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Performance analysis of an off-grid renewable energy hybrid powered CPU system with storage

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Abstract

This paper presents the prototype of the Cathodic protection unit (CPU) powered by the hybrid energy system. The aim is to verify the technical feasibility of the proposed system. The CPU supplies a maximum voltage of 24 V DC, at a current of 10 A, supplied by a wind/PV/battery hybrid energy system. The prototype is of a smaller size compared to the actual proposed system. However, the architecture is maintained. The CPU is controlled by a microcontroller, which regulates the voltage output of the hybrid system, using the PWM technique. Furthermore, the system uses a fixed potential concept, to manage the controller. Moreover, remote monitoring is being experimented with, where the unit monitors the voltage, current and upload the readings on the Cloud storage, for remote accessibility. The experimental results, therefore, confirm that the combination of solar and wind resources with battery storage can be employed for the operation of CPUs.

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Keywords: Hybrid system; Cathodic protection; Pulse width modulation; Remote monitoring and microcontroller

1. Introduction

Cathodic protection (CP) is the most common way of preventing corrosion of metallic materials through the application of electrochemical principles. CP is practiced In the early 20th century, to prevent corrosion of buried metal pipes, docks, ships, offshore platforms, and other metal structures [1–3], in the 1970s, the impressed current cathodic protection (ICCP) was applied to the steel sheet pile wharf at Lianyungang Port, which increased the service time of the harbor and achieved good economic results [3]. It requires a very tiny current density to polarize a structure using an ICCP system, thereby reducing the structural corrosion rate, and it can last for up to 30 years to 40 years. Nowadays, the use of ICCP is widespread, and the economic impact is considerable. The ICCP technique is considered to be one of the most effective approaches [4,5]. A cathodic potential of 850 mV vs. copper sulfate

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electrode (CSE) [6,7] is the CP requirement recommended by NACE International to protect underground steel structures from corrosion attack, provided that the AC density is less than 20 A/ m^2 [8,9]. Several scientists have performed in-depth research on the implications of cathodic defense for variables such as pH and potential [4,10]. Further, researches were conducted to study the use of renewable energy on ICCP systems. In Ref. [11], the author performed the sizing of the off-grid wind solar-PV hybrid system with a battery energy storage system (BESS) to power an ICCP system. Moreover, in Ref. [12]. The use of solar and wind energy was dynamically evaluated to assess if it will sufficiently meet the requirements of the ICCP system. The results presented does show that the CP system may sufficiently prevent corrosion with supplied with renewable energy. However, the experimenting of these systems is yet to be conducted. Hence, this paper presents the Prototype implementation and analysis of an off-grid Wind and solar-PV hybrid system powered CPU system with BESS.

2. Block diagram and description

This section outlines the block diagrams of the CPU powered by the wind/PV/battery energy system. In these block diagrams, all components of the proposed system are clearly shown. These are the hybrid energy system, control unit, CPU monitor and test-post unit, which monitors a dedicated point on a pipe.

2.1. Control circuit

Fig. 1 shows the block diagram of the CPU control circuit, with the hybrid system. Furthermore, the system has the DC–DC buck–boost convertor, which regulates the 12 V DC voltage from the hybrid system to a value required to protect the pipeline. This voltage is regarded as having a maximum point of 24 V DC and a minimum of 0 V DC. The voltage is controlled by a microcontroller ATmega328. The microcontroller is used to increase and decrease the duty cycle, hence achieving pulse width modulation (PWM). This is carried out with reference to two input signals, namely, the setpoint and the feedback.

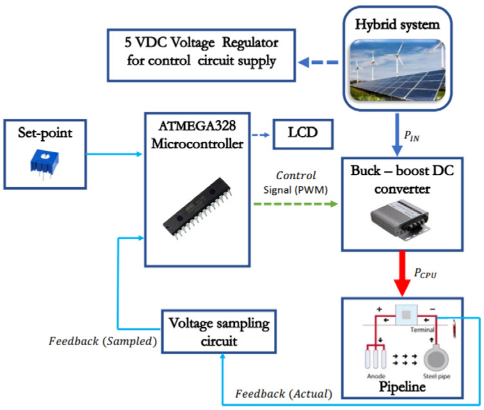

Fig. 1. Block diagram of the CPU control circuit with the hybrid system and load.

