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Design of a flywheel energy storage system (fess) with plc node-red control system for electrical energy generation during off-peak hours

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Abstract –*This paper presents the design, simulation, and implementation of a Flywheel Energy Storage System (FESS) integrated with a Node-RED Programmable Logic Controller (PLC) supervisory control system. The system is engineered to store electrical energy during off-peak hours and generate/discharge it during periods of high demand or grid instability. The core electromechanical design focuses on a high-speed composite rotor operating in a low-vacuum environment, coupled with a permanent magnet synchronous motor/generator (PMSM). Numerical simulations and prototype data confirm a designed storage capacity of 5.0 kWh and a maximum continuous output power of 100 kW. The system achieves a round-trip efficiency (RTE) of 87% when operating over a 15-minute discharge cycle, with rotor speeds ranging from 8,000 RPM at minimum state-of-charge (SoC) to 20,000 RPM at maximum. The bespoke Node-RED control interface, communicating via Modbus TCP/IP with the industrial PLC, enables automated scheduling for off-peak charging (simulated nightly from 00:00 to 05:00 hrs) and on-demand dispatch. Real-time monitoring of key parameters—including rotor speed (accuracy ±50 RPM), chamber pressure (maintained below 0.1 mbar), and bearing temperature—demonstrates stable operation. Economic analysis for the scaled prototype indicates a levelized cost of storage (LCOS) of $0.15/kWh over a 20-year lifespan, primarily driven by the high cycle life (>100,000 deep cycles) of the FESS. The results validate the proposed FESS-PLC-Node-RED architecture as a reliable, efficient, and programmable solution for temporal energy arbitrage and grid support, effectively shifting off-peak energy for use during peak periods.*

Keywords: *Flywheel Energy Storage System, Programmable Logic Controller, Node-RED, Off-Peak Energy Utilization, Voltage and Frequency Regulation, Energy Management,*

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I. Introduction

The rapid penetration of intermittent renewable energy sources, combined with growing electricity demand, has accelerated the need for efficient and responsive Energy Storage Systems (ESS). Among the available storage technologies, Flywheel Energy Storage Systems (FESS) offer several distinctive advantages, including high power density, long service life, fast response time, and minimal environmental impact. FESS store energy in the form of kinetic energy within a rotating mass and reconvert it into electrical energy when required, making them particularly suitable for applications such as frequency regulation, load leveling, uninterruptible power supply (UPS), and short-term backup power [1,2].
A major challenge in contemporary power systems is managing the mismatch between energy supply and demand, particularly during off-peak periods when electricity generation exceeds consumption. Conventional storage solutions such as pumped hydroelectric storage and electrochemical batteries have been widely adopted for load shifting; however, they

suffer from limitations related to geographical constraints, efficiency degradation, slow response, and high lifecycle costs. In this context, FESS emerge as a compelling alternative, offering efficient short-duration energy storage and rapid power dispatch during peak demand, thereby improving grid performance and reducing reliance on fossil-fuel-based peaking units [3].

The effective design of a Flywheel Energy Storage System requires the integration of advanced mechanical and electrical components, including high-speed rotors, low-loss magnetic bearings, and robust power electronic converters. Beyond hardware considerations, system performance and operational safety strongly depend on the adopted control strategy, which must ensure efficient charge–discharge operation, rotor stability, and safe operation under varying load and grid conditions [4].

Recent developments in industrial automation and the Internet of Things (IoT) have enabled more intelligent energy storage management solutions. Programmable Logic Controllers (PLCs) are widely adopted due to their reliability, deterministic real-time control, and robustness in industrial environments. In parallel, Node-RED has emerged as a flexible, open-source, flow-based programming platform that supports real-time data visualization, system integration, and remote monitoring through web-based dashboards. The integration of PLC-based control with Node-RED-based supervision provides an effective hybrid architecture for monitoring, automation, and optimization of Flywheel Energy Storage Systems [5].

The rapid integration of renewable energy sources into modern power systems has intensified the need for flexible and reliable energy storage technologies capable of mitigating intermittency and maintaining grid stability. Large-scale storage solutions such as compressed air energy storage (CAES) have been widely investigated within integrated and urban energy systems, demonstrating their ability to absorb excess renewable generation and support load balancing under high wind penetration scenarios [6,7]. Despite their advantages in large-capacity applications, CAES systems are constrained by slow response times and infrastructure requirements, limiting their suitability for fast-acting and decentralized grid support services.

