

Design and Implementation of Wireless 4-20 mA Current Simulator

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Abstract

This paper presents new device to simulate and inject a 4-20 mA current signal to PLC and control on this signal wirelessly. The proposed simulator device has been designed and implemented by a PIC 18f4520 microcontroller and an Ethernet click. This device is connected to Wireless Local Area Network (WLAN) via Wi-Fi router using TCP/IP protocol. The simulator has two channels for 4-20 mA current output signals with two channels for digital output signals, controlled by a laptop or a smart mobile. The purpose of this work is to demonstrate the usefulness of the Wi-Fi wireless technology for remote controlling on the 4-20 mA output current signal and the digital output signal in the designed simulator device. The experiments indicate that the proposed wireless simulator outputs the 4-20 mA current with high accuracy and very fast response. The experiments also indicate that the proposed wireless simulator is easy, comfortable and convenient practically to use in the test operations of protections, interlocks and integrity of analog input channels for PLC compared to the wired simulator.

Index Terms— 4-20 mA current signal, PLC, simulator, wireless

I. INTRODUCTION

Programmable Logic Controllers (PLCs) usually deal with analog signals either input signals or output signals. 4-20 mA direct current loop signal is the most common analog signal in the industrial control fields [1]. One of the instruments which uses 4-20 mA current as an output signal, is transmitters. The transmitter is an instrument intended for measurement of process parameters as pressure, flow, level, temperature, etc. In order to test protections, interlocks, analog input channels for the PLCs and warning and emergency signals and response, range and reading of process parameters in Human Machine Interface (HMI), the output signal from a transmitter must be simulated and injected to receivers. These receivers includes the analog input modules in the PLCs, the pneumatic actuators controlled by the 4-20 current signal and the digital indicators).

The 4-20 mA current simulator is device which provides current from 4 to 20 mA. It can be

represented as a variable current source. There are many 4-20 mA commercial wired simulators like 705 loop calibrator or simulator manufactured by Fluke corporation as shown in Figure 1 [2]. Therefore, based on our knowledge, this paper presents new device to simulate and inject 4-20 mA output current signal to a PLC and control this signal wirelessly. The main benefit of this work is to conduct seamlessly and accurately the tests on PLC programs including the protections, the interlocks, etc. Especially, when the PLC 's terminals are far away a HMI room. The other benefit is to conduct these tests by less staff persons.

In the literatures, J. Hemalatha et al. [3] designed and developed wireless flow transmitter. They used the ATmega328 microcontroller with Bluetooth module to read the flow rate wirelessly and display it in their laptop. H. Sasaki and K. Ueda [1] presented design and development of wireless monitoring system for 4-20 mA loop sensors using Wireless Sensor Network (WSN). Their system consists three kinds of nodes: sensor node, relay node and gateway node. All of the

values, which sensor nodes collect from the sensors, are gathered at the gateway node through the full mesh network. Then, they are downloaded to the Personal Computer (PC) via Universal Serial Bus (USB), and stored in the PC database. Waluya et al. [4] implemented wireless monitoring system for the saving and managing the electrical energy using a PLC. Temperature, humidity, lighting and electric active power sensors were equipped by 4-20 mA transmitters. These transmitters entered to the four channels of analog input module of the PLC. From the PLC, using a router, the signals were transmitted wirelessly to the computer. The above papers focused on sending the 4-20 mA current analog input signal for the transmitters to the computers in wireless remotely. While, this paper will focus on sending of the 4-20 mA current analog output signal for the simulator device from the computer in wireless remotely.

