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DESIGN AND DEVELOPMENT OF MICROCONTROLLER BASED SERVO VOLTAGE STABILIZER FOR POWER QUALITY IMPROVEMENT

Pratik D. Mali*[1], Pratik B. Pandhare[2], Pratiksha G. Kumbhar[3], Meharun S. Mulla[4], Dr. Vaibhav B. Magdum[5]

[1,2,3,4]Student, [5]Associate Professor, Electrical Engineering Department,
DKTE Society's Textile and Engineering Institute, Ichalkaranji, Maharashtra, India.

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***Corresponding Author: Pratik D. Mali**
Student, Electrical Engineering Department, DKTE Society's Textile and Engineering Institute, Ichalkaranji, Maharashtra, India.
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ABSTRACT

Voltage instability in low-voltage distribution systems leads to malfunction, overheating, and premature failure of sensitive electrical and electronic equipment. To address this challenge, this paper presents the design and development of a 5 kVA single-phase microcontroller-based servo voltage stabilizer that maintains a nearly constant output voltage of 230 V despite wide input variations. The proposed system combines a servo-driven variac (autotransformer) with a buck–boost transformer and a microcontroller-based control card employing an LM324 operational amplifier for voltage sensing and feedback. The microcontroller continuously monitors the input and output voltages and drives an AC servo motor via relay/driver circuitry to adjust the variac position, providing smooth, continuous correction with typical accuracy of ±1% of nominal voltage. The stabilizer incorporates protection features such as overvoltage, undervoltage, overload, and short-circuit protection using an MCB, fuses, contactors, limit switches, and control logic. Experimental results on a laboratory prototype demonstrate successful regulation of output voltage at 230 V for input voltages in the 170–270 V range, confirming the effectiveness of the proposed design for domestic, commercial, and small industrial loads up to 5 kVA.

KEYWORDS: Servo voltage stabilizer, microcontroller, buck–boost transformer, LM324, power quality, single-phase regulation.

1. INTRODUCTION

Modern households, commercial establishments, and small industries rely heavily on sensitive electronic equipment that requires a stable AC supply, typically around 230 V in single-phase systems. In many developing regions, however, the utility voltage frequently deviates from nominal due to heavy load variations, long distribution feeders, network congestion, and unbalanced loading, resulting in undervoltage or overvoltage conditions. These fluctuations cause reduced efficiency, overheating, insulation failure, data loss, and, in severe cases, permanent equipment damage.

Voltage stabilizers are widely employed to mitigate these issues by maintaining a constant output voltage in the presence of input fluctuations. Conventional relay-type stabilizers operate by switching between discrete transformer taps, which leads to stepwise correction, contact wear, arcing, and relatively slow response. In contrast, servo-controlled stabilizers use a motor-driven variac to provide smooth, continuous regulation and are therefore more suitable for sensitive loads such as computers, medical instruments, CNC machines, and laboratory equipment.

With advances in digital electronics, microcontroller-based control has enabled higher precision, faster response, and additional intelligent features in stabilizers. A microcontroller can monitor voltages, implement flexible protection logic, and provide digital display and diagnostics at relatively low cost. This paper presents the design and implementation of a 5 kVA single-phase microcontroller-based servo voltage stabilizer, which integrates electromechanical servo regulation with digital feedback control for improved performance and reliability.

2. LITERATURE REVIEW

Several researchers have proposed automatic voltage regulators and servo-based stabilizers to improve low-voltage power quality.

R. Gupta (2006) presented an automatic voltage regulator using a servo mechanism, employing an operational amplifier as a comparator to detect deviations and drive a servo-controlled variac, achieving higher accuracy than relay-based systems at the cost of increased mechanical maintenance.

S. Rajkumar et al. (2010) designed a microcontroller-based automatic voltage stabilizer using a PIC microcontroller that senses the input through a transformer and employs PWM to control a servo motor, achieving improved efficiency and reduced response time compared with purely analog designs. M. N. Ramesh et al. (2013) implemented a single-phase servo voltage stabilizer with an LM324-based comparator circuit and a digital display, providing real-time monitoring and overload protection for domestic and laboratory applications.

P. Sharma et al. (2015) introduced a microcontroller-based servo stabilizer with integrated protection against under-voltage, over-voltage, and short circuits, with relays providing isolation during faults. S. Bhattacharya et al. (2017) used an ATmega328 microcontroller with ADC-based sensing for a digital servo voltage regulator, incorporating automatic cutoff during overvoltage and overload events and demonstrating enhanced regulation accuracy.

