Received: 23 June 2023 | *Revised: 21 November 2023* | *Accepted: 21 December 2024*
DOI: 10.37917/ijeee.21.1.8 *Early View* | *June 2025*

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

IJEEE University of Basrah College of Engineering

PLC/HMI Based Portable Workbench for PLC and Digital Logic Learning and Application Development

Jawad Radhi Mahmood, Ramzy Salim Ali*
Department of Computer Engineering, University of Basrah, Basrah, Iraq

Correspondance
*Ramzy Salim Ali
Department of Electrical Engineering
University of Basrah, Basrah, Iraq
Corresponding address
Email:rsalwaily@ieee.org

Abstract
A Programmable logic controller (PLC) uses the digital logic circuits and their operating concepts in its hardware structure and its programming instructions and algorithms. Therefore, the deep understanding of these two items is staple for the development of control applications using the PLC. This target is only possible through the practical sensing of the various components or instructions of these two items and their applications. In this work, a user-friendly and re-configurable ladder, digital logic learning and application development design and testing platform has been designed and implemented using a Programmable Logic Controller (PLC), Human Machine Interface panel (HMI), four magnetic contactors, one Single-phase power line controller and one Variable Frequency Drive (VFD) unit. The PLC role is to implement the ladder and digital logic functions. The HMI role is to establish the virtual circuit wiring and also to drive and monitor the developed application in real time mode of application. The magnetic contactors are to play the role of industrial field actuators or to link the developed application control circuit to another field actuator like three phase induction motor. The Single -phase power line controller is to support an application like that of the soft starter. The VFD is to support induction motor driven applications like that of cut-to-length process in which steel coils are uncoiled and passed through cutting blade to be cut into required lengths. The proposed platform has been tested through the development of 14 application examples. The test results proved the validity of the proposed platform.

Keywords
Programmable logic controller (PLC) , Variable Frequency Drive (VFD)

I. INTRODUCTION

A Programmable logic controller is a microprocessor-based control system, designed for automation processes in in-dustrial environments [1]. Early PLCs were designed to replace relay logic systems [2]. Currently, PLCs control the operation of large number of devices and machines with an incresed reliability and cost reduction [3]. these controllers will continue to be required to a considerable extent for the production of tomorrow [4]. They are used to create teachable filling applications. They are used to coordinate the switching of motorized circuit breakers in switchgears.

Digital logic is a fundamental course typically offered to electrical engineering, computer engineering, and computer science students. Ladder logic and PLC programming naturally fit in digital logic course [5]. Digital logic circuits are also widely used in various electronic devices including programmable logic controllers (PLC). Logic gates, relational circuits, counters and shift registers are also significant components both in the PLC programming environment and digital logic design circuits [6]. From these samples of applications, one can sense the importance of developing a re-configurable plat-form that can be used to develop and test ladder-logic and/or digital logic circuits based applications.

As mentioned in the abstract, this proposed platform uses five of the well-known and widely used industrial devices which

are represented by the PLC, the HMI, the magnetic contactor, the single -phase power line controller and the VFD. The PLC is a special industrial control computer. It has the ability to accept digital and analog input signals coming from the industrial field pushbuttons, selector switches, mechanical limit switches, electronic proximity switches, shaft encoders, and analogue transmitters like that of temperature and pressure.
It also has the ability to generate and send digital and analog driving signals for the industrial field output devices like magnetic contactors, variable speed drives, and single phase and three phase power controllers. As a computer, the PLC is a computerized control station. From the point of view of operation modes, the PLC widely used modes of operation are the repetitive operation mode and the interrupt mode. The repetitive or scan mode of operation is the main operation mode that each PLC should have at least one of it. In this mode, the user application program is repetitively executed from its start statement to its end statement as long as the PLC is in the run mode. Here the program execution does not depend upon any condition.
The interrupt operation mode is event driven one. In this mode of operation, the user application program includes more than one program. Mainly, it consists of a main scan program and one or more interrupt service or event driven programs. The interrupt service program execution does not occur automatically. Its execution is always stipulated to the occurrence of a certain interrupt signal. When an interrupt signal takes place, the currently executed program is suspended and the interrupt program is executed. From the point of view of programming languages, all the PLCs support ladder language and some of them in addition to the ladder language support function block and /or structured text programming languages. In this work, the structured text programming language has been used. This language is very close to the well-known Pascal language. The PLC programming language's user defined function block feature and the repetitive mode of operation of the PLC have been used to create the configurable feature of this proposed platform.
The HMI is also an industrial programmable device. It has the ability to monitor and / or modify the memory locations of its partner (PLC, VFD, etc.). The HMI programming or configuring software provided by the HMI vendor allows the systems integrators to create interfacing screens in which the HMI partner's memory devices are pictorially represented and treated as bit type and word types devices.
The magnetic contactors are power switching devices. They use low current signals (around 200 mA) to switch ON and OFF large current loads. Their low current consumption allows them to be directly connected to the PLC relay type output contacts. With transistor type PLC outputs, the magnetic contactors can be directly or indirectly derived depending on their coil's voltage rating.
The single -phase power line controller are also power switching and control devices. It consists of two antiparallel connected thyristors along with an electronic circuit responsible to convert the analog control signal (voltage or current) coming from the PLC digital to analog module to a thyristor delay firing signal. Combining single -phase power line controller with magnetic contactors creates what is called soft starter.
The VFD is a microprocessor controlled variable voltage variable frequency inverter used for controlling the torque and speed of the ac induction machine. It has a user friendly control and communication facilities. These facilities allow the PLC to master the control of the driven machinery as specified by the user defined program.
Many papers deal with digital logic and PLC learning and applications. Calazans et al. [7] proposed the integration of computer architecture with digital design for undergraduate courses. Hacker and Sitte [8] presented interactive a computerised teaching tool for the design of combinatorial and sequential logic circuits within the WinLogiLab environment. Stanisavljevic et al. [9] developed a software system for digital logic design and simulation (SDLDS) to support the teaching of digital logic. Alsadoon et al. [10] used software simulators to enhance the learning of digital logic design for information technology students. Saygin and Kahraman [11] used a PLC to implement a laboratory for manufacturing engineering Maria G. Ioannides [12] introduced PLC-based monitoring control system for induction motor.
Bassily et al. [13] used PLC in the teaching of mechatronics. Yasar BirBir and H. Selcuk Nogay [14] introduced PLC/HMI based monitoring and control system for three-phase induction motor fed by VFD. Michael Barrett [15] proposed portable PLC training system for use outside of the automation laboratory. The proposed system is a collection of PLCs (Mitsubishi FX1n 10 I/O), two magnetic contactors, and three miniature circuit breakers mounted on timber structure in the form of "A" frame rotated through 45 degree. Yilmaz Er, Katrancioglu S. [16] designed PLC experiment set for education. The set consisted of PLC (S7-200 CPU 212), dc motor model (with encoder), stepper motor model, traffic light model, and 8 ON/OFF switches. The set supports 8 digital inputs and 6 digital outputs and this limits the type and number of experiments that can be done with this platform, also the embedded modules are simple and do not reflect what are going on in the real industrial field. Ibrahim Burhan et al. Introduced [17] multi input / output PLC module for education applications. The module involves PLC (NAIS FPI-C24), two 24VDC motors, 24VDC piston cylinder, 24VDC power supply, 24VDC relay, five normally open pushbutton, three indication lamps. The platform is provided with 32 female connectors (8 for the PLC inputs, 8 for the PLC outputs, 4 for the dc power

supply, 3 for the indication lamps, 2 for the dc motor, 1 for the relay, 1 for the piston cylinder, and 5 for the normally open pushbut-tons).The proposed module did not came across the analog module. It only allows the ON/OFF running of the DC motors. The embedded pushbutton should be of normally open and normally closed to cope with the real situations. Akparibo et al. [18] introduced cheap and portable trainer kit consisted of PLC (Delta DVP 14ss211R, which has 8 inputs, 3-relay output, and 3 transistor outputs), 6 toggle switches, 3 pilot lamps, 2 magnetic contactor.

