Monitoring and Control on Impressed Current Cathodic Protection for Oil Pipelines

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Abstract

This research is devoted to design and implement a Supervisory Control and Data Acquisition system (SCADA) for monitoring and controlling the corrosion of a carbon steel pipe buried in soil. A smart technique equipped with a microcontroller, a collection of sensors and a communication system was applied to monitor and control the operation of an ICCP process for a carbon steel pipe. The integration of the built hardware, LabVIEW graphical programming and PC interface produces an effective SCADA system for two types of control namely: a Proportional Integral Derivative (PID) that supports a closed loop, and a traditional open loop control. Through this work, under environmental temperature of 30°C, an evaluation and comparison were done for two types of controls tested at low soil moisture (48%) and high soil moisture (80 %) to study the value of current, anode voltage, pipe to soil potential (PSP) and consumed power. The results show an decrease of 59.1% in consumed power when the moisture changes from the low to high level. It was reached that the closed loop controller PID is the best solution in terms of efficiency, reliability, fast response and power consumption

Keywords: Impressed Current Cathodic Protection, PID Control, Oil Pipeline, SCADA.

1. Introduction

Many serious engineering and economic problems result from pipelines corrosion in oil production, transportation and industry. This requires employing suitable procedures and techniques for protection from corrosion. Impressed current cathodic protection (ICCP) is one of most used effective methods in oil industry to reduce the corrosion of carbon steel pipelines that are in direct con-tact with the ground, buried in soil, immersed in water or any aqueous environment. It is well known that Iraq has a large number of pipeline networks in oil industry and transportation crude oil, natural gas and final hydrocarbon products. Unless suitable protection techniques are used, these networks are exposed to extensive damage due to the ground and underground corrosion processes resulting in serious engineering and economic problems. As a matter of fact, many methods are used to reduce the corrosion of carbon steel pipes in that field such as painting, coating and cathodic protection (CP) systems. The latter is considered as one of the most important and effective methods [1]. CP is a technique used throughout the world to control and prevent the electro-chemical corrosion for metallic structures, that are buried or submerged in corrosive environments such as wet soil or water by making them the cathode of an electrochemical cell [2]. Corrosion occurs if four components exist namely: anode, cathode, electrolyte and metallic path. A natural potential develops when two or more dissimilar metal or alloys are placed in an electrolyte or an aqueous environment. One metal plays the role of anode and gets corroded while the other becomes the cathode. The behavior of a metal as an anode or a cathode depends on its position in the galvanic series, in which the different alloys are ranked according to their anodic or cathodic tendencies in a particular environment [1, 2].

CP operation is based on making the potential of the structure sufficiently negative (cathode) with respect to the surrounding medium to ensure no cur-rent flows from the metal to the medium. This is done by forcing the electric current to flow through the electrolyte towards the surface of the protected metal. CP does not work on structures exposed to poor electrolyte (nonconductive environment), such as air, that prevents the current from flowing from the anode to cathode [3]. CP may be achieved in one of two methods:

1) Sacrificial anode: based on forming an electrochemical circuit by achieving an electrical connection between the protected metallic structure (cathode) to a sacrificial metal of more negative potential acts as the anode. The anode corrodes (sacrificed) while the metal structure is protected. Electrons are supplied to the cathode and a corresponding amount of anode material goes into solution as metal ions. The sacrificial anode, typically zinc or magnesium, is consumed and must eventually be replaced. CP relatively requires small current where the soil resistivity is low (less than 10,000 Ω. cm).

2) Impressed current cathodic protection (ICCP): this technique employs a di-rect current source to impress current between an auxiliary external inert an-ode, such as scrap iron, and the cathode (protected structure) [1,4].

Nowadays, a lot of smart industrial control systems include supervisory control and data acquisition (SCADA) systems that are used to control dispersed distant operations. A SCADA consists of a number of remote terminal units (RTUs) collecting field data connected back to a central unit through a communications system. The central unit monitors the acquired data and al-lows the operator to perform different remote control tasks allowing the optimization of the controlled application to take place [5].