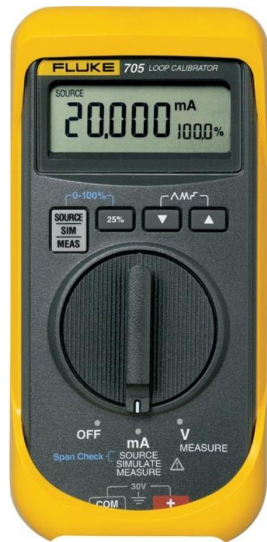


Figure 1: The commercial 705 loop simulator or calibrator manufactured by Fluke corporation

II. HARDWARE COMPONENTS OF THE PROPOSED WIRELESS SIMULATOR SYSTEM

In the present work, the main components of the wireless simulator system are: Terminal Control Unit (TCU) : a laptop or a smart mobile, a Wi-Fi router and the simulator device as shown Figure 2. This system represents a small wireless local

area network. The network consists of a one server and many clients. The simulator device represents server and has 192.169.1.60 IP/ 5678 port. While, the TCUs represent clients. The simulator device is connected to a Wi-Fi router by Ethernet cable. Here, the router is used to link between the simulator and a laptop or a smart mobile wirelessly via Wi-Fi technology. In this paper, the simulator is focused and explained its work principle, hardware components and programs.

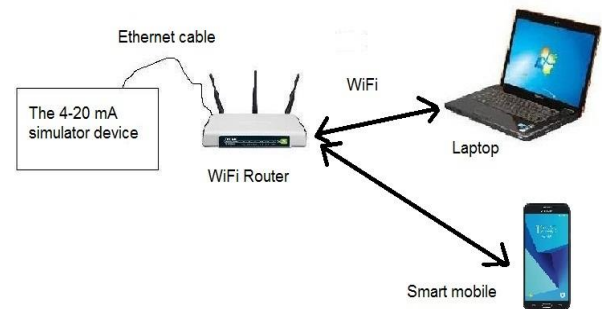


Figure 2: Block diagram of the proposed wireless 4-20 mA simulator system

The new simulator device consists of the following hardware components as shown in Figure 3:

1. An Ethernet click: It features ENC28J60, a 28-pin, 10Base-T stand-alone Ethernet controller with an on-board MAC and PHY, 8K Bytes of buffer RAM and SPI serial interface [5].
2. An enhanced flash microcontroller (PIC 18f4520): It represents center of the simulator device. The key features for this microcontroller are [6]:
 - ✓ Operating frequency of DC - 40 MHz.
 - ✓ Flash program memory of 32K bytes.
 - ✓ SRAM data memory of 1536 bytes.
 - ✓ EEPROM data Memory of 256 bytes.
 - ✓ 40 pins and I/O Ports A,B,C,D,E.
 - ✓ Supporting 3 wires SPI and I²C master and slave modes. In this work, SPI is used to communicate between the microcontroller and the Ethernet click.

In this work, PIC 18f4520 is selected as controller because it meets the hardware requirements (number of I/O pins) and the software requirements (sizes of program and data memories).

3. An octal bus transceiver integrated circuit (74HTC245): It is used to interface and convert digital signals between 5V powered to the microcontroller and 3.3V powered to the Ethernet click.
4. Two Digital-Analog Converter integrated circuits (DAC-08): Each 4-20 mA channel uses one DAC-08 independently to convert 8 bits parallel digital signals coming from the microcontroller to analog current signal which ranges 0 to -2.273 mA as shown in Figure 4. Firstly, the reference current (I_{ref}) is calculated by [7]:

$$I_{ref} = \frac{V_{ref}}{R_{ref}} = \frac{5V}{2.2K\Omega} = 2.273 \quad (1)$$

Then, the output current of the DAC (I_{DAC}) for the channel 1 which ranges 0 to -2.273 mA, is given as:

$$I_{DAC} = -\frac{x}{255} * I_{ref} \quad (2)$$

Where x is a 8 bit variable inside the microcontroller program which represents the DAC quantization level for the channel 1 of the 4-20 mA output current. Thus, it ranges from 0 to 255. Firstly, the TCU sends command to the microcontroller wirelessly to change value of the variable. Then, this variable controls on the 8 bits parallel output digital signals of the microcontroller connecting to the DAC.

