International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2014 | Issue 18 | Volume 6 | Number 1 | Pages 27-33

DESIGN AN INTELLIGENT SOLAR PHOTOVOLTAIC POWER FOR CATHODIC PROTECTION SYSTEM TO PROTECT UNDER GROUND GAS PIPELINE

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Abstract- In this paper, photovoltaic power systems are used for the cathodic protection of underground pipelines. The arrangement of the system is as follows, first the solar cell array is connected to a buck converter, then the battery and the Buck-Boost converter are located, respectively, and finally the system is connected to equivalent circuit of the pipeline and the anode-bed. The buck converter is used to reduce the voltage, which comes from the solar cell array and to provide an appropriate voltage for the batteries. Two new controllers are proposed in this system. The first type of the controller controls battery charging and discharging modes. The second controller controls the voltage at underground pipeline's drain point. The advantage of this controller is that the injected (drained) voltage can be set in any arbitrary number. Through calculation process, the worst conditions have been considered to increase the lifetime of the system and to cause the designed system to be useful in different climatic conditions.

Keywords: DC-DC Converter, Photovoltaic (PV), Maximum Power Point Tracking (MPPT), Corrosion, Pipeline, Anode-Bed, Battery, Cathodic Protection.

I. INTRODUCTION

Corrosion is a malicious chemical or electrochemical reaction between the metal surface and the surrounding environment. However, a variety of coatings are used in underground steel pipes (water, gas, oil), but still oxidation process occurs and causes corrosion in pipes and destroys them. In cathodic protection, by cathodization of under corrosion structures (that were anodic), one can prevent them from corrosion.

Cathodization of a structure is done with replacing electron's power supply that either is an electric source or a steel that is more active (more anodic) than our buried structure. Cathodic protection can be applied to the naked surfaces of the steels, but it is often uneconomical because the needed current density is much. An appropriate coating can protect steels.

However, a combination of both protections (coating and cathodic protection) is often used that has many advantages. Current injection technique or sacrificial anodes are used in cathodic protection [1-5]. In current injection cathodic protection, it is possible to use the photovoltaic system instead of power supply. DC-DC buck and boost-buck converters are used in solar cathodic protection systems to increase or decrease the voltage produced by the solar array that have been arranged in series in the circuit [6-9].

Comparing with traditional systems (that are using current injection by a rectifier transformer), solar smart cathodic protection system has many advantages such as the follows.

1- Construction and installation costs are lower than traditional systems.
2- The former system needs for a balanced three-phase electrical system but the later one uses clean solar energy.
3- Due to removing the transformer and oil tank from the structure, the weight and dimensions of the system are dramatically reduced.
4- Due to automatic voltage regulation, periodic inspections for adjusting the drain point voltage are removed.
5- Ease and low cost of maintenance there are two methods proposed for implementing solar cathodic protection system, in the first method.

Two converters that have been arranged parallel to each other are used and each one can directly protect underground transmission lines. First, a buck-boost converter has been used that allows generating larger or smaller voltages than the input voltage for voltage regulation requirements of underground steel pipelines [10]. In addition, a DC-DC bidirectional converter has been used for battery charging and discharging [11]. In the second method, two converters are used in series, so that the first converter is used to generate the voltage required to charge the battery and the second converter is used to adjust the voltage at the connection point of the system with the pipelines [12, 13].

In this paper, the second method has been adopted. In this system, there are three controllers. Due to the variation in powers produced by the solar modules, the controller should be able to take consistently maximum power from the solar modules. To Increase battery life and to control battery charging and discharging modes, another controller is needed.