CP has been investigated by many specific researches for studying the different aspects of such processes. Ali [6] studied several ICCP factors that affect the pipe protection from corrosion such as anode position (distance and depth), soil resistivity (wet and dry), the pipe condition (coated and un-coated) and the amount and distribution of required current to achieve protection for a carbon steel pipe that is buried in soil. Turc [7] has presented a solution for managing the devices and virtual instruments in a SCADA system by introducing a platform that makes use of semantic protocols to achieve flexible communication. Balla [8] has designed a simulation and online implementation that works to control ICCP systems for carbon steel pipes. The obtained model shows a good representation of ICCP systems and the confirmed experimental results show a good response to the set point changes. Gopalakrishnan [9] has developed a PID corrosion controller using VI (LabVIEW) for a CP process. At the field, the PSP potential was within the safe operating limits and the external corrosion was controlled for underground natural gas metallic pipelines.

This investigation is concerned with the design and implementation of a SCADA system for monitoring and controlling an ICCP system. This ICCP system was built to control the electrochemical corrosion of a lab scale carbon steel pipe in two modes namely; the traditional open loop mode and PID closed loop mode. The control process was materialized by controlling the ap-plied anode voltage to keep the protection potential (Pipe to Soil Potential (PSP)) within the anticorrosion limits. The objective is to build an ICCP smart station rather than the traditional manually controlled station.

As known, in open loop systems the inputs are applied to drive the out-puts with no knowledge of the system output through feedback signal. There-fore, this type of control is not attractive and is mostly affected by the disturbances [10]. The closed loop developed to use the concept of open loop with addition of one or more feedback between the output and the input. Proportional Integral Derivative (PID) control is a closed loop control strategy that uses proportional, integral, and derivative feedback as shown in the Figure (1). A PID controller adjusts the output at a level of less difference between the sensing value (sv) and the specified set point (sp) [11].

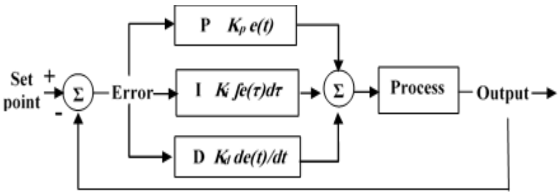


Figure 1: PID block diagram [11].

With proportional controller (P), the signal changes in proportion to the error between the set point and the process variable. Adding integral controller (I) can eliminate the steady-state error but may increase overshoot. The derivative (D) part of the controller is mostly known for its ability to reduce rate of change of the controller output. The response of the PID system adds the three required components [12]:

$$U = k_p e + k_i \int_0^t e dt + k_d \frac{de}{dt} \quad (1)$$

$$k_i = \frac{kp}{Ti} \quad (2)$$

$$k_d = k_p \times T_d \quad (3)$$

$$e = sp - pv \quad (4)$$

where, U is the controller (output), k_p, k_i and k_d are the gains for proportional, integral and derivative respectively. Ti is the integral time (s), Td is the derivative time (s) output, e is the error, sp is set point or the desired value, pv is process variable (sensor measured value).

Table (1) describes the relation between PID parameter performance and their influence in the system stability.

Table 1: PID Parameters [12].

PID Parameter	k_p	k_p	k_p
Overshoot	Increase	Increase	Decrease
Rise time	Decrease	Decrease	Small change
Setting time	Increase	Increase	Decrease
S-S Error	Decrease	Eliminate	Small change

2 Experimental Work

2.1 Materials

A low carbon steel, grade X1325, pipe was used in this work, the choice of this type of material is related to its wide use in oil and natural gas industry and transportation. Carbon steel alloys are characterized with good ductility and toughness. Typically, they have a yield strength of 275 MPa, tensile strengths of 415 to 550 MPa, and a ductility of 25% EL. Table (2) presents the chemical composition analysis of the selected metal which is done at the Corrosion Department Laboratory-Ministry of Science and Technology.

Table 2: The chemical composition of the used carbon steel pipe.

C %	0.25
Si %	0.6
Mn %	1.65
S %	0.03
P %	0.03
Cr %	0.3
Ni %	0.3
Cu %	0.5
V %	0.06
Fe %	95.21
others	1.07

The segment of carbon steel pipe has dimensions of 27 cm length, 11.5 cm out-side diameter and 1cm wall thickness. A second segment of scrap iron of 30 cm length, 3.5 cm width and 2 cm height was used as anode.

