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Modelling and experimental verification of droop-based synthetic inertia for inverter-connected sources

Marián Tomašov[1*], *Pavel* Stanko[1], *Martin* Matejko[1], and *Filip* Petrík[1]

[1]Department of Power Systems and Electric Drives, Faculty of Electrical Engineering and Information Technology, University of Žilina, Žilina, Slovakia

Abstract. This paper presents the implementation and analysis of a simplified synthetic inertia concept using a droop control approach for inverter-connected sources within a microgrid environment. The motivation arises from the increasing share of renewable energy systems connected through power electronics, which inherently lack natural mechanical inertia and therefore weaken overall frequency stability. The proposed droop-based control structure enables inverter-based sources to support system frequency stabilization by adjusting their active power output proportionally to frequency deviations. A simulation model of a simplified power system was developed in MATLAB/Simulink to analyse the dynamic behaviour of the droop-controlled inverter under various operating scenarios. The same control concept was implemented on a physical microgrid model to validate the simulation results and examine practical limitations related to hardware response and measurement accuracy. The results demonstrate that even a basic droop-based approach can effectively mitigate frequency deviations following load disturbances and enhance short-term system stability. Finally, the paper discusses potential extensions toward more advanced synthetic inertia algorithms, such as Virtual Synchronous Generator control, which may further improve performance in low-inertia power systems.

1 Introduction

The growing penetration of renewable energy sources interfaced through power electronic converters is fundamentally transforming the dynamics of modern power systems. Unlike conventional synchronous generators, inverter-connected sources do not inherently provide mechanical inertia, which has traditionally played a key role in stabilizing system frequency during sudden disturbances. The gradual displacement of conventional generation by renewable units therefore results in reduced system inertia, leading to faster frequency deviations and an increased risk of instability.

To address these challenges, various control strategies have been proposed to enable inverter-connected resources to emulate the inertial response of synchronous machines. These so-called synthetic inertia or artificial inertia control methods allow the inverters to adjust their active power output dynamically in response to system frequency changes. Depending on their implementation, these strategies can be broadly categorized into droop-based control, virtual synchronous generator (VSG) control, and model predictive control approaches.

Among these methods, droop-based synthetic inertia represents a simple yet effective approach to providing primary frequency support. It allows inverter-connected sources to modulate active power according to frequency deviations without the need for complex emulation of synchronous machine dynamics. This makes droop control particularly suitable for smaller-scale applications, such as microgrids or distributed generation systems, where computational simplicity, robustness, and ease of implementation are critical.

This paper focuses on the modelling and experimental verification of droop-based synthetic inertia applied to inverter-connected sources within a microgrid environment. The proposed method is validated through both simulation and hardware experiments, demonstrating its potential to improve short-term frequency stability in low-inertia power systems.

2 Literature review

Inverters, as interface components between energy sources and the power grid, can mediate the injection or absorption of active power significantly faster than conventional synchronous machines. Suitable inverter-connected sources, particularly battery energy storage systems (BESS), are therefore widely investigated as fast-acting providers of frequency support, including synthetic inertia, inertia emulation, and primary frequency control. Early practical strategies often combine inertia emulation with droop-like behaviour, enabling BESS to contribute both fast inertial response and steady-state primary frequency support [1]. More advanced approaches, such as VSG control, emulate the swing equation and provide tunable virtual inertia and damping. The review presented in [2] summarizes VSG variants, hardware requirements, and implementation challenges for grid-forming inverters.

Several experimental and field-scale studies have demonstrated both the feasibility and the limitations of these approaches. Laboratory and microgrid experiments show that droop-based and VSG controllers can effectively share power, stabilize frequency following disturbances, and enable parallel operation of inverter-based sources with synchronous machines. However, hardware response limitations, measurement delays, and state-of-charge (SoC) management constraints significantly influence achievable performance [3, 4].

* Corresponding author: marian.tomasov@uniza.sk

Recent research increasingly focuses on hybrid control schemes that combine very fast inertia-like responses sometimes provided by supercapacitors with slower energy support from batteries, as well as adaptive schemes that adjust virtual inertia or droop gains based on operating conditions or SoC [5].

Work conducted at EPFL has further demonstrated the importance of higher-level control and scheduling layers, validating coordinated day-ahead dispatch, intra-day setpoints, and real-time frequency control for BESS providing frequency containment reserves while respecting converter limits and SoC constraints [4]. Optimization-based frameworks are also widely investigated to co-optimize market participation, SoC trajectories, and multi-service provision, such as the simultaneous delivery of energy arbitrage and frequency support. These studies highlight the strong impact of revenue optimization and battery degradation trade-offs on the techno-economic viability of synthetic inertia provision [1, 4, 5].