Flywheel Energy Storage Systems (FESS) have gained increasing attention as an alternative or complementary technology due to their high power density, rapid charge–discharge capability, and long cycle life. Recent studies have shown that FESS are particularly well suited for grid applications requiring fast dynamic response, such as frequency regulation and short-term power smoothing [8,9]. Advances in power electronic interfaces and optimized circuit topologies have further enhanced the efficiency, controllability, and grid compatibility of flywheel systems, making them viable candidates for medium-scale energy storage applications [10].

In this context, Programmable Logic Controllers (PLCs) remain a cornerstone of industrial automation, offering deterministic real-time control, high reliability, and strong fault-handling capabilities. Their application in energy storage systems enables precise management of charging and discharging cycles, protection mechanisms, and operational safety [11,12].

In parallel, the adoption of Industrial Internet of Things (IIoT) technologies has enabled advanced system supervision, remote monitoring, and data-driven control. Node-RED has emerged as a flexible, flow-based programming environment for developing IoT-enabled control interfaces and integrating heterogeneous industrial data sources [13,14].

This research contributes to the field of energy storage and smart grid systems through the development of a scalable and cost-effective FESS tailored for small- to medium-scale applications, such as microgrids, renewable energy smoothing, and UPS systems. Unlike most existing studies that focus on large-scale grid-level flywheel installations, this work addresses decentralized and modular energy storage solutions. The integration of robust PLC-based control with IoT-enabled Node-RED visualization advances the current research frontier toward more intelligent, connected, and manageable Flywheel Energy Storage Systems, supporting the transition toward resilient and sustainable power infrastructures.

II. Methodology

The methodology adopted in this study combines system design, control development, simulation, and experimental validation to investigate the performance of a Flywheel Energy Storage System (FESS) integrated with a Programmable Logic Controller (PLC) and a Node-RED–based supervisory interface. The overall approach follows a hierarchical control philosophy, where the PLC ensures deterministic real-time control and system safety, while Node-RED provides high-level monitoring, visualization, and user interaction suitable for smart grid and off-peak energy management applications.

The proposed FESS is designed to store electrical energy in the form of rotational kinetic energy and convert it back into electrical energy during discharge. The mechanical subsystem consists of a high-inertia flywheel rotor coupled to a motor–generator unit and enclosed in a low-vacuum chamber to minimize aerodynamic losses. The energy stored in the flywheel is governed by the rotational energy relationship

$$E = \frac{1}{2} I\omega^2$$

Where:

- E = the energy stored (Joules),
- I = the moment of inertia (kg·m²),
- ω = the angular velocity (rad/s).

The rotor geometry, material selection, and operating speed limits were chosen to maximize energy storage while ensuring mechanical integrity and safe operation as shown in Figure 1.

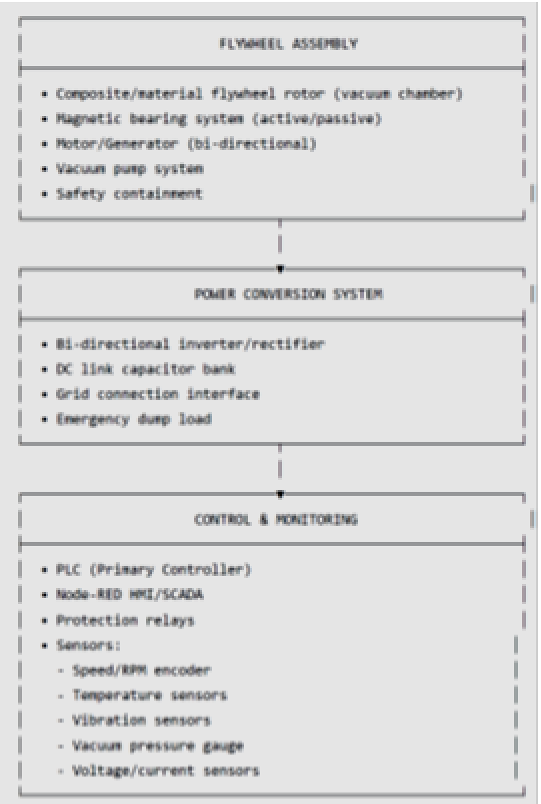

Figure 1. FESS physical components

A permanent magnet synchronous motor/generator (PMSM) is employed to enable bidirectional energy conversion. During off-peak periods, the machine operates as a motor to accelerate the flywheel and store energy, while during peak demand it functions as a generator to supply electrical power to the load. A variable frequency drive (VFD) regulates motor speed and torque based on reference signals generated by the PLC. This configuration allows smooth acceleration and deceleration of the flywheel while maintaining electrical stability.