2.2 Experimental Setup

A Copper wire was brazed to the carbon steel pipe (cathode) outside surface to achieve tight negative electrical connection with the system, then it horizontally buried inside a wooden box filled with soil at a depth of 0.5 m. Like cathode, a copper wire was brazed to the iron segment (anode) outside surface to achieve the positive electrical connection with the system. The anode was located horizontally opposite to the pipe at the same level.

A number of electrical and electronic components were integrated with the setup to build the ICCP control system as shown in Figure (2). The PID closed loop control system elements and function are simply illustrated in the form of block diagram in Figure (3). An important sensor named copper copper sulfate reference electrode (CCSRE) was installed above the submerged pipeline to measure the potential protection voltage PSP and send it to the microcontroller as a feedback signal for continuous monitoring and controlling. The microcontroller, which is considered a Remote Terminal Unit (RTU), is based on the Arduino platform controller. It has a very fast response to deal with the feed-back and generate an error signal. The later value is essential for making the necessary correction to the applied anode voltage to reduce the error and keep the PSP value within the specified limits (-0.85 V to -1.125 V). The microcontroller drives a dual full bridge driver type Lm298N to supply the necessary clockwise or counter clockwise 0-12 V anode voltage and keep the protection potential within the mentioned limits. A number of sensors were employed to sense and feed the microcontroller the important ICCP system parameters such as soil humidity, environment temperature, drain current and anode voltage.

Figure 2: The built ICCP system components.

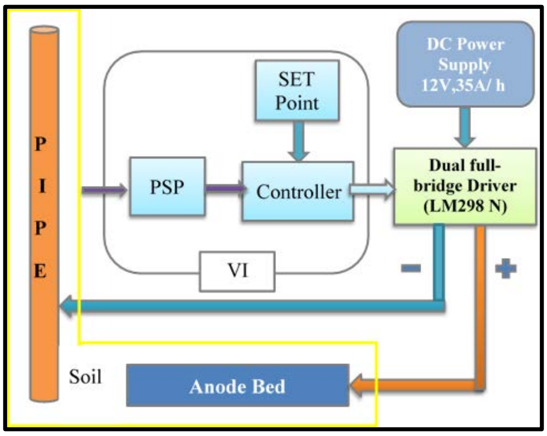
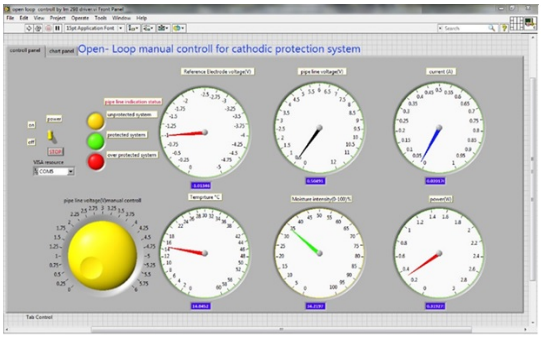


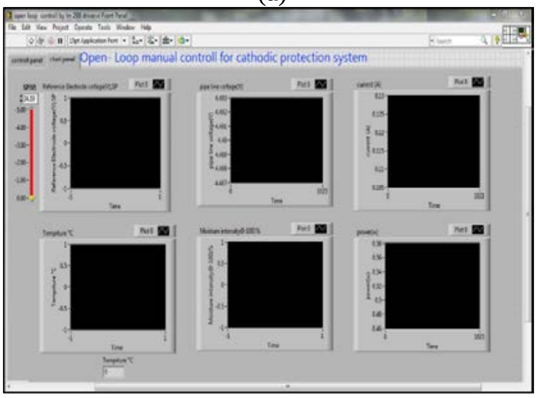
Figure 3: The ICCP system block diagram.

2.3 ICCP System Design

The built ICCP system was operated in two modes of operations: the traditional open loop mode and PID closed loop mode. The first one is adjusted and monitored manually and the latter is a smart system in terms of monitoring and control operations. The LabVIEW package, which is a system design platform and development environment from National Instruments, was used for designing and implementing the experimental part of the control system for both modes. It provides the sufficient tools to design and implement a real time smart SCADA system. With LabVIEW graphical programming a human machine interface (HMI) was implemented to present the ICCP system information to the operator, collect data, and control the process. Figure (4) shows the HMI for the open loop control system where data visual monitoring and manual adjusting processes are carried out. Through the front panel, the operator manually adjusts the applied anode voltage and measures the protection potential PSP, applied anode voltage, current flow, power consumption, environment temperature and soil moisture.



