OPTIMAL DESIGN AND SIMULATION OF SOLAR PHOTOVOLTAIC POWERED CATHODIC PROTECTION FOR UNDERGROUND PIPELINES IN LIBYA

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Abstract: In Libya, pipelines are being used as means of transferring hydrocarbon from wellheads to export sea ports, refineries, storage tanks, steel factory and power plants. Steel pipeline is widely used because it is of the safest means of transporting hydrocarbon and other oil products as well as its cost effective. However, one of the challenges facing oil and gas sector is corrosion on infrastructure facilities and processing units. Cathodic-Protection (CP) is an electrical method used to protect metallic body in contact with the earth from corrosion. A photovoltaic (PV) provides a reliable solution for powering remote CP stations, enabling the placing of CP units in any location along the underground pipeline, thus ensuring optimal current distribution for the exact protection requirements. In this paper the sizing of the system is determined based on the electrical power needed for the catholic protection, characteristics of the used PV module and the meteorological data of the installation site. Math/Lab Simulink and PvsystV6.43 software's are used as tools for optimal design, sizing and simulation of the PV powered cathodic protection system components. In addition to that estimation of system cost was investigated and compared with the conventional system. The results show that using solar energy powered cathodic protection system for underground pipelines is practical and very beneficial besides being economical, especially considering the rapid decreasing in the prices of PV systems components and the increasing of its efficiencies and reliability.

Keywords: Libya, PV, cathodic protection, solar energy, Matlab/Simulink, Pvsyst.

INTRODUCTION

Crude oil and natural gas transfer pipelines pass through Libyan's desert areas where a frequent problem in Cathodic Protection (CP) is that extending the normal electric power supply from the utility grid would be very costly.

Libya is blessed with a rich and reliable supply of solar energy and with an average sunshine duration of more than 300 days per year. In this paper, the study has been conducted for a pipeline cathodic protection site Ras-Lanuf which is located on the Gulf of Sirt of Libya. The pipeline 36" is running from Amal Field to Ras Lanuf Tank Farm for a distance of approximately 273km, and buried in the desert sand. With coordinates are 30°.19' N latitude and 18°.5' E longitude.

By using solar photovoltaic (PV) system provides a reliable solution for powering remote cathodic protection stations, enabling the placing of cathodic protection units in any location, thus ensuring an optimal current distribution for the exact protection system requirements.

Corrosion is defined as an electrochemical process in which a current leaves a metal body at the anode area, passes through an electrolyte, and reenters the metal structure at the cathode area. Corrosion in pipeline leads to material loss, gas and oil leakage, and interruption in gas and oil supply. In addition, problems and failures of pipeline networks not only have an economic cost; it can also present a threat to life and the environment (Beavers & Neil, 2006; Yang, 2008).

Cathodic-Protection (CP) is an electrical technique used to protect metallic bodes in contact with the earth from corrosion by minimizing the potential difference between anode and cathode. This is achieved by supplying electrical current to the

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structure to be protected from some outsider source. When enough current is applied, the whole structure will be at one potential level; thus, anode and cathode will disappear. The simplest method to apply cathodic protection is by connecting the metal body to be protected with another more easily corroded metal to act as the anode of the electrochemical cell (Edward and Winston, 2010). There are two main types of cathodic protection systems one is the galvanic cathodic protection systems and the other is the impressed current cathodic protection (ICCP) systems. Both types have anodes (from which current flows into the electrolyte), a continuous electrolyte from the anode to the protected metal structure, and an external metallic connection. The potential for the use of ICCP was first recognized by (Baboian, 1974). Since that time, the performance and development of various platinum surfaced anodes has been widely covered in the literature (Baboian, 1974). The correct application of cathodic protection can extend the design life of oil, gas and water underground pipeline networks, saving the energy and the money necessary to build a new one. Therefore, cathodic protection is a tool to achieve energy efficiency. In the impressed current cathodic protection system, it is possible to use the photovoltaic system as a power supply.

