Cathodic Protection of an underground Pipeline by Photovoltaic Power System using Intelligent Method

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Abstract- In this paper, the intelligent cathodic protection of underground pipelines is presented using the photovoltaic power system. The structure of the system is as follows: solar cell array converts irradiation to electrical energy and acts as a voltage source. The high DC voltage generated by the module must be attenuated to provide an appropriate voltage for the batteries by using buck converter. The battery and the Buck - Boost converter are connected to the output of the buck converted and in final the circuit of the pipeline and the anode-bed is feed by the Buck - Boost converter. The power delivered from the module is very sensitive to the point of operation, and the converter should therefore incorporate a function for tracking the maximum power point (MPPT). In this paper new controller is designed so that, to take maximum power delivered from the solar array, therefore the overall efficiency of the system is improved significantly. Moreover, a new circuit model is proposed for underground pipelines and can be used in the simulation of cathodic protection systems. In simulation, 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 Converter1, Photovoltaic (PV)2, Maximum power Point Tracking (MPPT)3, Corrosion, pipeline4, Anode-bed, Battery5 , Cathodic Protection6.

1. 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. Steels can be protected by an appropriate coating. But 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 [1,2,3,4,5]. 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]. 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 is removed 6 - 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 [7]. Also, a DC-DC bidirectional converter has been used for battery charging and discharging [8]. 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 [9,10].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 consistently take maximum power from the solar modules. To increase battery life and to control battery charging and discharging modes, another controller is needed. Generating the appropriate voltage at the connection point of the system with the pipelines is done by the third controller. 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. [11]. Conductance incremental (C.I) 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 [11]. 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 [11]. 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... .The neural network controller is another method which is used in control [11] . In this paper, the proposed MPPT is the combination of P & O and C.I 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 [13]. In this paper, first, the smart system components are introduced and 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.

2. Introduction

Solar cathodic protection systems, is composed of the following parts: 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.

2.1. 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 Ardebil. The respective data are presented in Tables 7 and 8. 275w modules from Ferrand company have been used to simulate and its features are shown in Table 1.

Table 1. Electrical characteristic data of 275w pv module (faran co.)

Description	Rating
Rated power	275w
Voltage at maximum power(Vmp)	36.1v
Current at maximum power(Imp)	7.62
Open circuit voltage(Voc)	44.1v
Total number of cell	148
1000w/m^2 &T=25°C	

Table 2. Electrical parameter for bock converter

V_{imax}	V_{inom}	V_{imin}	V_o	I_{omin}	I_{omax}	η	f_s	Vr/Vo
200	125	50	26	1	20	%97	10000	≤ 1%
L_{min}	C	r_c	R_{Lmax}	R_{Lmin}	P_{omax}	P_{omin}	D_{max}	D_{min}
1150μh	250μf	120mΩ	26	1/3	520w	26w	0/536	0/134

2.2. DC-DC buck and buck-boost converters

2.2.1. buck converters

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 [8].

2.2.2. 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. But 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 is given in Table 3 [8] . .

Table 3. Electrical parameter for bock-boost converter

V_{imax}	V_{inom}	V_{imin}	V_o	I_{omin}	I_{omax}	η	f_s	V_r/V_o
34	30	20	50	1	22	%95	10000	≤ 1%
R_{Lmax}	R_{Lmin}	L_{min}	r_{cmax}	C_{min}	D_{max}	D_{min}	P_{omax}	P_{omin}
50Ω	2/2727Ω	400µh	5.584mΩ	3884/4µf	0/7246	0/6075	1100w	50w

2.3. *MPPT Controller unit and the controller of the Buck converter output*

Since the output power of the solar arrays depends on light intensity as well as temperature, thus controlling their working (operating) point to get the maximum power from the solar array is of high importance. In most of the methods presented in papers, optimal operating point is estimated by means of linear-point approximation. While here, an algorithm is proposed that obtains the optimal operating point (the point where the maximum power can be taken from the solar modules) by considering non-linear characteristics of the voltage - power under different working conditions.

