

Article

A Finite Control Set–Model Predictive Control Method for Hybrid AC/DC Microgrid Operation with PV, Wind Generation, and Energy Storage System

Muhammad Nauman Malik , Qianyu Zhao and Shouxiang Wang * 

School of Electrical & Information Engineering, Tianjin University, Tianjin 300072, China; 6121000184@tju.edu.cn (M.N.M.); zhaoqianyu@tju.edu.cn (Q.Z.)

* Correspondence: sxwang@tju.edu.cn

Abstract

The global transition towards decentralized, decarbonized energy systems worldwide must include robust methods for controlling hybrid AC/DC microgrids to integrate diverse renewables and storage technologies effectively. This paper presents a Finite Control Set–Model Predictive Control (FCS-MPC) architecture for coordinated control of a hybrid microgrid comprising photovoltaic and wind generation, along with an energy storage system and MATLAB/Simulink component-level modeling. The islanded and grid-connected modes of operation are seamlessly simulated at the component level, ensuring maximum power point tracking and stability. The method has been experimentally validated through dynamic simulations across a range of operating conditions, demonstrating good performance: PV and wind MPPT efficiency > 99%, DC-link voltage control with <2% overshoot, AC voltage THD < 3%, and efficient grid synchronization. It is superior to conventional PID and sliding mode control in terms of dynamic response, voltage deviation (reduced compared to before), and power quality. The proposed FCS-MPC is an all-in-one solution to enhance the stability, reliability, and efficiency of modern hybrid microgrids.

Keywords: hybrid microgrid; model predictive control; renewable

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent imperatives of climate change, energy security, and technological advancement [1]. This shift is characterized by a decisive move away from centralized, fossil-fuel-based power generation towards a decentralized, digitalized, and decarbonized paradigm heavily reliant on distributed energy resources (DERs), which are primarily renewable sources like solar photovoltaics and wind turbines [2]. While this transition is crucial for a sustainable future, the inherent intermittency and stochastic nature of these resources pose significant challenges to the stability, reliability, and power quality of the traditional electrical grid. The microgrid concept has emerged as a foundational solution to this challenge, representing a localized cluster of DERs, energy storage systems, and controllable loads that can operate both interconnected with the main grid and autonomously as an island. This dual operational capability is paramount, as it ensures continuous power supply to critical loads during main grid outages, enhances resilience against extreme weather events, and allows for optimal utilization of local renewable generation [3]. Consequently, the development of sophisticated control strategies that can seamlessly manage this complex hybrid system



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across its two distinct operational modes is not merely an academic exercise but a critical enabler for the future resilient and efficient smart grid [4].

A microgrid's architecture fundamentally defines its capabilities and operational philosophy, with its configuration being primarily distinguished by its physical network type and its operational mode [5]. In terms of connectivity, a microgrid operates in either grid-connected or islanded mode. In the former, it synchronizes with the main utility grid, importing or exporting power to enhance stability, reduce energy costs, and provide ancillary services, while in the latter, it autonomously disconnects and self-governs during faults or planned isolation, maintaining its own voltage and frequency stability through local generation and storage to ensure uninterrupted power to critical loads [6]. Physically, the architecture can be designed as an AC, DC, or hybrid AC/DC microgrid: a traditional AC microgrid interfaces seamlessly with the existing AC utility infrastructure and most commercial loads, but requires inverters for DC sources like solar PV, introducing efficiency losses; a DC microgrid, more suited for data centers or electric vehicle charging stations, offers higher efficiency for integrating native DC sources and storage without conversion losses, yet necessitates inverters for AC loads; and a hybrid AC/DC microgrid elegantly bridges this divide, employing interconnected AC and DC sub grids linked through a bidirectional power converter, which allows for the flexible and efficient integration of diverse AC and DC sources and loads, optimizing overall system performance, reducing conversion stages, and enhancing reliability by providing multiple paths for power flow [7,8]. This architectural versatility enables the microgrid to function as a resilient, self-healing entity within the broader smart grid ecosystem.

The maximum power point tracking (MPPT) technique is essential for enabling photovoltaic (PV) and wind generation systems to operate at their highest efficiency under variable environmental conditions. In PV systems, MPPT algorithms dynamically adjust the operating voltage and current to maximize power extraction corresponding to changes in irradiance and temperature. Common PV MPPT techniques include perturb and observe [9], incremental conductance [10], fractional open-circuit voltage [11], and advanced approaches, such as fuzzy logic, neural networks, and hybrid approaches [12–14]. Similarly, wind generation systems rely on MPPT strategies that regulate the turbine's tip-speed ratio or generator torque to optimize aerodynamic energy capture. Popular methods include tip-speed ratio control [15], power signal feedback [16], and optimal torque control [17], along with intelligent methods, such as adaptive fuzzy controllers and machine learning-based approaches [18]. Without effective MPPT, a considerable portion of renewable energy remains untapped, leading to reduced energy yield and inefficiencies. In hybrid AC/DC microgrids, accurate and fast MPPT not only increases renewable penetration but also enhances power balance, reduces the dependency on storage and grid support, and ensures stable and cost-effective operation under dynamic operating conditions [19].

PID controllers are widely used in microgrid power electronics, but their reliance on parameter tuning, nested feedback loops, and PWM modulation makes the design complex and prone to latency, resulting in slow dynamic response. Their fixed gains and linear nature limit adaptability to renewable energy fluctuations, causing oscillations and degraded power quality [20–22]. To improve load sharing among distributed generation units (DGs), hierarchical control combining droop methods with inner current and outer voltage loops is commonly adopted, though still dependent on PID control and its associated complexity [23]. Enhancements, such as derivative-integral droop control [24] and adaptive virtual impedance strategies [25], have shown better transient and reactive power sharing. However, these methods increase control complexity and often depend on communication networks, which compromise reliability during failures [26]. The Lyapunov-based controller offers significant advantages for microgrid operation, pro-

viding a mathematically rigorous framework for ensuring large signal stability and robust performance under large disturbances. However, its practical implementation is often hindered by computational complexity and the challenge of accurately formulating the Lyapunov function for highly nonlinear and uncertain system dynamics [27]. The sliding mode control (SMC) overcomes these shortcomings by enforcing a sliding manifold that renders the system invariant to matched uncertainties and disturbances, ensuring robust stability without relying on precise system parameters. This approach eliminates the need for complex gain scheduling and provides consistently fast transient response, even under significant nonlinearities and varying operating conditions [28]. SMC faces chattering issues, which are mitigated in improved SMC techniques through methods, such as higher-order sliding modes, boundary layer saturation, or intelligent adaptive gains [29]. Despite their advancements, improved SMC techniques often still struggle with inherent chattering, complex gain tuning for time-varying systems, and limited ability to explicitly handle system constraints and multi-objective optimization [30,31]. A hybrid AC/DC microgrid topology that uses a three-port converter to realize significant benefits, such as the single power conversion process between subgrids that has less losses and higher efficiency, fewer semiconductors (12 IGBTs versus 18), a smooth transition between grid-connected and islanded-operating modes without controller reconfiguration, plug and play interface to distributed energy resources, and predictive online high-speed MPPT algorithm of solar energy (takes only low-level computing). Nevertheless, the suggested system has significant drawbacks: its offline MPPT is based on a fixed-temperature assumption, which restricts its flexibility to thermal changes in reality; the topology does not include fault-tolerant behavior and comprehensive protection mechanisms with respect to semiconductor failures; and the control strategy implies depending on pre-computed curves, which can be detrimental when the grid is affected by uncharacterized dynamic disturbances [32]. The unified control architecture offers the following benefits: smooth, communication-free operation with proportional power sharing; intrinsic fault tolerance against source failures and line faults without reconfiguring controllers; plug-and-play scaling to keep RESs at their peak power points; and experimental operation across a wide range of operating conditions. Nevertheless, it too has some drawbacks, including the complexity of control through the need to inject small AC values in DC connections, possible accuracy losses when communications fail or gross imbalances, sensitivity to parameter settings and changes in system topology in virtual impedance design, and the lack of validation of large-scale real-world deployments, which leaves the problem of practical implementation unresolved [33]. Distributed robust sliding mode control has key strengths: effective power sharing and balance control between parallel interlinking converters; robust disturbance rejection by an active built-in observer, which reduces chattering; robustness when trying to operate under a communication failure; plug-and-play events; and more advantages over traditional approaches when attempting to operate in the presence of an unknown disturbance. Conversely, its weaknesses include increased implementation complexity from combined observer and sliding mode designs, reliance on communication to coordinate and thus reduced autonomy in the face of disturbances in a network, sensitivity of parameter tuning to disturbance-estimation errors, and high computational cost from high-frequency control updates [34].

To overcome these limitations, the Model Predictive Control (MPC) scheme is adopted in the literature, where the optimal switching state of the power converter is determined in real time according to a specified cost function, enabling precise constraint handling, superior dynamic performance, and direct minimization of operational objectives. Despite its advantages, MPC is seldom reported in the coordinated control of multiple converters within microgrids, as existing research has primarily focused on system-level algorithms

for objectives [35,36]. However, these system-level approaches often neglect the structural intricacies of microgrids and the critical device-level control of power converters, creating a significant gap between high-level optimization and practical, reliable implementation. Furthermore, previous studies have predominantly focused on either AC or DC microgrids, while hybrid AC/DC architectures that combine the benefits of both remain underexplored. The lack of unified control strategies capable of coordinating PV, wind, ESS, and grid interfaces under both islanded and grid-connected modes represents a critical limitation in the current literature.

