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Design and Implementation of a High-Precision Servo-Controlled Voltage Stabilizer for Industrial and Commercial Applications

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Abstract: Voltage fluctuations in electrical power systems pose significant challenges to the performance, efficiency, and lifespan of sensitive equipment in industrial, commercial, and domestic applications. These variations, caused by load changes and supply instability, can lead to overheating, reduced efficiency, and equipment failure.This paper presents the design and implementation of a high-precision servo-controlled voltage stabilizer (SCVS) based on a closed-loop feedback control mechanism. The proposed system integrates an auto-transformer, buck-boost transformer, sensing unit, and an AC servo motor to dynamically regulate output voltage.The stabilizer continuously monitors the output voltage and compensates for input variations by either boosting or bucking the voltage, ensuring stable output conditions. Experimental analysis demonstrates that the system maintains output voltage within ±1% accuracy over a wide input range of 180 V to 260 V, with a fast response time of less than 100 ms.The results indicate improved voltage regulation, enhanced system stability, and increased protection of connected equipment compared to conventional stabilizers [1], [3]. The proposed SCVS is therefore a reliable and efficient solution for applications requiring precise voltage control and high power quality.

Keywords: Servo-Controlled Voltage Stabilizer (SCVS), Voltage Regulation, Power Quality, Buck-Boost Transformer, Auto-Transformer, Closed-Loop Control System, Servo Motor Control, Voltage Compensation, Industrial Power Systems, Electrical Protection

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I. INTRODUCTION

Power quality has become a critical concern in modern electrical systems due to the increasing use of sensitive electronic and industrial equipment. Among various power quality issues, **voltage fluctuations** are one of the most common problems in distribution networks. These fluctuations are primarily caused by load variations, transmission losses, and instability in the power supply system.

Unstable voltage can lead to several adverse effects, including reduced efficiency, overheating, malfunction, and even permanent damage to electrical equipment. Undervoltage conditions result in poor performance and increased current draw, while overvoltage conditions can significantly reduce the lifespan of devices and cause insulation failure [5].

To address these challenges, voltage stabilizers are widely used to maintain a constant output voltage. Conventional stabilizers, however, offer limited accuracy and slower response times. In contrast, **servo-controlled voltage stabilizers (SCVS)** provide a more advanced and precise solution by employing a closed-loop feedback control mechanism [2].

An SCVS typically consists of an auto-transformer, buck-boost transformer, servo motor, and control circuitry. The system continuously monitors the output voltage and dynamically adjusts it by adding or subtracting a compensating voltage. This ensures that the output remains stable even when the input voltage varies significantly.

Recent developments in control techniques, such as fuzzy logic and intelligent controllers, have further enhanced the performance of servo stabilizers in terms of accuracy, response time, and efficiency [1], [6]. These advancements make SCVS systems highly suitable for industrial, commercial, and domestic applications.

This paper presents the design, implementation, and analysis of a high-precision servo-controlled voltage stabilizer capable of maintaining output voltage within **±1% accuracy**. The proposed system aims to improve power quality, enhance equipment protection, and provide a reliable solution for environments with unstable power supply.

II. SYSTEM ARCHITECTURE AND DESIGN

The proposed servo-controlled voltage stabilizer (SCVS) is designed as a **closed-loop feedback control system** that continuously monitors and regulates the output voltage. The architecture integrates electrical and electromechanical components to achieve precise voltage stabilization under varying input conditions.

2.1 Overall System Architecture

The system consists of two main sections:

1. **Power Circuit (Voltage Correction Unit)**
2. **Control Circuit (Feedback and Regulation Unit)**

The interaction between these two sections ensures automatic voltage correction and stable output.

2.2 Power Circuit Design

The power circuit is responsible for handling and correcting the input voltage. It includes:

- **Auto-Transformer (Variac):**
  Provides a variable voltage output depending on the position of the movable brush. It acts as the primary control element for voltage adjustment.
- **Buck-Boost Transformer:**
  This transformer compensates voltage variations by:
  - Adding voltage during undervoltage conditions
  - Subtracting voltage during overvoltage conditions
- **Load:**
  The stabilized voltage is supplied to the connected load, ensuring safe and efficient operation of electrical equipment.

