Received Date:3rd November, 2025
Revision Date: 15th December, 2025
Accepted Date: 28th January, 2026

Dual-Loop Virtual Synchronous Machine to Enhance Frequency and Voltage Stability in PV-Hydro Microgrids

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Abstract— This paper investigates a dual-loop Virtual Synchronous Machine (VSM) to enhance frequency and voltage stability in a PV-Hydro microgrid supplemented by a lithium-ion storage battery system. The proposed VSM simultaneously emulates the inertia and damping property of a synchronous generator and mitigates the voltage dip problem during transient period due to the large perturbation of P-Q load. The VSM injects active and reactive power during transient period through an inverter with a storage battery at dc side. MATLAB/ Simulink simulations were carried out under severe load disturbances for two cases: (i) PV-Hydro micro-grid without VSM, (ii) PV-Hydro micro-grid with proposed dual-loop VSM. Without VSM support, frequency and voltage dropped to 0.57 pu and 0.78 pu respectively during transient period, exhibiting unstable behaviour. The proposed dual-loop VSM improved stability, limiting frequency deviation to 0.86 pu and voltage sag to 0.9 pu with faster recovery during transient period.

Keywords — Virtual synchronous machine, microgrid, voltage stability, frequency stability, PV-hydro system

I. Introduction

Renewable-based microgrids are increasingly being used for reliable power supply, combining photovoltaic (PV) arrays, hydropower, and energy storage to meet demand with reduced carbon emissions. However, high penetration of inverter-based generation reduces system inertia, making islanded microgrids more vulnerable to rapid frequency and voltage fluctuations under load changes or resource intermittency. In particular, PV-hydro microgrids can exhibit significant transient instability during disturbances, as documented by Tamrakar *et al.* [1].

Virtual Synchronous Machine (VSM) control has been proposed as a solution to emulate the inertial and damping behavior of synchronous generators in power-electronic systems [2-3]. While conventional VSM implementations have shown effectiveness in frequency regulation, they often overlook voltage stability issues. This paper addresses these gaps by introducing a dual-loop VSM architecture with both frequency and voltage control, thus improving the dynamic stability and robustness of PV-hydro microgrids under various operating conditions.

II. Literature review

the concept of VSMs has gained attention due to their ability to emulate synchronous generator dynamics in inverter-based systems. Several topologies and control strategies have been proposed, including droop-based and swing-equation-based models [2], [4]. Sa'ed *et.al.* [3] and Shadoul *et.al.* [4] highlight the importance of coordinated frequency and voltage control to enhance grid stability.

Tamrakar *et.al.* [1], [5] and Adhikari *et.al.* [6] have demonstrated the application of VSMs in PV-hydro systems, noting improvements in transient stability. However, these studies focused primarily on frequency stability under active power load perturbations. The voltage dip problem caused by reactive load perturbations has not been adequately addressed. This work proposes an integrated approach combining dual-loop control to overcome these performance constraints and provide a more comprehensive solution for microgrid stability, particularly in systems with hybrid PV-hydro configurations.

As per standard microgrid operation criteria, the frequency should not exceed ±15% of the nominal rated frequency during the transient period and ±2% during steady-state operation. The voltage magnitude should not fall below 0.85 pu during transient conditions.

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III. SYSTEM MODEL

The microgrid under study consists of:

- A 200-kW hydro generator,
- A 5- kWp photovoltaic array,
- A VSM with dual loop control,
- Load with step changes in real and reactive power.

The hydro plant provides base power with mechanical inertia, while the PV unit operates in MPPT mode using a boost converter. The VSM controller interfaces with the inverter using Li-ion batteries to provide frequency and voltage support under dynamic conditions. The schematic of the system in consideration is shown in Fig. 1.

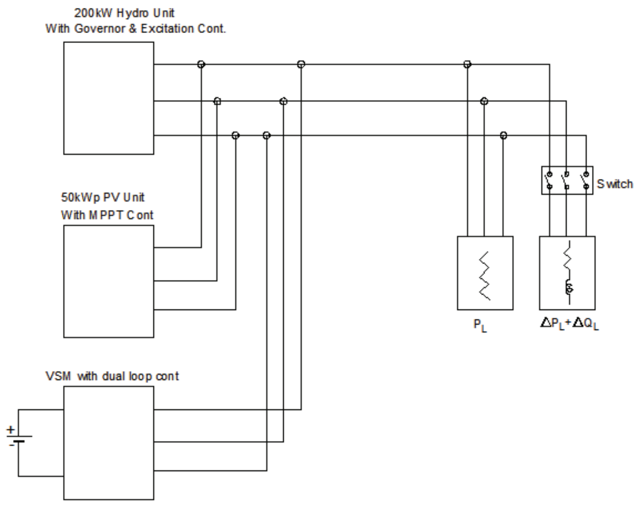

Fig. 1 Schematic Diagram of the Proposed Scheme

IV. PROPOSED METHODOLOGY

The proposed virtual frequency and voltage supporter builds upon a conventional Virtual Synchronous Machine (VSM) by incorporating an additional voltage control loop. This dual-loop design allows the system to simultaneously address frequency and voltage instability under large active and reactive load disturbances in PV-Hydro microgrids. The methodology comprises two simulation cases i) without VSM and ii) with proposed dual-loop VSM.