Figure 2 illustrates the electrical and power conversion layout of the proposed Flywheel Energy Storage System. The diagram shows the bidirectional energy flow between the electrical grid and the flywheel through the motor–generator unit and the variable frequency drive (VFD). During charging, electrical energy is supplied to the motor to accelerate the flywheel, while during discharging the stored kinetic energy is converted back into electrical power through generator operation. This configuration ensures efficient energy transfer, controllable power flow, and smooth transitions between operating modes, which are essential for off-peak energy storage and peak-time power support in grid-connected and standalone applications.

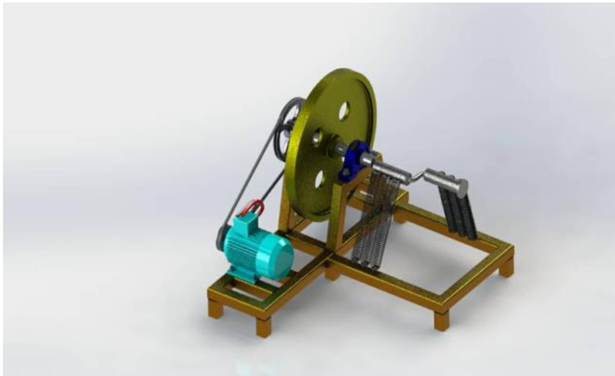

Figure 2. 3D view of the Flywheel – generator assembly

Figure 3 presents the overall control system architecture of the FESS, highlighting the interaction between the physical components, the PLC-based real-time control layer, and the Node-RED supervisory interface. The PLC is responsible for deterministic control tasks such as speed regulation, safety interlocks, and motor–generator switching, while Node-RED operates at the supervisory level, providing visualization, data logging, and user interaction. Communication between the control layers is achieved via industrial Ethernet protocols, enabling reliable data exchange and remote monitoring. This layered architecture enhances system reliability, scalability, and operational flexibility, making it suitable for intelligent energy storage management in smart grid environments [15].

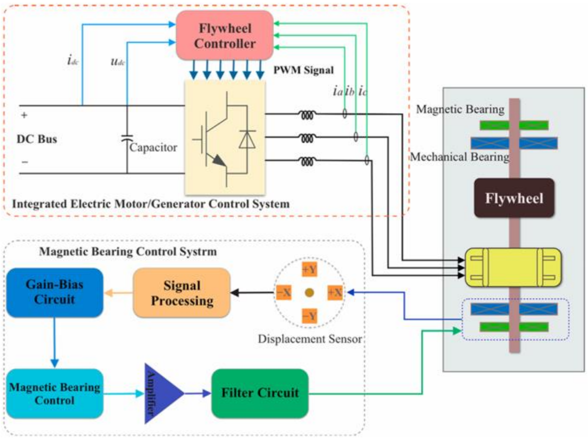

Figure 3. Flywheel energy storage circuit system layout

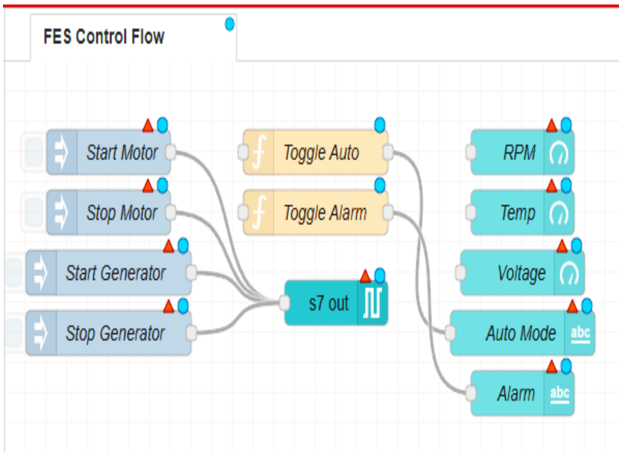

Figure 4. Flow control with Node-RED Configuration

The control architecture adopts a two-layer structure combining PLC-based real-time control with Node-RED supervisory control. A Siemens S7-1200 PLC manages all time-critical functions, including motor–generator control, speed regulation, and safety interlocks. Key parameters such as flywheel speed, voltage, current, and temperature are continuously monitored, with protective actions triggered under abnormal conditions. State-based logic governs transitions between charging, holding, discharging, and standby modes, ensuring safe and reliable operation under varying load conditions.