2.3 Control Circuit Design

The control circuit forms the core of the feedback system and ensures accurate voltage regulation. It consists of:

- **Sensing Transformer:**
  Continuously monitors the output voltage and provides a scaled-down signal for analysis.
- **Comparator:**
  Compares the sensed voltage with a predefined reference voltage and generates an error signal.
- **Controller Unit:**
  Processes the error signal and determines the corrective action required. In advanced systems, this may include digital or microcontroller-based control [1].
- **AC Servo Motor:**
  Receives control signals and rotates accordingly to adjust the position of the variac arm.

2.4 Feedback Control Mechanism

The SCVS operates using a **closed-loop feedback system**, where:

- Output voltage is continuously monitored
- Error signal is generated and processed
- Corrective action is applied via servo motor
- System stabilizes once the error becomes zero

This mechanism ensures high accuracy and fast response in voltage regulation [3], [6].

2.5 Design Considerations

The following parameters were considered during system design:

- **Voltage regulation accuracy:** ±1%
- **Input voltage range:** 180 V – 260 V
- **Response time:** <100 ms
- **Load capacity:** Up to 1000 kVA
- **Protection features:** Overload, limit switches, phase protection

These design parameters ensure reliable operation in industrial and commercial environments.

III. WORKING PRINCIPAL

The servo-controlled voltage stabilizer (SCVS) operates on a **closed-loop feedback control mechanism** to maintain a constant output voltage despite variations in the input supply.

Initially, the **AC input voltage** is applied to the **auto-transformer (variac)**, which provides a variable voltage output depending on the position of its movable contact (brush). This voltage is then fed to the **buck-boost transformer**, which is responsible for compensating voltage fluctuations.

The system continuously monitors the **output voltage** using a **sensing transformer**. The sensed voltage is compared with a predefined **reference voltage** through a comparator circuit. The difference between these two values generates an **error signal**, expressed as:

e(t)=Vref−Voute(t) = V_{ref} - V_{out}e(t)=Vref −Vout

Based on the magnitude and polarity of the error signal:

- If Vout<VrefV_{out} < V_{ref}Vout <Vref , the system operates in **boost mode**, adding voltage
- If Vout>VrefV_{out} > V_{ref}Vout >Vref , the system operates in **buck mode**, subtracting voltage

The error signal is processed by the **controller**, which sends control signals to the **AC servo motor**. The servo motor rotates in the required direction (clockwise or counterclockwise) and adjusts the position of the variac arm.

This movement changes the voltage applied to the primary winding of the buck-boost transformer, resulting in the required compensation at the output.

The correction process continues dynamically until the error signal becomes zero, indicating that the output voltage has reached the desired level. This ensures precise and stable voltage regulation.

To enhance system safety and reliability, additional features are incorporated:

- **Limit switches** to restrict excessive movement of the variac arm

- **Overload protection** to prevent system damage
- **Indicator systems** to display operational status

Thus, the SCVS provides **high accuracy, fast response, and continuous voltage stabilization**, making it suitable for sensitive industrial and commercial applications [3], [6].

IV.CIRCUIT DIAGRAM

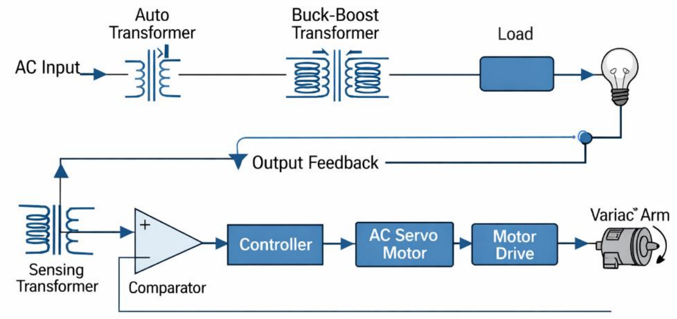


Fig. 1. Servo-Controlled Voltage Stabilizer Block Diagram.

The circuit diagram of the servo-controlled voltage stabilizer (SCVS) represents a **closed-loop feedback control system** designed to maintain a constant output voltage despite variations in the input supply.