A. *Virtual Synchronous Machine with Dual-Loop Control*

A conventional VSM only utilizes a frequency control loop that emulates inertia and damping of a synchronous machine by generating the reference d-axis current I_d for inverter control. This loop mitigates frequency deviations during load changes. In this work, an additional control loop is designed to regulate voltage by generating the reference q-axis current I_q. The I_d and I_q are generated to satisfy the following equations:

$$I_d = K_d\left(\frac{d(\Delta f)}{dt}\right) + K_p(\Delta f) \qquad (1)$$

$$I_q = K_d\left(\frac{d(\Delta V)}{dt}\right) + K_p(\Delta f) \qquad (2)$$

That means I_d and I_q references are only generated when Δf and ΔV exceed their acceptable limits during transient period. VSM does not inject P and Q during steady state operation. The complete VSM generates both I_d and I_q, which are then transformed to three-phase reference currents I_{abc} using a dq-to-abc transformation as shown in Fig. 2. A hysteresis band current controller ensures that the inverter current tracks these references, enabling real-time power injection.

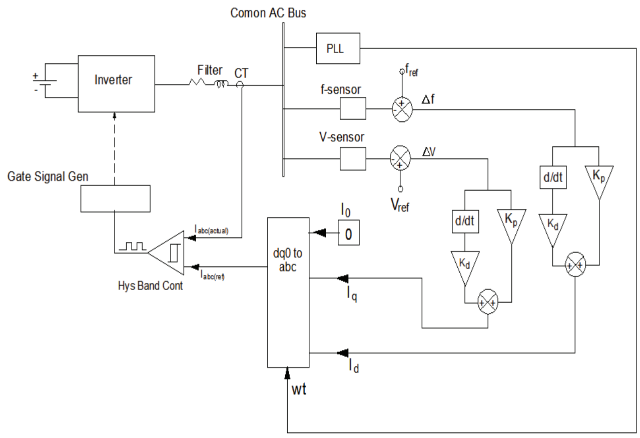

Fig. 2 Control Logic for the Proposed Scheme

B. *Simulation Without VSM*

To establish a base case, a standalone PV-hydro micro-grid without VSM is modelled in MATLAB/Simulink as shown in Fig. 3, the model includes a 200kW hydro generating unit with governor and excitation control systems, a 50kW PV-plant with MPPT control. Load disturbances are applied at t=30 seconds to observe natural system response in terms of frequency and voltage behaviour.

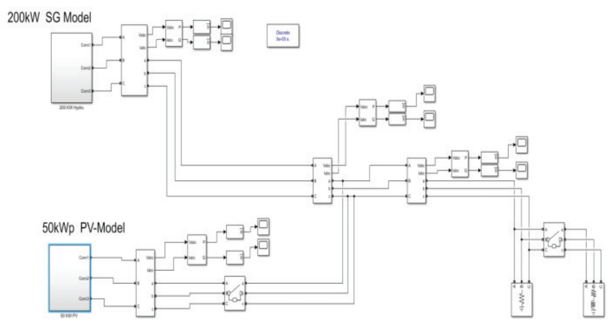

Fig. 3 PV-Hydro micro-grid without VSM

The initial load is 100 kW and after 30 seconds, additional load of 80 kW + 30 kVar is switched on. The speed and voltage are found to be as shown in Fig.4 and Fig.5 respectively.