The objectives of this paper are designing, and simulation of solar photovoltaic powered cathodic protection system for underground pipelines transporting hydrocarbon and other oil products in Libya. The design was based on the pipeline dimensions, the percentage of protected surface area, the electrical parameters of pipeline surrounding environments, characteristics of the used PV module and the meteorological data of the site of installation. ICCP system design calculation methodologies adopted a step-by-step approach and to validate the design a simulation is carried out using Matlab/ Simulink and Pvsyst 6.43 software's.

PRINCILPES OF CATHODIC PROTECTION

Oil and gas pipelines have been made from its primary ore metal oxides with to a natural tendency to revert to that state under the action of oxygen and water. This behaviour is called corrosion. This is an electrochemical process that involves the passage of small scale electrical currents (Mathiazhagan, 2010). The change from the metallic to the combined form occurs by an "anodic" reaction:

$$Fe \rightarrow Fe^{++} + 2e- \quad (1)$$

This reaction produces free electrons, which pass within the metal to another position, on the metal surface (the cathode), where it is consumed by the cathodic reaction.

In acid solutions the cathodic reaction is (Ronald, 2001):

$$2H^{+} + 2e- \rightarrow H2 \quad (2)$$

Corrosion occurs at the anode but not at the cathode. The anode and cathode in a corrosion process may be consisting of two different metals connected together forming a bimetallic couple, or, as with rusting of steel, they may be close together on the same metal surface. The principle of cathodic protection is in connecting an external anode to the metal surface to be protected and passing of an electrical dc current such that the whole area of the metal surface become cathodic and hence corrosion do not occur. The external anode may be a galvanic anode, where the current is a result of the potential difference between the two metals, or it may be an impressed current anode, where the dc current is impressed from an external power supply (Euring, 1981).

In electrochemical process, the electrical potential between the metal and the surrounding electrolyte with which it is in contact is made more negative, by supplying negative charged electrons, to a value at which the corroding (anodic) reactions are suppressed and only cathodic reactions can take place.

Components of the ICCP System

The main components of the ICCP system powered by PV solar energy are PV generator to supply dc current, DC-DC, converters used to increase or decrease the voltage produced by the solar array, batteries storage system, coated pipeline structure system and impressed current anodes. Figure.1 shows block diagram for the whole PV powered ICCP system.

Design of Cathodic Protection Systems

The design process for cathodic protection of underground pipelines network includes the various necessary input parameters such as soil resistivity, current density protection criteria and design life. Soil resistivity is a function of soil moisture and the concentrations of ionic soluble salts and is considered most comprehensive indicator of a soil's corrosively. Typically, the lower the resistivity, the higher will be the corrosively as indicated in (Table 1).

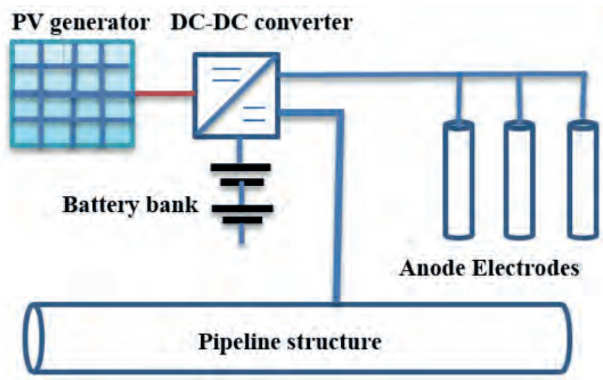

Fig. 1. Block diagram of ICCP system powered by PV.

In this paper, a design was carried out for Harouge Oil Operations' Ras-Lanuf, which is located on the Gulf of Sirt of Libya. The pipeline 36" is running from Amal Field to Ras Lanuf Tank Farm for a distance of approximately 273 km, and buried in the desert sand. In this design an assumptions of coating efficiency 90%, design life 35 years and pipe joint length is 4m are considered. The electrical parameters for pipeline, anode and surrounding environments are shown in (Tables 2 & 3) (Sami, 2008).

Design of the impressed current cathodic protection system was carried out based on the pipeline information and Tables (1 to 3). The procedure for the design starting with calculating the current required to catholically protect the pipeline under consideration or change its potential to minimum value of 0.85 volts. The current requirement depends on pipe coating quality, soil resistivity of pipeline route and total external surface area of the pipeline.