Table 1. Electrical characteristic data of 275 W photovoltaic module (Faran Company)

Description	Rating
Rated power	275 W
Voltage at maximum power (V_{mp})	36.1 V
Current at maximum power (I_{mp})	7.62
Open circuit voltage (V_{oc})	44.1 V
Total number of cell	148
1000 W/m^2 & T = 25˚C	

Table 2. Electrical parameter for Buck converter

$V_{i,\ max}$	$V_{i,\ nom}$	$V_{i,\ min}$	V_o	$I_{o,\ min}$	$I_{o,\ max}$	η	f_s	V_r / V_o
200	125	50	26	1	20	97%	10000	≤ 1%
L_{min}	C	r_c	$R_{L,\ max}$	$R_{L,\ min}$	$P_{o,\ max}$	$P_{o,\ min}$	D_{max}	D_{min}
1150 µH	250 µf	120 mΩ	26	1.3	520 W	26 W	0.536	0.134

The third controller does generating the appropriate voltage at the connection point of the system with the pipelines. The system needs the Maximum Power Point Tracking (MPPT) controller to be able to take maximum power from the solar modules. Perturbation and Observation algorithm (P & O) is an iterative method to find the maximum power point. The disadvantages of this algorithm are when a sudden change occurs in brightness, the *P-V* graph and working (operating) point are changed, and therefore it will not show us the actual point [14].

Conductance Incremental (CI) algorithm is a developing method that is an alternative method for P & O. The main advantage of this algorithm is its high speed under rapid climate changes, and its small fluctuations around the maximum point, in spite of a P & O algorithm that has had many fluctuations around this point. The disadvantage of this method is the complexity of its control circuit [14]. In look-up table method, initially, the voltage and current values of the photovoltaic converter are measured and then theses values are compared with values stored in the control system that is the maximum power obtained in tough climate conditions.

Requiring large memory to store the information is among its disadvantages, the implementation of this method should be set to a specific panel (not suitable for every module), and additionally it is hard to all store all conditions in the system [14]. Fuzzy logic controller method can deal with fuzzy inputs and does not require an accurate mathematical model, it has fast convergence, and fluctuations around the MPP are very low. Disadvantage of this method, a designer must be in a good command of error calculation and etc.

The neural network controller is another method, which is used in control [14]. In this paper, the proposed MPPT is the combination of P & O and CI controllers. Generally, the cost of corrosion is staggering and some part of it is unavoidable, but some percentage of these costs is preventable so that, 30% of these costs can be reduced By means of cutting edge science [16].

Table 3. Electrical parameter for buck-boost converter

$V_{i,\ max}$	$V_{i,\ nom}$	$V_{i,\ min}$	V_o	$I_{o,\ min}$	$I_{o,\ max}$	η	f_s	V_r / V_o
34	30	20	50	1	22	95%	10000	≤ 1%
$R_{L,\ max}$	$R_{L,\ min}$	L_{min}	$r_{c,\ max}$	C_{min}	D_{max}	D_{min}	$P_{o,\ max}$	$P_{o,\ min}$
50 Ω	2/2727 Ω	400 µH	5.584 mΩ	3884.4 µf	0.7246	0.6075	1100 W	50 W

In this paper, first, the smart system components are introduced, algorithms of the control circuits are given, and the proposed system is compared with traditional methods in terms of cost. Finally, simulation results are presented.

II. EQUIPMENT USED IN SOLAR SMART CATHODIC PROTECTION SYSTEMS

Solar cathodic protection systems are composed of the five parts as, 1- Solar array, 2- DC-DC converter includes Buck and Buck-Boost, 3- Battery, 4- Equivalent circuit of the pipeline and the anode-bed, 5- The controller unit includes MPPT controller, Buck converter controller, battery charging, and discharging mode controller, and the voltage drain point, which is described briefly below.

A. Solar Array

The maximum power consumption by underground pipes is considered for solar array design. In this regard, the information is used that obtained during 11 years measurement of output voltage and current of rectifier transformers for cathodic protection of the pipelines in Ardabil. The respective data are presented in Tables 7 and 8, 275 W modules from Ferrand Company have been used to simulate and its features are shown in Table 1.

B. DC-DC Buck and Buck-Boost Converters

B.1. DC-DC Buck Converter

A buck converter is a DC-DC converter in which the output voltage of its converter is lower than input voltage. Characteristics of designed buck converter are given in Table 2 [11].