Unlike traditional linear and nonlinear controllers, Finite Control Set–Model Predictive Control (FCS-MPC) directly predicts converter behavior using a discrete model and applies the input that minimizes a predefined cost function [37]. The proposed FCS-MPC has a finite set of control points, making it computationally feasible via iteration-based optimization, and it provides a fixed, predictable computational load per sampling period of 25 μ s. In larger microgrids with several distributed generators, one can consider a decentralized or distributed MPC architecture, in which each local controller controls a set of converters, and some global coordination is provided through communication with neighbors. Moreover, event-based systems can reduce communication and computational loads by updating control actions on demand, thereby preserving performance and improving scalability.

There is still a severe divide between theory and practice. Current MPC work in microgrids focuses mainly on system-level power management that defines power set points but ignores the dynamic, switching-level behavior of power converters. These methods are based on ideal converter responses and do not address problems, such as switching losses, harmonic distortion, or short-term stability during mode switching. On the other hand, converter-level MPC studies typically consider individual converters without synchronizing multiple sources in a hybrid infrastructure. This is shown in this work, which suggests a single FCS-MPC model that considers discrete time models of all the essential converters, including PV boost, wind rectifier boost, bidirectional ESS converter, and connecting VSI, into one predictive control loop. This guarantees the simultaneous enforcement of high-level goals, such as power balance and MPPT, and low-level constraints, such as voltage/current limits and switching frequency.

Typically, based on the Euclidean distance between reference and actual signals, this approach offers robustness, fast transient response, and flexibility in handling nonlinearities, constraints, and multiple objectives. Owing to these advantages, FCS-MPC has gained prominence in power electronics applications such as grid-connected converters, active filters, and electrical drive control [38]. Nevertheless, the excellent performance of MPC depends on the availability of precise and timely future state information. Practical microgrids are criticized for this assumption because of the susceptibility of sensor networks and communication links. As critically noted in the literature on resilient load frequency control (LFC), Phasor Measurement Unit (PMU) faults and communication intermittency are common attacks that may result in data loss. Unless the control design explicitly accounts for these realistic imperfections, the stability and power quality of this system may be seriously impaired during such events, and the reliability of advanced control is compromised. Another similar issue crucial to the implementation of practical MPC is that its computational cost is inherently high and increases with system complexity, making it challenging to avoid communication networks for time-sensitive data exchange. This has been countered through the development of event-triggered control (ETC) schemes. Memory-based event-triggering with maximum time interval allowed conditions can achieve advanced ETC, resulting in a significant reduction in computation and communication burden by updating the control action only when needed, without compromising closed-loop performance. However, this is promising, and incorporating mechanisms of communication responsive-

ness into FCS-MPC models of microgrids is a delicate field that permits further analysis. In addition to single-point failures, the control structure should generally be resilient to system-wide uncertainty and coordinate among complex systems. This requires leaving behind the design of centralization or local designs. Studies of robust distributed control focus on such strategies in which the networked system has two or more controllers. Still, these controllers collaborate to maintain system stability and performance in the face of uncertainty in renewable generation, load changes, and the PMU failures described above. To ensure the stable operation of modern hybrid microgrids, it is necessary to design an MPC strategy that reflects this architectural resilience: the coordination of different sources, such as PV, wind, and storage, across AC and DC lines [39–41].

This work presents a unified application of FCS-MPC for hybrid AC/DC microgrids that ensures reliable and efficient operation under islanded and grid-connected modes. Unlike prior studies that focus either on converter-level dynamics or high-level optimization, the proposed approach bridges this gap by incorporating detailed converter modeling into the predictive control framework. Furthermore, the work demonstrates enhanced operational flexibility, reduced voltage deviations, and robust transient performance compared to conventional control methods. By explicitly handling system constraints and nonlinearities, FCS-MPC regulates the DC bus voltage, achieves accurate MPPT, and coordinates ESS charging and discharging for power balance.

In addition, the proposed framework enables seamless grid synchronization and manages bidirectional power flow in grid-connected mode, thereby enhancing dynamic stability, renewable utilization, and overall microgrid reliability. The key contribution of the article is given as follows:

1. Unlike conventional cascade linear control, the proposed Finite Control Set–Model Predictive Control (FCS-MPC) approach eliminates the need for PID tuning, PWM modulation, and complex coordinate transformations.
2. Switching level simulations are carried out using wind, PV, and battery modules to emulate realistic AC/DC microgrid operation. This ensures effective integration and control under dynamic, real-time conditions rather than relying on fixed reference profiles.
3. The proposed FCS-MPC strategy enhances DC bus voltage regulation by minimizing overshoot and oscillations under varying load and generation conditions, while also improving AC bus voltage quality with reduced harmonic distortion.

2. Architecture of Microgrid

The AC/DC microgrid architectures are categorized in the literature as AC-coupled, DC-coupled, and AC/DC-coupled microgrids, depending on the technique of how sources, loads, and buses are interconnected. It assesses power management techniques for both grid-connected and islanded operational modes, with control goals focused on voltage control, power balancing, and smooth mode changes. The study also discusses practical applications, communication systems, and how interlinking converters can be used to coordinate power flow between the AC and DC subsystems. Therefore, it presents future trends and research gaps, where AC/DC-coupled microgrids are becoming increasingly significant due to their ability to integrate renewable energy and DC loads efficiently [42]. This research is based on a hybrid AC/DC microgrid structure, an advanced topology designed to overcome the weaknesses of homogeneous AC or DC systems by combining the benefits of both. The main design idea, as explained in Figure 1, is to design a partitioned and fully integrated energy system whereby the sources of generation, storage, and loads are positioned on an AC or DC electrical bus depending on the characteristics of its origin to reduce the number of redundant power conversion steps and the corresponding power

conversion losses. It is a divided architecture consisting of two coupled sub-grids. The sub-grid is built around a shared DC link and is characterized by a voltage V_{dc} . This bus is the natural junction point between DC sources: the photovoltaic (PV) array, driven with a unidirectional DC-DC boost converter that has embedded maximum power point tracking (MPPT); and the battery energy storage system (BESS), which is linked via a bidirectional buck–boost converter to allow controlled charging and discharging. This DC bus is served by a wind generation system (WGS), which includes an AC generator, a front-end AC-DC rectifier, and a DC-DC boost converter to convert its variable AC output into a controlled DC input. This DC bus focus maximizes such primary resources and storage resources. In parallel with this, the AC sub-grid has standard distribution voltage and frequency (230 V/50 Hz) in Table 1. It feeds conventional AC loads and provides an interface to the primary utility grid at the point of common coupling (PCC). The nexus between these two separate electrical spheres is a two-way voltage-sourced interlinking converter (ILC), a flexible power-electronic interface. The ILC is not in a fixed operational mode; it is dynamically reconfigured by the central controller based on the system’s global state, enabling the architecture’s defining dual-mode functionality. The microgrid is synchronized with the primary grid in grid-connected mode. In this case, the ILC operates in grid-following mode. It controls the transfer of power P_{grid} and Q_{grid} between the DC and the AC sub-grids as set by an energy management system, effectively enabling the DC-side resources to either export excess energy or import during a power shortage. The primary grid provides a strict voltage and frequency reference V_g and f_g to ensure overall stability. The BESS in this state operates strategically in response to economic dispatch signals or in response to high-frequency ancillary services, such as ramp-rate control, and the PV and WGS in this state run at their peak available power.

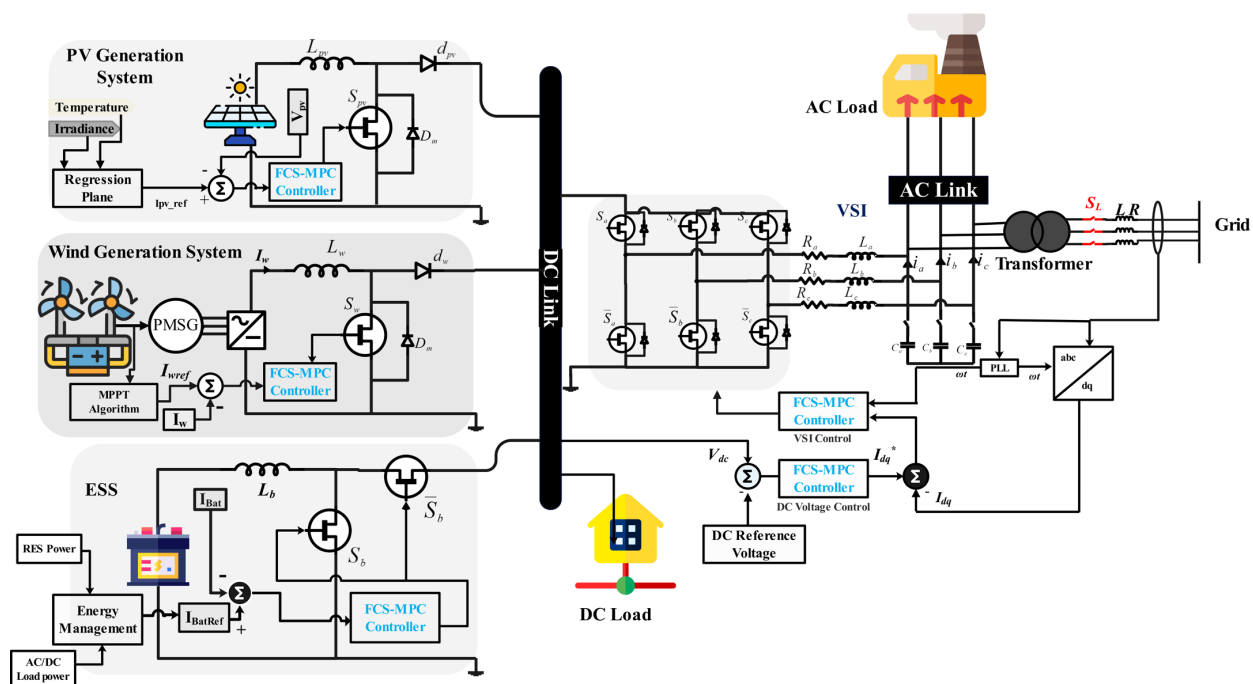


Figure 1. The architecture of the hybrid AC/DC microgrid is designed to operate in both islanded and grid-connected modes.