Overall, the literature indicates that droop-based and VSG-based strategies are sufficiently mature for laboratory-scale validation and pilot deployments. However, their large-scale practical adoption requires careful coordination between control design, energy management, and market or operational constraints. Fewer studies focus on experimentally validating simplified droop-based synthetic inertia strategies using coordinated simulation and physical microgrid models, which motivates the approach presented in this paper.

3 Simulation model

To identify and verify the properties of synthetic inertia control algorithms, it is necessary to employ a simulation model, as the majority of published algorithms are primarily validated through simulation studies. A review of the existing literature indicates that such verification is often performed using significantly simplified representations of the power system and its individual components. In many cases, the inverter is replaced by an idealized programmable voltage or current source; in other studies, lower-order transfer function models are used, or only active power flows are analysed without considering the underlying electromagnetic and control dynamics of the system [6, 7].

In this paper, a more comprehensive simulation model of a microgrid is developed, with explicit consideration of its subsequent transition to a physical laboratory model. The simulated microgrid consists of a synchronous generator (SG), which establishes the system voltage and frequency reference, and an inverter-based source capable of synthetic inertia response, representing the integration of renewable energy sources. Frequency disturbances are introduced through step changes in load demand. The inverter operates in a grid-following mode and synchronizes to the microgrid frequency via the reference defined by the synchronous generator.

3.1 Mathematical model

The selection of an appropriate mathematical model represents the first step in the development of the simulation framework. The complexity, robustness, and number of equations used determine the overall level of detail of the mathematical model. While higher model complexity generally leads to improved accuracy, it also raises the requirements for parameter identification and implementation effort within the simulation environment.

An equally important step is the practical implementation of the selected mathematical models in a computational environment. For this work, MATLAB/Simulink was chosen as the simulation platform, as it provides validated and widely used models for key power system components, including synchronous machines and power electronic converters. These built-in blocks are based on relatively high-level, physically motivated mathematical models. Their use, rather than developing custom component models from scratch, significantly reduced development time and facilitated the subsequent transition to a physical laboratory implementation. An additional advantage of this approach is direct interoperability with the dSPACE real-time interface used in the laboratory setup. Control structures developed within Simulink can therefore be transferred directly to the physical inverter without structural modification.

A detailed description of the mathematical models, equations, wiring diagrams, input parameters, assumptions and limitations can be found in the corresponding documentation and references of the employed Simulink blocks, which are listed in the following section.

3.2 Simulink model

The synchronous generator was modelled using the Synchronous Machine SI Fundamental block [8]. The electrical and mechanical parameters of the machine were obtained through experimental identification following conventional measurement procedures. These parameters were subsequently optimized to match the characteristics of the laboratory synchronous generator with identical nominal ratings. The final parameter set used in the simulations is summarized in Table 1.

The inverter was modelled using the Universal Bridge block [9], complemented with a custom-built control structure implementing the synthetic inertia functionality. The voltage levels and power ratings of all microgrid components were selected to correspond to their physical counterparts used in the experimental setup. This modelling approach ensures a consistent representation of system dynamics across simulation and experimental validation.

To establish a complete and dynamically consistent microgrid model, additional subsystems were implemented for the synchronous generator. The mechanical input was represented by a controlled torque source securing the required nominal rotational speed. A damping element was incorporated within the drive feedback loop to achieve realistic transient behaviour and stable settling to a new operating point following load disturbances. Furthermore, an excitation control loop was included to regulate the generator terminal voltage.