The whole kit was mounted on wooden board. The proposed kit is suitable for understanding a lot of the PLC instructions. It can be used to implement simple industrial ap-plications that need minimum output points like star delta starting if provided with an extra magnetic contactor. Sukir, Soeharto and A S J Wardhana [19] developed PLC based electrical machine trainer kit composed of PLC (Zelio SR2-201FU), 4 magnetic contactors, 2 thermal overload relays, 1 emergency stop switch, 1 single phase and 1 three phase miniature circuit breakers, 32 indication lamps, and large number of female terminals. The kit is smart, its four contactor support bidirectional star / delta starting in addition to the direct on line and star/delta starting. It must be provided with normally open and normally closed pushbuttons to ease the execution of magnetic contactor explements.

The number of indication lamps is more than what is required. Shruti and Prof Sudhir [20] introduced an implementation of PLC based star/delta starter and direction control of three-phase induction motor. Mahmood et.al. [21] developed a PLC-HMI driven platform to control the speed of three phase induction motor using a fuzzy logic controller and the traditional Proportional-Integral-Derivative (PID) controller. Mahmood et al. [22] presented a PLC/HMI-based real-time educational power system protective relay platform, to facilitate the understanding of the operating principle of the Inverse Definite-Minimum-Time relays (IDMT). Liton Ahmed et.al. [[23] introduced a small scale and simple filling system using PLC. The proposed system composed from conveyor belt driven by brushless dc motor, dc pump to control the filling process, and infrared sensor to stop the conveyor and start the filling process. Czerwinski R. and Chmiel M [24] introduced an idea for hardware acceleration of standard PLC trigger functions that enables to build single-clock-cycle edge detectors. Mocanu et al. [25] implemented a PLC-based automated system for solar conversion control. The aimed outcomes of the proposed platform described in this research work are to (1) Tie the class theoretical ma-terial to real word systems or applications. (2) Use the PLC instructions and the HMI devices to develop multi-application virtual workbench. (3) Create user defined mapping utility between the PLC's output points and those of the virtual work-bench. (4) Allow real time monitoring for the various points of the workbench. (5) Facilitate the saving and loading of the developed circuits.

II. The Proposed Platform Hardware and HMI Interfacing Screens

To fulfill the requirements of the work's aim, the platform's overall construction has been divided into two parts. These are the hardware part and the software one.

A. *The Platform's Hardware*

This hardware part consists of two units (see Fig. 1). These are the PLC/HMI unit and the actuators unit. The PLC/HMI unit is the main one. It is the building and control unit. It is the station where the user constructs his or her ladder and digital logic circuits and it is also the station through which the user controls the field devices. This part has thirty-four connection terminals distributed as follows: twelve for the PLC inputs I00 to I11, ten for the PLC outputs Q00 to Q09, four to two PLC analog input channels, four to two PLC analog output channels, two for the 0V, and two for the 24V.

The actuators unit consists of four magnetic contactors, one single -phase power line controller and one VFD. The four magnetic contactors have been added to allow the PLC/HMI unit to drive magnetic contactor driven applications like three-phase induction motor starters and change over switches. The single -phase power line controller has been added to allow the user to understand the solid-state relay (SSR) operating modes, the difference between the magnetic contactor and the SSR, and how to make use of these two to create soft starter. The VFD has been added to allow the construction of VFD driven application like cut to length. Fig. 1-a shows the proposed platform kit, and Fig. 1-b illustrates the PLC and HMI wiring and status LEDs.

B. *The Platform's Interfacing Screens*

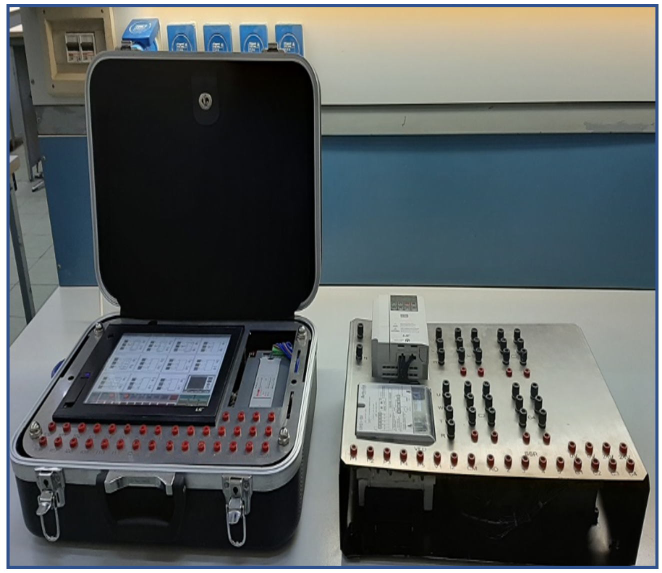
The platform's objectives fulfillment requires the existence of configurable work bench, an easy assignment utility for the software and hardware components, circuit saving utility, and circuit loading utility. All these facilities are done by the HMI via the operation screen shown in Fig. 2 in which.

(1) is the circuit building area. It consists of 11 building blocks. each block can be assigned 1 out of 24 functions.

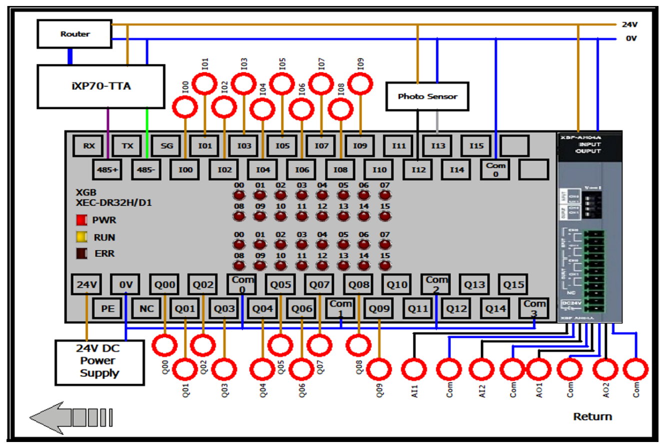
(2) Are the application start / stop switches. The run switch runs the application and blocks circuit modification. The stop switch stops the application and allows the circuit modification.

(3) Hardware and software driving sources selection area. The software devices in this area allow the user to assign the hardware switches (using the popup window screen shown in Fig.

3-a), software switches (A, B, C, D, S3, S2, S1, S0), and the constants (0, 1) to the work bench's building blocks inputs.
(4) With the help of the screen change switch devices, the users can:
a- Link any PLC digital output (Q00 to Q09) to any points in the workbench (P00 to P21) and the hardware and software switches mentioned above using the popup screen in Fig. 3-b.
b- Select and assign the required function (see Fig. 3-c) to any one of the 11 building blocks.
c- Work with the PLC digital to analogue and analogue to digital channels (see Fig. 3-d).
d- Configure the PLC high speed counter 1 (see Fig. 3-e).
e- Load previously tested circuits and save new circuits (see Fig. 3-f, and Fig. 3-g).
(5) This part is the oscilloscope like utility. It is equipped with "Set" screen change switch to display the oscilloscope configuration screen (see Fig. 3-h), yellow and red pushbutton like momentary bit switches to run and stop the oscilloscope utility.
- Setting the building blocks inputs (Xij) configuration registers (HMI word switch type devices with "SET "action type and indirect type operand) to address the driving sources whose identification registers are HMI word switch devices with" SET" action type and constant type operand. The configuration process is executed in two steps, the first is to click the driving source identification register icon to assign the source code to a temporally PLC memory location (indirect operand address) and the second is to transfer this code value to the intended building block input con-figuration register.
- Setting or resetting the building blocks inputs inversion bits.
- Setting the building blocks functions configuration registers (HMI word switch type devices with "SET" action type and indirect type operand) to address the building blocks functions whose identification registers are HMI word switch devices with "SET" action type and constant operand. The configuration process is identical to that of the building blocks inputs, here the function icon is pressed first to assign its code value to a temporally PLC memory location (the indirect operand of the building blocks configuration word switches) and the second is to transfer this function addressing code to the intended building block function configuration register.