Table 1. Parameters of the hybrid AC/DC microgrid.

Component	Rated Value
DC Bus Voltage	400 V
AC Bus Voltage	230 V, 50 Hz
PV System	5 kW
Wind System	3 kW
BESS Capacity	10 kWh
BESS Converter	5 kW Bidirectional
Interlinking Converter	8 kVA

Islanded mode is a test of the system's resilience and is activated when a grid fault is detected or a planned disconnection is initiated at the PCC. This shift alters the control goals which is shown in Table 2. The entire grid reference is lost, and the BESS converter now maintains the DC-link voltage V_{dc} at a constant value to provide a stable, stiff DC bus for the entire microgrid. At the same time, the ILC is reformed into a grid unit. It stops the existing control and starts producing a high-quality, stable sinusoidal voltage waveform V_{ac} and f_{ac} on the AC bus, acting as a virtual synchronous generator to provide voltage and frequency references for all islanded AC loads. The renewable generators remain in MPPT mode, and the BESS actively corrects the real-time imbalance in power demand $\Delta P = P_{gen} - P_{load}$ through its dispatch, maintaining uninterrupted power balance and frequency stability of the isolated system.

Table 2. Detailed parameters of renewable sources and storage.

Component	Parameter	Value
PV Module	Maximum Power	250 W
	Open Circuit Voltage	37.5 V
	Short Circuit Current	8.5 A
	Diode Ideality Factor (a)	1.3
Wind Turbine	Rated Power	3 kW
	Blade Radius	2.5 m
	Optimal Tip-Speed Ratio λ_{opt}	8
	Optimal C_p	0.48
Battery (Li-ion)	Nominal Voltage	48 V
	Capacity	10 kWh
	SOC Operating Range	20–95%
	Charging and Discharging Efficiency	95%

2.1. Modeling of PV Generation System

An exact and computationally economical way to calculate the five major electrical parameters of a photovoltaic model or module with just one diode model. The authors use a genetic algorithm in combination with particle swarm optimization to optimize the model parameters, balancing speed and precision by maximizing the number of measurement points required to plot an I–V curve, typically 20–30 points per plot. Their method reduces computational cost by more than 60 percent, and fitting errors are very low across monocrystalline, polycrystalline, and amorphous PV technologies. This concentrates the approach highly applicable to integrating it into the PV system modeling and monitoring architecture, where accuracy and real-time performance are crucial [43]. The PV generation system is one of the core renewable energy sources in the microgrid that converts sunlight into electrical energy through PV panels. The PV generation system consists of a PV panel, a non-inverting buck–boost converter, and an MPPT controller [44]. The boost converter is connected to the output of PV panels and operates in continuous conduction mode to

track the MPPT. Figure 2 illustrates the internal circuit diagram of PVGS. The single diode equation of the PV module can be presented as

$$I_{pv} = I_{ph} - I_0 \left(e^{\frac{V_{0-pv} + I_{pv} R_s}{\alpha_{pv} V_t}} - 1 \right) - \frac{V_{0-pv} + I_{pv} R_s}{R_{sh}} \quad (1)$$

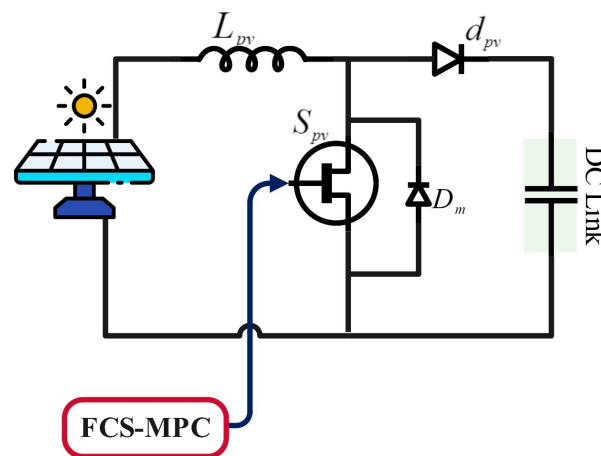


Figure 2. Circuit diagram of a PV generation system.

The boost converter is integrated with PV panels to step up the DC voltage, as shown in Figure 2. The configuration consists of one switch (S_{pv}), one diode (d_1), an inductor (L_{pv}), and an input capacitor (C_{pv}). The converter operates in two modes. In Mode I (switch ON), the diode d_1 is reverse-biased, and the input PV voltage (V_{pv}) is applied across the inductor L_{pv} , causing it to store energy. In Mode II (switch OFF), the diode d_1 becomes forward-biased, allowing the inductor to release its stored energy to the output and the load. This process results in an output voltage higher than the input voltage. The output voltage can be regulated by adjusting the duty cycle.

(D_{pv}) of the switching signal, thereby controlling the voltage gain of the converter. The mathematical model for the non-inverting buck–boost converter is expressed as follows:

$$\frac{dI_{pv}}{dt} = \frac{V_{pv} + I_{pv} R_{pv}}{L_{pv}} + \frac{V_{dc}}{L_{pv}} (1 - D_{pv}) \quad (2)$$

$$\frac{dV_{dc}}{dt} = \frac{(1 - D_{pv}) I_{pv} - I_{pvref}}{C_{dc}} \quad (3)$$

2.2. Modeling of Wind Generation System

A wind generation system (WGS) converts kinetic energy from wind into electrical energy through the use of wind turbines. These turbines incorporate permanent magnet synchronous generators, which efficiently convert the rotational energy from the turbine blades into electricity and allow efficient energy generation from different combinations of wind conditions. Furthermore, power generated from WGS is injected into a three-phase rectifier, which converts the AC power into DC. The output from this rectifier is then connected to a DC boost converter, which steps up the voltage to achieve the desired level. The unidirectional boost converter operates in continuous conduction mode to ensure power conversion and delivery. MPPT is essential for WGS to optimize the energy harvested from wind turbines. Two primary methods for implementing MPPT are the direct and indirect approaches. The indirect method is preferred for WGS due to the non-minimal phase characteristics of boost converters. This approach uses wind current

as a reference instead of voltage for more efficient and stable power extraction [45]. The internal circuitry of WGS and its integration with the grid are shown in Figure 3.

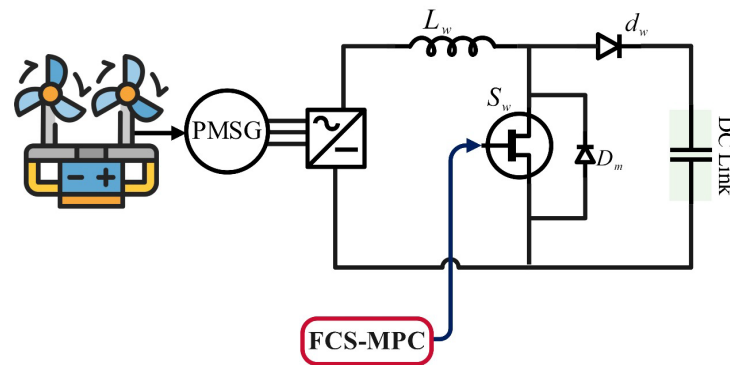


Figure 3. Circuit diagram of a wind generation system.

The extracted power from the wind turbine can be expressed as [46]

$$P_w = \frac{1}{2} \pi \rho V_s^3 r^2 C_p(\lambda, \alpha) \quad (4)$$

By substituting the value of V_s from $\lambda = \frac{\omega_r r}{V_s}$ into Equation (4), we get

$$P_w = \frac{1}{2\lambda^3} \pi \rho \omega_r^3 r^5 C_p(\lambda, \alpha) \quad (5)$$

Equation (5) highlights the dependence of extracted power on the tip-speed ratio, wind speed, turbine radius, and the power coefficient, as well as the rotational speed, with the blade pitch angle influencing the overall system performance. A boost converter is connected with a wind turbine generator that consists of a switch (S_w), and a diode (d_w). This converter has two modes: Mode I, which is when the S_w is ON and it allows current (I_w) to flow through the inductor (L_w). During this mode, the inductor stores energy. Mode II, which is when S_w is OFF, the stored energy in the inductor is released. The inductor generates a voltage that adds to the input voltage (V_w), resulting in a higher output voltage. The mathematical expression can be expressed as

$$\frac{dI_w}{dt} = \frac{V_w + I_w R_w}{L_w} + \frac{V_{dc}}{L_w} (1 - D_w) \quad (6)$$

$$\frac{dV_{dc}}{dt} = \frac{(1 - D_w) I_w - I_{wref}}{C_{dc}} \quad (7)$$

2.3. Modeling of Energy Storage System

ESS is an important aspect of RES-based microgrids. It serves to balance supply and demand, store excess energy generated by RESs, and provide backup during outages or peak demand periods. This backup system enhances the reliability, stability, and efficiency of microgrid operations. The key components of ESS include a battery bank, a bidirectional buck–boost converter, and SOC monitoring. A battery bank stores excess energy during periods of surplus generation and supplies power during deficits. A bidirectional buck–boost converter controls the charging and discharging operations by flowing power in both directions. The SOC monitoring system tracks the battery's energy level relative to its total capacity, ensuring optimized operation and longevity. Figure 4 depicts the internal circuitry of ESS that highlights the equivalent circuitry model of ESS and its integration with a bidirectional buck–boost converter.