Node-RED serves as the supervisory control and monitoring platform, providing a web-based interface for visualization and data logging. Communication with the PLC is achieved via Modbus TCP/IP, enabling real-time display of system parameters, alarms, and operator commands, including mode selection and scheduled charging and discharging.

Figure 4 illustrates the Node-RED flow configuration used for supervisory control and monitoring of the Flywheel Energy Storage System. The flow shows how real-time data from the PLC, including flywheel speed, temperature, and electrical parameters, are acquired through industrial communication nodes and processed within Node-RED. Control nodes enable bidirectional interaction, allowing operator commands such as start, stop, and mode selection to be sent back to the PLC. Dashboard nodes are used to visualize system status, generate alarms, and display key performance indicators in real time. This flow-based structure provides a flexible and scalable framework for integrating industrial control with IoT-based monitoring and remote supervision [16].

To validate the proposed control strategy prior to physical testing, modeling and simulation were carried out using MATLAB/Simulink. The simulation model incorporates flywheel dynamics, motor–generator characteristics, power conversion behavior, and control setpoints derived from the PLC logic. Virtual testing involved applying load variations during discharge and observing system response in terms of speed regulation, voltage stability, and frequency recovery. Control parameters were tuned iteratively to minimize transient deviations and ensure smooth mode transitions.

A laboratory-scale prototype was subsequently developed to experimentally validate the proposed methodology. The prototype integrates the flywheel assembly, motor–generator unit, VFD, PLC, sensors, and a Node-RED server deployed on a Raspberry Pi platform. The system was tested under charging and discharging scenarios to evaluate its dynamic behavior and operational stability. Key parameters such as flywheel speed, output voltage, frequency, and temperature were recorded in real time through the Node-RED interface and stored for post-processing.

The FESS performance was evaluated by comparing simulation and experimental results with theoretical flywheel energy calculations. Key metrics, including response time, efficiency, electrical regulation, and thermal behavior, were analyzed to validate the feasibility of the PLC–Node-RED–controlled system for off-peak energy storage and on-demand power generation.

Table 1 summarizes the main mechanical, electrical, and control components of the experimental setup, defining the system's operational limits and serving as the basis for performance and reliability evaluation.

Table 1. Key hardware components

Component	**Specification**
Flywheel	Solid steel disc, 15 kg, radius = 0.25 m, housed in a vacuum enclosure
Electric Motor	3-Phase Induction Motor, 1.5 kW, controlled by VFD
Generator	1.2 kW synchronous generator, output: 220V AC, 50Hz
PLC	Siemens S7-1200, programmed using TIA Portal V17
Sensors	RPM sensor (hall effect), thermistor for temperature, voltage/current sensors
VFD	Delta VFD-M series, compatible with PLC analog output
Emergency Brake	Electromechanical brake with relay actuation from PLC
Node-RED Server	Raspberry Pi 4 (8 GB RAM), Node.js + Node-RED v3.1
Communica-tion Protocol	Modbus TCP/IP (PLC ↔ Node-RED)

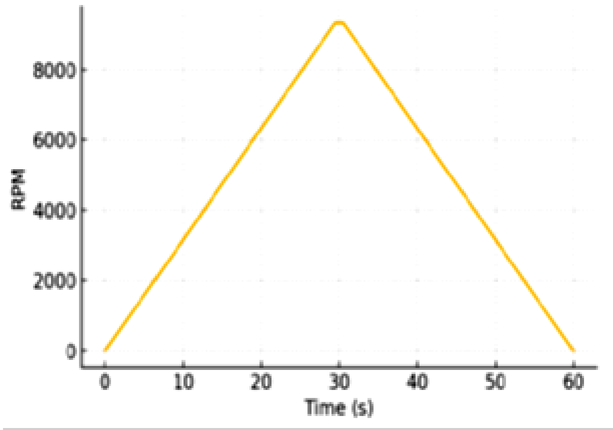

Figure 5. Flywheel RPM vs Time (Charging and Discharging)

III. Results

3.1. Results on System Performance and Observations

During the test results, the initial set up was to increase the load which resulted to a frequency drop below nominal value for few seconds. On the other hand during load decrease the frequency overshoot to above nominal value of 50 Hz on which the emergency breaking was applied with response time of less than 0.5 seconds. During the system operations, the charging completion with maximum achieved speed of 9500 RPM as shown in Table 2.