B.2. DC-DC Buck-Boost Converter

The output voltage of the buck converter can be higher and lower than input voltage, so that by considering that the output voltage in the cathodic protection system changes over time and since the coating of the pipe is new and the sacrificial anodes have lower resistance, so in the early installation, low power consumption is required. However, over time, coatings and anodes are lost their property, so the power consumption too will increase and correspondingly, the output voltage is increased. Parameters of the designed Buck-Boost Converter are given in Table 3 [11].

C. Battery and Battery Charging/Discharging Modes Controller

The battery is used just when the photovoltaic panels cannot supply needed power to protect the buried steel pipes in the soil and this happens just in the case in which sunny hours during the day comes to minimal or zero. The proposed method for the battery charging and discharging is summarized in Figure 1. In Figure 1, V_{DC} is the output voltage of the buck converter where its maximum and minimum values are assumed 26 V and 20 V, respectively.

First, the battery voltage and the output voltage of the Buck converter are measured if the battery voltage is greater than the maximum battery voltage (26 V) or if $V_{DC} \geq V_{DC,\min}$, the battery will be removed from the system, otherwise the battery will stay connected to the circuit. The command to remove the battery from the circuit is offered in two situations as, a. the battery is fully charged, b. the output voltage of the buck converter is greater than the minimum value, which has been determined (in this case the minimum value for the output voltage of the converter is assumed to be 20 V).

In addition, the command to connect the battery to the switch is offered in two situations as, a. the battery is discharged, b. the output voltage of the buck converter is less than its minimum value and cannot supply the transmission pipeline.

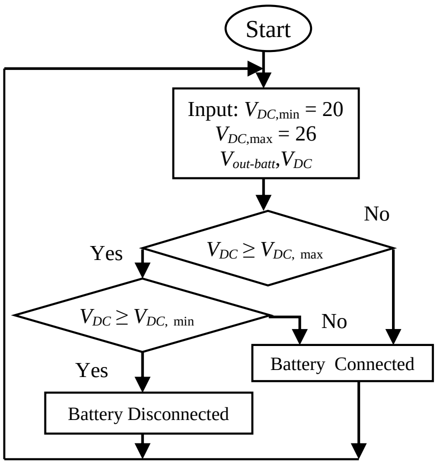

Figure 1. Flowchart of battery controller

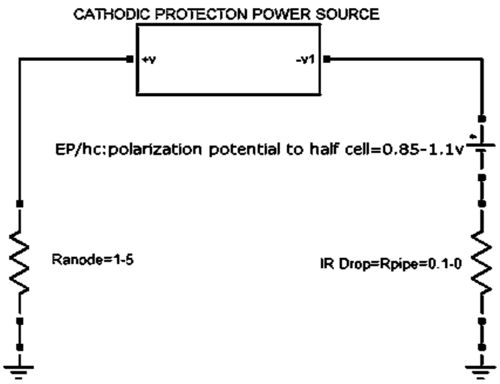

Figure 2. Equivalent circuit of pipeline and ground bed

D. Equivalent Circuit of the Pipeline and Anode-Bed

A handbook in cathodic protection has been used to find parameters of the equivalent circuit of the pipeline [1, 15]. By considering parameters of the final equivalent circuit, a pipeline with the anode bed is shown in Figure 2 that is supplied with a DC source.

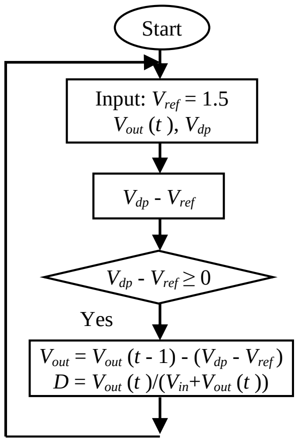

Figure 3. Flowchart for drain point controller of cathodic protection systems

E. Drain Point Voltage Controller (V_{dp})

The main purpose of the design is to control drain point voltage. Drain point voltage should be fixed on a constant value. Where, this value is depends on type of the coating and the voltage at the end of the transmission line. According to National Iranian Gas Company standard and National American Corrosion standards (NACE), drain point voltage should set at -1.5 V for cold coating, -2.1 V for warm coating and -1.2 V for three-layer polyethylene coating. Generally, this value can vary between at least 0.85 and at most -1.2 V with respect to conditions of the transmission lines. This value in the following proposed flowchart is shown as V_{ref} and we assume it to be 1.5 V (the flowchart is given in Figure 3).

