0.250-1.200
10	10 3/4	0.307-2.000	–
12	12 3/4	0.330-2.312	–
14	14	0.375-2.000	–
16	16	0.375-2.000	–
18	18	0.375-1.562	–
20	20	0.375-1.512	–
22	22	0.375-1.375	–
24	24	0.375-1.250	–
26	26	0.375-1.125	–

1 Sizes between NPS 1 1/2 and 26 not listed subject to inquiry.
2 Maximum wall varies for grades over X42 and is subject to mill inquiry.

Electric Resistance Weld (ERW) Standard Pipe and Line Pipe

U. S. Steel Tubular Products' ERW Standard Pipe and Line Pipe are smoothly finished, thin-walled, extra-long products produced by continuously forming coiled bands and welding the longitudinal seam using high-frequency electric resistance welding. Chemical and mechanical property requirements are as prescribed by current API 5L and applicable ASTM standards.

ERW Standard Pipe and Line Pipe are widely used throughout the oil and gas industry, as well as for pipe piling, pipe-type cable systems and hydraulic hoists.

Characteristics and Advantages

Eighty-Foot Lengths – Ultra-long lengths of U. S. Steel Tubular Products ERW pipe, available from McKeesport Tubular Operations minimize handling time in transportation and installation, and significantly reduce field welding labor, time and costs.

Smooth Surfaces – U. S. Steel Tubular Products hot rolled strip steel is continuously cold formed into smooth-surfaced, uniform-gage pipe for superior flow characteristics.

Stronger, Lighter Walls – The improved, higher strength, lighter gage steel bands used by U. S. Steel Tubular Products are fused by high-frequency electric resistance welders into rugged pipe that can meet exacting tolerances and strength specifications.

Uniform Dimensions and Quality – Higher automated production, combined with continuous non-destructive and visual inspection and hydrostatic testing, assures a pipe product of excellent quality. And, because the pipe is made from flat-rolled steel, it has highly uniform wall thicknesses.

McKeesport, PA Availability (Subject to inquiry)

Size[1]		Wall Thickness,[2] Inches
NPS	OD	
8	8 5/8	0.172-0.406
10	10 3/4	0.172-0.400
12	12 3/4	0.188-0.406
14	14	0.188-0.406
16	16	0.203-0.406
18	18	0.219-0.406
20	20	0.250-0.413

1 Sizes not listed subject to inquiry.
2 Maximum wall varies for grades over X42 and is subject to mill inquiry.

Lone Star, TX Availability (Subject to inquiry)

Size[1]		Wall Thickness,[2] Inches
NPS	OD	
2	2 3/8	0.218-0.344
2 1/2	2 7/8	0.203-0.375
3	3 /1/2	0.216-0.300
3 1/2	4	0.226-0.318
4	4 1/2	0.237-0.531
5	5 9/16	0.258-0.500
6	6 5/8	0.280-0.432
8	8 5/8	0.250-0.438
10	10 3/4	0.279-0.500
12	12 3/4	0.250-0.500
14	14	0.312-0.562
16	16	0.375-0.562

1 Sizes not listed subject to inquiry.
2 Maximum wall varies for grades over X42 and is subject to mill inquiry.

COMPARATIVE SPECIFICATIONS

The following information is summarized from ASTM standards and API Specification 5L in effect at the time of publication. Please refer to the specific standards or specifications for more details.

A53 Seamless and Welded Standard Pipe

Specification A53 covers seamless and welded, black and hot-dipped galvanized nominal (average) wall pipe for coiling, bending, flanging and other special purposes and is suitable for welding.

Mechanical Properties – Tensile Requirements

Seamless and ERW	Grade A	Grade B
Tensile Strength, min., psi	48,000	60,000
Yield Strength, min., psi	30,000	35,000

Chemical Requirements

Seamless and ERW	C max %	Mn max %	P max %	S max %
Grade A	0.25	0.95	0.05	0.045
Grade B	0.30	1.20	0.05	0.045

COMPARATIVE SPECIFICATIONS

Testing Requirements

Hydrostatic Testing

Hydrostatic inspection test pressures for plain end and threaded and coupled pipe are specified. Hydrostatic pressure shall be maintained for not less than 5 seconds for all sizes of Seamless and ERW pipe.

Mechanical Tests

Tensile Test – Two transverse tests required on ERW for NPS 8 and larger, one across the weld and one opposite the weld

Flattening Test – On ERW for NPS 2 and larger, STD and XS walls (not required for XXS pipe)

Bending Test (Cold) – for NPS 2 and under, XS wall and under; for NPS 1-1/4 and under, XXS wall

	Degree of Bend	Diameter of Mandrel
For Normal A53 Uses	90	12 x nom. dia of pipe
For Close Coiling	180	8 x nom. dia of pipe

Number of Tests

Seamless and Electric Resistance Weld – bending, flattening, tensile on one length of pipe from each lot of 500 lengths, or less, of each pipe size.

API 5L Line Pipe

Specification API 5L covers seamless and welded pipe suitable for use in conveying gas, water, oil and other liquefied media.

Chemical Requirements

Specification	Grade	Cb	Mnb	P	S	Si	Cr	Mo	Ni	V	Cb	Ti
API 5L 44th Ed (PSL 1) Seamless	A25	.21	.60	.030	.030	–	–	–	–	–	–	–
	A	.22	.90	.030	.030	–	–	–	–	–	–	–
	B	.28	1.20	.030	.030	–	–	–	–	c,d	c,d	d
	X42	.28	1.30	.030	.030	–	–	–	–	d	d	d
	X46	.28	1.40	.030	.030	–	–	–	–	d	d	d
	X52	.28	1.40	.030	.030	–	–	–	–	d	d	d
	X56	.28	1.40	.030	.030	–	–	–	–	d	d	d
	X60	.28[e]	1.40[e]	.030	.030	–	–	–	–	f	f	f
	X65	.28[e]	1.40[e]	.030	.030	–	–	–	–	f	f	f
	X70	.28[e]	1.40[e]	.030	.030	–	–	–	–	f	f	f
API 5L 44th Ed (PSL 1) Welded	A25	.21	.60	.030	.030	–	–	–	–	–	–	–
	A	.22	.90	.030	.030	–	–	–	–	–	–	–
	B	.26	1.20	.030	.030	–	–	–	–	c,d	c,d	d
	X42	.26	1.30	.030	.030	–	–	–	–	d	d	d
	X46	.26	1.40	.030	.030	–	–	–	–	d	d	d
	X52	.26	1.40	.030	.030	–	–	–	–	d	d	d
	X56	.26	1.40	.030	.030	–	–	–	–	d	d	d
	X60	.26[e]	1.40[e]	.030	.030	–	–	–	–	f	f	f
	X65	.26[e]	1.40[e]	.030	.030	–	–	–	–	f	f	f
	X70	.26[e]	1.65[e]	.030	.030	–	–	–	–	f	f	f

a. .50% max Cu, Ni, Cr and .15 max Mo. For grades up to and including X52, Cu, Cr and Ni shall not be added intentionally.
b. For each reduction of .01% below the max C, and increase of .05% Mn is permitted up to a max of 1.65% for grades B, X42 and X52, up to 1.75% for grades >X52 and < X70, and 2.0% for X70.
c. Unless otherwise agreed Cb + V < = .15%.
d. Cb + V + Ti < = .15%.
e. Unless otherwise agreed.
f. Unless otherwise agreed the sum of Cb + V + Ti < = .15%.

Specification	Grade	Cond	Cb	Mnb	P	S	Si	V	Cb	Ti	Other	IIW	Pcm
API 5L 44th Ed (PSL 2) (Seamless & Welded)	B	R or N	.24	1.20	.025	.015	.40	c	c	.04	e	.43	.25
	X42	R or N	.24	1.20	.025	.015	.40	.06	.05	.04	e	.43	.25
	X46	N	.24	1.40	.025	.015	.40	.07	.05	.04	d, e	.43	.25
	X52	N	.24	1.40	.025	.015	.45	.10	.05	.04	d, e	.43	.25
	X56	N	.24	1.40	.025	.015	.45	.10[f]	.05	.04	d, e	.43	.25
	X60	N	.24[f]	1.40[f]	.025	.015	.45[f]	.10[f]	.05[f]	.04[f]	d, h	as agreed to	
API 5L 44th Ed (PSL 2) (Seamless & Welded)	B	Q	.18	1.40	.025	.015	.45	.05	.04	.04	e	.43	.25
	X42	Q	.18	1.40	.025	.015	.45	.06	.05	.04	e	.43	.25
	X46	Q	.18	1.40	.025	.015	.45	.07	.05	.04	e	.43	.25
	X52	Q	.18	1.50	.025	.015	.45	.10	.05	.04	e	.43	.25
	X56	Q	.18	1.50	.025	.015	.45	.10	.05	.04	d, e	.43	.25
	X60	Q	.18[f]	1.70[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			e	.4	.25
	X65	Q	.18[f]	1.70[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			h	.43	.25
	X70	Q	.18[f]	1.80[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			h	.43	.25
	X80	Q	.18[f]	1.90[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			i, j	as agreed to	

Chemical Requirements (cont)

Specification	Grade	Cond	Cb	Mnb	P	S	Si	V	Cb	Ti	Other	IIW	Pcm
API 5L 44th Ed (PSL 2) (Welded Only)	B	M	.22	1.20	.025	.015	.45	.05	.05	.04	e	.43	.25
	X42	M	.22	1.30	.025	.015	.45	.05	.05	.04	e	.43	.25
	X46	M	.22	1.30	.025	.015	.45	.05	.05	.04	e	.43	.25
	X52	M	.22	1.40	.025	.015	.45	(V + Cb + Ti < = .15)			e	.43	.25
	X56	M	.22	1.40	.025	.015	.45	(V + Cb + Ti < = .15)			e	.43	.25
	X60	M	.12[f]	1.60[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			h	.43	.25
	X65	M	.12[f]	1.60[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			h	.43	.25
	X70	M	.12[f]	1.70[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			h	.43	.25
	X80	M	.12[f]	1.85[f]	.025	.015	.45[f]	(V + Cb + Ti <= .15)			I	.43 f	.25
	X90	M	.12[f]	1.85[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			I	–	.25
	X100	M	.12[f]	1.85[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			i, j	–	.25
	X120	M	.12[f]	1.85[f]	.025	.015	.45[f]	(V + Cb + Ti < = .15)			i, j	–	.25

b. For Seamless pipe wall thickness > .787" CE shall be by agreement.
c. For each reduction of .01% below the max C, and increase of .05% Mn is permitted up to a max of 1.65% for grades B, X42 and X52, up to 1.75% for grades >X52 and < X70, and 2.0% for grades X70 and X80, 2.20 for grade > X80.
d. Unless otherwise agreed Cb + V < = .06%.
e. Cb + V + Ti < = .15%.
f. Unless otherwise agreed, .50% max Cu, .30% max Ni, .30% max CR and .15% max Mo.
g. Unless otherwise agreed.
h. Unless otherwise agreed the sum of Cb + V + Ti < = .15%.
i. Unless otherwise agreed .50% max Cu, Ni, Cr and Mo.
j. Unless otherwise agreed .50% max Cu, Cr, Mo and 1.00% max Ni.
k. .004% max B.