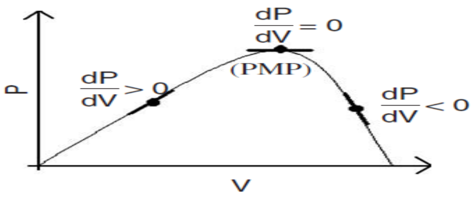

Fig. 1. Characteristics curve of the P-V photovoltaic generator. Variation of the dp/dv [11]

As considered in Figure (1), the voltage changes compared with the power changes when the power is in its maximum value is set to zero, and the following results are obtained from this diagram [11]:

$$\frac{dPpv}{dVpv} > 0 \rightarrow Vpv < Vpmp \qquad (1)$$

$$\frac{dPpv}{dVpv} = 0 \rightarrow Vpv = Vpmp \qquad (2)$$

$$\frac{dPpv}{dVpv} < 0 \rightarrow Vpv > Vpmp \qquad (3)$$

Our proposed model includes a combination of p & o and Conductance incremental models and has the following advantages: 1 – it is relatively simple and low cost. 2 – Due to reduced calculations, the speed of this model is high compared to the p & o. The results obtained from the (1), (2), (3) are used and the flowchart is proposed in Figure 2 for implementation. In the above algorithm, Ii (t), Vi (t) are the output current and voltage of the solar module at time t. First, the output voltage and current of the module at time t are measured and the power at this t is calculated and then derivation of ($\frac{dP(t)}{dV(t)}$) is obtained. If the value of this derivation becomes zero, the measured current and voltage are in their maximum value at time t and otherwise if it does not become zero, one can set the $\frac{dP(t)}{dV(t)}$ derivation to zero by adding or subtracting a constant value (0.01) to the input voltage. To verify the performance, MATLAB software is used in simulation. Since the maximum power should be taken from the solar array and simultaneously output of the buck converter circuit should be regulated, hence, one needs another combined controller which is proposed in Figure (3).

In Figure 3, Block of a solar module is connected to a buck converter. A capacitor is used as a filter at the input of the buck converter, and a resistive load is used at the output of the converter. In this circuit, the reference voltage is 26 volts. As you can see the difference between the reference voltage and the output voltage of the converter is subtracted from MPPT output and is given to a pulse generator by means of a Proportional-Integral (PI) in order to provide the appropriate pulse required for the switch be generated.

2.4. *Equivalent circuit of the pipeline and the anode-bed*

A handbook in cothodic protection has been used to find parameters of the equivalent circuit of the pipeline [1, 12]. By considering parameters of the final equivalent circuit, a pipeline with the anode bed is shown in Figure 5 that is supplied with a DC source.

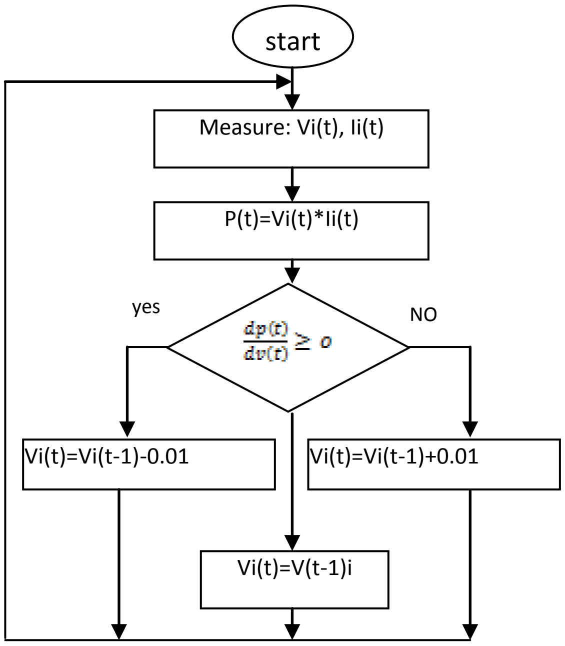

Fig. 2. Proposed flow chart of MPPT algorithm

Table 5. generated power by one & four 275w 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 module)	Average production on month in wh	The difference between production and consumption in a month
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

