Grenze International Journal of Engineering and Technology, June Issue

Analysis and Modeling of Cascaded DC-DC Converters in Grid-Connected PV-HYDRO Power Systems at Medium Voltage AC

H.Kishan[1], K.Meghana[2], S.Vishnu Preetham[3] and K.Jeetender Vemula[4]
[1-4]Vignan Bharathi Institute of Technology, Telangana, India
Email: kishan252@gmail.com, meghana19001@gmail.com, sanghivishnupreetham25@gmail.com, jeetender.eee@gmail.com

***Abstract*—The cascaded DC-DC converter remains a preferred topology in medium-voltage photovoltaic (PV) and hydro power systems, offering high voltage conversion efficiency, flexibility, and independent control capabilities. However, conventional centralized control methods face challenges in achieving optimal string maximum power point tracking (MPPT) due to power mismatches. Additionally, the high costs and delays caused by the spatial separation of PV arrays and hydro power stations make centralized control less practical. To address this, we propose a distributed multimode control strategy for cascaded DC-DC converters that incorporates voltage, power, and gain constraints alongside distributed MPPT control. Within this frame-work, each sub module (SM) can dynamically switch between multiple operational modes to optimize energy extraction from both solar and hydro sources. This distributed approach enables independent string MPPT and self-regulated voltage distribution without requiring real-time communication, thereby improving system versatility and resilience. The proposed strategy extends the optimal operating range, simplifies mode transitions, and enhances overall applicability for medium voltage AC grid-connected PV-hydro power systems.**

***Index Terms*— Cascaded DC-DC converter, Distributed control, Multimode control, medium voltage systems, Photovoltaic (PV) stations, Maximum power point tracking (MPPT).**

I. Introduction

The integration of renewable energy sources such as photovoltaic (PV) and hydropower into medium-voltage alternating current (MVAC) grid-connected systems poses significant challenges due to their inherent variability and intermittency. Fluctuating solar irradiance and hydrological conditions lead to unpredictable energy outputs, demanding advanced energy management and power conversion strategies. Cascaded DC-DC converter topologies have emerged as an effective solution for such hybrid systems, offering advantages in modularity, reliability, and scalability [1], [2], [5]. These converters enable high voltage gain, galvanic isolation when necessary, and independent regulation of power from multiple distributed sources, facilitating efficient interfacing with the grid [1], [3], [6]. Traditional centralized power conversion approaches often suffer from increased system losses, reduced efficiency, and control complexity, particularly in geographically distributed installations [4]. Centralized maximum power point tracking (MPPT) algorithms also face limitations under non-

Grenze ID: 01.GIJET.11.2.521

uniform environmental conditions, resulting in power mismatches [10]. Additionally, centralized architectures introduce communication delays, wiring complexity, and higher operational costs in large-scale solar farms [3], [4]. To overcome these issues, this paper proposes a distributed multimode control framework tailored for cascaded DC-DC converters in MVAC grid-connected PV-HYDRO systems [5], [8]. The framework integrates distributed MPPT algorithms and operational constraints such as voltage stability, power-sharing balance, and converter gain optimization [6], [7]. Each sub-module (SM) is equipped with autonomous control, enabling dynamic state transitions based on real-time inputs [8]. This decentralized approach enhances system robustness, fault tolerance, and transient response, while maximizing energy harvesting from each source [9], [10]. The method also introduces adaptive voltage regulation to ensure efficient energy transfer and voltage balance across the system [6], [11], enhancing flexibility and grid stability [12]. Validation through simulations and scaled-down experiments of a 35-kV/6-MW system confirmed the method's effectiveness in improving efficiency and resilience [11], [12].