(a)



(b)

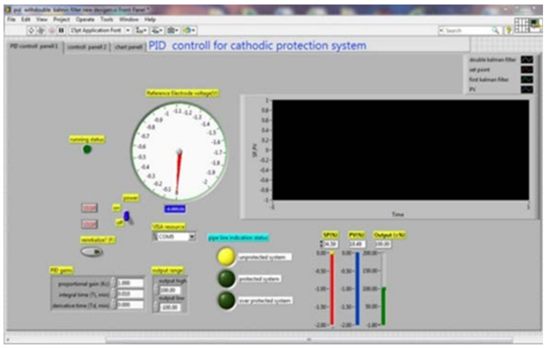
Figure 4: LabVIEW HMI design for the open loop system; (a) front panel and (b) Time graphs panel for the measured parameters.

Figure (5) shows the LabVIEW design of SCADA system HMI for PID real time controller for the ICCP system. With this inter-face, the role of the operator is limited to the adjustment of the set point, while the other procedures of monitoring and controlling take place automatically.

3 Result and Discussion

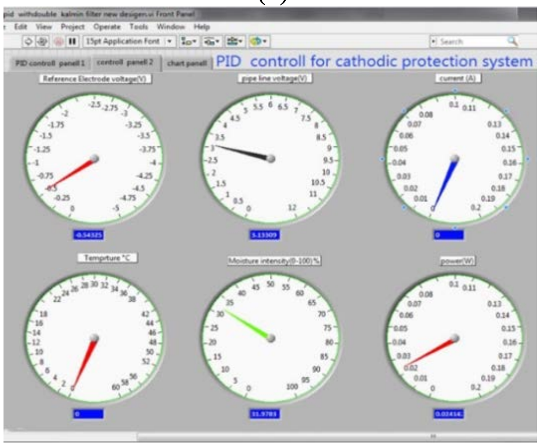
The investigation strategy is based on applying an ICCP control on a carbon steel pipe with two control modes, the traditional and smart, to maintain the protected pipe within the upper and lower protection limits. If the PSP drops below the lower limit the CP will lose its function and oxidation occurs. On the contrary, when the PSP overshoots beyond the upper limit, the pipe will suffer from surface coating degradation.

The goal is to find the optimum working parameters and test the performance and effectiveness of both control modes. The results of both modes are taken under the same condition of temperature environment (30 ○□C) and two levels of soil moistures: the medium level of 48% (symbolized by M) and the high level of 80% (symbolized by H).



(a)

(b)



(c)

Figure 5: LabVIEW HMI design for the PID closed loop system; (a) front panel and (b) Time graphs panel for the measured parameters and (c) meters panel.

3.1Traditional Open Loop Results

In this mode, reaching the PSP steady state value of -0.9 V for both soil moisture levels requires more than 90 s which is so small when compared with the long protection lifetime of the pipe as seen in Figure (6).

The protection voltage region is limited between the upper limit of -0.85 V and the lower limit of -1.125 V. The measurements through the LabVIEW HMI show that when the open loop system reaches the setting time the anode voltage and the drain cur-rent settle at 3.18 V and 0.155 A respectively for the M-level, and 7.7 V and 0.49 A respectively for the H-level as graphed in

Figure (7). Also, this test shows a dramatic increase in the consumed power from 0.494 W to 3.77 W when the soil moisture changes from M to H level.

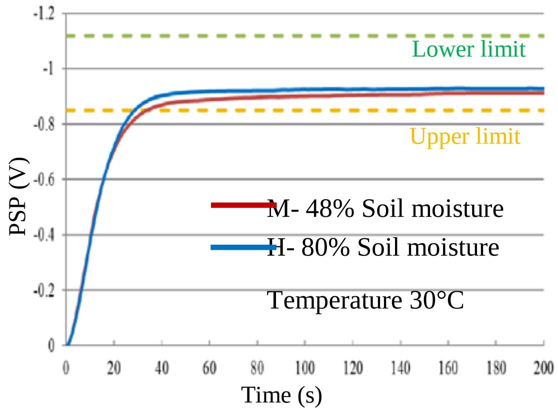


Figure 6: PSP value and setting time for M and H soil moisture levels of traditional open loop control.