(a)



(b)

Fig. 1. (a) Hardware kits, (b): PLC and HMI wiring and status LEDs

III. The Platform Methodology and Execution

As mentioned before, the proposed platform allows control circuit development, allows the user defined drive of the PLCs' output, allows the real time monitoring, and also allows the saving and loading of the developed circuits. The implementation of these objectives has been done by the following software utilities:

A. *Circuit's development and execution utility*

The implementation of this utility depends mainly upon the virtual work bench shown in Fig. 4-a and its building blocks details shown in Fig. 1-b. The virtual bench's structure has been executed making use of the PLC's user defined function block approach. According to this structure, the execution passes through two phases. These are the circuit configuration phase and the circuit running phase. In the circuit configuration or wiring phase the following steps are executed with the help of the HMI interfacing screens.
Setting the building blocks data blocks (each data block con-

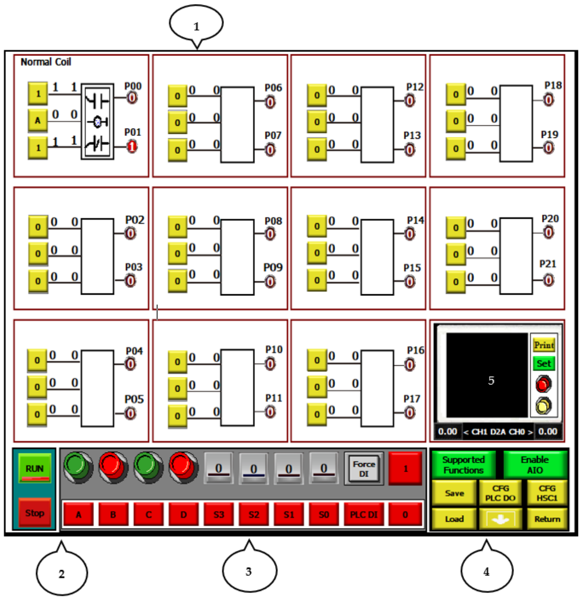


Fig. 2. Platform's operation screen

sists of numeric input and numeric display HMI devices) according to the selected function requirements. In the real time circuit execution phase, the PLC executes:
1. Gets the building blocks inputs logic from their driving sources.
2. XORed the building blocks inputs with their corresponding inversion bits to get the function digital input arguments.
3. Execute the building blocks functions.
This phase can be described by the following equations:

$$X[i,j] = BFi\_State(Xreg[i,j]) \tag{1}$$

$$In[i,j] = X[i,j]\ XOR\ N[i,j] \tag{2}$$

$$\begin{gathered}[P2i-2, P2i-1, Cent[i], Acct[i]] = \\ Bfi(X[i,1], X[i,2], X[i,3], X[i,4], \\ X[i,5], BFreg[i], PR[i], Spec[i], ITaddr[i], Des[i])\end{gathered} \tag{3}$$

Where $i = 1\ to\ 11$, $j = 1\ to\ 5$, the BFi_State is an instance of the user defined function block labeled "State" to assign the logic state of the driving source addressed by Xreg[i, j] to the i^{th} input of i^{th} block , and Bfi is the i^{th} instance of the user defined function block "Bf" to execute the building block assigned function.

B. *User defined mapping of PLC's output points*

The PLC used in this platform has 12 relay output points (ten of them have been connected to the connection terminals). With this utility, any PLC output point (Q00 to Q09) can be linked to any point in the workbench (P00 to P21) and the hardware and software switches supported by this platform (A, B, C, D, S3, S2, S1, S0, 1, 0, I00 to I11). This utility is executed by:

$$Q[k] = PLC\_Do\_state(Qreg[k]) \tag{4}$$

Where $k = 0\ to\ 9$, Qreg[k] is the drive source identification register of k^{th} PLC's Output point, and PLC_DO_State is an instance of the user defined function block "State".

C. *Circuit real time monitoring*

The circuit's points monitoring is done by 8 HMI graph trend devices which form 8 channels like oscilloscope. The channels configuration is also identical to that of the building blocks inputs configuration. The equation governing this utility is:

$$\begin{gathered}CH[n] = BOOL - To - INT(OSC\_CH\_State(CHreg[n])) \\ +offset[n]\end{gathered} \tag{5}$$

Where $n = 1\ to\ 8$, CHreg[n] is the identification register of the point to be monitored, and OSC_CH_State is an instance of the user defined function block "State".

D. *Circuits saving and loading utilities*

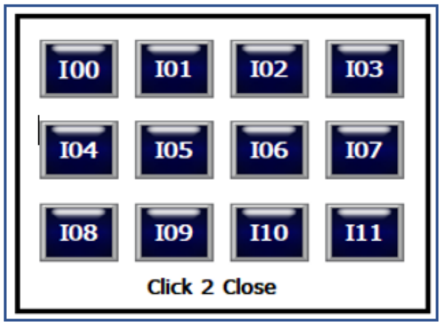
These two utilities are executed by the HMI as a recipe function. Fig. 5 illustrates the methodology and execution sequence of the platform tasks.

IV. Performance Test's Examples

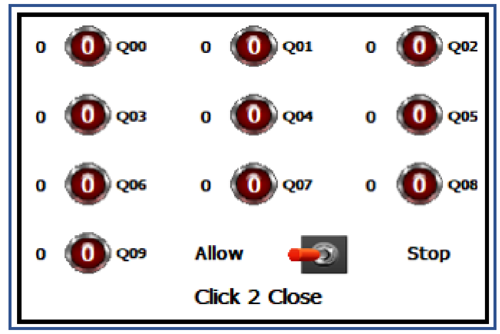
The proposed platform has been tested for number of PLC-based control circuits and digital logic circuits. The test examples have been saved in the HMI as a recipe blocks and can be loaded by the user. The test circuits were:

1) *Three Sources Change Over Switch Control circuit (see Fig. 6):*

Change over switch is used to connect the load to one of its power-supported sources. Its behavior is priority dependent. For this application, it is assumed that the sources existences are represented by I01 for the 1^{st} source, I02 for the 2^{nd} source, and I03 for the 3^{rd} one. It is also assumed that I04, I05, and I06 represent the sources related contactors states respectively.



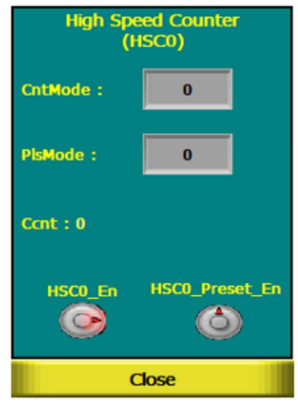
(a)



(b)

(c)

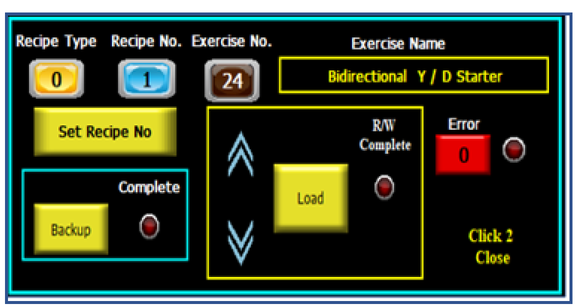
(d)



(e)

(f)

(g)



(h)

Fig. 3. Popup service widows

The first AND/NAND block belongs to the highest order priority source. It issues the connection command of the 1^{st} source if the source is available (I01=1) and the 2^{nd} and the 3^{rd} sources connection contactors are completely open. The AND/NAND block in the 2^{nd} row belongs to the mid priority source. They allow the connection of the second source if the 1^{st} source is absent and its connection contactor and that of the 3rd are opened. The AND/NAND blocks in the $3^{r}d$ row belongs to the lowest priority source. They allow the connection of the 3^{rd} one if the 1^{st} and the 2^{nd} sources are absent and their connection contactors are opened. The ON delay timers in the second and the third columns are to ON delay the load powering and also to prevent any overlapping.