The setpoint is obtained from CP standard document, named SANS 155891:2009. The standard requires that the pipeline potential should be more negative than – 850 mV and not less than – 1200 mV, with reference to the copper–copper sulfate reference electrode (CSE), to avoid the detrimental effects of hydrogen production and a high pH level at the metal surface [13]. Therefore, for this project, the aim is to maintain the voltage setpoint to 1200 mV, throughout the design life of the pipeline. The second input is the feedback voltage, measured from the pipeline, with reference to the CSE. To maintain the voltage to 1200 mV, the control system pushes more power from the hybrid energy system, when the feedback voltage is less than the set value. When the feedback voltage is higher than the set value, the control system decreases the power output from the hybrid energy system.

The potential measurements are obtained through the use of the voltage sampling circuit, which will be discussed later. The sampling circuit is mainly for safety purposes, in case the pipeline potential rises beyond the maximum specified voltage input of the microcontroller. The Liquid crystal display (LCD), shows the status of the operation, by displaying the duty-cycle in percentage, the specified voltage setpoint, as well as the feedback voltage, at the point where the CPU is installed. The power supply for the control circuit is achieved using a 5 VDC voltage regulator, rated at 3 A. This voltage is obtained from the hybrid output terminals, which have a nominal voltage of 12 VDC. The power drawn by the whole CPU circuit is referred to as P_{IN}, while P_{CPU} is the power impressed to the pipeline for its protection.

2.2. CPU monitoring circuit

Due to the fact that the networking takes a few seconds for signal reception, and further, the fact that the DC–DC convertor runs at a high frequency, the CPU monitoring circuit had to run on a separate microcontroller. Fig. 2 shows the block diagram of the CPU monitoring circuit, where the setpoint and feedback are obtained, as previously mentioned. This circuit is connected in parallel with the circuit in Fig. 1 Furthermore, the voltage sampling circuit functions the same as the one used in the control circuit, where two resisters 7.5 kΩ and 30 kΩ are connected in series, to implement the voltage divider circuit.

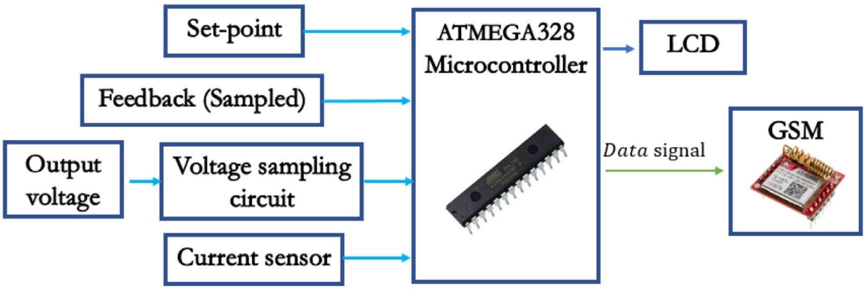

Fig. 2. CPU remote monitoring circuit.

The reason for this is to lower the voltage to levels suitable for those of the microcontroller operation. The sampled voltage ratio used, is 1:5. The output voltage is the voltage measured from the terminals of the DC–DC converter, with the positive terminal connected to the anode and the negative terminal to the pipeline. The LCD displays the output voltage, current, power, voltage feedback and the setpoint. The current is measured using the current sensor ACS712, rated at 20 A. The current sensor samples the current and provides a DC voltage signal, corresponding to the input current. All the measured parameters are transmitted to the server thingspeak, using the Global system of mobile communication (GSM) module SIM800L. The system is programmed to send short message texts (SMS), when the pipeline penitential rises above – 850 mV, or significantly below – 1200 mV. However, the measuring cables polarities have been reversed for circuit simplicity.

2.3. Test post (TP) monitoring

The pipeline with cathodic protection has to be monitored at different intervals. This is carried out, mainly, after every 500 m interval, at both ends of the pipeline and/or each end of the possible isolation point, such as river crossings, road or rail crossings, ensuring that the pipeline is protected. Fig. 3 shows the block diagram of the monitoring circuit used to monitor all the test posts. The circuit reads the pipeline voltage at the specified point. The microcontroller reads the input signal from the sampling circuit and calculates the actual voltage while displaying this on the LCD. The measured value is transmitted to the thingspeak so that when the value falls outside of the range, a warning SMS is sent to the maintenance supervisor.