Tensile Properties – Tensile Requirements Seamless and Welded Pipe

Specification	Grade	Yield		Tensile		Y/T Ratio
API 5L 44th ed		Min.	Max.	Min.	Max.	Max.
PSL-1	A25	25,400	–	45,000	–	–
	A	30,500	–	48,600	–	–
	B	35,500	–	60,200	–	–
	X42	42,100	–	60,200	–	–
	X46	46,400	–	63,100	–	–
	X52	52,200	–	66,700	–	–
	X56	56,600	–	71,100	–	–
	X60	60,200	–	75,400	–	–
	X65	65,300	–	77,600	–	–
	X70	70,300	–	82,700	–	–
PSL-2	B	35,500	65,300	60,200	110,200	.93
	X42	42,100	71,800	60,200	100,200	.93
	X46	46,400	76,100	63,100	110,200	.93
	X52	52,200	76,900	66,700	110,200	.93
	X56	56,600	79,000	71,100	110,200	.93
	X60	60,200	81,900	75,400	110,200	.93
	X65	65,300	87,000	77,600	110,200	.93
	X70	70,300	92,100	82,700	110,200	.93
	X80	80,500	102,300	90,600	119,700	.93
	X90	90,600	112,400	100,800	132,700	.95
	X100	100,100	121,800	110,200	143,600	.97
	X120*	120,400	152,300	132,700	166,100	.99

*Only available as DSAW

COMPARATIVE SPECIFICATIONS

API 5L Line Pipe

Testing Requirements

Hydrostatic Testing

Lists hydrostatic inspection test pressures for all sizes and grades covered by the specification. Test pressures are held for not less than:

- Seamless (all sizes) – 5 seconds
- Welded (NPS 18 and smaller) – 5 seconds
  (NPS 20 and larger) – 10 seconds

Mechanical Tests

Tensile Test
- Seamless – longitudinal
- ERW – longitudinal and transverse

Charpy Tests – PSL 2

Flattening Test – ERW – All sizes

Number of Tests

Flattening – Non-expanded ERW for single lengths, crop ends from each length; for multiple lengths, crop ends from first and last pipe of each coil, plus 2 intermediate rings.

Tensile –

NPS	On One Length From Each Lot of
5 and smaller	400 or less
6 through 12	200 or less
14 and larger	100 or less

Permissible Variations

Wall Thickness

Seamless: 0.158"–0.983" wall, tolerance = -12.5 % / +15 %
> = 0.984" wall, tolerance = -0.120" / +0.146" or - /+ 10 % whichever is greater
(except if OD is >= 14" & wall is >=.984" then tolerance is -10 /+15%)

HFW: < = 0.197" wall, tolerance = - /+ .020"
= 0.198"–0.590" wall, tolerance = - /+ .10.0%"
≥ 0.591" wall, tolerance = - /+ .060"

Weights per Foot

For Single Lengths Special Plain End and Grade A25 – Not more than plus 10% minus 5%

For Single Lengths Other Pipe – Not more than plus 10% minus 3.5%

For Carload Lots – Not more than minus 1.75%

Note: NPS 4 OD and smaller may be weighed individually or in convenient lots; larger sizes by length

API 5L Line Pipe

Wall, Diameter and Out of Roundness

OD	Diameter Tolerance				Out of Round Tolerance			
	Pipe Body		Pipe Ends		Pipe Body		Pipe Ends	
	SMLS	Welded	SMLS	Welded	SMLS	Welded	SMLS	Welded
< 2.375	- 0.031 / + 0.016		- 0.016 / + 0.063		Included in the diameter tolerance			
2.375 - 6.625	-/+ 0.0075 (D)		- 0.016 / + 0.063		020 (D)		0.015 (D)	
> 6.625 - 24.00	-/+ 0.0075 (D)	-/+ 0.007 5 (D) up to -/+ 0.125	-/+ 0.005 (D) up to -/+ 0.063"		020 (D)		0.015 (D)	

Lengths

Plain End Pipe	Shortest Length in Entire Shipment	Minimum Avg. Length in Entire Shipment	Maximum Length
20' Nominal	9'0"	17'6"	22'6"
40' Nominal	14'0"	35'0"	45'0"
60' Nominal	21'0"	52'6"	65'0"
80' Nominal	28'0"	70'0"	85'0"

Marking Requirements on Each Length

Paint Stenciled or Die Stamped manufacturer's name or mark, Spec 5L, size, weight per foot, grade, process of manufacture, type of steel, length (NPS 4 and larger only). Test pressure when higher than tabulated (NPS 2 and larger only).

Supplemental Annexes

API Specification 5L contains 15 Supplemental Annexes that address special conditions and/or additional requirements.

Annex A Specification for welded jointers
Annex B Manufacturing procedure qualification for PSL 2 pipe
Annex C Treatment of surface imperfections and defects
Annex D Repair welding procedure
Annex E Non-destructive inspection for other than sour service or offshore service
Annex F Requirements for couplings (PSL 1 only)
Annex G PSL 2 pipe with resistance to ductile fracture propagation
Annex H PSL 2 pipe ordered for sour service
Annex I Pipe ordered as "Through the Flowline" (TFL) pipe
Annex J PSL 2 pipe ordered for offshore service
Annex K Non-destructive inspection for pipe ordered for sour service and/or offshore service
Annex L Steel designations
Annex M Correspondence of terminology between ISO 3183 and its source documents
Annex N Identification/Explanation of Deviations
Annex O API Monogram

COMPARATIVE SPECIFICATIONS

API 5L Line Pipe

API Specification 5L PSL 1 and PSL 2 Comparison

Summary of Differences Between PSL1 and PSL2			
Parameter	PSL 1	PSL 2	Reference
Grade Range	L175 or A25 through L485 or X70	L245 or B through L830 or X120	Table 1 Table 2
Grade Suffix	—	R, N, Q or M	Table 2 Footnote b
Type of Pipe Ends	Plain End, Belled End, Threaded, Special Coupling Pipe End	Plain End Only <=0.125"t Square Cut >0.125" 30° Bevel Unless Otherwise Agreed	Table 2, 9.12.1.2 9.12.5, 9.12.5.3
Manufacturing Routes	Not Defined in Detail	Defined in Detail	Table 3
Manufacturing Procedure Qualification	—	If Agreed	7.2 c) 40) Annex B
Resistance to Ductile Fracture	—	If Agreed	7.2 c) 49) Annex G
For Sour Service	—	If Agreed	7.2 c) 50) Annex H
Offshore Pipe	—	If Agreed	7.2 c) 54) Annex J
Steel Making	—	Killed, Fine Grain Practice	8.3.2
Heat Treatment of Weld Seam and the HAZ of HFW Pipe	Simulate Normalizing OR by Agreement Other Methods	Heat Treated so as to Simulate Normalizing	8.8.1 - 8.8.2
Chemical Traceability of Heat Identity	Traceable Only Until All Related Chemical Tests are Performed and Conformance is Shown	Each Length of Pipe Must be Traceable Even After Completion of all Related Chemical Tests and Conformance is Shown	8.13.1 - 8.13.2
Physical Properties Traceability of Unit Identity	Traceable Only Until All Related Mechanical Tests are Performed and Conformance is Shown	Each Length of Pipe Must be Traceable Even After Completion of all Related Mechanical Tests and Conformance is Shown	8.13.1 - 8.13.2
Max C Seamless Pipe N	0.28% for Grades B - X60	0.24% for Grades B - X60	9.2.2, Table 4 & 5
Max C Seamless Pipe Q	0.28% for Grades B - X60	0.18% for Grades B - X60	Table 4 & 5
Max C Welded Pipe M	0.26% for Grades B - X70	0.22% for Grades B - X56 0.12% for Grades 60 - X70	Table 4 & 5
Max Si Seamless Pipe R	—	0.40% for Grades B - X46 0.45% for Grades 52 - X70	Table 4 & 5
Max Si Welded Pipe M	—	0.45% for Grades B - X70	Table 4 & 5
Max Mn Seamless Pipe R	1.30% for Grade X42	1.20% for Grade X42	Table 4 & 5
Max Mn Seamless Pipe N	1.30% for Grade X42	1.20% for Grade X42	Table 4 & 5
Max Mn Seamless Pipe Q	1.20% for Grade B 1.30% for Grade X42 1.40% for Grades X46 - X70	1.40% for Grades B - X42 1.50% for Grades X52 - X56 1.70% for Grades X60 - X70	Table 4 & 5
Max Mn Welded Pipe M	1.40% for Grade X42 1.40% for Grade X60 1.45% for Grade X65 1.45% for Grade X70	1.30% for Grade X42 1.60% for Grade X60 1.60% for Grade X65 1.70% for Grade X70	Table 4 & 5
Max P Seamless Pipe	0.030% for Grade B - X70	0.025% for Grade B - X70	Table 4 & 5
Max P Welded Pipe	0.030% for Grade B - X70	0.025% for Grade B - X70	Table 4 & 5
Max S Seamless Pipe	0.030% for Grade B - X70	0.015% for Grade B - X70	Table 4 & 5
Max S Welded Pipe	0.030% for Grade B - X70	0.015% for Grade B - X70	Table 4 & 5
Max V Seamless Pipe N	—	0.06% for Grade X42 0.07% for Grade X46 0.10% for Grade X52 - X60	Table 4 & 5
Max V Seamless Pipe Q	—	0.05% for Grades B - X52 0.07% for Grades X56	Table 4 & 5
Max V Welded Pipe M	—	0.05% for Grades B - X46	Table 4 & 5
Max Nb Seamless Pipe N	—	0.05% for Grades X42 - X60	Table 4 & 5
Max Nb Seamless Pipe Q	—	0.05% for Grades B - X56	Table 4 & 5
Max Nb Welded Pipe M	—	0.05% for Grades B - X46	Table 4 & 5
Max Ti Seamless Pipe N	—	0.05% for Grades B - X60	Table 4 & 5
Max Ti Seamless Pipe Q	—	0.04% for Grades B - X56	Table 4 & 5
Max Ti Welded Pipe M	—	0.04% for Grades B - X46	Table 4 & 5

