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Design and Implementation of a Virtual Synchronous Generator Control System for Power Electronic Inverters Interfaced with Energy Storage Systems

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Abstract - **The integration of power electronic inverters with energy storage systems presents challenges in maintaining voltage stability and frequency control, functions traditionally managed by synchronous generators in power grids. To address these challenges, Virtual Synchronous Generator (VSG) control systems have been proposed as a viable solution. This study aims to design and implement a VSG control system for power electronic inverters interfaced with energy storage systems and to evaluate its performance compared to inverters lacking VSG controls. The VSG control scheme was developed using virtual inertia control, damping control, and active control mechanisms to emulate the behavior of conventional synchronous generators. The system was tested for its ability to maintain stable input and output voltage, regulate output load, manage battery capacity, and stabilize input frequency and temperature under varying operational conditions. The VSG control system effectively maintained voltage stability and frequency control, demonstrating superior stability and reliability compared to inverter systems without VSG controls. The findings indicate that implementing VSG control in inverters is essential for ensuring voltage stability and frequency regulation in microgrids. Future research should focus on optimizing VSG control schemes for various load conditions and system configurations to enhance their applicability across diverse scenarios.**
Keywords: **Virtual Synchronous Generator (VSG), Power Electronic Inverters, Energy Storage Systems, Voltage Stability, Frequency Control**

I. INTRODUCTION

Power electronic inverters interfaced with energy storage systems play a crucial role in modern power grids [1], providing a flexible and efficient means of integrating renewable energy sources, stabilizing grid operations, and enhancing overall system reliability. The integration of energy storage with inverters enables the storage of excess energy during periods of low demand and its release during peak demand [2], effectively mitigating the intermittency of renewable energy sources such as solar and wind. This capability is essential for maintaining grid stability and ensuring a consistent power supply to consumers.

One of the key advancements in this field is the implementation of Virtual Synchronous Generator (VSG) control, which introduces a new dimension to the operation of power electronic inverters interfaced with energy storage systems [3]. Traditionally, synchronous generators have served as the backbone of power systems [4], providing inertia and stability to the grid.

However, with the increasing penetration of renewable energy and the integration of energy storage, the need for alternative stability solutions has become evident. VSG control addresses this need by emulating the behavior of synchronous generators through power electronic inverters and energy storage systems. It enables inverters to mimic key characteristics of synchronous generators, such as inertia and damping [5], thereby enhancing grid stability, improving fault ride-through capability, and supporting ancillary services such as frequency regulation and voltage control.

Consequently, the integration of VSG control with power electronic inverters and energy storage systems represents a significant advancement toward a more resilient and sustainable power grid. This study compares the performance of the VSG control scheme with inverter systems lacking such controls, emphasizing their impact on voltage and frequency stability.

II. STATEMENT OF THE PROBLEM

Microgrids, consisting of power electronic inverters interconnected with energy storage systems, have been reported to experience stability issues. While some studies attribute inadequate performance to a lack of expertise, others associate the challenges observed in power electronic inverters interfaced with energy storage systems with the absence of inherent inertia response in converter-based distributed generators.

The absence of rotating masses in these systems necessitates the implementation of virtual inertia to enhance stability. However, the key challenge lies in developing an effective control scheme, such as the Virtual Synchronous Generator (VSG), capable of emulating the behavior of a conventional synchronous generator and mitigating frequency fluctuations and voltage variations in microgrids. This necessity serves as the primary motivation for this study.

III. AIM AND OBJECTIVES OF THE STUDY

This study aimed to evaluate and compare the performance of the Virtual Synchronous Generator (VSG) control scheme with that of an inverter system in a power grid lacking such controls.

Specifically, the objectives were to:

1. Design a VSG control scheme for power electronic inverters coupled with energy storage units.
2. Evaluate the performance and stability of the VSG control scheme in comparison to an inverter system without VSG controls.

A. Research Questions:

1. How can a Virtual Synchronous Generator (VSG) control scheme be effectively designed and implemented in power electronic inverters?
2. What are the performance differences between a system utilizing VSG control and an inverter system without such controls in terms of frequency and voltage stability?

