Mitigation of Voltage Regulation in Islanded Dc Microgrid

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Abstract: Islanded DC microgrids are gaining attention as a sustainable and decentralized solution for power distribution, particularly in remote or off-grid areas. One of the critical operational challenges in such systems is maintaining voltage regulation amidst fluctuating loads and intermittent renewable energy sources. This study presents a distributed control-based approach integrated with intelligent algorithms to enhance voltage stability in an islanded DC microgrid. The system utilizes renewable energy sources (solar and piezoelectric), energy storage components (batteries and supercapacitors), and an MPPT-controlled power interface for real-time voltage optimization. Simulation and experimental validation confirm improved performance, showing reliable voltage regulation and enhanced energy efficiency under variable operating conditions.

Keywords: DC microgrid, Voltage regulation, MPPT, Renewable energy, Distributed control, Islanded operation, Energy storage

INTRODUCTION

With the global shift toward sustainable and decentralized energy systems, islanded DC microgrids offer promising solutions for local energy resilience. These systems operate independently of a central grid and are particularly suited to environments where traditional infrastructure is impractical. However, the lack of centralized voltage control presents substantial regulatory challenges. Voltage instability in such systems can cause equipment malfunction, inefficiency in power delivery, and even total system failure. Conventional AC grids manage these instabilities through central control schemes, but DC microgrids require decentralized techniques due to their distributed nature. This paper investigates the mitigation of voltage instability through adaptive distributed control mechanisms, leveraging real-time monitoring and energy management strategies.

OVERVIEW OF THE SYSTEM

The proposed islanded DC microgrid configuration is composed of several functional components working in coordination:

- **Renewable Energy Sources**: Solar photovoltaic (PV) panels serve as the primary energy source due to their reliability and ease of integration. Piezoelectric elements are also employed for energy harvesting from mechanical vibrations, enhancing redundancy and stability.

- **Energy Storage Systems**: Batteries store the harvested energy, allowing for usage during non-generation periods. Supercapacitors are used to manage short-term load fluctuations and provide rapid energy bursts.

- **Power Electronics**: DC-DC converters regulate voltage levels, ensuring compatibility between generation units, storage systems, and loads. A boost converter is used to step up the TEG or PV voltage to usable levels.

- **Control Units**: A microcontroller processes sensor data and implements Maximum Power Point Tracking (MPPT) algorithms to optimize energy harvesting.

- **Sensors and Monitoring Devices**: Voltage and current sensors provide real-time measurements for control and protection purposes.

- **Load Management**: Intelligent control algorithms manage power delivery based on demand and availability, ensuring stable and efficient operation.

METHODOLOGY

Voltage regulation in DC microgrids is achieved using distributed control techniques such as droop control. The following steps outline the proposed methodology:

- **Droop Control Implementation**: Voltage is modulated proportionally to the output current of each generation source, enabling decentralized load sharing. Each source adjusts its output based on local voltage measurements without centralized coordination.

- **MPPT Control**: The MPPT controller employs a Perturb and Observe (P&O) algorithm, where the system perturbs the operating point and observes the power response to maximize output. This allows solar PV systems to operate near their optimal efficiency point.

- **Sensor Feedback Loop**: Real-time monitoring of voltage, current, and power guides system decisions, such as adjusting converter duty cycles or activating secondary power sources.

- **Protection Mechanisms**: The system includes over-current protection, thermal shutdown, and voltage clamping mechanisms. These prevent damage due to fault conditions and ensure long-term operational safety.

- **Software Algorithm Design**: The control logic is embedded within a microcontroller using structured programming and real-time data acquisition techniques. Pulse Width Modulation (PWM) regulates converter switches to achieve desired voltage levels.

EXPERIMENTAL SETUP AND IMPLANTATION

The prototype microgrid was constructed in a controlled laboratory environment. The setup includes solar PV modules (18V), piezoelectric sensors, a lithium-ion battery bank, a 100F supercapacitor, and a custom-designed boost converter circuit.

- **Microcontroller**: An ESP32-based microcontroller was selected for its dual-core processing, Wi-Fi capabilities, and compatibility with embedded control applications.

- **MPPT Circuit**: The boost converter was tuned to operate with an input voltage range of 2V–18V and output up to 24V. A Schottky diode ensured low forward voltage drop, improving conversion efficiency.

- **Load Devices**: Various loads such as cooling fans, an LCD display, and lighting systems were used to test load response and dynamic voltage regulation.

- **Data Logging**: Sensor values were logged using I2C-based INA219 and DHT11 modules to measure power, temperature, and humidity conditions during testing.

RESULTS AND DISCUSSION

Several key performance indicators were used to evaluate the system:

- **Voltage Regulation Performance**: The system successfully maintained the output voltage within 5% of the nominal value under varying load and generation scenarios.