Table 1. Parameters of SG Simulink block

<table>
<tr><th colspan="2">Nominal power</th><th>Voltage</th><th colspan="2">Frequency</th><th>Field current</th></tr>
<tr><td colspan="2">Pn (VA)</td><td>Vn (Vrms)</td><td colspan="2">fn (Hz)</td><td>ifn (A)</td></tr>
<tr><td colspan="2">1500</td><td>400</td><td colspan="2">50</td><td>6.8</td></tr>
<tr><th colspan="6">Stator</th></tr>
<tr><td>Rs (ohm)</td><td>Ll (H)</td><td>Lmd (H)</td><td colspan="2">Lmq (H)</td><td>Lc (H)</td></tr>
<tr><td>3.5</td><td>0.013108</td><td>0.49964</td><td colspan="2">0.37893</td><td>0</td></tr>
<tr><th colspan="6">Field</th></tr>
<tr><td colspan="3">Rf' (ohm)</td><td colspan="3">Llfd' (H)</td></tr>
<tr><td colspan="3">4.3179</td><td colspan="3">0.052301</td></tr>
<tr><th colspan="6">Dampers</th></tr>
<tr><td>Rkd' (ohm)</td><td>Llkd' (H)</td><td colspan="2">Rkq1' (ohm)</td><td colspan="2">Llkq1' (H)</td></tr>
<tr><td>3.5348</td><td>0.13212</td><td colspan="2">4.7733</td><td colspan="2">0.44938</td></tr>
<tr><th colspan="2">Inertia</th><th colspan="2">Friction factor</th><th colspan="2">Pole pairs</th></tr>
<tr><td colspan="2">J (kg.m^2)</td><td colspan="2">F (N.m.s)</td><td colspan="2">p ()</td></tr>
<tr><td colspan="2">0.0284</td><td colspan="2">0.001</td><td colspan="2">2</td></tr>
</table>

The overall configuration of the simulation model is shown in Figure 1. It represents a laboratory-scale three-phase islanded microgrid consisting of a inverter operating in parallel with a synchronous generator and multiple configurable loads. The structure enables dynamic analysis of frequency and power behaviour under load disturbances with implemented synthetic inertia control.

The inverter subsystem is supplied from a controlled DC voltage source representing the DC-link of a power electronic converter. The inverter switching signals are generated by a PWM generator driven by the control subsystem. An essential component of the power stage is the output LC filter, which converts the switched inverter voltage into a near-sinusoidal waveform. This filtering is necessary to ensure accurate measurement of electrical quantities and to support proper control, synchronization, and stable operation.

The inverter is using a droop-based control strategy for active power adjustment. The active power operating point is determined by a frequency droop controller that compares the measured system frequency with its reference value (50 Hz). The resulting frequency deviation is multiplied by the droop gain Kd, producing a corrective power reference component.

The droop control alone is not sufficient to ensure stable operation, synchronization capability, or bidirectional power flow. Therefore, a conventional dq-based control structure is implemented as the inner control layer. The power reference is passed to this inner control structure, which includes forward and inverse abc to dq coordinate transformations and a phase-locked loop (PLL) used to estimate the angular position of the rotating reference frame. The voltage reference produced by the controller is subsequently supplied to the PWM generator to produce gating signals for the inverter.

The synthetic inertia algorithm is thus integrated into the standard inverter control structure used for non-inertial operation.

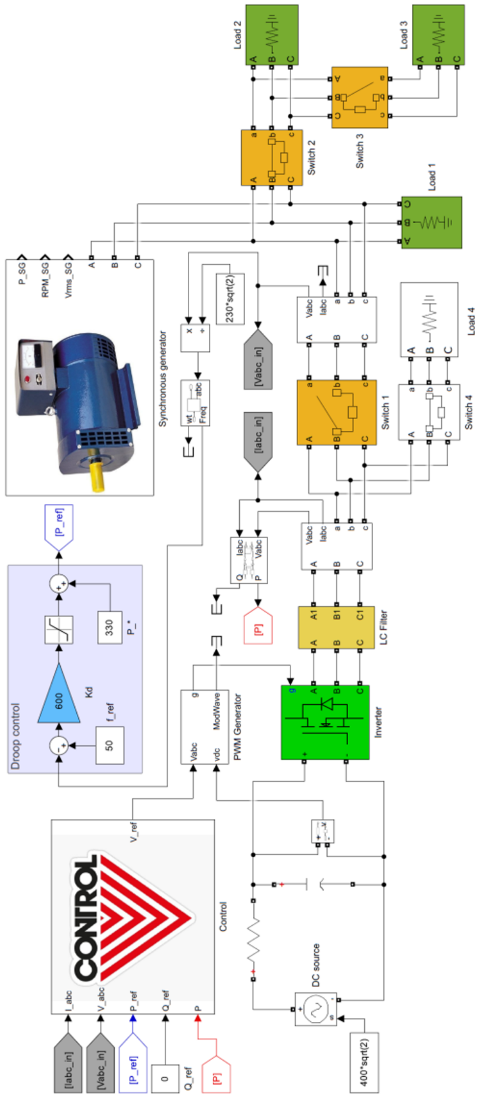

Fig. 1. Overall configuration of the simulation model

4 Physical model of the microgrid

In the subsequent stage of the work, a physical laboratory model of the microgrid was developed, incorporating a real power inverter and a set of devices representing a simplified power system. Components of the simulation model that represented physical devices were replaced by laboratory equipment with identical or comparable electrical parameters. To enable experimental verification of synthetic inertia algorithms, the physical model must be capable of emulating grid behaviour, particularly with respect to frequency dynamics following active power imbalances.

