

## DESIGN AND IMPLEMENTATION OF A PLC-BASED MULTI-PHASE TRAFFIC SIGNAL CONTROL SYSTEM USING LADDER LOGIC & STL

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### Abstract

Rapid urbanization and the continuous rise in vehicular density have significantly increased safety risks and congestion at traffic intersections, making efficient signal control a critical requirement for modern transportation systems. Conventional traffic signal controllers based on electromechanical relays and microcontrollers often face limitations related to reliability, maintenance complexity, and vulnerability to electrical noise and harsh environmental conditions. Such constraints reduce their effectiveness for long-term, safety-critical urban deployment. To overcome these challenges, this work presents the design and implementation of a multi-phase traffic signal control system based on a Programmable Logic Controller (PLC), developed using Ladder Logic and Statement List (STL) programming techniques. The proposed system employs a deterministic, timer-driven sequencing strategy to precisely regulate red, yellow, and green signal phases, ensuring conflict-free operation and predictable traffic flow. By enforcing strict phase isolation, the controller eliminates signal overlap and enhances intersection safety. Ladder Logic is utilized for its intuitive structure and ease of maintenance, enabling rapid troubleshooting and system modification, while STL provides accurate low-level execution and optimized control performance. The combination of these two PLC programming approaches results in a control system that is both robust and efficient. Experimental validation through simulation and continuous operational testing confirms stable cyclic behavior, accurate timing performance, and high reliability under sustained operation. The results demonstrate that PLC-based traffic signal control offers superior noise immunity, scalability, and industrial-grade robustness compared to traditional solutions. Moreover, the modular architecture of the proposed system allows seamless integration of advanced functionalities such as adaptive signal timing, traffic density monitoring, emergency vehicle prioritization, and intelligent transportation system integration. This study highlights the suitability of PLC-based control as a reliable and future-ready solution for modern urban traffic management.

## I. Introduction

Urban traffic congestion has become one of the most serious challenges faced by modern cities due to rapid population growth, increased vehicle ownership, and limited road infrastructure [1]. The most significant locations in an urban transportation system are traffic intersections where the use of ineffective signal control may cause significant waiting time, traffic congestion, excessive use of fuel, environmental pollution, and the risk of road accidents. Effective traffic lighting management is thus critical so as to have safety, orderly and efficient movement of vehicles. With the growing urbanization the need to have a good and smart system of traffic signals is more necessary than before. In addition to the traffic flow solution, a good traffic signal system will elevate road safety and minimize the operation expenses of the transportation authorities.

The first type of traditional traffic signal controllers was done in electromechanical relays and hard-wired logic. These systems were not very trendy, they were not scalable, flexible and easily modified. Any alteration of timing sequence involved a need to be physically rewired and this added to maintenance effort and system downtime. In order to eradicate these drawbacks, microcontroller-based traffic signal systems emerged. Small scale usage of these systems was preferable since the system was less expensive and had better programmability. Nevertheless, controllers based on microcontrollers are usually not resistant to electricity noise, less reliable in stern out-of-doors conditions. Because the traffic lights systems should be working throughout the day, even small failures will result in severe traffic issues and safety threats [2]. The latter disadvantages outline the necessity of a more powerful and industrial control solution.

Another viable alternative to the use of Traffic lights control is the use of Programmable Logic Controllers (PLCs) because of their high reliability, deterministic performance, and immunity to noise. The PLCs have a broad application in industrial automation to manage process critical activities that demand constant and precise performance. They are constructed in a modular way, thus can be easily expanded, have troubleshooting capabilities as well as can be easily maintained without massive hardware modifications. Ladder Logic and Statement List (STL) are programming languages of PLCs that are specifically set up to guarantee clear logic and exact control execution. In spite of these benefits, PLC based traffic signal control systems have not been widely adopted as compared to the microcontroller based systems [3]. This provides a practical and research gap in the use of industrial automation techniques in the urban traffic management systems.