Corrosion Current Calculation

Design of ICCP starting with calculating the current required to catholically protect the pipeline under consideration or change the structure potential to minimum value of 0.85 volts. The required DC current to prevent corrosion is calculated based on the quantities of current density (which is the minimum quantity of electrical current required to prevent corrosion from occurring on the pipeline steel surface), coating quality, and soil resistivity (along the right of way and total external surface area of the pipeline; Ezeiel, 2015). The required current IR was calculated using the following equation:

Table 1. Soil Resistivity Vs Degree of Corrosively.

Soil resistivity (ohm-cm)	Degree of corrosively
0–500	Very corrosive
500–1,000	Corrosive
1,000–2,000	Moderately corrosive
2,000–10,000	Mildly corrosive
Above 10,000	Negligible

Table 2. Electrical Parameters of Pipeline Surrounding Environments.

Soil resistivity (ohm-cm)	Degree of corrosively
0–500	Very corrosive
500–1,000	Corrosive
1,000–2,000	Moderately corrosive
2,000–10,000	Mildly corrosive
Above 10,000	Negligible

Table 3. Anode Data.

Anode material	Platinum clad
Current density	$30mA/m^2$
Design life	35 years
Anode dimension	0.75m x 0.75m x 3.00m
Utilization of platinum clad	65% kg/amp-yr
Weight of anode	30kg
Backfill length surrounding anode	0.5m
Backfill diameter surrounding anode	0.15m
Cable wire specification	0.0212 ohms per 100ft

$$I_R = A_t \times j_c \quad (3)$$

Where, A_t is the total external pipeline surface area and Jc the current density.

The total external surface area of the pipeline can be determined using the following equations which is applied on cylindrical shape as the distributed pipeline depending on the length of the pipeline (L) and the diameter of the pipeline (D), Surface area of pipeline. And considering the coating efficiency ηc = 0.9 based on the total external surface area of the pipeline is estimated as following:

$$A_t = \pi \times D \times L \times \eta c \quad (4)$$

Where; D = 0.762m (36"), and L=273,000m.

$$\therefore = 3.142 \times 0.9144 \times 273 \times 1000 \times (1 - 0.9) = 78434.123 m^2$$

The total current required for ICCP IR using based on the pipe surface area and current density jc in Table 1 for desert environment yield.

$$I_R = 0.0004 \times 78434.123 = 31373.649\ mA$$

Next step is calculating the required number of anodes needed to meet current density limitation specified by the manufacturer which is found as follows

$$N_A = \frac{I_R}{A_t \times J_c} \qquad (5)$$

Where NA is the required number of anodes and A_t , is the anode surface area estimated using Table 2 as:

$$A_a = \pi \times d \times l = 3.142 \times 0.75 \times 3 = 7.1 m^2 \qquad (6)$$

Therefore,

$$N_A = \frac{I_R}{A_t \times J_c} = \frac{31373.649}{7.1 \times 30} = 148\ anodes \qquad (7)$$

Then required number of anodes needed to meet 35 years intended design life based on the required current was calculated using the following formula (Dwing, 1936).

$$N_A = \frac{D_L I_R}{1000 \times A_W} \qquad (8)$$

Where DL the design life and AW the anode weight

Therefore

$$N_A = \frac{35 \times 31373.649}{1000 \times 30} \cong 37\ anodes \qquad (9)$$

Additionally, anode spacing is an important design parameter that is used to ensure maximum allowable voltage drop is not exceeded. The anode spacing can be reduced if the permissible voltage drop is exceeded by choosing anode with lower weight or increasing the number of anodes. The anode spacing (AS) is estimated with the following equation:

$$A_S = \frac{Pipeline\ length}{N_a} = \frac{273 \times 1000}{37} \cong 7378.378m \qquad (10)$$

Next is calculation of interval of pipe joint to determine interval of anode bracelet that will be placed. The interval of pipe joint is given as:

$$interval = \frac{A_S}{average\ length\ of\ pipe\ joint} = \frac{7378.378}{4} = 1844.595\ joint \qquad (11)$$