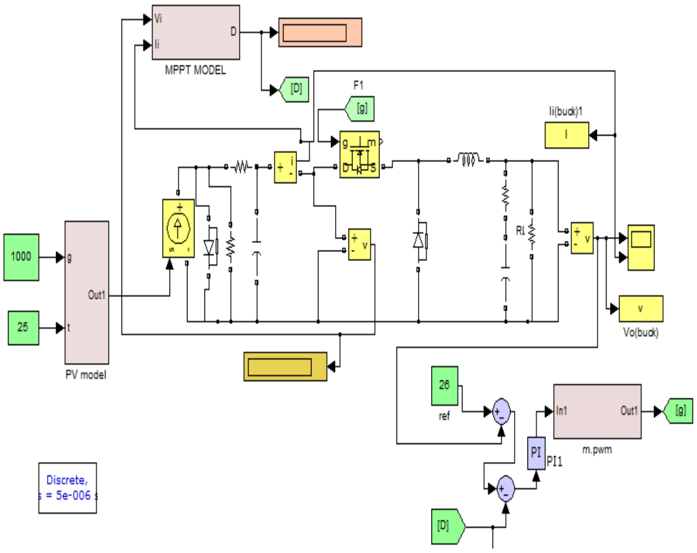

Fig. 3. The combination of Buck Output Voltage Controller and MPPT controller

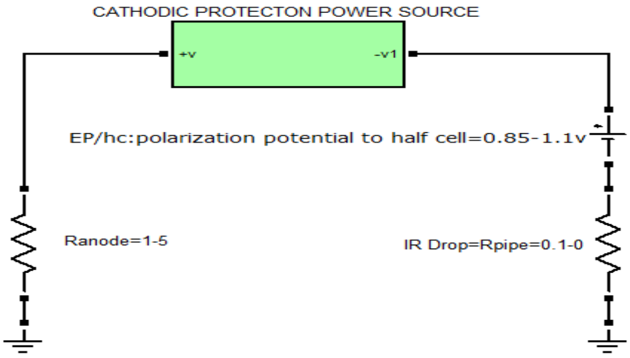

Fig. 5. Equivalent circuit of pipeline and ground bed

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

	Iout	Vout	Vdp
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

3. Total modeling of solar cathodic protection

Figure (7), shows the entire solar cathodic protection system. Initially, a 2750w 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 [9]. 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.

4. Calculations and optimal selection of the facilities

For designing the entire solar cathodic protection system, the lifetime is assumed to be 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 5.004kwh in 24 hours. The output voltage of the transformer in early years of foundation was very low but over the time that was along with weakening the coating of the 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 (8), (9) in graphs V-P , V-I show a sample of a 275w solar panel of the FARAN company. As you can see the solar array in the worst climate conditions of December (Brightness 422.1 w/m2) generates an 118w power and in the best climate in July it can generate a power around 275w. It should be noted that these figures have been achieved by applying the actual data obtained from Meteorological Organization of Ardebil to designed pv model. obtained from Meteorological Organization of Ardebil 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. 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 116649.6wh power deficiency in the months of October, November and December, and, given that there is 15834wh power overproduction in the months of January and February and this can be enough to make up for the months of March and April and there will be 30184.8wh 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 to be 21 years and the battery life is assumed to be 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 155760wh and the difference between production and consumption will be 5640wh and 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's 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, 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= 5004wh

Power deficiency in a day from December= $\frac{8520}{30}$= 284wh

Power deficiency on a cloudy day in the 29 days of December + Consumption on a cloudy day = 8236+5004=13240wh

That is, the battery should be selected so that, it can stores 13240wh, 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.

5. The economic comparison between cathodic protection with the photovoltaic system and cathodic protection with the 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. Also it is necessary to have a rectifier transformer with relevant chamber. Every USD is assumed to be 3,000 Iranian Toman.