3. Hardware description

Shown in Fig. 4, is the soldered control circuit, CPU monitoring circuit and TP circuit. The circuits contain all components required to perform the function of the proposed system, namely, the CPU control and remote monitoring. The PCB circuits were cased and installed in a CPU unit, with charge controllers and protection fuses, to form a complete CPU panel, for cathodic protection. All termination and connection tests were conducted.

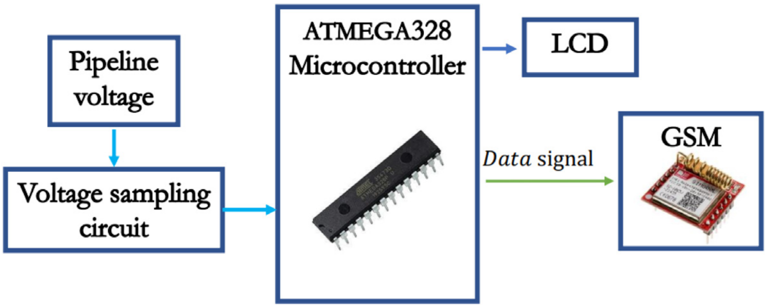

Fig. 3. TP remote monitoring circuit.

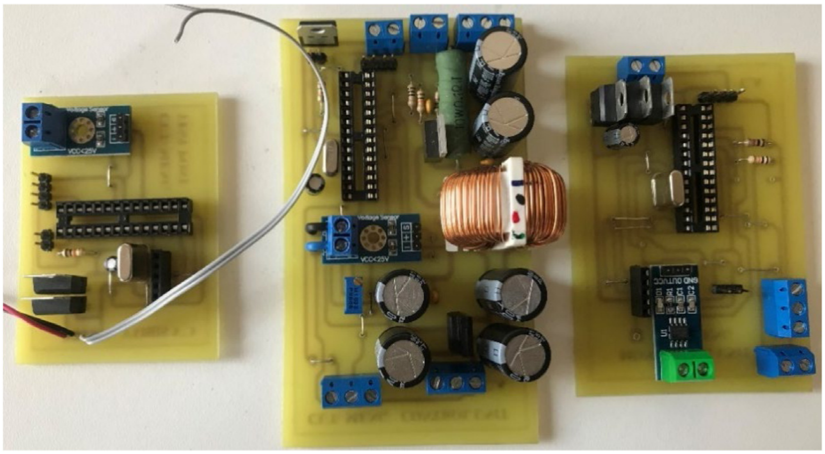

Fig. 4. Soldered PCB circuits.

These soldered PCB circuits were cased and installed in a CPU unit, with charge controllers and protection fuses, to form a complete CPU panel for cathodic protection. All the termination and connection tests were conducted and the results are presented in the sections below.

Fig. 5(a) and (b), show the installation of the metal bar and an anode underground. The two were installed half a meter apart, in parallel, to enhance better conductivity. The metal bar representing a pipeline of 2 m long, with the anode being 1 m long. Both of them were covered underground at a depth of 0.2 m, with cables exposed for further connections. The anode was connected to the positive side of the voltage source and the metal bar (pipeline), to the negative side.

Fig. 6 shows the complete project setup with solar panel, DC generator 12 V battery, laptop and internet connection router, GSM module antennas and testing devices, such as an oscilloscope and multi-meter. The inverter is installed to power the oscilloscope for testing purposes, as well as for changing the laptop during on-site testing. The DC generator, acting in place of a wind turbine, is coupled to a DC motor, to drive the generator as a prime mover.

4. Testing, analysis and discussion

In this section, the test results and analysis of the CPU are discussed. Fig. 7(a) and (b), show the measurement setup to monitor the ground potential of the selected test site. The ground potential was first measured to monitor whether the ground is corrosive and the reading was −0.785 V DC, which is more than the required minimum of −0.85 V DC. This was further tested using the designed TP unit, to monitor its measurement accuracy. It was discovered that the TP unit has an error of approximately 0.07 V. This is due to various factors, such as the resistor tolerance, as well as the voltage drop on the testing leads, caused by test lead resistance.