IV. LITERATURE REVIEW

Microgrids, which integrate power electronic inverters with energy storage systems, have garnered substantial attention for their ability to enhance the resilience and efficiency of power distribution networks [6]-[8]. However, the increasing complexity of these systems has introduced stability challenges, sparking considerable debate among researchers regarding their causes and potential solutions [9]-[13]. One perspective attributes microgrid stability issues primarily to a lack of expertise in designing and implementing these intricate systems.

Choudhury [14] acknowledges that the complex interplay between power electronic inverters and energy storage systems necessitates a comprehensive understanding of control strategies and system dynamics, which may not always be adequately achieved. This viewpoint aligns with the notion that improving training and knowledge dissemination for engineers and designers is essential to effectively address stability concerns as microgrids become more prevalent and complex.

Another perspective suggests that stability challenges in power electronic inverters interfaced with energy storage systems stem from the inadequate or entirely absent inertia response in converter-based distributed generators [15]-[19]. Unlike traditional synchronous generators, which naturally exhibit inertia due to their rotating masses, converter-based systems lack this inherent stability.

To mitigate this deficiency, the implementation of virtual inertia has been proposed to replicate the stabilizing effects typically provided by synchronous generators. Saffar [18] and Suvorov *et al.,* [19] emphasize the importance of Virtual Synchronous Generators (VSGs) in mimicking the inertial response of traditional synchronous generators, thereby addressing the stability challenges associated with the absence of rotating masses in modern microgrids.

VSGs are designed to emulate the characteristics of synchronous generators by providing inertia and damping to the grid, thus stabilizing frequency fluctuations. Studies by Rehman *et al.,* [20] and Mallemaci *et al.,* [21] reinforce these findings, demonstrating that VSGs enhance frequency regulation stability compared to conventional inverter systems lacking such controls.

Comparative analyses by Da Silva *et al.,* [22] and Cheema *et al.,* [23] further support this conclusion, showing that VSGs outperform traditional inverter-based systems in maintaining grid frequency and damping oscillations. The limitations of conventional inverter controls-stemming from their lack of dynamic response capabilities-are highlighted by Ramaprabha and Rithika [24].

This underscores the importance of incorporating virtual inertia through advanced control schemes to enhance microgrid stability, particularly as the integration of renewable energy sources increases. The ongoing debate regarding effective microgrid control strategies has led to advocacy for VSGs as a potential solution.

Kumar *et al.,* [25] argue that adopting VSGs as a control strategy can effectively emulate the behavior of synchronous generators in converter-based distributed generators, addressing inherent stability concerns. However, some researchers, including Ahmed *et al.,* [26], suggest exploring alternative control schemes and comparing their effectiveness in ensuring microgrid stability. Recent studies have further investigated the role of VSGs in improving microgrid stability. For instance, Pournazarian *et al.,* [27] propose an enhanced voltage and frequency control strategy using an Advanced Virtual Synchronous Generator (AVSG) model designed for islanded microgrids. Yap *et al.,* [28] review the effectiveness of VSGs in improving grid-connected microgrid performance, particularly in frequency and voltage control.

Additionally, Idan *et al.,* [29] explore techniques for stabilizing grid frequency through virtual inertia integration via energy storage and power electronic converters, while Harasis and Sozer [30] focus on stabilizing the frequency of grid-feeding active distributed generators using active damping control.

While these studies highlight the critical role of VSG control in enhancing stability and regulating frequency and voltage within microgrids, a gap remains in the literature regarding the specific regulation of voltage and frequency through droop control methods in grid-connected microgrids. Further research in this area is necessary to optimize the stability and performance of future microgrid systems.