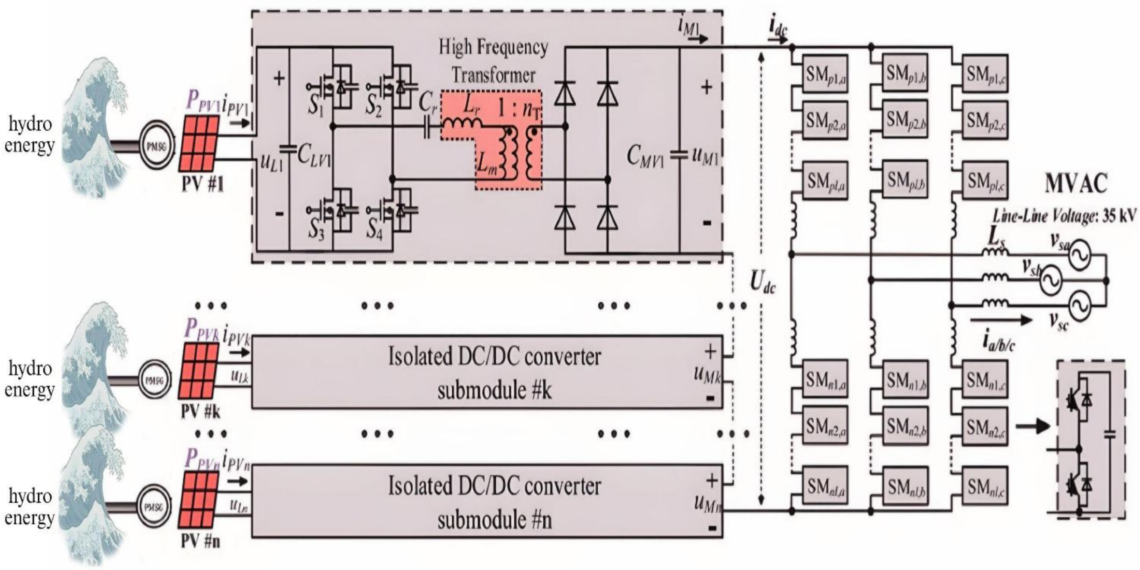

Figure 1 The Proposed System Configuration

II. LITERATURE SURVEY

Recent research has increasingly focused on integrating renewable energy sources such as photovoltaic (PV) and wind into medium voltage AC (MVAC) grids, driven by the global push for sustainable energy and climate change mitigation [5], [6]. Cascaded DC–DC converters are pivotal in this context, serving as essential interface devices for voltage regulation and power flow control in MVAC-connected PV-hydro systems [1]. Literature reveals a wide scope of investigations into converter topology, control strategies, performance optimization, and grid integration [2], [3]. Key areas include the design of suitable cascaded converter topologies like multi-level, modular, and hybrid configurations, with an emphasis on efficiency, voltage regulation, fault tolerance, and cost-effectiveness [4], [11]. Comparative studies help evaluate trade-offs between complexity, reliability, and performance [2], [5]. Control strategies such as fuzzy logic (FLC), sliding mode (SMC), model predictive (MPC), and PID control are explored to improve dynamic response and system stability under variable conditions. Advanced modeling and simulation techniques including CFD, EMT, and FEA are employed to analyze converters' thermal and electromagnetic behavior under diverse scenarios [6], [9]. Optimization algorithms and sensitivity analyses further refine performance metrics like power density and efficiency [9]. Efforts to enhance grid compliance focus on harmonic mitigation, reactive power control, and virtual inertia to support MVAC grid stability. Technological innovations such as wide-band gap semiconductors and integrated power management are also under active investigation [1]. Overall, the literature reflects a multidisciplinary push to overcome integration challenges and accelerate the deployment of reliable, efficient MVAC-connected PV-hydro systems.

III. DESIGN METHODOLOGY

The integration of hydropower and photovoltaic (PV) systems into medium voltage AC (MVAC) grid-connected configurations represents a promising path toward achieving renewable energy goals. A central component of this integration is the cascaded DC–DC converter, which enables efficient power transfer, voltage regulation, and grid synchronization [1], [5]. The proposed system architecture leverages the complementary nature of hydro and solar resources to enhance reliability and energy harvesting. PV arrays generate electricity from solar radiation, while hydro turbines convert hydraulic energy into electrical power at suitable locations [5]. Cascaded DC–DC converters, consisting of multiple converter stages connected in series, serve as vital links between renewable sources and the grid. These converters support step-up or step-down voltage conversion, modular operation, and precise power control [1], [2], [4], [8]. Sophisticated modeling techniques, using simulation tools like MATLAB/Simulink, are employed to evaluate parameters such as voltage regulation, energy efficiency, and dynamic performance [9]. The control strategy includes maximum power point tracking (MPPT), voltage regulation, and grid synchronization using advanced algorithms to maintain stable and optimal performance in varying environmental and electrical conditions [6], [10]. The Simulink model simulates each subsystem with detailed dynamics and control. Hydro units include turbine models, synchronous generators, speed governors, and excitation systems for voltage and frequency control [6]. Solar MPPT subsystems model PV arrays affected by irradiance and temperature and use DC-DC boost converters managed by P&O or Incremental Conductance MPPT algorithms [10]. Inverter blocks convert DC to grid-compatible AC using techniques like Sinusoidal or Space Vector PWM and include PLLs, closed-loop controllers, and protection mechanisms [3], [11]. Transformers step up inverter output to transmission voltage levels, with detailed simulation of losses and transient behavior [9]. A centralized DC link stabilizes voltage fluctuations and provides energy buffering to optimize conversion efficiency [1]. The system also features a Cascaded Subsystem for power combining and phase synchronization before grid injection. Smart relays and switchgear simulate fault protection and grid disconnection scenarios. Finally, the Grid Interface Block simulates grid parameters and disturbances such as harmonics and voltage sags to evaluate system resilience. The Power GUI manages solver settings and enables visualization for system analysis [1], [4], [6]. This comprehensive framework ensures optimized performance, fault tolerance, and grid compliance for PV-hydro systems, offering a robust foundation for future renewable energy integration [1], [5], [7].