Furthermore, anode to electrolyte resistance known as resistance to earth remains a critical parameter in cathodic protection system design evaluation in predicting anode current output. The other resistances include structure to electrolyte and cabling resistance and are often neglected in design for offshore location. The resistance of a single vertical anode R_A was calculated using the following equation (Abdulamer, 2013):

$$R_A = 0.00512 \times \rho \times \frac{[\ln\left(8 \times {A_l}/{A_d}\right) - 1]}{A_l} \qquad (12)$$

Where, A_l is the anode length plus backfill, A_d is the anode diameter plus backfill and ρ is the average soil resistivity taken as 65 Ω.m against taking the lowest value since there was no significant variations of the values.

$$R_A = 0.0052 \times 65 \times \frac{[\ln {\{8 \times (3+0.5\}}/{\{0.75+0.15\}}) - 1}{(3+0.5)} = 0.24\ \Omega \qquad (13)$$

Anode lead wire cable was supplied in ohms per 100ft per manufacturer's specification and the cable wire resistance was computed with equation:

$$R_W = \frac{\Omega\ L}{100ft} \qquad (14)$$

Where, is the length of structure (pipeline) measured in ft.

$$\therefore\ R_W = \frac{0.00212 \times 328ft}{100ft} = 0.070\Omega \qquad (15)$$

The structure to electrolyte resistance (Re) is calculated as following:

$$R_e = \frac{R_c}{A_C} \qquad (16)$$

Where, R_c is the coating resistance and AC is the area of the coated pipeline surface. The entire pipeline length under consideration has been coated. So, AC = AT

$$\therefore\ R_e = \frac{18}{86405} = 0.0002\Omega \qquad (17)$$

The total circuit resistance was estimated using the follows formula (Abdulamer, 2013):

$$R_T = R_G + R_W + R_e \qquad (18)$$

$$\therefore\ R_T = 0.24 + 0.070 + 0.0002 = 0.3102\Omega$$

The voltage requirement was calculated with following equation:

$$V_T = I_T \times R_T \times 150\% \quad (19)$$

Where, V_T is the voltage output requirement and the 150% represent design factor to ensure supply voltage not below the needed voltage:

$$V_T = \frac{31373.649 \times 0.3102 \times 150}{100} = 14598.159\, m\, V \quad (20)$$

PV Generator Sizing

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

Required Power And Energy For ICCP System: The required power PR for ICCP system can be calculated using the following in the equation;

$$P_R = I_R \times V_R \quad (21)$$

$$\therefore \; P_R = 31.374 \times 14.598 = 457.998\text{Watt}$$

Therefore the required energy ER needed for ICCP system in one day can be found using the as following:

$$E_R = P_R \times 24 \quad (22)$$

$$E_R = 457.998 \times 24 = 10991.944 wh$$

Power Produced From PV Generator: The power produced PPV from PV generator can be determined using the following equation.

$$P_{PV} = \frac{E_R}{\eta_C} \times 1.15 \times \frac{1000W}{5400Wh/day} \quad (23)$$

$$\therefore P_{PV} = \frac{10991.944}{0.9} \times 1.15 \times \frac{1000}{5400} = 2601W$$

Number of Modules: Factors affecting the selection of a PV module are the efficiency of the module and its cost. To decide whether to use poly-crystalline or mono-crystalline modules is not easy; it requires weighing costs against efficiencies. PV modules are sized depending on the peak power of one module Pmax under Standard Testing Conditions (STC). Specifically, STC are 1,000 W/m2 solar irradiance and 25^{o}C.

In this design, the Canadian solar power of 400 Wp production is selected and adopted. The parameters of the chosen PV module are given in Table 4, (WWW//us.sunpower.com).