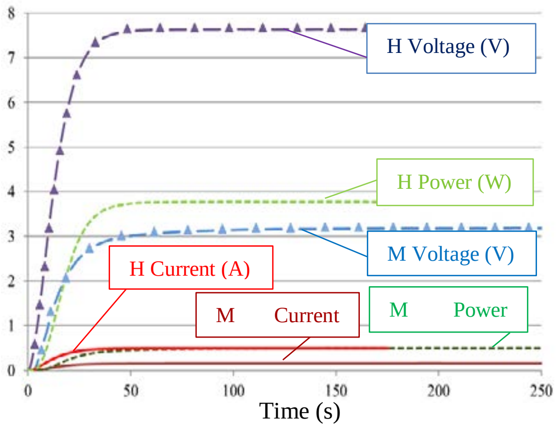


Figure 7: Open loop control setting time of the anode voltage, drain current and consumed power for both levels of soil moisture (M and H levels).

The evident variation between the results of both tests, M and H, can be related to the changes in soil resistance due to soil moisture variations. The increase of the water content in the soil increases the moisture and decreases the soil electrical resistance. This imposes maintaining the protection voltage PSP within the protection limits. According to Ohm's law (V=RxI) when the soil resistance between anode and cathode decreases, the applied current should be increased. Thus, the applied voltage should be increased manually to reach to the required PSP voltage. This explains the current, voltage and power consumption increasing in open loop ICCP system.

3.2 The Smart PID Closed Loop Results

Unlike the manual traditional control in previous section, the smart PID controller activates the system with the required anode voltage to verify the protection PSP voltage within the required limits (-0.85 V to -0.12 V). The first experiment was done under the M-level of soil moisture and the second one was done while the soil moisture changes from M-level of 48% to the H-level of 80% during its normal operation. Furthermore, the smart PID system was tested for a long time under intentional changes for the environmental conditions. The dynamic measurement of the PSP voltage is accomplished with electronic and environmental noises. Therefore, filters were used to reduce the signals noise and make the readings more stable. The PSP voltage measurement was carried out at three different conditions of measurements namely: direct measurement without using filters, measurement with using the Kalman filter and measurement with using double Kalman filter.

Figure (8) illustrates the value of measured PSP voltage as a function of time at the above three mentioned measurements. As shown, the PID controller tries to keep the PSP voltage almost constant along the protection time within the protection limits. The drawback of signal measurement without filter is the accomplished environmental or systematic errors that appears in form of ripples as seen inside the magnified circles in the graph. This imposes using filters to remove the unwanted components. The aim of using Kalman filter is to smooth the noisy data and provide accurate estimates of the ICCP dynamic system parameters. By using single Kalman filter, the protection voltage approaches its final value (-0.9 V) gradually taking more time than the no filter case. The set-ting time in the case of using double Kalman filters is much higher than single filter case. The essential function of the feedback is to reduce the error between the variable and the specified set point value to zero quickly. The error signal was calculated through the integral absolute error (IAE) and the integral square error (ISE) [8]:

$$\text{IAE}=1/n\sum_0^n |E| \qquad (5)$$

$$\text{ISE}=1/n\sum_0^n E^2 \qquad (6)$$

where n is the number of readings and E the estimated error.

The calculation shows remarkable results of 0.00057466 and $1.15\text{x}10^{-6}$ for the ISE and IAE respectively. Three sides in Figure (9) can be seen, the first one shows the function of PID control in maintaining the PSP voltage within the protection limits when the soil moisture changed from the M-level to H-level (48% to 80%) after adding an amount of water along the pipe layout as shown in the magnified zone of Figure (9a) in Figure (9b). The PID controller monitors the output and compares it with the set point value.

The returned feedback signal form the PSP is analyzed by the PID controller.