5. Two Light Emitted Diodes (LEDs): They are used to indicate the close status of the 4-20 mA current loop.
6. Two operation amplifiers (LM324): They are a quart operation amplifier. The DAC-08 outputs current of 0-2.273 mA. This current is converted to voltage (V_o) which ranges 0-5 V by the operation amplifier (Op1) with 2.2

K Ω resistor as shown in Figure 4. This voltage is calculated by:

$$V_o = \frac{x}{255} * 5V \quad (3)$$

While, the operation amplifier (Op2) with 235 Ω resistor are used as converter from the input voltage signal (0-5V) to the output current signal for the channel 1 (I_{ch1}) which ranges from 0 to 21.277 mA according to the following equation:

$$I_{ch1} = \frac{x}{255} * \frac{5V}{235\Omega} = \frac{x}{255} * 21.277mA \quad (4)$$

Since the channel 1 and the channel 2 for 4-20 mA output currents are identical, the equation 4 is rewritten to calculate the output current signal for the channel 2 (I_{ch2}):

$$I_{ch2} = \frac{y}{255} * 21.277mA \quad (5)$$

Where y is a 8 bit variable inside the microcontroller program which represents the DAC quantization level (0-255) for the channel 2 of the 4-20 mA output current. The equations 4 and 5 are basic equations which are used in this work.

Since the DAC used in this simulator is 8 bit, the resolution (Re) of the output current signal is calculated by:

$$Re = \frac{I_{max}}{255} = \frac{21.277mA}{255} = 0.0834mA \quad (6)$$

Finally, the operation amplifier (Op3) is used as a comparator with +5V to detect the closed current loop. The voltage level limit (V_L) of the comparator is selected as +5V according the following equation:

$$V_L = V_{cc} - I_{max} * R_{PLC} \quad (7)$$

$$V_L = 12V - 21.277mA * 250\Omega = +6.68V$$

Where I_{max} is the maximum value of the output current passing in 250 Ω resistor, V_{cc} is supply voltage and R_{PLC} is resistor of a PLC analogue input module which is selected as 250 Ω since it is the maximum

value of this resistor for PLCs existed in Nassiriyah thermal power plant. For ensuring the safe operation, V_L is selected as +5V.

7. Two 12 VDC relays: they is used to control two digital outputs signals (normal open contact).

8. Power supplies: They are +12V and -12V voltage supplies with 5V voltage supply

regulator (7805) and 3.3V voltage supply regulator (LM317).

Figure 5 shows the proposed 4-20 mA simulator under the running connected with the Wi-Fi router and the multimeter to measure the output current from the channel 1.

