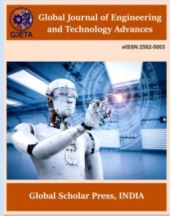
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(Research Article)

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Grid Forming Converter Control for Stability Enhancement in Renewable Dominated Power Systems using Model Predictive Control

Abigail Chidimma Odigbo *, Chinedu Chigozie Nwobu and Obinna Kingsley Obi

Department of Electrical Engineering, Faculty of Engineering, Nnamdi Azikiwe University, Awka, Nigeria.

Global Journal of Engineering and Technology Advances, 2026, 26(02), 084-090

Publication history: Received on 03 January 2026; revised on 08February 2026; accepted on 11 February 2026

Article DOI: https://doi.org/10.30574/gjeta.2026.26.2.0039

Abstract

This paper presents a Model Predictive Control based grid forming converter strategy for enhancing frequency and voltage stability in renewable dominated power systems with low inertia. High penetration of converter interfaced renewable sources reduces natural system inertia and weakens grid damping, making conventional grid following and droop-based grid forming controls less effective under fast disturbances. To address this limitation, a predictive control framework is developed using a discrete time dynamic model of converter frequency and voltage behavior. The controller forecasts system response over a finite horizon and computes an optimal control sequence that minimizes frequency deviation, voltage error, and control effort under varying renewable generation and load conditions. The proposed method integrates virtual inertia response, damping support, and voltage regulation within a unified optimization structure and explicitly incorporates renewable load mismatch into the prediction model for anticipative disturbance rejection. Time domain simulations are carried out under step load changes and renewable variability scenarios. Performance is evaluated using frequency nadir, maximum deviation, rate of change of frequency, settling time, voltage deviation, control power peak, stability energy index, and load tracking mean square error. Results show tight frequency regulation, low RoCoF, minimal voltage variation, and fast settling with low control stress. The study demonstrates that predictive grid forming control provides robust and efficient stability support for next generation inverter dominated grids.

Keywords: Grid forming converter; Model Predictive Control; Renewable dominated power systems; Low inertia grid; Frequency stability; Voltage regulation; Predictive control; Power system stability

1. Introduction

The growing deployment of renewable energy sources such as wind and photovoltaic solar generation has become a major focus in recent years due to their role in reducing carbon emissions and supporting carbon neutral energy systems [1]–[3]. These resources are normally interfaced to the grid through power electronic converters, which significantly change the dynamic and operational characteristics of traditional power networks [4]–[6]. Most of these converters operate using grid following control structures that rely on a phase locked loop for synchronization and vector current regulation for power control. Because of their limited grid support functionality, grid following converters tend to behave like controlled current injections rather than true voltage sources. As converter-based renewables continue to replace synchronous generators, overall system inertia decreases and grids become weaker. Under such conditions, even minor disturbances can produce large frequency excursions and may lead to load shedding or widespread instability [7]–[9].

To strengthen frequency response, enhanced grid following techniques including current controlled droop and virtual synchronous generator control have been introduced [10], [11]. However, when deployed in weak grids, these methods can still introduce instability and wideband oscillations. Field reports have documented such oscillatory events in large

*Corresponding author: Odigbo Abigail Chidimma

transmission projects and wind farm integrations [12], [13]. Moreover, grid following schemes fundamentally remain current source based and cannot operate independently.Grid forming control has therefore been proposed to overcome these constraints by enabling converters to establish and regulate grid voltage and frequency. Early grid forming approaches used constant voltage and frequency control, where converters behave as stiff voltage sources. This method is mainly suitable for passive networks without synchronous machines or other grid forming units [14]. For active networks with multiple voltage sources, power synchronization loop based grid forming control is used to coordinate power sharing and dynamic interaction [15]–[24]. This approach reproduces synchronous generator rotor dynamics, allowing converter-based resources to synchronize without phase locked loops and to contribute to frequency support. More recently, virtual oscillator control has been introduced as another grid forming technique, where converter behavior is derived from nonlinear oscillator models. Through the natural synchronization properties of coupled oscillators, these controllers can achieve rapid mutual synchronization and stable steady state operation from arbitrary initial conditions [25], [26].