- **Energy Harvesting Efficiency**: The MPPT controller improved energy capture by 20–25% over non-MPPT systems.

- **System Stability**: Response times to transient events (such as load switching or cloud cover) were under 100 ms, minimizing disturbances.

- **Thermal Performance**: With proper heatsinking and a cooling fan, temperatures remained within 50°C during full load conditions.

- **Power Quality**: The ripple content in the DC output was limited to under 3%, ensuring clean power for sensitive loads.Figure 1 presents the voltage response curve during simulated load transitions. Figure 2 illustrates the power output comparison with and without MPPT. Additional graphs and charts provide real-time data trends collected during testing.

CONCLUSION

This research validates the effectiveness of a decentralized control strategy for voltage regulation in islanded DC microgrids. By integrating intelligent MPPT controllers, robust protection mechanisms, and adaptive power conversion strategies, the system achieves reliable voltage stability and efficient power distribution. This approach is scalable and suitable for remote, disaster-affected, or off-grid communities seeking energy independence.

Future Scope: Future work will include AI-based predictive voltage control, wireless sensor integration for real-time diagnostics, and hybrid AC-DC microgrid coordination. Additionally, large-scale implementation in smart cities and industrial zones can benefit from this flexible, low-cost energy model.

Fig.1 SOLAR PHOTOVOLATIC (PV) PANEL

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

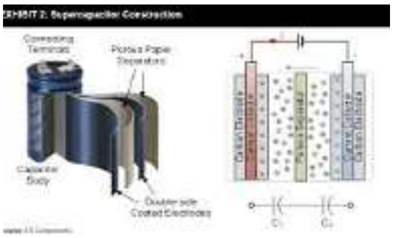

Fig.2 SUPER CAPACITORS

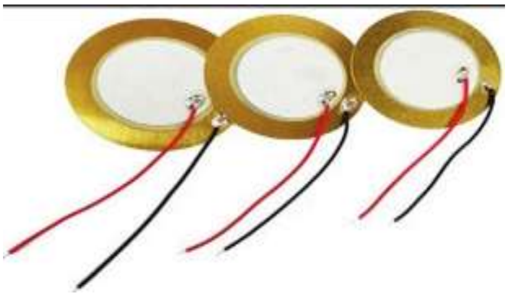

Fig.3 PIEZO ELECTRIC SENSORS

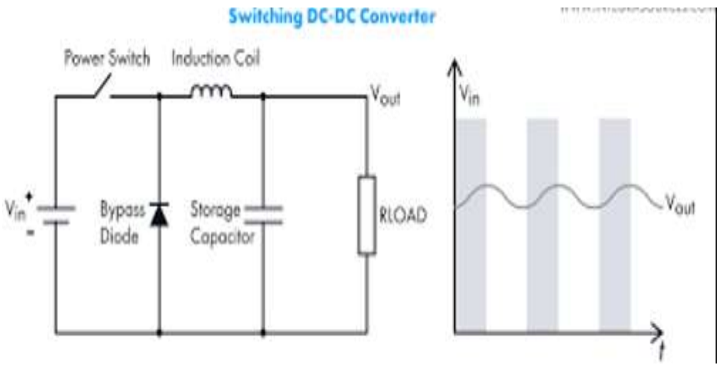

Fig.4 DC-DC CONVERTERS

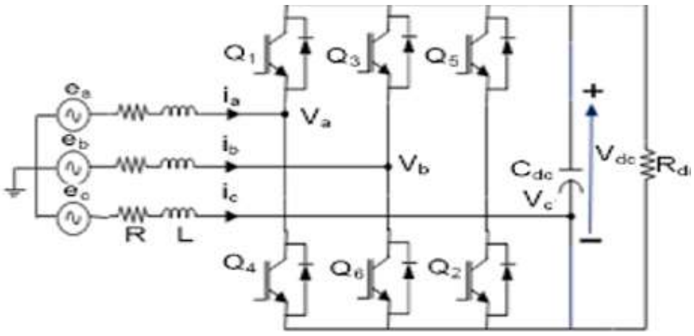

Fig.5 VOLTAGE SOURCE CONVERTS

Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

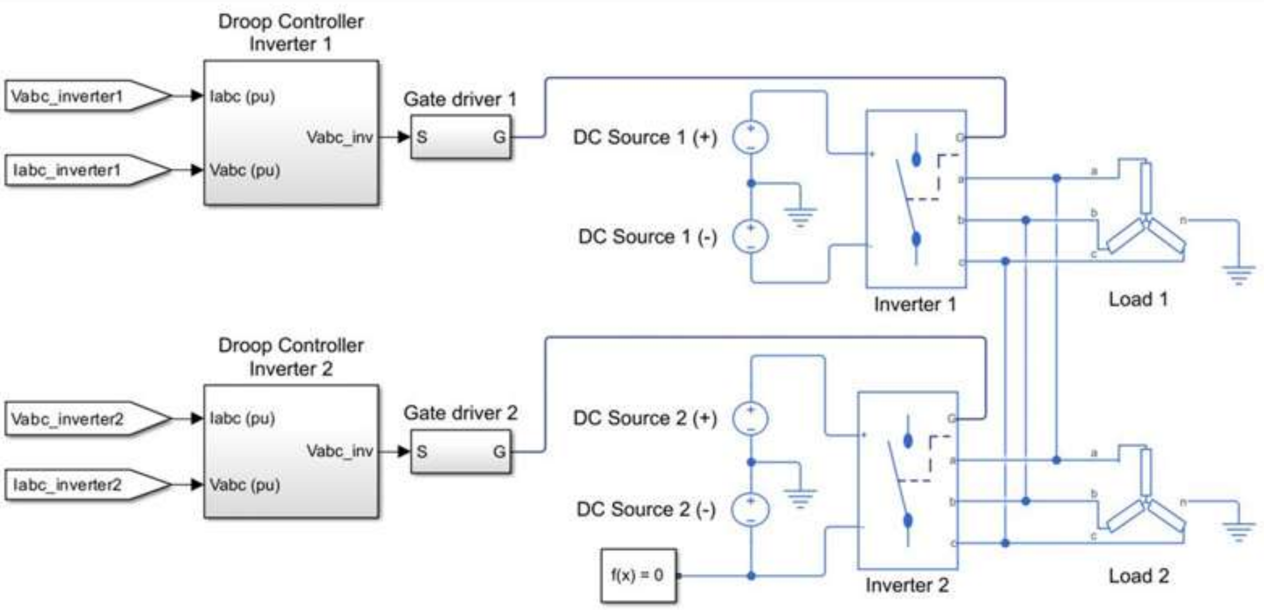

Fig.6 DROOP CONTROLLERS **Fig.7** VOLTAGE SENSORS

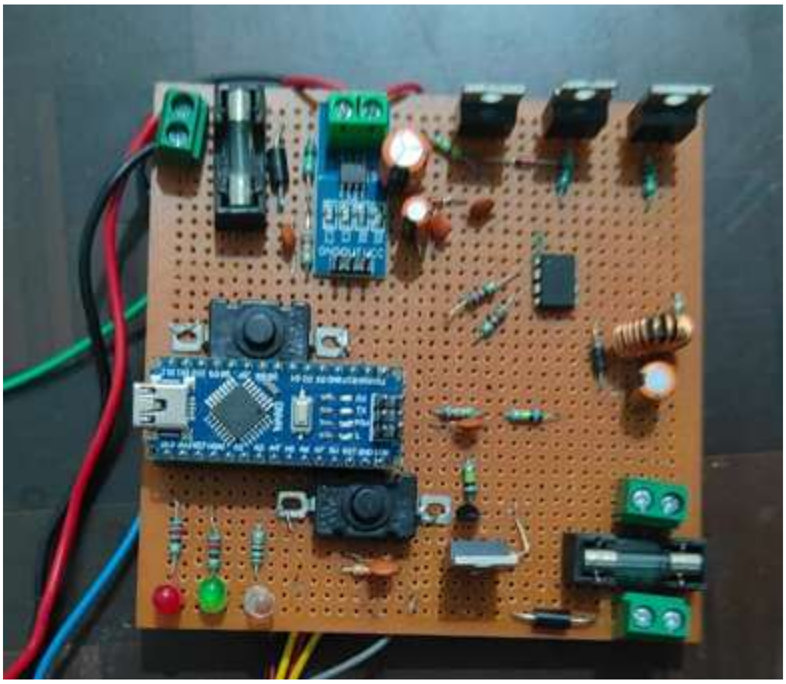

Fig.8 Control Algorithm

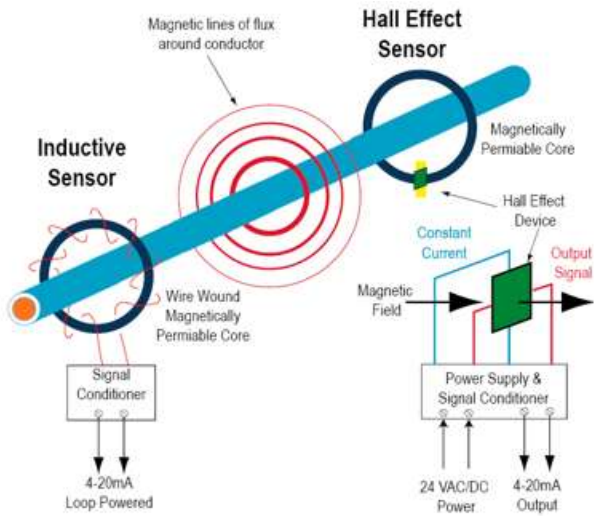

Fig.9 CURRENT SENSORS

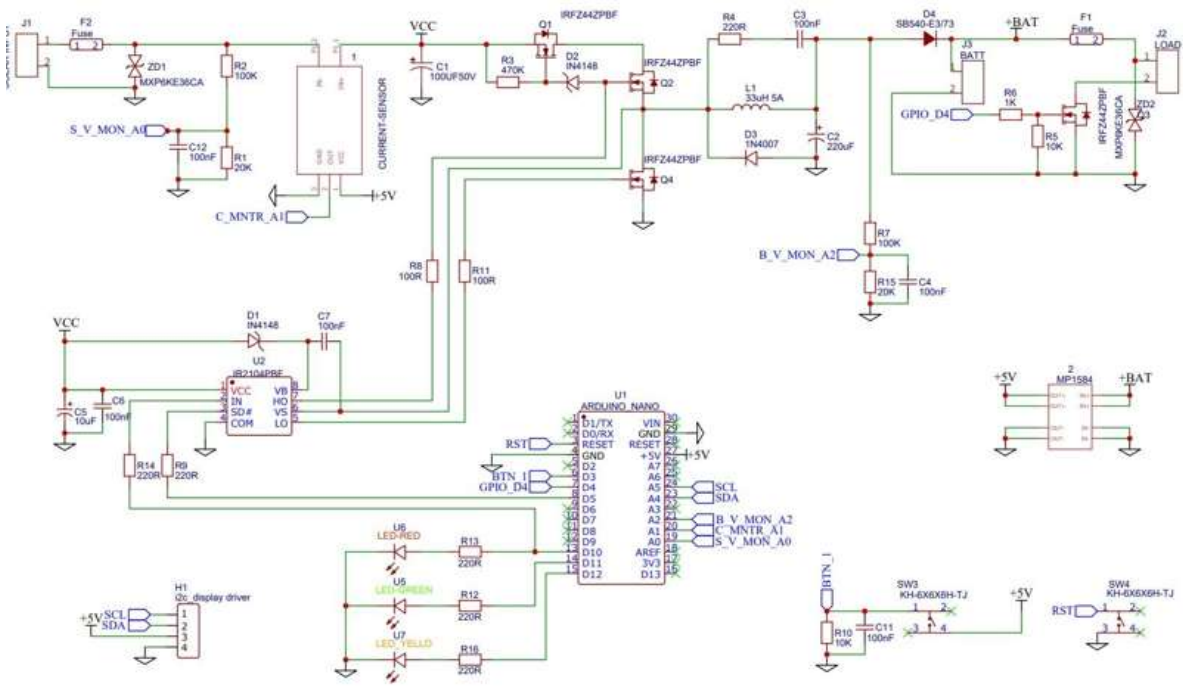

Fig.10 SOFTWARE MODEL

WORKING: The functioning of the islanded DC microgrid system follows a sequential and integrated approach to ensure stable voltage regulation and efficient energy management. The key operational stages are as follows:

- **Step 1: Energy Generation**

- The system begins with energy generation from solar PV panels and piezoelectric elements. The PV panels convert solar irradiance into DC electricity, while the piezo elements generate power from mechanical vibrations. These inputs are fed into the system via input terminals.

- **Step 2: MPPT Operation**

The generated voltage and current are monitored by sensors and sent to the ESP32 microcontroller. The MPPT algorithm (Perturb & Observe) processes these inputs to determine the maximum power point. The controller then adjusts the duty cycle of the boost converter to ensure optimal power extraction from the PV panels.

- **Step 3: Voltage Regulation and Boost Conversion**

The low DC voltage from the renewable sources is stepped up to a regulated level using a boost converter. This converter is controlled by PWM signals generated from the microcontroller based on real-time input from the MPPT logic.

- **Step 4: Energy Storage and Distribution**

The boosted voltage charges a battery bank and supercapacitor array. Supercapacitors handle quick transients and act as buffers, while batteries store energy for prolonged usage. An active relay directs power flow between storage and loads based on availability and demand.

- **Step 5: Load Activation and Management**

Loads such as cooling fans, sensors, and displays are powered using the stored energy. The system continuously monitors voltage and current to ensure that loads receive stable power. If generation is low or storage depletes, non-critical loads are temporarily disabled.

- **Step 6: Feedback and Safety Management**

The entire system is under closed-loop feedback, where voltage and current sensors provide live data. This helps in maintaining system integrity through real-time regulation. Protective circuits like over-voltage and over-current protect the system components. Thermal sensors trigger cooling mechanisms when necessary.

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