Outside Diameter NPS [inches]	Wall			Weight		Grade	Specified Minimum Strength [psi]		Mill Hydrostatic Test Pressure [psi]		Ultimate Burst [psi]
	Inches	Schedule Number	Class	lb/ft Plain End	Tons/ Mile		Yield	Tensile	Standard	Alternate	
OD 8.625											
NPS 8 OD 8.625 Seamless	0.594	100		51.00	134.63	X52	52,200	66,700	3,000	5,390	9,190
	0.594	100		51.00	134.63	X56	56,600	71,100	3,000	5,850	9,790
	0.594	100		51.00	134.63	X60	60,200	75,400	3,000	6,220	10,390
	0.594	100		51.00	134.63	X65	65,300	77,600	3,000	6,750	10,690
	0.594	100		51.00	134.63	X70	70,300	82,700	3,000	7,260	11,390
	0.594	100		51.00	134.63	X80	80,500	90,600	3,000	7,260	12,480
	0.625			53.45	141.11	B	35,500	60,200	2,800	2,800	8,720
	0.625			53.45	141.11	C	40,000	70,000	2,800		10,140
	0.625			53.45	141.11	X42	42,100	60,200	3,000	4,580	8,720
	0.625			53.45	141.11	X46	46,400	63,100	3,000	5,040	9,140
	0.625			53.45	141.11	X52	52,200	66,700	3,000	5,670	9,670
	0.625			53.45	141.11	X56	56,600	71,100	3,000	6,150	10,300
	0.625			53.45	141.11	X60	60,200	75,400	3,000	6,540	10,930
	0.625			53.45	141.11	X65	65,300	77,600	3,000	7,100	11,250
	0.625			53.45	141.11	X70	70,300	82,700	3,000	7,260	11,990
	0.625			53.45	141.11	X80	80,500	90,600	3,000	7,260	13,130
	0.719	120		60.77	160.42	B	35,500	60,200	2,800	2,800	10,040
	0.719	120		60.77	160.42	C	40,000	70,000	2,800		11,670
	0.719	120		60.77	160.42	X42	42,100	60,200	3,000	5,260	10,040
	0.719	120		60.77	160.42	X46	46,400	63,100	3,000	5,800	10,520
	0.719	120		60.77	160.42	X52	52,200	66,700	3,000	6,530	11,120
	0.719	120		60.77	160.42	X56	56,600	71,100	3,000	7,080	11,850
	0.719	120		60.77	160.42	X60	60,200	75,400	3,000	7,260	12,570
	0.719	120		60.77	160.42	X65	65,300	77,600	3,000	7,260	12,940
	0.719	120		60.77	160.42	X70	70,300	82,700	3,000	7,260	13,790
	0.719	120		60.77	160.42	X80	80,500	90,600	3,000	7,260	15,110
	0.812	140		67.82	179.04	B	35,500	60,200	2,800	2,800	11,340
	0.812	140		67.82	179.04	C	40,000	70,000	2,800		13,180
	0.812	140		67.82	179.04	X42	42,100	60,200	3,000	5,950	11,340
	0.812	140		67.82	179.04	X46	46,400	63,100	3,000	6,550	11,880
	0.812	140		67.82	179.04	X52	52,200	66,700	3,000	7,260	12,560
	0.812	140		67.82	179.04	X56	56,600	71,100	3,000	7,260	13,390
	0.812	140		67.82	179.04	X60	60,200	75,400	3,000	7,260	14,200
	0.812	140		67.82	179.04	X65	65,300	77,600	3,000	7,260	14,610
	0.812	140		67.82	179.04	X70	70,300	82,700	3,000	7,260	15,570
	0.812	140		67.82	179.04	X80	80,500	90,600	3,000	7,260	17,060
	0.875		XXS	72.49	191.38	B	35,500	60,200	2,800	2,800	12,210
	0.875		XXS	72.49	191.38	C	40,000	70,000	2,800		14,200
	0.875		XXS	72.49	191.38	X42	42,100	60,200	3,000	6,410	12,210
	0.875		XXS	72.49	191.38	X46	46,400	63,100	3,000	7,060	12,800
	0.875		XXS	72.49	191.38	X52	52,200	66,700	3,000	7,260	13,530
	0.875		XXS	72.49	191.38	X56	56,600	71,100	3,000	7,260	14,430
	0.875		XXS	72.49	191.38	X60	60,200	75,400	3,000	7,260	15,300
	0.875		XXS	72.49	191.38	X65	65,300	77,600	3,000	7,260	15,740

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Appendix (2): Different Impressed Current Anodes Properties

The represented data in this section is taken from: "Impressed Current Cathodic Protection, Section Two, Cathodic Protection Co. Limited, Venture Way, Grantham, Lincs NG31 7XS UK. Tel: +44 (0)1476 590666 Fax: +44 (0)1476 570605, Email: cpc@cathodic.co.uk Website: www.cathodic.co.uk, Registered Office: Minalloy House, Regent Street, Sheffield S1 3NJ, UK VAT No.116 8408 71, Reg'd in England No. 478098"

IMPRESSED CURRENT CATHODIC PROTECTION DATASHEET 2.1.1

SILICON IRON ROD ANODES

REVISION 1

APPLICATION

Marine Structures, Seawater Intakes, Deepwell Groundbeds, Horizontal Groundbeds, Distributed Anodes, Tank Internals & Tank Bottoms. Suitable For Use In Soils, Mud, Carbonaceous & Petroleum Coke Backfill; Fresh, Brackish and Sea Water.

SILICON IRON ANODE DATA

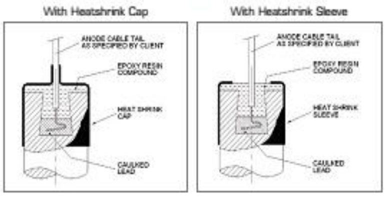
CHEMICAL COMPOSITION

	Normal	Chrome
Silicon	14.50%	14.50%
Manganese	0.75%	0.75%
Carbon	0.85%	0.95%
Chromium	-	4.50%
Iron	Remainder	Remainder

CONSUMPTION RATES

Typical Rates	
Normal Alloy	0.5 kg/Amp/year
Chrome Alloy	0.2 kg/Amp/year

CABLE CONNECTION



Anode/Cable Connection : Connection less than 0.001 Ohm

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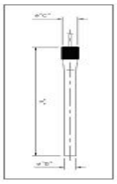
DATASHEET 2.1.1

SILICON IRON ROD ANODES

REVISION 1

CABLE TYPES

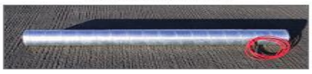
Available cable types include : XLPE/PVC, HMWPE, PVDF(Kynar), XLPE/PVC/SWA/PVC, EPR/CSPE



STANDARD ANODE TYPES AND WEIGHTS

Type	A	B	C	Surface Area		Approx Wt	
	(in)	(in)	(in)	(m^2)	(ft^2)	(kg)	(lbs)
36/2.0	36	2.0	3.0	0.16	1.70	14.50	32
36/2.5	36	2.5	3.5	0.20	2.1	22.30	49
36/3.0	36	3.0	4.0	0.23	2.50	31.40	69
48/2.0	48	2.0	3.0	0.20	2.20	19.10	42
48/2.5	48	2.5	3.5	0.25	2.70	28.60	63
48/3.0	48	3.0	4.0	0.30	3.30	40.90	90
60/2.0	60	2.0	3.0	0.25	2.70	22.70	50
60/2.5	60	2.5	3.5	0.32	3.40	35.90	79
60/3.0	60	3.0	4.0	0.38	4.0	50.00	110
60/4.5	60	4.5	4.5	0.55	5.90	99.10	218

CANISTERED ANODES



Standard Sizes	Standard Gauges
150mmDia x 1500mm L	1.0mm 20bg
200mmDia x 2000mm L	1.2mm 18bg
250mmDia x 2000mm L	1.5mm 18bg
300mmDia x 2000mm L	2.0mm 14bg

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SILICON IRON TUBULAR ANODES

REVISION 1

APPLICATION

Marine Structures, Seawater Intakes, Deepwell Groundbeds, Horizontal Groundbeds, Distributed Anodes, Tank Internals & Tank Bottoms (not recommended for large diameter tanks). Suitable For Use In Soils, Mud, Carbonaceous & Pet Coke Backfill; Fresh, Brackish and Sea Water

SILICON IRON TUBULAR ANODE DATA

CHEMICAL COMPOSITION

Silicon Iron ASTM A518 – 86 Grade 3

Silicon	14.20 – 14.75%
Manganese	1.50% Max
Carbon	0.75 – 1.15%
Chromium	3.25 – 5.00%
Copper	0.50% Max
Molybdenum	0.20%Max
Iron	Remainder

TECHNICAL DATA

Tensile Strength (1/2"Dia bar)	15,000 psi
Compressive Strength	100,000 psi
Brinell Hardness	520 bhn
Density	7.0 gr/ml
Melting Point	2,300 °F

