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Research Article

Cathodic Protection of Pipeline Using Distributed Control System

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Distributed control system (DCS) is available in most of the compressor stations of cross-country pipeline systems. Programmable logic controller (PLC) is used in all the intermediate pigging (IP) stations/sectional valve (SV) stations to collect the field data and to control the remote actuated valves. This paper presents how DCS or PLC can be used for cathodic protection of gas pipelines. Virtual instrumentation (VI) software is used here for simulation and real-time implementation purpose. Analog input channels available in DCS/PLC can be used to measure pipe to soil potential (PSP) with the help of half-cell and voltage transducer. Logic blocks available in DCS can be used as low selector switch to select the lowest PSP. Proportional-integral (*PI*) controller available in DCS/PLC can be used for taking the controlling action. *PI* controller output varies the firing angle of AC phase controller. Phase controller output is rectified, filtered, and fed to the pipeline as cathodic protection current. Proposed scheme utilizes existing infrastructure to control pipeline corrosion.

1. Introduction

Corrosion is a phenomenon by which metal is etched away naturally contributing to material loss. Corrosion reduces the life of metal structures. Methane rich natural gas is being transported through underground metal pipeline at high pressure. Corrosion in pipeline leads to material loss, gas leakage, and interruption in gas supply. Underground metallic pipelines are primarily protected by coatings. Impressed current cathodic protection is used to protect pipelines from coating defects. When pipeline is laid underground, soil acts as electrolyte in a corrosion cell and corrosion occurs in metal pipeline primarily due to differential corrosion cell. By impressing current to the pipeline, the entire structure is made to become a cathode of the corrosion cell. Impressed current corrosion controller should be dynamic enough to protect pipelines from ill effects due to variation in coating defects, soil resistance, soil pH, temperature, and so forth. The main objectives and requirements of cathodic protection (CP) systems are to prevent external corrosion throughout the design life of the pipeline by providing sufficient current to the pipeline to be protected. Distributed control system (DCS) is available in most of the compressor stations of cross-country natural gas pipeline systems. Programmable logic controller (PLC) is used in all the intermediate pigging (IP) stations to collect the field data and to control the remote actuated valves.

Impressed current cathodic protection and details on pipe to soil measurement and half-cell are available in [1]. Laboratory set-up for impressed current cathodic protection is given in [2]. Details on *PI* controllers and their tuning are given in [3, 4]. Module type switching rectifier for maritime application is given in [5, 6]. Virtual instrumentation (VI) basics and its application for fault diagnostic are given in [7]. Application of virtual instrumentation for cathodic protection stray current monitoring is reported in [8]. Virtual instrumentation for natural gas pipeline corrosion control is reported in [9] and its autotuning is discussed in [10]. This paper deals with how DCS/PLC can be utilized for gas pipeline corrosion monitoring and control.

2. Experimental Procedure

Schematic diagram of the proposed pipeline cathodic protection through DCS is shown in Figure 1. Portable Copper-Copper Sulphate (Cu $CuSo_4$) half-cell reference

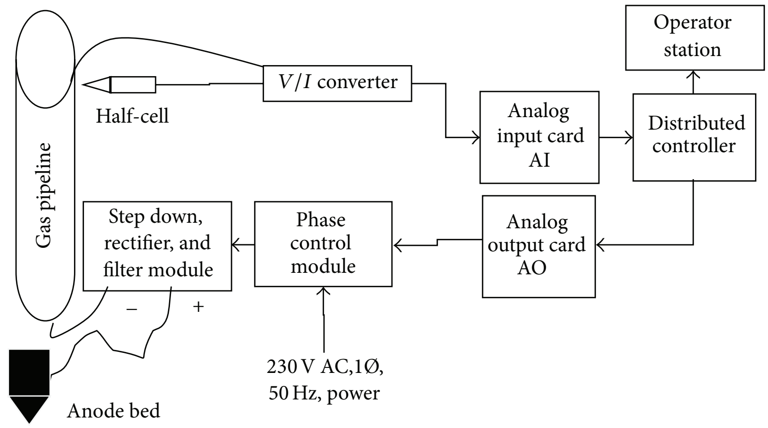

Figure 1: Schematic diagram of cathodic protection through distributed control system.

