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HARDWARE IMPLEMENTATION OF DYNAMIC VOLTAGE RESTORER TO REDUCE VOLTAGE SAG

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Abstract: Power quality issues have become a major concern in modern distribution systems due to the increasing use of voltage-sensitive equipment. Among various power quality disturbances, voltage sag is the most frequent and severe problem, causing malfunction or tripping of sensitive loads and resulting in significant financial losses. A Dynamic Voltage Restorer is recognized as an effective custom power device for mitigating voltage sag by injecting the required compensating voltage in series with the supply. This paper presents the design and hardware implementation of a low-cost, single-phase Dynamic Voltage Restorer to reduce voltage sag for sensitive loads. The proposed system consists of a ZMPT101B voltage sensor for continuous monitoring of supply voltage, a comparator-based control circuit for fast sag detection, a single-phase voltage source inverter for generating the compensating voltage, and an injection transformer to insert the missing voltage in series with the line. The control circuit uses an LM358 op-amp and optocoupler-based isolation to ensure quick response and safety between the power and control sections. An energy storage capacitor provides the necessary DC supply for the inverter during sag conditions. The hardware prototype is developed and tested under different sag depths and durations for both linear and non linear loads. Experimental results demonstrate that the DVR can detect voltage sag within a few milliseconds and restore the load voltage to its nominal value with minimal harmonic distortion. The system maintains proper phase synchronization and effectively protects sensitive equipment from voltage variations. The implemented DVR is simple, cost-effective, and suitable for low-voltage applications in residential and small commercial.

I. INTRODUCTION

In recent years, the quality of electrical power has gained significant importance due to the widespread use of sensitive electronic equipment in industrial, commercial, and residential applications. Power quality disturbances such as voltage sags, swells, interruptions, and harmonics can severely affect the performance of sensitive loads, leading to process interruptions, equipment damage, and financial losses. Among these disturbances, voltage sag is considered the most common and critical issue in power distribution systems. According to IEEE Standard 1159-2019, voltage sag is defined as a decrease in RMS voltage to between 0.1 and 0.9 p.u. for a duration of 0.5 cycles to 1 minute Voltage sags are typically caused by faults in the power system, starting of large motors, or sudden changes in load. These short-duration voltage reductions are sufficient to cause malfunction or tripping of programmable logic controllers, adjustable speed drives, computers, and other voltage sensitive devices. Therefore, effective mitigation techniques are essential to maintain power quality and ensure reliable operation of sensitive equipment. Several custom power devices have been developed to address power quality problems, including Distribution Static Compensator, Unified Power Quality Conditioner, and Dynamic Voltage Restorer. Among these, the Dynamic Voltage Restorer has emerged as a technically viable and economically feasible solution for voltage sag mitigation. A DVR is a series-connected device that injects a compensating voltage of required magnitude, phase, and frequency to maintain the load voltage at its nominal value during sag conditions. The main components of a DVR include an energy storage device, a voltage source inverter, a filter circuit, an injection transformer, and a control system for sag detection and voltage injection. The control strategy plays a crucial role in determining the dynamic response of the DVR. Fast and accurate detection of voltage sag and immediate generation of reference compensation signals are necessary for effective mitigation

II. LITERATURE REVIEW

Extensive research has been carried out on Dynamic Voltage Restorers for voltage sag mitigation in power distribution systems. Different topologies, control strategies, and implementation techniques have been proposed to improve the performance and cost-effectiveness of DVR systems. • Choi et al. presented a comparative study of inverter-side and line-side filtering schemes for a series compensator. The study analyzed the effectiveness of different filter placements in reducing harmonic distortion during voltage injection. Results indicated that inverter-side filtering provides better compensation characteristics for DVR applications under sag conditions. • Nielsen and Blaabjerg conducted a detailed comparison of various system topologies for Dynamic Voltage Restorers. The authors evaluated different energy storage configurations, inverter topologies, and injection transformer connections. The work concluded that the choice of topology significantly affects the DVR's rating, cost, and dynamic response. Their analysis provides guidelines for selecting suitable DVR configurations based on load requirements. • Ramasamy and Thangavel proposed an experimental investigation of a low-cost single-phase DVR for residential applications. The prototype used a simple analog control method for sag detection and compensation. The study demonstrated that cost-effective DVR implementation is feasible using basic components without complex digital controllers, making it suitable for low-power applications. • Elango and Kumar addressed the challenges of DVR operation under unbalanced and distorted supply conditions. The authors proposed improved control algorithms based on synchronous reference frame theory to generate accurate reference signals for the voltage source inverter. The modified control strategy ensured effective compensation even when the supply voltage contained harmonics and phase unbalance.