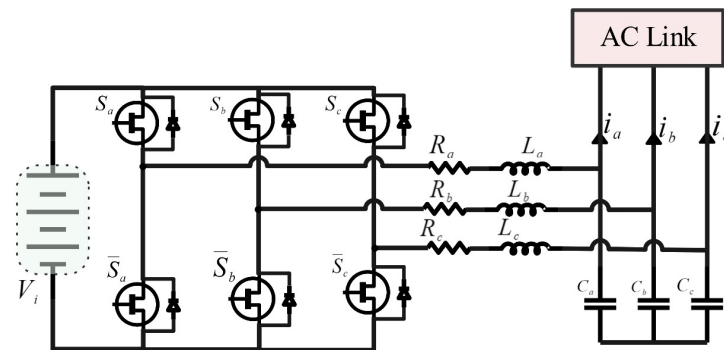


Figure 4. Circuit diagram of a voltage source inverter.

The battery model includes the following:

- SOC Limits: Operation is constrained between $SOC_{min} = 20\%$ and $SOC_{max} = 95\%$ to prevent over-discharge and overcharge, extending battery life.
- Efficiency Losses: Charging and discharging efficiencies $\eta_{ch} = \eta_{dis} = 0.95$ are incorporated into the power balance equations.
- Aging Effects: While detailed aging dynamics (cycle life and temperature effects) are not simulated in this study to focus on the primary control validation, the impact of efficiency and SOC limits is considered. Future work will integrate a comprehensive aging model.

A bidirectional buck–boost converter is connected with ESS to transfer energy in both directions. During the charging phase, the converter operates in buck mode, effectively reducing the input voltage to a level suitable for charging the battery. Conversely, during the discharging phase, the converter operates in boost mode to increase the battery voltage and fulfill the associated load requirements. The circuitry of the buck–boost converter consists of two IGBT switches S_b and $\bar{S}_b$, high-frequency inductor L_b and filter capacitor C_{dc} . It is essential that both switches of the bidirectional buck–boost converter are not ON simultaneously to prevent short circuits and ensure proper operation by allowing only one path for current flow at any given time. The operation of the bidirectional buck–boost converter can be expressed as

$$M_{op} = \begin{cases} 1, & \text{if } I_{bref} > 0 \\ 0, & \text{if } I_{bref} < 0 \end{cases} \quad (8)$$

In Equation (8), M_{op} represents the mode of operation of the converter, while I_{bref} denotes the reference current of the battery. This reference current is determined according to SOC and load demand through the energy management system. When $I_{bref} > 0$, the battery operates in discharging mode. In this mode, switch S_b is turned ON for a time $T_s D_{b1}$, where D_{b1} represents the duty cycle for discharging and T_s is the switching period. During this time, the converter boosts the battery voltage to meet the load requirements. Conversely, switch $\bar{S}_b$ is turned ON for a time $T_s(1 - D_{b1})$ and S_b is off. The mathematical expression of this boost mode can be expressed as

$$\frac{dI_b}{dt} = \frac{V_b - I_b R_b}{L_b} - \frac{V_{dc}}{L_b} (1 - D_{b1}) \quad (9)$$

$$\frac{dV_{dc}}{dt} = \frac{I_b D_{b1} - I_b}{C_{dc}} \quad (10)$$

In the above equations, I_b and V_b represent the battery current and voltage, respectively. Additionally, R_b and L_b denote the resistance and inductance associated with the converter

circuitry. Furthermore, I_b is the internal current of the battery. When the $I_{bref} < 0$, the converter operates in buck mode to charge the battery. In this mode, the switch S_b is OFF for time $T_s D_{b2}$ and switch $\overline{S_b}$ is ON for time $T_s(1 - D_{b2})$. The mathematical expression of this mode can be expressed as

$$\frac{dI_b}{dt} = \frac{V_b - I_b R_b}{L_b} - \frac{V_{dc}}{L_b} D_{b2} \quad (11)$$

$$\frac{dV_{dc}}{dt} = \frac{I_b}{C_{dc}} D_{b2} - \frac{I_b}{C_{dc}} \quad (12)$$

A centralized control duty cycle can be generated through virtual control, which simplifies the overall control system, as indicated by the equation below:

$$D_b = [(1 - D_{b1}) M_{op} + D_{b2}(1 - M_{op})] \quad (13)$$

This approach allows for the organized management of various system parameters, enhancing the efficiency and responsiveness of the control mechanism. By employing virtual control (D_b), the complexity associated with individual control actions is reduced, facilitating a more streamlined response to changes in system conditions. This unified control signal ultimately contributes to improved performance and stability of the system. The above equations can be simplified through virtual control as

$$\frac{dI_b}{dt} = \frac{V_b - I_b R_b}{L_b} - \frac{V_{dc}}{L_b} D_b \quad (14)$$

$$\frac{dV_{dc}}{dt} = \frac{I_b}{C_{dc}} D_b - \frac{I_b}{C_{dc}} \quad (15)$$

2.4. Modeling of Voltage Source Inverter

The operation of VSI is to convert the DC into AC and allow it to inject or absorb power with the main grid as needed. The circuitry of VSI is shown in Figure 4. To a better decoupled control of PQ grid-tied Voltage Source Inverters (VSIs). The HSRC provides an effective solution to the current harmonics introduced by nonlinear loads by integrating a Second-Order Generalized Integrator (SOGI) as a notch filter into the cascaded PI controllers in the synchronous rotating reference frame, which also independently follow active and reactive power references. The method is much more effective at enhancing the quality of power, as simulations show output current THD reduces to 2.21–16.53% with this method, and it provides an inexpensive, stable, and predictable alternative to complicated multi-controller or active filter designs [47]. The AC loads are modeled as balanced three-phase with a nominal power of 5 kW. DC loads are represented as constant power loads connected to the 400 V DC bus. Harmonic distortion is limited by the FCS-MPC cost function, ensuring THD < 3% under linear and nonlinear loading conditions. Unbalanced operation is reserved for future study. The LCL filter parameters are developed with a switching frequency $f_{sw} = 20$ kHz, a suitable current ripple < 10%, and a resonant frequency range of 500 Hz to 10 kHz. A damping resistor R_f is added to reduce resonance. The design has been optimized to achieve THD less than 3% under nonlinear loads. The mathematical modeling of the VSI by utilizing Park's and Clarke's dq transformations can be represented by the following set of equations:

$$\frac{dI_d}{dt} = -\frac{V_d}{L_f} - \frac{I_d R_f}{L_f} + \frac{V_0}{L_f} U_d + \omega_0 I_q \quad (16)$$

$$\frac{dI_q}{dt} = -\frac{V_q}{L_f} - \frac{I_q R_f}{L_f} + \frac{V_0}{L_f} U_q - \omega_0 I_d \quad (17)$$

$$\frac{dV_d}{dt} = -\frac{V_d}{RC_f} + \frac{I_d}{C_f} - \frac{I_{gd}}{C_f} + \omega_0 V_q \quad (18)$$

$$\frac{dV_q}{dt} = -\frac{V_q}{RC_f} + \frac{I_d}{C_f} - \frac{I_{gq}}{C_f} + \omega_0 V_d \quad (19)$$

In the above equations, R_f represents the resistance, L_f denotes inductor, C_f indicates a capacitor, and ω_0 represents the angular frequency. V_d and V_q are the voltage components in the dq axes, while I_d and I_q represent the current components in the same axes. Additionally, I_{gd} and I_{gq} signify the grid output currents in dq axes, respectively. If R_g and L_g denote the resistance and inductance of the grid, the rate of change in the direct axis grid currents can be expressed as

$$\frac{dI_{gd}}{dt} = -\frac{V_d}{L_g} - \frac{I_{gd} R_g}{L_g} - \frac{V_{gd}}{L_g} + \omega_0 I_{gq} \quad (20)$$

$$\frac{dI_{gq}}{dt} = -\frac{V_q}{L_g} - \frac{I_{gq} R_g}{L_g} - \frac{V_{gq}}{L_g} + \omega_0 I_{gd} \quad (21)$$

3. Proposed Methodology

A Finite Control Set–Model Predictive Control methodology is used in this work to control the operation of the proposed hybrid AC/DC microgrid. The controller diagram is shown in Figure 5. The process begins with mode selection, where the microgrid operates in either grid-connected or islanded mode. A reference generator produces set points for controlling, depending on system requirements. The predictive capability of the proposed controller is enhanced by external inputs such as temperature, irradiance, wind speed, and turbine operational data, which help anticipate variations in renewable generation. The controller solves a cost function and optimization problem to minimize operational costs, tracking errors, and other performance metrics while adhering to system constraints. The solution yields an optimal control action, which adjusts set points like PV reference current or wind reference current to MPPT operations of the RESs.

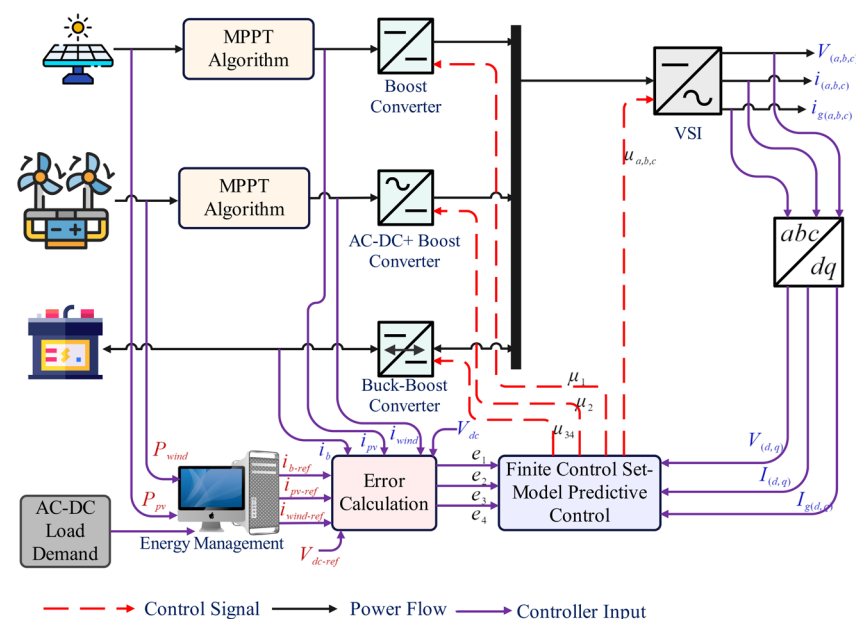


Figure 5. Block diagram of the proposed Finite-Control-Set-based Model Predictive Controller.