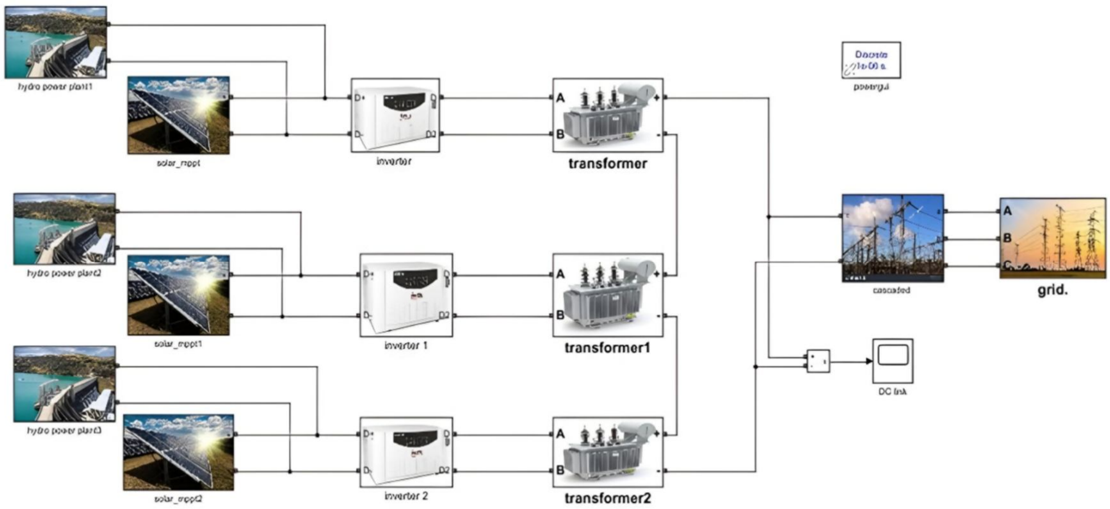

Figure 2 The Simulink Diagram of Proposed system

IV. RESULTS & DISCUSSION

The Simulink model illustrated above demonstrates the successful integration and coordination of multiple renewable energy sources specifically hydroelectric and photovoltaic systems within a unified grid-connected architecture. By employing discrete inverters, transformers, and control strategies for each hybrid subsystem, the model facilitates seamless energy conversion and synchronization with the main utility grid. The inclusion of MPPT control for solar arrays, dynamic turbine regulation for hydro plants, and real-time DC link voltage stabilization ensures optimal performance under varying environmental and load conditions. The cascading and transformer stages enable effective voltage transformation and power merging, while the grid interface accurately reflects real-world operational dynamics. Overall, the simulation yields robust and coherent results, validating the efficacy of the hybrid configuration in delivering stable, efficient, and grid-compliant power output.

