

Article

Distributed Model Predictive Control-Based Power Management Scheme for Grid-Integrated Microgrids

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Abstract

Transitioning from traditional electrical grids to smart grids is currently an ongoing process that many nations are striving for due to their access to renewable resources. Energy management is one of the key parameters that decides the performance of such complex systems. Distributed Model Predictive Control (DMPC) is a promising technique that can be used to improve the energy management of grid-connected systems. This paper analyzes a grid-connected inverter system with DMPC that exchanges key operating parameters with the grid to optimize coordinated power sharing between its respective loads. The state-space model for the inverter is derived and verified to ensure controllability and observability. A state observer for an inverter system is then developed to estimate the nominal states in the derived state-space model. The system performance is evaluated with MATLAB simulation by implementing load disturbances, which validate the effectiveness of the proposed power management control algorithm.

Keywords: distributed model predictive control; load frequency control; grid-connected systems; renewable energy sources; smart grids; inverters; and synchronous generators

1. Introduction

Many nations have made it a goal to reduce greenhouse gas emissions and are slowly transitioning from traditional electrical grids to smart grids [1]. The biggest concern with adding renewable sources to conventional power system networks is that the power output varies in nature [2]. Additionally, the majority of renewable sources solely generate direct current, making inverters a must. With modern technology, engineers are able to apply different control strategies to the electrical grids we have today.

Centralized and distributed control schemes are popular strategies used in power systems [3–5] to efficiently manage power. In distribution system operations, centralized control is a common method that facilitates optimized operation. However, centralized control relies on a complex communication network, which can create delays and scalability issues when there are many nodes. Therefore, with advanced research in smart grid systems, the conventional power system turns to a distributed-control-based infrastructure with millions of controllable nodes [3]. These distributed control-based power systems will be



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capable of (i) distributed optimization and control, (ii) real-time optimization and learning, and (iii) data-driven optimization and control with system dynamics, stability, energy management, etc.

The work in [3] focuses on distributed power system control. Figure 1 shows the architecture of a distributed multi-agent system for microgrid frequency control. In the primary control layer, local controllers control the voltage and frequency. The secondary control is responsible for restoring frequency and voltage to nominal values after the primary control has occurred. The tertiary control redispatches systems and changes unit commitment to restore the reserves that were expended during the operation of primary and secondary frequency control. Therefore, loss of communications between agents will not result in the collapse of the system if there is a single unit failure.

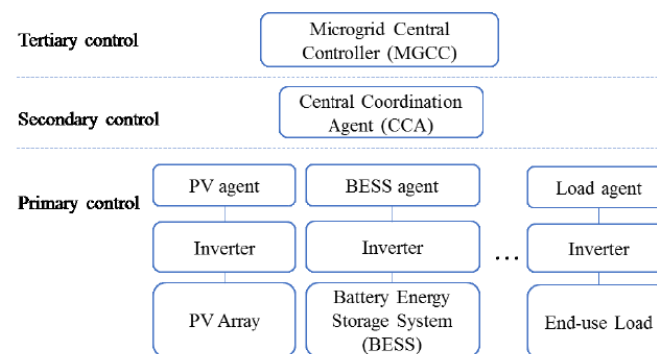


Figure 1. Architecture of a distributed multi-agent system for microgrid frequency control [3].

Ensuring effective communication between agents is a challenging task due to the necessity to analyze all kinds of different variables and communicate optimally between agents. Many different controllers have been researched [6–9] and one that is growing in popularity is model predictive control (MPC). This has been widely applied to distributed multi-agent systems in the form of distributed MPC (DMPC) [10,11]. DMPC has drawn the attention of researchers due to its effectiveness in problem setup and solution processes [12–14]. One of its applications in microgrid systems is load frequency control (LFC) [15–17]. DMPC can be applied to both linear and nonlinear state-space models, whereas the time to obtain a solution and result accuracy can vary depending on what model is used for the controller [18]. A DMPC control managing frequency deviations in an AC microgrid due to load disturbance is discussed in [19]. This work discusses solar PV, a battery energy storage system, and an inverter and does not consider synchronous generators/grid-connected systems. Ref. [20] discusses off-grid inverter-based microgrids with loads and energy storage. In this paper each agent uses local predictions and neighbor references. Microgrid frequency and energy state equations are linearized and cast into a prediction model for MPC optimization. This work also uses direct measurements and state propagation within MPC; no explicit observer is detailed. An inverter-based multilayer DMPC control is discussed in [21]. It includes operational constraints such as harmonic suppression; voltage and phase tracking with communication delay are included in DMPC cost and constraints. The proposed DMPC control uses local measurement and neighbor information; no explicit observer is discussed.

Controlling multiple grid-connected Distributed Energy Resource (DER) systems and their dynamics is challenging. Therefore, analysis using their mathematical models, which incorporate state-space system dynamics, is one of the promising approaches. However, the converted state-space form usually contains states that are not directly measurable. State observers are then needed to estimate these hidden states [22]. The major limitations observed in various DMPC papers are given in Table 1.