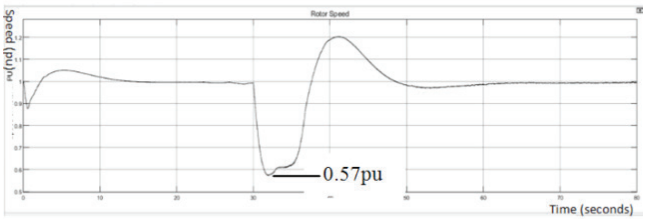

Fig.4 Speed response without VSM

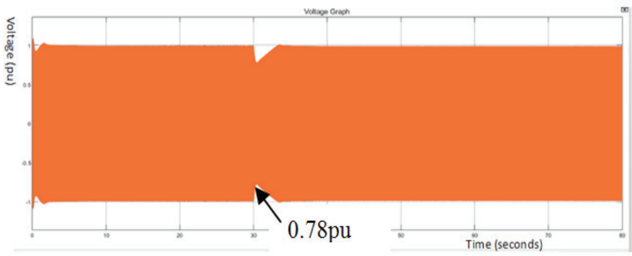

Fig.5 Voltage response without VSM

The speed drops to 0.57 pu and voltage drops to 0.78 pu with recovery times 40s and 30s respectively during the transient period. These results do not comply with micro-grid standards.

A. *Simulation with dual-loop VSM*

The MATLAB/Simulink model of proposed PV-Hydro micro-grid with dual loop VSM is shown in Fig. 6.

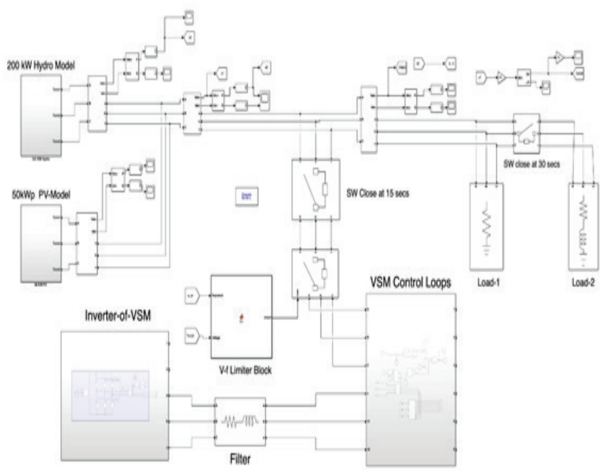

Fig. 6 PV-Hydro micro-grid with VSM

The speed and voltage responses with a large P-Q load perturbations are as shown in Fig. 7 and Fig. 8 respectively.

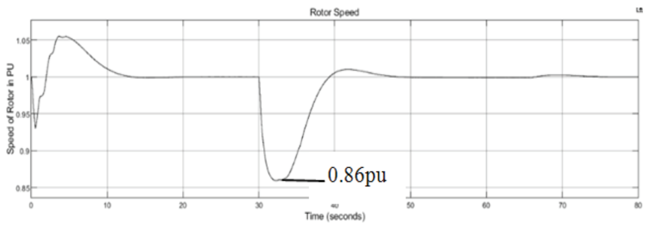

Fig. 7 Speed response with VSM

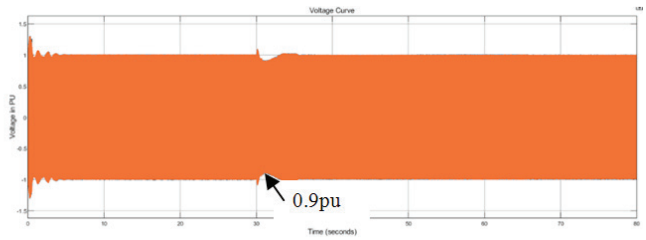

Fig. 8 Voltage response with VSM

Fig. 9 shows the inverter-injected current tracking the reference current within the set hysteresis band.

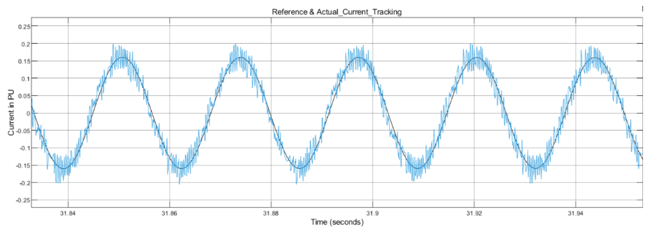

Fig. 9 Inverter current tracking the reference current

The speed drop has improved to 0.86 pu and voltage drop has improved to 0.9pu with recovery times 15s and 6s respectively during the transient period. These results comply with microgrid standards.

V. Conclusions

This paper presented a dual-loop VSM for frequency and voltage control in PV-Hydro micro-grid during transient period. The transient response of the PV-Hydro micro-grid due to the sudden large P-Q load perturbation has been analyzed with MATLAB/Simulink models. The PV-Hydro micro-grid suffers from large drop in speed and large voltage dip during the transient period due to the sudden large P-Q load perturbation. The proposed VSM with dual control loop has mitigated the problems of speed drop and voltage dip during the transient period, providing a faster dynamic response and ensuring stable recovery to nominal values.

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