A. DC Link Voltage

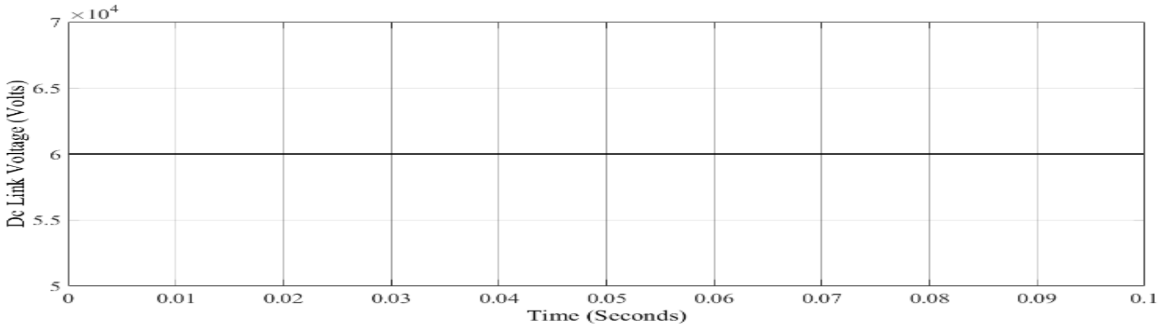

Figure 3 Dc Link Voltage (volts) vs. Time (seconds)

Figure 3 shows how a hybrid PV-hydro plant's DC link voltage varies over time due to changing solar and hydro input, with dynamic control ensuring stability and preventing overvoltage.

B. Synchronous Machine Voltage

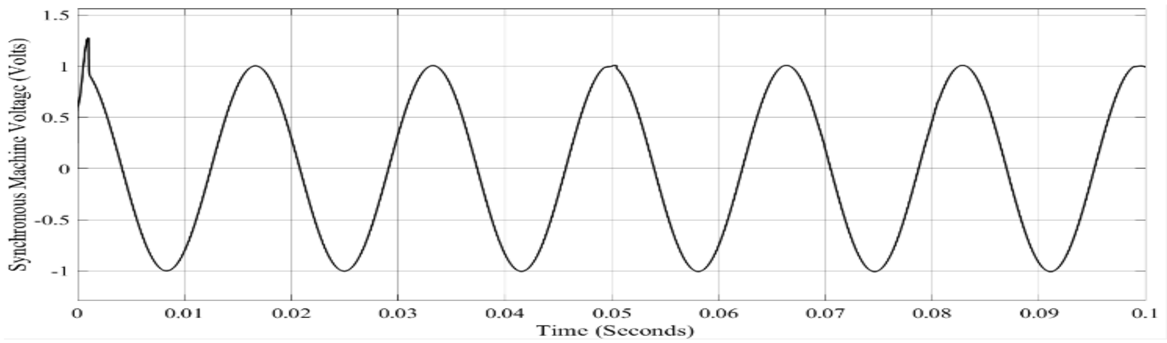

Figure 4 Synchronous Machine Voltage (volts) vs. Time (seconds)

Figure 4 illustrates the synchronous machine current in a hybrid PV-hydro system, showing initial sinusoidal transients followed by steady-state current, indicating effective stabilization by the cascaded DC-DC converter.

C. Synchronous Machine Current

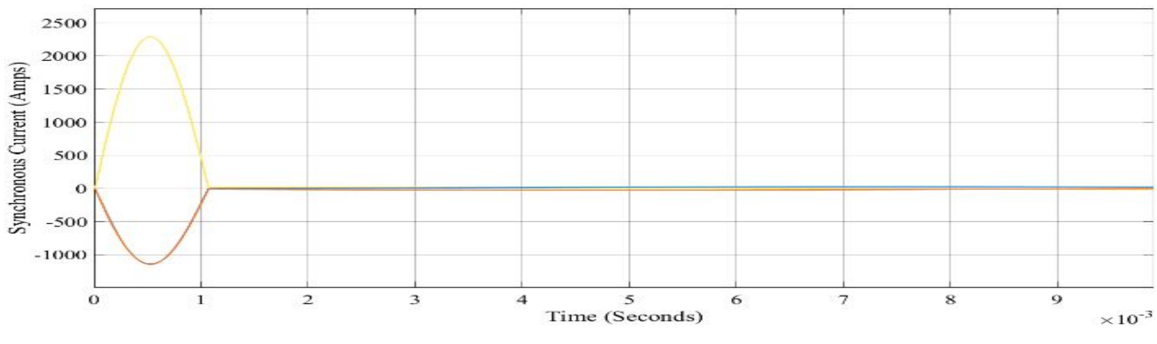

Figure 5 Synchronous Machine Current (amps) vs. Time (seconds)

Figure 5 shows synchronous current behavior in a hybrid PV-hydro system, highlighting effective cascaded DC-DC converter control that ensures rapid stabilization, reduced oscillations, and smooth grid synchronization for power quality.