The number of modules Nm is calculated in equation 21 depending on the peak power of one module Pmax which is taken as 435W, this value referred to:

$$N_M = \frac{P_{PV}}{P_M} \quad (24)$$

$$\therefore \quad N_M = \frac{2601}{435} \cong 6$$

Battery Sizing and Selection

A battery bank is used as a backup system and it maintains constant voltage across the load. It is used to power the ICCP, when the solar power is not available basically during night time and cloudy days. The energy required by ICCP was calculated and equal to 10991.944wh and the battery operating voltage is 12V. The required battery capacity in ampere hour CAh was calculated based on the values of DOD of the battery (0. 85) and its average (efficiency =78) using the following equation:

$$\text{Battery capacity in Ah} = \frac{autonomy\ days \times E_R}{V_{battery} \times DOD \times \eta_{Battery} \times \eta_{inverter}} \quad (25)$$

Where:
Autonomy days =1
Eload = energy consumption Wh/day

Table 4. Specifications for Solar Panels.

Electrical Specifications (Standard Test Conditions = 25 ◦C, 1000W/m^2 irradiance and AM=1.5)	
Model	**SPR-E20-435-COM**
Max System Voltage	1000 V
Max Peak Power PmaX	435 W (±3%)
Maximum Power Point Voltage Vmpp	72.9 V
Maximum Power Point Current Impp	5.97 A
Open Circuit Voltage Voc	85.6 V
Short Circuit Current Isc	6.43 A
Module Efficiency (%)	20.3%
Temperature Coefficient of Voc	--235.5mV%°C
Temperature Coefficient of Isc	2.6mA% / °C
Temperature Coefficient of Pmax	-0.35% /C

DOD=battery Depth of Discharge =0.75

ηBattery = efficiency of battery =85%

$$\therefore\ battery\ capacity\ Ah = \frac{1\times 10991.944\text{Wh}}{0.78\times 0.85\times 12}$$

$$= 1381.592Ah \approx 1382\text{Ah}$$

Two 400Ah, 6V batteries in series yields 12 V at 400 Ah.

$$\text{series battery capacity}, = \frac{1382}{400} = 3.455 \approx 4\ batteries$$

Therefore, the total number of batteries in a battery bank (consisting of 4 batteries) will provide a capacity of 1600Ah.

SIMULINK OUTPUT OF DESIGNED GRID-CONNECTED PV PANEL

A block diagram of the PV model using Simulink is given in (Fig. 2). The block contains the sub models connected to build the final model. Variable temperature (T), and variable solar irradiation level (G) are the inputs to the PV model. The equation of the PV output current is expressed as a function of the array voltage as follows:

$$I = I_{ph} - I_D = I_{ph} - I_{sat}\left[e^{\frac{q(V+IR_S)}{nkT}} - 1\right]. \quad (26)$$

Where:

Iph the light current [A], Isat the diode reverse saturation current [A], Rs, the series resistance [Ω], V the operation voltage [V], and I the operation current [A].

q = charge of one electron($1.602\times 10^{-19}C$),

n= Diode idealizing factor, and k= Boltzman's constant (1.38×10^{-23} J/K).

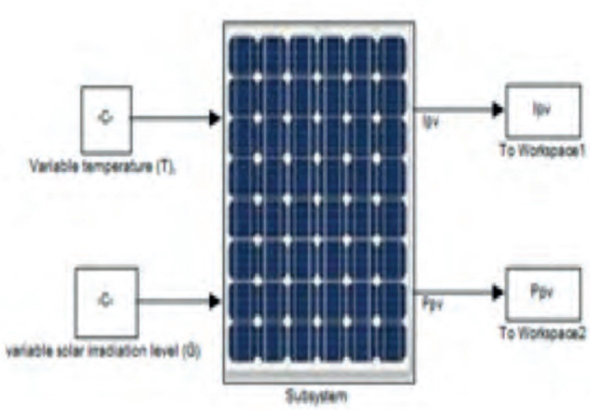

Fig. 2. Simulink model of PV module.

T=Junction temperature in Kelvin.

The modeling of the PV array for Matlab/Simulink environment is discussed in (Al-Refai, 2017). The final PV system design consists of six modules connected in parallel with manufacturer's specified nameplate as shown in Table 4. The I-V and P-V outputs characteristics of PV module with varying irradiation and constant temperature are shown in Figures 3 and 4. The P-V and I-V outputs characteristics of PV module with varying temperature at constant irradiation are shown in (Figs. 5 and 6). The results are verified and found matching with the manufacturer's data sheet output curves.