PV MPPT: The regression plane method is used to generate the reference voltage $V_{pv,ref}$ as a function of irradiance G and temperature T :

$$V_{pv,ref} = a_0 + a_1 \ln(G) + a_2 T \quad (22)$$

where coefficients a_0 , a_1 , and a_2 are determined from the PV module's characteristic curves.

Wind MPPT: The optimum torque control (OTC) method. The reference torque, T_{ref} , is determined based on the optimal power–speed curve:

$$T_{ref} = K_{opt} \omega^2 \quad (23)$$

where $K_{opt} = \frac{1}{2} \rho \pi r^5 \frac{C_{p,max}}{\lambda_{opt}^3}$ and ω represents the generator speed. The corresponding reference current, $I_{w,ref}$, is subsequently determined using the generator's torque constant.

The FCS-MPC strategy is applied and tested in MATLAB/Simulink (2024b) using a fixed-step discrete solver with $T_s = 25 \mu s$, corresponding to a switching frequency of $f_{sw} = 20$ kHz, DC bus voltage $V_{dc} = 400$, AC grid voltage of 230 V/50 Hz, LCL filter values $L_f = 3$ mH, $C_f = 10 \mu F$, and PV/wind/ESS models as in Section 2. Power electronic switches are idealized as antiparallel diodes of ideal IGBTs; sensor measurements are suitable, with no communication delays except noted. All simulations are performed in 10 s to capture dynamic transitions between islanded and grid-connected modes.

Converter Losses: Conduction losses in switches and diodes are modeled using equivalent series resistances (ESR) for inductors and capacitors, and diode forward voltage drops.

Switching Losses: While the simulations use ideal IGBTs for clarity, a switching loss factor is included in the efficiency calculations for each converter (boost, buck-boost, and VSI). The overall efficiency of the power stage is estimated at 96–98%, consistent with commercial components.

The primary focus of this paper is on the control strategy's dynamic performance and stability. Including detailed loss models does not alter the fundamental conclusions regarding FCS-MPC's superiority in voltage regulation, MPPT, and mode transition. However, error-sensitive optimization is noted as a valuable extension for future work.

The operation of the PV generation system, wind generation system, and ESS is controlled by providing the control signals generated. For the PV system, based on the PV module specification, we use the regression plane method to generate the MPPT references as given in [13]. For WGS, we generate the current reference through the optimum torque control method as given in [29]. FCS-MPC ensures that these RESs operate at their MPPT to maximize energy capture. The controller provides precise control signals to the power converters to maintain the optimal voltage and current levels required for MPPT.

This allows for efficient tracking of the reference values. The MPC controller manages the charging and discharging of the ESS in case of islanded mode to balance the power supply and demand. If renewable generation is less than the load, the controller commands the ESS to discharge. If there is a surplus of renewable power, it commands the ESS to charge, storing the excess energy for later use.

In the case of grid-connected mode, the MPC transfers the power to the main grid and ensures grid synchronization. VSI operation of the microgrid is controlled by using two complementary switches of each leg, whose states are digitally represented by the Boolean values 1 (ON) or 0 (OFF). These switches serve as the primary decision variables that actions are directly determine the inverter's output voltage, yielding eight distinct switching states that correspond to six active and two null voltage vectors.

This paper will fill this gap by proposing a single Finite Control Set–Model Predictive Control (FCS-MPC) framework to coordinate multiple power converters (PV, wind, ESS,

and interlinking converter) in a hybrid AC/DC microgrid. This framework is compatible with islanded and grid-connected operation without requiring reconfiguration or controller-mode-specific operation, and hence enabling robust transitions and steady operation. The suggested methodology integrates high-reliability, discrete-time models of each power electronic converter (PV boost converter, wind rectifier-boost system, bidirectional buck-boost ESS converter, and voltage source inverter) into the predictive control loop. This enables the controller to predict the system's behavior in dynamic situations and to tightly control the cost function (voltage/current limits and switching frequency) rather than requiring cascaded PID loops and external limiters. A new multi-objective idea is developed to maximize:

- DC bus voltage regulation;
- PV and wind power, and maximum power point tracking;
- Charging/discharging of the power balance ESS;
- Grid synchronization, power quality (harmonic reduction and unity power factor);
- Minimization of switching frequency.

This combined strategy enables the controller to address the system's limitations directly and achieve optimal performance between inconsistent goals without hierarchical or decoupled control structures. The proposed FCS-MPC is switching-level-based, and a finite set of possible inverter vectors is selected directly, without PWM modulation or duty-cycle computation. It eliminates delays caused by modulators, enhances dynamic response, and simplifies the control architecture by removing the need for coordinate transformations (dq decoupling networks) and PI tuning. A predictive voltage control scheme with a phase-locked loop (PLL) is developed to provide a smooth, continuous transition between islanded and grid-connected modes. When the interlinking converter operates in islanded mode, it acts as a voltage source to stabilize the AC voltage. As a grid-following source that uses active/reactive power control, it operates in grid-connected mode. A smooth transition is achieved by setting the frequency reference slightly above the grid frequency until phase matching is achieved, then reconnecting. The approach is confirmed by component-level simulations in MATLAB/Simulink using detailed models of PV modules (single-diode equation), wind turbines (aerodynamic power model), Li-ion batteries (SOC-based dynamics), and switching converters. This is to ensure the controller is used in real-time operation, dynamic conditions, rather than idealized, steady-state conditions, so that it can be applied in practice and tested for robustness.

The proposed FCS-MPC employs a centralized control architecture that utilizes measurements from the following sources:

- DC-bus voltage and currents associated with photovoltaic (PV) systems, wind turbines, and battery energy storage systems (BESS);
- AC-bus voltages and currents at the point of common coupling (PCC);
- Grid voltage and frequency measured using a phase-locked loop (PLL).

Inter-converter communication is not required for basic operation. For mode transitions and power sharing, a low-bandwidth communication link is assumed between the central controller, the grid relay for islanding detection, and the BESS controller. Sampling is performed synchronously with a period of $T_s = 25 \mu\text{s}$.

The sampling time T_s is also a design parameter that is vital in ensuring that the control performance and the hardware implementation meet the following requirements:

Nyquist Criterion and Control Bandwidth: The sampling frequency is required to be many times greater than the target control bandwidth, in this case, 1 kHz, which is sufficient to capture microgrid dynamics. $f_s = \frac{1}{T_s} = 40 \text{ kHz}$ satisfies this.

Relationship to Switching Frequency: In FCS-MPC, the maximum switch period possible is determined by the sampling period. With a switching frequency of 20 kHz $f_{sw,max} = \frac{1}{2T_s}$, a sampling time of 25 μ s, and not less than one sampling interval per switch transition, the maximum switching frequency of 20 kHz is achievable. This is in line with productive IGBT capabilities and restricts switching losses.

Computational Feasibility: 25 μ s gives enough time over a modern digital signal processor (DSP) to identify the optimizing voltages (9 vectors) by means of the computation.

The computational cost of the suggested controller is predictable and constant. During each sampling period, the cost function for the seven acceptable voltage vectors of a two-level VSI must be evaluated. The worst-case performance time has been profiled to about 10 μ s on a Random Instruments TMS320F28379D DSP (200 MHz), which is 40% of the 25 μ s sampling interval. This provides sufficient time to acquire sensor data, communicate, and perform other wasteful activities, and it has been proven that real-time implementation can be achieved on the industry-standard platform.

These possible voltage vectors are mathematically defined as

$$V_i = \begin{cases} \frac{2}{3} V_{dc} e^{j(i-1)\frac{\pi}{3}} & (i=1,2,\dots,6) \\ 0 & (i=0,7) \end{cases} \quad (24)$$

The operational framework of the microgrid encompasses islanded and grid-connected modes, each of which is detailed in the subsequent section.

3.1. Islanded Mode

The block diagram of the proposed control strategy for the AC/DC converter in islanded operation is illustrated in Figure 6. In this mode, the bypass switch is ON while the circuit breaker is OFF, decoupling the microgrid from the main grid. The dynamics of the LC filter capacitor are governed by

$$C_f \frac{dV_c}{dt} = I_f - I_L \quad (25)$$

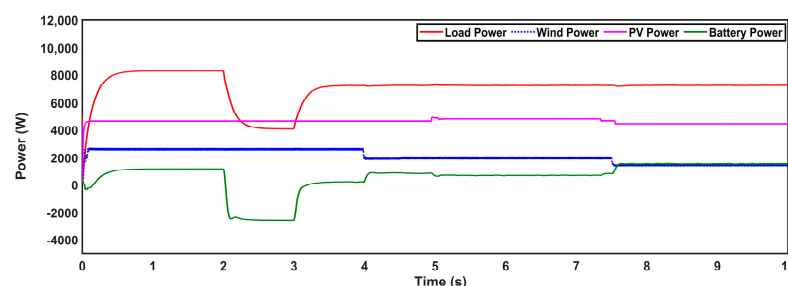


Figure 6. Islanded mode load profile and power contribution of various energy sources.

