RESEARCH ARTICLE OPEN ACCESS

Design and Implementation of a PLC-Based Microgrid Supervision and Control System for Efficient Renewable Energy Management

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Abstract:

The increased integration of renewable sources into the grid has created a number of problems in maintaining the stability and reliability of the grid. Some problems associated with the conventional grid include increased transmission losses, voltage instability, and the inability to handle distributed sources efficiently. To solve these problems, a Programmable Logic Controller-based microgrid supervision and control system is proposed in this paper, which can handle the management and switching of the sources in real time.In the proposed system, a number of sources such as solar photovoltaic, wind, battery, and grid have been integrated. A priority-based control scheme has been implemented using a Delta DVP series PLC, where the programming has been done using WPLSoft, a ladder logic programming language. The system is designed to automatically switch the sources based on the voltage conditions, thus ensuring the maximum utilization of the sources.The experimental validation proves the reliable performance, high switching speed, and battery protection. The system reduces the dependency on the grid and improves the efficiency of the operation while maintaining the complexity and cost low. The proposed system provides a viable option for the implementation of small-scale smart microgrid applications and can be extended for the integration of IoT and other sophisticated energy man- agement systems.

Keywords—Microgrid, PLC Automation, Renewable Energy Integration, Energy Management System, Ladder Logic Control, Automatic Source Switching, Smart Grid

I. INTRODUCTION

Significant growth in the demand for electrical energy has been observed on a global scale due to rapid industrialization, urbanization, and population growth. There are various challenges affecting the conventional centralized power generation systems, such as high transmission losses, voltage instability, environmental pollution, and lack of flexibility in accommo- dating distributed power sources. Therefore, there is a re- quirement for decentralized and intelligent power management systems that can efficiently accommodate renewable power sources.

Microgrids have thus been identified as a promising solution to overcome the aforementioned challenges through the local generation, storage, and consumption of energy. A microgrid includes various sources of energy, i.e., solar, wind, battery, and grid, which can be used in both grid-connected and is-landed modes. The coordination of multiple sources of energy is critical to achieve a reliable outcome.

Programmable Logic Controllers (PLCs) are commonly employed in automation systems in industry due to their reliability, de- terminism, and real-time response. The PLC- based system has many advantages in comparison to the con- ventional system implemented by a microcontroller, including noise immune, scalable, and maintenance-friendly features [3], [8]. Recent researchers have shown the usage of PLC in au- tomation systems, including energy management, industrial automation, and smart grids [1], [6].

However, the current microgrid-based energy management systems use intricate optimization techniques, artificial intelligence, and predictive control strategies. These strategies make the systems more intricate and computationally intensive. These strategies might not be easy to implement in small- scale and cost-constrained systems. Hence, a viable, cost- effective, and reliable control strategy is needed, which is easy to implement in real-world systems.

The remaining part of the paper is organized as follows: Section II describes the background and related work, while Section III includes the detailed literature survey. In Section IV, the proposed system architecture and methodology have been described. In Section V, the comparative analysis with the existing systems is provided. In Section VI, the results and performance evaluation have been discussed. In Section VII, the challenges and limitations have been addressed, and in Section VIII, the future scope is provided, followed by the conclusion in Section IX.

II. BACKGROUND AND RELATED WORK

In this paper, a PLC-based microgrid supervisory and con- trol system with a priority-based energy management strategy for efficient renewable energy usage with uninterrupted power supply will be presented. The sources used in this system are solar, wind, battery, and grid with automatic source switchings. The contributions of this research work are:

- Design and development of a PLC-based microgrid con- troller using ladder logic programming.
- Priority-based energy management strategy for optimal source selection.
- Integration of solar, wind, battery, and grid with experi- mental validation using simulation and hardware testing.
- Performance analysis of the proposed system in terms of reliability, switching time, and efficiency.

Distributed energy resources, storage devices, power con- verters, and control systems are integrated to provide a micro- grid, which is a promising solution to provide a stable power supply. Since solar and wind power are intermittent sources, managing the power supply is vital to ensure system stability. However, a centralised control approach is not flexible enough to manage such a dynamic system.