The frequency behaviour of an electrical grid in response to changes in the balance between generation and consumption is inherently linked to the presence of rotating masses. This behaviour can be most effectively emulated using a conventional synchronous machine. For this purpose, the experimental setup shown in Figure 2 was employed. It consists of a synchronous generator with external excitation, mechanically driven by an asynchronous motor (ASM). The ASM is supplied via a frequency converter, allowing controlled mechanical input and stable operation of the synchronous generator as a grid-forming source. The inertia of the synchronous generator rotor thus defines the natural frequency response of the laboratory microgrid.

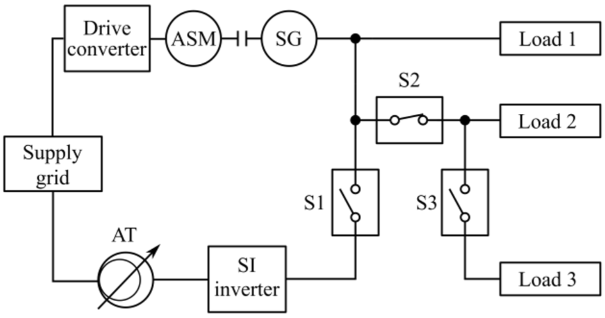

Fig. 2. Schematic diagram of the physical model.

After completion of the synchronization procedure, the inverter is connected to the microgrid via switch S1. As a load, passive resistive elements connected in a star configuration are used. These loads can be connected or disconnected as required using switches S2 and S3 to generate controlled load disturbances.

The dSPACE real-time platform enables direct transfer of control structures developed in the MATLAB/Simulink simulation environment to the physical inverter. In addition, it provides real-time measurement, data acquisition, and signal processing necessary for feedback control and experimental evaluation of the implemented algorithms.

5 Droop-based synthetic inertia

Droop control is one of the simplest and most widely adopted methods enabling inverter-connected sources to contribute to system frequency stabilization. Its principle originates from the behaviour of synchronous generators, where the electrical power output naturally decreases as the mechanical speed (and thus frequency) drops under load. By emulating this proportional relationship, inverter-based resources can provide fast active power support without requiring complex dynamic models or explicit emulation of rotational inertia [10].

The basic active power–frequency droop characteristic can be expressed as:

$$\Delta P_i = -K_d \cdot \Delta f \qquad (1)$$

where ΔP_i denotes the active power adjustment of the inverter, Δf is the system frequency deviation, and K_d is the droop coefficient. A higher value of K_d results in a stronger active power response for a given frequency deviation. In practical implementations, the droop coefficient is selected with respect to available power reserves, system stability requirements, and inverter power limits [10]. The negative sign in (1) ensures a corrective response, i.e., an increase in active power output during frequency drops and vice versa.

Classical droop control primarily provides quasi-steady-state frequency support and does not explicitly respond to the rate of change of frequency (RoCoF). However, when implemented with sufficiently high gains and fast control loops, droop-based control can deliver a rapid active power response following a disturbance, thereby mitigating the frequency nadir. For this reason, droop-based approaches are often regarded as a simplified form of synthetic inertia, particularly suitable for inverter-connected resources where implementation simplicity and robustness are prioritized [10].

6 Results

The initial simulation results focused on steady-state operation of the synchronous generator supplying various load levels. Key electrical quantities, such as voltages and currents, as well as derived values including active power and system frequency, were recorded and compared with corresponding measurements obtained from the physical model operating under identical conditions. This comparison served to verify the consistency of the microgrid topology and steady-state parameterization between the simulation model and the physical setup.

Subsequently, short-circuit events were introduced in both models to evaluate transient behaviour. The analysis concentrated on current transients and associated frequency deviations following the disturbance. Measured responses from the physical model were used as a reference for evaluating the transient performance of the simulation model. Based on this comparison, basic tuning of transient-related parameters was performed in order to achieve close agreement in terms of transient waveform shape and peak amplitudes between simulated and measured currents.