In above Equation (24), V_c denotes the capacitor voltage vector, C_f is the filter capacitance, and I_L is the filter capacitance. The mathematical model of the AC/DC interlinking converter is expressed as

$$V_i = I_f R_f + L_f \frac{dI_f}{dt} + V_c \quad (26)$$

In the above equation, V_i represents the converter output voltage vector, R_f and L_f are the filter resistance and inductance, respectively, and I_f is the filter current vector. Building upon this operational framework, during islanded mode, the ESS regulates the DC bus voltage to ensure continuous power availability. The AC/DC interlinking converter subsequently operates in a manner analogous to an uninterruptible power supply (UPS), employing a Model Predictive Voltage Control (MPVC) strategy to provide a stable and

high-quality AC voltage for critical loads. Consequently, the capacitor voltage of the LC filter is designated as the primary control objective for the predictive controller, ensuring precise regulation and robust performance in the absence of grid support. The state space representation for the islanded operational mode is derived by integrating Equations (25) and (26), yielding the following continuous-time linear system:

$$\dot{x} = Ax + Bu \quad (27)$$

In the above equation $x = [V_c, I_f]^T$, input vector $u = [V_i, I_L]^T$, and system matrices are defined as [34]

$$A = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} \end{bmatrix}, B = \begin{bmatrix} 0 & -\frac{1}{C_f} \\ \frac{1}{L_f} & 0 \end{bmatrix} \quad (28)$$

By solving the linear state-space differential Equation (27), the discrete-time predictive model is obtained through exact discretization [28]:

$$x(k+1) = e^{AT_s}x(k) + A^{-1}(e^{AT_s} - I_{2 \times 2})Bu(k) \quad (29)$$

This model enables the prediction of the capacitor voltage vector at the $(k+1)^{th}$ sampling instant. To ensure precise voltage regulation, the cost function is formulated to minimize the tracking error in the stationary $\alpha\beta$ reference frame:

$$J_v = (V_{c\alpha}^{ref} - V_{c\alpha}^{(k+1)})^2 + (V_{c\beta}^{ref} - V_{c\beta}^{(k+1)})^2 \quad (30)$$

The voltage vector that minimizes J_v is selected and applied during the next sampling period. This approach ensures tight decoupled control of the α & β components, forcing the capacitor voltage V_c to accurately track its sinusoidal reference, thereby establishing a stable and high-quality output voltage. Building upon the established predictive voltage control framework, grid synchronization is facilitated using a phase-locked loop (PLL) to accurately detect the grid voltage amplitude and frequency. A reference voltage for the cost function J_v in Equation (30) is then generated with the same amplitude as the grid but at a marginally higher frequency, while preserving the phase angle θ^* previously maintained during islanded operation. This deliberate frequency offset causes the microgrid voltage phasor to rotate at a slightly different angular velocity than the grid phasor, despite their identical amplitudes. Once the phase angles of both voltages align, a condition detected by the PLL, the circuit breaker can be closed, enabling a smooth and transient-minimized transition to grid-connected operation. Grid synchronization is performed using a SOGI-PLL with a 50 Hz bandwidth and a damping ratio of 0.707. Its dynamic response is quick and precise, with phase-sensitive disturbance detection, as confirmed during mode transitions. The dq transformations and reference generation of both grid-following and grid-forming modes are determined by the PLL angle θ .

Mode transition logic is a PLL phase alignment mode transition logic, but it is designed to be resistant to grid disturbances. The SOGI-PLL has harmonic rejection functions and ensures correct synchronization under grid voltage THD of 5%. Moreover, the circuit breaker closure is only activated when phase coordination is maintained, along with voltage and frequency variations within safe limits $|\Delta V| < 5\%$, $|\Delta f| < 0.2$ Hz over a specified duration of 5 cycles. The multi-condition check avoids undesirable transitions during distorted or transient grid conditions, as confirmed in simulation under harmonic, unbalanced, and sag conditions.

3.2. Grid-Connected Mode

When the microgrid is synchronized and tied to the utility, the interlinking converter operates as a grid-following power conditioner: it regulates the DC-bus energy by commanding active power exchange with the grid while maintaining a near unity power factor at the point of common coupling (PCC). The plant dynamics seen from the converter output (grid side of the filter) are well described by the lumped $L_f - R_f$ model:

$$V_i = V_g + R_f I_f + L_f \frac{dI_f}{dt} \quad (31)$$

where V_i is the inverter voltage vector selected from the finite set of two-level space vectors, V_g is the grid voltage at the PCC, and i_f is the filter inductor current. Using the power invariant $\alpha\beta$ frame, instantaneous three-phase active and reactive powers are

$$P = \frac{3}{2} \operatorname{Re}\{V_g \bar{i}_f\} = \frac{3}{2} (V_{g\alpha} i_{f\alpha} + V_{g\beta} i_{f\beta}) \quad (32)$$

$$Q = \frac{3}{2} \operatorname{Im}\{V_g \bar{i}_f\} = \frac{3}{2} (V_{g\beta} i_{f\alpha} - V_{g\alpha} i_{f\beta}) \quad (33)$$

with $(\bar{\cdot})$ the complex conjugate. Discretizing (34) with sampling time T_s (forward Euler), the one-step prediction of i_f under a candidate voltage vector $V_i^{(m)}$ is

$$i_f(k+1) = i_f(k) + \frac{T_s}{L_f} (V_i^{(m)} - V_g(k) - R_f i_f(k)) \quad (34)$$

Substituting (34) into (32) gives $P(k+1), Q(k+1)$ for each admissible vector $V_i^{(m)}$ without any continuous optimization.

Cost and selection (power domain form): With active/reactive references $\{P_{ref}, Q_{ref}\}$, the enumerative FCS-MPC selects

$$J_p^{(m)} = \left(P_{ref} - P^{(m)}(k+1)\right)^2 + \left(Q_{ref} - Q^{(m)}(k+1)\right)^2 + \lambda_{sw} \|\Delta S^{(m)}\| \quad (35)$$

and applies the minimizing vector $V_i^{(m^*)}$ during the next sample. The last term penalizes unnecessary commutations using the Hamming distance of the switch state S ; we also employ a small keep state hysteresis (if $J_{keep} - J_{best} < \epsilon$ retain the current state) to curb chatter.

Alternative current domain cost (dq form): Using the PLL angle θ to form the dq frame (with a built-in angle auto-alignment described below), the same predictor (34) is rotated to obtain $i_{dq}(k+1)$, and we minimize as follows:

$$J_I^{(m)} = \|i_{dq,ref} - i_{dq}^{(m)}(k+1)\|_2^2 + \lambda_i \|i_f^{(m)}(k+1) - i_f(k)\|_2^2 + \lambda_{sw} \|\Delta S^{(m)}\| \quad (36)$$

The tuning of the weighting factors in the cost functions (35) and (36) is through a systematic process. The initial values are set by physical scaling of individual terms, such as λ_{sw} , which is relative to the nominal power, to correct the switching effort. The reduction in the Integral of Time-weighted Absolute Error (ITAE) of DC voltage and AC power tracking over a variety of operating conditions is achieved through final tuning via simulation iteration. Sensitivity analysis, testing all weights with a 50% change, ensured that the leading performance indicators (DC voltage overshoot $< 2\%$, THD $< 3\%$) did not change significantly.

The transition is managed as follows:

Section 2.4 of the dq modeling presents a continuous-time dynamic model for controller design and stability analysis. In the case of FCS-MPC implementation, the system is discretized, and the prediction is made in the stationary $\alpha\beta$ frame to eliminate the need for coordinate transformations in the online optimization loop. The dq reference $I_{d,ref}, I_{q,ref}$ produced by the high-level power commands is converted to $\alpha\beta$ reference with the inverse Park transformation, depending on the angle of the PLL. The cost functional Equation (36) is computed in the $\alpha\beta$ frame, and the optimum voltage state is chosen directly in the finite space of the inverter switching states. This method does not require PWM modulators, making the predictive control loop much simpler than dq based reference generation.

where the damping term (second term) reduces the current ripple. We map power references to current references using the instantaneous PCC magnitude $|V_g| = \sqrt{V_{g\alpha}^2 + V_{g\beta}^2}$:

$$i_{d,ref} = \frac{2}{3} \frac{P_{ref}}{|V_g|}, \quad i_{q,ref} = -\frac{2}{3} \frac{Q_{ref}}{|V_g|} \quad (37)$$

Reference generation from DC side power balance: To regulate the dc bus without relying on a slow integral loop, we use a physics-based power command. Let $E = \frac{1}{2} C_{dc} V_{dc}^2$ be the capacitor energy. The net power into $\dot{E} = C_{dc} V_{dc} \dot{V}_{dc}$ neglecting small losses, balancing the DC link yields the feed-forward command:

$$P_{ref} = -C_{dc} V_{dc} \dot{V}_{dc} - K_d (V_{dc} - \ddot{V}_{dc}) \quad (38)$$

which we found gives faster and better damped V_{dc} regulation than a pure PI outer loop. (If desired, the closed-form mapping that includes R_f losses can be used: solve $P_{dc} = P_{ac} - \frac{2}{3} \frac{P_{dc}^2}{V_{dc}^2} R_f$ for P_{ac} and set $P_{ref} = P_{ac}$).

Specifically, the instantaneous PCC angle $\phi = \text{atan2}(V_{g\beta}, V_{g\alpha})$ computed from the power invariant Clarke variables is used to correct the PLL angle prior to the Park transformation, which enforces $V_q \approx 0$ at the PCC and improves i_{dq} tracking and power factor regulation even in the presence of sensor placement differences or transformer vector group shifts. Current references are synthesized from the instantaneous PCC magnitude $|V_g| = \sqrt{V_{g\alpha}^2 + V_{g\beta}^2}$ according to (37), avoiding RMS/peak conversion artifacts, e.g., $\sqrt{2}$ and $\sqrt{3}$ and maintaining consistency during voltage sags or harmonic distortion. To limit unnecessary commutations and the associated EMI, the selection cost includes a switching effort term $\lambda_{sw} \| \Delta S \|_1$, together with a small keep-state hysteresis band, this combination reduces chattering without resorting to mixed integer or variable-horizon optimization. Finally, because the inverter input belongs to a finite set of eight two-level space vectors, the controller operates by enumeration; the cost in (36) (power domain) or (37) (current domain) is evaluated for all admissible candidates each sampling period, and the minimizer is applied. No duty-cycle synthesis, PWM stage, or QP/MIQP solver is required, yielding a fixed and predictable computational load per sample.