A new trend is the development of PLCs, which have proved to be a reliable tool for real-time control of industrial automation [1], [4]. Determinism, reliability, and response time are key factors in microgrid control, and PLCs satisfy these conditions well [2], [11], [14]. Industry 4.0 has expanded the scope of PLCs, including training and IoT/ROS integration, thus enhancing their role in Industry 4.0. The development of PLCs for MPPT and process control has shown their potential for renewable energy sources [7], [10], [13].

However, the practical application of PLC in managing small-scale microgrid energy management is still limited, as most of the existing solutions are based on computationally intensive control strategies, which are not appropriate for resource-constrained applications. The proposed system offers a simple, practical, and cost-effective solution.

III. LITERATURE REVIEW

Recent research has verified the effectiveness of PLCs for real-time automation. Li [1] and Wang et al. [8] showed that a PLC-based control approach is superior to a conventional approach in terms of reliability and adaptability. Abdullah et al. [5] and Sarkar et al. [14] verified ladder logic as an efficient and applicable control programming method for real- time control. For power system applications, Zhang [4] verified the applicability of a PLC for electrical distribution monitor- ing. Yatimi et al. [13] applied a PLC-based MPPT control method for a photovoltaic system. For complex automation applications, Yaseen and Kalyan [7] applied a combination of a PLC and SCADA for automation. Pollak et al. [9] verified a modular PLC approach for automation. Chawlert and Anuntachai [12] applied a combination of a PLC and deep learning for automation. Industry 4.0 perspectives were provided by Kuong et al. [2] and Kim et al. [11].

A. Research Gap:

Though the use of PLC in industrial automation is quite common [3], [6], [10], the use of PLC in microgrid manage- ment is still in the initial stages. The microgrid management systems currently in use mainly employ intricate optimization techniques, AI/ML, and computationally advanced platforms, making the overall process quite expensive and complicated. This work attempts to bridge the gap by using a simple and cost-effective priority-based PLC technique, which provides reliable power supply and optimizes the use of renewable sources without requiring computationally advanced systems.

IV. PROPOSED METHODOLOGY

A. System Architecture:

The proposed PLC-based microgrid system utilizes various sources of energy, which include solar photovoltaic, wind, battery, and grid. The system will ensure the uninterrupted supply of power by automatically selecting the most appropriate source of energy based on the availability.

The architecture consists of the following major components:

- Solar PV system (primary renewable source).
- Wind energy system (secondary renewable source).
- Battery energy storage system.
- Utility grid supply (backup source).
- Programmable Logic Controller (PLC).
- Inverter and relay switching unit.
- Voltage sensing and monitoring circuits.

The solar and wind systems generate DC power, which is stored in the battery through a charging mechanism. The inverter converts DC power into AC for supplying the load. Voltage sensors continuously monitor the availability of each energy source and send signals to the PLC. Based on the programmed logic, the PLC controls relay switches to connect the appropriate source to the load.

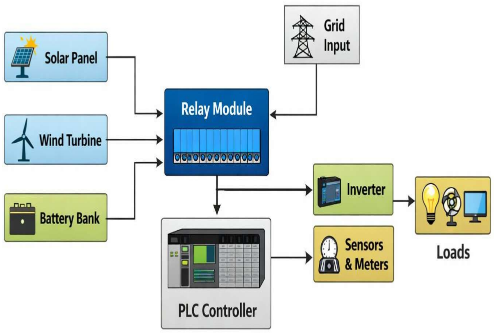

Fig. 1. Overall architecture of the proposed PLC-based microgrid supervision and control system.

B. Working Principle:

The system operates based on a priority-based control strategy to maximize renewable energy utilization. The priority sequence is defined as:
Solar → Wind → Battery → Grid
The working of the system is described as follows:

- When sufficient solar power is available, the load is supplied by the solar source.
- If solar power is unavailable or insufficient, the system switches to wind energy.
- If both solar and wind sources are unavailable, the battery supplies power through the inverter.
- When the battery voltage falls below a predefined thresh- old, the system automatically switches to the utility grid to prevent deep discharge.
- When renewable sources become available again, the system switches back automatically without manual in- tervention.