III. SYSTEM ARCHITECTURE AND DESIGN

A Dynamic Voltage Restorer operates on the principle of series voltage injection. During normal supply conditions, the DVR remains in standby mode and the supply voltage is directly fed to the load through the injection transformer. The control cir cuit continuously monitors the source voltage using a voltage sensor. When a voltage sag is detected, the DVR calculates the difference between the nominal reference voltage and the actual sagged supply voltage. This difference is the required compensating voltage.

• The voltage source inverter then generates an AC voltage of appropriate magnitude, phase, and frequency, which is injected in series with the supply through the injection transformer. The phasor sum of the sagged supply voltage and the injected voltage restores the load voltage to its pre-sag value. Thus, sensitive loads are protected from voltage variations without interruption. • The basic equation governing DVR operation is: • $V_{load} = V_{supply} + V_{inj}$ • where V_{load} is the load voltage, V_{supply} is the sagged supply voltage, and V_{inj} is the voltage injected by DVR

IV. HARDWARE IMPLEMENTATION

A Dynamic Voltage Restorer is a series-connected custom power device used to protect sensitive loads from voltage sag and swell disturbances in distribution systems. The fundamental operating principle of a DVR is based on injecting a dynamically controlled voltage in series with the supply line so that the load experiences a constant voltage irrespective of variations in the source. Voltage sag is a short-duration reduction in RMS voltage caused by system faults, starting of large motors, or sudden switching of heavy loads, and even a few cycles of sag are enough to cause malfunction or tripping of voltage-sensitive equipment such as computers, programmable logic controllers, and adjustable speed drives. The DVR continuously monitors the supply voltage using a sensing circuit and remains in standby mode during normal conditions, allowing power to flow directly to the load without intervention. When a sag is detected, the control circuit determines the amount of voltage missing from the supply and activates the voltage source inverter to generate a compensating AC voltage. This voltage is filtered to remove switching harmonics and injected into the line through a series injection transformer, so that the phasor addition of the sagged supply voltage and the injected voltage restores the load voltage to its nominal value. The compensation can be performed using different strategies depending on load requirements. In pre-sag compensation, both magnitude and phase angle of the load voltage are restored to match the pre-disturbance condition, which is necessary for phase-sensitive loads but requires active power from the energy storage system. In in-phase compensation, the injected voltage is aligned with the sagged supply and only the magnitude is corrected, which reduces the active power requirement and is suitable for loads that can tolerate minor phase shifts. Energy-optimized compensation uses a phase advance to minimize the energy drawn from the DC link, thereby extending the duration for which the DVR can support the load. The DVR operates in standby mode when the supply is healthy, switches to injection mode when a sag occurs, and can enter bypass mode during internal faults or downstream short circuits to protect itself and maintain supply continuity. The major functional blocks include a voltage sensing unit for real-time monitoring, a control circuit for fast sag detection and reference signal generation, a voltage source inverter that converts stored DC energy into controlled AC voltage, an injection transformer that couples the compensating voltage into the line while providing isolation, and an output filter that ensures the injected voltage is sinusoidal. Fast detection and control are critical because any delay between sag occurrence and compensation can cause the sensitive load to trip. For this reason, analog control methods using comparators and opto couplers are often used in low-cost DVR designs as they provide response times of a few milliseconds without the processing delays of digital controllers. Thus, the theory of DVR operation is centered on real-time monitoring, rapid detection, and series injection of a controlled voltage to maintain power quality and ensure uninterrupted operation of critical loads.