Table 2. System Response Characteristics during Load Variations

Test Scenario	**Observed Parameter**	**Value/Range**
Load Increase	Frequency Drop	47.8 Hz
	Frequency Recovery Time	1.2 s
Load Decrease	Frequency Overshoot	51.5 Hz
	Voltage Recovery Range	215–223 V
Emergency Braking	Response Time	Immediate (<0.5s)
Charging Completion	Max RPM Achieved	9500 RPM

Figure 5 demonstrates the dynamic behavior of the flywheel during the charge and discharge cycle. The RPM increases rapidly during charging, reaching a peak of 9500 RPM. Once the charging stops, the RPM gradually decays as the flywheel discharges energy into the generator. The smooth decline indicates a stable discharge process without mechanical anomalies.

3.2. Voltage response characteristics

The proposed Flywheel Energy Storage System achieved an overall efficiency of 85–92%, indicating effective energy conversion with low mechanical and auxiliary losses due to optimized motor–generator operation and efficient power electronic control.

The system demonstrated strong transient torque performance, with acceleration torques of 150–200% of the rated torque during charging, enabling rapid energy storage during off-peak periods. During discharge, a smooth torque ramp-down with programmable deceleration times of 0.5–5 s minimized mechanical stress, while torque ripple was limited to below 3%, confirming stable and precise PLC-based control.

Storage utilization results further validate the control strategy, with SOC estimation accuracy of ±1%, energy throughput of 90–95% of theoretical capacity, and a self-discharge rate of 0.5–2.0% per hour, depending on vacuum conditions.

Overall, the results confirm the system's robust dynamic response and the effectiveness of the integrated PLC–Node-RED architecture in ensuring stable, safe, and flexible operation. The proposed FESS represents a scalable and cost-effective solution for medium-scale energy storage applications (10–100 kWh) requiring fast response and frequent cycling, such as renewable energy smoothing and UPS systems.

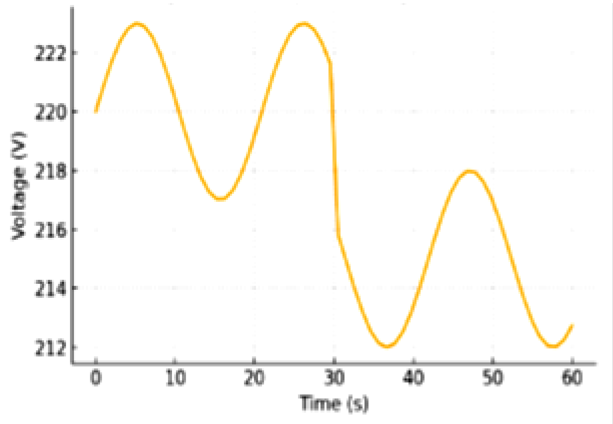

Figure 6. Output Voltage vs Time under Dynamic Load Conditions

3.3. Frequency regulation performance

Inertial Response: Provides 0.25-0.5Hz initial frequency stabilization
Droop Control: PLC-implemented droop characteristics (2-5% programmable)
Rate of Change of Frequency (RoCoF): Limits to <1.5Hz/s during generation loss
In this results, the Frequency regulation is crucial in maintaining grid compatibility. The graph in Figure 8 above shows that following a load application, frequency dropped momentarily to about 47.8 Hz, but quickly stabilized back to near 50 Hz within 1.2 seconds. This validates the responsiveness and tuning of the PID controller implemented in the PLC.

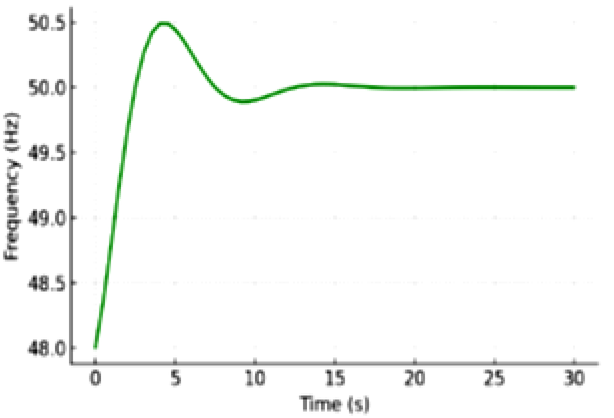

Figure 7. Frequency regulation profile during discharge

In the Figure 8 above , the system temperature gradually increased over the course of 60 seconds, reflecting normal thermal buildup from motor operation and generator load. No sharp temperature spikes were detected, indicating sufficient thermal management and no risk of overheating under the simulated conditions.