This ensures the efficient use of renewable sources of energy while maintaining the overall reliability of the system.

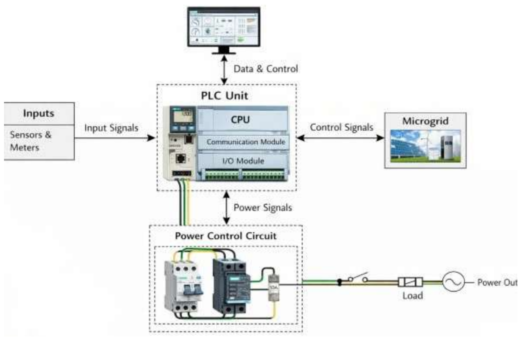

Fig. 2. Circuit diagram of the PLC-based microgrid system showing power and control connections.

C. PLC-Based Control Logic:

The control system is achieved through a Delta DVP series PLC, which is programmed using a ladder logic programming language and the WPLSoft programming tool. The PLC mon- itors the inputs, runs the control program, and updates the outputs in real time.

The assignments of the inputs and outputs are as follows:

TABLE I
PLC I/O CONFIGURATION

Single Type	Address	Description
Input	X0	Wind Availability
Input	X1	Solar Availability
Input	X2	Grid Availability
Output	Y0	Renewable Relay Control
Output	Y1	Grid Relay Control

The PLC logic ensures:

- Priority-based source selection.
- Safe switching between sources.
- Battery voltage monitoring and protection.
- Continuous load supply.

The timers and logical interlocks are implemented in the PLC to avoid any conflict in the relays and ensure a stable operation.

D. Algorithm for Source Selection:

The control algorithm for automatic source switching is described as follows:

BEGIN
IF Solar Available THEN Select Solar Source
ELSE IF Wind Available THEN Select Wind Source
ELSE IF Battery Voltage > Threshold THEN Select Battery Source
ELSE
Select Grid Source END IF
END

E. Mathematical Representation

Let:

- S = Solar availability (1 if available, 0 otherwise).
- W = Wind availability.
- B = Battery condition (1 if above threshold).
- G = Grid availability.

The source selection function F can be expressed as:

$$F=S+(1-S)W+(1-S)(1-W)B+(1-S)(1-W)(1-B)G \quad (1)$$

This equation ensures that higher priority sources are selected first.

F. System Features:

The proposed system has the following features:

- Fully automated switching of the energy sources.
- Maximum utilization of renewable sources
- of energy.
- Protection of the battery from deep discharge.
- Real-time monitoring and control.
- Low-cost and scalable architecture.

This methodology is a simple yet effective solution for the management of the microgrid, and it can be implemented in the real world.

V. COMPARATIVE ANALYSIS

In recent years, various microgrid energy management sys- tems have been proposed using different control techniques such as optimization techniques, artificial intelligence (AI), and PLC-based automation techniques. Each of these tech- niques has its own advantages and disadvantages in terms of complexity, cost, and implementation feasibility.

Most of the AI-based and optimization-based techniques have high theoretical efficiency but involve high computational complexity and require a large amount of data. On the other hand, PLC-based techniques involve simplicity and reliability in the control of the microgrid system.

Table II shows a comparative analysis of different methods of managing energy.

The proposed PLC-based system is a balanced solution as it is simple and reliable at the same time. The proposed system is free from the burden of training data and computational power, as required by AI-based systems. The proposed sys- tem is also superior to the microcontroller-based system in reliability, immunity, and determinism, as PLCs are reliable in industrial applications. The priority-based control method in the proposed system allows for the efficient use of renewable energy sources without adding any complexity in the system, making it highly suitable for real-time applications.

Moreover, the priority-based control strategy used in the proposed system enables efficient utilization of renewable sources of energy without any extra computational complexity. Hence, the proposed system is highly suitable for real-time applications.

A. Performance Comparison

A performance comparison between existing systems and the proposed system is provided in Table III.