Consumption Rate	Typical rates – Chrome: 0.2kg/A/yr For CP design a current density of not more than 30A/m^2 of anode surface is recommended
Anode/Cable Connection	Centre connection less than 0.001 Ohm resin encapsulated
Cable Types	XLPE/PVC, HMWPE, PVDF(Kynar); XLPE/PVC/SWA/PVC, EPR/CSPE

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IMPRESSED CURRENT CATHODIC PROTECTION — DATASHEET 2.1.2

SILICON IRON TUBULAR ANODES

REVISION 1

STANDARD ANODE TYPES, WEIGHTS, DIMENSIONS AND OUTPUTS

Type	Average Wt		Approx Area		Outside Dia		Inside Dia		Length		Nominal Discharge Amps
	lbs	kgs	ft²	m²	mm	in	mm	in	mm	in	
MS-1	31	14.1	2.4	0.2	71	2.8	45.7	1.8	1067	42	1.5-2.0
MS-2	46	20.9	4.0	0.4	58	2.3	35.6	1.4	2134	84	3.0-4.0
MS-3	63	28.6	4.9	0.5	71	2.8	45.7	1.8	2134	84	3.5-5.0
MS-4	85	39.2	6.9	0.6	96	3.8	74.4	2.9	2134	84	6.0-7.0
MS-5	110	49.9	8.7	0.8	124	4.9	99.0	3.9	2134	84	6.0-8.5

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IMPRESSED CURRENT CATHODIC PROTECTION — DATASHEET 2.2.1

MIXED METAL OXIDE TUBULAR ANODES

REVISION 1

APPLICATION

Marine Structures, Seawater Intakes, Deepwell Groundbeds, Horizontal Groundbeds, Distributed Anodes, Tank Internals & Tank Bottoms Suitable For Use In Soils, Mud, Carbonaceous & Pet Coke Backfill; Fresh, Brackish and Sea Water

TUBULAR MMO ANODE DATA

Substrate: Titanium ASTM B338 Grade 1 or 2

Coating: IrO_2/Ta_2O_5

Coating Method: Multi pass thermal decomposition of precious metal salts technique

Diameter: 25.4mm

Wall Thickness: 0.90mm

Consumption Rate: 0.5 - 4.0 mg/A/yr depending upon CP application conditions

Utilisation Factor: Dimensionally Stable

Working Environment: Suitable for Cl_2 & O_2 or combination of both

Operating Characteristics:

Environment	Max Current Density (A/m²)	Life (Years)
Carbonaceous Backfill	50	20
Calcined Petroleum Coke	100	20
Freshwater	100	20
Brackish Water	100-300	20
Seawater	600	20

Coating loading can be adjusted for specific lifetime/current density requirement

Cable Types: HMWPE/PVDF(Kynar); XLPE/PVC/SWA/PVC; EPR/CSPE

Maximum 1Cx50mm²

Anode/Cable Connection: Centre connection less than 0.001 Ohm, resin encapsulated & helium tested to prove effective seal

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MIXED METAL OXIDE TUBULAR ANODES

REVISION 1

STANDARD ANODE TYPES, DIMENSIONS AND OUTPUTS

Type	OD		Length		Current Output (Typical)	Current Output (Typical)
Soil (with carbon backfill)	mm	inches	mm	inches	(Amps from 5-70°C)	(Amps from 0-5°C)
S-2.5/50	25	1	500	19.7	4	2
S-2.5/100	25	1	1000	39.4	8	4
Fresh Water						
FW-2.5/50	25	1	500	19.7	4	2
FW-2.5/100	25	1	1000	39.4	8	4
Sea Water						
SW-2.5/50	25	1	500	19.7	25	5
SW-2.5/100	25	1	1000	39.4	50	10
Mud (*)						
M-2.5/50	25	1	500	19.7	2 - 4	1.5
M-2.5/100	25	1	1000	39.4	4 - 8	3
Brackish Water (**)					(Amps from 10-70°C)	(Amps from 0-10°C)
BW-2.5/50	25	1	500	19.7	4÷12	2÷6
BW-2.5/100	25	1	1000	39.4	8÷24	4÷12

(*) Current outputs in mud depend on site conditions (sea mud or river mud, etc)
(**) Current outputs in brackish water depend on site conditions & chloride concentrations.

NOTES

- Coating loading may be adjusted to suit a particular current density or design life
- Standard anodes are designed for 20 year life, however, design life of up to 50 years can be catered for.
- Tubular MMO anode strings can be supplied to Clients specific requirements.
- Other tube diameters are available on request, 16mm dia & 32mm dia.

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MIXED METAL OXIDE RIBBON ANODES

REVISION 1

APPLICATION

Reinforced Concrete Structures & Tank Bottoms

STANDARD ANODE TYPES, DIMENSIONS AND OUTPUTS

APPLICATION	Sand & Concrete
RIBBON MMO DATA	
Substrate	Titanium ASTM B338 Grade 1
Coating	IrO_2/Ta_2O_5
Coating Method	Multi pass thermal decomposition of precious metal salts technique
Width (Nom) Thickness (Nom) Standard Coil Length Standard Coil Weight	0.25" (6.35mm) 0.025" (0.635mm) 250' (76.22m) 2.5lbs (1.12kg)
Surface Area of Ribbon Consumption Rate	0.014m²/m 0.5 - 4.0 mg/A/yr depending upon CP application conditions
Utilisation Factor	Dimensionally Stable
Working Environment	Suitable for Cl_2 & O_2 or combination of both
Operating Characteristics	CURRENT OUTPUT IN FINE SAND 12.8mA/ft (42mA/m) when operating at a current density of 0.278A/ft² (3A/m²). 50 year design life when operating at a current density of 0.278A/ft² (3A/m²). CURRENT OUTPUT IN CONCRETE 0.45mA/ft (1.5mA/m) when operating at a current density of 10.19mA/ft² (110A/m²). 100 year design life when operating at a current density of 10.19mA/ft² (110A/m²).
Titanium Conductor Bar	Width: 0.50" (12.7mm); Thickness: 0.035" (0.9mm) Coil length: 250' (76.22m); Coil Weight: 8.5lbs (3.8kg)
Substrate	Titanium ASTM B 265 Grade 1

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MIXED METAL OXIDE WIRE ANODES

REVISION 1

APPLICATION

Tank Bottoms, Tank Internals, Pipeline Internals, Canistered Anodes, Continuous Horizontal Groundbeds, Discontinuous Horizontal Groundbeds, Shallow Vertical Groundbeds, Deep Anode Groundbeds.

STANDARD ANODE TYPES, DIMENSIONS AND OUTPUTS

Available in two standard sizes, with two standard current ratings. Other sizes and rating are available upon request.

MMO Wire Anode consists of solid titanium wire which meets ASTM B348 Grade 1 or 2 standards, that has been coated with Mixed Metal Oxide.

WIRE ANODES ELECTRICAL RESISTANCE

1.5mm diameter : 75,537 microhms/ft / 247,821 microhms/m
3.0mm diameter : 18,884 microhms/ft / 61,954 microhms/m

Approximate electrical resistance @ 25°C. Mechanical properties are based on typical room temperature.

PIGGYBACK WIRE ANODE SYSTEMS

For use on pipelines, the product comprises Mixed Metal Oxide Wire Anode material "piggybacked" to a cable at predetermined intervals (to aid current distribution and attenuation). The wire and cable is contained within a cotton sock filled with calcined petroleum coke breeze backfill. The Piggyback Sock Anode is placed alongside the pipeline with suitable lengths of cable at each end of the loop allowed for termination into a junction box.

PIGGYBACK WIRE SOCK ANODE SYSTEMS

For use on pipelines, the product comprises Mixed Metal Oxide Wire Anode material "piggybacked" to a cable at predetermined intervals (to aid current distribution and attenuation). The wire and cable is contained within a cotton sock filled with calcined petroleum coke breeze backfill. The Piggyback Sock Anode is placed alongside the pipeline with suitable lengths of cable at each end of the loop allowed for termination into a junction box.

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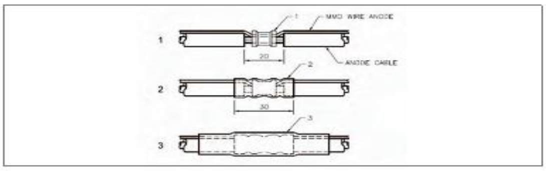
IMPRESSED CURRENT CATHODIC PROTECTION DATASHEET 2.2.3

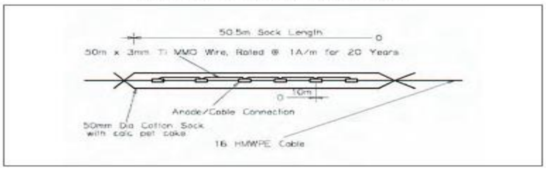
MIXED METAL OXIDE WIRE ANODES

REVISION 1

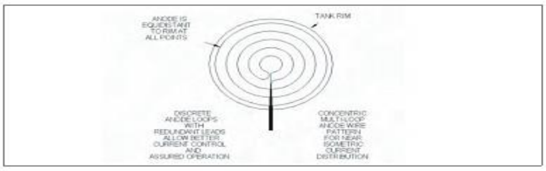
TYPICAL CABLE TO WIRE SPLICED CONNECTION



TYPICAL WIRE SOCK ANODE ARRANGEMENT



TYPICAL CONCENTRIC PATTERN WIRE ANODE ARRANGEMENT



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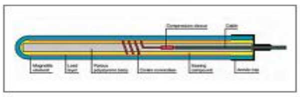
MAGNETITE ANODES

APPLICATION

Magnetite is a natural mineral with a high corrosion resistance making it an excellent anode material. The anodes are cast cylindrical and hollow. Cables are centre connected to give a uniform dissipation of current from the anode surface. The anode to cable connection is electrically sealed with a dielectric compound and an anode cap.
Suitable for use in Horizontal Groundbeds, Deep Well Groundbeds, Fresh Water Installations, Seawater Installation