D. Stator Current

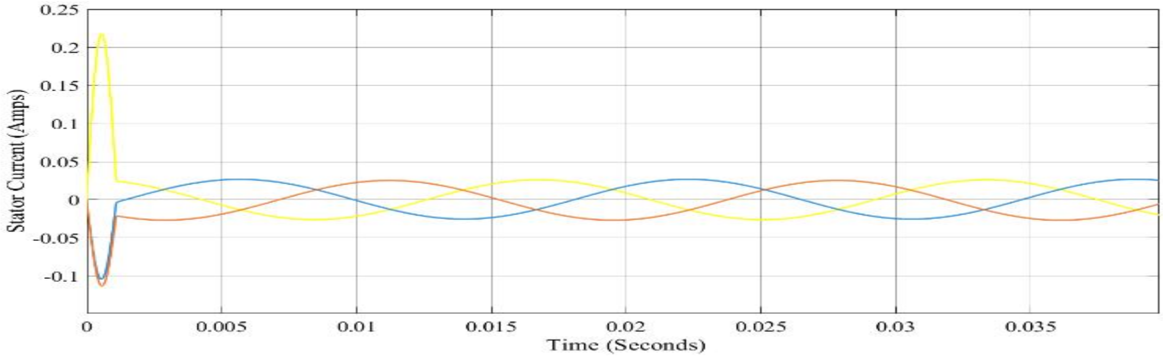

Figure 6 Stator Current (amps) vs. Time (seconds)

Figure 6 shows the stator current waveform in a hybrid PV-hydro system, illustrating transient oscillations, inrush current, and stable steady-state operation, emphasizing the importance of effective control for grid synchronization.

E. Rotor Speed

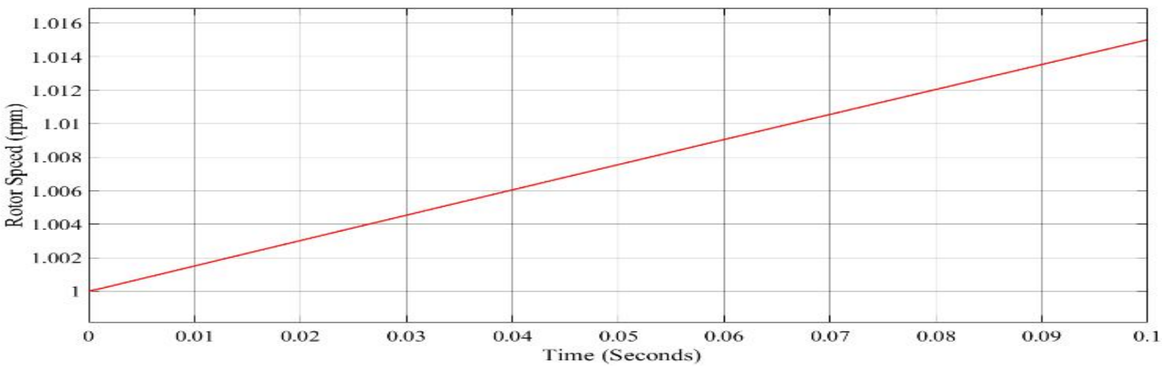

Figure 7 Rotor speed (rpm) vs. Time (seconds)

Figure 7 shows the rotor speed profile in a hybrid PV-hydro system, illustrating smooth acceleration to synchronous speed, highlighting the importance of coordinated cascaded DC-DC converter control for stable grid integration.

F. Voltage Frequency

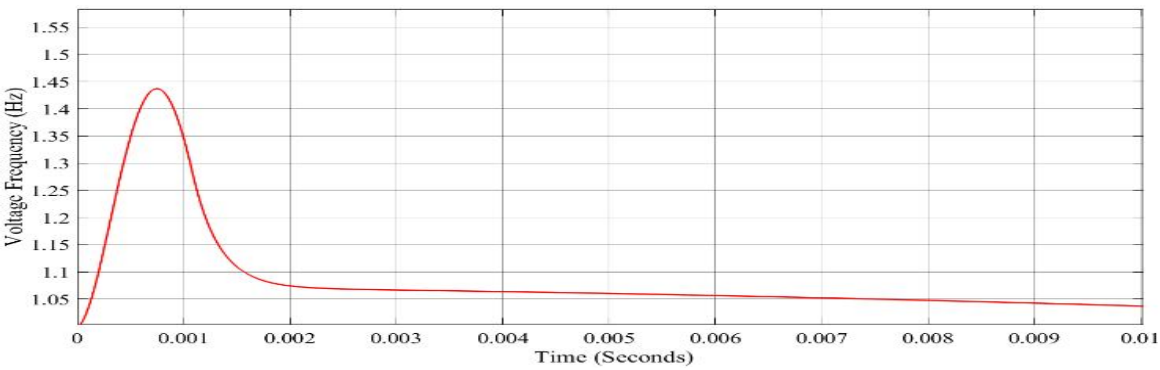

Figure 8 Voltage Frequency (Hz) vs. Time (seconds)