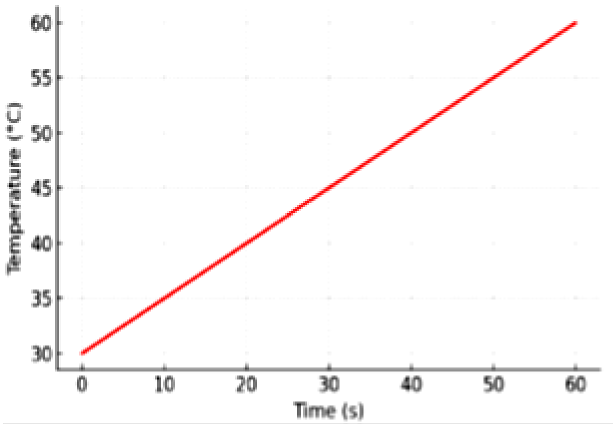

Figure 8. System temperature profile during continuous operation

3.4. Energy Conversion Efficiency

The overall system efficiency of the proposed Flywheel Energy Storage System was found to be in the range of 85–92%, reflecting effective energy conversion and low auxiliary losses. This high efficiency is primarily attributed to the optimized motor–generator operation, reduced mechanical losses, and efficient power electronic control.

The transient torque performance of the system demonstrates its capability to handle rapid dynamic conditions. During the charging phase, the flywheel experienced acceleration torques of approximately 150–200% of the rated torque, enabling rapid energy storage during off-peak periods. During discharge, the system exhibited a smooth and controlled torque ramp-down, with programmable deceleration times ranging from 0.5 to 5 s, which minimizes mechanical stress and ensures stable operation. Torque ripple was maintained below 3% peak-to-peak through PLC-controlled switching, confirming effective torque regulation and mechanical stability.

Storage capacity utilization results further validate the effectiveness of the proposed control strategy. The State of Charge (SOC) estimation achieved an accuracy of ±1% through PLC-based monitoring, enabling reliable energy management. The system delivered an energy throughput of 90–95% of the theoretical storage capacity, indicating efficient utilization of the flywheel's kinetic energy. The self-discharge rate was measured between 0.5–2.0% per hour, depending on vacuum conditions, which is consistent with expected aerodynamic and bearing losses.

These performance results demonstrate that the proposed flywheel energy storage system is a practical and efficient solution for storing and supplying electrical energy during off-peak periods. The system offers rapid energy release, long operational life, and high reliability with minimal environmental impact. While limitations such as relatively low energy density and safety considerations at high rotational speeds exist, the design is inherently scalable and can be optimized for a wide range of energy management applications.

Overall, the results confirm the system's robust dynamic response and its ability to regulate power output under simulated load disturbances. They also validate the effectiveness of the integrated PLC and Node-RED control architecture in achieving operational stability, safety, and flexible supervision. The proposed FESS represents a cost-effective and scalable solution for medium-scale energy storage applications (10–100 kWh), particularly those requiring frequent cycling and fast response, such as renewable energy smoothing, uninterruptible power supplies (UPS), and regenerative energy capture in industrial processes. Moreover, the combination of open-source Node-RED with industrial-grade PLC control provides a future-proof platform that can be readily adapted to evolving grid requirements and emerging smart energy storage applications.

IV. Conclusion

This study presented the design, control, and experimental validation of a Flywheel Energy Storage System (FESS) integrated with a Programmable Logic Controller (PLC) and a Node-RED–based supervisory interface for off-peak energy storage and on-demand power generation. The proposed hierarchical control architecture successfully combines deterministic real-time control with flexible, IoT-enabled monitoring, enabling reliable and intelligent energy management.