MAGNETITE ANODE DATA



Specific gravity	4.7–4.8	kg/dm3
Brinell hardness (WB5/187.5/15)	344	
Bending strength	5	kN/cm2
Density	4,71	g/cm3
Melting point	1500	°C
Coefficient of linear expansion	6.4x10-6	1/°C (0-100°C)
Consumption rate	0.02	kg/A year
Current density (1)	0.70	mA/dm2
Efficiency	90%	

(1) depends on environment

CHEMICAL COMPOSITION

FeO	28 - 32%
Fe3O4	60 - 64%
Balance	4 - 12%

IMPRESSED CURRENT CATHODIC PROTECTION DATASHEET 2.3.1

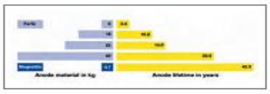
MAGNETITE ANODES

REVISION 1

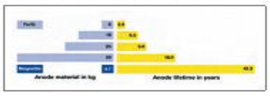
EXPERIENCE

Lifetime comparison - Basis: anode current load 5 A

CHLORINE CONTAINING SOIL

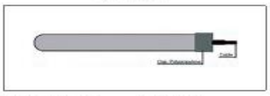


SEAWATER AND DEEP GROUNDBEDS



STANDARD ANODE TYPES WEIGHTS AND OUTPUTS

TYPE MA-U

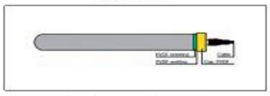


Surrounding electrolyte: neutral soil and water without chlorine and sulfate content

Applications: shallow groundbeds, deep groundbeds

Diameter	60	mm
Total length	720	mm
Effective length	670	mm
Total weight	6.0	kg
Min. effective mass	4.7	kg
Surface area	13.4	dm²
Max. current load	3.0	A

TYPE MA-CS



Surrounding electrolyte: chlorine and/or sulfate containing soil or stagnant water

Applications: shallow groundbeds, deep groundbeds

Diameter	60	mm
Total length	720	mm
Effective length	670	mm
Total weight	6.0	kg
Min. effective mass	4.7	kg
Surface area	13.4	dm²
Max. current load	6.0	A

DATASHEET 2.3.1
Venture Way, Grantham, Lincs NG31 7XS UK. Tel: +44 (0)1476 590666 Fax: +44 (0)1476 570605
Email: cpc@cathodic.co.uk Website: www.cathodic.co.uk
Registered Office: Minalloy House, Regent Street, Sheffield S1 3NJ, UK VAT No. 116 8408 71, Reg'd in England No. 478098

MAGNETITE ANODES

REVISION 1

STANDARD ANODE TYPES WEIGHTS AND OUTPUTS

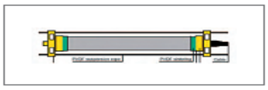
TYPE MA-SEA

Surrounding electrolyte: flowing seawater or brackish water

Applications: platforms, jetties, harbours

Diameter	60	mm
Total length	760	mm
Effective length	710	mm
Total weight	6.0	kg
Min. effective mass	4.7	kg
Surface area	13.4	dm²
Max. current load	16.0	A

TYPE MA-CHAIN

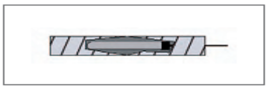


Surrounding electrolyte: chlorine containing soil or stagnant water

Applications: deep groundbeds open hole, deep groundbeds closed hole, water tank

Diameter	60	mm
Total length	740	mm
Effective length	600	mm
Total weight	6.2	kg
Min. effective mass	4.7	kg
Surface area	11.3	dm²
Max. current load (groundbeds)	6.0	A
Max. current load (tanks)	16.0	A

CANISTER FOR MA-U & MA-CS



COKE BACKFILL	
Minimum carbon content	90%
Maximum moisture content	5%
Maximum resistivity	1Ωm
Density	700-950 kg/m³
Particle size (dia.)	20 mm max.

Standard canister	Diameter (mm)	Length (mm)	Total weight (kg)
CAN 10	160	1000	22
CAN 15	300	1500	85
CAN 20	300	2000	110

GRAPHITE ANODES

REVISION 1

APPLICATION

Plain graphite anodes are used in dry soil conditions installed in groundbeds containing compacted carbonaceous backfill. Linseed oil impregnated anodes can be used in moist saline soils, in fresh and brackish water, and for seawater applications. Graphite anodes can be installed as horizontal or deepwell groundbeds to protect buried pipelines or due to their lightweight nature they can be suspended into the electrolyte to protect water tank internal surfaces or marine structures.

GRAPHITE ANODE DATA

Cathodic Protection Co Ltd graphite anodes are manufactured in two standard sizes - 3" dia up to 60" long & 4" dia up to 80" long. There are two types of graphite anodes - plain & linseed oil impregnated. Plain graphite anodes are used for ordinary soil conditions and linseed oil impregnated anodes are usually used for saline soil or seawater environments.

CONSUMPTION RATES

Environment	Current Density Amps/M²	Consumption Rate kg/Amp/Year
Fresh Water	2.5 - 3	0.1 - 0.3
Sea Water	10	0.3 - 0.5
Carbonaceous Backfill	10	0.1 - 0.3

GRAPHITE ANODES

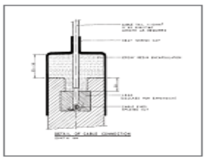
TYPICAL CHARACTERISTICS

Properties	gm/cm^2	Plain graphite	Impregnated graphite
Bulk density	gm/cm^3	1.55	1.65
Porosity	H_2O%	30	19
Flexural strength	N/mm^2	15	20
Compressive strength	N/mm^2	19	44
Electrical[1]	Ωμm	7.5	14
Resistivity[2]		12	20
Thermal conductivity	W/mk	198 116	38 35
Mean linear thermal coefficient of expansion	l/k	0.9 2.7	1.9 3.2
Ash	%	<0.5	<0.5

[1] parallel to grain structure
[2] perpendicular to grain structure

ANODE TO CABLE CONNECTION

Cable for Graphite Anodes is supplied according to customer requirements. We can offer the following insulation and sheathing types PVC. XLPE/PVC, HMWPE, KYNAR, HALAR, EPR/CSPE.



PLATINISED TITANIUM ANODES

APPLICATION

- Underwater steel structures - Wharves, jetties, sheet pile walls and piers. Usually rod type anodes distributed throughout the structure to be protected to give a good overall protective current distribution. Anodes should be installed in areas not liable to cause Anode damage i.e. out of the way of berthing vessels, mooring ropes, chains etc.
- Exterior protection of ships hulls - anodes in the shape of plates, discs or strips. Housed in chlorine resistant plastic as the anode operates at high current densities in seawater which produces chlorine.
- Water tank internal protection - usually distributed rod anodes are used for this type of installation by suspending from the tank roof.
- Internal protection of plant - large diameter water pipelines such as cooling water can be protected using rod or wire shaped anodes.

PLATINISED TITANIUM ANODE DATA

Platinised Titanium anodes are manufactured from a commercially pure titanium substrate plated with a very thin coating of platinum. The titanium serves simply as the anode body and the conductor, the active anode element being the platinum coating.

The usual thickness of the platinum coating is approximately 2.5 microns, however, this coating thickness should be increased to 5.0 microns for harsher environments. The base metal is available in a wide variety of standard shapes - rods, tubes, mesh, etc - which can be fabricated into non-metallic mounts for attachment to the structure to be cathodically protected.

The thickness of the platinum coating and the current density at which the anode is operated determine the useful life of the anode. The maximum voltage at the anode to electrolyte interface should not exceed 8 Volts in electrolytes containing chloride as voltages greater than this value could cause local corrosion on any unplatinised portions of the anode.

Platinised titanium anodes should not be used in electrolytes containing fluoride as titanium oxide dissolves in fluoride. Anodic passivation does not protect the titanium substrate in such electrolytes.

The advantage of platinised titanium anodes is that they can be operated at high current densities with very low consumption rates.

PLATINISED TITANIUM ANODES

REVISION 1

CURRENT DENSITY AND CONSUMPTION RATES

Max current density A/dm^2	30
Usual current density A/dm^2	1.0 - 10.0
Consumption rate g/A/yr	0.01 (at current density 5.50A/dm^2)

FEATURES

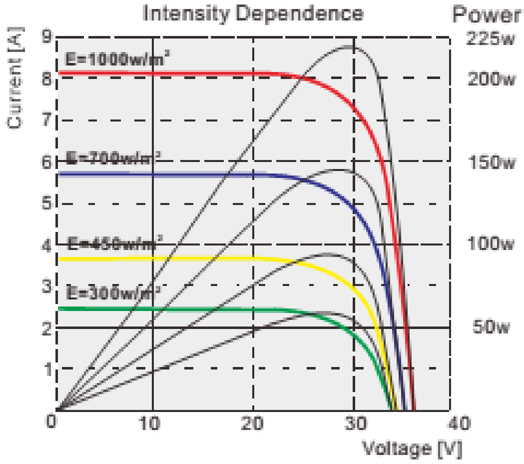
- Anodes can work at high current densities without decomposition or dissolving.
- Favourable strength to weight ratio.
- Anodes can be smaller and more compact than comparable conventional anodes.
- Can be manufactured in a wide variety of shapes and sizes.
- Lightweight support tube installation for Pt Ti anode installation.