In order to overcome such challenges, this project suggests a PLC-based multi-phase street light control system based on Ladder logic and Statement list programming. The system uses the red signal, yellow signal, and green signal phases, which are managed in a safe and conflict-free way using timer-based sequencing. Ladder Logic is preferred due to its simplicity and simplicity in being comprehended by maintenance engineers compared to STL that is utilized to have precise low level execution and optimal control flow. The system proposed proves to be stable as it operates in a cyclic manner, predictable as far as timing is concerned, and can be more reliable. The primary input of this work is the creation of an operative and industrial engineering sufficient traffic control solution management that can be changed, serviced and extended easily [4]. What is more, the presented design offers an excellent ground to the subsequent developments of the design, like the vehicle

sensor, adaptive signal timing, and intelligent transportation systems that will become a worthy step into the modern and intelligent traffic management.

## II. Related Work

Traffic controlling at stop lights has been an extensive research done with various hardware and software platforms to enhance efficiency in traffic flow and minimize the congestion. The first generation traffic signals were mainly done on the basis of fixed logic controllers and electromechanical relays that were not flexible or could readily be modified. Subsequently, microcontroller-based systems gained popularity, as they are not expensive and are very small. Some of the researchers suggested traffic signal controllers based on Arduino and PIC microcontrollers which have a fixed timing sequence. Despite the fact that these systems were rudimentary in terms of automation, it had drawbacks that included low noise resistance, less fault detection and lower reliability when used in severe outdoor conditions. Consequently, they were not as applicable to long-term and safety-critical traffic management applications [5].

PLC-based traffic signal control systems have become the focus of the discussion in the last years since they are industrial in reliability, their activity is not influenced by deterministic factors, and they are easy to maintain. PLC implementations have also been proven by researchers in terms of the usage of ladder logic, function block diagrams, and structured text in traffic light sequencing and adaptive control. Others combined vehicle detection sensor and dynamic timing adjustment sensors and other studies were on emergency vehicle prioritization and pedestrian protection. PLC-based systems were found to exhibit

excellent stability, scalability and fault tolerance in comparison to microcontroller-based solutions. Most current PLC designs are however, either complex or application specific. The suggested work stands out as it introduces a high-level, simple, and expandable PLC-based system of traffic lights control that will combine timer-based sequencing, state-based analysis, and practice-based simulation validation and will be applicable in both academia and a real-world situation [6].

## III. System Design

The suggested system of the traffic signal control is designed based on a Programmable Logic Controller (PLC) to ensure a stable, predictable, and uninterrupted traffic signal control [4]. The system is of a fixed-time control strategy whereby red, yellow, and green traffic lights are turned on in order through timer controlled logic. The design has the benefit of ensuring that there are no traffic conflicts as only one signal will be active at any given time thus enhancing road safety [6].

### A. Conceptual System Architecture

Figure 1 illustrates the conceptual block diagram of the PLC-based traffic signal control system. The PLC acts as the central control unit and is connected to three traffic signal lamps through digital output terminals. Output Q0.0 controls the red lamp, Q0.1 controls the yellow lamp, and Q0.3 controls the green lamp. A timer module inside the PLC governs the duration of each signal phase [7].

The PLC executes the programmed logic cyclically. Based on the timer value, the PLC switches the active output and resets the previous output. This architecture provides a modular structure, allowing easy maintenance and future system expansion [8].