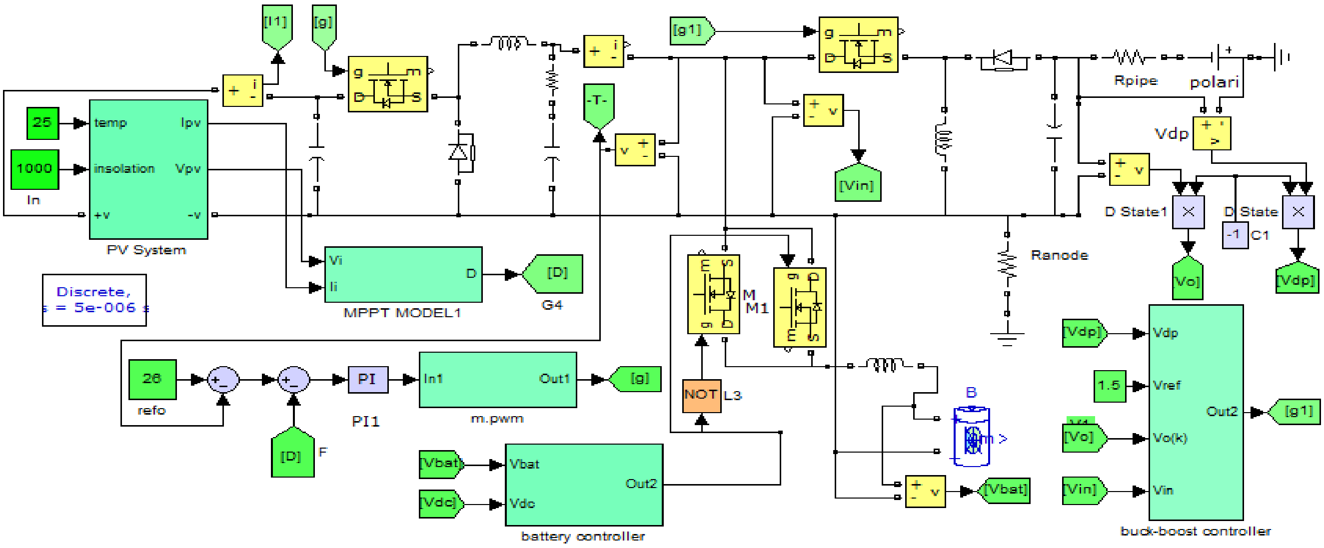

Fig. 7. Circuit diagram of the intelligent solar cathodic protection

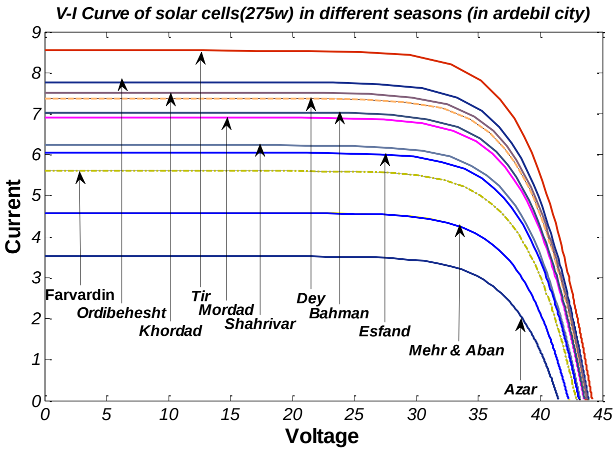

Fig. 9. Curve V-I for 275w module

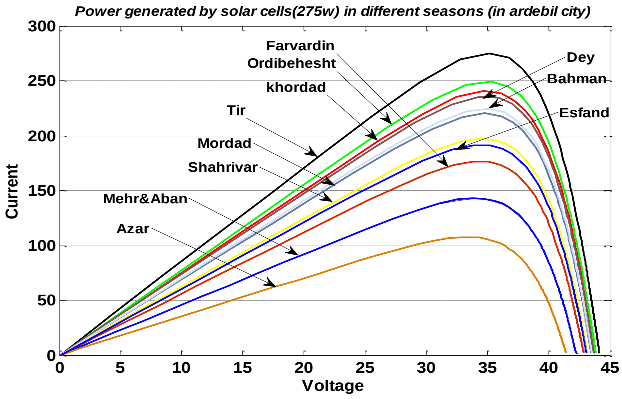

Fig. 8. Curve P-V for 275w module

6. Sımulatıon 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 10 show that one can take maximum power from the solar cell with this controller(solkar 36WPV controller, a variable load ranging from 5 to 1000 ohms is inserted instead of the battery. Since the 24v battery has been used, hence for charging the battery, a higher voltage should be used, so the constant value is assumed to be 26v. Simulation results are shown in Figure 11. 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(12), 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 (1.5v). To show the appropriate performance of the controllers, the system is tested with the voltages above the level of the designed voltage. Figure 13 is the output voltage curves of the solar cathodic protection system with different inputs. As can be seen, no fluctuation is found in the output voltage of the system, indicating that the system is functioning properly.