electrode is used to measure the pipe to soil potential (PSP) of the underground metallic gas pipeline. For simulation and implementation [2] purposes virtual instrumentation (VI) software (which contains most of the features available in the commercially available DCS systems) is used. In normal case PSP will be in the range of −0.4 to −1.5 volts. PSP signal is fed to the analog input card. Desired set point (normally −1.2 volts) is fed through operator station. Proportional-integral (*PI*) controller is used to take corrective action. Output of the controller is used to vary the single phase AC phase controller triggering angle. Varied AC is rectified, filtered, and fed to the pipeline as counter corrosion current (impressed current).

Operator screen is designed in such a way that user can monitor and control PSP from a single screen. Designed operator screen is shown in Figure 2. Desired proportional gain and integral time are set through operator screen. Auto/manual action can be selected. In manual mode, set point (SP) goes as manipulated variable (MV), that is, output; whereas in auto mode *PI* controller takes corrective action.

Program written to control the corrosion in pipeline is shown in Figure 3. Conventionally, for impressed current control purpose, 24 V/20 A or 50 V/50 A transformer rectifier unit is used based on the line size and line length. In the proposed controller, instead of using single unit, it is split into four units of 24 V/5 A. Normally one unit will cater the impressed current requirement of the pipeline and additional power modules of 24 V/5 A will be added (switched on) based on the load (pipeline coating damage/line exposure) requirement. To avoid abrupt change in the output when the two power modules are added in parallel, gradual loading of additional module is done by introducing slope. Flip flop is used to switch on the additional power module. For instance, in the program, additional module is selected once the output current crosses 8 A and additional module is disconnected once the output current is reduced to 5 A.

PI (proportional-integral) control is the most common control used in industry. *PI* controller consists of two basic coefficients, proportional gain (*P*) and integral constant (*I*), which are varied to get optimal response. The basic idea behind a *PI* controller is to read a signal and compare it with the set point and then compute the desired actuator output by calculating proportional and integral responses and summing those two components to compute the output as given in

$$\mathrm{CO} = K_p e + K_i \int e\,dt, \quad (1)$$

where CO is the controller output, e: Error (e) = Set point − Process Value, K_p is the proportional gain, and K_i is the integral constant.

The proportional component [4] depends only on the difference between the set point and the process variable. This difference is referred to as the "*error*" term (e). The proportional gain determines the ratio of output response to the error signal. For instance, if the error term has a magnitude of 10, a proportional gain of 5 would produce a proportional response of 50. In general, increasing the proportional gain will increase the speed of the control system response. However, if the proportional gain is too large, the process variable will begin to oscillate. The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. Steady-state error is the final difference between the process variable and the set point. The integral response will continually increase over time unless the error is zero, so the effect is to drive the steady-state error to zero.

The process of setting the optimal gains for *P* and *I* to get an ideal response from a control system is called *tuning*. Once the proportional gain is increased then the system becomes faster, but care must be taken not to make the system unstable. Once *P* has been set to obtain a desired fast response, the integral term *I* is increased to stop the oscillations.

A sensor (half-cell) is used to measure the process variable (PSP) and it provides feedback to the control system. The set point is the desired or the command value for the process variable. The difference between the process variable (PSP) and the set point is used by the control system to determine the desired actuator output to drive the system.

Controller module output is fed to the phase control module (output AC voltage varies based on controller output). For zero crossing detection purpose synchronous voltage has to be given to the phase controller. AC phase controller output