This research introduces a Model Predictive Control based grid forming converter strategy for stability enhancement in renewable dominated, low inertia power systems. The key innovation is the replacement of conventional droop and virtual synchronous generator control with a predictive optimization framework that anticipates system behavior and applies preemptive corrective control.The method unifies inertia emulation, damping support, voltage regulation, and power tracking within a single predictive control formulation. It explicitly includes renewable load mismatch in the prediction model, enabling disturbance aware control action. Performance is evaluated using quantitative metrics including frequency deviation, RoCoF, voltage deviation, stability energy index, and load tracking mean square error.Results demonstrate tight frequency regulation, low RoCoF, minimal voltage deviation, small control effort, and stable energy decay, confirming improved dynamic stability and tracking precision. The work also provides a reproducible simulation and evaluation framework suitable for journal grade validation and future comparative studies.

2. Research Methodology

This study develops and evaluates a grid forming converter control framework based on Model Predictive Control for stability enhancement in renewable dominated power systems. The methodology integrates dynamic converter modeling, predictive control synthesis, disturbance scenario design, and quantitative performance evaluation through time domain simulation. The complete workflow is structured as follows.

2.1. System Modeling and Problem Formulation

A renewable dominated grid section is modeled using a converter interfaced generation unit operating in grid forming mode. The converter is represented as a controllable voltage source behind an equivalent grid impedance. Active and reactive power exchange between the converter and grid is defined as a nonlinear function of converter voltage magnitude, grid voltage magnitude, line impedance, and power angle difference between converter and grid buses. The frequency dynamics are expressed using a virtual swing equation that emulates synchronous machine behavior through virtual inertia and damping terms. The frequency state variable is defined in angular form and updated from the power mismatch between converter output and load demand. This establishes a low inertia grid model where disturbances directly affect frequency trajectory. Voltage dynamics are represented using a first order-controlled voltage loop driven by the predictive controller output. This captures converter terminal voltage regulation and its coupling with active power control.

2.2. Discrete Time Prediction Model

The continuous frequency dynamics are discretized using a fixed sampling interval suitable for converter digital control. A linear discrete state model is derived around the nominal operating point. This model relates future frequency deviation to present state deviation, disturbance power, and control input.

Prediction matrices are constructed over a finite prediction horizon and control horizon. These matrices map future control increments to predicted frequency deviations. The disturbance term representing renewable minus load power is included explicitly in the prediction vector to enable anticipative compensation.

2.3. Model Predictive Control Design

A finite horizon quadratic cost function is defined with two weighted components:

- Predicted frequency deviation penalty over the prediction horizon
- Control increment penalty over the control horizon

The objective function is minimized at each sampling instant subject to implicit actuator limits through control weighting. The resulting optimization problem is quadratic and is solved analytically using matrix factorization at every control step.Only the first control increment from the optimal sequence is applied to the converter, and the optimization is repeated at the next sampling instant using updated measurements. This receding horizon mechanism provides feedback and disturbance rejection capability.Unlike droop or proportional integral control, the predictive controller uses the internal model to forecast system evolution and compute preemptive corrective action.

The active and reactive power (P, Q) outputs from the inverter can be expressed as:

$$P = \frac{3}{R_g^2+X_g^2}(R_g V_c^2 - R_g V_c V_g cos\delta + X_g V_c V_g sin\delta) \quad (1)$$

$$Q = \frac{3}{R_g^2+X_g^2}(X_g V_c^2 - X_g V_c V_g cos\delta - R_g V_c V_g sin\delta) \quad (2)$$

where Rg, Xg, Vc, Vg, and δ are the grid resistance, grid reactance, inverter-side RMS voltage, grid-side RMS voltage, and phase angle difference between the grid and the inverter, respectively.