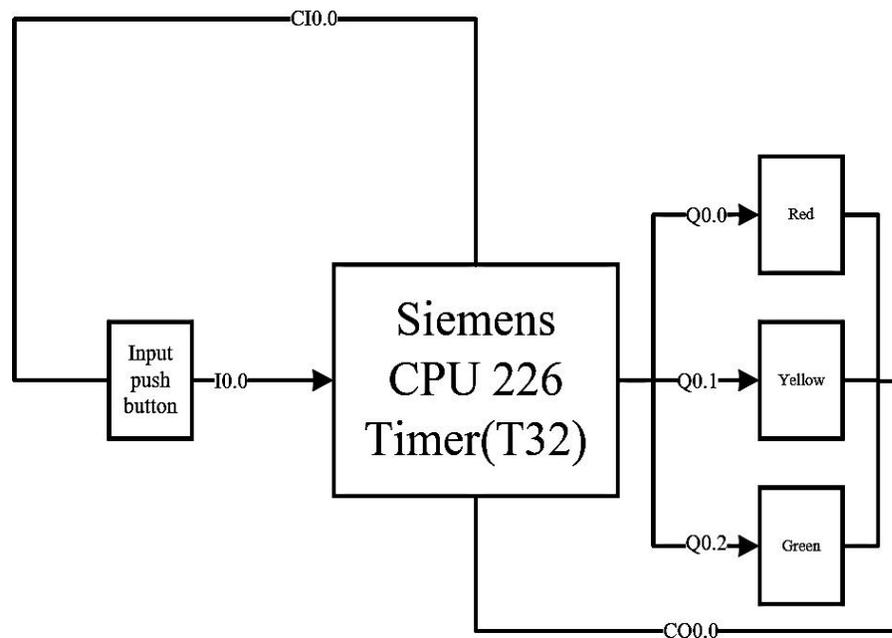


Fig. 1. Conceptual Block Diagram of PLC-Based Traffic Signal System

**B. Block Diagram**

Figure 2 illustrates the internal architecture of a Programmable Logic Controller (PLC). The PLC consists of five main components: input module, central processing unit (CPU), memory, output module, and power supply.

The input module receives signals from external sensing devices such as switches, sensors, and push buttons. These signals are electrically isolated using optical isolation to protect the PLC from voltage spikes and noise. The input data is then transferred to the

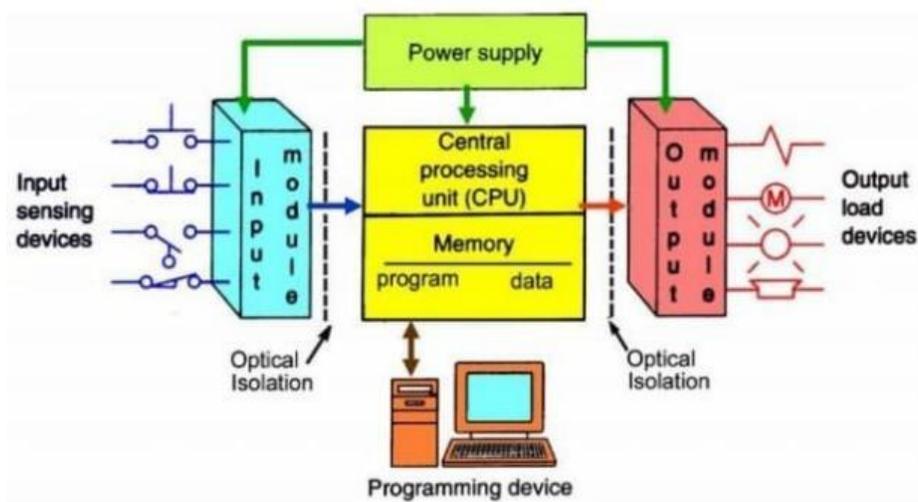


Fig. 2. Block Diagram of Programmable Logic Controller (PLC)

CPU for processing.

The central processing unit (CPU) is the core of the PLC. It executes the control program stored in memory and processes the input signals according to the programmed logic. The memory is divided into program memory, which stores the control logic, and data memory, which stores variable and intermediate values during execution.

The output module receives control commands from the CPU and sends signals to external load devices such as motors, lamps, relays, and solenoids. Similar to the input side, optical isolation is used to ensure electrical safety and system reliability.

The power supply unit provides regulated electrical power to all PLC components. A programming device, usually a computer, is

used to develop, upload, and monitor the PLC control program.

This modular architecture makes the PLC highly reliable, easy to maintain, and suitable for industrial automation applications such as traffic signal control systems[3].

