Research Paper

Xbee-based Wireless Automatic Level Control for Cascaded Water Tanks using PLC

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ABSTRACT : *This paper proposes an optimized wireless automatic control technology using a programmable logic controller through a wireless communication network. A remote control platform is designed and implemented using xbee wireless control modules for level control of a cascaded tank system using programmable logic controllers.*
First, a prototype system is designed and built. Second, the remote control algorithm is applied via xbee wireless modules. The power consumption and cost is minimized for the proposed implemented technology. The process control is successfully tested and evaluated to demonstrate the reliable, robust and accuracy of the proposed method. This remote control process verifies the use of wireless control network in industrial type environment.
Keywords: *Automatic Control, Programmable Logic Controller, Wireless Control, Xbee, Level Control*

I. INTRODUCTION

Wireless Technology has been always the goal for automation industry and control systems worldwide because of many remote industrial control applications. Wireless control networking concept had difficulties to pave its pathway into replacing the conventional control networks. In many terms, the wireless control network would have been the optimum solution that is able to reduce the cost substantially by simply replacing the running cables, wires and required infrastructure. Today, the wireless control network is undergoing extensive studies and piloting to address the issues in order to mitigate the risk and clear the path for it.

For the past decades, many industries have been working extensively to overcome the issues which become obstacles towards the development of such an important and essential field.

Overall, the industrial control system standards in most cases require a level of robustness in terms of reliability and availability as a challenge for the wireless control. For that reason, manufacturers are working thoroughly to improve and to develop the needed technology. In addition, meeting the standards and deploy the concept of wireless control network have been investigated more widely in the automation industries.

Most of the experiments that have been done using the xbee as a wireless control media for a wireless control network focused on two concepts. Realization of the xbee behavior with simple plant structure considering the analog output control signals has not been applied. Usually, these systems did not get controlled by a PLC as an industrial controller and micro-controllers are used instead. Also, most of the processes were simple and didn't fully load the xbee modules which might be a bottleneck in some applications.

An experiment performed by SRM University [1] presented bees as wireless control modules using the PLC as control platform. The level was controlled through an ON/OFF solenoid valve, they used the digital input/output pins to control the level by either fully open the valve or completely closed. The process was one tank which might not give an enough insight on an application where interactions in the process might contribute to the performance differently.

Other work presented in [2] uses the xbee as a wireless control network, it is actually using the PWM signal as an analog output for simple application such as the control of a servo motor [5]. We noticed that the servo motor is receiving the PWM to control the motor directly but that would not show the xbee capability to control devices that don't receive PWM as an analog form of signal which requires an extra interface hardware to be designed.

This project presents two main significant subjects which makes it to be different from previous studies in literature. First, it uses xbees as wireless modules with low power consumption and capable of providing a

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robust control network with the most feasible and efficient way. The project illustrates how xbee devices are compatible with industrial control applications. This is a crucial point for many wireless devices that require special software or complex hardware to establish their interface. Second, this project uses xbee direct connections instead of having an extra hardware of micro-controller for execution and control. This is found to be very useful when analog output control signals converts to a PWM signal and vice versa. Thus, controlling a valve was a bit challenging before, but with this feature it can now be done with very minimal hardware for compatibility only.

In this project, a stereotype model of two tanks connected in series is designed and built to represent a small scale of a process or a plant for the proposed wireless control network experiment. The tank's level controlled by RSLogix5000 PLC manufactured by Rockwell Automation [7]. The tanks' levels communicate with the controller remotely using low power consumption devices produced from Digi Company called xbee RF modules [9]. Using the direct connection method or as known as peer-to-peer, between the two wireless modules, the base model receives the data from the remote model wirelessly and connects it directly to the PLC through the IOs cards. PLC includes a ladder logic control strategy using two Proportional-Integral-Derivative (PID) automatic control loops [1]. Also, a Human Machine Interface (HMI) is developed to emulate the control panel and to monitor the tanks' control valves as well as the pumps. The HMI is developed using Rockwell Automation suite which is known as Factory Talk Studio Site [8]. This environment and media helps accomplish the goal of having a wireless control with a continuous reading with bi-directional data communication. The next following chapters will go in details, starting from the technical background for the major components, mathematical modeling and analysis, design and implementation and eventually with the results and conclusion.