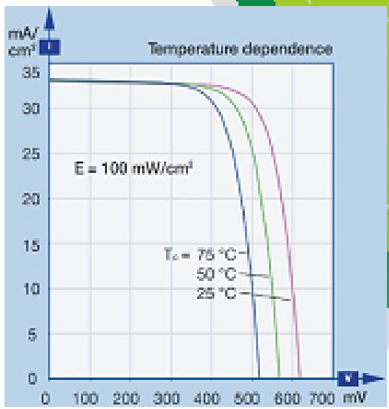
ANODE INSTALLATION EXAMPLES

Venture Way, Grantham, Lincs NG31 7XS UK. Tel: +44 (0)1476 590666 Fax: +44 (0)1476 570605
Email: cpc@cathodic.co.uk Website: www.cathodic.co.uk
Registered Office: Minalloy House, Regent Street, Sheffield S1 3NJ, UK VAT No. 116 8408 71, Reg'd in England No. 478098

Appendix (3): 240 W and 50 W PV Modules Datasheets

Datasheet of 240 W Module





SPECIFICATION	P630-210W	P630-220W	P630-230W	P630-240W
Max Power (Pmax)	210W	220W	230W	240W
Open circuit voltage (Voc)	36.36	36.66	37.02	36.90
Short circuit current (Isc)	7.89	8.09	8.34	8.46
Voltage at max power (Vmp)	29.0	29.2	29.6	30.6
Current at max power (Imp)	7.25	7.53	7.79	7.96
Efficiency: Cell / Module (%)	14.8 / 12.9	15.2 / 13.5	15.8 / 14.2	16.6 / 14.8
Module Technology	Glass-foil-laminate with aluminum frame			
Module Design	High transparent solar glass (tempered), 3.2mm			
	Encapsulation :EVA-Solar Cell-EVA			
Type of Solar Cells	Poly-crystalline solar cells, 156 x 156mm			
Array	6 x 10			
Dimensions (LxWxH)mm	993 x 1635 x 40			
Weight kg	20			
Temperature Coefficients (max.)	Pmax : -0.41% /°C // Voc : -0.36% /°C // Isc : +0.046% /°C			
Operating Temperature	-40 ~ +80 °C			
Ambient Temperature Range	-40 ~ +45 °C			
Qualification	Comply with IEC 61215 / IEC 61730			

* Specifications are for reference only, and are subjected to changes due to technology advancements from time to time.

IEC61215, IEC61730 accredited for : RS-P618-130W, RS-P624-190W, RS-P630-220W, RS-P636-270W series

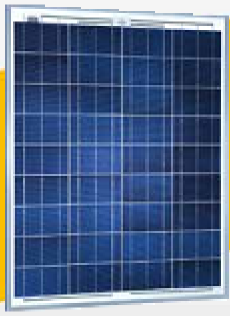
Warranty	
5 years	product quality limited warranty
10 years	90% power limited warranty
25 years	80% power limited warranty

RED SUN ENERGY
JOINT STOCK COMPANY

Office : 17 Phan Phu Tien, District 5, Hochiminh City, Vietnam
Factory : C2 Duc Hoa Ha Ind. Park, Duc Hoa, Long An, Vietnam
Tel: (84-8) 626 11 071 Fax: 626 11 072 www.redsun-solar.com

P618-105~120W-1111

Datasheet of 50 W Module



Length	26.77 in (680 mm)
Width	26.77 in (680 mm)
Height	1.34 in (34 mm)
Frame	Aluminum
Weight	5.6 kg

ÖKO-TEST
LIFE WORTH LIVING
SolarWorld
Sunmodule Plus
SW 225 poly
excellent
issue 05/2010

Sunmodule®
SW 50 poly RMA

World class quality
SolarWorld produces the best products with the highest quality, manufactured according to German and US quality standards in fully-automated ISO 9001 and 14001 certified factories.

Outstanding products
SolarWorld's modules were assessed by the ÖKO-TEST consumer magazine as "excellent".

An experienced industry leader
With over 30 years of experience in off-grid solar applications – SolarWorld delivers top products and technical experience at the highest levels. Our modules are installed in over 100,000 Telecom/Industrial systems worldwide. Nobody else comes close.

SOLARWORLD
We turn sunlight into power.

www.solarworld-usa.com

Sunmodule®
SW 50 poly RMA

SW-01-5050US 07-2011

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

		SW 50
Maximum power	P_{max}	50 Wp
Open circuit voltage	U_{oc}	22.1 V
Maximum power point voltage	U_{mpp}	18.2 V
Short circuit current	I_{sc}	2.95 A
Maximum power point current	I_{mpp}	2.75 A

*STC: 1000W/m², 25°C, AM 1.5

PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 50
Maximum power	P_{max}	35.9 Wp
Open circuit voltage	U_{oc}	19.8 V
Maximum power point voltage	U_{mpp}	16.3 V
Short circuit current	I_{sc}	2.38 A
Maximum power point current	I_{mpp}	2.20 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200W/m², 95% (+/-3%) of the STC efficiency (1000 W/m²) is achieved.

COMPONENT MATERIALS

Cells per module	36
Cell type	Poly crystalline
Cell dimensions	2.44 in x 6.14 in (62 mm x 156 mm)
Front	tempered glass (EN 12150)

SYSTEM INTEGRATION PARAMETERS

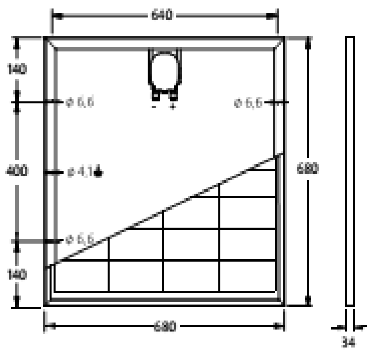
Maximum system voltage SC II	1000 V
Maximum reverse current	12 A
Increased snowload acc. to IEC 61215	5.4 kN/m²
Number of bypass diodes	2

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.034 %/K
TC U_{oc}	-0.34 %/K
TC P_{mpp}	-0.48 %/K

ADDITIONAL DATA

Power tolerance	+/- 10 %
Junction box	IP65
Maximum outer cable diameter	0.31 in (7.8 mm)
Maximum wire cross section	4 mm²



- Qualified, IEC 61215
- Safety tested, IEC 61730
- Periodic Inspection

SolarWorld AG reserves the right to make specification changes without notice. This data sheet complies with the requirements of EN 50380.

Appendix (4): Classic Solar Batteries Datasheet

GNB
INDUSTRIAL POWER
A Division of Exide Technologies

Industrial Batteries / Network Power

Classic Solar

»Powerful energy storage for renewable energy systems«

Classic

GNB Industrial Power

Industrial Batteries

The powerful range of Network Power

Energy storage solutions for critical systems that require uninterrupted power supply. GNB® Industrial Power offers powerful batteries for your individual needs. The below table is only indicative and depends on customers' specific applications. For more information please ask a GNB sales representative.

Applications	Battery ranges																			
	Sonnenschein							Marathon		Sprinter			Absolyte	Powerfit	Classic					
	A400/ A600	A400 FT	A500	A700	SOLAR	RAIL	Power Cycle	M - FT	M/L/ XL	S	P/XP	XP - FT	GP/GX	S300	GRoE	OCSM	OPzS	Energy Bloc/OGi	Solar	rail
Telecom	●	●	●	●			●	●	●	●		●	●			●	●	●		
UPS		●	●	●			●	●	●	●	●	●	●			●		●		
Emergency lighting	●		●						●		●	●		●			●	●		
Security	●		●	●							●	●		●		●	●			
Utility	●	●		●			●	●	●	●			●		●	●	●	●		
Railways	●	●	●	●		●	●	●	●	●			●			●		●		●
Photovoltaic					●		●						●						●	
Universal	●	●	●	●			●	●	●	●	●	●	●	●		●	●	●		

The GNB Network Power brand overview

ABSOLYTE · Marathon · Sprinter · Powerfit

- VRLA batteries (Valve Regulated Lead Acid) in which the electrolyte is fixed in an absorbent glass mat (AGM)
- Excellent high current capability
- Very economical
- Maintenance-free (no topping up)

Sonnenschein

- VRLA batteries (Valve Regulated Lead Acid) in which the electrolyte is fixed in a gel (dryfit technology)
- Inventor of Gel technology
- Highest reliability, even in non-optimal conditions
- Particularly suitable for cyclic applications
- Maintenance-free (no topping up)

Classic

- Conventional lead-acid batteries with liquid electrolyte
- Extreme reliability, proven over decades
- Low maintenance

- Further information about service is available on page 10

Classic OPzS Solar

Technical data

Technical characteristics and data

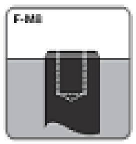
Type	Part number	Nom. voltage V	Nominal capacity C_{120} 1.85 Vpc 25 °C Ah	Length (l) max. mm	Width (b/w) max. mm	Height* (h) max. mm	Installed length (L) max. mm	Weight incl. acid approx. kg	Weight acid** approx. kg	Internal resistance mOhm	Short circuit current A	Terminal	Pole pairs
OPzS Solar 190	NVSL020190WC0FA	2	190	105	208	395	115	13.7	5.20	1.45	1400	F-M8	1
OPzS Solar 245	NVSL020245WC0FA	2	245	105	208	395	115	15.2	5.00	1.05	1950	F-M8	1
OPzS Solar 305	NVSL020305WC0FA	2	305	105	208	395	115	16.6	4.60	0.83	2450	F-M8	1
OPzS Solar 380	NVSL020380WC0FA	2	380	126	208	395	136	20.0	5.80	0.72	2850	F-M8	1
OPzS Solar 450	NVSL020450WC0FA	2	450	147	208	395	157	23.3	6.90	0.63	3250	F-M8	1
OPzS Solar 550	NVSL020550WC0FA	2	550	126	208	511	136	26.7	8.10	0.63	3250	F-M8	1
OPzS Solar 660	NVSL020660WC0FA	2	660	147	208	511	157	31.0	9.30	0.56	3650	F-M8	1
OPzS Solar 765	NVSL020765WC0FA	2	765	168	208	511	178	35.4	10.8	0.50	4100	F-M8	1
OPzS Solar 985	NVSL020985WC0FA	2	985	147	208	686	157	43.9	13.0	0.47	4350	F-M8	1
OPzS Solar 1080	NVSL021080WC0FA	2	1080	147	208	686	157	47.2	12.8	0.43	4800	F-M8	1
OPzS Solar 1320	NVSL021320WC0FA	2	1320	212	193	686	222	59.9	17.1	0.30	6800	F-M8	2
OPzS Solar 1410	NVSL021410WC0FA	2	1410	212	193	686	222	63.4	16.8	0.27	7500	F-M8	2
OPzS Solar 1650	NVSL021650WC0FA	2	1650	212	235	686	222	73.2	21.7	0.26	7900	F-M8	2
OPzS Solar 1990	NVSL021990WC0FA	2	1990	212	277	686	222	86.4	26.1	0.23	8900	F-M8	2
OPzS Solar 2350	NVSL022350WC0FA	2	2350	212	277	836	222	108	33.7	0.24	8500	F-M8	2
OPzS Solar 2500	NVSL022500WC0FA	2	2500	212	277	836	222	114	32.7	0.22	9300	F-M8	2
OPzS Solar 3100	NVSL023100WC0FA	2	3100	215	400	812	225	151	50.0	0.16	12800	F-M8	3
OPzS Solar 3350	NVSL023350WC0FA	2	3350	215	400	812	225	158	48.0	0.14	14600	F-M8	3
OPzS Solar 3850	NVSL023850WC0FA	2	3850	215	490	812	225	184	60.0	0.12	17000	F-M8	4
OPzS Solar 4100	NVSL024100WC0FA	2	4100	215	490	812	225	191	58.0	0.11	17800	F-M8	4
OPzS Solar 4600	NVSL024600WC0FA	2	4600	215	580	812	225	217	71.0	0.11	18600	F-M8	4
OPzS Solar 280	NVSL060280WC0FB	6	294	272	206	347	282	41.0	13.0	2.68	2283	F-M8	1
OPzS Solar 350	NVSL060350WC0FB	6	364	380	206	347	392	56.0	20.0	2.39	2600	F-M8	1
OPzS Solar 420	NVSL060420WC0FB	6	417	380	206	347	392	63.0	20.0	1.96	3106	F-M8	1
OPzS Solar 70	NVSL120070WC0FB	12	82.7	272	206	347	282	35.0	15.0	18.1	688	F-M8	1
OPzS Solar 140	NVSL120140WC0FB	12	139	272	206	347	282	45.0	14.0	9.26	1314	F-M8	1
OPzS Solar 210	NVSL120210WC0FB	12	210	380	206	347	392	64.0	19.0	6.46	1884	F-M8	1