Experimental and simulation results confirm that the developed FESS operates stably during both charging and discharging modes. The flywheel reached a maximum rotational speed of approximately 9500 RPM during charging, demonstrating effective kinetic energy storage. During discharge, the system supplied electrical power while maintaining smooth speed deceleration and mechanical stability. The output voltage remained within 215–223 V, close to the nominal 220 V, even under dynamic load variations, indicating robust voltage regulation.

Frequency regulation performance further validated the system's capability to support grid stability. Following load disturbances, the frequency deviation was limited to a minimum of 47.8 Hz, with recovery to the nominal 50 Hz occurring within 1.2 s. During load reduction, a short overshoot up to 51.5 Hz was observed and successfully managed by the PLC-based protection logic. These results demonstrate the inherent inertial response of the flywheel combined with effective control tuning.

Simulation and virtual testing confirmed the system's responsiveness to dynamic load changes, its ability to maintain output frequency and voltage stability, and the reliability of the integrated control system.

The results indicate that the flywheel system, when fully charged, is capable of delivering 5 kW of mechanical power to the generator. The generator successfully converts 85% of this mechanical input into usable electrical energy, amounting to 4.25 kW output and it suitable for supplying small industrial loads, backup systems, or supplementing power during short-term peak demand. The findings affirm the potential of FESS systems as viable short-duration energy storage solutions, particularly in industrial and distributed renewable energy applications.

This FESS design effectively bridges the gap between high-speed energy storage hardware and modern Industrial IoT (IIoT) principles. The synergy of the PLC's reliability and Node-RED's connectivity creates a system that is not only technically proficient but also adaptable to smart grid and Industry 4.0 environments, paving the way for more intelligent and integrated energy storage solutions.

The core contribution is the hierarchical architecture combining a Siemens S7-1200 PLC for fail-safe, deterministic, low-level control (critical for protecting the high-speed rotor) with a Node-RED server for high-level, web-based visualization, data logging, and remote command. This ensures both operational safety and user-friendly accessibility.

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Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

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APPENDIX A: Node-RED Flow Codes

A.1 Toggle Auto Mode Button

```
context.state = !context.state;
msg.payload = context.state ? "AUTO ON" : "AUTO OFF";
return msg;
```

A.2 Generate Random Load for Testing

```
msg.payload = (Math.random() * 5 + 2).toFixed(2);
return msg;
```

A.3 Conditional Alarm Based on RPM

```
if (msg.payload > 10000) {
    msg.payload = "ALARM: Over-speed";
} else {
    msg.payload = "RPM Normal";
}
return msg;
```

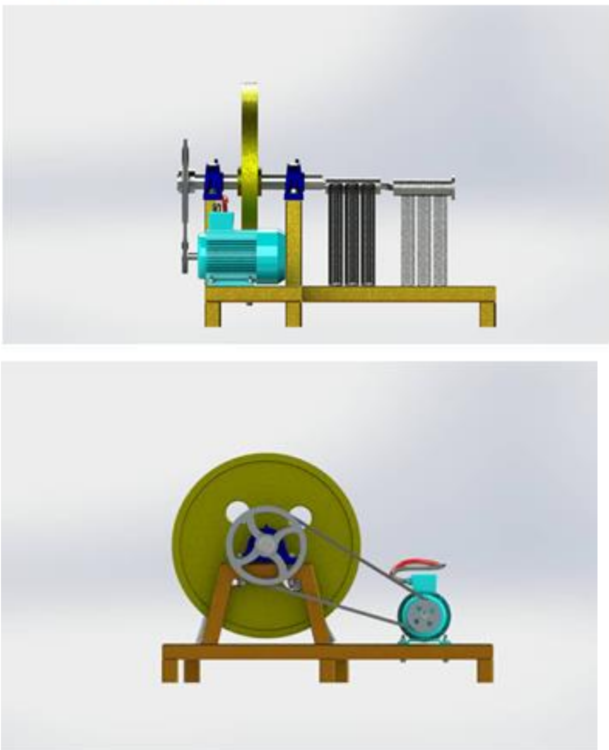
A.4 Temperature Threshold Warning

```
if (msg.payload >= 80) {
    msg.payload = "High Temp! Activate Cooling";
} else {
    msg.payload = "Temp Normal";
}
return msg;
```

A.5 Start/Stop Generator via Dashboard Button

```
if (msg.payload === true) {
    msg.payload = 1; // Start generator
} else {
    msg.payload = 0; // Stop generator
}
return msg;
```

APPENDIX C: 3D VIEWS



APPENDIX B: PLC Ladder Logic