Table 1. Comparison of the prior DMPC literature versus the proposed grid-integrated microgrid DMPC scheme.

Ref.	System	Control Structure	Hybrid Generator/ Inverter	Explicit Constraints	State-Space & C/O Analysis	State Estimation	Implemented in MATLAB/Simulink	Validation/Evidence
[3]	Multi-area power system	Distributed/hierarchical DMPC-inspired control	No	No	No	No	Yes	Time-domain simulations
[5]	Multi-area power system	Generic DMPC formulation	No	No	Yes	No	Yes	Analytical and numerical examples
[6]	MG control	Survey of DMPC architectures	No	No	No	No	No	Literature review
[10]	Multi-area power system	DMPC roadmap	No	No	No	No	No	No validation
[15]	Multi-area power system	MPC-based load frequency control	No	No	No	No	Yes	Numerical simulations
[23]	AC/DC interconnected system	Cooperative DMPC	No	No	No	No	Yes	Simulation studies
[16]	Power generation systems (generic)	DMPC tool development	No	No	No	No	Yes	Simulation validation
Proposed	Grid-integrated two-area microgrid.	Two local DMPCs coordinating to regulate frequency/load and drive tie-line power exchange to zero	Yes	Yes (generator/inverter constraints modeled in the DMPC setup)	Yes (state-space modeling with controllability/observability verification)	Yes (observer designed/tuned for inverter states)	Yes, with APMonitor (local server; coordinated solve cycle)	Time-varying load disturbance simulations; observer convergence shown

MPC problems have been implemented and solved using different platforms [23,24]. The APMonitor Optimization Suite [25] is a comprehensive optimization software designed for solving mixed-integer and differential algebraic equations, as well as MPC problems. It integrates with large-scale solvers, such as APOPT, and IPOPT, for linear (LP), quadratic (QP), nonlinear (NLP), and mixed-integer (MILP and MINLP) programming. The modeling language is compiled to byte-code for efficient function and derivative calculations through automatic differentiation. The modes of operation include data reconciliation, optimization, dynamic simulation, and nonlinear predictive control. APMonitor is accessible through MATLAB Simulink [14,26,27] and Python through the GEKKO package [28]. The APMonitor Optimization Suite is used in both academic research and industrial applications. There are many studies using Gekko and APMonitor, with applications including continuous-time optimal control frameworks for trajectory planning under uncertainty, advanced methodologies for model-based optimization and control of pharmaceutical processes, and quantization of large language models. This contribution is another example of solving a complex optimization problem with a gradient-based optimization method.

This paper advances distributed MPC for microgrid power management in three ways, each addressing a gap that is not explicitly covered by existing DMPC/LFC studies. The first way is a *novel hybrid grid-connected formulation*: Unlike most DMPC/LFC formulations that assume frequency-regulating generation only, we develop a two-area DMPC framework for a hybrid system that combines a droop-governed synchronous generator with a *grid-following* inverter that does not inherently provide frequency regulation. We further embed an LFC-inspired objective that drives the *steady-state* tie-line exchange toward zero while permitting power sharing only during transients, which is not typically enforced in existing DMPC microgrid formulations. The second way is a *novel deployment-oriented modeling pipeline*: Existing work often starts from simplified analytical state-space models and assumes readily available states; in contrast, we derive tractable subsystem state-space models directly from a detailed Simulink implementation via MATLAB linearization, explicitly interpret the resulting internal states, and verify subsystem controllability/observability to justify MPC applicability for the obtained models. The third way involves *novel implementation and estimation elements*: beyond reporting closed-loop tracking results, we implement the DMPC controllers in MATLAB/Simulink R2024b using a local APMonitor server and report solver timing to support real-time feasibility claims. Moreover, because key inverter states are not directly accessible from the Simulink inverter model, we introduce a state observer (pole placement) to estimate those states; this explicit state-accessibility-driven estimation add-on is not commonly included in existing DMPC/LFC microgrid implementations.

The remainder of this paper is organized as follows. Section 2 presents the detailed system modeling in the transferfunction format, the derivation of the state-space model, and the controllability and observability analysis. Section 3 presents the implementation of the proposed DMPC method, the state observer, and the configuration of the APMonitor platform. Section 4 focuses on the simulation results, and Section 5 concludes this paper.

2. System Modeling

2.1. Problem Description

Most commercial and residential applications use inverters to connect renewable energy resources to the grid. These systems can be connected to the grid to improve reliability and power-sharing capabilities. The power-sharing feature can be designed with many optimization techniques. The proposed system consists of an AC microgrid connected to the grid, as shown in Figure 2. In other words, an AC grid with a synchronous generator and loads is considered as Area#1. A grid-following inverter (GF-I) is considered

as an AC microgrid, and its loads are in Area#2. The complete system is considered as a smart grid with a grid-connected mode. It is assumed that during normal operation, both areas generate their own power, and the net tie-line power is zero. During transients due to deviation in the load power, each area can share the power as required. In other words, the objective function is formulated in such a way that both areas mimic load frequency control (LFC) to maintain the tie-line power equal to zero.