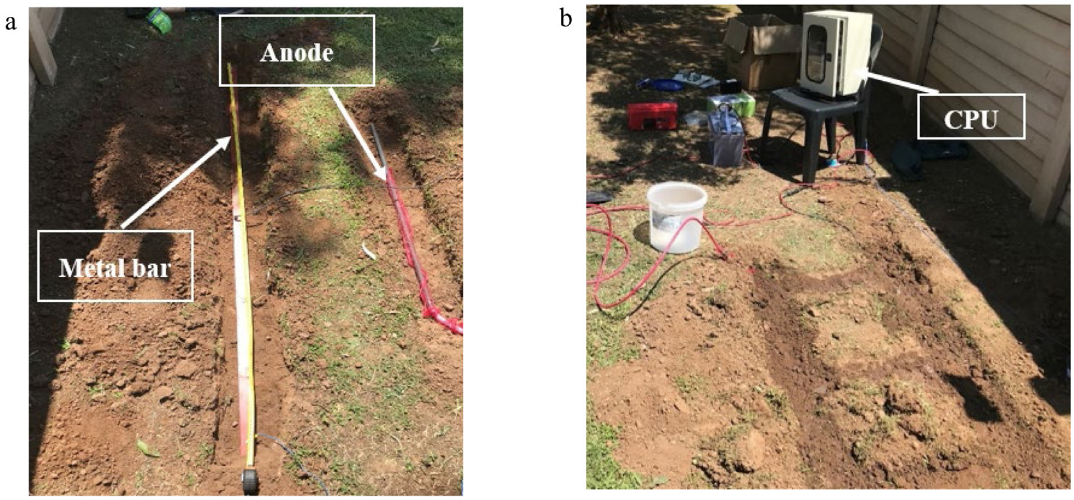

Fig. 5. (a) Ground installations; (b) Anode and metal bar installed.

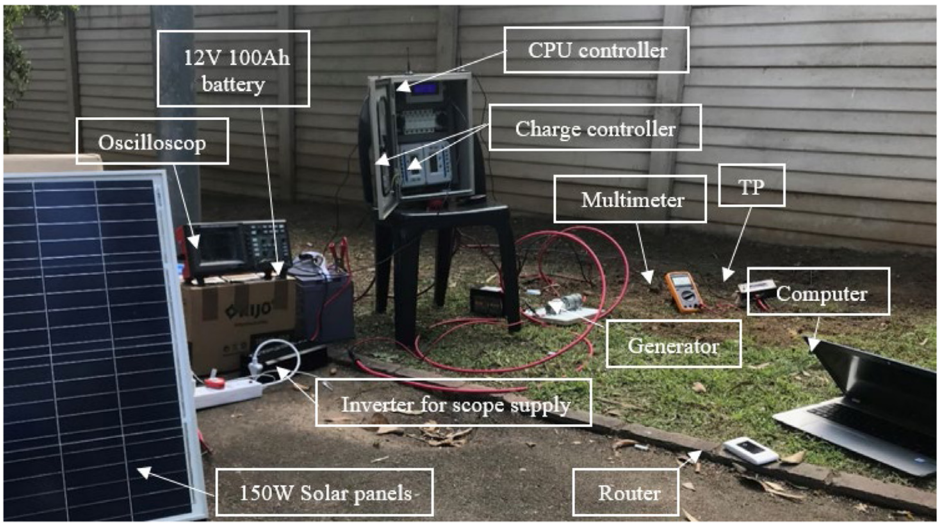

Fig. 6. Final project setup.

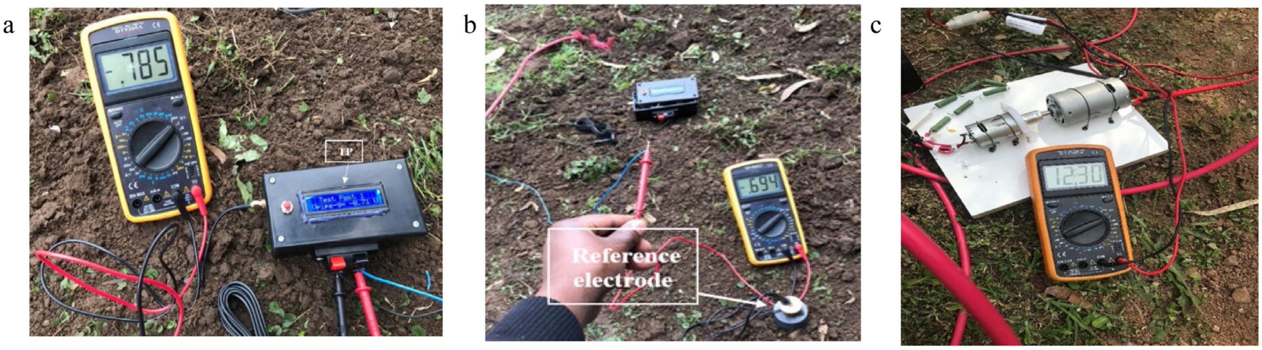

Fig. 7. (a) Ground test with reference to CSE; (b) Ground test setup; (c) DC generator output voltage (V).