A similar verification procedure was applied to the synthetic inertia inverter. The processes of synchronization, grid connection, steady-state operation, and transient response following load disturbances were investigated in both simulation and physical models. In the case of the inverter, not only parameters but also the coefficients of the control structures, including PI controller gains and droop coefficients, were tuned. Since the primary objective of this work was to verify the feasibility of implementing a droop-based synthetic inertia algorithm on a real inverter, rather than to develop a market-ready solution, the tuning was considered sufficient as long as stable operation was ensured across the investigated operating conditions. Advanced features such as automatic self-tuning, additional safety feedback layers, and real-time supervisory monitoring were considered beyond the scope of this study.

6.1 Simulation results

Figure 3 shows the simulated system frequency response during a sequence of load changes. In the initial steady state, prior to the frequency disturbance at time $t = 0$ s, the synchronous generator supplied 720 W of active power, while the inverter supplied 330 W, to a total load of 1050 W. To induce frequency events, the load was increased by

220 W at $t = 0$ s. After reaching a new steady state, the load was decreased by 450 W at $t = 5$ s and finally increased by 230 W at $t = 10$ s, returning the system close to its initial operating point. The same load change sequence was applied in the physical model.

The grey curve represents the reference case without the droop-based synthetic inertia algorithm. In this case, both the RoCoF and the steady-state frequency deviation are governed solely by the inertia of the synchronous generator. The blue curve corresponds to the case with the droop-based synthetic inertia algorithm enabled, with the droop coefficient set to $K_d = 600$.

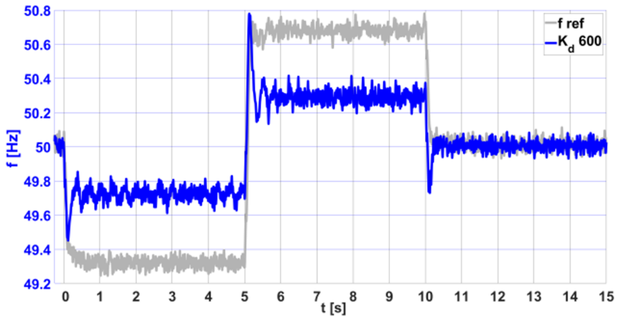

Fig. 3. Waveform of simulated frequency.

Without droop control, the system frequency exhibits a pronounced drop following the load increase, with a short transient most clearly visible between 0 and 1 s. When the droop-based synthetic inertia is activated, the RoCoF is not significantly altered; however, the steady-state frequency deviation from the nominal value of 50 Hz is considerably reduced. This improvement results from the inverter increasing its active power output and supplying a larger share of the microgrid load, thereby allowing the synchronous generator to maintain the system frequency closer to its nominal value. The RoCoF remains primarily influenced by the inertia of the synchronous generator and by delays in the inverter control structures.

Several values of the droop coefficient K_d were evaluated in the simulations. The dominant effect of increasing K_d was a higher level of inverter power participation. As expected, higher values of K_d led to stronger suppression of frequency deviations Δf, but also increased the tendency toward control instability. Considering the power ratings of the simulated machines, the selected value of $K_d = 600$ provided a sufficiently stable response while remaining representative.

The minor oscillations and frequency overcorrection observed around $t = 10$ s, could be reduced through additional tuning and optimization of the inverter control structures.

6.2 Results of the physical model

The results obtained from the physical model under operating conditions comparable to the simulations are presented in Figure 4. The upper part of the figure shows the measured system frequency over time. The grey curve represents the reference case without the droop algorithm, while the blue curve corresponds to operation with the droop control enabled and the coefficient set to $K_d = 600$, consistent with the simulation. The overall frequency response closely resembles the simulated results, exhibiting a unchanged RoCoF between cases and a slight frequency overcorrection following load changes.

The lower part of Figure 4 shows the measured active power. The blue, red, and green curves represent the active power of the synchronous generator, the inverter, and the load, respectively. The grey curve denotes the reference active power of the SG when the droop-based synthetic inertia algorithm is not applied.

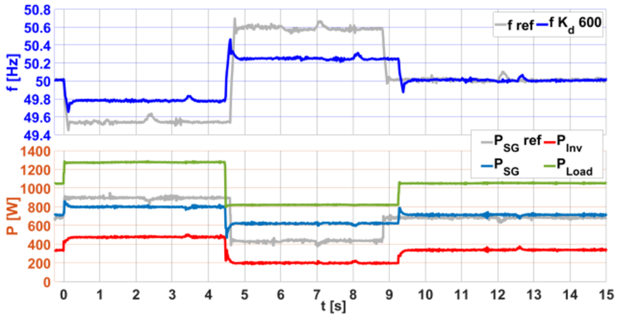

Fig. 4. Waveform of measured data.