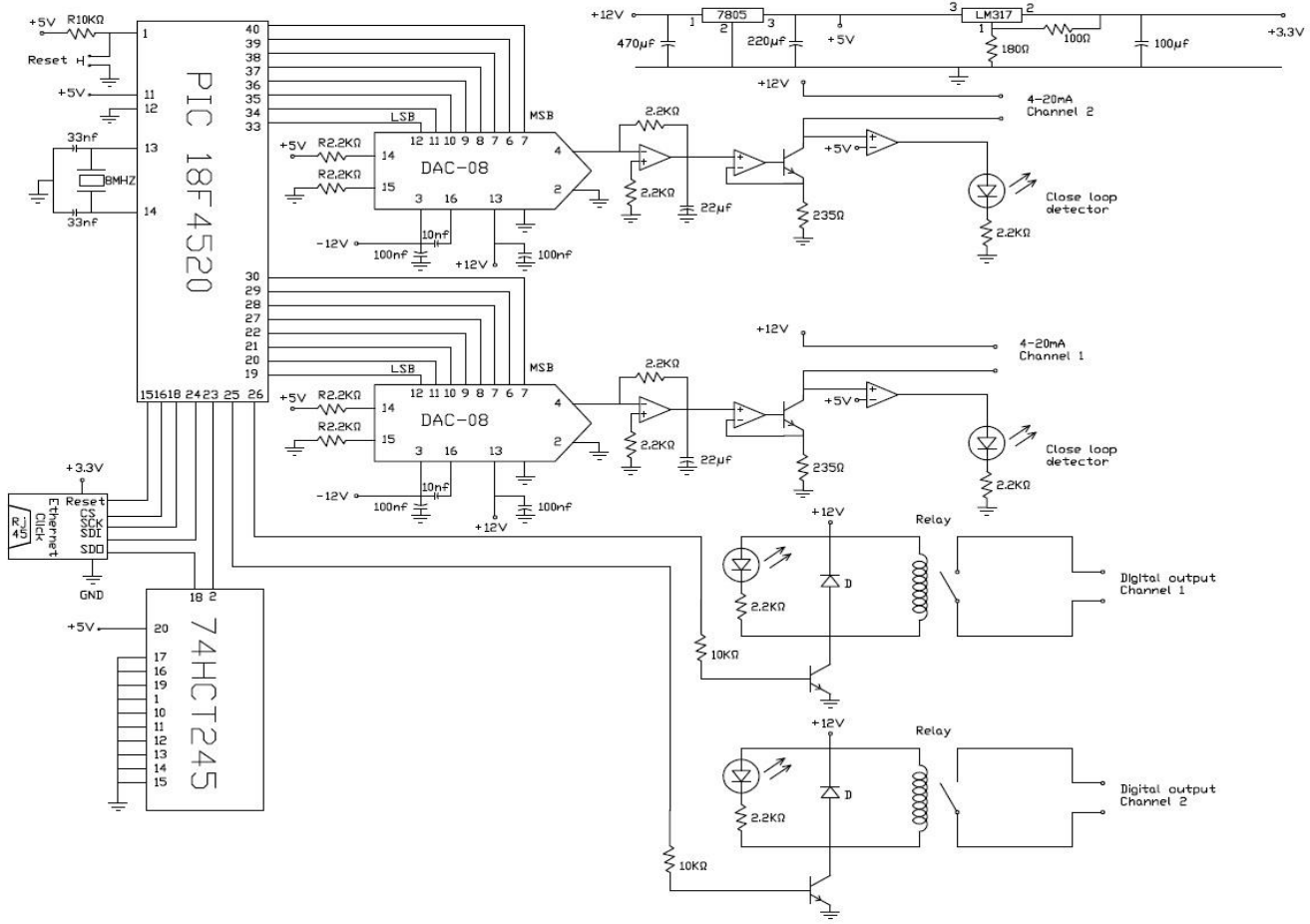


Figure 3: Circuit diagram of the whole proposed simulator

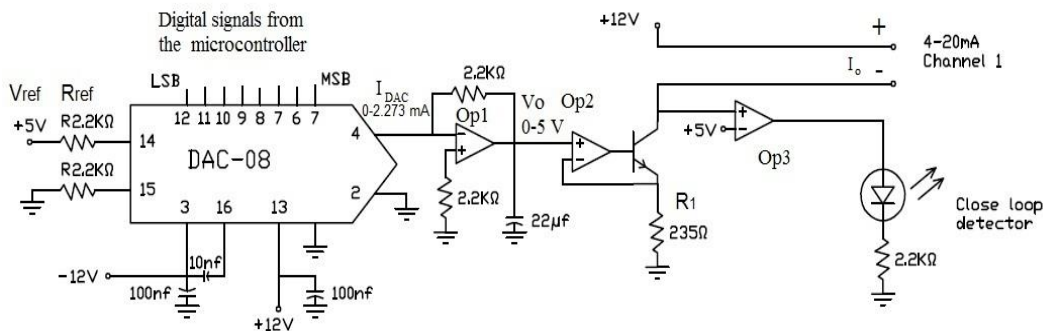


Figure 4: The signal conditioning circuit diagram for the channel 1 of the 4-20 mA output current