DESIGN AND SIMULATION OF PV SYSTEM USING PVSYS SOFTWARE

The final system design is performed using the Pvsyst V 6.43 simulation software (Fig. 7).

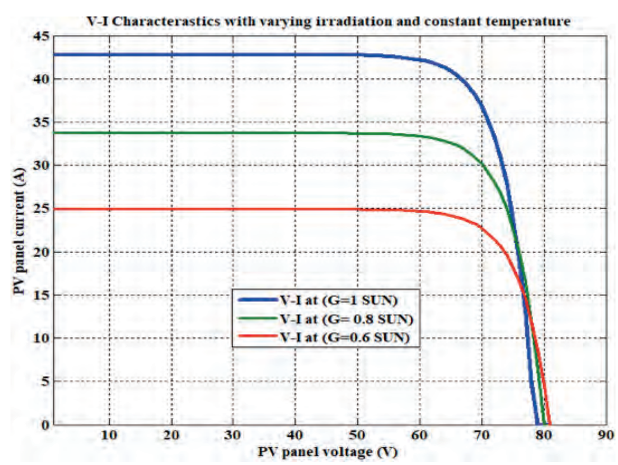

Fig. 3. V-I Characteristic curves at different insolation levels (G= 0.6 SUN, 0.8 SUN, 1 SUN) for 6 module in parallel.

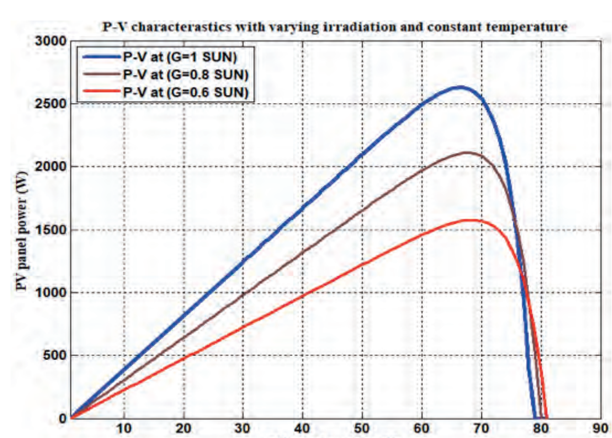

Fig. 4. P-V Characteristic curves at different insolation levels (G= 0.6 SUN, 0.8 SUN, 1 SUN) for 6 module in parallel.

PVSYST software is a PC package for analyzing the potential of a photovoltaic system at a known location. It consists of both meteorological data and the possibility to select system components from various manufacturers. The simulation results of designed PV system are displayed comprehensively through the created report by PVSYST.

Figure 8 gives the PV module and battery specification for modeling of standalone system. As per technical specification battery used is 12V, 296Ah, which can store energy of 1.184Kwh and number of battery required is 4. The PV module selected is of 435Wp, 61.5V with array voltage 61.5V, array current 36.9A, Array power (STC) generated is 2.6 kWp .The number of modules required as per calculation is 6. Design of solar PV standalone system evaluation mode as shown in (Fig. 9). PVsyst provides a detailed analysis of all losses flow diagram of the system as shown in (Fig. 10).

Figure 11 gives the normalized power production and loss factor which is yield annually. Table 5 gives the balance and main result, annual global horizon is 2121.8, available solar energy is 4588.8, unused energy is 451.93, and load connected is 4029.6.

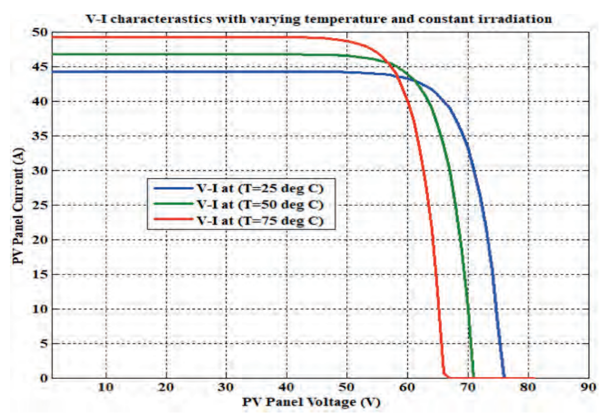

Fig. 5. V-I Characteristic curves at different cells working temperature (TC =25OC, 50OC, 75OC) for 6 module in parallel.