Type	C_5 1.75 Vpc	C_{10} 1.80 Vpc	C_{12} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc	C_{240} 1.85 Vpc
OPzS Solar 190	122	132	134	145	165	175	185	190	200
OPzS Solar 245	159	173	176	190	215	230	240	245	260
OPzS Solar 305	203	220	224	240	270	285	300	305	320
OPzS Solar 380	250	273	277	300	330	350	370	380	400
OPzS Solar 450	296	325	330	355	395	420	440	450	470
OPzS Solar 550	353	391	398	430	480	515	540	550	580
OPzS Solar 660	422	469	477	515	575	615	645	660	695
OPzS Solar 765	492	546	555	600	670	710	750	765	805
OPzS Solar 985	606	700	710	770	860	920	970	985	1035
OPzS Solar 1080	669	773	784	845	940	1000	1055	1080	1100
OPzS Solar 1320	820	937	950	1030	1150	1230	1295	1320	1385
OPzS Solar 1410	888	1009	1024	1105	1225	1305	1380	1410	1440
OPzS Solar 1650	1024	1174	1190	1290	1440	1540	1620	1650	1730
OPzS Solar 1990	1218	1411	1430	1550	1730	1850	1950	1990	2090
OPzS Solar 2350	1573	1751	1770	1910	2090	2200	2300	2350	2470
OPzS Solar 2500	1667	1854	1875	2015	2215	2335	2445	2500	2600
OPzS Solar 3100	2080	2318	2343	2520	2755	2910	3040	3100	3250
OPzS Solar 3350	2268	2524	2550	2740	2985	3135	3280	3350	3520
OPzS Solar 3850	2592	2884	2915	3135	3430	3615	3765	3850	4040
OPzS Solar 4100	2775	3090	3125	3355	3650	3840	4000	4100	4300
OPzS Solar 4600	3099	3451	3490	3765	4100	4300	4500	4600	4850
OPzS Solar 280	203	206	229	250	296	304	287	294	338
OPzS Solar 350	245	257	284	311	374	383	355	364	424
OPzS Solar 420	284	309	322	354	420	432	408	417	482
OPzS Solar 70	55.0	51.5	63.7	69.4	78.4	79.8	81.0	82.7	92.9
OPzS Solar 140	95.4	103	108	118	141	145	136	139	162
OPzS Solar 210	131	154	162	177	206	217	203	210	234

Capacities in Ah (C_5 – C_{240} at 25 °C)

* Includes installed connector, the above mentioned height can differ depending on the used vent(s).
** Acid density d_N = 1.24 kg/l

Terminal and torque



12 Nm for blocks;
20 Nm for cells

Data is also valid for dry charged version.
Change »W« (Wet) to »D« (Dry) in the part number.
E.g.:
> filled and charged: NVSL120070 **W** C0FB
> dry charged: NVSL120070 **D** C0FB

Classic EnerSol T

Technical data, Drawings

Technical characteristics and data

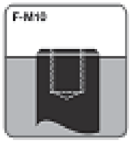
Type	Part number	Nom. voltage V	Nominal capacity C_{120} 1.85 Vpc 25 °C Ah	Length (l) max. mm	Width (b/w) max. mm	Height* (h) max. mm	Installed length (L) max. mm	Weight incl. acid approx. kg	Weight acid** approx. kg	Internal resistance mOhm	Short circuit current A	Terminal	Pole pairs
EnerSol T 370	NVTS020370WC0FA	2	376	83.0	199	445	93.0	17.3	5.10	0.70	2900	F-M10	1
EnerSol T 460	NVTS020460WC0FA	2	452	101	199	445	111	21.0	6.30	0.56	3625	F-M10	1
EnerSol T 550	NVTS020550WC0FA	2	542	119	199	445	129	24.7	7.50	0.46	4350	F-M10	1
EnerSol T 650	NVTS020650WC0FA	2	668	119	199	508	129	29.5	8.60	0.45	4500	F-M10	1
EnerSol T 760	NVTS020760WC0FA	2	779	137	199	508	147	31.0	10.0	0.38	5250	F-M10	1
EnerSol T 880	NVTS020880WC0FA	2	897	137	199	556	147	38.0	11.0	0.43	4660	F-M10	1
EnerSol T 1000	NVTS021000WC0FA	2	1025	155	199	556	165	43.1	12.6	0.38	5325	F-M10	1
EnerSol T 1130	NVTS021130WC0FA	2	1154	173	199	556	183	47.7	14.1	0.34	5991	F-M10	1
EnerSol T 1250	NVTS021250WC0FA	2	1282	191	199	556	201	52.8	15.6	0.30	6657	F-M10	1

* The above mentioned height can differ depending on the used vent(s).
**Acid density d_N = 1.26 kg/l

Type	C_1 1.75 V/C	C_{10} 1.80 V/C	C_{12} 1.80 V/C	C_{24} 1.80 V/C	C_{48} 1.80 V/C	C_{72} 1.80 V/C	C_{100} 1.85 V/C	C_{120} 1.85 V/C	C_{240} 1.85 V/C
EnerSol T 370	260	280	294	333	361	368	369	376	383
EnerSol T 460	327	350	367	416	437	460	444	452	478
EnerSol T 550	393	425	441	499	524	553	533	542	574
EnerSol T 650	492	527	552	625	656	668	647	668	719
EnerSol T 760	574	615	645	729	766	780	755	779	839
EnerSol T 880	654	714	742	840	854	953	869	897	966
EnerSol T 1000	755	809	848	960	1008	1089	993	1025	1104
EnerSol T 1130	850	910	954	1080	1134	1225	1117	1154	1242
EnerSol T 1250	944	1011	1060	1200	1260	1361	1241	1282	1380

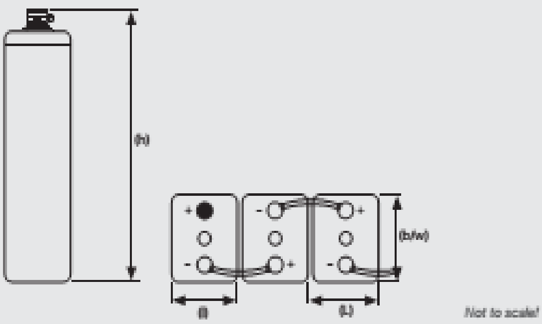
The capacities are given in Ah at 25 °C after 5 cycles.

Terminal and torque



25 Nm

Drawings with terminal position



Classic EnerSol

Technical data, Drawings

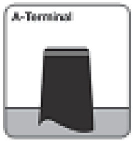
Technical characteristics and data

Type	Part number	Nom. voltage V	Capacity C_{100} 1.85 Vpc 25 °C Ah	Nominal capacity C_{120} 1.85 Vpc 25 °C Ah	Discharge current I_{120} 1.85 Vpc A	Length (l) max. mm	Width (b/w) max. mm	Hight (h) max. mm	Weight incl. acid approx. kg	Weight acid* approx. kg	Terminal	Terminal position
EnerSol 50	NVCE120050WC0TA	12	52.0	53.0	0.44	210	175	190	13.7	2.10	A-Terminal	1
EnerSol 65	NVCE120065WC0TA	12	65.0	66.0	0.55	242	175	190	17.3	2.70	A-Terminal	1
EnerSol 80	NVCE120080WC0TA	12	78.0	80	0.66	278	175	190	20.7	4.70	A-Terminal	1
EnerSol 100	NVCE120100WC0TA	12	97.0	99.0	0.82	353	175	190	26.4	7.00	A-Terminal	1
EnerSol 130	NVCE120130WC0TA	12	130	132	1.10	349	175	290	33.0	10.9	A-Terminal	1
EnerSol 175	NVCE120175WC0TA	12	175	179	1.49	513	223	223	47.8	14.6	A-Terminal	2
EnerSol 250	NVCE120250WC0TA	12	250	256	2.13	518	276	242	63.0	18.6	A-Terminal	2

* Acid density d_N = 1.28 kg/l

Terminal and torque

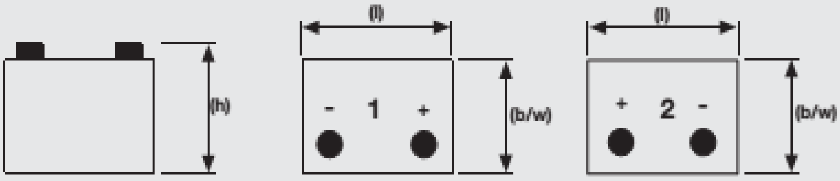
Don't use torque for adapter.