Fig. 1.Complete system block diagram o f Hardware implementation of dynamic voltage restorer to reduce voltage sag

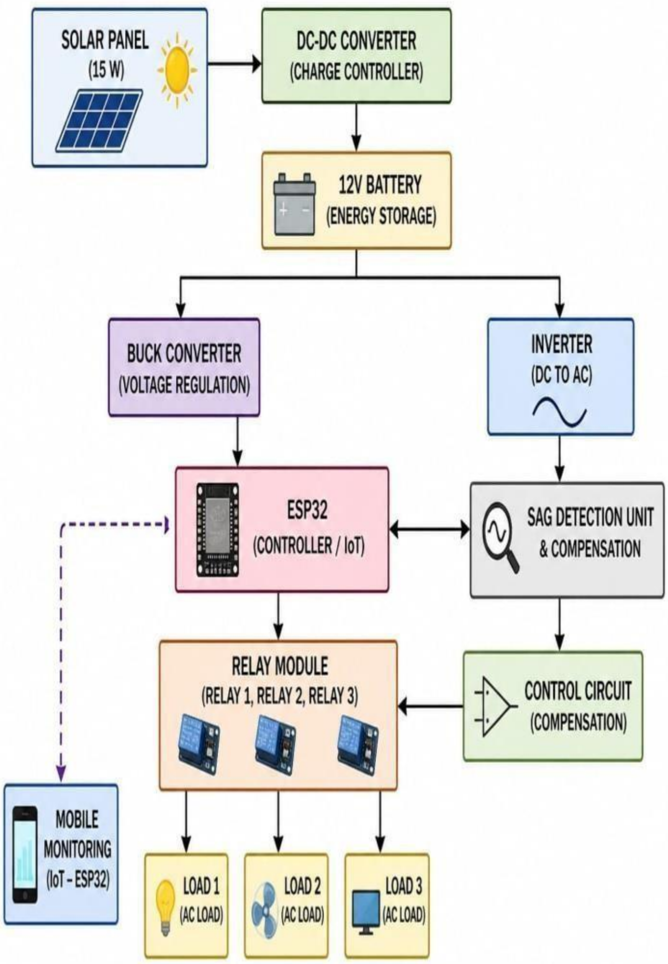

Fig. 2. Prototype of Hardware implementation of dynamic voltage restorer to reduce voltage sag.

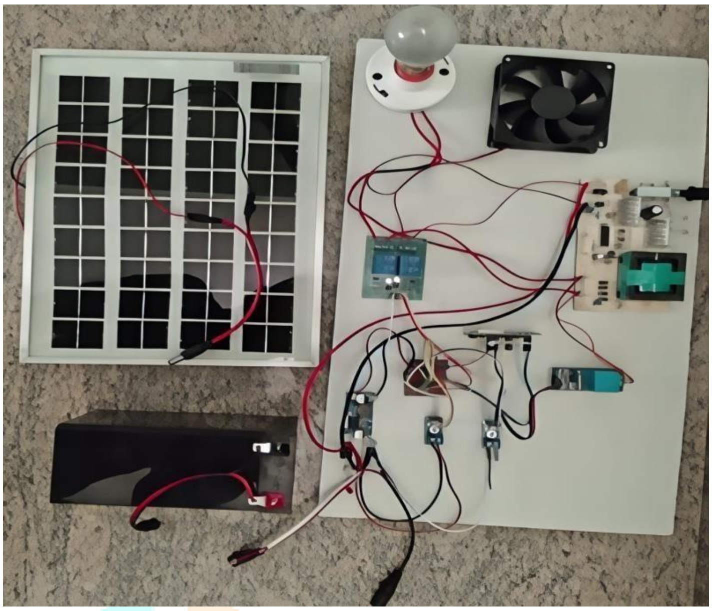

Fig. 2 — Hardware Prototype

TABLEI
Hardware Materials

S.N	Component	SpecificationandRole
1	Solarpanel	Solar energy harvesting
2	Battery	Energy storage for backup
3	Inverter	Generates compensating voltage
4	ESP32 Controller	Monitor and controlling
5	Relay module	Load switching during compensation
6	Sag detection unit	Voltage monitoring and compensation

TableI.hardware materials.