2) One-to-Two Lane Diverter (see Fig. 7):

One-to-two lane diverter control circuit controls the traveling paths of items like books and bottles in a certain industrial application. it consists of edge detection, ring counter, and T flip-flop blocks. the positive edge detection circuit clocks the ring counter at the positive edge of the item detecting sensor output signal I00 (for simulation, the OR/NOR block has been added to allow the software push button A to take the role of the real sensor). The ring counter's preset value is adjusted according to the required batch. The T flip-flop which powers the diverter solenoid is clocked by the negative transition of the ring counter's output.

3) Teachable tap control circuit (see Fig. 8):

This tap control circuit allows the tap to fill any can size. The required filling time (the pulse timer preset time) is determined through the teaching activity which is initiated and terminated by the software selector switch S1. The S1 ON period is the required filling time and this is calculated by the integration timer in the first block.

4) Star/ Delta Starter Control Circuit (see Fig. 9)

The star/delta starter consists of three magnetic contactors and one ON delay timer to start the motor in star connection for a period equals the ON delay timer preset value. For this application, P01 drives the main contactor coil (the first contactor), P12 drives the star contactor coil, and P18 drives the delta contactor coil.

5) Bidirectional Star/Delta Starter Control Circuit (see Fig. 10):

In this control circuit, the workbench points P06, P08, P14, and P20 have been allocated to generate the forward, reverse, star, and delta magnetic contactors switching signals, the star connection period is assigned to the ON delay timer and the reverse direction running delays have been assigned to the OFF delay timer in the 3^{rd} (to delay the backward rotation) and the 6^{th} (to delay the forward rotation) blocks.

6) Two motors washing machine control circuit (see Fig. 11)

For this application, the cyclic timer output P06 switches the washing motor forward and reverse, the up counter determines the washing period, the integration timer determine the drying period, and the set/reset coils block drives the drying motor.

7) Single phase soft starter control circuit (see Fig. 12)

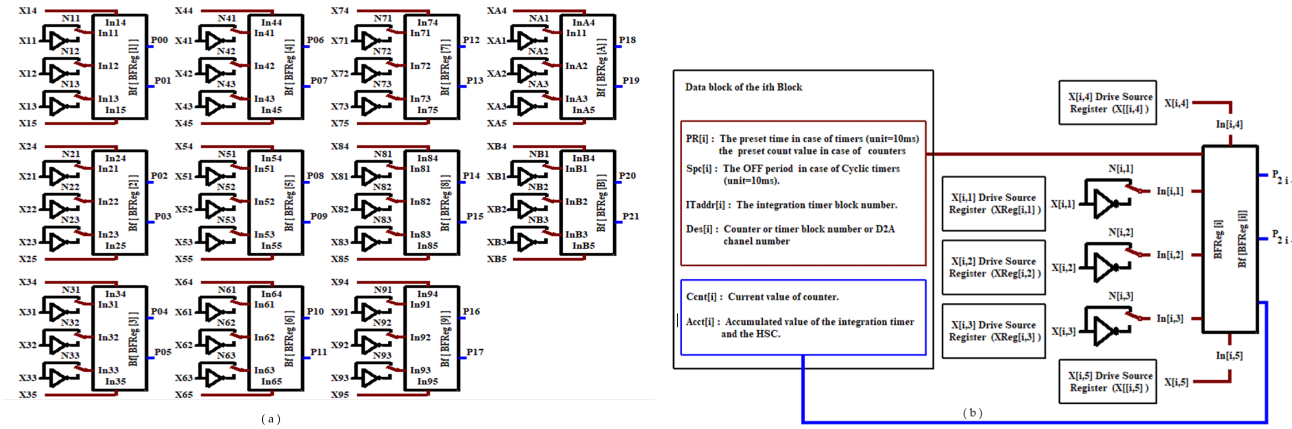
With this platform, single phase soft-starter control circuit can be constructed as shown in Fig. 12 in which the integration timer generates the required ramp function required to gradually decreasing the firing angle of the antiparallel connected thyristors of the single phase power line controller, the move instruction assigns the ramp function output to the digital to analog converter during the starting period, the set/reset coils block preceding the integration timer controls the activation and deactivation of the integration timer, and P02 is the bypass contactor switching signal.

8) Laboratory Steam Turbine Ignition System Control Circuit (see Fig. 13)

In this application, the control circuit checks the water pressure before running the water pump, uses the water pump running signal as a starting signal for the gas pump and the gas bypass solenoid, allows the gas line to be stable and then fire the ignition transformer and the gas injecting solenoid, waits for a period and then disconnect the ignition transformer and check the ignition state. On the success of the ignition process the controller continues running the water pump, the gas pump, and the gas injecting solenoid. On the failure, the controller stops the system and wait for new request. This operation requirements and sequence has been translated to the circuit shown in Fig. 13 in which S0 is assumed to play the role of the water pressure switch, S1 is assumed to play the role of ignition detector, P00 is the water pump switching signal, P06 is the gas pump control signal, P08 is the bypass solenoid control signal, P14 is the gas injection solenoid switching signal, and P18 is the ignition transformer control signal.

9) Conveyor belt control circuit (see Fig. 14)

In this test example, it is required to stop the conveyor motor in fixed station for a short period to execute some work (like covering the ice cream cans and filling bottles). To execute a precise stopping and at the same uses an acceptable traveling time, the conveyor should be allowed to run firstly at high speed and when come closer to the stop station runs at low speed. These requires two sensing proximity switches, one close to the stop point and the second exactly at the stop point. The circuit configuration for such controller is shown in Fig. 14 in which it is assumed, the motor is driven by AC drive unit, "A" is the starting push button, "B" is the stopping



(a) (b)

Fig. 4. Vertual Work bench: (a) : Overall structure, (b): Block details.