From the comparison, it is evident that the proposed system possesses:

- Faster response as a result of real-time operation of a PLC.
- Higher reliability due to the use of industrial-grade devices.
- Economical, as the control logic is simple.
- Efficient use of renewable energy sources by using a priority based control scheme.

B. Justification of Proposed Approach

The design of the proposed system has focused more on implementation than optimization. Although sophisticated control strategies might achieve a slightly higher degree of efficiency, they introduce a much higher degree of complexity and cost to the system.

The advantages of the PLC-based method are:

- Deterministic execution guarantees a predictable system behavior.
- Simple programming with ladder logic.
- Excellent performance in harsh environments.

TABLE II
COMPARISON OF EXISTING PLC-BASED AUTOMATION SYSTEMS WITH THE PROPOSED MICROGRID CONTROL SYSTEM

Ref.	Application	PLC-Based	Renewable Sources	Priority Control	Real-Time Switching	Remarks
[1]	Electrical automation control	Yes	No	No	Yes	Focuses on general domestic electrical automation
[3]	Water treatment plant automation	Yes	No	No	Yes	Suitable for industrial process automation only
[4]	Power distribution safety monitoring	Yes	No	No	Yes	Monitoring-oriented, not designed for energy source coordination
[7]	Product sorting and warehouse automation	Yes	No	No	Yes	Applicable to industrial handling systems
[11]	PLC with ROS-based implementation	Yes	No	No	Yes	Advanced framework with higher implementation complexity
[13]	PLC-based PV MPPT controller	Yes	Partial	No	Yes	Limited to solar energy optimization only
Proposed System	**Microgrid supervision and control**	**Yes**	**Yes**	**Yes**	**Yes**	**Integrates solar, wind, battery, and grid using simple priority-based PLC logic**

TABLE III
COMPARISON OF MICROGRID CONTROL TECHNIQUES

Method	Real-Time Control	Implementation
AI-Based Control	Moderate	Difficult
Optimization-Based Control	Moderate	Complex
Microcontroller-Based System	Limited	Moderate
Proposed PLC-Based System	High	Easy

TABLE IV
PERFORMANCE COMPARISON OF ENERGY MANAGEMENT SYSTEMS

Parameter	Existing Systems	Proposed System
Response Time	Moderate	Fast
Reliability	Medium	High
Cost	High	Low
Scalability	Moderate	High
Maintenance	Moderate	Low
Renewable Utilization	Medium	High

The proposed system thus offers an optimum balance of performance, cost, and implementation feasibility, making it suitable for practical implementation in a microgrid environment.

V. RESULTS

The performance of the proposed PLC-based microgrid sys- tem was verified by both simulation and hardware implemen- tation. The system was tested in different operating conditions to validate the effectiveness of the pro posed priority based control scheme and the reliability of the proposed source- switching scheme.

A. *Simulation Results*

The control algorithm was initially simulated using WPLSoft software to test the correctness of the designed ladder logic. Different scenarios were considered, including the availability and non-availability of renewable sources of energy. It was found through simulation that:

- The program prioritizes solar energy when available.

- Seamless switching is achieved when solar energy is unavailable.
- It switches to wind or battery power based on priority.
- It uses grid power when other sources of power are unavailable or battery voltage is low.

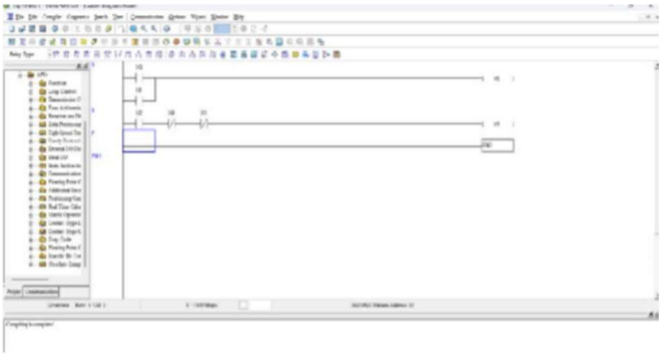

Fig. 3. Ladder logic program implemented in Delta WPLSoft for priority- based energy source selection.