II. SYSTEM SETUP

The system is simply recognized in Fig. 1. The system consists of two tanks, two valves and an inlet constant flow from a pump located at a basin. The pump feeds the tank 1 with a constant flow rate while the output of tank 1 will be considered the feed in to tank 2, the output from tank 2 will go to a basin (tank 3) where the water is circulated to tank 1 again. This setup is to simply build a reasonable model to test the wireless control network performance. The following ordinary differential equations are the mathematical modeling that represents the system [2]. For the first tank and for the second tank is

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$$\frac{dh_1}{dt} = \frac{F_{in1} - a_1.C_v\sqrt{2 \times g \times h_1}}{A_1} \qquad (1)$$
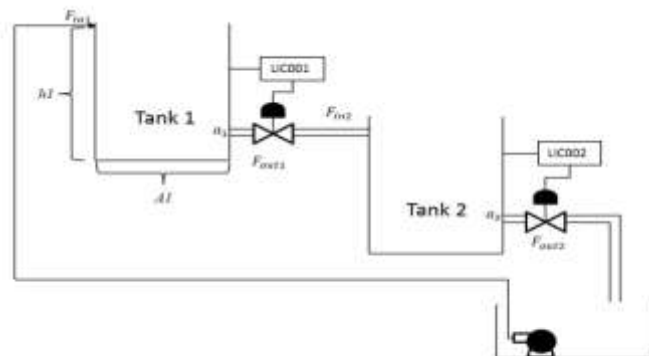
Fin1: Input flow rate of tank 1
A1: Area of the tank1
a1: Area of the first valve inlet diameter,
C_v: Flow coefficient
G: Gravitational constant 9.8 m^2/s.

$$\frac{dh_2}{dt} = \frac{a_1.C_v\sqrt{2 \times g \times h_1} - a_2.C_v\sqrt{2 \times g \times h_2}}{A_2} \qquad (2)$$

Fig. 1: Water level control system

The system's equilibrium point is 15.3 which are around 50% of the tank, and since these equations contain nonlinear portion. System equations are linearized at the equilibrium point to analyze the stability of the system. Hence, the system is represented in the following equation:

$$A_{(15.3,15.3)} = \begin{bmatrix} -0.000367 & 0 \\ 0.000367 & -0.000367 \end{bmatrix} \qquad (3)$$

Clearly from the matrix, it is concluded that the system is stable in the neighborhood of the operating point. Thus, the eigenvalue λ will equal to -0.000367 which means that the linearized system is stable node at the equilibrium point, and that the nonlinear system I showing the similar behavior and stable node in the neighborhood of the operating point. This helps us understand the behavior of the nonlinear system and analyze it over certain operating points.

III. SYSTEM DESIGN AND APPROACH

A cascaded tank system is built and set up for a wireless control network in order to demonstrate the wireless automatic control concept. The HMI is developed using the *Factory Talk Studio* package from *Rockwell Automation* creates a user interface control panel window to be used for controlling the plant.

The setup illustrated in Fig. 1 is developed using three tanks, two proportional solenoid valves and one extra pump to return the water back to tank 1 from basin or tank 3. RSLogix 5000 controls the level of the tanks 1 and 2 remotely; the signals are transmitted and received using xbee wireless RF modules.

Therefore, major components of the remote control system network are listed as follows:
1) Two xbee wireless RF module devices
2) RSLogix5000 PLC System
3) HMI development using Factory Talk Studio Site edition software
4) Electronic control units
5) Level transmitters

Pumps, PLC and xbee modules operate on different voltage ranges. In order to make these modules compatible, electronic interface modules are designed and implemented to overcome voltage range differences. Details of the system components along with designed interface boards are described in the next section.