V. THEORETICAL FRAMEWORK

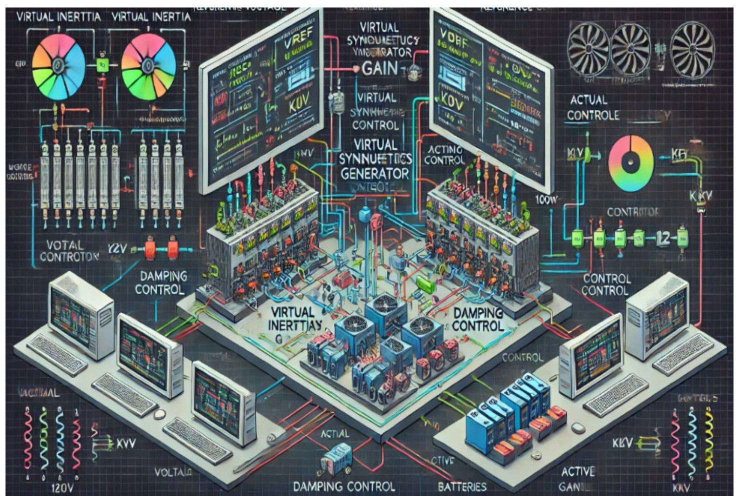
In 2021, Ambia *et al.,* [21] proposed the virtual synchronous generator (VSG) theory, which revolutionized the control of power electronic inverters interfaced with energy storage systems (ESS). The VSG theory treats the inverter and ESS as a virtual synchronous machine, enabling the use of conventional synchronous machine control techniques. This approach improves the stability and performance of the system, allowing for more efficient and reliable operation [21].

The VSG theory is highly relevant to the design and implementation of virtual synchronous generator control systems for power electronic inverters interfaced with ESS, as it provides a powerful framework for achieving optimal control and coordination between the inverter and ESS. By leveraging the VSG theory, engineers can develop more advanced and sophisticated control strategies, leading to improved system performance and reliability.

VI. MATERIALS AND METHODS

This study involved designing and implementing a virtual synchronous generator (VSG) control scheme in power electronic inverters. The system consists of a VSG, two 12V, 100W inverters, a load, a power source (solar panels), a battery, and a control system. The control system uses virtual inertia control, damping control, and active control to maintain the voltage and frequency at the desired levels.

One inverter was equipped with the VSG control capable of replicating the properties of a synchronous generator, providing virtual inertia and damping control to maintain voltage stability and frequency control. The second inverter did not have such control, serving as a comparison to assess the impact of the VSG control scheme as indicated in Fig. 1.



Source: Researcher's conceptualization (2024)

Fig. 1 Schematic Drawing Showing the Proposed Design for this Study

Measurements were conducted for different load conditions, and the corresponding voltages and frequencies were recorded. The system parameters include the reference voltage (V_{ref}), the reference frequency (f_{ref}), virtual inertia control gain (K_i), damping control gain (K_d), voltage measurement gain (K_v), frequency measurement gain (K_f), and active control gain ($K_{control}$).

The actual voltage (V) and frequency (f) were measured and compared with the reference values to generate control signals. The provided equations describe the operation of different system components.

Simulation results for the inverter with control were obtained using proprietary software and analyzed to evaluate system performance. The steady-state error ($Error_{ss}$) and dynamic error ($Error_{dyn}$) were calculated and compared against acceptable limits. If the errors were within acceptable limits, the control system design was considered successful. Otherwise, the system parameters were adjusted, and the simulation was repeated.

The equation models are presented below:

A. Virtual Inertia Control Equation:

$I_v = K_i * (f_{ref} - f)$

where:

I_v = the virtual inertia control,

K_i = the gain of the virtual inertia control,

f_{ref} = the reference frequency,

f = the actual frequency.

B. Damping Control Equation:

$D = K_d * (df/dt)$

where:

D = the damping control,

K_d = the gain of the damping control, *df/dt* = the rate of change of frequency.

C. Load Measurement Equation:

$P_{load} = V_{load} * I_{load}$
where:
P_{load} = the power consumed by the load,
V_{load} = the voltage across the load,
I_{load} = the current flowing through the load.

D. Voltage Measurement Equation:

$V = V_{ref} + K_v * (V_{load} - V_{ref})$
where:
V = the measured voltage,
V_{ref} = the reference voltage,
K_v = the gain of the voltage measurement,
V_{load} - = the actual voltage across the load.

E. Frequency Measurement Equation:

$f = f_{ref} + K_f * (f_{load} - f_{ref})$
where:
f = the measured frequency,
f_{ref} = the reference frequency,
K_f = the gain of the frequency measurement,
f_{load} = the actual frequency.

F. Power Electronics Model Equation:

$V_{out} = F(V_{in}, I_{in})$
where:
V_{out} = the output voltage,
V_{in} = the input voltage,
I_{in} = the input current,
F = the power electronics model function**.**

G. Lithium Iron Phosphate Battery Equation:

$SOC = SOC_{initial} - (I_{charge} * t) / C$
where:
SOC = the state of charge of the battery,
$SOC_{initial}$ = the initial state of charge,
I_{charge} = the charging current,
t = the charging time,
C = the battery capacity.