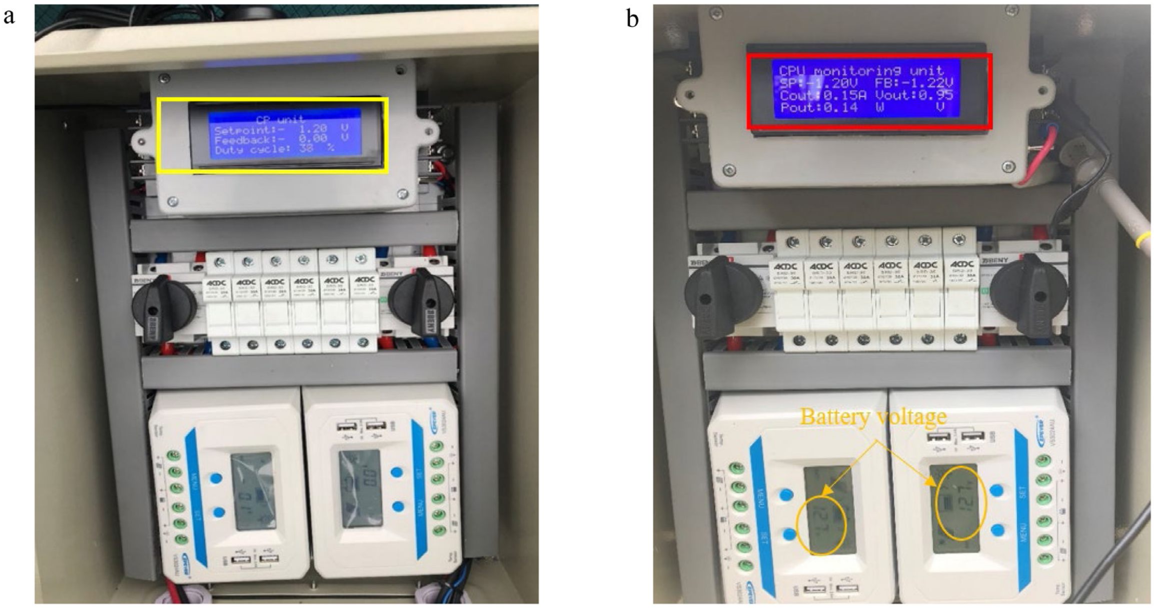

Fig. 8. (a) CPU site testing with 38% duty cycle; (b) Tested with a feedback of −1.22 V.

Fig. 9. Pipeline test using TP.

Fig. 7(c), shows the DC generator output feed to the CPU via a Charge controller. The CPU is supplied from the solar panel and wind turbine, of which the total power is fed to the battery bank, through the charge controller. The power is later used to impress current to the ground, via the CPU. Initially, the feed was not detected by the CPU, due to the polarity of the connection. When this occurred, the unit increases the duty of the PWM, in order to increase the voltage output and raise the pipeline voltage to the required value. Hence, Fig. 8 shows that the duty cycle is 38% and this constantly rises, so long as the power generated by the wind turbine and PV system is less than required. During this time, the CPU reaches the feedback voltage of −1.22 V, while drawing a current of 0.15 A. A voltage of 0.95 V is therefore supplied to the pipeline via the anode, which translates into a power consumption of 0.14 W. At this point, the battery voltage is 12.7 V, as shown in Fig. 9.

The pipe to ground voltage was further tested at one end of the metal bar, to test whether the anode is showering the whole bar. This is shown in Fig. 10. May be seen that the unit measured the voltage of −1.22 V, which is verified by the multimeter to be corrected, owing to the fact that it measured 1.2 V later, while the TP monitoring unit measured −1.22 V, with the lead reversed.