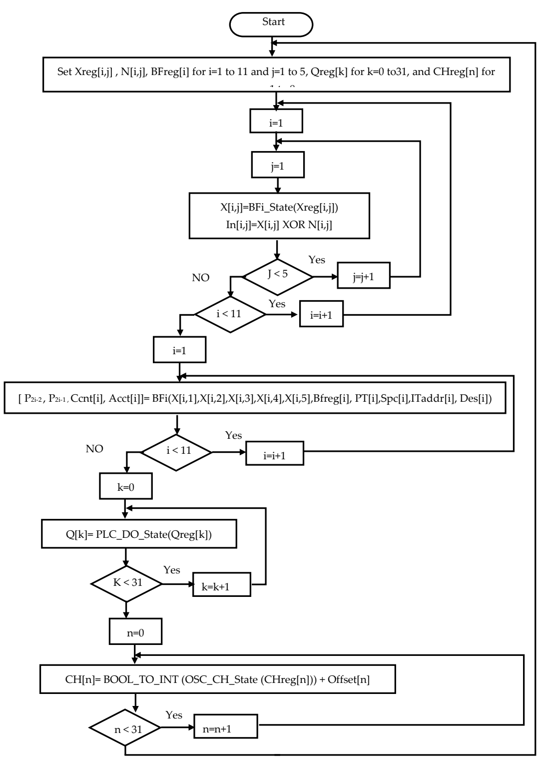


Fig. 5. Methodology and execution sequence flowchart

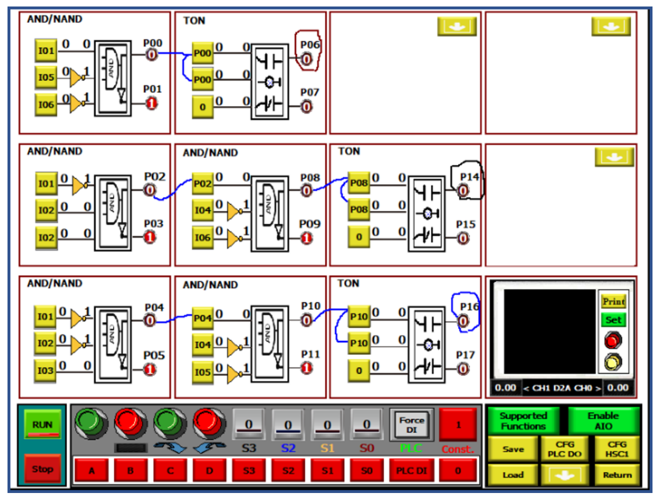


Fig. 6. Three sources changeover switch control

push button, P00, P07,and P06 are the AC drive forward, high speed, and low speed commands, respectively, "C" is the low-speed start proximity switch, "D" is the temporarily stop proximity switch. The pulse timer setting is the required temporary stopping period.

10) Cut to length control circuit (see Fig. 15)

Cut to length utility is widely used in roll forming machinery. It uses the PLC's high-speed counter (HSC) instruction to run the machine the required length and also issues the cutting command. Fig. 15 is a cut to length utility in which P07, P13, and P18 are the AC drive low speed, high speed and forward commands control signals determined by the HSC instruction (the 2nd and the 3rd building blocks in the 1st row), P08 is the hydraulic cutter down solenoid command signal and P14 is the cutter up solenoid command signal. The lower and upper positions of the cutter are determined by proximity or limit switches connected to I05 and I06 respectively (for simulation

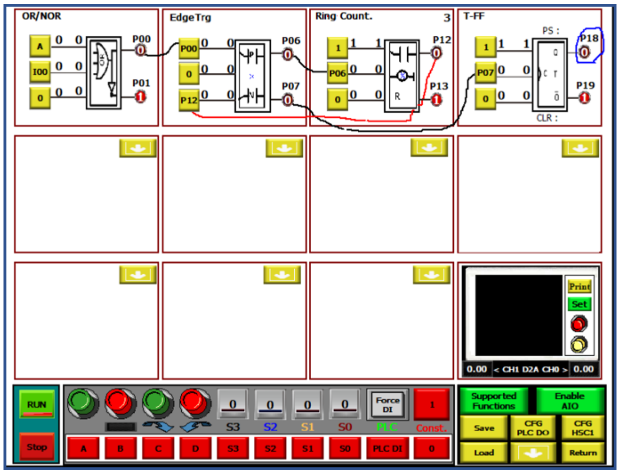


Fig. 7. One-to-two lane diverter control circuit

or off line test, the software normally closed push buttons B and D can play the role). The number of sheets per batch is determined by the preset count of the up counter.

11) Decoder and Multiplexer circuits (see Fig. 16)

These two combinational digital logic circuits are constructed as shown in Fig. 16 in which the 1^{st} row performs the decoder construction and the 2^{nd} and the 3^{rd} perform the multiplexer circuit.

12) Four-bit ripple through counter circuit (see Fig. 17)

Fig. 17 shows how ripple through counter is constructed in this platform. In this circuit P00 represents the least significant output bit and P18 represents the most significant one. The driving clock signal can be taken from different sources but here it has been generated using cyclic timer PLC instruction.