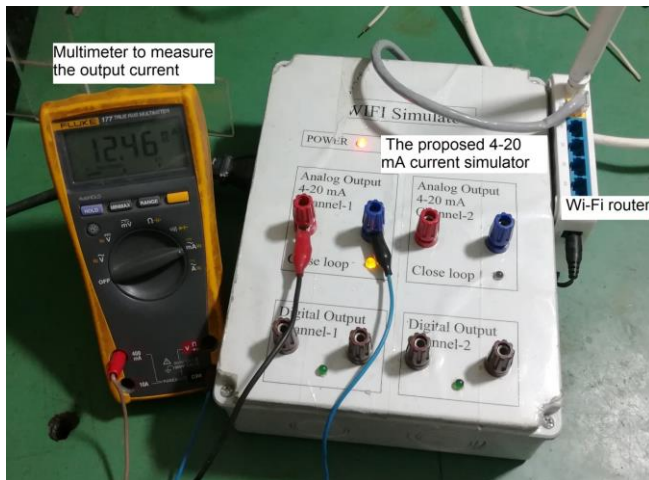
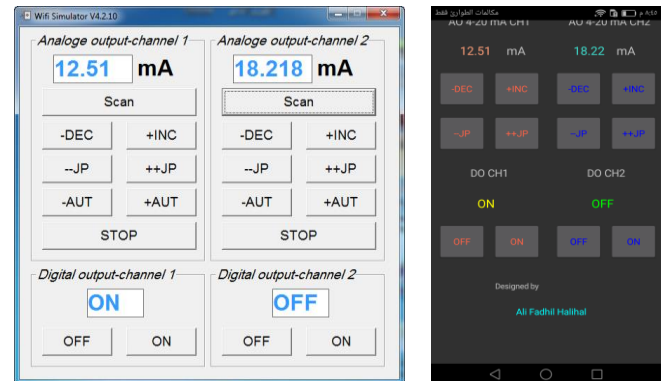


Figure 5: The proposed 4-20 mA simulator under the running with the Wi-Fi router and the multimeter

III. DESCRIPTION OF THE CONTROL PROGRAMS

There are two programs: the first is particular to the TCU, while the other is particular to the microcontroller. As stated before, the TCU is either laptop or smart mobile. Laptop software, under windows XP or 7 operating system, has been programmed by visual basic 6, while smart mobile software, under Android operating system, has been programmed by Basic4android V3.82. The PIC 18f4520 microcontroller has been programmed by mikro C compiler V8.1. Figure 6 shows screenshots of the control programs for the proposed simulator in a laptop and a smart mobile. The control programs either in the laptop or the smart mobile consist of text boxes and command buttons. Text boxes are used to display value of the two channels of the 4-20 mA output current signals and the two channels status of the output digital signals. Command buttons are used to control on the two channels of the 4-20 mA output current signal as well as the two channels of the digital output signals. When an user clicks any command button in the control program, the TCU will send specific data packet corresponding to this button, to the simulator device via the Wi-Fi router using TCP/IP. Table1 shows description of command

buttons and their data packets. Size of these data packet is selected as one byte because of small number of the command buttons.



(a) (b)

Figure 6: Screenshots of the control programs for the proposed simulator by (a) a laptop and (b) a smart mobile.

After the simulator receives the data packet, the microcontroller compares the data packet with the predetermined data to do the required action. Then, the simulator sends or returns the new value of the 4-20 mA output current signal and the new status of the digital output signal to the TCU to state the user that the command is executed. The cycle time for the microcontroller program is selected as 500 ms. Figure 7 shows flow chart of the TCU control program. While Figure 8 shows flow chart of the microcontroller program.

Really, the current displayed by the TCU is predetermined calculated current and is not measured current because this work is based on the open loop control strategy. In other word, the microcontroller does not measure the new value of the 4-20 mA current and it only sends value of x software variable stored in the microcontroller to the TCU, then the TCU calculates the new value of the 4-20 mA current from this variable according the equations 4.