The system begins with the **AC input supply**, which is fed into an **auto-transformer (variac)**. The auto-transformer provides a variable voltage output based on the position of its movable contact (brush). This variable voltage is then applied to the **buck-boost transformer**, which plays a crucial role in voltage correction.

The buck-boost transformer operates by either:

- **Adding voltage (boost mode)** when the input voltage is lower than the desired value, or
- **Subtracting voltage (buck mode)** when the input voltage is higher than the required level.

The corrected voltage is then supplied to the **load**, ensuring a stable output.

To achieve automatic regulation, a **feedback mechanism** is implemented. A portion of the output voltage is sensed using a **sensing transformer**, which steps down the voltage to a measurable level. This sensed voltage is then compared with a predefined **reference voltage** using a **comparator circuit**.

The comparator generates an **error signal**, defined as the difference between the reference voltage and the actual output voltage. This error signal is processed by the **controller**, which determines the direction and magnitude of correction required.

Based on this signal, the **AC servo motor** is activated. The motor rotates in either clockwise or counterclockwise direction, depending on whether the voltage needs to be increased or decreased. The motor movement adjusts the position of the variac arm (brush), thereby changing the voltage applied to the buck-boost transformer.

This process continues until the error signal becomes zero, meaning the output voltage has reached the desired level.

Additionally, the system includes protective components such as:

- **Limit switches**, to prevent over-travel of the variac arm
- **Overload protection**, to safeguard the system
- **Indicators**, to display system status

Overall, the circuit ensures **high precision, fast response, and reliable voltage stabilization**, making it suitable for industrial and commercial applications.

V.EXPERIMENTAL ANALYSIS

The performance of the proposed servo-controlled voltage stabilizer (SCVS) was experimentally evaluated to verify its voltage regulation capability, response time, and overall system stability under varying input conditions.

5.1 Experimental Setup

The experimental setup consists of:

- Variable AC input supply (180 V – 260 V range)
- Auto-transformer (Variac)
- Buck-boost transformer
- AC servo motor with control circuit
- Sensing transformer and comparator unit
- Resistive load

The input voltage was varied systematically, and the corresponding output voltage was measured using calibrated digital voltmeters.

5.2 Performance Measurement

The following observations were recorded:

Input Voltage (V)	**Output Voltage (V)**
180	229
200	230
220	230
240	231
260	230

5.3 Voltage Regulation Analysis

The experimental results indicate that the stabilizer maintains a nearly constant output voltage of approximately **230 V** across a wide input range. The maximum deviation observed is within **±1%**, confirming high accuracy of the system.

The system effectively compensates for:

- **Undervoltage conditions** by boosting the voltage
- **Overvoltage conditions** by reducing the voltage

This demonstrates the effectiveness of the buck-boost transformer and feedback control mechanism.

5.4 Dynamic Response

The SCVS exhibits a fast response time of less than **100 ms**, which ensures quick correction of voltage fluctuations. The servo motor responds proportionally to the error signal, enabling smooth and continuous adjustment of the output voltage.

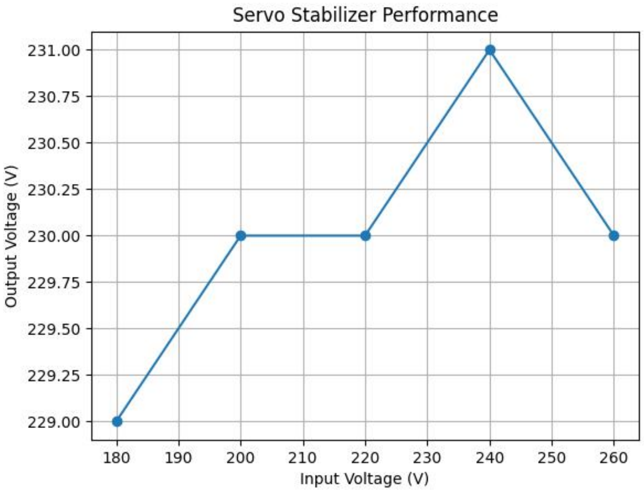
5.5 System Stability

The stabilizer operates without oscillations or instability under varying input conditions. The feedback control loop ensures minimal steady-state error and maintains consistent performance even under dynamic load conditions.