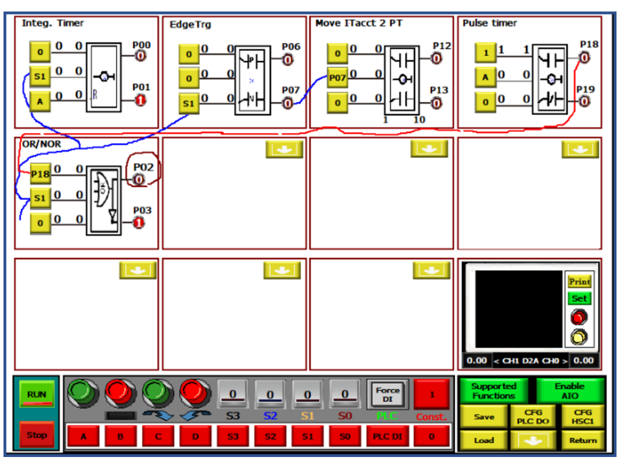


Fig. 8. Teachable tap control circuit

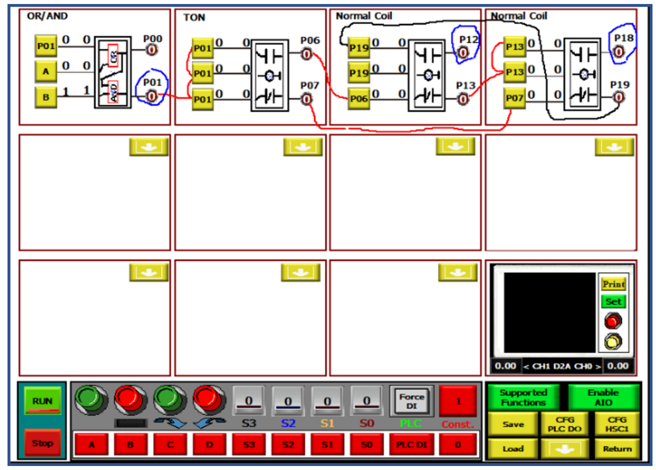


Fig. 9. Star/delta starter control circuit

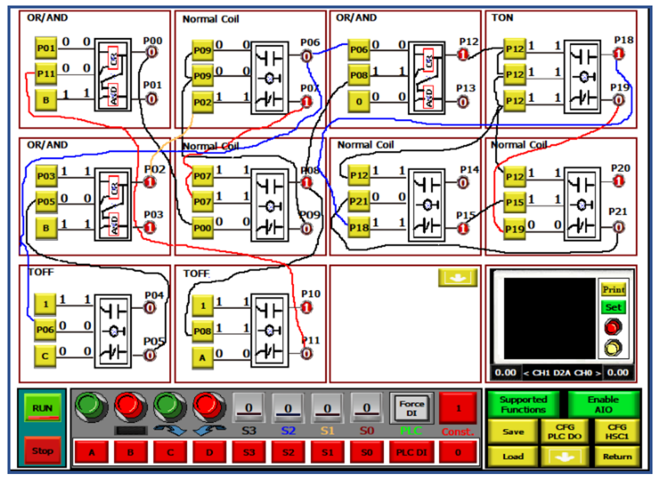


Fig. 10. Bidirectional star/delta starter control

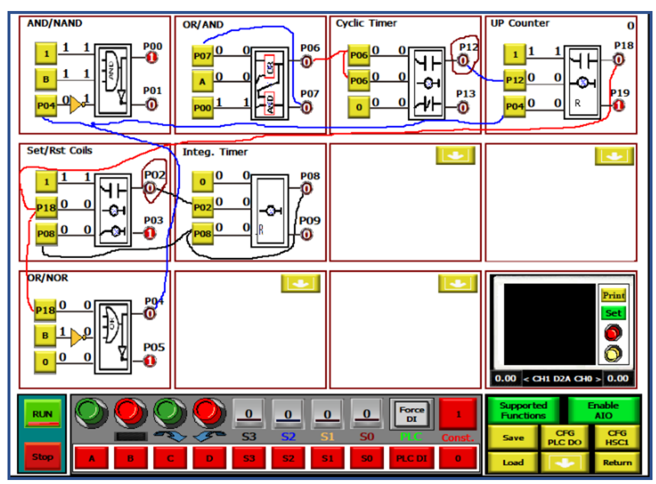


Fig. 11. Two motor washing machine control

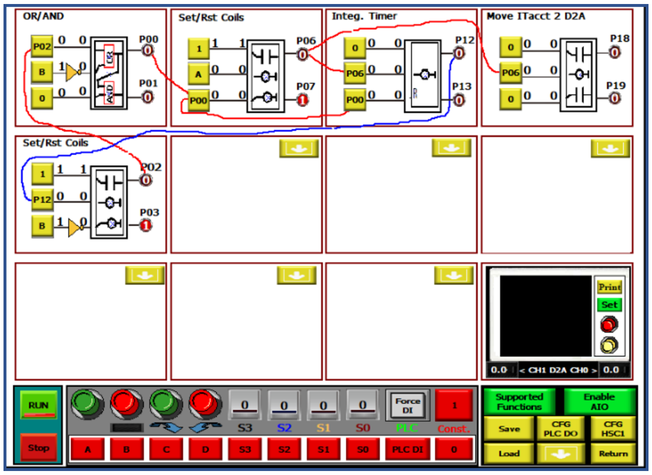


Fig. 12. Single phase soft starter control circuit

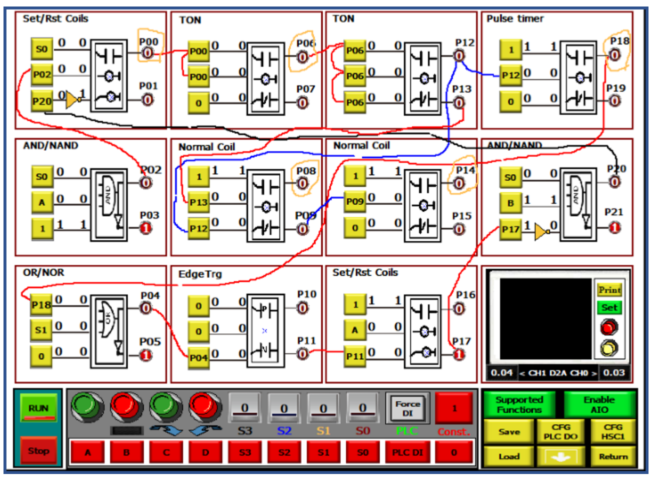


Fig. 13. Laboratory steam turbine ignition controller

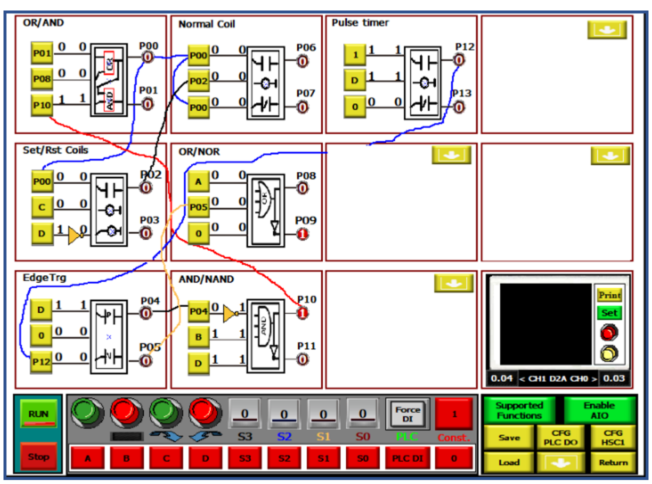


Fig. 14. Conveyor belt control circuit

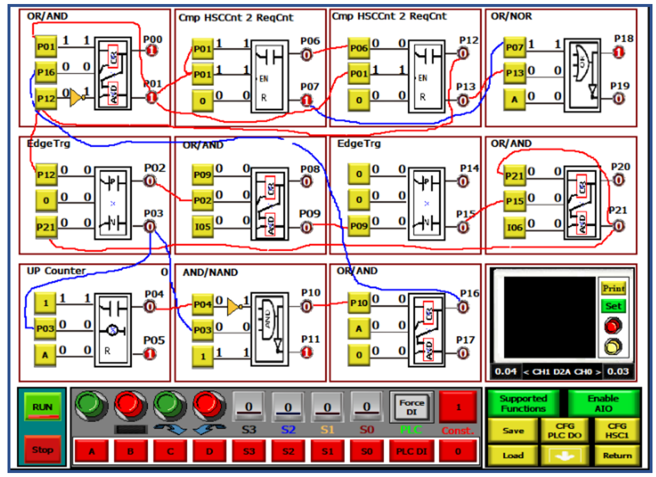


Fig. 15. Cut-to-length control circuit

13) *Ring Counter Circuit (see FFig. 18)*

This test example is 4-bit synchronous type ring counter in which the cyclic timer's output P16 is the common clock signal; the information is shifted from the left to the right and back around through P02, P08, P14, and P20. The initialization activity is the responsibility of the JK flip-flop in the 3rd row and the AND/NAND blocks in the 1st row. The initialization is fired by the software pushbutton “A”.

14) *Parallel-In-Serial-Out Shift Register Circuit (see Fig. 19)*

Fig. 19 is Parallel-In-Serial-Out Shift Register in which , the 4 AND/NAND blocks strobe the preset inputs of the shift register flip-flops, the parallel loading is the responsibility of the JK flip-flop. the software push button “A” issues the parallel loading command and the software push button “C”

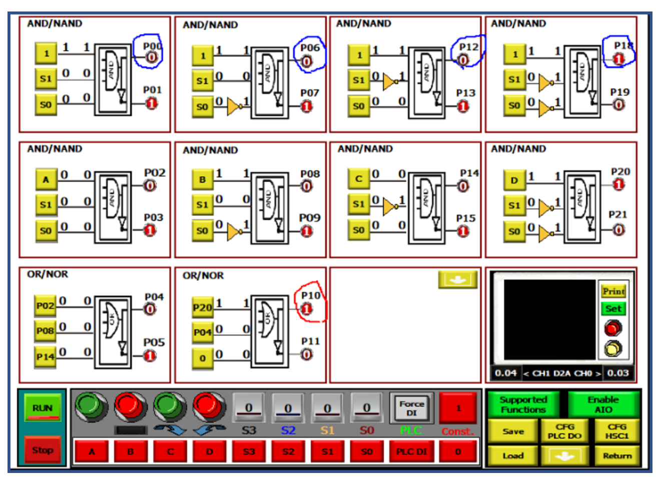


Fig. 16. Decoder and multiplexer circuits

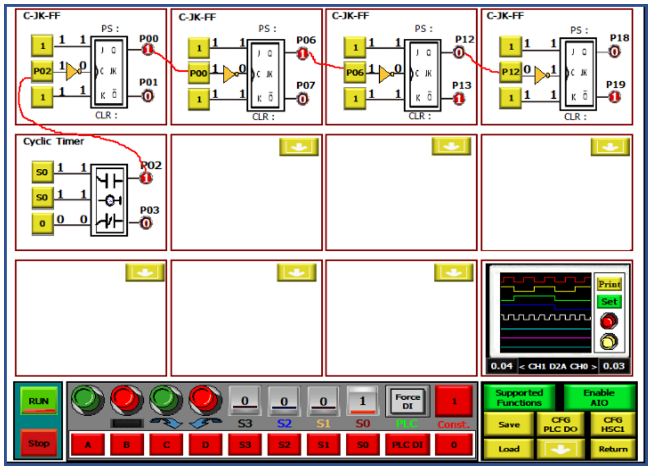


Fig. 17. Ripple through counter circuit

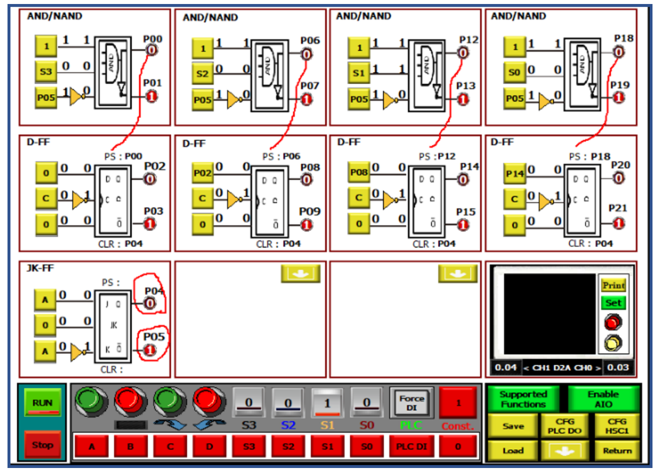


Fig. 19. Parallel-in-serial-out shift register

is the clock signal. P20 is the register output terminal.