Later works expanded functionality using networked monitoring. V. Reddy and R. Kumar (2019) developed an IoT-based voltage monitoring and stabilization system that combined servo regulation with Wi-Fi-enabled remote monitoring and data analytics. A. Patel et al. (2021) reported a 5 kVA microcontroller-based servo stabilizer featuring LM324 sensing, digital display, and advanced protection, maintaining output within ±1% over a broad input range.

These contributions show a clear evolution from analog servo regulators toward microcontroller- and IoT-based systems that provide higher accuracy, faster response, enhanced protection, and remote supervision. The present work follows this trend by implementing a microcontroller-based 5 kVA servo stabilizer with emphasis on practical hardware design and experimental validation for single-phase applications.

3. SYSTEM DESIGN AND HARDWARE ARCHITECTURE

The proposed stabilizer is rated at 5 kVA and designed for single-phase 230 V, 50 Hz operation. The overall architecture integrates a variac-type autotransformer, a buck–boost transformer, an AC servo motor, voltage sensing circuitry, and a microcontroller-based control card with protection components.

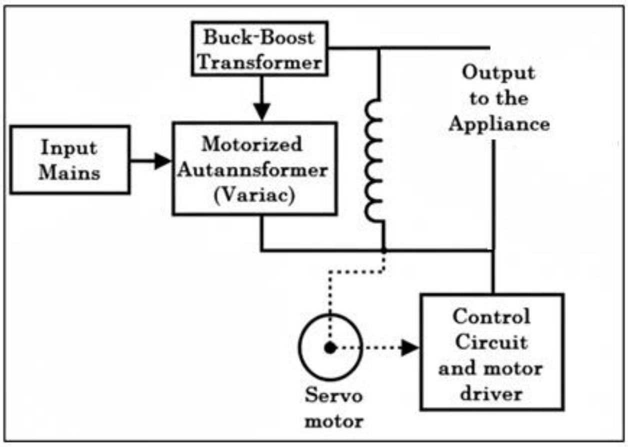

Fig-3.1 Block Diagram.

3.1 Main Power Components

The autotransformer (variac) is a continuously variable transformer (shell type) with a maximum input voltage of 250 V, minimum operating voltage of 80 V, and nominal output of 220 V, designed for natural air cooling. A carbon brush slides along the winding surface to vary the output voltage smoothly; the brush position is adjusted by a servo motor through a 3/8 inch, 96-tooth dimmer gear, realizing fine mechanical control.

The buck–boost transformer is connected in series with the input to add or subtract a controlled portion of voltage, thereby compensating for line variations. When input voltage is low, the transformer injects a boosting voltage in phase with the supply, and when input voltage is high, it introduces a bucking voltage out of phase. The transformer is implemented with laminated iron core and copper windings for high efficiency and low losses and is rated for 20 A to match the 5 kVA capacity.

An AC servo motor rated for 230 V AC, delivering approximately 3 kg-cm torque, is mechanically coupled to the variac shaft via the dimmer gear arrangement. The motor direction (clockwise or anticlockwise) is controlled by the microcontroller through relay/driver circuitry, enabling incremental adjustments to the autotransformer output. A power contactor rated at 40 A is used to connect/disconnect the stabilized output to the load and to control power paths safely.

3.2 Sensing and Control Circuitry

Voltage sensing is achieved using a 230/12 V sensing transformer, which steps down the line voltage to a low AC level that is subsequently rectified and filtered for measurement. The resulting DC voltage is fed to an LM324 quad operational amplifier, which is configured to perform comparison and signal conditioning functions. The LM324 provides an error signal proportional to the deviation from the reference value and offers amplification and filtering as required.

The core controller is a microcontroller board that receives the processed voltage signals and executes the regulation algorithm. The microcontroller utilizes its ADC channels (either directly on the board or via conditioned inputs from the LM324) to sample input and output voltages, compares them with preset thresholds, and generates control outputs for the servo motor via relay drivers and optocouplers. An LCD module (typically 2×16) displays parameters such as input voltage, output voltage, output current, frequency, and system status.

Auxiliary components include optocouplers for galvanic isolation between low-voltage control and high-voltage power circuits, BC547 NPN transistors as driver elements, IGBTs or additional switches where high-speed control is needed, diodes for rectification and freewheeling, capacitors for filtering, a crystal oscillator for microcontroller clock generation, and a 7805 regulator IC to provide a regulated 5 V DC supply to logic circuits.

3.3 Protection and Safety Elements

Protection is implemented through a combination of mechanical and electrical devices. A 32 A single-pole miniature circuit breaker (MCB) is installed at the input to protect against overcurrent and short-circuit conditions, replacing traditional fuse-based protection and allowing easy reset after fault clearance. A 1 A control fuse safeguards the microcontroller card, LM324 circuit, display, and sensing components against abnormal currents.