3.1. Xbee Device Configuration

Xbee RF modules are embedded solutions to provide a communication media between devices [9]. The transceiver uses the IEEE 802.15.4 networking protocol that will provide fast point-to-multipoint or peer-to-peer networking [9]. They are easy to use, setup and program to be used in many applications that need low cost and low-power consumption to control devices through a wireless network. In this project, xbee Pro S1 model is used which is a version of xbee products with a higher power to provide a wider range network coverage, for indoor can cover up to 300 feet while outdoor up to 1 mile (Line-of-Sight) range. The device output power is about 63mW (18 dBm) and operates with a 3.6V power supply. The operation frequency is the open bandwidth 2.4GHz with 250 Kbps data rate. It provides different types of network. The peer-to-peer network approach in the project is utilized. One is the transmitter or remote module and the other is receiver or the base module. One method of communication is *Direct Connectivity* or what is known as ADC I/O line passing which xbee provides for easy setup. Using XCTU [10] software, the two xbee modules configurations made to accomplish the needed. Fig 2 shows the configuration page for both the Xbee transmitter and the receiver. xbees are not able to transmit analog signal directly. However, he analog signals can be transmitted as pulse-width modulated (PWM) signals. The signal duty cycle represents the value in the digital form. So for analog inputs, they are received at the other ends PWM signals that represent the analog signals based on the duty cycle at specific frequency. Thus, it can be filtered and converted into an analog output.
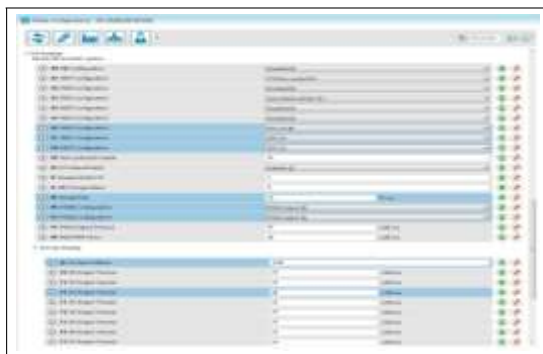

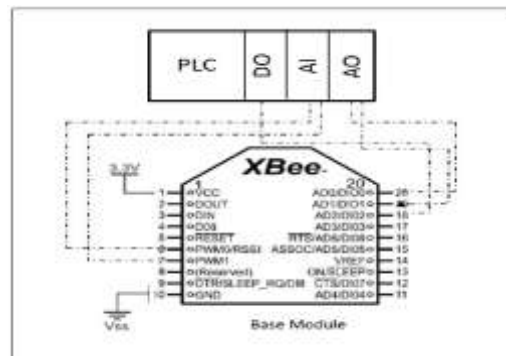**Fig 2**. Xbee transmitter configuration used in the project

Fig 3. PLC to xbee connection diagram

Fig 3 depicts the connection diagram between the PLC and xbee wireless module. Two Analog Outputs (AO) ports, one Digital Output (DO) port and one Analog input (AI) port from PLC are connected to the xbee. As shown in Fig. 4, solenoid valves, level transmitters and tank 3 pump are connected to the second remote xbee module via its AO, AI and DO ports.
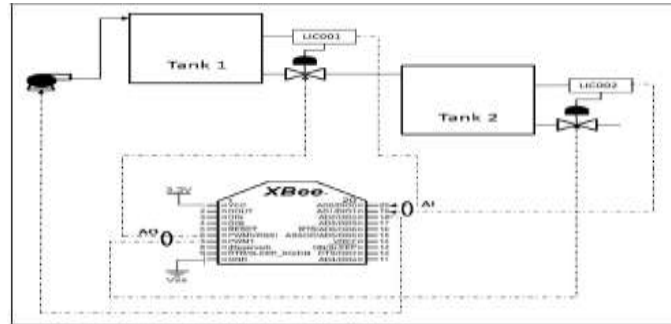
Fig 4. Xbee receiver configuration used in the project

3.2 RSlogix5000 PLC Configuration

This system is equipped with 2 Analog inputs, 2 Analog outputs and built-in 16-Digital inputs/outputs. One Analog input card is using 0-10 Vdc connection and the other is using the regular 4-20mA, the same for the analog output card as well. The well-known *Allen Bradley* PLC 1769 *Compact Logix* L18ER, as shown in Fig. 5, is used in this project. The controller has the advantage of the size where it compacts the I/O modules as well as the controller with the power supply. The system is preferred for applications where size and space matter.