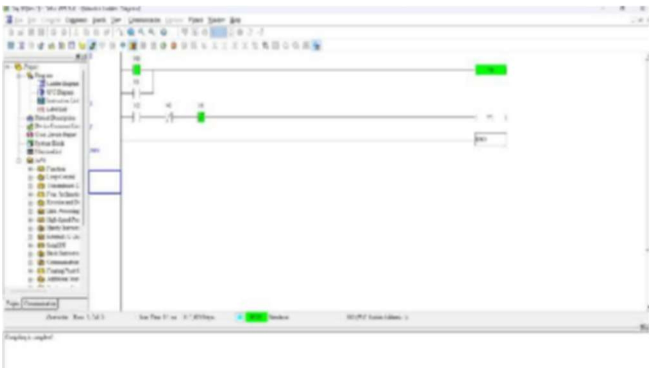

Fig. 4. Simulation results of ladder logic showing active output (Y0/Y1) based on input conditions (X0, X1, X2).

The ladder logic program for the proposed system is shown in Fig. 3. The PLC is programmed using Delta WPLSoft software, where input signals represent the availability of different energy sources. Specifically, X0 corresponds to wind energy, X1 represents solar energy, and X2 indicates grid availability.

This system is based on priority and utilizes renewable resources first. If the sun (X1) is not able to generate enough energy, then the wind (X0) comes into operation, after which there is always a backup (Y1). According to the obtained results of simulation, one can state that the system operates effectively. In general, the system offers an automated mode of switching from one source of energy to another.

B. *Experimental Results*

Experimental Results A hardware prototype of the micro- grid system was devel- oped to evaluate real-time performance. The PLC successfully monitored voltage conditions and per- formed automatic switch- ing between energy sources.

Table V presents the observed results under different oper- ating conditions.

TABLE V
EXPERIMENTAL RESULTS OF SOURCE SWITCHING

Condition	Solar	Wind	Output Source
1	ON	OFF	Solar
2	OFF	ON	Wind
3	OFF	OFF	Grid
4	ON (Return)	OFF	Solar

Fig. 5. Hardware prototype of the PLC-based microgrid system showing solar panel, wind turbine, battery bank, PLC controller, relay module, inverter, and connected loads.

C. *Performance Metrics*

System performance was evaluated based on some impor- tant parameters like response time, switching reliability, and energy utilization efficiency.

- Switching Time: It was found that the PLC responded quickly in 1-2 seconds in the case of source transitions.
- Reliability: It was found that the system

provided con- tinuous power supply in all test scenarios.

- Battery Protection: It was found that the system did not allow deep discharge, as the grid supply was automati- cally switched in when the battery voltage went below a certain level, i.e., 10.5V in the case of a 12V battery.
- Renewable Utilization: It was found that the system utilized the renewable sources efficiently, as it gave preference to the use of these sources.

The hardware prototype of the proposed system, as illus- trated in Fig. 5, was developed for the performance validation of the proposed PLC-based microgrid system.

VI. DISCUSSION

The results show that the proposed PLC-based microgrid system provides reliable and efficient energy management under various conditions. It eliminates manual intervention and offers scalability for different applications. Although its performance depends on renewable energy availability, the backup power source ensures continuous supply. Overall, the system is effective and suitable for practical use.

VII. CONCLUSION

The paper focuses on the design and implementation of a microgrid control and supervision using a PLC for the efficient management of renewable energy sources. It in- corporates solar, wind, battery, and grid sources of power using a priority control strategy for automatic selection of the sources. It provides reliable real-time control, switching, and uninterrupted power supply through the efficient utilization of renewable energy and battery protection by monitoring the voltage. It is a simple and cost-effective solution for microgrid control and supervision using a PLC, compared to complex AI and optimization techniques, and has the potential for further development using IoT, SCADA, and intelligent EMS.

ACKNOWLEDGMENT

The authors are obliged to express their sincere thanks to the Department of Electrical Engineering, College Name, for providing the necessary facilities to carry out this project. The authors are especially grateful to guidance, continuous encour- agement, and technical support throughout the development of this work. They are also grateful to the support and cooperation provided by faculty members.

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