III. TOTAL MODELING OF SOLAR CATHODIC PROTECTION

Figure 4 shows the entire solar cathodic protection system. Initially a 2750 W solar array with maximum power has been used on the system and then, using a buck DC-DC converter the input voltage is reduced to generate a voltage suitable for charging the battery [12]. For this part, a controller circuit is designed to take power from the solar array and also to keep the output voltage of the buck converter fixed at a certain level. The battery in the system is used at night and on cloudy days that the power generated by the solar cells is minimal or zero. In the next step, the buck-boost converter is used and finally, this system is connected to the circuit model of the pipeline and the anode-bed.

Table 4. The output voltage and current of the rectifier transformer in an 11-year period

	I_{out}	V_{out}	V_{dp}
2002	2.76	4.91	1.75
2003	1.8	3.98	1.39
2004	2.7	3.88	1.43
2005	2.1	4.21	1.4
2008	4.23	11.2	1.5
2009 (1)	5.03	15.84	1.51
2009 (2)	4.1	16.25	1.5
2010	4.41	20.7	1.5
2011	5.47	24.53	1.5
2012	5.56	37.5	1.5

IV. CALCULATIONS AND OPTIMAL SELECTION OF THE FACILITIES

For designing the entire solar cathodic protection system, the lifetime is assumed 21 years and the worst conditions are considered. First, the daily consumption of the pipeline should be calculated and then calculations of the converters and the batteries should take place. Table 4 shows the measured data obtained from the output voltage and current of the rectifier transformer in Razei station during an 11-year period. In which its power consumption is almost 5.004 kWh in 24 hours.

The output voltage of the transformer in early years of foundation was very low. However, over the time that was along with weakening, coatings of pipelines as well as increasing in resistance in the anodes of the anode-bed, which comes from corrosion of the anodes by electrolysis, have caused the output voltage and current of the transformer to increase. Figures 5 and 6 in graphs *V-P*, *V-I* show a sample of a 275 W solar panel of the FARAN Company. As you can see the solar array in the worst climate conditions of December, (Brightness 422.1 W/m^2) generates a 118 W power and in the best climate in July, it can generate a power around 275 W.

It should be noted that these figures have been achieved by applying the actual data obtained from meteorological organization of Ardabil to designed PV model, obtained from meteorological organization of Ardabil to designed *PV* model. To optimize the system, first the calculations of the production and consumption during the year is implemented then the number of modules and the batteries are specified with respect to the annual production and consumption and finally they are analyzed in terms of cost and the optimal system is selected in terms of the number of modules and the batteries.