The waveforms obtained using the oscilloscope during testing, are displayed in Figs. 10 and 11. Fig. 10 shows the PWM signal when the CPU is switched off, while Fig. 12 shows the signal for a duty cycle of 7%, which corresponds to the operation point, where the feedback voltage meets the desired value. For demonstration purposes, the anode

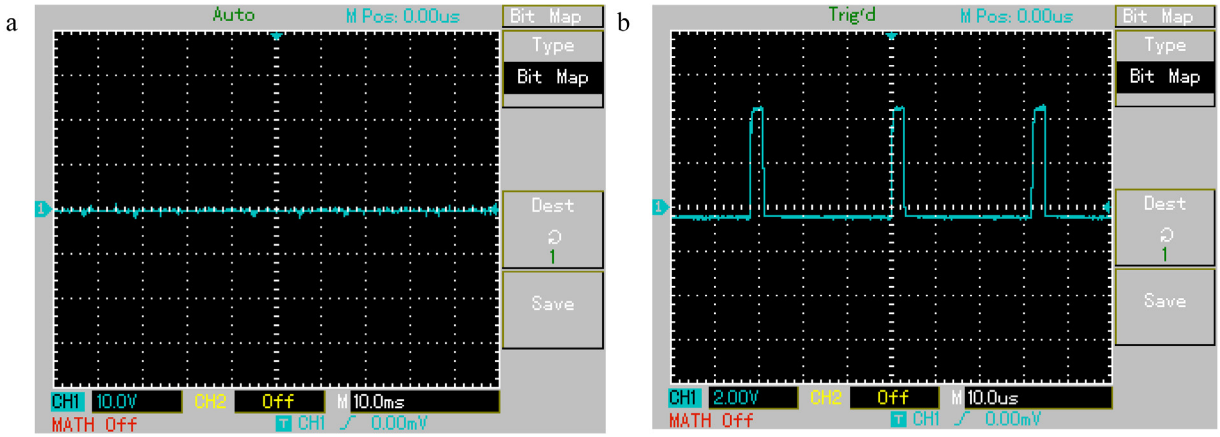

Fig. 10. (a) PWM waveform at no output; (b) PWM waveform at duty cycle of 7%.

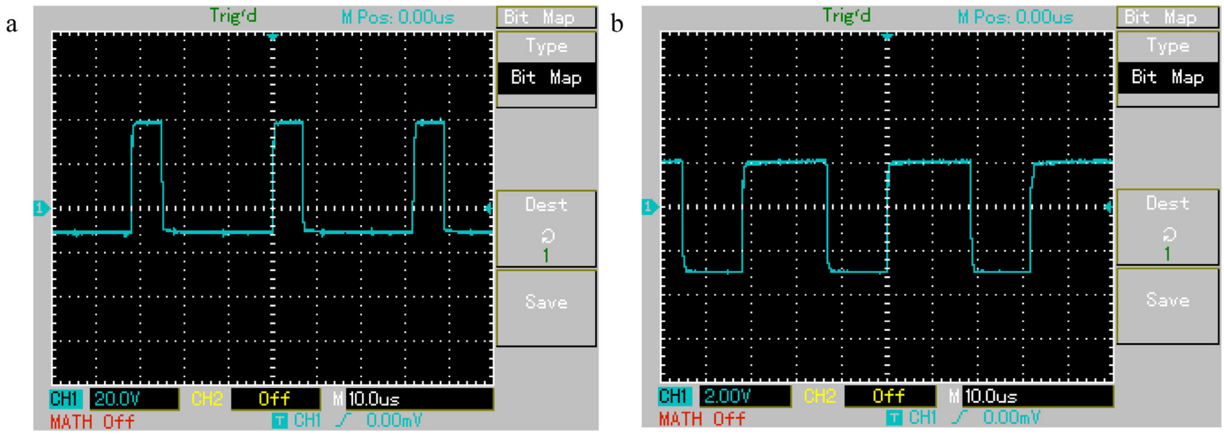

Fig. 11. (a) PWM waveform at duty cycle of 23%; (b) PWM waveform at duty cycle of 63%.

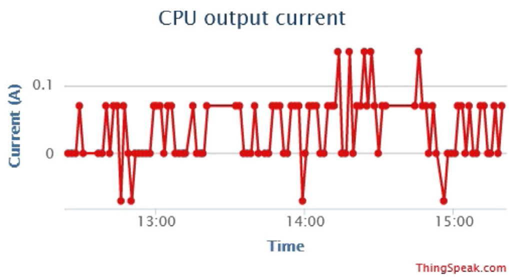

Fig. 12. CPU output current.

supply was taken off, to get the feedback to a lower value than the setpoint. At this point, the CPU increased the output voltage, to push more current, to pick up the feedback to the desired value, as shown in Fig. 11(a) and (b).