Figure 8 shows voltage frequency variation in a hybrid PV-hydro system, illustrating the cascaded DC-DC converter's role in controlling power flow, reducing frequency oscillations, and ensuring stable grid synchronization.

G. Solar Voltage

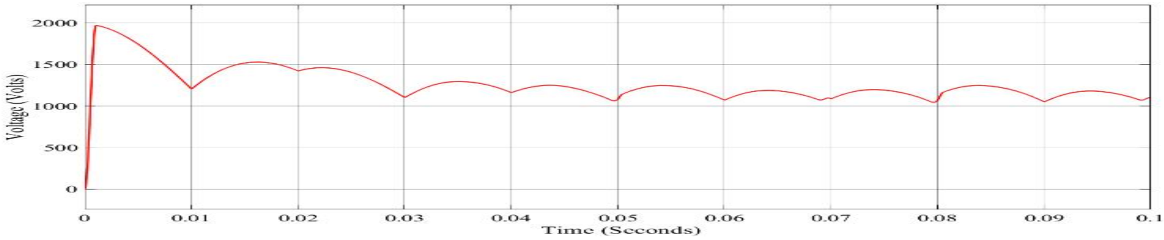

Figure 9 Solar Voltage (volts) vs. Time (seconds)

Figure 9 shows the solar voltage profile in a hybrid PV-hydro system, demonstrating the cascaded DC-DC converter's role in smoothing voltage fluctuations and ensuring stable, regulated power output to the grid.

H. Grid Input Voltage

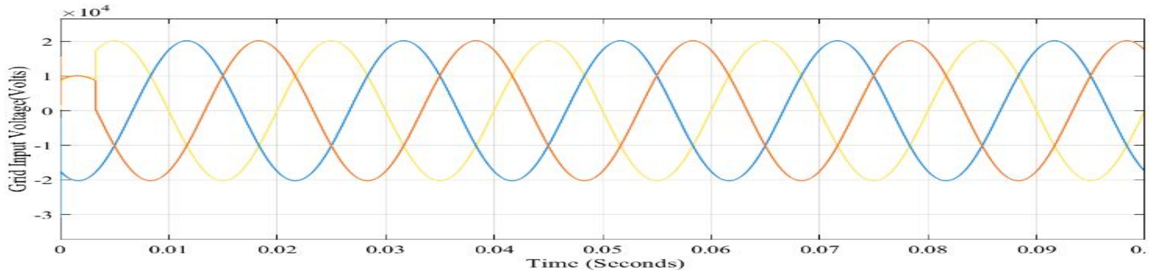

Figure 10 Grid input voltage (volts) vs. Time (seconds)

Figure 10 shows the hybrid PV-hydro plant's grid current, highlighting variations due to renewable energy availability, storage, and dynamic load management, ensuring stable supply and optimized grid integration for reliability.

I. Grid Input Current

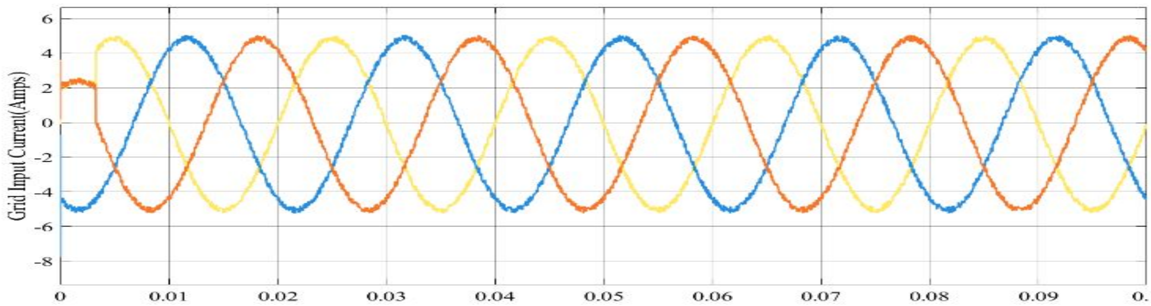

Figure 11 Grid Input current (amps) vs. Time (seconds)

Figure 11 shows the load current profile, illustrating spikes during peak demand and drops during off-peak hours. Load balancing mechanisms regulate current flow, ensuring grid stability without overloading the system.