The equation of power balance between ESS and the grid as the secondary source is as follows:

$$P_{dc} = P_{pv} + P_{wind} + P_{batt} - P_{load,dc} \quad (39)$$

The BESS in the islanded mode sustains the DC-link voltage by

$$C_{dc} \frac{dV_{dc}}{dt} = I_{pv} + I_{wind} + I_{batt} - I_{load,dc} \quad (40)$$

where I_{batt} is controlled by FCS-MPC in the compensation of $\Delta P = P_{gen} - P_{load}$.

In grid-connected mode, the grid compensates for any power mismatch.

$$P_{grid} = P_{load} - (P_{pv} + P_{wind} + P_{batt}) \quad (41)$$

The cost function of the FCS-MPC combines this approach by deriving the reference for the interlinking converter from the power balance error.

The uncertainty of the grid impedance is recognized as a practical challenge. The predictive model uses the grid voltage V_g measured at the PCC, which is inherently affected by grid impedance. The controller's tolerance to incompatibilities in the model is tested through simulations in which L_g and R_g vary by ± 20 percent. Enhanced robustness across a broad range of impedances may be incorporated into future research by including a disturbance observer or an adaptive prediction model.

4. Results and Discussion

To validate the effectiveness of the proposed FCS-MPC strategy, dynamic simulations of a hybrid AC/DC microgrid integrating PV, wind, battery energy storage, and the main grid were carried out for a period of 10 s under two distinct operating conditions as shown in Table 3. The analysis focuses on evaluating renewable power extraction, load support, battery management, voltage regulation, and grid synchronization performance. The MPPT of the PV generation system and the wind generation system is shown in Figure 6. It is observed that the proposed controller efficiently tracks PV reference voltage and wind reference current, which are generated via the regression plane method and optimum torque control method, respectively.

Table 3. Comparison of multiple techniques.

Performance Metric	Proposed FCS-MPC	Cascaded PID	SMC	Hierarchical Droop	Summary
DC Voltage Overshoot	<2%	8–10%	5%	Varies	For a 1 kW load step
DC Voltage Settling Time	<20	>100	<50	>200	-
AC Voltage THD	<3%	<5%	<4%	<3%	With a nonlinear load
Mode Transition Time	<30	Requires logic reset	-	Requires logic reset	Grid connected to the islanded mode

Although component-level simulations rigorously validate the dynamic performance and control logic of the FCS-MPC strategy across a broad range of conditions, this paper limits its scope to simulation. A weakness in evaluating real-time computation burden, electromagnetic interference, and long-term reliability under physical limitations is the lack of Hardware-in-the-Loop (HIL) or experimental validation.

The findings for both islanded and grid-connected operations collectively underscore the robustness and adaptability of the proposed control method. The obtained results are presented for islanded operation and grid-connected operation, which collectively highlight the robustness and adaptability of the proposed control.

The main aim is to confirm the dynamic response and stability characteristics of the FCS-MPC algorithm, which operates on the milliseconds-to-seconds time scale. Although longer stochastic profile simulations would be helpful for studies of energy management, they are less valuable for validating control algorithms when dynamic performance is determined. Every test sequence, run at 10 s intervals, includes 3–5 full transient events, providing a strict test of the controller's behavior in the worst case while remaining computationally efficient as shown in Table 4.

Table 4. Performance comparison of the proposed FCS-MPC with contemporary control techniques.

Control Domain/Feature	Proposed FCS-MPC	Comparison with Other Techniques
Dynamic Response and Transient Performance	Superior and Fast. Achieves direct switching control without modulator delay, enabling a rapid response to generation and load transients	• PID: Slow due to nested loops and PWM latency [20,21] • SMC: Fast but prone to chattering [28,30] • Hierarchical: Moderate, limited by inner loop bandwidth [23]
Constraint Handling and Multi-Objective Control	Explicit and Direct. System constraints (e.g., voltage limits, current saturation) are seamlessly integrated into the cost function, allowing for simultaneous optimization of multiple objectives like voltage regulation and MPPT	• PID and Hierarchical: Cannot handle constraints inherently; require external limiters and complex cascaded structures [20,23] • SMC: Limited capability for explicit multi-objective optimization and constraint handling [30,31]
Structural and Implementation Complexity	Simplified Architecture. Eliminates the need for multiple inner/outer PID loops, PWM modulators, and decoupling networks (e.g., dq transformations), reducing tuning effort and system complexity	• PID and Hierarchical: Highly complex due to cascaded loops and required coordinate transformations [20,23] • SMC: Complex design needed for chattering mitigation and gain tuning [29,30]
Unified Strategy and Operational Mode Transition	Seamlessly Unified. A single control framework manages both islanded (voltage control) and grid-connected (current/power control) modes, ensuring smooth transitions and consistent performance	• Other techniques typically require completely different control logics or hardware reconfiguration for each operational mode, leading to potential instability during transitions [6,32]
Robustness under Intermittent Renewables	Inherently Robust. The Finite-Control-Set approach and discrete model predict system behavior effectively, handling the nonlinear and stochastic nature of PV and wind generation	• PID: Performance degrades under significant nonlinearities and parameter variations [20,21] • SMC: Highly robust to disturbances, but chattering can excite modeled dynamics [28,30]

4.1. Performance During Islanded Mode

When the hybrid AC/DC microgrid operates in islanded mode, PV and wind generation act as the primary sources, while the energy storage system is coordinated by the MPC controller to compensate for the power imbalance between renewable generation and load demand. The load profile and the contribution of energy sources to fulfill the load demand are shown in Figure 6. The upper line of the graph represents the system's total power consumption profile over time, while the stacked areas below it depict the real-time power supplied by each source: PV, wind, and energy storage system. This representation clearly

demonstrates the system's ability to maintain a consistent power balance by integrating intermittent renewable sources. Specifically, it highlights how the battery is managed to compensate for fluctuations in PV and wind generation, thereby ensuring that the total power supply consistently meets the system's variable load requirements. The analysis of this load profile underscores the robustness and adaptability of the control strategy in a hybrid AC/DC microgrid setting.

The performance of ESS is shown in Figure 7. The ESS power profile shows that the MPC dispatches the ESS whenever there is a mismatch between renewable generation and load as shown in Table 5. During generation deficits, it discharges to support the loads. The SOC profile remains within safe operating limits, demonstrating effective cycle management. The output of the DC bus voltage and a reference DC voltage over time is shown in Figure 8. The figure shows that the DC bus voltage is successfully tracked to the reference voltage, with minimal deviation. This performance is verified during sudden disturbances, such as changes in load demand and the intermittent power output from renewable sources. The DC voltage is stable, which is essential for the stability of the microgrid.

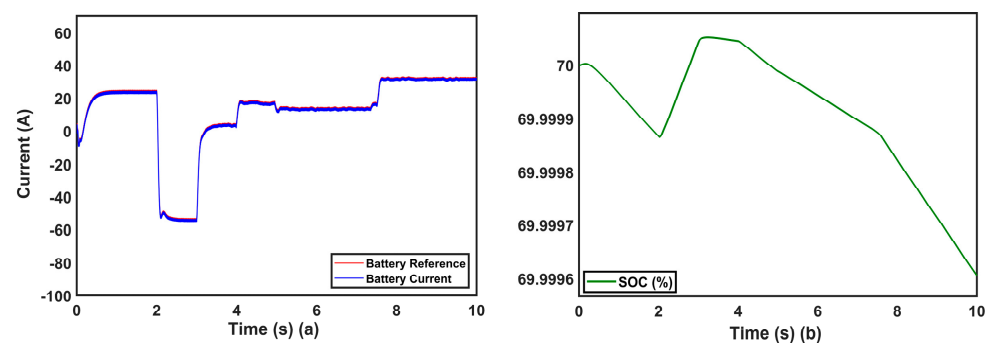


Figure 7. Performance of energy storage system (a). Energy storage system current (b).

Table 5. Structural comparison of MPC-based hybrid microgrid studies.

Study	Control Focus	Key Limitations	Proposed FCS-MPC Advantages
Shan et al. [32]	Systems Level Optimization	A two-level hierarchy only limits the power; there is no more transition handling	Single-layer direct control, multi-constraint (voltage, current, switching, SOC), seamless PLL-based transition
Jing et al. [33]	HHL-based MPC	Centralized, high computational load, only energy constraints, not scalable	Low computational burden, numerical-based model, modular and scalable, real-time converter level coordination
Proposed FCS-MPC	Converter level coordination	-	Unified framework, explicit constraints, seamless mode switching, scalable architecture

The output AC voltage shown in Figure 9 exhibits a stable sinusoidal waveform, which is essential for the reliable operation of a microgrid. At $t = 3$ s, AC loads were switched on. The figure presents both the AC bus voltage age and the corresponding current from the VSI, clearly demonstrating that the proposed control strategy consistently delivers a high-quality sinusoidal output over the entire ten-second interval. Such stable and clean voltage is critical for ensuring compatibility with sensitive electronic devices and for maintaining the overall stability of the power system.