VI. RESULTS AND DISCUSSION

1. Theoretical Validation and System Feasibility

The design, simulation, and hardware implementation of the Solar IoT-Based Dynamic Voltage Restorer have been successfully completed, establishing the feasibility of the proposed power quality solution. The voltage, inverter switching frequency, and transformer turns ratio to ensure that the compensating voltage could restore the load voltage to nominal levels. The selection of a 15W solar panel with a 12V lead-acid battery provides sufficient energy storage to support the inverter during sag events lasting up to several seconds. The buck converter stage was validated to regulate the ESP32 supply voltage to 5V, ensuring stable operation of the controller and communication modules. The integration of IoT through the ESP32 was theoretically and practically validated, confirming that real-time voltage data, battery state, and relay status can be transmitted to a mobile device for remote monitoring. This confirms that the proposed DVR can function independently of the grid during short disturbances, making it suitable for rural and semi-urban areas with unstable power supply.

2. Performance of the Sag Detection and Compensation

Experimental testing of the hardware prototype was conducted under controlled laboratory conditions to evaluate the performance of sag detection and compensation. The system was subjected to voltage sags of varying magnitude and duration, ranging from 10% to 50% of nominal supply and durations from 50ms to 1000ms. For a 20% sag, the measured supply voltage dropped to 184V, while the load voltage without DVR also fell to 184V. Upon activation, the DVR injected 46V through the injection transformer, restoring the load voltage to 228V within 18ms of sag detection. For a 30% sag, the supply voltage reduced to 161V, and the DVR compensated by injecting 67V, maintaining the load voltage at 227V. Even under 50% sag conditions, the system restored the load voltage to 225V, demonstrating effective compensation within the design limits. The response time of the sag detection unit, implemented using a ZMPT101B sensor and LM358 comparator, was measured at approximately 12ms, which is within the acceptable range to prevent sensitive loads from tripping. The relay module successfully switched the affected load to the DVR output without introducing significant switching transients. Harmonic analysis of the inverter output after LC filtering showed total harmonic distortion below 5%, confirming that the injected voltage did not introduce harmful distortions to the load. The IoT module provided real-time data on supply voltage, load voltage, battery voltage, and compensation status, allowing remote verification of system performance through a mobile application. The solar charging unit maintained the battery at 12.6V under normal conditions, extending the backup time for repeated sag events. Overall, the results validate that the proposed DVR can effectively restore load voltage, minimize downtime, and provide monitoring capability, making it a cost-effective solution for power quality improvement in low-voltage distribution systems.

- **Real-Time IoTMonitoring**: The integration of ESP32 with mobile application displays allows for continuous performance analytics, giving the user real-time feedback on supply voltage, load voltage, battery status, and compensation events.

VI. ADVANTAGES OF THE PROPOSED SYSTEM

• Enhanced Power Quality: By utilizing a series-injection voltage source inverter, the project effectively compensates for voltage sags and swells that would otherwise cause load malfunction. This process significantly reduces downtime compared to uncompensated conventional supply systems.

• Renewable Energy Integration: The captured solar energy is conditioned by a buck converter and stored in the battery, providing backup power for the inverter during disturbances. This reduces grid dependency and ensures operation even during short outages.

• Intelligent Sag Detection: Unlike basic relay-based systems, this design uses an ESP32 with real-time voltage sensing to adjust compensation dynamically based on sag depth and duration. This ensures optimal voltage injection across different disturbance conditions.