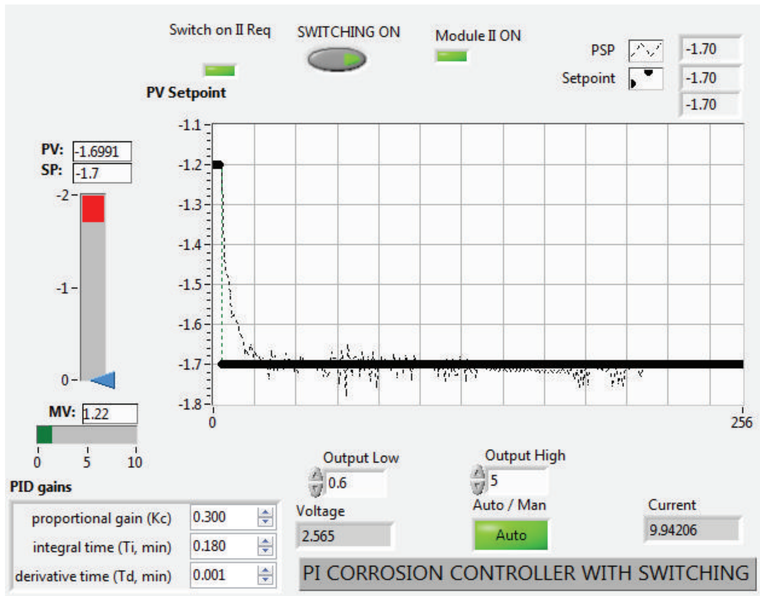

Figure 2: Operator screen of corrosion controller.

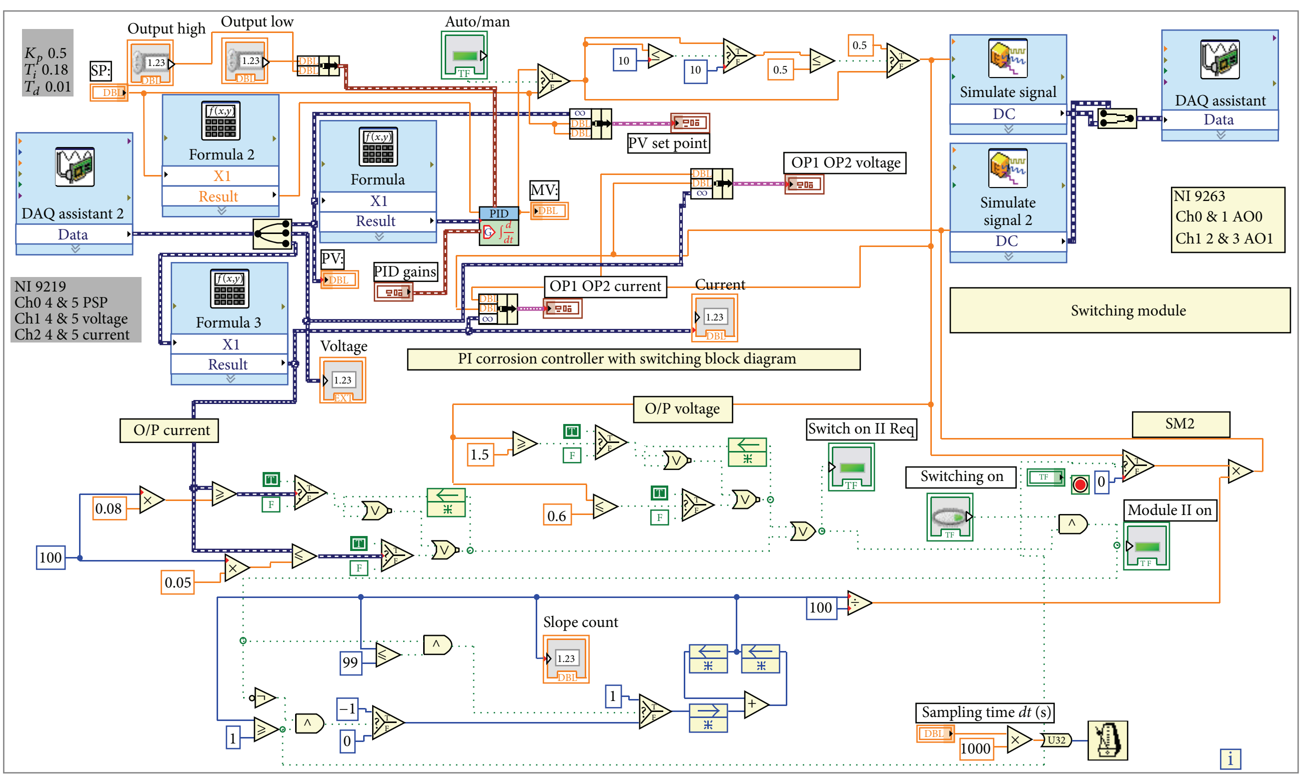

Figure 3: Corrosion controller program.