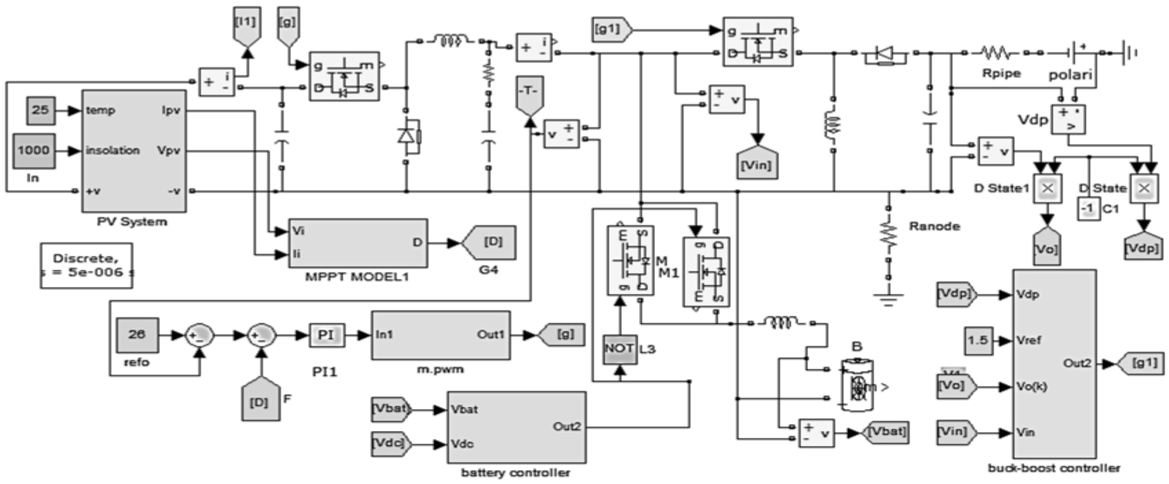

Figure 4. Circuit diagram of the intelligent solar cathodic protection

These results are given in Tables 5 and 6. In Table 5, for designing the system a number of different modules are used to select the best among them. For example, if the four solar modules used then the entire system will face with a 116649.6 Wh power deficiency in the months of October, November and December, and given that there is 15834 Wh power overproduction in the months of January and February. This can be enough to make up for the months of March and April and there will be 30184.8 Wh power deficiency for just these two months so the power deficiency in the months of October, November and December can be summed to obtain the number of batteries needed by the system.

In calculations, the lifetime of the solar panel is assumed 21 years and the battery life is assumed 3 years, and the price is calculated based on every USD to be 3,000 Iranian Toman. If the number of modules was 11, production in December becomes 155760 Wh and the difference between production and consumption will be 5640 Wh, so the production is more than annual consumption and since the battery is not used, so on a cloudy day and at nights the system cannot feed (supply) the line. By studying the data, it is clear that in some months of the year, due to cloudy conditions there is a day in which the maximum daily sunshine is one hour or zero.

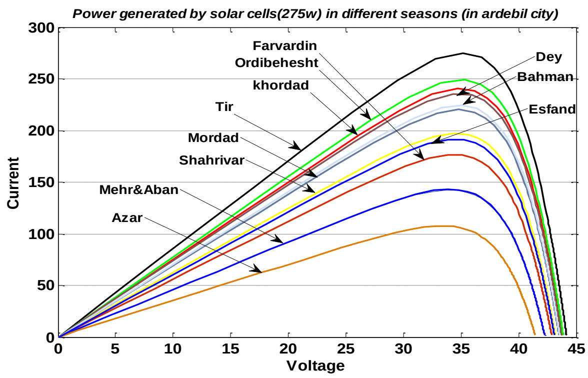

Figure 5. *P-V* characteristic for 275 W module

So the battery should be selected so that, it should be able to feed the transmission lines up to 24 hours, as well as to compensate the power deficiency in the month of December. Performed calculations and studies show that the best option to optimize the system is to choose 10 modules. Calculation method is as the follows:

Consumption on a completely cloudy day = 5004 Wh.

Power deficiency in a day from Dec. = 8520/30 = 284 Wh.

Power deficiency on a cloudy day in the 29 days of December + Consumption on a cloudy day = 8236 + 5004

= 13240 Wh. That is the battery should be selected so that, it can stores 13240 Wh, then amp hour of the battery should be 551.67 Ah. With respect to power drop in the modules and in the battery as well as battery charging percentage, we choose 640 Ah battery for the systems we consider the modules in the proposed system are considered in two parallel rows with 5 cells in series.