8 Nm

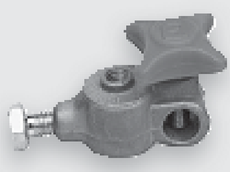
Data is also valid for dry charged version.
Change »W« (Wet) to »D« (Dry) in the part number. E.g.:
> **filled and charged:** NVCE120050 W C0TA
> **dry charged:** NVCE120050 D C0TA

Drawings with terminal position

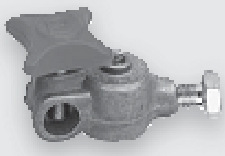


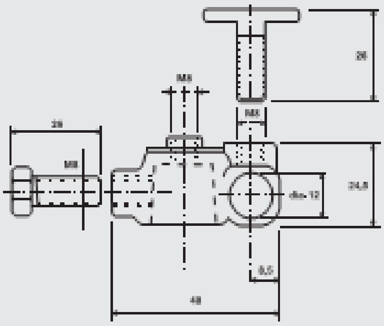
Accessories

EnerSol adapter negative



EnerSol adapter positive





Not to scale!

GNB INDUSTRIAL POWER
A Division of Exide Technologies

Exide Technologies, with operations in more than 80 countries, is one of the world's largest producers and recyclers of lead-acid batteries. Exide Technologies provides a comprehensive and customized range of stored electrical energy solutions. Based on over 120 years of experience in the development of innovative technologies, Exide Technologies is an esteemed partner of OEMs and serves the spare parts market for industrial and automotive applications.

GNB Industrial Power – A division of Exide Technologies – offers an extensive range of storage products and services, including solutions for telecommunication systems, railway applications, mining, photovoltaic (solar energy), uninterrupted power supply (UPS), electrical power generation and distribution, fork lifts and electric vehicles.

Exide Technologies takes pride in its commitment to a better environment. An integrated approach to manufacturing, distributing and recycling of lead-acid batteries has been developed to ensure a safe and responsible life cycle for all of its products.

NXCSLTEPDF00014 Subjects to alterations

GNB® INDUSTRIAL POWER devises enduring energy concepts that convince with efficiency, flexibility and profitability.

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Appendix (5): 8% Interest Rate Table

8% — Compound Interest Factors — 8%

	Single Payment		Uniform Payment Series				Arithmetic Gradient		
	Compound Amount Factor Find *F* Given *P*	Present Worth Factor Find *P* Given *F*	Sinking Fund Factor Find *A* Given *F*	Capital Recovery Factor Find *A* Given *P*	Compound Amount Factor Find *F* Given *A*	Present Worth Factor Find *P* Given *A*	Gradient Uniform Series Find *A* Given *G*	Gradient Present Worth Find *P* Given *G*	
n	*F/P*	*P/F*	*A/F*	*A/P*	*F/A*	*P/A*	*A/G*	*P/G*	*n*
1	1.080	.9259	1.0000	1.0800	1.000	0.926	0	0	**1**
2	1.166	.8573	.4808	.5608	2.080	1.783	0.481	0.857	**2**
3	1.260	.7938	.3080	.3880	3.246	2.577	0.949	2.445	**3**
4	1.360	.7350	.2219	.3019	4.506	3.312	1.404	4.650	**4**
5	1.469	.6806	.1705	.2505	5.867	3.993	1.846	7.372	**5**
6	1.587	.6302	.1363	.2163	7.336	4.623	2.276	10.523	**6**
7	1.714	.5835	.1121	.1921	8.923	5.206	2.694	14.024	**7**
8	1.851	.5403	.0940	.1740	10.637	5.747	3.099	17.806	**8**
9	1.999	.5002	.0801	.1601	12.488	6.247	3.491	21.808	**9**
10	2.159	.4632	.0690	.1490	14.487	6.710	3.871	25.977	**10**
11	2.332	.4289	.0601	.1401	16.645	7.139	4.240	30.266	**11**
12	2.518	.3971	.0527	.1327	18.977	7.536	4.596	34.634	**12**
13	2.720	.3677	.0465	.1265	21.495	7.904	4.940	39.046	**13**
14	2.937	.3405	.0413	.1213	24.215	8.244	5.273	43.472	**14**
15	3.172	.3152	.0368	.1168	27.152	8.559	5.594	47.886	**15**
16	3.426	.2919	.0330	.1130	30.324	8.851	5.905	52.264	**16**
17	3.700	.2703	.0296	.1096	33.750	9.122	6.204	56.588	**17**
18	3.996	.2502	.0267	.1067	37.450	9.372	6.492	60.843	**18**
19	4.316	.2317	.0241	.1041	41.446	9.604	6.770	65.013	**19**
20	4.661	.2145	.0219	.1019	45.762	9.818	7.037	69.090	**20**
21	5.034	.1987	.0198	.0998	50.423	10.017	7.294	73.063	**21**
22	5.437	.1839	.0180	.0980	55.457	10.201	7.541	76.926	**22**
23	5.871	.1703	.0164	.0964	60.893	10.371	7.779	80.673	**23**
24	6.341	.1577	.0150	.0950	66.765	10.529	8.007	84.300	**24**
25	6.848	.1460	.0137	.0937	73.106	10.675	8.225	87.804	**25**
26	7.396	.1352	.0125	.0925	79.954	10.810	8.435	91.184	**26**
27	7.988	.1252	.0114	.0914	87.351	10.935	8.636	94.439	**27**
28	8.627	.1159	.0105	.0905	95.339	11.051	8.829	97.569	**28**
29	9.317	.1073	.00962	.0896	103.966	11.158	9.013	100.574	**29**
30	10.063	.0994	.00883	.0888	113.283	11.258	9.190	103.456	**30**
31	10.868	.0920	.00811	.0881	123.346	11.350	9.358	106.216	**31**
32	11.737	.0852	.00745	.0875	134.214	11.435	9.520	108.858	**32**
33	12.676	.0789	.00685	.0869	145.951	11.514	9.674	111.382	**33**
34	13.690	.0730	.00630	.0863	158.627	11.587	9.821	113.792	**34**
35	14.785	.0676	.00580	.0858	172.317	11.655	9.961	116.092	**35**
40	21.725	.0460	.00386	.0839	259.057	11.925	10.570	126.042	**40**
45	31.920	.0313	.00259	.0826	386.506	12.108	11.045	133.733	**45**
50	46.902	.0213	.00174	.0817	573.771	12.233	11.411	139.593	**50**
55	68.914	.0145	.00118	.0812	848.925	12.319	11.690	144.006	**55**
60	101.257	.00988	.00080	.0808	1 253.2	12.377	11.902	147.300	**60**
65	148.780	.00672	.00054	.0805	1 847.3	12.416	12.060	149.739	**65**
70	218.607	.00457	.00037	.0804	2 720.1	12.443	12.178	151.533	**70**
75	321.205	.00311	.00025	.0802	4 002.6	12.461	12.266	152.845	**75**
80	471.956	.00212	.00017	.0802	5 887.0	12.474	12.330	153.800	**80**
85	693.458	.00144	.00012	.0801	8 655.7	12.482	12.377	154.492	**85**
90	1 018.9	.00098	.00008	.0801	12 724.0	12.488	12.412	154.993	**90**
95	1 497.1	.00067	.00005	.0801	18 701.6	12.492	12.437	155.352	**95**
100	2 199.8	.00045	.00004	.0800	27 484.6	12.494	12.455	155.611	**100**

جامعة النجاح الوطنية
كلية الدراسات العليا

تصميم و محاكاة انظمة الحماية المهبطية المغذاة بالطاقة المولدة من الخلايا الشمسية

إعداد
عبد الرحمن جمال خالد سمودي

إشراف
أ. د. مروان محمود

قدمت هذه الأطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك، كلية الدراسات العليا، جامعة النجاح الوطنية، نابلس، فلسطين.
2015

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الملخص

تتناول هذه الأطروحة استخدام تكنولوجيا الحماية المهبطية لتوفير الحماية من التآكل لشبكة توزيع أنابيب تحت سطح البحر و تحت الأرض في فلسطين. نظام الحماية الهبطية يستخدام الطاقة الكهربائية المولدة من الخلايا الكهروضوئية لتزويد نظام الحماية المهبطية المغذى بمصدر تيار خارجي. تصميم نظام الحماية المهبطية المغذى بالطاقة المولدة من الخلايا الكهروضوئية يتعامل مع ثلاث حالات تعتمد على نسبة المساحة المحمية من المساحة الإجمالية لخطوط الأنابيب، والحالات هي:(أ) و (ب) و (ج) تمثل 90٪ و 95٪ و 98٪ على التوالي. تم عمل محاكاة لنظام الحماية المهبطية باستخدام الخلايا الكهروضوئية وذلك من خلال استخدام تطبيق السميولنك في برنامج الماتلاب

تم عمل تحليل اقتصادي للمقارنة بين إعادة تأهيل خطوط الأنابيب التالفة نتيجة لتآكل واستخدام نظام الحماية المهبطية المغذى بالطاقة المولدة من الخلايا الكهروضوئية في كل الحالات. يظهر التحليل الاقتصادي أن استخدام نظام الحماية المهبطية المغذى بالطاقة المولدة من الخلايا الكهروضوئية بدلا من إعادة تأهيل خطوط الأنابيب ينتج عنه فرق كبير جدا في التكلفة. المدخرات من تكلفة إعادة التأهيل في الحالة (أ) هو 3985440 $ من 5371493 $، وفي الحالة (ب) هو 1840670 $ من 2688311 $ وفي الحالة (ج) هو 1015603 $ من 1075350 $. هذه المدخرات وتمثل نسبة 74.2٪ و 68.47٪ و 94.44٪ من تكلفة إعادة تأهيل بدائل (أ) و (ب) و (ج) على التوالي.