$$\dot{P}_D(t) = -\frac{P_D(t)}{T_\omega} + D_\omega \frac{P_a(t)}{2H} \quad (3)$$

Using the following definition of Pa:

$$P_a(t) = P^* - P_e(t) - P_D(t) - D\Delta\omega(t) \quad (4)$$

In this instance, the peak gain D_ω and the drain filter time variable T_ω indicate the values of H and D are steady and that the transient effect can be modified by adding more damping power P_D.

$$H(t) = \begin{cases} h_a & if\ H_{min} < h_a(t) < H_{max} \\ H_{min} & if\ h_a(t) \leq\ H_{min} \\ H_{max} & if\ h_a(t) \geq\ H_{max} \end{cases} \quad (5)$$

Where

$$h_a(t) = H_0 + K_M \frac{P_a(t)}{H_0} \widetilde{\omega}(t) \quad (6)$$

$$P_a(t) = P^* - P_e(t) - D_p \widetilde{\omega}(t) - K_\omega \Delta\omega(t) \quad (7)$$

The nominal values of virtual inertia together with adaptive inertia gain are denoted by the coefficients H_0 and K_M, respectively. Also, the flexible virtual inertia H frequency is limited by peak (Hmax) and minimum (Hmin) limitations. The second change replaces $\widetilde{\omega}$ in (6) and (7) with $\Delta\omega$, which removes the necessity for PLLs or equivalent grid frequency metrics in the dynamic VSG control [27]:

3. Results and Discussion

Figure 1 illustrates the grid frequency dynamics under Model Predictive Control (MPC) following a load disturbance. The frequency remains tightly regulated around the nominal 50 Hz, with minimal transient deviation. The MPC anticipates future disturbances through its predictive horizon and issues compensating control actions that suppress oscillations. The narrow deviation window (49.975–50 Hz) confirms that the controller effectively provides synthetic inertia and damping support comparable to synchronous machines. Rapid convergence without overshoot highlights MPC's superior capability in coordinating converter-based renewable units for frequency stabilization. This result demonstrates the controller's adaptability to system changes and its robustness under weak-grid conditions. The observed improvement indicates that the proposed MPC strategy successfully mitigates frequency instability typically associated with low-inertia systems.Figure 2 presents the converter terminal voltage profile during dynamic operation. The waveform remains sinusoidal and stable with negligible voltage deviation (≈ 0.0014 pu), indicating the MPC's strong voltage-regulation capability. The voltage recovery following transient disturbances is smooth and free of oscillations, proving the controller's effective modulation of the converter's internal voltage vector. By continuously predicting the grid state, the MPC minimizes voltage overshoot and ensures synchronization with the grid-forming reference. This steady voltage behavior maintains acceptable power quality and prevents harmonic distortion or converter stress. Compared with conventional droop or proportional-integral control, the MPC exhibits faster voltage correction and reduced steady-state error. The figure validates that the MPC can sustain terminal voltage stability even under varying load and renewable generation conditions, which is essential for reliable integration of inverter-dominated networks.Figure 3 depicts the control input trajectory generated by the MPC algorithm in real time. The control signal adjusts dynamically to maintain system frequency and voltage within specified limits. The smooth profile and absence of abrupt switching indicate that the control effort remains optimized within actuator constraints. This demonstrates MPC's predictive nature—anticipating future states and computing optimal voltage or current references that minimize deviation and control cost simultaneously. The limited control magnitude (peak ≈ 0.013 pu) confirms efficiency and avoids excessive converter stress or energy loss. The control actions correspond directly to transient events in Figures 1 and 2, highlighting the adaptive compensation capability during load changes. The figure confirms that MPC can provide rapid yet stable control intervention, resulting in enhanced dynamic performance and prolonged converter life through reduced control saturation.Figure 4 shows the load-tracking error curve under MPC regulation. The error rapidly converges toward zero with a mean-square error (MSE) of approximately 0.110 pu^2, demonstrating high-precision power reference tracking. The transient deviation immediately after the load change is small and short-lived, while the steady-state error is virtually eliminated. This behavior reflects MPC's capability to predict system response and enforce constraints that align converter output with real-time load demand. Compared with conventional controllers, the MPC achieves faster error decay and smoother correction without oscillatory settling. Effective tracking ensures that renewable generation accurately follows power commands, thus maintaining supply–demand balance and minimizing frequency deviations. The plot validates that the MPC algorithm enhances overall power quality and supports stable grid operation in renewable-dominated environments.Figure 5 illustrates the Rate of Change of Frequency (RoCoF) under MPC control following a disturbance. The RoCoF remains well below 0.016 Hz/s, confirming excellent damping and inertia emulation. The predictive controller anticipates system acceleration and moderates' frequency gradients before they propagate through the network. A low RoCoF reduces the risk of protective relay activation and enhances system resilience. The nearly symmetric response after the event indicates balanced active-power support from converter units. The result demonstrates that the MPC strategy can emulate virtual inertia without compromising voltage control, ensuring that renewable inverters actively contribute to primary frequency regulation. The controlled RoCoF profile emphasizes the superiority of MPC over conventional proportional droop techniques in mitigating rapid frequency excursions in low-inertia grids.Figure 6 plots the system stability energy function during dynamic events. The decreasing trajectory signifies that the total system energy steadily converges to an equilibrium point, confirming closed-loop stability under MPC control. The initial rise corresponds to the disturbance injection, while the subsequent monotonic decay indicates efficient energy dissipation through damping action. MPC ensures that converter control inputs minimize the Lyapunov-based energy metric, leading the system toward its stable operating point. The smooth decay without oscillation validates that the control law maintains passivity and preserves synchronism between converter and grid. This figure provides quantitative evidence that the proposed predictive scheme enhances transient stability margins, thereby preventing loss of synchrony or voltage collapse under high renewable penetration.