Two limit switches are placed at the mechanical extremes of the variac rotation range to prevent over-travel of the servo motor and avoid mechanical damage to the brush and gear mechanism. High-current input and output connectors rated at around 30 A ensure safe and reliable connection to the mains and the load. Proper wiring using multi-strand copper conductors, with power and control circuits separated and appropriately gauged, contributes to safe operation and reduced losses.

An RC filter network is used to smooth signals and attenuate high-frequency noise in the sensing and control paths, improving stability of the regulation loop.

4. OPERATING PRINCIPLE AND CONTROL STRATEGY

The stabilizer operation can be understood as a closed-loop feedback system with the microcontroller at its core. The control algorithm proceeds in several steps, corresponding to sensing, decision, actuation, and protection.

4.1 Voltage Sensing and Error Detection

The incoming 230 V AC supply is first stepped down to 12 V AC by the sensing transformer, then rectified and filtered to obtain a scaled DC representation of the line voltage. The microcontroller, directly or through LM324 comparator stages, compares this sensed value against a predefined reference corresponding to 230 V nominal output. The same or an additional sensing path can be used to monitor the actual output voltage after compensation.

When the measured voltage deviates beyond an allowable band, an error condition is detected. If the voltage is below the lower threshold, the system interprets it as undervoltage; if it exceeds the upper threshold, it is treated as overvoltage.

4.2 Servo Control and Variac Adjustment

On detecting undervoltage, the microcontroller sends a control signal to drive the servo motor in a direction that increases the variac output, thereby boosting the voltage applied to the buck–boost transformer. Conversely, in an overvoltage condition, the motor is driven in the opposite direction to reduce the variac output. The dimmer gear provides fine mechanical resolution, allowing smooth variation without abrupt steps.

Limit switches at the mechanical ends of travel cut off motor drive if the variac reaches its minimum or maximum position, preventing damage due to over-rotation. The control logic ensures that the motor is only energized when correction is needed and for the duration required to bring the voltage back within the acceptable band, thus minimizing mechanical wear.

4.3 Buck–Boost Compensation and Load Connection

The output of the variac feeds the primary of the buck–boost transformer. Depending on the variac setting, the transformer injects a suitable series voltage to either add to or subtract from the supply, resulting in a nearly constant 230 V at the output terminals. The corrected voltage is then passed through a 40 A contactor or power relay before powering the load.

The microcontroller supervises the contactor via its control outputs. If input conditions exceed the designed correction range or if severe faults are detected, the controller de-energizes the relay, thereby disconnecting the load to prevent damage.

4.4 Protection and Fault Handling

The stabilizer incorporates multiple layers of protection. Overcurrent and short-circuits at the input are handled by the MCB, while the 1 A fuse protects sensitive control circuits. Overvoltage and undervoltage beyond permissible limits trigger automatic cutoff via the power relay. Overload conditions at the output can be detected by monitoring current (through shunt or CT) and processed in the microcontroller firmware to initiate disconnection.

The LCD provides user feedback on measured voltages, current, frequency, and system status (e.g., “OK”, “Overvoltage”, “Undervoltage”). This aids in diagnostics and verification of correct operation.

5. EXPERIMENTAL RESULTS

A prototype of the 5 kVA microcontroller-based servo voltage stabilizer was assembled using the hardware components described, and tests were conducted under laboratory conditions on a single-phase 230 V, 50 Hz supply. The setup included the control card with LCD, sensing transformer, variac and buck–boost transformer, servo motor with dimmer gear, contactor, MCB, fuses, and wiring mounted on a panel.

One representative test case recorded an input voltage of 198 V, significantly below the nominal 230 V level. The control circuit detected the undervoltage condition and commanded the servo motor to adjust the variac position, resulting in an output voltage stabilized at 230 V. The LCD display indicated: input voltage 198 V, output voltage 230 V, output current 0.00 A (no load), frequency 50 Hz, and status “OK”, confirming correct regulation and normal operating state.

Qualitatively, the system maintained a constant output voltage of approximately 230 V over a typical input range of about 170–270 V, as intended in the design. During operation, the servo motor adjustments were smooth, with no noticeable oscillations, and the buck–boost transformer delivered the required compensation. The contactor correctly isolated the load under simulated extreme conditions outside the designed regulation window.