H. Solar Panels Equation:
$P_{solar} = A * G * \eta$
where:
P_{solar} = the power generated by the solar panels,
A = the area of the solar panels,
G = the solar irradiance,
η = the efficiency of the solar panels**.**

I. Solar Controller Equation:

$V_{out} = F(V_{in}, I_{in}, G)$
where:
V_{out} = the output voltage of the solar controller,
V_{in} = the input voltage,
I_{in} = the input current,
G = the solar irradiance,
F = the solar controller function.

J. VSG Active Control Equation:

$Control = K_{control} * (V_{ref} - V)$
where:
Control = the active control signal,
$K_{control}$ = the gain of the active control,
V_{ref} = the reference voltage,
V = the actual voltage.

K. Steady-State Performance Equation:

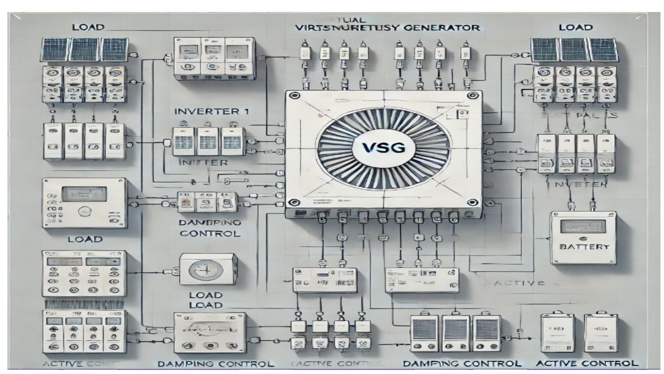
$Error_{ss} = V_{ref} - V$
where:
$Error_{ss}$ = the steady-state error,
V_{ref} = the reference voltage,
V = the actual voltage**.**

L. Dynamic Performance Equation:

$Error_{dyn} = V_{ref} - V$
where:
$Error_{dyn}$ = the dynamic error,
V_{ref} = the reference voltage,
V = the actual voltage.

VII. RESULTS AND DISCUSSIONS

A. Research Question 1:
How can a Virtual Synchronous Generator (VSG) control scheme be effectively designed and implemented in power electronic inverters interfaced with energy storage systems?



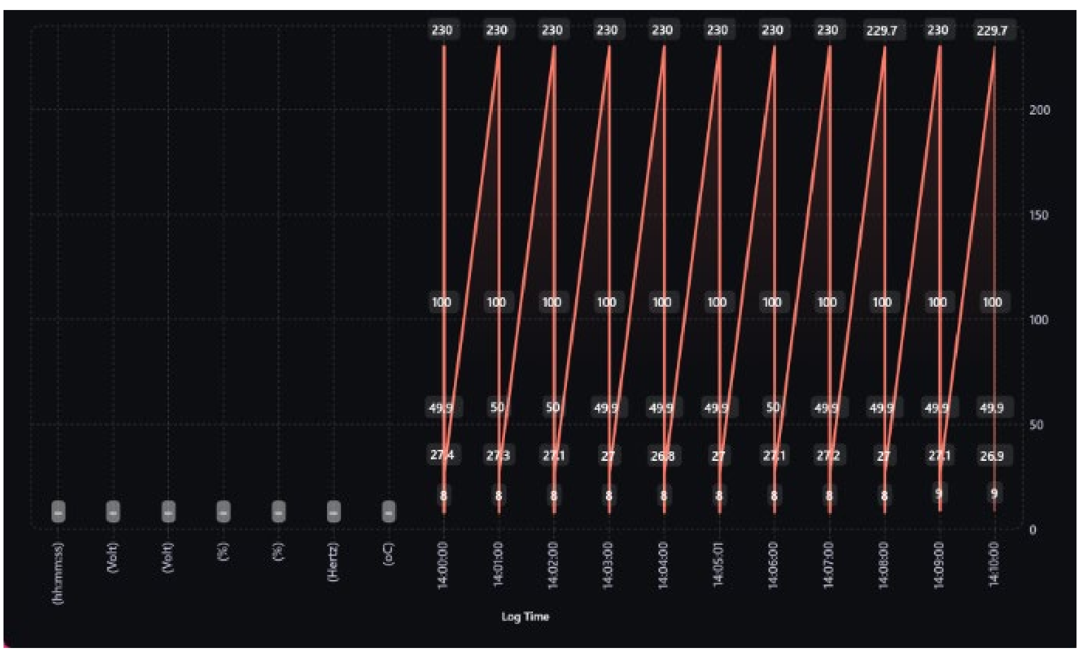
Source: Researcher's conceptualization (2024)
Fig. 2 Schematic Diagram Illustrating the Implementation Design of the VSG for this Study