Table 5. Generated power by one & four 275 W modules on different seasons based on actual data obtained from the meteorological organization of Iran (Ardabil Province, 2012)

The monthly average	Average shiny hours	Average DSR radiation of sky	Average power production on a day	Average Wh Production on a day	Average Production on four days (Wh)	Average Production on month in Wh	The difference between production and consumption in a
April	6.43	671.6	177	1138.11	4552.44	136573/2	-13546.8
May	7.34	930.5	250	1835	7340	220200	70080
June	10.56	899.8	240	2534.4	10137.6	304128	154008
July	8.64	1022.5	275	2376	9504	285120	135000
August	10.74	827.1	220	2362.8	9451.2	283536	133416
September	6.9	746	197	1359.3	5437.2	163116	12996
October	8.13	548.2	142	1154.46	4617.84	138535.2	-11584.8
November	5.6	550.8	142	1154.46	4617.84	138535.2	-1154.8
December	4	422.1	118	472	1888	56640	-93480
January	5.77	883.3	235	1355.9	5423.8	162714	12594
February	5.68	842.3	225	1278	5112	153360	3240
March	5.16	725.2	190	980.4	3921.6	117648	-32472

Table 6. Optimization calculations of the module and the battery in solar cathodic protection systems

Costs ($)	4 module 275 W	6 module 275 W	7 module 275 W	8 module 275 W	9 module 275 W	10 module 275 W	11 module 275 W
Power deficiency on a month by Wh	- 164370	- 65160	- 51000	- 36840	- 22680	- 8520	+ 5640
Number of the batteries 24 V, 400 Ah [17]	15.29525	6.7875	5.3125	3.8375	2.3625	0.8875	0
The total battery price	2090.35	927.625	726.04	524.458	322.875	124.3	0
The total module price	2200	3300	3850	4400	4950	5500	6050
The total cost of the battery the module	4290.35	4227.625	4576.04	5272.875	5272.875	5621.3	6050
The total cost of the battery the module, after 21 years	16832.456	9793.375	8932.3	8071.2	7210.125	6349.04	6050

V. ECONOMIC COMPARISON BETWEEN CATHODIC PROTECTION WITH PHOTOVOLTAIC SYSTEM AND CATHODIC PROTECTION WITH RECTIFIER TRANSFORMER

Financial estimates of the ordinary method of power supplying in cathodic protection stations, is compared with the cost of photovoltaic systems. To calculate the cost of electricity delivery to the station, it is necessary to calculate the line establishment cost that includes concrete construction, power pole installing, and cabling costs and sum up them with other costs shown in Table 7. In addition, it is necessary to have a rectifier transformer with relevant chamber. Every USD is assumed 3,000 Iranian Toman.

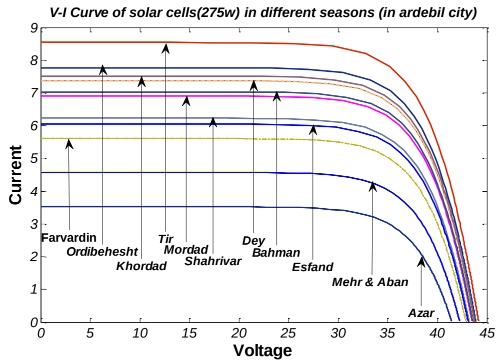

Figure 6. *V-I* characteristic for 275 W module

Table 7. Comparison between the traditional cathodic protection station construction costs with the solar cathodic protection station construction costs in a period of 21 years

	cathodic protection with photovoltaic system	traditional cathodic protection	
Subject	Cost in $	Cost in $	Subject
Photovoltaic panel	5500	16666.7	Establishing the power line (1km)
Battery	218.7	2666.7	Purchasing, transferring and installing of transformer
The cost of battery replacement after 21 years	1530.7	2533.33	Purchasing power demand
dc-dc controllers and converter	1666.7	1333.33	Purchasing, transferring and installing of rectifier transformer
Building the chamber	1666.7	2000	Building the chamber
Structure to install the panel	333.33	2520	Power consumption of station in 21 years regardless of inflation cost
The cost of installation and operation of the system	333.33	333.33	The cost of installation and operation of the system
Total cost of maintenance of photovoltaic systems after 21 years	1540	14000	The total cost of maintenance after 21 years
Unforeseen costs	666.7	666.7	Unforeseen costs
Total	13456.16	41386.76	Total

VI. SIMULATION RESULTS

In order to test MPPT precisely, the equivalent circuit of the battery is used in the output of the buck converter. Values in Figure 9, shows that one can take maximum power from the solar cell with this controller (solar 36 WPV module). To more evaluation of the performance of the controller, a variable load ranging from 5 to 1000 ohms is inserted instead of the battery. Since the 24 V battery has been used, hence for charging the battery, a higher voltage should be used, so constant value is assumed 26 V.