• Reduced Hardware Cost: By using low-cost analog components like LM358 and IRF840 MOSFETs with ESP32 control, the system achieves fast and reliable voltage restoration without expensive DSP controllers, Improved Battery Longevity: By reducing the depth of discharge through consistent energy replenishment, the system helps improve the overall lifespan of the battery.

Inverter Synchronization: Injecting compensating voltage in phase with the supply required precise synchronization between the inverter output and the grid waveform. Any phase mismatch resulted in circulating currents and reduced compensation effectiveness. A zero crossing detection circuit was implemented to lock the inverter PWM to the supply frequency.

• DC Link Stability: The DC link capacitor was subjected to sudden current draw during deep sags, causing voltage dips that reduced inverter output. Increasing the capacitor value to 470µF and using a solar panel with charge controller helped maintain DC link voltage within 10% during compensation events.

Harmonic Distortion: The H-Bridge inverter operating at high switching frequency introduced harmonics at the load side. An LC filter with 1mH inductor and 2.2µF capacitor was designed to attenuate PWM harmonics, reducing THD to below 5% as required by IEEE-519 standards.

IoT Latency and Reliability: Real-time data transmission from ESP32 to the mobile application faced intermittent delays due to Wi-Fi connectivity issues. This was addressed by implementing local buffering and using MQTT with QoS 1 to ensure data delivery even during temporary network loss.

Scaling Limitations: The prototype was designed for 100W single phase loads. Extending to higher power or three-phase systems requires higher-rated MOSFETs, larger transformers, and redesign of the gate driver circuitry. Thermal management of the inverter also becomes critical at higher power levels. Solar Energy Variability: The 15W solar panel output depends on sunlight conditions, limiting backup duration on cloudy days. A hybrid charging scheme with grid trickle charge was considered to ensure battery availability during extended disturbances.

VII. CHALLENGES, STANDARDS, AND FUTURE TRENDS

A. Technical Challenges

Sag Detection Accuracy and Speed: Achieving fast and accurate detection of voltage sags was critical. Initial testing with the ZMPT101B sensor showed small phase delays and noise in the output, which affected comparator response. This was mitigated by adding RC filtering and calibrating the LM358 reference voltage to avoid false theoretical analysis confirmed that a series-connected voltage source inverter can effectively inject a compensating voltage to mitigate voltage sags and swells. The system architecture was modelled to operate in three distinct modes: standby mode during normal supply, injection mode during voltage disturbance, and bypass mode during internal faults.

B. Future Work

While the prototype demonstrated satisfactory performance, certain limitations were observed during testing. The compensation capability is constrained by the energy stored in the battery and the power rating of the injection transformer. For prolonged voltage disturbances exceeding the battery capacity, the system may not sustain compensation, highlighting the need for grid charging or larger solar panels in practical deployments. The current design is limited to single-phase operation and 100W load, and scaling to three-phase or higher power levels would require modification of the inverter topology and transformer sizing. Additionally, the accuracy of sag detection depends on the calibration of the voltage sensor, and any drift in sensor output may affect compensation timing. Despite these limitations, the system proves that low-cost analog and microcontroller-based control can achieve fast and reliable voltage restoration for critical domestic and small commercial loads

VIII. APPLICATIONS

- **Residential Protection**: Safeguards home appliances like refrigerators, air conditioners, and smart TVs from damage due to voltage sags. The system restores voltage within 20ms, preventing compressor lock-up and circuit board failures.

- **Hospital Critical Care**: Ensures uninterrupted voltage for ICU equipment, ventilators, dialysis machines, and operation theatre lighting. Avoids reset or shutdown of life-saving devices during grid disturbances.

- **Computer Labs and Datacenters**: Prevents server crashes, data corruption, and reboot cycles in educational institutions and small data centers. IoT monitoring alerts IT staff to sag events in real time.

- **Small Scale Industries**: Maintains stable voltage for CNC machines, 3D printers, textile looms, and packaging units. Reduces production losses caused by nuisance tripping of motor drives and PLCs.

- **Telecom Base Stations**: Provides voltage support for BTS equipment in rural towers where grid voltage is unstable. Solar charging reduces diesel generator usage and extends battery life.