Shown by Figs. 12 to 15, are the results for current, voltage and power, obtained during testing. These results were recorded using hardware and software components. The telemetry, part of the prototype as previously described, was utilized, to remotely measure the current, system voltage, power output, setpoint voltage and pipe potential and vail these to the server (thingspeak). The information is sent via a GSM network to the Cloud. The voltage for the pipe to the ground has been inverted, to simplify reading and analyzing.

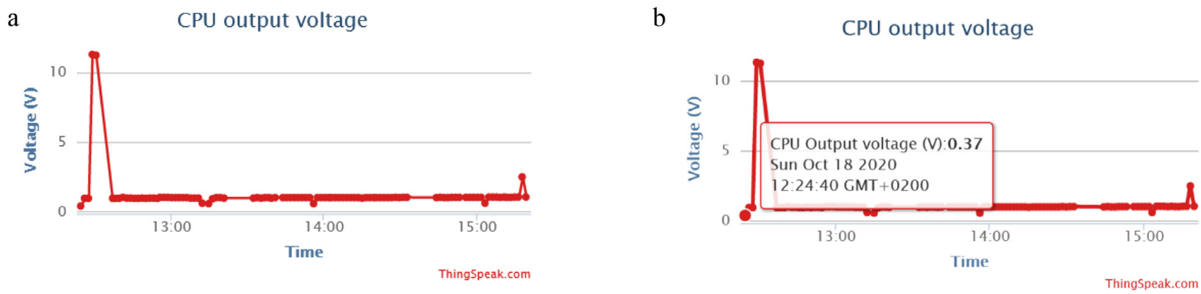

Fig. 13. (a) CPU output voltage; (b) CPU output voltage with zoomed details.

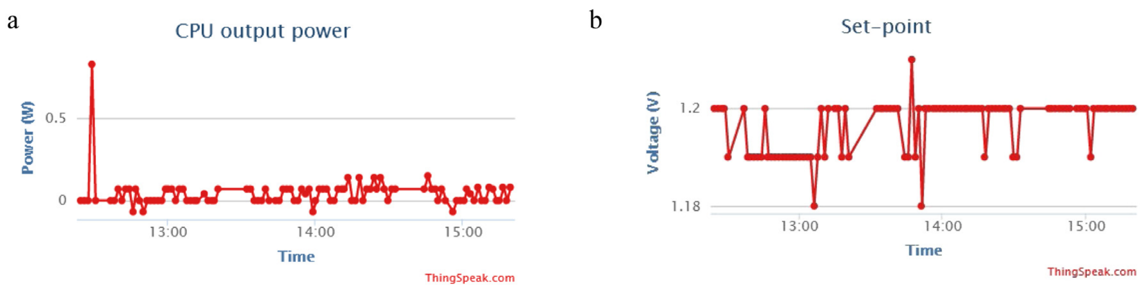

Fig. 14. (a) The output power of the CPU protecting a 2 m; (b) CPU set-point voltage.

Shown in Fig. 12, is the CPU output current being delivered to the steel plate installed underground, via an anode. As seen from the graph above, the highest current value on record for the given setpoint of 1.2 V is 0.15 A, with the lowest value of −0.07 A, which occurs when where the CPU control unit is switched off. Furthermore, the current stays at 0.07 A during operation and fluctuates between 0 and 0.07 A. The results displayed were recorded from 12:30 to 15:30, on the day of tests.

As seen from Fig. 13(b), the first point is recorded at 12:24:40 with a voltage of 0.37 V. The controller starts with the lowest voltage and constantly increases, until the feedback voltage is obtained from the CPU measuring unit. The voltage increased to the value of approximately 11.28 V DC since the feedback was not yet connected. After the connection of the feedback cable, the voltage dropped to a value of 0.93 V DC, measured between the steel bar and the ground, through the reference electrode. The voltage is then maintained around the value of 0.93 V DC, while the feedback is maintained on the set-point value.