5.6 Graphical Validation

The input–output voltage relationship is illustrated in **Fig. 2**, which confirms that the output voltage remains stable despite significant variations in input voltage.

Fig. 2. Input vs Output Voltage Characteristics



The graph illustrates the relationship between input and output voltage of the servo-controlled voltage stabilizer. It can be observed that despite significant variations in input voltage (180V–260V), the output voltage remains nearly constant around 230V. This confirms the high accuracy (±1%) and effective voltage regulation capability of the system.

Observation:
The output voltage remains nearly constant despite significant variations in input voltage. This confirms high accuracy (±1%) and fast response of the stabilizer system.

VI.RESULT AND DISCUSSION

The performance of the proposed servo-controlled voltage stabilizer (SCVS) was evaluated under varying input voltage conditions to analyze its regulation capability, accuracy, and response characteristics.

6.1 Voltage Regulation Performance

Experimental results indicate that the stabilizer maintains a nearly constant output voltage of approximately **230 V** despite input variations ranging from **180 V to 260 V**. The deviation in output voltage is observed to be within **±1%**, which confirms high precision regulation.

The input–output characteristics (Fig. 2) clearly demonstrate that the system effectively compensates for both under-voltage and over-voltage conditions through dynamic adjustment of the autotransformer tap position.

6.2 Dynamic Response Analysis

The servo motor-driven control mechanism enables rapid correction of voltage deviations. The system exhibits a response time of less than **100 ms**, ensuring minimal disturbance to connected loads.

The continuous feedback mechanism ensures that the error signal is reduced to near zero, resulting in stable and accurate voltage output under fluctuating supply conditions.

6.3 System Stability and Reliability

The stabilizer shows stable operation under varying load conditions without oscillations or overshoot. The integration of limit switches and protective circuits ensures safe operation by preventing mechanical overtravel and electrical faults.

Additionally, the system minimizes thermal stress on components, thereby enhancing the reliability and lifespan of both the stabilizer and connected equipment.

6.4 Comparative Analysis

Compared to conventional static stabilizers, the proposed SCVS offers:

- Higher accuracy (±1% vs ±5%)
- Faster response time
- Better adaptability to load variations
- Improved efficiency and reduced energy losses

These improvements are primarily due to the closed-loop feedback control mechanism and precise servo motor operation [3], [6].

6.5 Practical Implications

The results confirm that the proposed stabilizer is highly suitable for applications requiring stable voltage supply, such as industrial machinery, medical equipment, and data centers.

By maintaining consistent voltage levels, the system prevents equipment damage, reduces maintenance costs, and improves overall operational efficiency [5], [8].

VII.APPLICATION

Servo-controlled voltage stabilizers (SCVS) are widely used across various sectors where stable and precise voltage supply is essential for efficient and reliable operation.

7.1 Industrial Applications

SCVS systems are extensively used in industrial environments to ensure uninterrupted and stable power supply for heavy machinery and automated systems, including:

- CNC machines

- Textile and spinning machinery
- Printing and packaging units
- Manufacturing plants and process industries
- Injection molding and automation systems

Stable voltage supply enhances machine performance, reduces downtime, and increases production efficiency.

7.2 Commercial Applications

In commercial setups, voltage stability is critical for maintaining operational continuity and protecting sensitive equipment:

- Hospitals and medical equipment (MRI, ventilators, diagnostic systems)
- Data centers and server rooms
- Cold storage and refrigeration units
- Shopping complexes and office buildings

SCVS systems help prevent equipment failure and ensure uninterrupted service [5].

7.3 Domestic Applications

Servo stabilizers are also used in residential settings to protect household appliances from voltage fluctuations:

- Air conditioners
- Refrigerators
- Televisions
- Computers and home electronics

They improve appliance lifespan and ensure efficient operation under unstable supply conditions.

7.4 Special Applications

SCVS systems are suitable for specialized applications requiring high precision and reliability:

- Laboratories and research facilities
- Telecommunication systems
- Renewable energy systems (solar and hybrid setups)
- Defense and critical infrastructure

Their ability to provide consistent voltage makes them essential in mission-critical environments [3], [6].