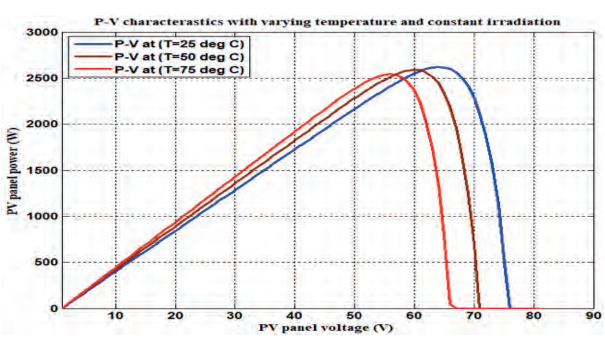

Fig. 6. P-V Characteristic curves at different cells working temperature (TC =25OC, 50OC, 75OC) for 6 module in parallel.

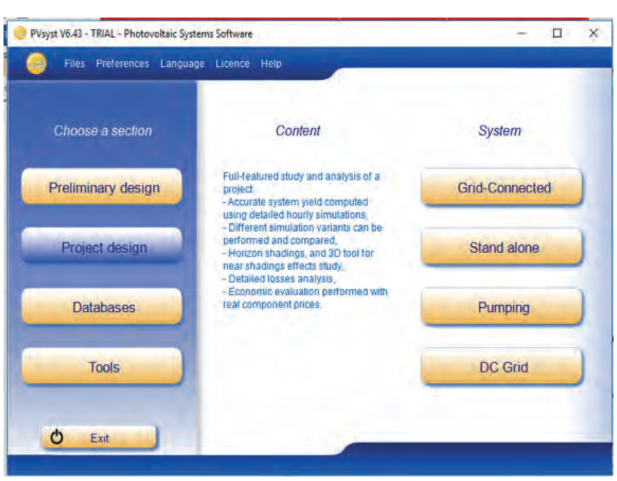

Fig. 7. PVSYST V6.43 Simulation software.

CONCLUSION

The proposed renewable supply is most viable solution for powering impressed current cathodic

Table 5. Balance and Main Results.

Simulation variant : Ras-Lanuf Pipeline Cathodic Protection

Ras-Lanuf Pipeline Cathodic Protection
Balances and main results

	GlobHor KWh/m²	GlobEff KWh/m²	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	108.2	160.2	338.7	0.02	18.25	324.0	342.2	0.947
February	126.3	165.6	347.0	33.34	19.20	289.9	309.1	0.938
March	172.4	198.2	408.4	52.67	9.77	332.5	342.2	0.971
April	201.9	202.6	410.6	60.16	0.00	331.2	331.2	1.000
May	229.1	206.1	408.1	45.59	0.00	342.2	342.2	1.000
June	245.1	208.1	399.5	54.55	0.00	331.2	331.2	1.000
July	248.6	216.6	415.0	51.17	4.07	338.2	342.2	0.988
August	232.5	222.6	424.7	61.53	0.00	342.2	342.2	1.000
September	189.0	206.6	394.5	47.93	3.76	327.4	331.2	0.989
October	150.3	189.8	378.2	28.10	9.63	332.6	342.2	0.972
November	117.3	167.2	343.5	13.28	21.34	309.9	331.2	0.936
December	101.1	152.8	320.6	3.57	42.66	299.6	342.2	0.875
Year	2121.8	2296.4	4588.8	451.93	128.67	3900.9	4029.6	0.968

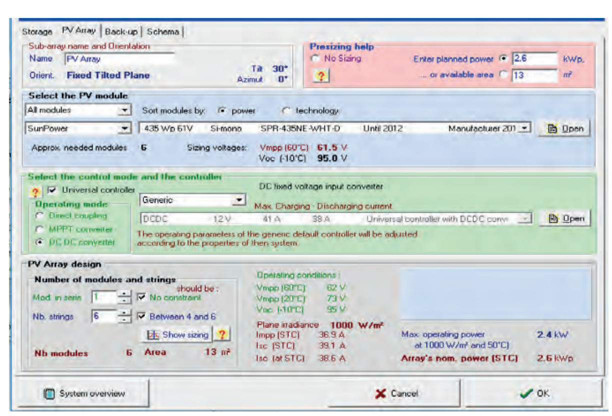

Fig. 8. System design in PVsyst.