Compared to the reference case, the synchronous generator requires smaller power corrections due to the active contribution of the inverter. The imposed load changes are shared between the synchronous generator and the inverter according to the selected droop coefficient K_d. The transient behaviour of the synchronous generator power confirms its inertial response, whereas the inverter reacts directly to frequency deviations without exhibiting inertial dynamics. The measured waveforms were synchronized at $t = 0$ s, minor time shifts observed later in the record are caused by manual switching of the load elements.

Figure 5 illustrates the influence of different droop coefficient values on the frequency response and inverter active power. Consistent with the simulation results, higher values of K_d lead to a reduced steady-state frequency deviation caused by larger active power variations demanded from the inverter.

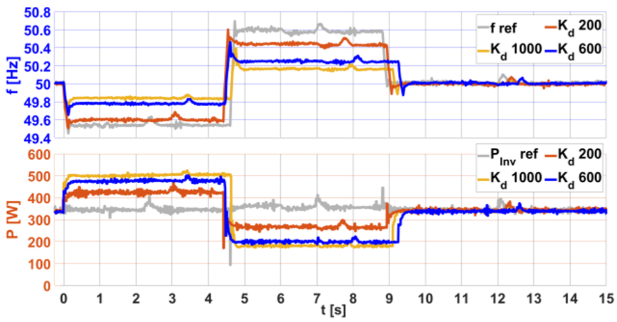

Fig. 5. Comparison of different droop coefficient values.

It is mathematically possible to further increase K_d in order to reduce the frequency deviation Δf. However, in this case, additional modifications to the control structure and further tuning were required, as higher values of K_d resulted in unstable inverter behaviour during experimental testing. Moreover, a clear point of diminishing returns can be observed, since no significant improvements are achieved by linearly increasing the value of K_d. The physical capabilities of the inverter, including its power limits and the availability of supply power, also represent important constraints that must be considered in practical application.

7 Future work

The successful implementation and demonstration of a droop-based algorithm on the presented microgrid model open up possibilities for investigating more complex and more effective synthetic inertia algorithms. The basic feasibility and limitations of simplified frequency-support strategies were confirmed, along with their positive impact on frequency stability. However, modern power systems with a high share of converter-based resources require more advanced control methods.

Future research will focus on the implementation and comparison of more advanced control concepts, particularly VSG algorithms, which explicitly emulate the swing equation and allow independent tuning of virtual inertia and damping. Such approaches are expected to further improve frequency dynamics, especially during fast transients and under low-inertia operating conditions.

8 Conclusion

This paper investigated the implementation of droop-based synthetic inertia for inverter-connected sources within a simplified microgrid environment. The motivation for this work stems from the ongoing reduction of natural rotational inertia in modern power systems due to the increasing penetration of inverter-connected renewable energy sources, which challenges traditional frequency stability mechanisms.

A combined simulation and experimental framework was developed to evaluate the behaviour of a droop-controlled inverter operating in parallel with a synchronous generator. The simulation model, implemented in MATLAB/Simulink, was designed with a direct transition to a physical laboratory setup in mind. The corresponding physical microgrid model enabled experimental validation of the proposed control strategy. Both simulation and measurement results confirmed that the droop-based approach can effectively support system frequency by adjusting the active power of the inverter-connected source following disturbances and by reducing steady-state frequency deviations.

The results further demonstrate that, although classical droop control does not provide true inertial response in terms of RoCoF reduction, it can act as a simplified form of synthetic inertia by rapidly injecting active power and mitigating frequency nadir. Limitations related to controller tuning, inverter power capability, and diminishing returns for high droop gains were also identified, highlighting practical constraints relevant for real-world applications. It is important to note that symmetrical provision of frequency support requires the energy source to be capable of both increasing and decreasing its active power output. While this requirement can be readily met by BESS operating within appropriate SoC limits, photovoltaic sources operating at their maximum power point lack the capability to provide upward power regulation.

Overall, the presented work demonstrates that even simple droop-based control strategies can provide meaningful frequency support in low-inertia systems. The established modelling and experimental framework provide a solid foundation for future research on more advanced synthetic inertia concepts, such as VSG control, and for their systematic evaluation in both simulation and hardware environments.

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