The following list contains the major parts that are configured in this project:
- 2 PID blocks for each tank, LIC001 and LIC002
- Two HMI manual valve control tags for each tanks
- HMI MAN1 and HMI MAN2
- HMI Pump start and stop tags, HMI START and HMI STOP
- Tags trend for level controllers LIC001 and LIC002

Fig 5. The PLC hardware 1769 Compact Logix controller

For each tank in this project, a controller loop named *LIC*001 and *LIC*002 are developed for tanks 1 and 2, respectively. The tank levels are being measured using level transmitters and sent wirelessly to the PLC. Therefore, both LV001 and LV002 are connected to AI channels 0 and 1 of the PLC, respectively. These two are actually coming directly from the xbee base module and connected to the analog input module. Fig 6 shows a simple schematic diagram for the connection.
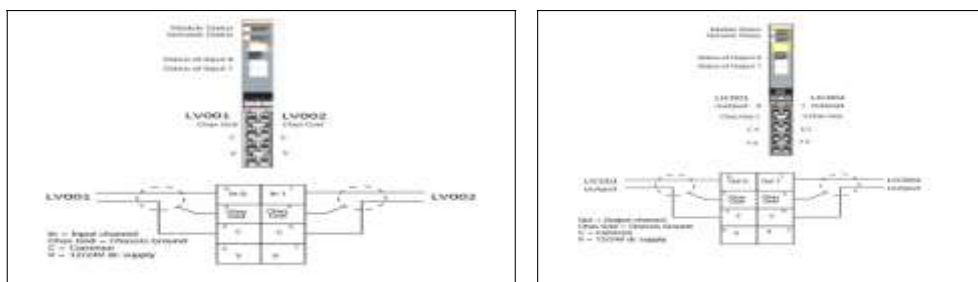
Fig 6. Analog input wiring for the level transmitters on the PLC   **Fig 7.** Analog output wiring for the control valves

The output of PID controllers for each tank sends their control commands to the analog output ports LIC001 and LIC002. They are wired directly to the xbee base input port which transmits the analog control signals to the tank system. Fig 7 shows a schematic diagram for the wiring of analog output. For the digital output to start and stop the pump located at tank 3, a digital I/O port is used. Digital output port sends a signal to the tank 3 pump to turn it on or off when needed as indicated in Fig 8.

Fig 8. Digital output wiring schematic diagram	Fig 9. The main ladder logic program
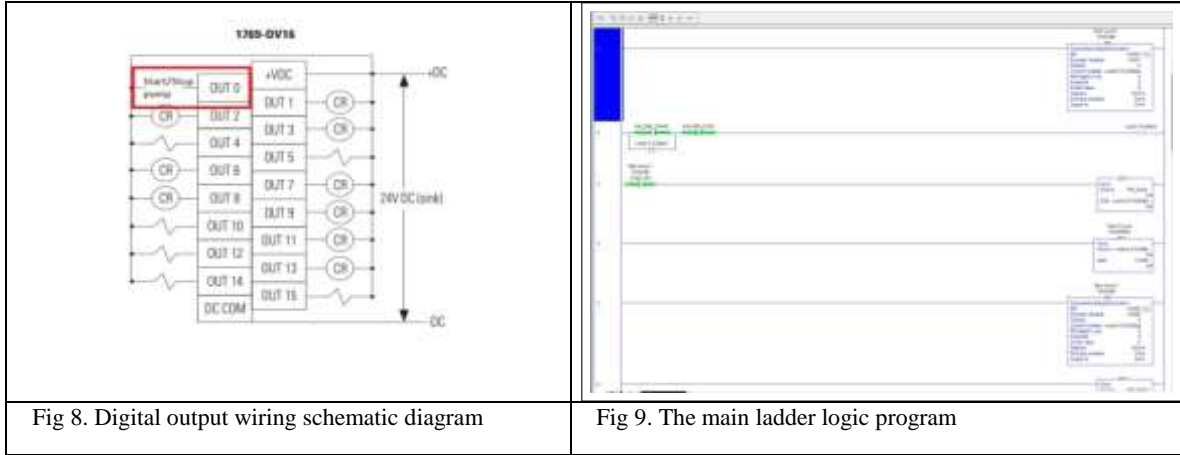
The main ladder program includes the whole control logic. The logic will have 2 PID blocks, several *MOV* blocks and the pump's operation's logic as shown in the Fig 9. There are internal logic's which are added to the ladder to accommodate the communication with HMI configuration. For instance, dummy tags are needed to control the operation of the pump as well as the controllers' mode.