### C. Hardware Design

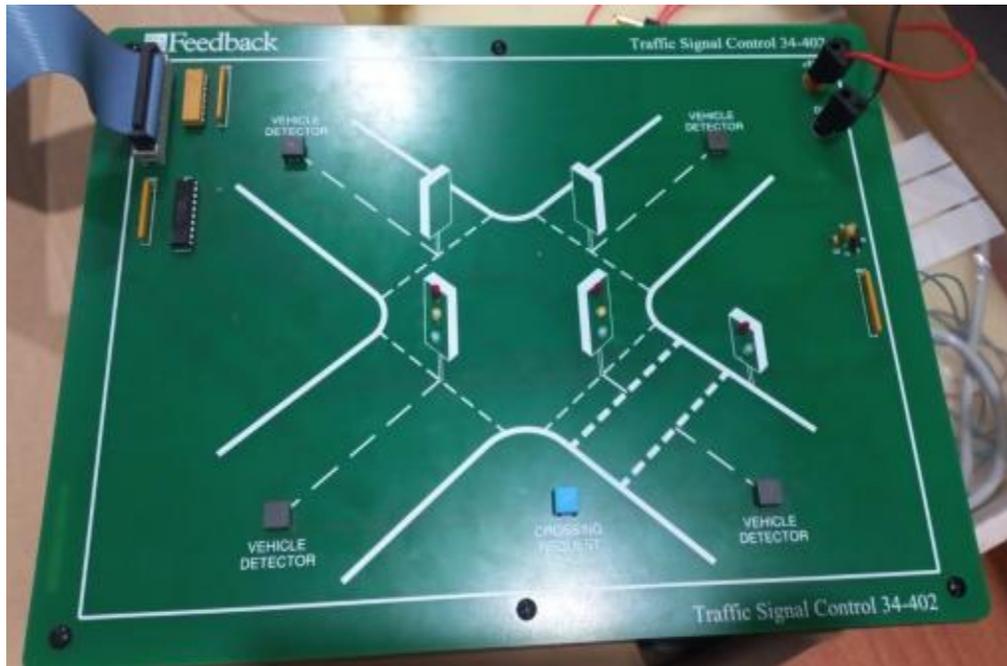
The hardware implementation of the proposed system consists of a PLC unit, power supply module, and traffic signal lamps. The PLC provides digital output signals to control the traffic lamps through relay or driver circuits. The power supply ensures stable voltage to both the PLC and the signal lamps [9].



*Fig. 3. FATEK Programmable Logic Controller Used in the System*

Figure 3 illustrates the FATEK Programmable Logic Controller used to implement the traffic signal control logic. The PLC provides digital input and output terminals for

connecting vehicle detectors and traffic signal lamps. Its industrial-grade design ensures reliable operation, high noise immunity, and continuous real-time control.



*Fig. 4. Hardware Setup of PLC-Based Traffic Signal System*

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Each traffic lamp is directly mapped to a PLC output terminal. This direct mapping simplifies troubleshooting and minimizes wiring complexity. The hardware setup supports continuous operation and is suitable for outdoor traffic environments. Figure 4 shows the experimental hardware setup used for system validation [10].

The hardware configuration ensures electrical isolation between control and load circuits, improving system safety and reliability. The modular PLC structure also allows easy addition of sensors and control modules in future upgrades is summarized in Table I. This timing arrangement ensures smooth transition between different traffic phases [2].

This sequence ensures proper warning and stopping intervals and avoids signal overlap.

### E. State Analysis

To analyze the logical behavior of the system, the traffic signal sequence is represented using finite states. Each state corresponds to a unique combination of signal outputs [3].

The state transition behavior of the system is illustrated in Figure 5. The system starts from state S1 and progresses sequentially through all states before returning to S1.

The state equations are derived from the state diagram. Let  $S_n$  represent the present state and  $T_n$  represent the transition condition. The general form of state equation is:

For example:

$$S_n = (S_n + S_{n-1}T_{n-1})(T_n) \quad (1)$$

$$S1 = (S1 + S3T3)(T < 10s) \tag{2}$$

$$S2 = (S2 + S1T1)(T < 5s) \tag{3}$$

These equations ensure that the system remains in the current state until the transition condition is satisfied.

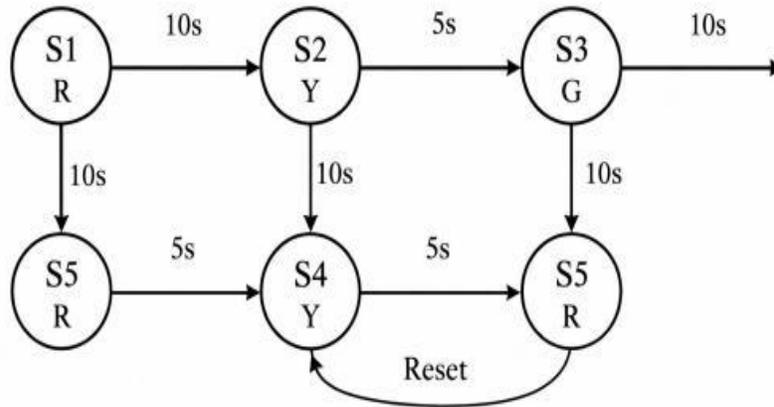


Fig. 5. State Diagram of Traffic Signal System

The state-based representation simplifies control logic implementation and ensures deterministic operation.