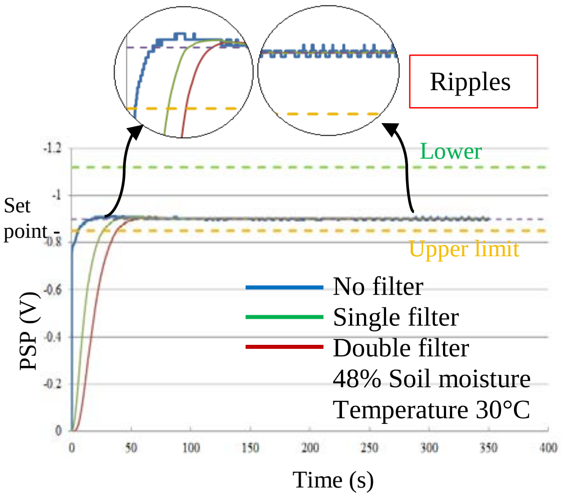


Figure 8: PSP value and setting time for M soil moisture level of the PID controller.

The returned feedback signal form the PSP is analyzed by the PID controller. The difference between the actual and desired output (error signal) is applied as feedback to the input system to bring the actual output closer to the set point of -0.9 V. The second one is the effectiveness of the system to keep the PSP voltage within the specified limits at -0.9 V. The last side is the reliability of the system to maintain the PSP voltage at -0.9 V under different environmental conditions of soil moisture and environment temperature and humidity. Figure (9c) shows a magnified zone on the graph of Figure (9) for a period of time after two days from the commencement point, at that time the system was tested under intended rain which was done by the researcher. Here, the important feature is the fast response time (about 3 min) of the controller with respect to the protection lifetime.

Once again, as shown, the set point was adjusted at the -0.9 V value for the protection voltage PSP. Without using filters, the system output rapidly reaches to the set point value accomplished with ripples. While by using filters, the unwanted components were removed. The role of using the Kalman filter in the PID tests is for smoothing noisy data and providing estimates of ICCP dynamic system parameters. By using single Kalman filter, the protection voltage approaches its final value (-0.9 V) gradually taking more time than the no filter case. The setting time in the case of using double Kalman filters is much higher than single filter case.

Figure (10) shows the collection of parameters measurements for the M and H levels of soil moisture. The applied anode voltage shows a vivid increase at the commencement of protection then settles at a voltage of 2.9 V and 7.7 V for the M and H levels respectively. Likewise, the behavior of the drain current and the consumed power are the same, they settle at the values of 0.136 A and 0.381 W respectively for the M-level. Also, the drain current and consumed power for the H-level settle at 0.13 A and 3.8 W respectively. The protected pipe was tested periodically to ensure that the ICCP process works within the standard protection methods.

4. Conclusions

The following points are the concluding remarks from the current investigation:

1. Using the closed loop PID control in an ICCP process is more effective and reliable than the traditional open loop one. The later needs continuous monitoring and manual adjustment according to the visually observed PSP voltage. The system offers a real-time observation for the PSP value and automatic controlling through applying the appropriate value of impressed anode voltage.
2. Using Kalman filter is essential to reduce the fluctuation and ripples in the observed PSP signal and enhance the process of control.
3. The PID controller offers a fast response time at the starting of the process and during the protection time. The recorded values of response time are 10 s for without filter, 40 s with single filter, 70 s with double filter and about 3 min for environmental changes of soil moisture.
4. The measured working parameters namely: the applied anode voltage, drain current and consumed power increase with increasing the soil moisture for both the traditional and the smart systems. For the PID control system the consumed power shows an increase by 11 %, the anode voltage 40 % and drain voltage 44 % when the soil moisture moves from the M-level to the H-level.
5. It can be ensured that the PID controller had the capability of minimizing the visual monitoring works and give an excellent response when compared with the open loop controller. Therefore, the PID controllers are the best alternative for the traditional open loop systems.