Table 1: Command buttons description in the control program for the TCU with their data packets

| Command buttons | Description of the actions | Mathematical operation | Data packet |
|-----------------------------------------|---------------------------------------------------------|------------------------|-------------|
| Channel 1 of the 4-20 mA current signal | | | |
| +INC | Slow increasing the current of 0.0834 mA per one click | $x = x + 1$ | a |
| -DEC | Slow decreasing the current of 0.0834 mA per one click | $x = x - 1$ | b |
| ++JP | Fast increasing the current of 0.834 mA per one click | $x = x + 10$ | c |
| --JP | Fast decreasing the current of 0.834 mA per one click | $x = x - 10$ | d |
| Scan | Request for knowing value of the channel current signal | | n |
| Channel 2 of the 4-20 mA current signal | | | |
| +INC | Slow increasing the current of 0.0834 mA per one click | $y = y + 1$ | e |
| -DEC | Slow decreasing the current of 0.0834 mA per one click | $y = y - 1$ | f |
| ++JP | Fast increasing the current of 0.834 mA per one click | $y = y + 10$ | g |
| --JP | Fast decreasing the current of 0.834 mA per one click | $y = y - 10$ | h |
| Scan | Request for knowing value of the channel current signal | | m |
| Channel 1 of the digital output signals | | | |
| ON | Switching on relay A (normal open) | | i |
| OFF | Switching off relay A (normal open) | | j |
| Channel 2 of the digital output signals | | | |
| ON | Switching on relay A (normal open) | | o |
| OFF | Switching off relay A (normal open) | | p |

IV. THE CONNECTION MODES OF THE SIMULATOR TO THE PLC

There are two modes in the proposed 4-20 mA simulator as in the commercial wired simulator. These modes are source mode and simulate mode. The source mode is selected when the simulator is connected to the analog input module of the PLC directly without a power supply as shown in Figure 9 (a). While, the simulate mode is selected when the simulator is connected to the analog input module of the PLC with a power supply as shown in Figure 9 (b). This power supply feeds 24 V DC voltage to the transmitters. The simulate mode always is used when the transmitter type is loop powered (two wires) transmitter.

V. EXPERIMENTAL RESULTS

Firstly, the proposed simulator device and the router switch on and a laptop connects with the router via Wi-Fi wireless technology. Then, the transmitters terminals are disconnected from PLC and the two channels of the 4-20 mA current loop signals for the simulator are connected with PLC instead of the transmitters. This PLC locates in

Nassiriyah power thermal plant and has 250 Ω input resistor. After clicking command buttons in the laptop program for different samples of the currents, the measured currents (I_{meas}) have been recorded with the currents displayed (I_{disp}) by the laptop and listed in Table 2.

Table 2: The error between the measured current and the displayed current for different samples

| The measured current (mA) | The displayed current (mA) | Error (%) |
|---------------------------|----------------------------|-----------|
| Channel 1 | | |
| 4.033 | 4.03 | 0.015 |
| 7.982 | 7.976 | 0.03 |
| 12.028 | 12.006 | 0.11 |
| 16.053 | 16.036 | 0.085 |
| 20.028 | 19.982 | 0.23 |
| Channel 2 | | |
| 4.099 | 4.094 | 0.025 |
| 8.1154 | 8.106 | 0.047 |
| 12.135 | 12.117 | 0.09 |
| 16.166 | 16.129 | 0.185 |
| 20.026 | 19.973 | 0.265 |