15) Three-bit Synchronous Up/Down Counter (see Fig. 20)
A 3-bit up/down synchronous counter is constructed in Fig. 20. The AND/NAND blocks in the 1^{st} column and the OR/NOR block in the 2^{nd} column form a multiplexing circuit to drive the 2^{nd} flip-flop's inputs. The 2 AND/NAND blocks in the 3rd column and the OR/NOR block in the 4^{th} column form a multiplexing circuit to drive the 3^{rd} flip-flop's inputs. The software switch S1 determines the counting direction (S1=1 for up counting), "C" is the clock pulse generator, P00 is the least significant bit and P12 is the most significant bit.

16) Counters with MOD Number less than 2N (see Fig. 21, and Fig. 22)
The 2^N is the maximum MOD number that can be obtained using N flip-flops, but this can be modified to produce MOD number less than 2^N by allowing the counter to skip states that are normally part of the counting sequence. Fig. 21 is MOD-6 asynchronous counter derived from the MOD-8 asynchronous counter. Fig. 22 is MOD-16 synchronous binary counter.

V. Conclusions

In this paper, design of PLC/HMI based portable workbench for PLC and digital logic learning and application development has been introduced. The platform's design depended on the PLC user defined function block feature, which forms one of the most useful features of the PLC programming environment, and also the powerful graphical user interface of the HMI panels. Regarding the PLC, two user defined function block instructions have been designed. These were the State labeled one and the Bf labeled one. The State labeled one assigns the driving sources to their targets. Three instances

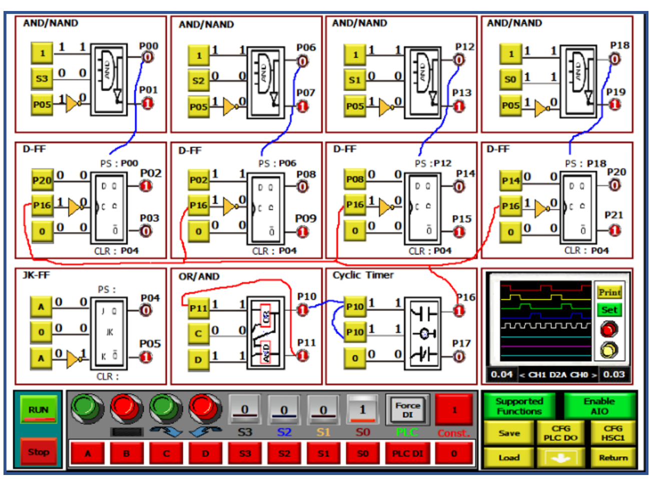


Fig. 18. Ring counter circuit

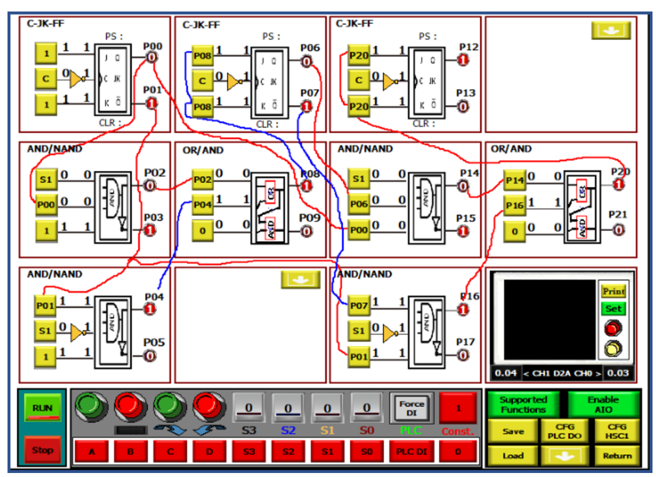


Fig. 20. R3-bit synchronous up/down counter circuit

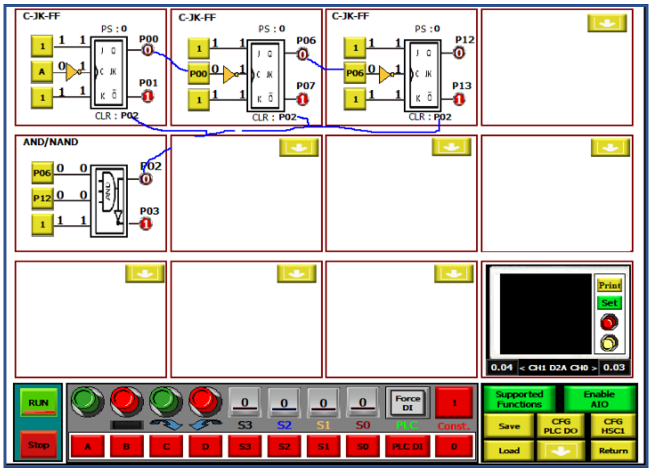


Fig. 21. MOD-6 asynchronous counter

have been created using this user defined function block. The created instances are labeled as Bfi_State, PLC_DO_State, and OSC_CH_State. The Bfi_State instance assigns the logical state of the supported driving sources (A, B, C, D, S3, S2, S1, S0, 1, 0, I00 to I11, P00 to P21) to their destination points (workbench building blocks digital inputs), the PLC_DO_State as-signs the driving sources to the PLC digital outputs (Q00 to Q09), and the OSC_CH_State links the oscilloscope like utility eight channels to the driving sources. The Bf labeled one has been designed to execute the building blocks assigned functions. Eleven instances have been created (Bf1, Bf2, ... Bf11), one for each building block. These eleven instances provide opportunities for exploring and testing various circuits and configurations at ease.

The HMI bit or word devices (bit switches, bit lamps, word switches, and word lamps) provide an interactive display and

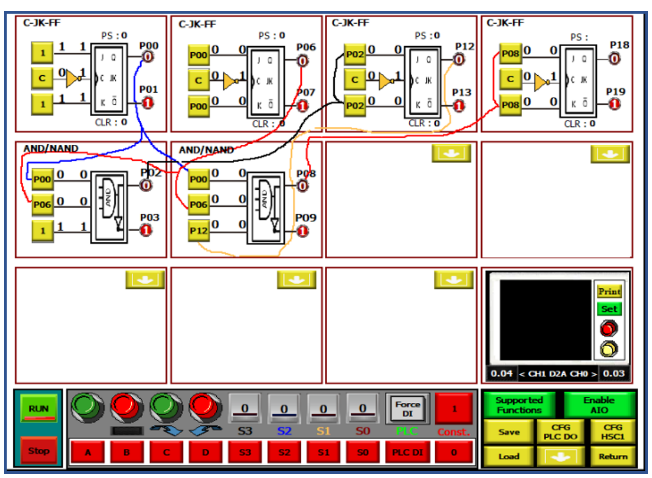


Fig. 22. MOD-16 synchronous counter

drive facility for the PLC program variables and functions or function blocks. The HMI graph trend enables an oscilloscope like functionality for the program variables. The HMI basic recipe device allows the storage facility for the PLC variable values at the calling instant. Using the proposed platform, the user is able to adopt either virtual or real wiring and can create many ladder logic based control circuits.