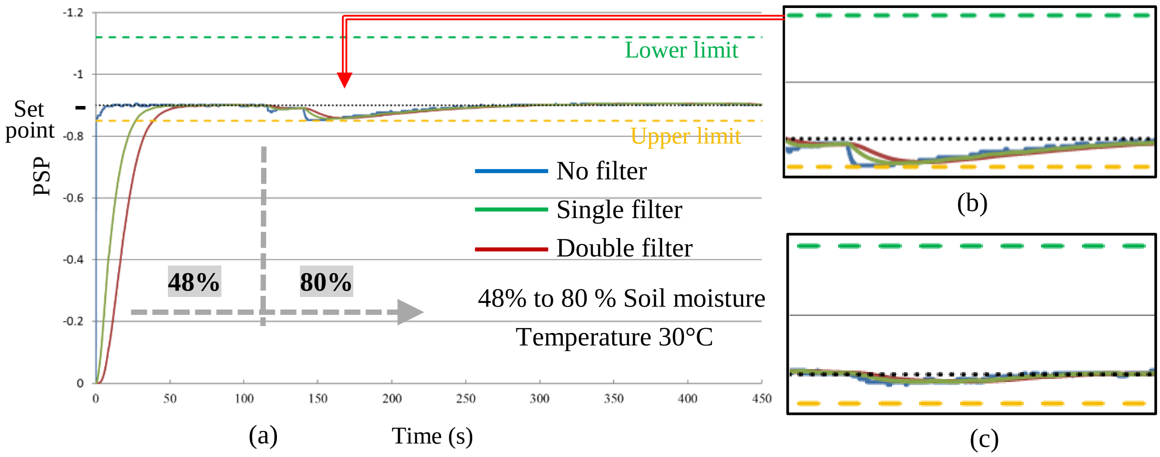


Figure 9: PID control setting time of the anode voltage, drain current and consumed power for both levels of soil moisture (M and H).

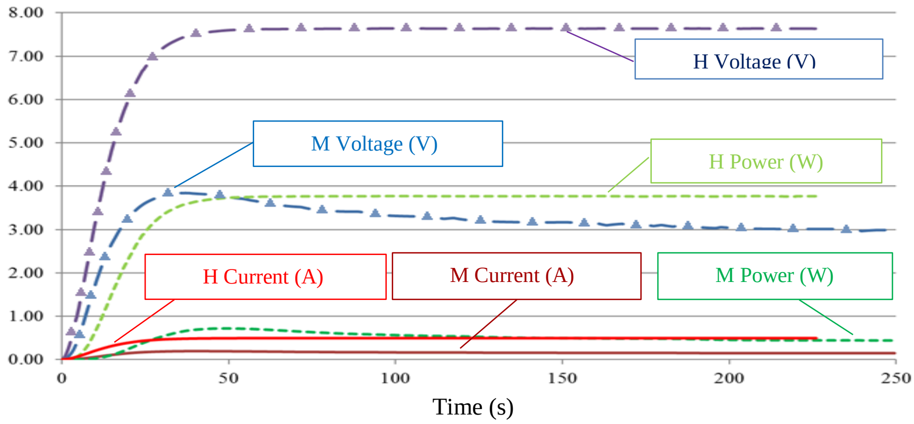


Figure 10: PID control setting time of the anode voltage, drain current and consumed power for both levels of soil moisture (M and H levels).

Acknowledgments

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تنفيذ منظومة للمراقبة و السيطرة على منظومة حماية كاثودية ذات التيار القسري المسلط لأنابيب النفط

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الخلاصة

يتضمن البحث تصميم وتنفيذ منظومة مراقبة اشرافية وجمع المعلومات والسيطرة المسماة الاسكادا (SCADA) لغرض المراقبة والسيطرة على تاكل انابيب الكاربون ستيل المدفونة تحت سطح التربة والمخصصة لنقل النفط ومنتوجاته. حيث تم تصميم منظومة ذاتية باستخدام المسيطر الدقيق (المايكروكونترولر) ومجموعة من المتحسسات لمراقبة منظومة الحماية الكاثودية ذات التيار القسري. استخدم برنامج اللاب فيو لبناء البرنامج الخاص بمنظومة الاسكادا حيث تم استخدام هذا البرنامج لبناء نوعين من المنظومات, الاولى تحاكي المنظومة التقليدية والمنظومة الثانية هي منظومة سيطرة البي اي دي (PID) المتقدمة. تمت عمليات الاختبار و المقارنة للمنظومتين في ظروف تغيير الرطوبة النسبية من 48% المتوسطة الى 80% العالية في درجة حرارة 30C° لدراسة التيار المسلط وجهد الانود والقدرة المستهلكة للمنظومة حيث وجد ان القدرة المستهلكة قلت الى 59.1% عند تغيير رطوبة الرطوبة النسبية للتربة من الادنى الى الاعلى وعند استخدام المسيطر البي اي دي. كان استخذام هذا المسيطر هو الحل الامثل والاكثر دقة واعتمادية وسرعة استجابة بالاضافة الى ناحية القدرة المستهلكة.