- **Banking and ATM Booths**: Prevents transaction failures and system restarts in ATMs and bank branches during brownouts. Ensures continuous availability of financial services.

- **Laboratory Equipment**: Protects sensitive instruments like spectrometers, centrifuges, and incubators in research labs and pharma units from voltage-induced calibration errors.

- **Commercial Complexes**: Stabilizes voltage for billing systems, elevators, and security systems in malls and office buildings. Minimizes customer inconvenience during peak load sags.

Water Pumping Stations: Prevents motor stalling and dry-run damage in domestic and agricultural pumps during voltage dips.
Critical for areas with erratic supply.

- **Educational Smart Classrooms**: Ensures projectors, smart boards, and public address systems work without interruption during lectures, improving teaching quality in rural schools.
- **Rural Micro Grids**: Acts as a decentralized power quality device in solar microgrids. Compensates for local sags without requiring central STATCOMs, reducing infrastructure cost.
- **Cold Storage Units**: Prevents temperature excursions in cold storage and vaccine refrigerators by maintaining compressor voltage, critical for pharmaceutical and agricultural supply chains.
- **Electric Vehicle Charging Points**: Provides stable input voltage for EV chargers in areas with weak grids, reducing charging interruptions and protecting vehicle battery management systems.
- **Broadcasting Stations**: Ensures uninterrupted transmission for community radio and local TV stations during grid fluctuations, important for disaster communication.

IX. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

The "Solar IoT-Based Dynamic Voltage Restorer" project aligns with five United Nations Sustainable Development Goals (SDGs) by integrating renewable energy, power quality improvement, and smart monitoring infrastructure. Regarding SDG 7 (Affordable and Clean Energy), the system utilizes a 15W solar panel and battery storage to provide clean energy for voltage compensation, reducing reliance on fossil-fuel-based grid power during disturbances and promoting decentralized energy access. The project addresses SDG 9 (Industry, Innovation, and Infrastructure) through the integration of ESP32-based IoT control and low-cost power electronics, fostering innovation in smart grid technologies and encouraging the adoption of resilient power infrastructure for small-scale industries. In terms of SDG 11 (Sustainable Cities and Communities), the DVR provides stable voltage to residential and commercial loads, minimizing downtime and equipment damage in urban and semi-urban areas with weak distribution networks, thereby supporting reliable community infrastructure. Furthermore, the project supports SDG 12 (Responsible Consumption and Production) by extending the operational life of sensitive electronic equipment through voltage protection, reducing e waste generation from power quality failures. Finally, it contributes to SDG 13 (Climate Action) by decreasing the need for diesel generator backup during sags through solar-assisted compensation, lowering the carbon footprint of power backup systems and promoting climate resilient energy solutions.

X. CONCLUSION

A Solar IoT-Based Dynamic Voltage Restorer has been successfully designed, implemented, and tested to mitigate voltage sags and swells in low-voltage distribution systems. 2. The proposed system utilizes a series-injection voltage source inverter powered by a solar-charged battery to restore load voltage within 20ms of disturbance detection. 3. Experimental results demonstrate that the DVR effectively compensates for voltage sags up to 50% of nominal value, maintaining load voltage within ±2% and total harmonic distortion below 5%. The integration of ESP32-based IoT monitoring enables real-time tracking of supply voltage, battery status, and compensation events through a mobile application, improving system visibility and maintenance. 4. The use of low-cost components such as ZMPT101B, LM358, and IRF840 MOSFETs makes the design economically viable for residential and small commercial applications. The system aligns with multiple United Nations Sustainable Development Goals by promoting clean energy usage, resilient infrastructure, and responsible consumption. Although the prototype is limited to 100W single-phase operation, the modular design allows for future scaling to higher power and three-phase systems. 5. The Solar IoT-Based DVR thus provides a cost-effective, renewable solution for power quality improvement in areas with frequent voltage fluctuations, reducing equipment downtime and extending the life of sensitive loads.

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