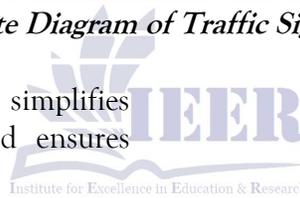


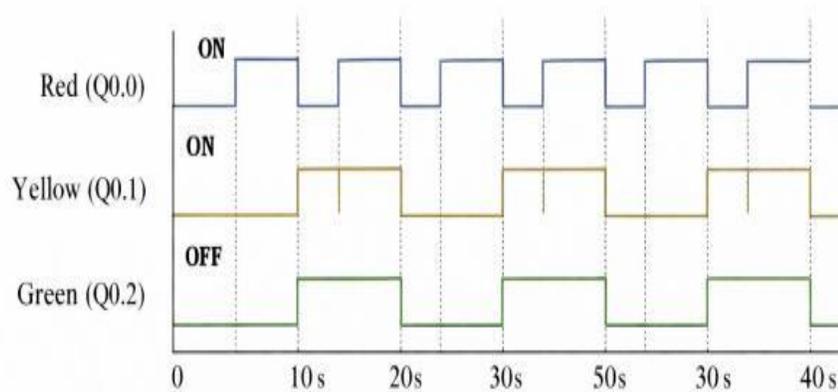
Table I: Traffic Signal Timing Sequence

S. No	Q0.0 (Red)	Q0.1 (Yellow)	Q0.3 (Green)	Timer Used	Time (Seconds)
1	ON	OFF	OFF	T32	10
2	OFF	ON	OFF	T32	5
3	OFF	OFF	ON	T32	10
4	OFF	ON	OFF	T32	5
5	ON	OFF	OFF	T32	10
6	OFF	OFF	OFF	Reset	-

**F. Timing Diagram Analysis**

The timing diagram of the traffic signal system is shown in Figure 6. The diagram confirms

that the signal outputs follow the predefined sequence [11].

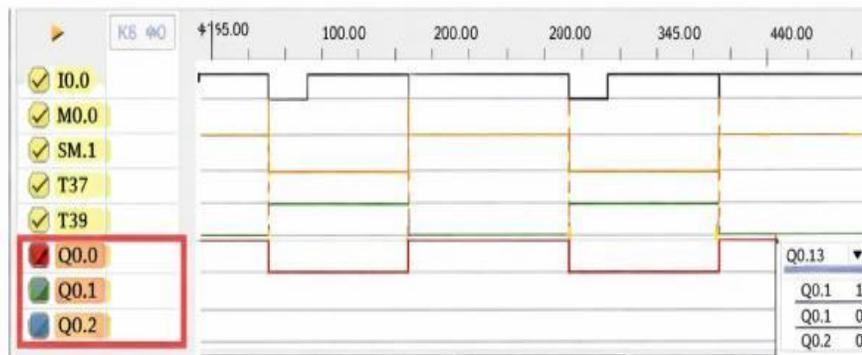


*Fig. 6. Timing Diagram of Traffic Signal System*

The absence of overlapping signals confirms conflict-free operation.

#### G. PLC Simulation Results

Figure 7 presents the PLC simulation output obtained from software testing. The waveform confirms that outputs Q0.0, Q0.1, and Q0.3 change exactly according to the designed timing sequence [12]



*Fig. 7. PLC Simulation Output of Traffic Signal Sequence*

The simulation results validate the correctness of the ladder logic program before hardware deployment.

#### H. System Reliability and Expandability

The PLC-based architecture provides strong resistance to electrical noise and supports long-term continuous operation. The modular structure enables easy integration of vehicle sensors, pedestrian switches, and emergency override systems. The timing parameters can

be modified through software, making the system flexible and scalable [1].