3.3 HMI Configuration

Human Machine Interface is a crucial tool in the field of automation and control. Therefore, a HMI window is designed to display the plant's data and to control the valves and pump's operation. HMI contributes greatly to the process optimization and efficiency. The operator's focus helps mitigate the risk involved with the complexity of the plants. Moreover, the plant's optimization and control efficiency increases. In modern automation world, optimization is a crucial element and has been always challenging to come up with the best results. In this project, the Factory Talk View Machine Site is used. This software is developed by *Rockwell Automation* which allows users to create the HMI or the control panel and communicate with PLC through RSlogix5000. This provides easy access to the controller database and use them directly into building the HMI whether using them as graphics, faceplate, pushbuttons and etc.

For the tanks, level indicators and controllers, the common industrial standards are followed where the graphic usually shows the following:
1) The Controller Mode
2) The Set point
3) The level of the tank
4) The control valve manual control
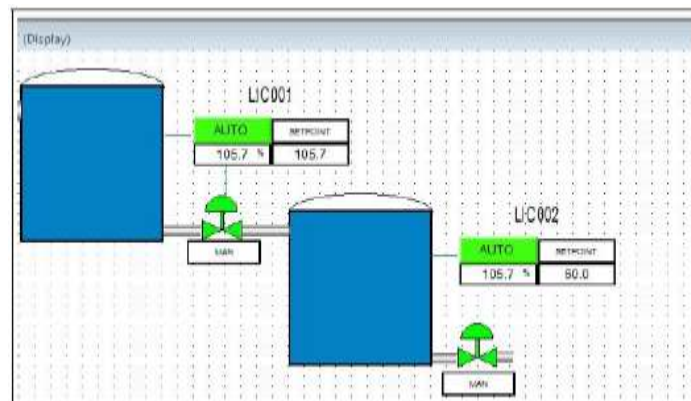
Fig 10. The complete process control graphics

3.4 Operational Solenoid Valve

Considering the size and cost limitation, The Red Hat SD8202G87V stainless steel 3/8" valve [11] was selected as shown in Fig 11. The solenoid valve will be controlled through an electrical control unit. Although that the valve would work better in higher velocity or pressure flow, it works with very reasonable and satisfactory performance even at low velocity flow.

An electrical control unit was designed and connected between the xbee device and the valve to convert the xbee output PWM signal to an analog output 0-10V. The generated control signal from xbee module is a PWM signal with proper duty cycle proportional to the current needed to maintain the valves at certain position. Due to very high frequency in signal output, the valves operate smoothly and constantly.

Fig 11. Red Hat SD8202G87V proportional solenoid valve

The duty cycle variations or ripples will not be noticed. The current sensor will maintain the output of the current no matter what the voltage or coil current variations are.

3.5 Electronic Control Interface

To read the output xbee signal by the PLC input and drive the tank valves, an electronic logic controller is designed. The schematic in Fig 12 consists of a RC filter and non-inverting amplifier which is designed for this purpose. The filter cut-off frequency is set to be 160 Hz and the amplifier gain is adjusted to 3.09. The xbee output PWM signal gets converted to a 0-3.3 V analog signal and steps up to 0-10V range.
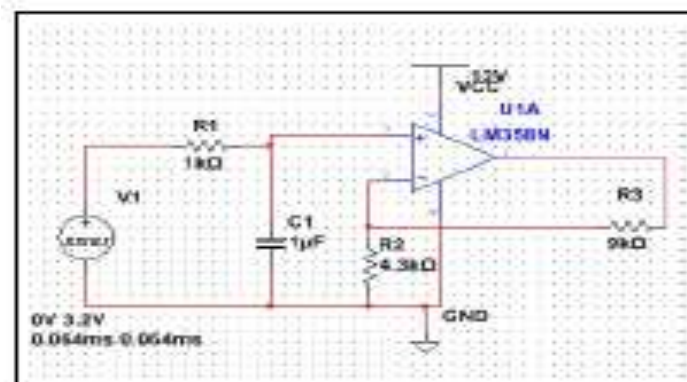

Fig 12. Electrical control circuit diagram

The electronic controller output voltage drives an axiomatic connector amplifier model P/N400070 [12] which is selected to drive the tank valves.