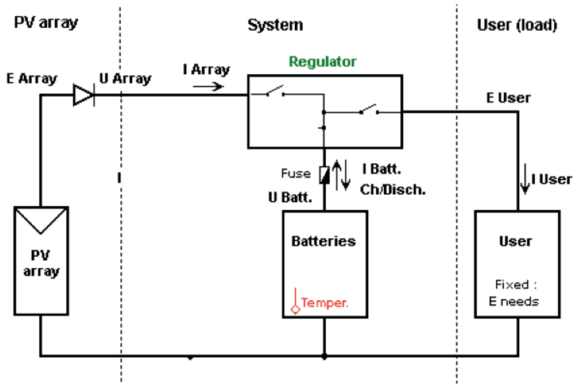

Fig. 9. Typical layout of PV system.

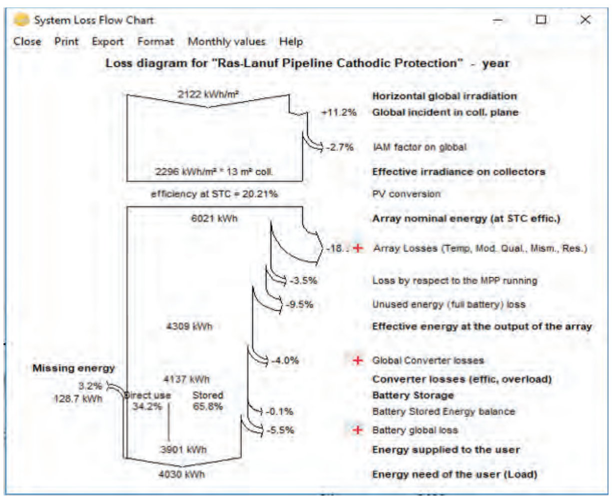

Fig. 10. System loss flow diagram.

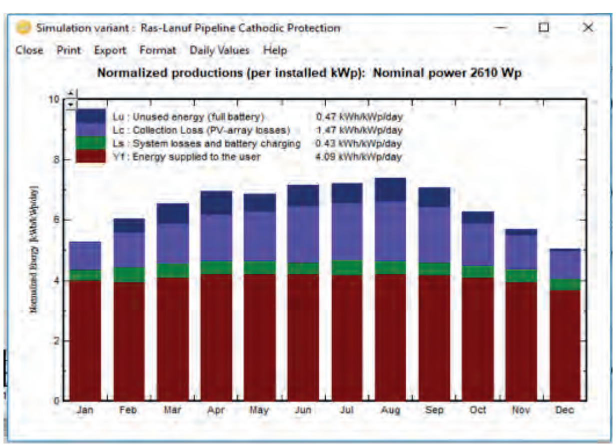

Fig. 11. Normalized production per installed KWP.

protection (ICCP) system, which is available throughout the year. This paper shows that using solar photovoltaic powered cathodic protection for buried pipelines transporting hydrocarbon and other oil products in Libya is feasible. The design was based on the pipeline dimensions, the percentage of protected surface area and the electrical parameters of pipeline surrounding environments.

This paper, also describe that numerical calculation and simulations can be useful tool in the design and evaluation of the cathodic protection of buried pipeline networks. The results show that using solar energy powered cathodic protection system for underground pipelines is practical and very beneficial besides being economical, especially considering the rapid decreasing in the prices of PV systems components and the increasing of its efficiencies and reliability. In addition to that powering ICCP of the pipeline by renewable energy system, will reduce the carbon and other harmful gases emission.

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