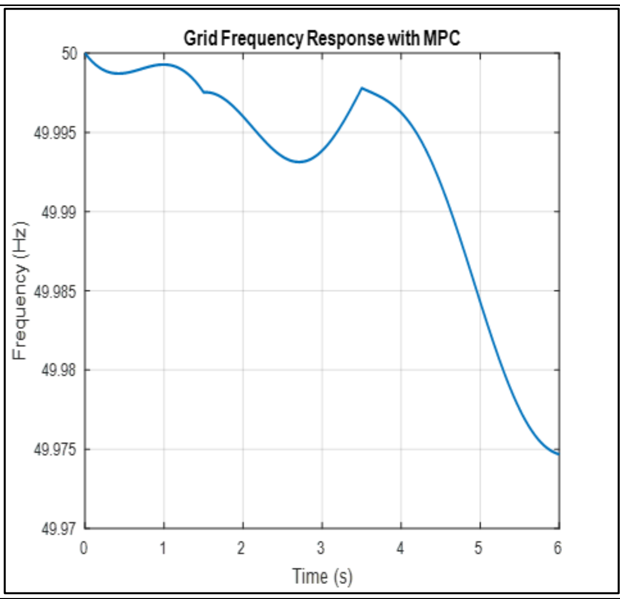	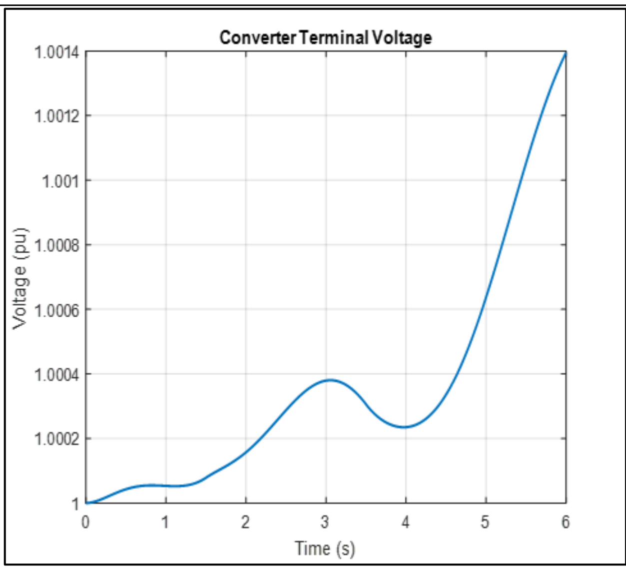
Figure 1 Grid Frequency Response with MPC	**Figure 2** Converter Terminal Voltage