The experiments conducted show that the user can use this platform to develop or understand and teach an acceptable number of ladder logic and digital logic circuits. Briefly one can say, the proposed platform in this paper is characterized by having the following features:

- It can be interfaced with the real environment because of its ability to accept driving signal from the sensors or the control contacts of the magnetic contactors and also because of using relay type output points, it can be directly connected to the industrial field power actuators like magnetic contactors and solid state relays, a situation which cannot be reached by simulators or traditional training platforms.
- Need short time to construct the applications through allowing the user to adopt virtual wiring by clicking the source and destination points.
- Does not need real oscilloscope for illustrating the timing diagram of the executed experiments. It provides eight channels oscilloscope like utility with zero power consumption and zero cost., a situation which allows the user to monitor all or most nodes of his or her circuit. Doing so, the teacher spares time because he or she is not in need to spend time in drawing the timing diagrams on the illustrating board and this will allow the teacher to cover more topics.
- It offers eleven multifunction or programmable building blocks (each block can be assiged one of 25 functions). This feature increases the number of circuits that can be constructed and tested. In traditional hardware Labs, each block has only one function and this limits the tested circuits band.
- It has a storage utility. This utility stores the pre executed experiment or application in coded form. This feature allows the user to save time in teaching process. By the help of this feature, the teacher can prepare and test all the circuits he or she is going to discuss in the class room or the Lab room. Such service is not supported in traditional hardware Labs.
- Using the HMI as an interfacing layer between the user and the PLC allows the remote control and monitoring of this platform and doing so enhance the class room teaching process.
- It can be used as a PLC teaching platform without any modifications because most of the building blocks functions are PLC instructions (AND, OR, NOT, XOR,XNOR, normally open contact, normally closed contact, positive transition sensing contact, negative transition sensing contact, Normal coil, Negated coil, Set/Rest coils, ON delay timer, OFF delay timer, Pulse timer, Integration timer (TMR), Cyclic timer (TMR-

FlK),Up counter, Down counter, Up/Down counter, Ring counter, High speed counter, and Move instructions.
- The stored test examples can be used as an illustrative application for the PLC instructions.
- The user defined coupling between the workbench various points and the PLC's relay output gains the user an opportunity to test the circuit before using it to drive the field actuators.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

REFERENCES

[1] R. Czerwinski and M. Chmiel, "Hardware-based single-clock-cycle edge detector for a plc central processing unit," *Electronics*, vol. 8, no. 12, p. 1529, 2019.

[2] V. Sadegh and V. Amir, "Plc and its applications," *International Journal of Multidisciplinary Science and Engineering, vol2*, no. 8, 2011.

[3] R. Pawar and N. Bhasme, "Application of plc's for automation of processes in industries," *Int. Journal of Engineering Research and Applications*, vol. 6, no. 6, pp. 53–59, 2016.

[4] R. Langmann and M. Stiller, "The plc as a smart service in industry 4.0 production systems," *Applied Sciences*, vol. 9, no. 18, p. 3815, 2019.

[5] F. Hassan, M. J. Rider, H. LeBlanc, and J. K. Hurtig, "Introducing plc programming in the digital logic course," 2018.

[6] W. Bolton, *Programmable logic controllers*. Newnes, 2015.

[7] N. L. V. Calazans and F. G. Moraes, "Integrating the teaching of computer organization and architecture with digital hardware design early in undergraduate courses," *IEEE Transactions on Education*, vol. 44, no. 2, pp. 109–119, 2001.

[8] C. Hacker and R. Sitte, "Interactive teaching of elementary digital logic design with winlogilab," *IEEE Transactions on Education*, vol. 47, no. 2, pp. 196–203, 2004.

[9] Z. Stanisavljevic, V. Pavlovic, B. Nikolic, and J. Djordjevic, "Sdlds—system for digital logic design and simulation," *IEEE Transactions on Education*, vol. 56, no. 2, pp. 235–245, 2012.

[10] A. Alsadoon, P. Prasad, and A. Beg, "Using software simulators to enhance the learning of digital logic design for the information technology students," *European Journal of Engineering Education*, vol. 42, no. 5, pp. 533–546, 2017.

[11] C. Saygin and F. Kahraman, "A web-based programmable logic controller laboratory for manufacturing engineering education," *The International Journal of Advanced Manufacturing Technology*, vol. 24, pp. 590–598, 2004.

[12] M. G. Ioannides, "Design and implementation of plc-based monitoring control system for induction motor," *IEEE transactions on energy conversion*, vol. 19, no. 3, pp. 469–476, 2004.

[13] H. Bassily, R. Sekhon, D. E. Butts, and J. Wagner, "A mechatronics educational laboratory–programmable logic controllers and material handling experiments," *Mechatronics*, vol. 17, no. 9, pp. 480–488, 2007.

[14] Y. Birbir and H. S. Nogay, "Design and implementation of plc-based monitoring control system for three-phase induction motors fed by pwm inverter," *International journal of systems applications, engineering & development*, vol. 2, no. 3, pp. 128–135, 2008.

[15] M. Barrett, "The design of a portable programmable logic controller (plc) training system for use outside of the automation laboratory," in *International Symposium for Engineering Education*, pp. 1–5, Citeseer, 2008.

[16] E. Yilmaz and S. Katrancioglu, "Designing programmable logic controller (plc) experiment set with internal experiment blocks," *Procedia-Social and Behavioral Sciences*, vol. 28, pp. 494–498, 2011.

[17] I. Burhan, A. A. Azman, and S. Talib, "Multiple input/outputs programmable logic controller (plc) module for educational applications," in *2015 Innovation & Commercialization of Medical Electronic Technology Conference (ICMET)*, pp. 39–43, IEEE, 2015.

[18] A. R. Akparibo, A. Appiah, O. Fosu-Antwi, *et al.*, "Development of a programmable logic controller training platform for the industrial control of processes," *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, vol. 15, no. 1, pp. 186–196, 2016.

[19] S. Sukir and A. Wardhana, "Performance of a programmable logic controller based electrical machine trainer kit," in *Journal of Physics: Conference Series*, vol. 1413, p. 012011, IOP Publishing, 2019.

[20] S. Kharait and P. Phulambrikar, "Implementation of plc based star delta starter for starting and direction control of three phase induction motor," *vol*, vol. 2, pp. 2881–2886.

[21] J. R. Mahmood, R. S. Ali, H. Migdadi, R. A. Abd-Alhameed, and E. M. Ibrahim, "Development of educational fuzzy control laboratory using plc and hmi," in *2015 Internet Technologies and Applications (ITA)*, pp. 383–387, IEEE, 2015.

[22] J. Radhi Mahmood, R. Salim Ali, and R. A. Abd-Alhameed, "Plc/hmi-based implementation of a real-time educational power system protective relays platform," *Electronics*, vol. 9, no. 1, p. 118, 2020.

[23] M. L. Ahmed, S. Kundu, and M. Rafiquzzaman, "Automatic bottle filling system using plc based controller," *Journal of Advancement in Mechanics*, vol. 4, no. 1, pp. 17–24, 2019.

[24] R. Czerwinski and M. Chmiel, "Hardware-based single-clock-cycle edge detector for a plc central processing unit," *Electronics*, vol. 8, no. 12, p. 1529, 2019.

[25] D.-A. Mocanu, V. Bădescu, C. Bucur, I. Ștefan, E. Carcadea, M. S. Răboacă, and I. Manta, "Plc automation and control strategy in a stirling solar power system," *Energies*, vol. 13, no. 8, p. 1917, 2020.