is fed to the step down transformer. Step down transformer output is rectified, filtered, and then fed to the pipeline. Purpose of the step down transformer is to reduce the voltage to nonobjectionable level and to meet the load side current requirement. Output voltage of AC phase control circuit is governed by

$$V_{d\propto} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_{\max}\sin\omega t d(\omega t) = \frac{V_{\max}}{2\pi}(1+\cos\propto), \quad (2)$$

where ∝ is the phase angle.

Table 1 shows the result obtained between the DC output voltage of the *PI* controller and the corresponding variable

Table 1: Control voltage versus output AC voltage.

Control voltage DC	Output voltage AC
6.05	10
5.56	26.5
5.07	45.6
4.55	68.6
4.06	94
3.42	126.6
2.99	148
2.57	168.7
2.09	188.2
1.57	203
1.07	216
0.64	223

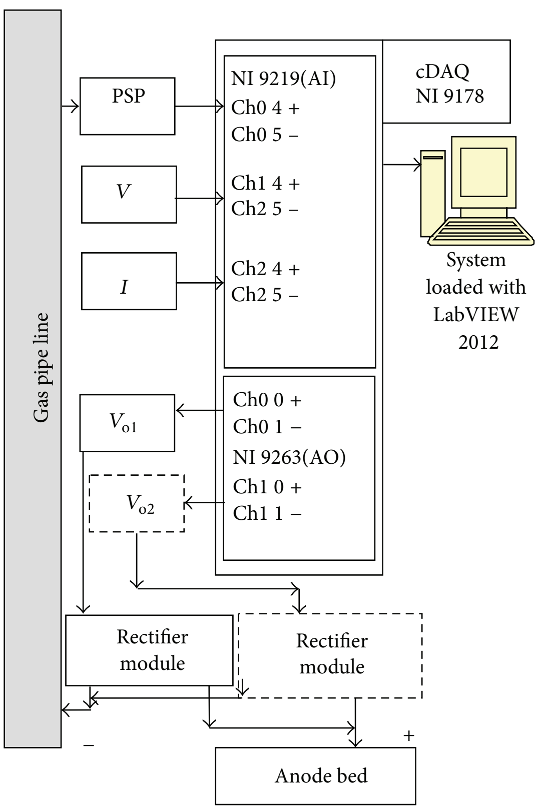

Figure 4: Experimental set-up.

AC obtained. Here single phase 230 V AC 50 Hz power supply is used. Scaling and mapping may be done to match the DCS *PI* controller output to control the single phase AC controller either through hardware or software.

Experimental set-up is shown in Figure 4. Three-analog input channels and two-analog output channels are used for experiment purpose. In the figure, dotted line shows the additional power supply module, which will become online when first module is unable to cater the load demand. Rectifier module consists of phase control module, step down transformer, rectifier, and filters.

AC phase controller rating selection is purely based on the pipeline size, pipeline length, type of coating used, and current density used for protection. Total current requirement to protect the pipeline is calculated as shown in (3). Surface area of the pipeline is calculated as shown in (4):

$$I_t = \frac{S_a C_d S_f}{10^6} \text{ amperes}, \quad (3)$$

where S_a is the total surface area of the gas pipeline in square meters, C_d is the current density ($125\,\mu\text{A/M}^2$) for marshy area, and S_f is the safety factor (1.3):

$$S_a = \pi D L\,\text{M}^2, \quad (4)$$

where S_a is the total surface area of the gas pipeline in square meters, D is the diameter of the pipeline in meters, and L is the length of the pipeline in meters.

3. Results and Discussions

Designed controller is checked with different PSP set points and it is controlling perfectly. Output response obtained through the designed *PI* controller is shown in Figure 5(a). Set point has been changed from −1.2 to −1.5 and then to −1.7 volts; PSP is maintained at set level. Controller is giving desired result; that is, process value is tracking the set point. Here PSP is the process value.