Simulation results are shown in Figure 7. To test the performance of the controller as well as the entire system and with respect to the input voltage changes in solar modules due to changes in solar radiation and sunny hours during the day, we have tested the system with different inputs. In Figure 8, the drain point voltage is drawn for different inputs, as can be seen, it has kept the drain point voltage fixed on the reference voltage (1.5 V). To show the appropriate performance of the controllers, the system is tested with the voltages above the level of the designed voltage. As can be seen, no fluctuation is found in the output voltage of the system, indicating that the system is functioning properly.

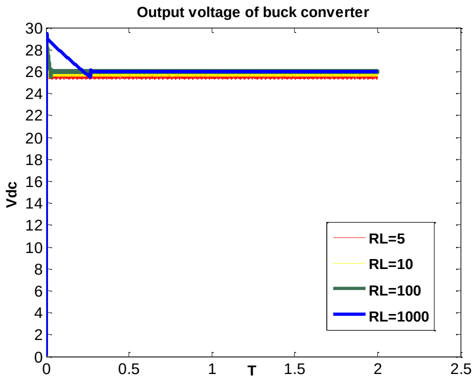

Figure 7. Output voltage of buck converter with different load

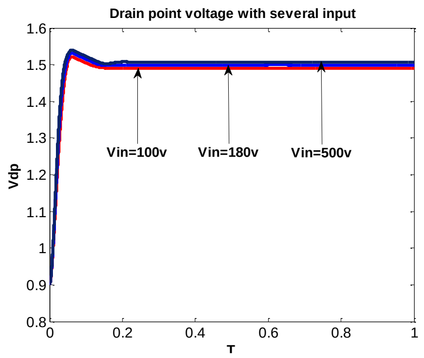

Figure 8. Drain point voltage with several input

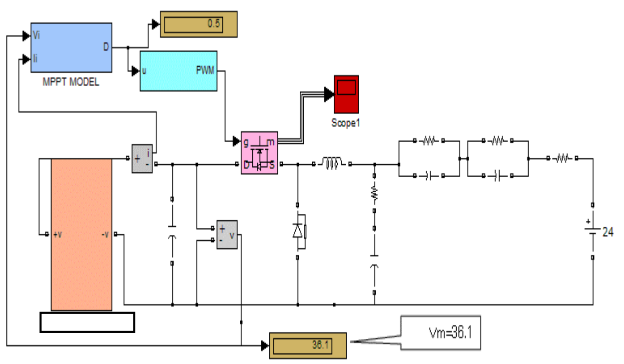

Figure 9. The results of the MPPT control circuit acts on Buck Converters

VI. CONCLUSIONS

Maximizing energy generation from solar energy has become highly interested. One popular way to maximize the PV generation is use of MPPT and DC-DC converter. In this paper, the solar smart cathodic protection systems have been studied. The new system is designed to significantly reduce the cost of construction, installing, and due to removing the transformer and oil tank from the structure, weight, and dimensions of system are reduced.

To control this system, two controllers have been proposed, the first type of the controller controls battery charging and discharging modes. The second controller controls the drain point voltage. Due to changes in solar radiation and sunny hours during the day, the system was tested with different inputs. Results from simulations of the entire system, prove the accuracy of performance of the proposed controllers and of entire system's circuit with different inputs.

ACKNOWLEDGEMENTS

This study was directed with the financial support of Ardabil Province Gas Company.

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BIOGRAPHIES

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