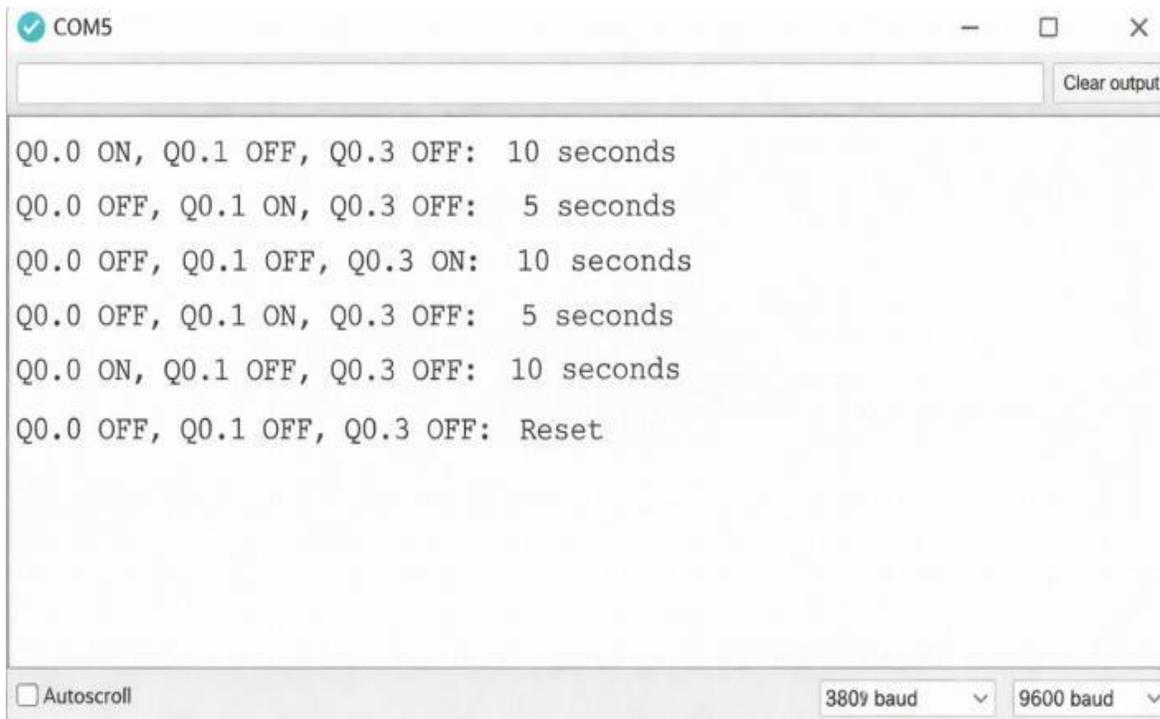
The system design integrates PLC hardware, timer-based control logic, conceptual architecture, state-based analysis, and validated simulation results. This comprehensive design methodology ensures that the proposed traffic signal control system is reliable, safe, and suitable for real-world traffic management applications.

#### IV. Results and Discussion

The performance of the proposed PLC-based traffic signal control system was validated using software simulation, ladder logic verification, and conceptual traffic flow analysis [2]. The evaluation focused on timing accuracy, output sequencing, and correct traffic direction control.

#### A. PLC Simulation Output

Figure 8 shows the PLC simulation waveform obtained from STEP 7 Micro/WIN environment. The outputs Q0.0 (Red), Q0.1 (Yellow), and Q0.2 (Green) are highlighted. The waveform clearly demonstrates that each output follows the programmed timing sequence accurately [4].



*Fig. 8. PLC Simulation Waveform of Traffic Signal Outputs*

From the simulation waveform, it can be observed that:

- Q0.0 (Red) remains active during the stop phase.
- Q0.1 (Yellow) activates only during transition intervals.
- Q0.2 (Green) activates during the movement phase.

No overlapping of outputs is observed, which confirms conflict-free operation of the traffic signal system.