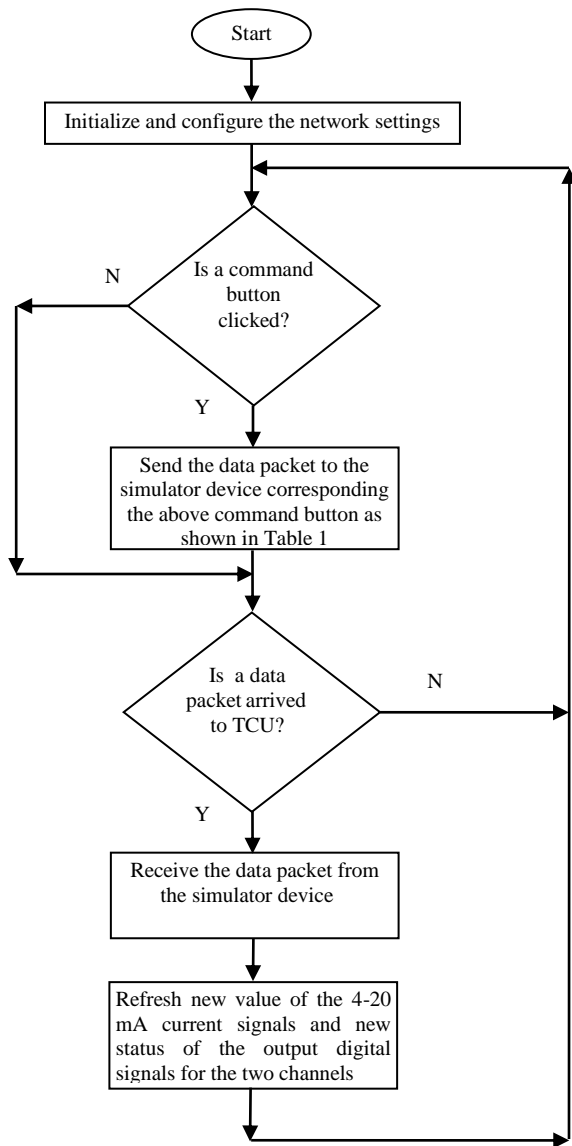


Figure 7: Flow chart of the TCU control program

The error (Err) between the measured current and the displayed current, is calculated as follows:

$$Err = \frac{I_{meas} - I_{disp}}{Span} 100\% \quad (8)$$

Where Span is span of the full current signal range which is 20 mA and is not 16 mA because this simulator outputs 0-20 mA.

The experimental results show that the measured resolution is 0.0835 mA or 0.4175 % with respect to 20 mA. This confirms the resolution, which is calculated by the equation 6. As seen in Table 2, notice that the maximum error is 0.265 %. However, the resolution selection plays a major role in determining the accuracy of the designed

simulator device. This leads that this device has high accuracy and can be used in testing the protections and the interlocks reliably.

The wireless simulator accuracy also is investigated experimentally under different input resistors (R) for analog input modules in PLCs. The results show that the proposed simulator generates the current precisely under the different input resistors according to the required command from the TCU as shown in Table 3.

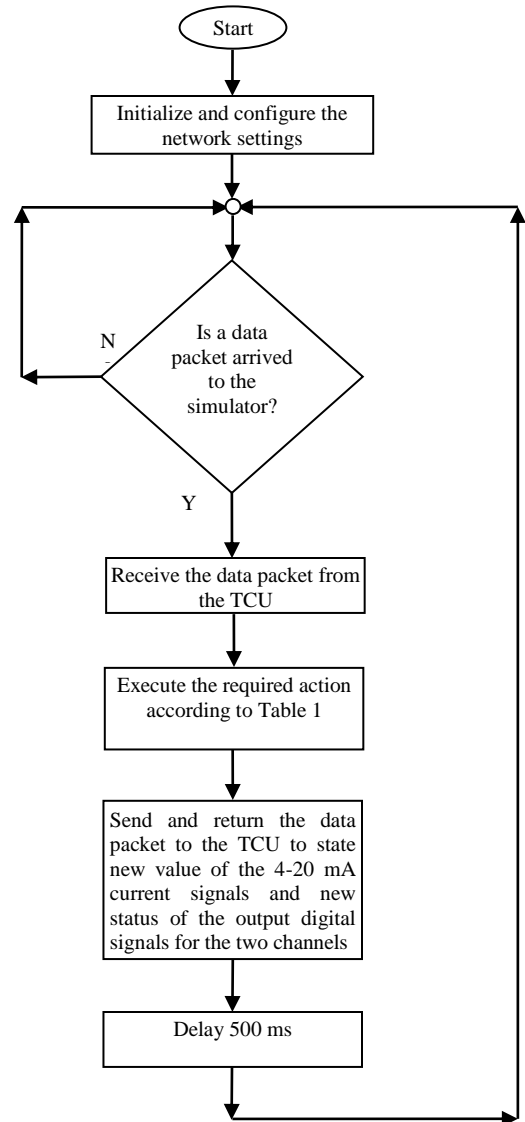
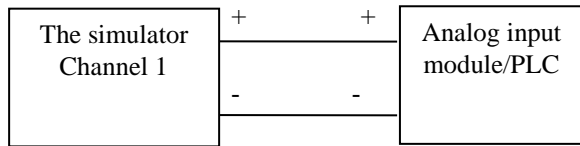
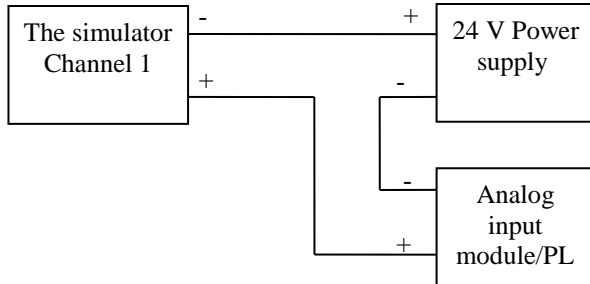