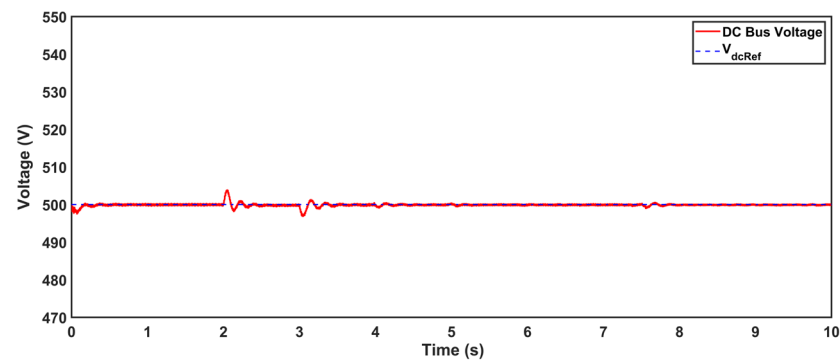


Figure 8. DC bus voltage during islanded mode.

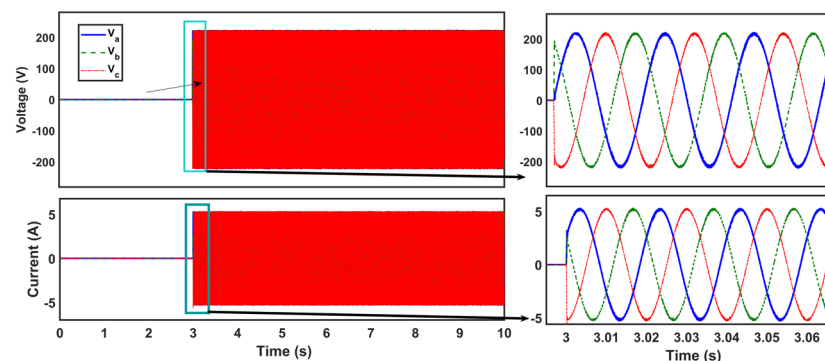


Figure 9. AC voltage output during islanded mode.

Overall, the results for the islanded mode demonstrate that the proposed control strategy effectively manages PV, wind, and the energy storage system to ensure a stable and continuous power supply to the load. The system successfully maintains DC bus voltage stability and produces a high-quality sinusoidal voltage, confirming its robustness and reliability even when disconnected from the main grid.

4.2. Performance During the Grid-Connected Mode

When the hybrid AC/DC microgrid is connected to the utility grid, PV and wind remain the primary sources of generation, while the main grid serves as an auxiliary source to compensate for any power surplus or deficit. The load demand and generation of renewable energy sources are shown in Figure 10. This figure provides a comprehensive overview of power management within a hybrid AC/DC microgrid. From 0 to 2 s, the total load demand exceeds the power generated by renewable sources (PV and wind). During this period, the power deficit is compensated for by importing power from the main grid, ensuring the load is fully supplied. From 2 to 10 s, the renewable power generation surpasses the load demand, creating a surplus of power. This excess power is then exported back to the main grid to maintain power balance and stability within the microgrid. This demonstrates the system's ability to seamlessly manage bidirectional power flow with the main grid, highlighting the effectiveness of the control strategy in maintaining a stable and reliable power supply under varying conditions. The grid power is shown in Figure 11, which demonstrates the bidirectional power flow between the microgrid and the main grid. From 0 to 2 s, the grid supplies power to the load, indicated by a negative value, to meet demand. Conversely, from 2 to 10 s, the microgrid exports surplus power to the main grid, as shown by the positive value, to maintain power balance. This illustrates the effective grid-connected operation of the system.

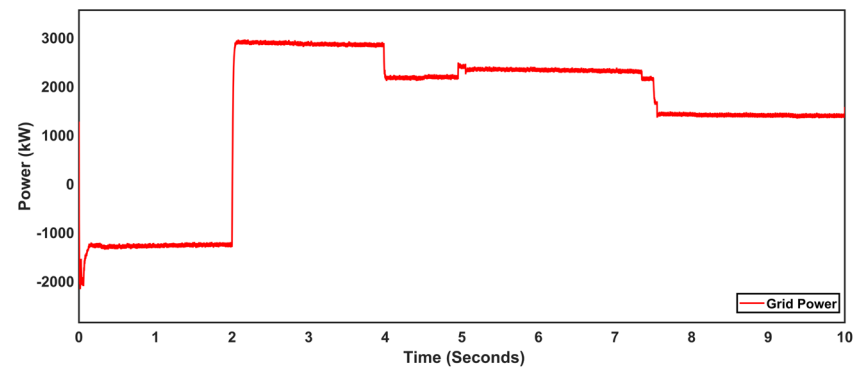


Figure 10. Response of the main grid during surplus or deficit power.

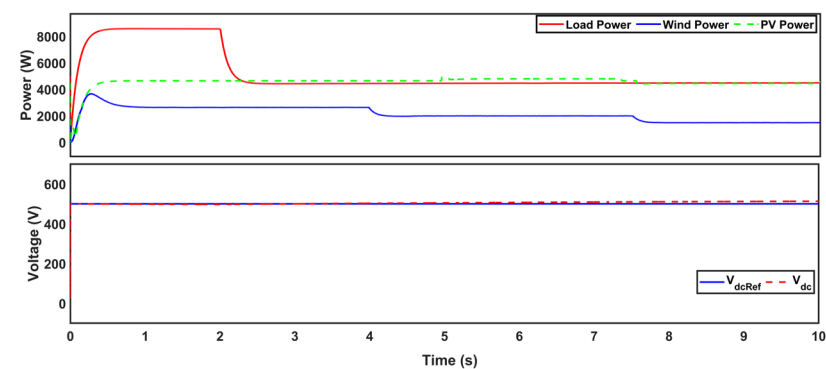


Figure 11. Grid-connected mode: load profile and power contribution of various energy.

The output of the DC bus voltage is also shown in Figure 11. It can be observed that the proposed controller efficiently tracks the reference voltage, maintaining a stable and consistent DC voltage output. Although there is a small delay in reaching the reference value during grid-connected operation, likely due to computational burden, the overall performance demonstrates the controller's effectiveness in providing a stable voltage.

The AC voltage output, displayed in Figure 12, demonstrates the effectiveness of the proposed controller in achieving AC voltage regulation. While the initial transient period shows some minor instability, likely linked to the settling time of the DC bus voltage tracking, the controller quickly stabilizes the output. The zoomed windows clearly show that the system successfully produces a consistent and clean sinusoidal waveform.

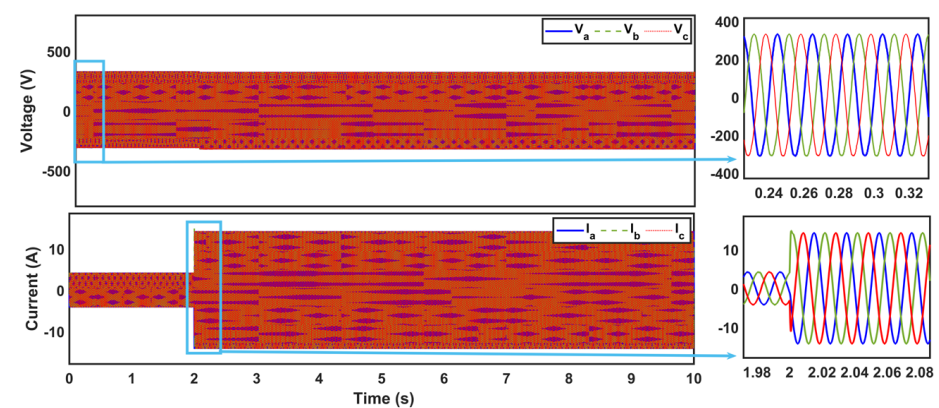


Figure 12. Output of AC bus voltage in case of grid-connected mode.

5. Conclusions

The paper has presented a Finite Control Set–Model Predictive Control (FCS-MPC) framework for the coordinated operation of a hybrid AC/DC microgrid comprising PV, wind generation, ESS, and the utility grid. Extensive modeling of renewable sources and power electronic converters was performed to capture system dynamics under varying operating conditions. In MATLAB/Simulink, a component-level simulation environment is built. The simulation results showed that the proposed strategy provides complete power extraction from renewable resources, power regulation, stable sinusoidal AC production, and effective power exchange in both directions on the grid. The controller has shown strong performance under both operational conditions. In islanded operation, it operated the DC bus at 400 V with slight variation with minimal deviation and high-quality AC output with low THD and controlled ESS SOC that was within safe ranges; in grid-connected operation, it was able to achieve smooth two-way flow of power, importing during operation shortage (0 to 2 s) and exporting during operation surplus (2 to 10 s) without significant deviation in voltage profiles. These quantitative findings confirm that the framework offers better dynamic response, greater disturbance resistance, and better power quality than standard methods. In the future, future studies will aim at improving practical resilience by using communication-planned event-based implementations, creating distributed architectures to coordinate multi-microgrids, and conducting hardware-in-the-loop tests to help resolve challenges associated with real-world implementation. To achieve scalability, a distributed FCS-MPC model will be implemented, in which groups of converters are controlled via low-bandwidth communication to facilitate control of larger systems such as 69-bus or 136-bus microgrids. This will counter the computational blockage of centralized optimization. In general, the results demonstrate the effectiveness of FCS-MPC as a sophisticated control method for increasing the stability, resilience, and performance of hybrid AC/DC microgrids in the context of renewable energy integration and the future climate of smart grids. Specifically, the suggested controller eliminates standard cascaded PID tuning, PWM modulation, and additional coordinate transformation layers, yet it can operate at the switching level and has been tested on full-scale PV, wind, and battery systems with embedded MPPT under dynamically operating conditions. These design solutions provide tight DC-bus regulation (reduced overshoot and oscillation) and better AC-bus voltage quality (reduced harmonic distortion) during mode transitions, validating the feasibility and performance of the single FCS-MPC system.

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