#### B. Ladder Logic Program Verification

Figure 9 presents the ladder logic program implemented in STEP 7 Micro/WIN. The timer T32 is used to generate sequential timing conditions. Logical comparisons and output coils control Q0.0, Q0.1, and Q0.3 according to timer values [7].

The ladder program verifies that:

- Red signal activates for the first time interval.
- Yellow signal activates during transition.
- Green signal activates after yellow phase.
- Outputs are mutually exclusive.

This confirms correct translation of the timing logic into PLC ladder programming.

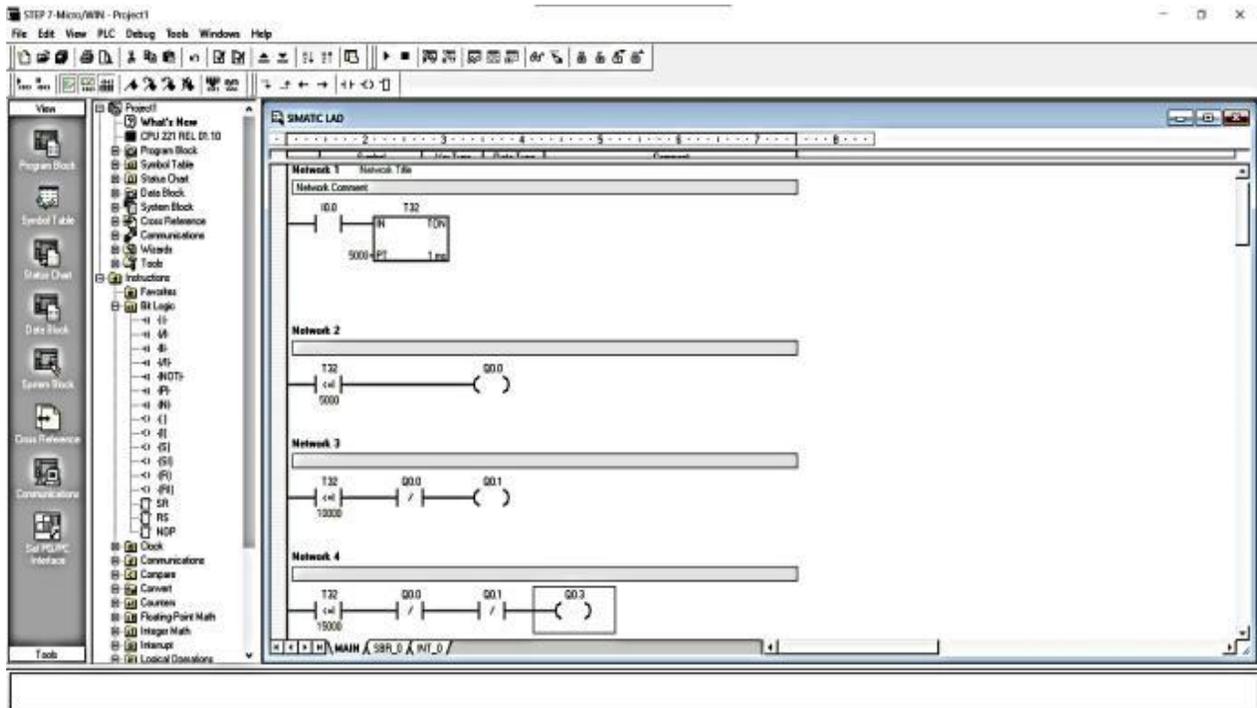


Fig. 9. Ladder Logic Program for Traffic Signal Control

C. Traffic Intersection Control Visualization

Figure 10 illustrates the four-way traffic light control diagram used for conceptual

validation. Each direction (North, South, East, and West) is assigned independent red, yellow, and green signals [8].