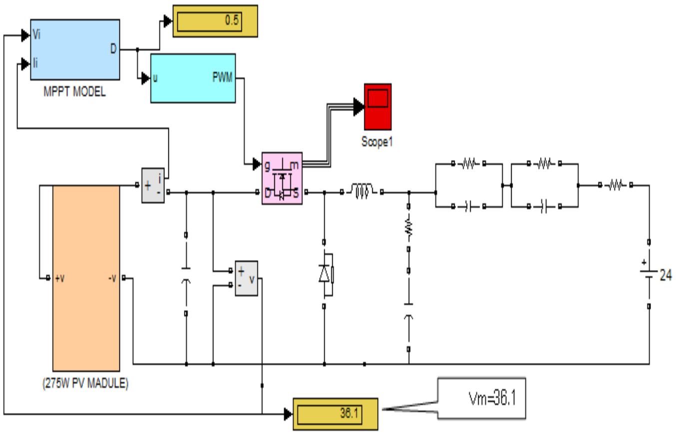

Fig. 10. The results of the MPPT control circuit acts on Buck Converters

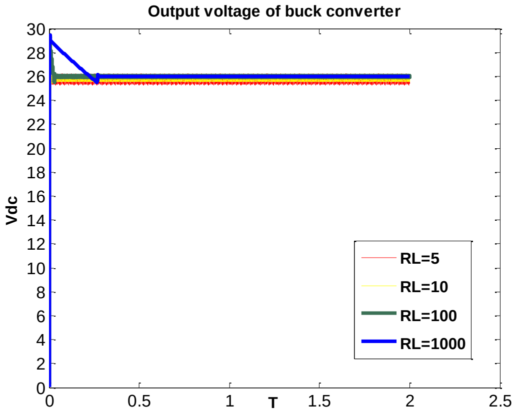

Fig. 11. output voltage of buck converter with diffirent load

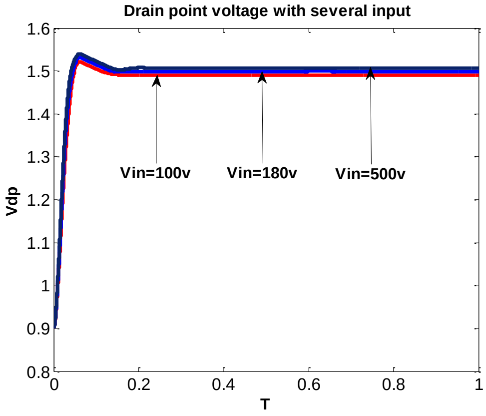

Fig. 12. Drain point voltage with several input

7. 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, the weight and dimensions of the system are reduced. To control this system, the first and second controller is related to the combined controller of the MPPT with the controller of the output voltage of the buck converter. 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.

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	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 the 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
The total cost of maintenance of the 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

Acknowledgement

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