J. Inverter Voltage

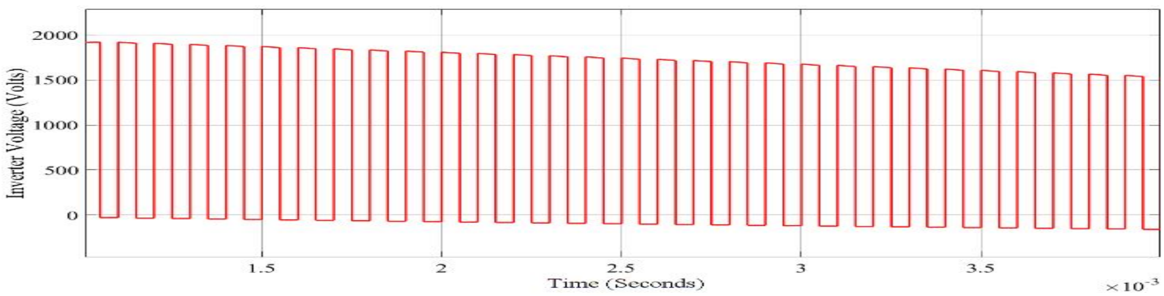

Figure 12 Inverter Voltage (volts) vs. Time (seconds)

Figure 12 shows the inverter voltage waveform of a hybrid PV-Hydro system with PWM control, converting DC to AC, filtered to produce a sinusoidal voltage, ensuring smooth integration and grid synchronization.

K. Inverter Current

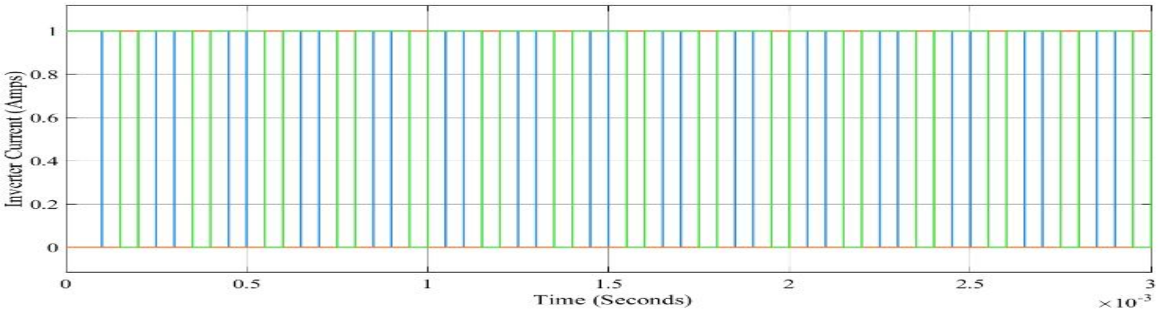

Figure 13 Inverter current (amps) vs. Time (seconds)

Figure 13 illustrates the inverter output current in the hybrid PV-hydro system, showing a stepped waveform typical of PWM operation, indicating raw output before filtering for grid synchronization.

V. CONCLUSION

This study offers a comprehensive analysis of cascaded DC-DC converters in medium-voltage AC grid-connected PV-hydro hybrid power systems, utilizing MATLAB/Simulink simulations to evaluate dynamic behavior, control mechanisms, and system performance. A key focus is enhancing energy efficiency, with particular emphasis on optimizing the electrical parameters and control strategies of the DC-DC converter stages. The Incremental Conductance (INC) algorithm for Maximum Power Point Tracking (MPPT) in PV systems demonstrates superior energy extraction under varying irradiance conditions, improving overall system efficiency. The study highlights the importance of robust control strategies, such as proportional-integral (PI) controllers, fuzzy logic, and model predictive control (MPC), for ensuring system stability and grid synchronization. Grid integration challenges, including voltage regulation, power quality, and power factor correction, are addressed, with converters incorporating features like reactive power compensation and harmonic suppression. Comparative analysis of converter topologies helps guide the selection of optimal configurations based on specific application requirements. The simulation outcomes validate control strategies and system performance under realistic conditions, providing valuable insights for renewable energy system design and implementation. Below are the tabular explanations of results compared with PV-Wind system and PV-Hydro system.