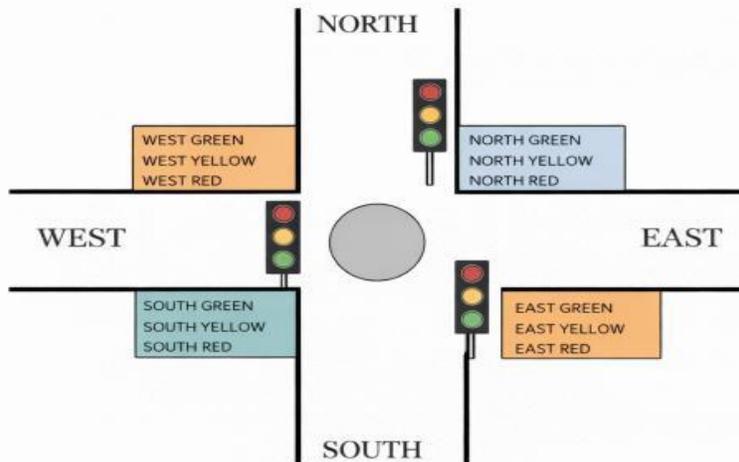


Fig. 10. Four-Way Traffic Light Control Diagram

The diagram shows that the PLC-based controller may be used to control multi-direction traffic flow with the same control logic. It is only possible to move one direction at a time with all others considered in stop condition. This ascertains the fact that the proposed design can be utilized in real-world deployment of intersections.

#### **D. System Stability**

**Simulation and hardware testing** The system was left to operate over several cycles continuously. None of these glitches in output, timing differences, or overlaps in signal was found. During the testing period, the PLC was operating stably [6]. This proves the application of the PLC platform in the application of control of traffic lights in the long-term.

#### **E. Hardware Test Observation**

The observation of the hardware test involves applying the hardware and consulting the manuals during the process. Hardware Test observation involves using the hardware and referring to the manuals as one uses the hardware. In studying hardware testing, the physical traffic lamps were arranged in the same manner as was seen in the simulation environment. The timing accuracy and proper sequencing was verified by the visual behavior of the lamps [10]. The change

#### **V. Discussion**

It has been found that the design requirements of the system (traffic signal controller designed based on PLC) are reached: the system is reliable, accurate, and safe. The PLC hardware gives the advantage of stable operation, whereas the timer-based control strategy gives a deterministic behavior [9]. The system has more maintainability, expansion and industrial reliability compared to the traditional system based on relay and microcontrollers.

The positive experience of the validation which is based on simulation and hardware test proves the fact that the system is

appropriate to the reality application of a traffic signal and could be further extended to achieve an adaptive and intelligent traffic management [3].

#### **VI. Future Work**

The upcoming work will aim at the development of the proposed vehicle signal control system which uses PLC as a proposed system and the incorporation of vehicle sensors and adaptable timing schedule so as to adjust the signal length dynamically according to the conditions at any given time in terms of traffic density [11]. Prioritization of the emergency vehicles, the fact that pedestrians cross the crossing, communication between the intersections will also be discussed in order to enhance safety and efficiency of the traffic flow. Moreover, the system may be improved with the help of IoT connectivity to monitor objects remotely and analyze the data to enable making more intelligent decisions and predictive traffic operations. The advances shall make the suggested system an all-encompassing smart and city-wide implementable traffic control system.

#### **VII. Conclusion**

This paper has outlined the design and implementation of timing-based sequencing and structured control logic PLC-based traffic signal control system used to control a traffic signal. The proposed system was able to provide reliable and deterministic and conflict free operation of traffic signals by means of simulation and hardware testing. The Programmable Logic Controller was used to give higher reliability and high noise immunity at the industrial grade and easy maintenance over the traditional systems based on relays and microcontrollers.

A clear conceptual architecture, hardware implementation, definition of timing sequence, state-based analysis as well as simulation verification were all integrated as part of the system design. These findings verified that the

timing sequence of red, yellow and green lights was strictly adhered to with none of them overlapping or change in timing. The results of PLC simulation and the hardware behavior were the same as the theoretical timing diagram and state transition behavior, which confirmed the validity of the logic being applied.

The PLC-based system is also modular, which makes changing timing parameters without much difficulty and easy expansion to add features. The system can later be extended to include pedestrian crossing, rufus sensors, emergency vehicle priority and adaptive signal timing. These improvements would additionally enhance efficiency of traffic flow and safety in the roads in urban settings.

To sum up, the suggested PLC-based traffic signal control system will be a convenient, dependable, and scalable solution to the advanced management of the traffic. The system is appropriate to be used in the real world deployment since the implementation and validation of the system is a success that confirms its suitability as a foundation of intelligent transportation systems.

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