Figure 8: Flow chart of the microcontroller program



(a)



(b)

Figure 9: Scheme of the simulator connection to the PLC: (a) source mode (without the power supply) (b) simulate mode (with the power supply)

Table 3: The error between the measured current and the displayed current for different values of input resistors for analog input modules in PLCs

| R (Ω) | The measured current (mA) | The displayed current (mA) | Error (%) |
|-----------|---------------------------|----------------------------|-----------|
| Channel 1 | | | |
| 50 | 12.026 | 12.006 | 0.1 |
| 100 | 12.027 | 12.006 | 0.105 |
| 150 | 12.026 | 12.006 | 0.1 |
| 200 | 12.027 | 12.006 | 0.105 |
| 250 | 12.028 | 12.006 | 0.11 |
| Channel 2 | | | |
| 50 | 12.14 | 12.117 | 0.115 |
| 100 | 12.14 | 12.117 | 0.115 |
| 150 | 12.141 | 12.117 | 0.12 |
| 200 | 12.142 | 12.117 | 0.125 |
| 250 | 12.135 | 12.117 | 0.09 |

The proposed simulator response is investigated experimentally with respect to commands coming from the TCU. After the ++JP command button is clicked from the TCU program, the output current of the simulator will change from 7.98 mA to 8.82 mA during 4 ms settling time as shown in

Figure 10. The delay time occurs because of the capacitor connected across input resistor for analog input modules in the PLC. It is concluded that the wireless simulator has very fast response.

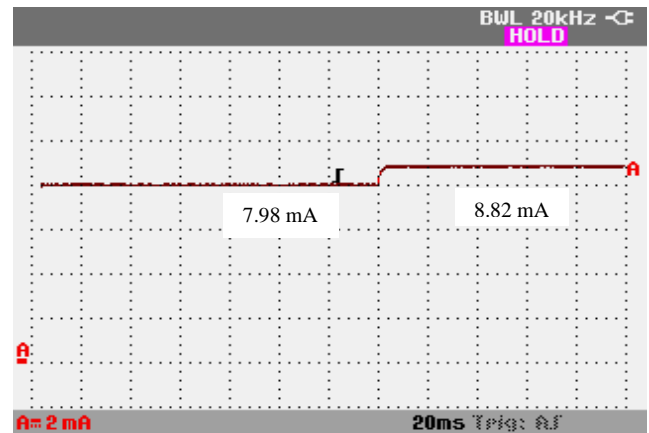


Figure 10: The practical response of the output current of the simulator after clicking on the ++JP command button from the TCU program

VI. CONCLUSIONS

In this paper, the wireless 4-20 mA current loop simulator has been designed and implemented using a PIC 18f4520 microcontroller and an Ethernet click. The experiments indicate that the proposed wireless simulator outputs the 4-20 mA current with high accuracy and is easy, comfortable and convenient to use in the test operations of protections, interlocks, analog input channels response for a PLC compared to the wired simulator. Also, The experimental results show that the proposed simulator generates the output current precisely under the different input resistors for the receivers according to the required command from the TCU and the simulator has very fast response. The future scope of this work is design and implementation of wireless simulator for Resistance Temperature Detectors (RTDs) and thermocouple sensors.

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