Load variation (perturbation introduced into the system) has been created by varying the electrolyte resistance. Response of the controller is shown in Figure 5(b). Initially electrolyte conductivity is varied by diluting with water and controller performance is observed. Controller brought the process value (PSP) towards the set point. Variation in electrolyte pH affects corrosion process and acidic nature accelerates corrosion process. Then electrolyte pH is varied by adding sodium chloride to it and then controller performance is observed. In both cases the controller is taking corrective action and brining process value towards set point.

As shown in Table 2 given below, protection current requirement drastically varies based on the coating resistance. When the coating is in good condition, current requirement will be very low; it may be one or two amperes for 10 miles of 36″ diameter pipeline, whereas when the coating is damaged or pipe line exposure occurred in one or more locations, more protection current will be required (till the time coating is repaired), say, 15 amperes. In practical applications, 50 V 50 A rated transformer is used to provide protection current. Normally this transformer may be supplying only one or two amperes to the pipeline when the pipe coating is in good condition; hence, idle loss will be more in it.

Instead of designing 50 volts 50 A as a single unit, five units of 50 volts 10 A can be designed and operated in parallel. Normally only one unit (rated 50 V 10 A) will be online to cater the current demand; another power module of 50 V 10 A will be added once the first module reaches 80% of its capacity (say 8 A). As written in the program (Figure 3), additional module is added once the output current crosses 8 A. As

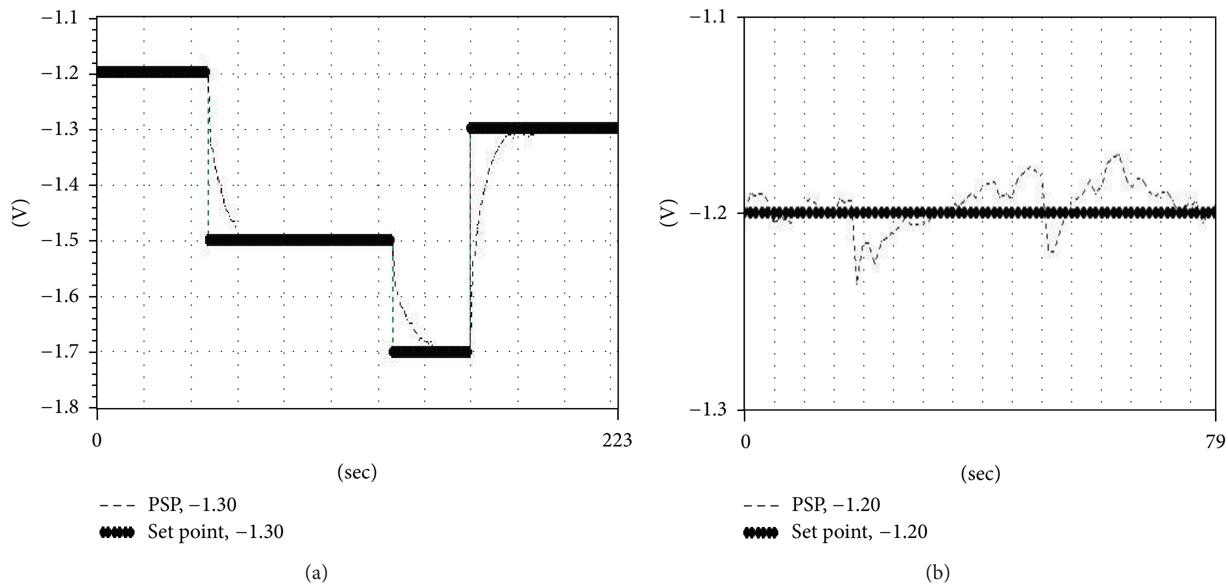

Figure 5: (a) Response of the designed *PI* controller to set point change. (b) Response of the *PI* controller to load variation.

Table 2: Range of current required for protection of 10 miles 0f 36″ diameter pipe [1].