Fig. 2 presents a detailed block diagram illustrating the design and implementation of a control scheme for a Virtual Synchronous Generator (VSG) in power electronic inverters interfaced with energy storage. The diagram features well-defined lines and precise proportions, ensuring technical clarity. At the center of the diagram is a rectangular enclosure labeled as the VSG. Flanking the VSG on either side are two smaller rectangular enclosures representing the inverters. To the left of the inverters, a rectangular enclosure symbolizes the load, which consumes the generated power. On the right side, another rectangular enclosure represents the power source, indicating the solar panels serving as the primary power supply. Additionally, interconnected with the inverters and the power source are rectangular enclosures representing the battery and control system, both of which play a critical role in maintaining voltage stability and frequency control. Arrows and lines illustrate the flow of power and control signals between the components. The diagram also includes elements depicting various control strategies, including virtual inertia control, damping control, and active control.

TABLE I: FEATURES OF VSG CONTROL SYSTEM

Log Time (hh:mm:ss)	**Input Voltage (Volt)**	**Output Voltage (Volt)**	**Output Load (%)**	**Battery Capacity (%)**	**Input Frequency (Hertz)**	**UPS Temperature (°C)**
14:00:00	230.4	230.0	8	100	49.9	27.4
14:01:00	231.7	230.0	8	100	50.0	27.3
14:02:00	231.7	230.0	8	100	50.0	27.1
14:03:00	231.2	230.0	8	100	49.9	27.0
14:04:00	233.3	230.0	8	100	49.9	26.8
14:05:01	229.5	230.0	8	100	49.9	27.0
14:06:00	230.0	230.0	8	100	50.0	27.1
14:07:00	229.5	230.0	8	100	49.9	27.2
14:08:00	228.8	229.7	8	100	49.9	27.0
14:09:00	228.8	230.0	9	100	49.9	27.1
14:10:00	226.3	229.7	9	100	49.9	26.9

The data in Table I show that the VSG control system maintains a stable input voltage (230 V ± 5 V) despite minor fluctuations, ensuring a constant output voltage at an 8% load and balanced power demand. The VSG control system effectively regulates the output load (UPS system), battery capacity (%), input frequency (Hz), and UPS temperature (°C), ensuring reliable operation and a consistent power supply to connected devices.



Source: Researcher's Analysis (2024)

Fig. 3 Showing Measurements of a VSG Control System

The dataset in Fig. 3 provides minute-by-minute measurements of a VSG control system for a power electronic inverter connected to an energy storage system. It covers a 10-minute period and includes data on voltage, current load, battery capacity, frequency, and temperature. The battery remains fully charged (100%) throughout the monitoring period, indicating effective power management. The load remains mostly stable at 8%, with a slight increase to 9% toward the end, suggesting low demand. The inverter temperature decreases from 27.4°C to 26.9°C, demonstrating efficient cooling despite a constant load and battery capacity. Overall, the power system operates efficiently despite voltage fluctuations and slight variations in demand.