3.6 Level Transmitter

Measuring the water level in the tank is another challenge, however, A *Etape* level transmitter, as shown in Fig. 13, produced by *MiltoneTech* company is used for this set up [13]. The level transmitter resistance output is a variable resistance and gets converted to voltage using a linear resistor-to-voltage module. The module is a circuit consists of a differential Op-Amp which generates an output voltage signal proportional to the measured tank level. The output voltage is adjusted to be in range of 0-3 V matching xbee modules voltage range.

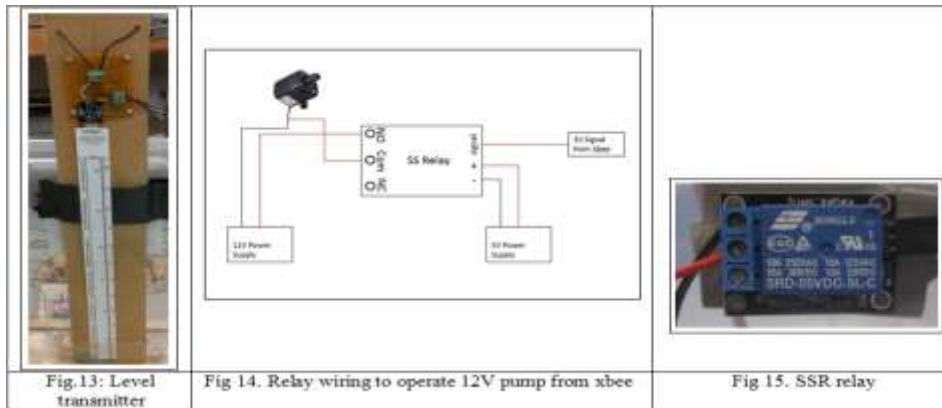### 3.7 Water Return Pump Connection and Wiring

A pump has been added to the third tank as part of the system to have a constant flow going to the first tank. The pump requires 12Vdc to operate, for that we will be using SSR relay to control the pump operation. xbee remote base provides the control signal to the relay, and the relay starts and stops the pump accordingly.

IV. EXPERIMENTAL RESULTS

Fig 16 shows the overall system built at the ECE department of California State University Northridge. The xbee devices are classified to the base and the remote modules. The base module is where the xbee is receiving the data from the remote one and is wired directly to the PLC system. The remote xbee is the transmitter where all remote devices and instruments are wired to it directly. It is very important to develop a procedure that serves the objectives defined for this project. Therefore, the following procedure is developed where the wireless control performance of the tanks level control can be tested.

The following steps are required to be applied in order to generate the plotted results of the experiment depicted in Figs 18, 19 and 20.

- Powering up The system
- Starting the Pump to fill the first tank to reach 50
- Set LIC001.SP = 40% and LIC002.SP = 30%
- Tune the PI controller accordingly to adjust the step response
- Shutting off the pump when level at tank 1 reached 50
- Change the Set point of LIC002.SP from 30% to 20%

| Fig.13: Level transmitter | Fig 14. Relay wiring to operate 12V pump from xbee | Fig 15. SSR relay |

It is noted that the level started at 40% and after starting the pump the level went up all the way to almost 55% where the control valve opened immediately after the level rose above the set point. The control valve went wide open to compensate the level increment. However, once the pump stopped the level decreased until it reached to 40% set point where the valve closed and maintained the level at the set point. It is noticed that the tank is quite small compared to the velocity of the flow rate coming out of the valve, however, that explains the time been taken to reach the set point which took around 4 minutes. Also, the fluctuation of the level reading was observed. That is very common and normal but it is worth of mentioning that this is basically due to some hydrostatic shocks created by the valve's reaction toward the water.
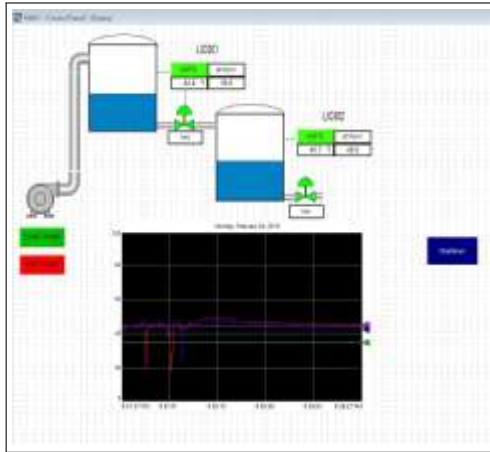