Effective coating resistance in ohms for one average square foot	Current required in amperes
Bare Pipe[@]	500
10,000	14.91
25,000	5.964
50,000	1.491
5,00,000	0.1491
10,00,000	0.0298
Perfect coating	0.000058

[@]Bare pipe assumed to require a minimum of 1 mA/ft^2.

shown in the graph (Figure 6(a)), additional module (OP2) is gradually loaded and existing module (OP1) is gradually unloaded. When load demand is reduced to less than 50% of the first module rating (say 5 A), then added module is gradually unloaded as shown.

If first power module failed, then second module will come online automatically. For instance, say, first power supply module failed and controller output voltage to first power module reached 1.5 V (this value can be set through program) then second power module will come online gradually as shown in Figure 6(b).

As shown in Figure 7(a), if the additional module is taken online immediately, it creates disturbance in PSP by impressing more current. For instance, at 32 seconds, additional module is added immediately (due to total current demand which is increased to more than 8 amperes); process value (PSP) is disturbed from −1.7 volts to −2.1 volts for brief period. Such disturbance is avoided by gradually loading the additional power module as shown in Figure 7(b). To achieve gradual loading and unloading, upward and downward counter is introduced in the program (in Figure 3) and counter value is multiplied by controller output (for additional module).

Successful implementation of cathodic protection using DCS helps us to centralize monitoring and control of pipeline corrosion. Different channel has to be allotted for different pipeline and anode bed. PSP historical trend can be recorded; PSP variation can be easily identified. With DCS operation switchover from auto to manual mode and manual to auto mode is easy. Manual mode is used during start-up. Alarm record will be available with time stamp. Autotuning feature is available in DCS/PLC. It is a modular concept. Fault diagnosis [7] is easy. Rate alarm can be used to find the damage in the pipeline coating. Simulation can be done without affecting the process. In the designed software based cathodic protection controller and addition/deletion of logic modifications are easier. Signal repetition is easier with highest possible accuracy. For data transmission, implementation of MODBUS, Profibus, industrial Ethernet communication, and so forth is easier with DCS/PLC.

Stray current monitoring [8] is possible with virtual instrumentation. Impressed current cathodic protection [1] is commonly used in pipeline industries for corrosion protection. Corrosion protection can be implemented using simple *PI* controller [9]. Simple controller will not provide a lot of features available in DCS such as graphic operator station, trending, alarm, and data transmission. Autotuning of *PI* controller [10] helps in selecting optimum control parameters.

4. Conclusions

Design and development work of *PI* corrosion controller with switching module is undertaken for underground pipeline in