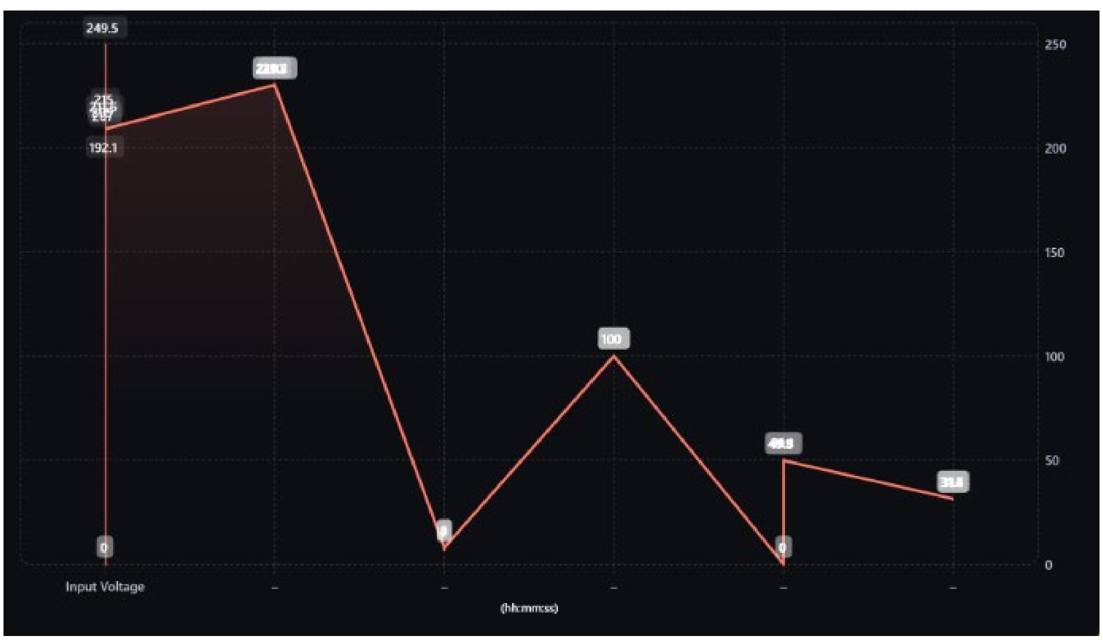
TABLE II: FEATURES OF INVERTER SYSTEM WITHOUT VSG

Log Time (hh:mm:ss)	Input Voltage (Volt)	Output Voltage (Volt)	Output Load (%)	Battery Capacity (%)	Input Frequency (Hertz)	UPS Temperature (oC)
14:00:00	0.0	230.2	8	100	0.0	31.4
14:01:00	249.5	229.5	7	100	50.1	31.3
14:02:00	0.0	230.2	8	100	0.0	31.3
14:03:00	0.0	230.0	8	100	0.0	31.3
14:04:00	207.0	230.0	8	100	49.8	31.2
14:05:01	211.6	229.7	7	100	49.9	31.2
14:06:00	192.1	230.0	8	100	49.5	31.3
14:07:00	215.0	229.7	8	100	49.9	31.3
14:08:00	0.0	229.7	8	100	0.0	31.1
14:09:00	0.0	230.2	8	100	0.0	31.1
14:10:00	209.0	230.2	8	100	49.8	31.1

Table II presents data from an inefficient micro power grid system. The input voltage column reveals instances of complete power loss, indicating an unreliable power source-an inverter integrated with a microturbine.

The output voltage column exhibits fluctuations, failing to consistently maintain the desired 230 V, which poses risks to the power supply and connected devices. The battery capacity remains between 30% and 40%, suggesting incomplete charging or discharging of the UPS system. Variations in the input frequency column indicate an unstable power supply frequency. Additionally, the UPS temperature column consistently records a high temperature of approximately 31°C, signifying inadequate cooling and potential inefficiencies in thermal management.

Collectively, these issues highlight the need for improvements in power source reliability, voltage regulation, frequency stability, and thermal management to enhance system efficiency and reliability.



Source: Researcher’s Analysis (2024)

Fig. 4 Showing Measurements of an Inverter System Without VSG

In Fig. 4, the dataset illustrates that the maximum observed voltage, recorded at 14:01:00, was 249.5 V, exceeding the average voltage for that time by 138.3 V. Notably, the ‘output voltage’ data exhibits a substantial decline within a one-minute interval. Starting at 249.5 V at 14:01:00, it precipitously drops to 0.0 V at 14:02:00, raising concerns about a potential complete power outage. Additionally, the dataset for input frequency reveals an irregular pattern, oscillating between 0.0 Hz and approximately 50 Hz on a minute-by-minute basis. Such steep fluctuations in the power grid are atypical and indicate the presence of inadequate or improperly configured equipment.