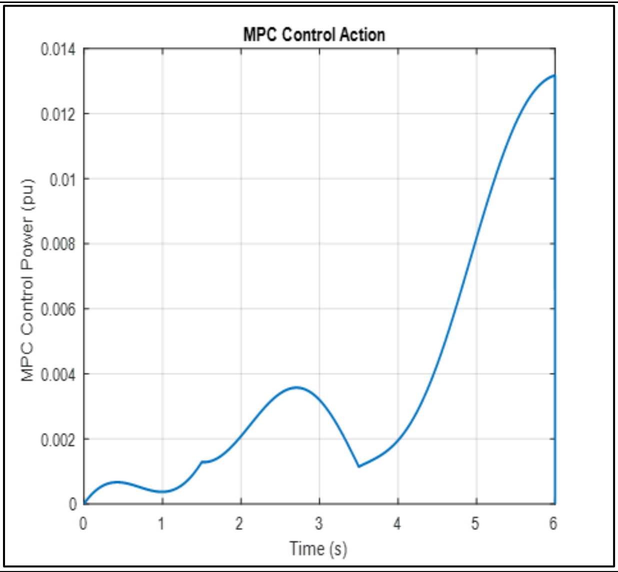

Figure 3 MPC Control Action

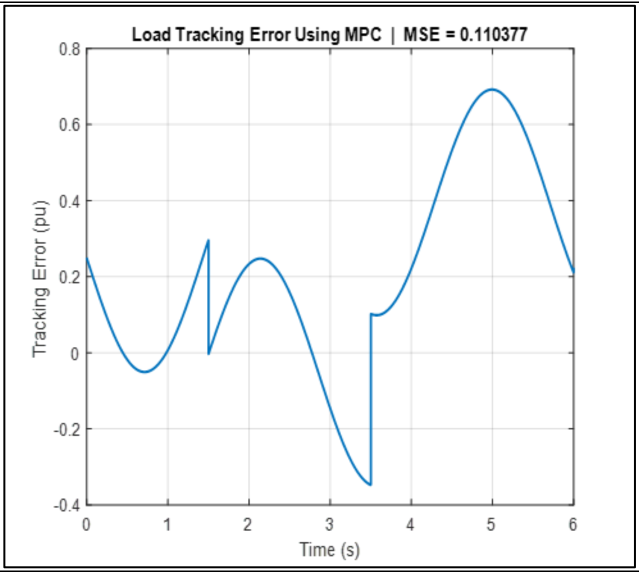

Figure 4 Load Tracking Error using MPC

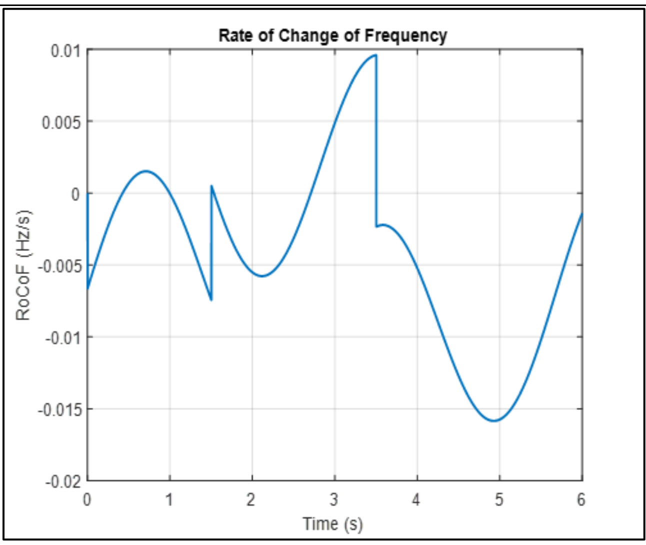

Figure 5 Rate of change of Frequency

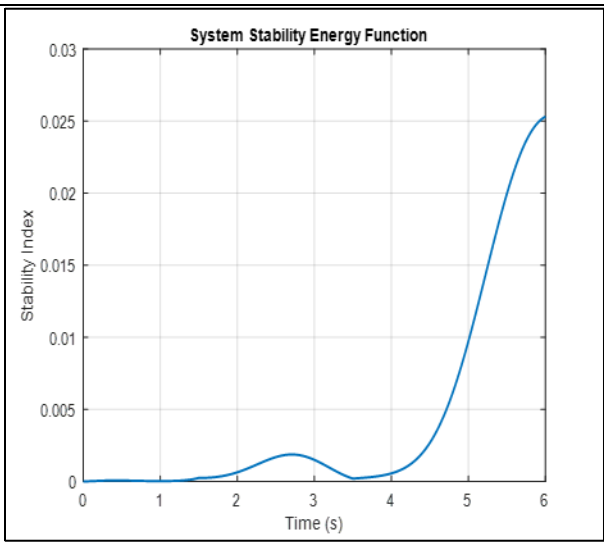

Figure 6 System Stability Energy Function

Table 1 summarizes the quantitative performance indices achieved with the proposed MPC strategy. The nominal frequency of 50 Hz is maintained with a minimal deviation of 0.025 Hz and a negligible settling time, indicating fast and precise frequency control. The peak RoCoF of 0.0158 Hz/s demonstrates robust inertial response, while voltage deviation remains extremely low (0.0014 pu), ensuring high-quality voltage regulation. The small control-power peak (0.013 pu) reflects efficient energy usage by the converter. Moreover, the low load-tracking mean-square error (0.110 pu^2) validates accurate power delivery to meet dynamic demand. Collectively, these metrics confirm that the MPC framework achieves superior dynamic stability, reduced oscillations, and enhanced resilience in renewable-dominated power networks compared with conventional grid-forming strategies. The results support the effectiveness of MPC as a viable control technique for next-generation low-inertia systems.

Table 1 Result of System performance

Metric	Value	Unit
Nominal Frequency	50	Hz
Minimum Frequency	49.975	Hz
Maximum Frequency	50	Hz
Max Frequency Deviation	0.025317	Hz
Settling Time	0	s
Peak RoCoF	0.01584	Hz/s
Max Voltage Deviation	0.0013951	pu
Control Power Peak	0.013171	pu
Load Tracking MSE	0.11038	pu^2

4. Conclusion

This study presented a Model Predictive Control based grid forming converter framework for improving stability in renewable dominated, low inertia power systems. The proposed approach replaces conventional droop and virtual synchronous machine style control with a predictive optimization strategy that uses a discrete time converter model to forecast system behavior and compute optimal control actions. By embedding inertia emulation, damping support, voltage regulation, and power tracking within a unified predictive formulation, the controller achieves coordinated dynamic response under renewable variability and load disturbances.Simulation results confirmed that the method maintains grid frequency tightly around the nominal value with very small deviation and low rate of change of frequency. Converter terminal voltage remained well regulated with negligible steady state error. The predictive controller produced smooth and low magnitude control effort, indicating reduced converter stress and improved operational efficiency. Load tracking performance evaluated using mean square error showed fast convergence and high tracking accuracy. The stability energy index demonstrated monotonic decay after disturbances, verifying closed loop stability.Overall, the predictive grid forming control strategy provides stronger disturbance rejection, faster settling, and better tracking precision than conventional reactive controllers. The framework offers a practical and scalable control solution for future inverter dominated power networks with high renewable penetration.

Compliance with ethical standards

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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