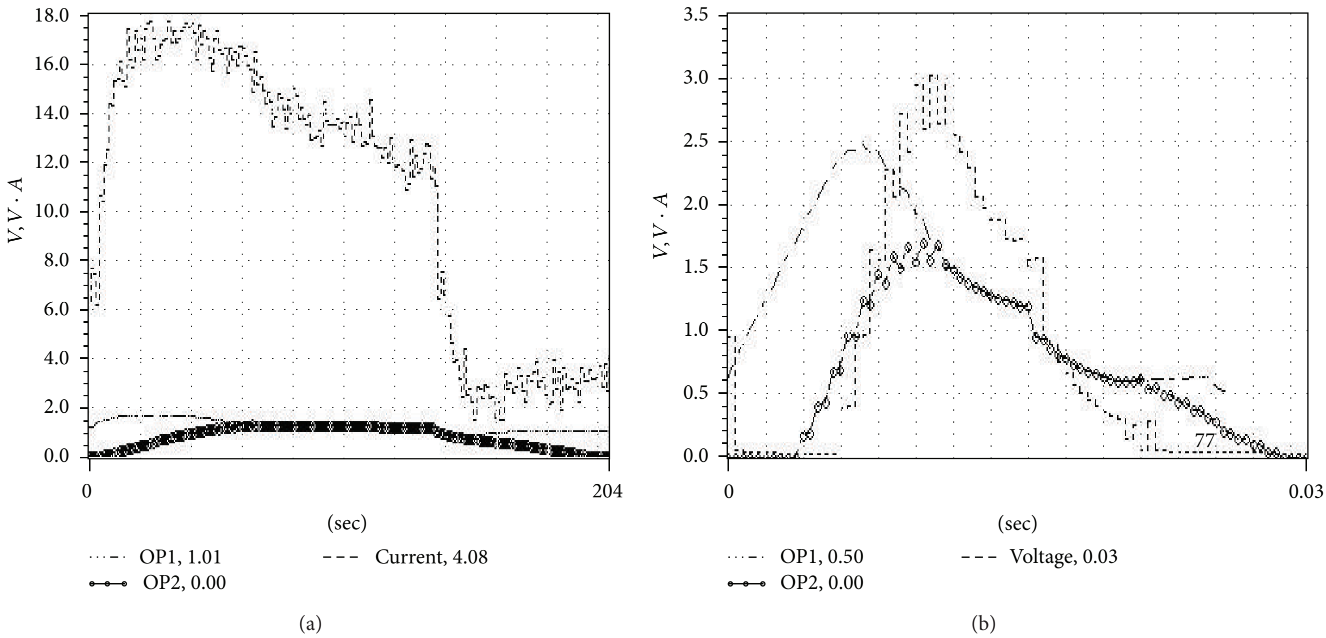

FIGURE 6: (a) Output module switching on output current condition. (b) Output module switching on output voltage condition.

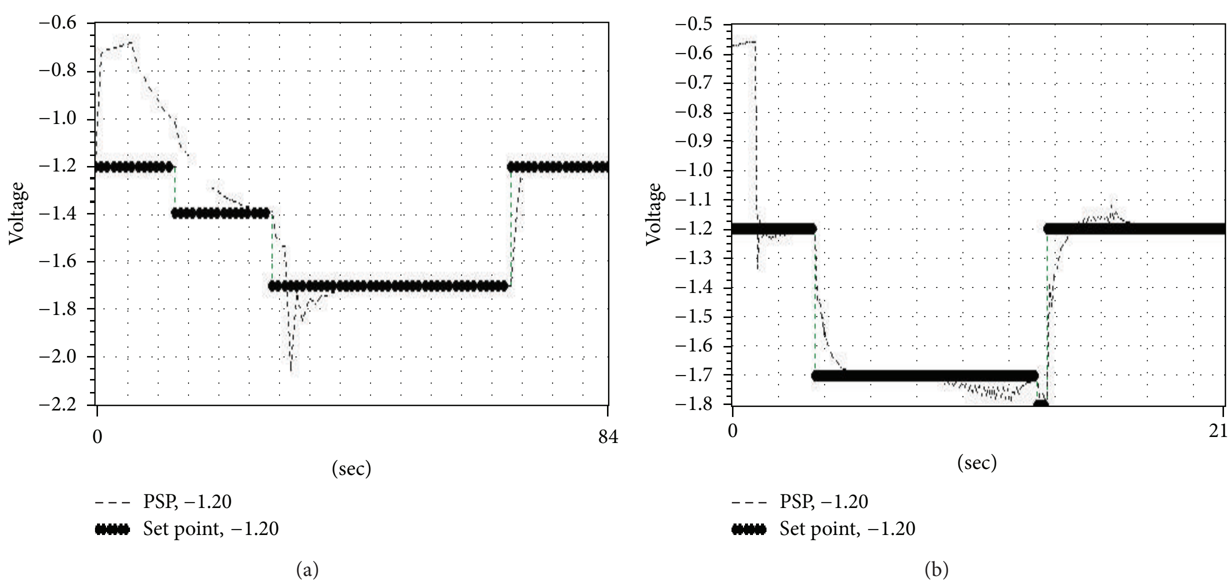

FIGURE 7: (a) Impact of immediate loading of additional module. (b) Gradual loading of additional module.

distributed control system. It prevents the pipeline corrosion by precisely controlling the pipe to soil potential (PSP) at the desired level. Self-tuning feature available in DCS can be used for optimum selection of *PI* controller parameters. Instead of using single high current rated transformer rectifier unit, multiple modules connected in parallel configuration can be used. Output module switching is discussed in detail. The same application can be extended to any of the other steel structures like underground tank and so forth.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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