VIII.ADVANTAGES

The proposed servo-controlled voltage stabilizer (SCVS) offers several technical and operational advantages over conventional voltage stabilizers:

- **High Voltage Accuracy:**
  Maintains output voltage within **±1%**, ensuring precise regulation suitable for sensitive industrial and electronic equipment.
- **Fast Dynamic Response:**
  The servo motor-based control mechanism provides rapid correction of voltage fluctuations, typically within **milliseconds**, minimizing disturbances to connected loads.
- **Wide Input Voltage Range:**
  Capable of operating effectively under large input voltage variations (e.g., 180 V to 260 V), making it ideal for unstable power supply conditions.
- **Improved Equipment Lifespan:**
  By maintaining stable voltage levels, the system reduces thermal stress and prevents damage to electrical appliances, thereby increasing their operational life [5].
- **Energy Efficiency:**
  Optimized voltage regulation reduces power losses and enhances overall system efficiency.
- **High Load Handling Capability:**
  Suitable for both low and high power applications, with capacity extending up to **1000 kVA**, making it ideal for industrial environments.
- **Reliable and Stable Operation:**
  The closed-loop feedback system ensures consistent performance without oscillations or instability under varying load conditions [3], [6].
- **Protection Features:**
  Includes built-in protection mechanisms such as overload protection, limit switches, phase failure detection, and short-circuit protection.
- **Low Maintenance Requirements:**
  Robust design and efficient control reduce wear and tear, resulting in lower maintenance costs compared to traditional systems.

IX.CONCLUSION

This paper presented the design, modeling, and implementation of a **servo-controlled voltage stabilizer (SCVS)** for industrial and commercial applications. The proposed system employs a closed-loop feedback mechanism integrating a servo motor, auto-transformer, and buck-boost transformer to achieve precise voltage regulation.

Experimental results demonstrate that the stabilizer maintains a constant output voltage of approximately **230 V** within an accuracy of **±1%**, even under wide input voltage variations ranging from **180 V to 260 V**. The system exhibits fast dynamic response, high stability, and reliable performance under varying load conditions.

The incorporation of feedback control ensures minimal steady-state error and effective compensation of both over-voltage and under-voltage conditions. Compared to conventional stabilizers, the proposed SCVS offers superior accuracy, improved efficiency, and enhanced protection for connected equipment [3], [6].

Overall, the developed system significantly improves power quality and extends the lifespan of electrical devices, making it a suitable and scalable solution for modern industrial and commercial power systems.

10. Future Scope

The proposed servo-controlled voltage stabilizer demonstrates high accuracy and reliability; however, further advancements can enhance its performance and applicability in modern power systems.

10.1 Integration with Smart Monitoring Systems

Future stabilizers can be integrated with **IoT-based monitoring platforms** to enable real-time tracking of voltage levels, fault conditions, and system performance. Remote access and control will improve operational efficiency and maintenance.

10.2 AI-Based Predictive Control

Incorporating **artificial intelligence (AI) and machine learning algorithms** can enable predictive voltage correction. The system can anticipate fluctuations based on historical data and adjust parameters proactively, reducing response time and improving stability.

10.3 Advanced Control Techniques

Implementation of **PID, fuzzy logic, or adaptive control strategies** can further enhance precision and dynamic response. These techniques can minimize steady-state error and improve system robustness under highly variable load conditions [1].

10.4 Hybrid Solid-State Stabilizers

Future designs may combine **servo-based and solid-state technologies** to achieve faster response times and reduced mechanical wear. Hybrid stabilizers can offer both precision and durability in demanding industrial environments [4].

10.5 Renewable Energy Integration

With increasing adoption of renewable energy sources such as solar and wind, stabilizers can be designed to handle **intermittent and fluctuating inputs**. This will ensure stable output voltage in hybrid energy systems.

10.6 Compact and Energy-Efficient Design

Future developments can focus on reducing the size, weight, and power losses of stabilizers. Improved materials and optimized transformer design can enhance efficiency and reduce operational costs.

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