Fig 16. Overall system built

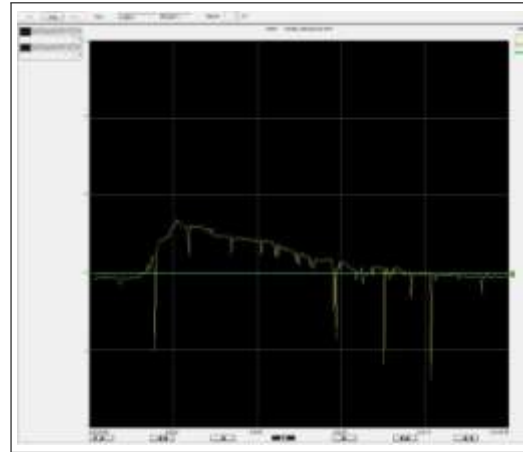**Fig 17.** The HMI control window during the startup

Fig 18. Tank level was 40% and then reached to 30%

For the second tank level controller LIC002, we noticed that the level started at 30% and stayed steady as the flow rate coming from the first tank is equal to the flow rate going out from the second tank. Fig 19 indicates this satisfactory control action at the beginning of the trend the level controller was trying to maintain the level. Then the set point changed to 20% and that took almost 3 ~ 4 minutes to settle the steady state point similar to the first tank.

In the second test, the set point for LIC 001 and LIC 002 was changed from 30% to 35%. Fig. 20 shows the tank level change which follows the LIC 002 new set point successfully.
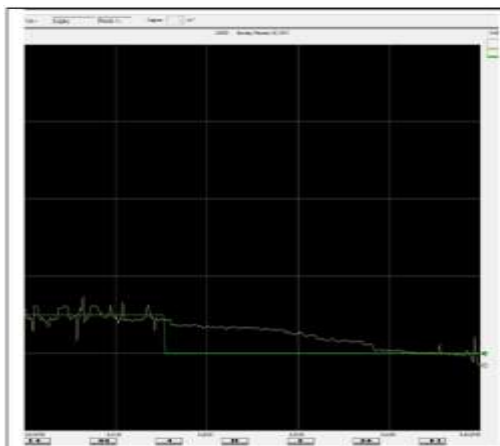

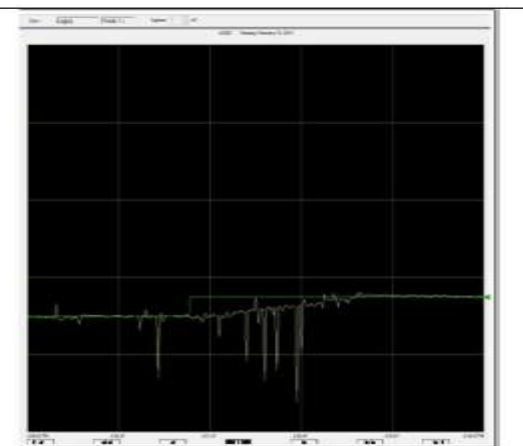Fig 19. LIC002: Tank level was 30% then dropped to 20%

Fig. 20. LIC002: Tank level was 30% and reached 35%

The effect of the flow-in is observed clearly when the pump is ON causing water level instability which is a very common situation. The input flow causes the level or the process disturbed or to be unstable. Once the pump is OFF the level settled in both tanks and the reading was steady again. As the previous test, almost the time required to reach the set point is approximately around 3 minutes which is a reasonable time when compared to the output flow with respect to the tank volumes.

V.   CONCLUSION

This paper proposed an optimized wireless automatic control technology using a programmable logic controller a long with a wireless communication network. The remote control platform was designed and implemented using xbee wireless control modules for level control of a cascaded tanks system by programmable logic controllers.

A prototype system is designed and built. The power consumption and cost is minimized for the proposed implemented technology. The process control is successfully tested and evaluated to demonstrate the reliable, robust and accuracy of the proposed method. This remote control process verifies the use of wireless control network in industrial type environment.

The proposed set up helps realize and impose a drastic improvement in the automation and control industry. Conducting a full and thorough feasibility study at least for such a small scale process helps advance and accelerate the implementation of wireless control system in wider and broader ranges. This model is a

potential to develop many control strategies such as optimum control, predictable control, multi-variable control and etc., as a milestone targets for future research on wireless control network.

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