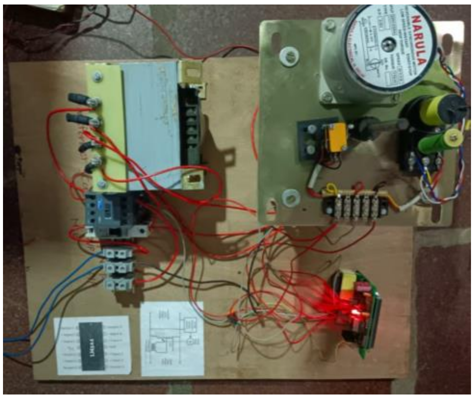

Fig-5.1 Layout.

Fig-5.2 Result for overvoltage

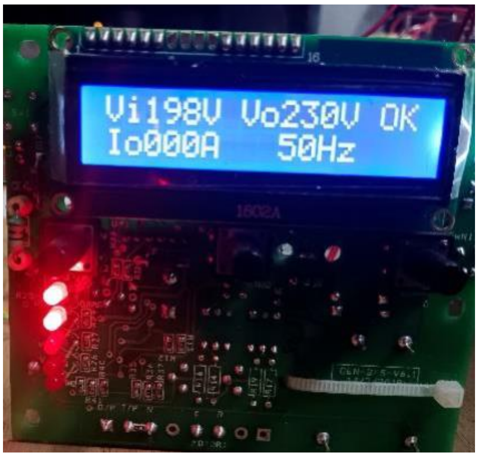

Fig-5.3 Result for undervoltage

From these observations, the following performance points can be noted:

- Accurate sensing of input fluctuations and appropriate control actions.
- Smooth servo operation with effective variac positioning.
- Effective stabilization of output voltage within a narrow band around 230 V.
- Correct display of real-time voltage, current, and frequency parameters.

Although detailed numerical efficiency data and dynamic response times were not fully quantified, the qualitative performance indicates that the prototype meets its intended function for medium-power single-phase loads.

6. APPLICATIONS AND FUTURE WORK

6.1 Application Areas

Owing to its 5 kVA rating and high regulation accuracy, the proposed stabilizer is suitable for a variety of use cases. In domestic settings, it can protect refrigerators, air conditioners, washing machines, televisions, audio systems, and personal computers from voltage fluctuations. In offices and IT environments, it ensures stable operation of PCs, printers, routers, servers, and communication equipment, reducing the risk of data loss and system crashes.

In industrial and commercial setups, it can be used with CNC machines, small industrial motors, PLC panels, testing and calibration benches, and medical diagnostic equipment such as X-ray units and ECG machines, where regulated supply is critical for accuracy and safety. Educational and research laboratories can also use the stabilizer to power experiments, measuring instruments, and microcontroller-based projects while protecting sensitive devices like oscilloscopes and precision supplies.

6.2 Future Work

Several enhancements can be envisioned for future versions of the stabilizer. The current microcontroller-based control can be upgraded to DSP or PLC platforms for faster computation, more advanced control algorithms, and richer data handling. A fully solid-state implementation using IGBTs, MOSFETs, or SCR-based converters could eliminate moving parts, improving response time and reducing maintenance.

Integration of IoT modules (Wi-Fi or GSM) would allow remote monitoring of input/output voltages, load current, and fault status, enabling predictive maintenance and cloud-based analytics. Adaptive or machine learning-based control schemes could automatically tune correction parameters according to line fluctuation patterns and load behavior, increasing efficiency.

The design can be extended from single-phase to three-phase versions for larger industrial and commercial installations. Further optimizations in magnetic design and packaging can yield more compact and modular systems with higher power density. Additional protection features such as surge and temperature protection with automatic fault indication and reset can enhance user safety and convenience, and adaptation to renewable energy systems (e.g., solar and hybrid supplies with variable outputs) would broaden the stabilizer's applicability.

7. CONCLUSION

This paper has presented the design, implementation, and testing of a 5 kVA single-phase microcontroller-based servo voltage stabilizer intended to improve power quality for sensitive loads. The system combines a servo-driven variac, a buck–boost transformer, and a microcontroller-based control card with LM324-based sensing to achieve smooth, continuous regulation around 230 V under varying input conditions.

The prototype incorporates comprehensive protection mechanisms, including MCB, fuses, limit switches, and intelligent cutoff logic, and provides user feedback through an LCD display. Experimental results demonstrate that the stabilizer maintains a constant output voltage within its designed operating range, validating the effectiveness of the proposed architecture for domestic, commercial, and small industrial applications up to 5 kVA.

By integrating electromechanical precision with digital intelligence, the stabilizer offers improved accuracy, faster response, reduced maintenance compared to traditional relay-based designs, and potential for further enhancement toward solid-state and IoT-enabled solutions. As such, it represents a practical and cost-effective approach to protecting modern electrical and electronic equipment from voltage-related disturbances.

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