Fig. 14(a), shows the output power for the CPU to protect the steel piece against corrosion. The power starts from zero and increases as the CPU feeds more power to the anode to shower the steel piece with electrons. The power becomes negative when the CPU is suddenly switched off, while the anode provides feedback power to the CPU unit. This may be prevented by connecting a diode on the anode feeder cable. The set-point is set to −1.2 V, which is 1.2 V in Fig. 14(b), due to ground values, inverted for simplicity of measurement. The inversion was carried out by swapping the positive and negative terminals on the measuring unit. Results show that the setpoint fluctuates between 1.18 V to 1.21 V DC, which is due to the sampling changes in the measuring unit.

The set-point is used as a reference to the feedback voltages obtained from the CPU point pipe (metal 2 m bar) to the ground, as well as the end of the metal piece. Fig. 15(a) shows the metal piece to ground measured voltages, where the lowest point is 0.5 V, −0.5 V DC when not inverted. The voltage picks up with time and maintained at the set-point voltage of 1.2 V, −1.2 V DC, when not inverted.

In practice, the pipeline is sufficiently protected when the pipe to ground potentials are within the allowable range. Hence, it is important to test as many points as possible on the pipeline. The results are shown in Fig. 15(b), outlining the readings obtained from a test point (TP). The lowest value on record is 0.56 V, with 1.2 V being observed at most times during the test. The highest value on record is 6.67 V, which is the value recorded when the feedback was discounted and the CPU was pushing more voltage to, increase the pipe potential. The metal to ground voltages reaches 0.66 V, 0.66 V, 0.68 V and 0.61 V at 13h14, 13h56, 15h03 and 15h17, respectively.

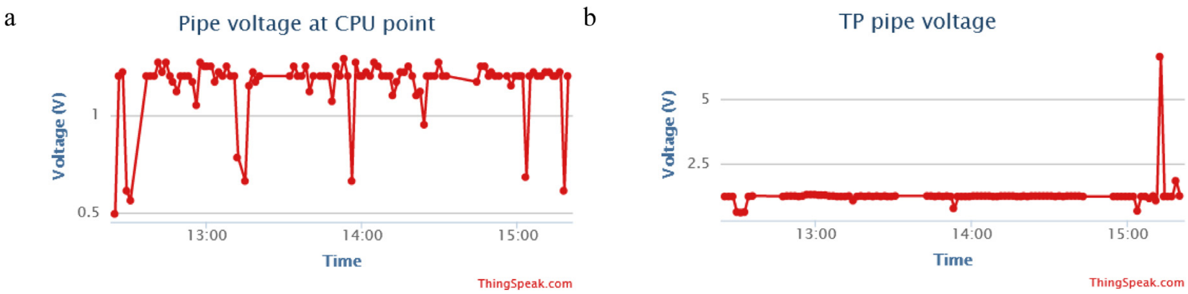

Fig. 15. (a) Pipe voltage at the CPU location; (b) Test post (TP) pipe voltage.

The metal to ground voltages was, again, measured from the end of the bar, to ensure that the entire bar is protected against corrosion. This point is referred to as a test post one (TP1). A pipeline may have as many TPs as possible, depending on the owner affordability. However, the TPs have to be placed every 500 m to 1 km, depending on the length of the pipeline. Fig. 15(b) shows the voltages on record for the end of the bar. As seen in Fig. 15(b), between 14h00 and 15h00, the voltage is maintained at 1.2 V DC, which is −1.2 V when not inverted. When the feedback was disconnected, the voltage raised to a value of 6.67 V, after 15h00 and later decreased to a normal value of 1.2 V, when the connection was re-established.

5. Conclusion

This paper focused on the prototype of the proposed system, where the CPU was constructed. The built CPU was supplied by the PV panel together, with a 12 V DC generator, coupled to a 12 V DC motor, used as a prime mover of the wind turbine generator. The CPU further contained as a separate module, which is a monitor and records voltage, current, power, pipe to ground voltages, as well as the set-point voltage. All monitored measurement values were uploaded to the Cloud, for recording purposes.

The experimental results have demonstrated the technical feasibility of the proposed hybrid energy system, powering a CPU. Moreover, the online monitoring system was effective and provided a true reflection. The power consumed by the CPU is significant, thus making the supply sufficient for the system. The experimental results, therefore, confirm that the combination of solar and wind resources with battery storage may be employed for the operation of CPUs.

More analysis studies have to be carried out on the system feasibility using economic conditions, such as economic factors, duration of payback, and cost of life cycle or breakeven study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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