TABLE I. COMPARISON OF PV-WIND SYSTEM & PV-HYDRO SYSTEM

Aspect	Results	
	PV-Wind System	PV-Hydro System
Dc Link Voltage Stability	Maintained consistently at 60,000 V; No observable fluctuation.	Shows dynamic variation with solar/hydro input; stable under hybrid operation.
MPPT Voltage	Efficient string-level MPPT without communication delays.	High responsiveness under irradiance changes using INC algorithm.
Grid Voltage Behavior	Stable 33kV with minor variations during load shifts.	Voltage profile varies with load and generation; managed via voltage regulation.
Grid Current Behavior	Varies with solar/wind conditions; dynamically managed via distributed control.	Shows sinusoidal to flat transition; quick settling indicating strong control.
Inverter Performance	Modular multilevel inverter yields clean stepped sinusoidal output.	PWM based inverter shows raw to filtered transition; accurate grid synchronization.
Rotor Speed Profile	Not applicable because no presence of synchronous machine.	Smooth acceleration to synchronous speed; indicates good hybrid energy coordination.
Voltage Frequency Stability	Frequency stabilized after transient startup.	Frequency shows transient spike, then smooth decline to nominal range.
Control adaptability	Modules adapt to varying conditions without real time communication	Cascaded system dynamically adjust to PV/Hydro input shifts in real time
Overall system efficiency	Improved power conversion, fault tolerance, and reduced losses.	High energy extraction, improved power quality, and robust transient response.

REFERENCES

[1] Liu, Q., Liu, Y., Liu, H., & Yang, Y. (2018). Review on recent developments and future trends of cascaded DC–DC converters. IEEE Transactions on Power Electronics, 33(8), 6400-6418.

[2] Zhang, H., & Zheng, X. (2016). Research and development of DC–DC converters in renewable energy systems: A review. IEEE Transactions on Power Electronics, 32(5), 3570-3588.

[3] Li, Y., Liu, J., Wu, Y., & Zhang, H. (2018). A review of modular multilevel converters in medium-voltage grid-connected wind power systems. IEEE Transactions on Power Electronics, 33(4), 2959-2980

[4] Hu, Y., Sun, K., & Shen, Y. (2017). A review on topologies and control of multilevel converters for medium-voltage drives. IEEE Transactions on Power Electronics, 32(3), 2424-2440.

[5] Guerrero, J. M., Blaabjerg, F., Zhelev, T., & Baker, N. (2017). Cascaded converters in renewable energy systems: A review. IEEE Transactions on Sustainable Energy, 8(3), 1028-1040

[6] Bin, W., Guo, Y., & Fu, W. (2018). An overview of medium voltage power electronic converters for offshore wind energy systems. Renewable and Sustainable Energy Reviews, 82, 3300-3316.

[7] Azaza, M. S., & Sbihi, A. (2019). Modelling and control of a multi-level converter for medium voltage grid connected photovoltaic system. International Journal of Electrical Power & Energy Systems, 104, 533-547.

[8] Kermani, H., & Bazargan, M. (2017). A new single-stage high step-up DC–DC converter for medium voltage renewable energy systems. IEEE Transactions on Power Electronics, 33(7), 5820-5830.

[9] Wang, Z., Cao, Y., Liu, J., & Wu, H. (2019). Modeling and simulation of a wind-solar hybrid generation system based on PSCAD/EMTDC. IEEE Access, 7, 126486-126494

[10] Belhocine, M., Meziane, A., Kherbeche, A., & Rekioua, D. (2017). Performance comparison between traditional and improved MPPT algorithms for photovoltaic system under partial shading conditions. Energy Conversion and Management, 143, 300-312

[11] Kouro, S., Malinowski, M., Gopakumar, K., Pou, J., Franquelo, L. G., & Bin, W. (2017). Recent advances and industrial applications of multilevel converters. IEEE Transactions on Industrial Electronics, 64(11), 7269-7275.

[12] Lin, L., Li, X., & Jiao, L. (2019). Stability analysis and control strategy for cascaded wind turbine converters under unbalanced grid voltage conditions. IEEE Access, 7, 68671-68682.