TABLE III: FREQUENCY COMPARISON IN VSG CONTROL VS INVERTER SYSTEM

Log Time (hh:mm:ss)	Input Frequency (Hertz) - Table I	Input Frequency (Hertz) - Table II	Frequency Performance Difference
14:00:00	49.9	0.0	49.9
14:01:00	50.0	50.1	0.1
14:02:00	50.0	0.0	50.0
14:03:00	49.9	0.0	49.9
14:04:00	49.9	49.8	0.1
14:05:01	49.9	49.9	0.0
14:06:00	50.0	49.5	0.5
14:07:00	49.9	49.9	0.0
14:08:00	49.9	0.0	49.9
14:09:00	49.9	0.0	49.9
14:10:00	49.9	49.8	0.1

The data in Table III compare the micro power grid frequency and performance at different log times. Table I consistently shows input frequencies ranging from 49.9 to 50.0 Hz, indicating a relatively stable and consistent power grid frequency due to the implementation of a Virtual Synchronous Generator (VSG) control system for power electronic inverters interfaced with energy storage systems.

In contrast, Table II exhibits erratic input frequencies, with values ranging from 0.0 to 50.1 Hz, resulting from an inverter-integrated microturbine with energy storage but without VSG implementation. This inconsistency suggests a less stable power grid frequency in Table II. The implications of these differences are significant. A stable power grid frequency, as observed in Table I, is crucial for the proper functioning of electrical equipment and devices.

In contrast, the erratic frequency in Table II may lead to operational issues and potential damage to sensitive equipment. The best-performing power grid frequency is evident in Table I, where the consistent input frequency indicates a well-regulated power supply. The erratic performance in Table II may be attributed to potential issues with the power grid infrastructure or fluctuations in the power supply, leading to inconsistent frequency outputs.

TABLE IV: COMPARISON OF VOLTAGE STABILITY IN VSG CONTROL VS. INVERTER SYSTEM

Log Time	Input Voltage Table I (Volt)	Output Voltage Table I (Volt)	Input Voltage Table II (Volt)	Output Voltage Table II (Volt)
14:00:00	230.4	230.0	0.0	230.2
14:01:00	231.7	230.0	249.5	229.5
14:02:00	231.7	230.0	0.0	230.2
14:03:00	231.2	230.0	0.0	230.0
14:04:00	233.3	230.0	207.0	230.0
14:05:01	229.5	230.0	211.6	229.7
14:06:00	230.0	230.0	192.1	230.0
14:07:00	229.5	230.0	215.0	229.7
14:08:00	228.8	229.7	0.0	229.7
14:09:00	228.8	230.0	0.0	230.2
14:10:00	226.3	229.7	209.0	230.2

The data in Table IV compare the micro power grid voltage and performance at different log times. The data from Table I, which incorporate a Virtual Synchronous Generator (VSG) control scheme, exhibit remarkable consistency in both input and output voltages, indicating strong voltage stability in the micro power grid. The minimal voltage fluctuations suggest that the VSG control scheme effectively integrates renewable energy sources and energy storage systems, ensuring smooth operation. In contrast, Table II, which lacks VSG implementation, displays greater variations in input and output voltages, signifying potential challenges in maintaining voltage stability within the same micro power grid setup. This stark contrast underscores the significant impact of the VSG control scheme in enhancing the integration of renewable energy and energy storage systems, ultimately contributing to a more reliable and stable power grid.

VIII. CONCLUSION

In conclusion, this study successfully designed and implemented a Virtual Synchronous Generator (VSG) control scheme for power electronic inverters coupled with energy storage units. The VSG control scheme demonstrated improved stability and performance compared to an inverter system without such controls. The implementation of VSG control enabled more efficient and reliable operation, maintaining a stable input voltage and consistent output voltage. The control strategies, including virtual inertia control, damping control, and active control, effectively managed the output load, battery capacity, input frequency, and temperature, ensuring reliable operation and a consistent power supply. This study highlights the necessity of VSG control in inverters for maintaining voltage stability and frequency regulation in power grids. Optimizing the control scheme for diverse load conditions and system configurations in power grids is recommended. Future research should focus on integrating advanced control algorithms and further enhancing VSG performance in real-world applications.

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