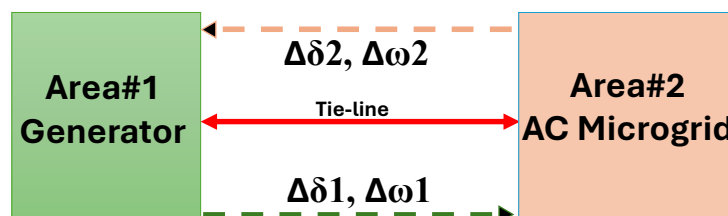


Figure 2. DMPC implementation in a two-area system.

Therefore, the objective function [5] is designed to minimize the deviation in frequency, phase angle, and power generation and is formulated as follows:

$$J_i(t) = \int_t^{t+T} \left[\sum_{\substack{j=1 \\ j \neq i}}^M p_{ij} (\Delta\delta_i(\tau) - \Delta\delta_j(\tau))^2 + q_i \Delta f_i^2(\tau) + r_i \Delta P_{gi}^2(\tau) \right] d\tau$$

where p_{ij} , q_{ij} , and r_{ij} are tunable weighting parameters. $\Delta\delta_i(t)$ is the continuous-time incremental change in the phase angle of the i -th generator bus in units of radians. $\Delta f_i(t)$ is the continuous-time incremental change in the frequency of the i -th generator bus in units of Hz, and $\Delta P_{gi}(t)$ is the continuous-time incremental change in the generator output of the i -th area in units per unit (p.u.). Variable M is the total number of areas in the system. Therefore, a DMPC controller can be designed to accomplish the objective. Although, to enable numerical solutions using APMonitor (APM MATLAB (version 0.7.2), <https://apmonitor.com/wiki/index.php/Main/MATLAB>, accessed on 13 November 2025) the continuous-time optimal control problem is transcribed into an equivalent discrete-time formulation over a finite prediction horizon. This discretization facilitates the implementation of MPC by converting the problem into a finite-dimensional optimization program. Following time discretization, the optimization problem is formulated as

$$\min_{u_i[k+j]} \sum_{\ell=0}^{N_p-1} \left(p_{ij} (\Delta\delta_i[k+\ell|k] - \Delta\delta_j^{\text{ff}}[k+\ell])^2 + q_i (\Delta f_i[k+\ell|k])^2 \right) + \sum_{\ell=0}^{N_c-1} r_i u_i[k+\ell|k]^2, \quad (1)$$

$$\text{s.t. } x_i[k+j] = A_{d,i} x_i[k+j] + B_{d,i} u_i[k+j], \quad j = 0, \dots, N_p - 1 \quad (2)$$

$$y_i[k+j] = C_{d,i} x_i[k+j] + D_{d,i} u_i[k+j], \quad j = 0, \dots, N_p - 1 \quad (3)$$

$$u_i^{\min} \leq u_i[k+j] \leq u_i^{\max}, \quad j = 0, \dots, N_c - 1 \quad (4)$$

$$|u_i[k+j] - u_i[k+j-1]| \leq \Delta u_i^{\max}, \quad j = 0, \dots, N_c - 1 \quad (5)$$

where $x_i[k]$ is the local state, $y_i[k]$ collects the controlled outputs (frequency deviation, phase angle, and the defined coordination error). $u_i[k]$ is the local manipulated variable (active power adjustment). $\Delta\delta_j^{\text{ff}}[k+\ell]$ is the coupling between areas, which is handled through the neighbor feedforward trajectory, which is communicated between controllers. $A_{d,i}$, $B_{d,i}$, $C_{d,i}$, $D_{d,i}$ denote discrete-time state transition matrices obtained by discretizing the continuous-time linearized model using a controller sampling period. N_p and N_c denote the prediction and control horizons, respectively, and the scalar weights. Only the first move is applied, $u_i[k] = u_i^*[k|k]$, using a zero-order hold until the next sampling instant $k+1$. Load disturbances are measured and supplied to the controller at each sampling instant but not

forecast over the prediction horizon; therefore, they are not included as additive inputs in the prediction model. This paper assumes ideal synchronized communication without delay, consistent with the implementation setup.

The DMPC application is solved through MATLAB Simulink with a local instance of the APMonitor server. In the Simulink model, DMPC 1 governs the synchronous generator system, while DMPC 2 governs the grid-connected inverter system. They are implemented through an interpreted MATLAB Function block that sends the subsystem's measurements states and feedforward information to the APMonitor solver and retrieves updated measurements and feedforward information from the other controller. A master scheduler in MATLAB initiates the solution and waits for a successful solution report from the server. Upon successful solution, the newly optimized values are implemented in the simulated system as a zero-order hold. When the next cycle time is reached, the process is repeated by recording measurements and feedforward information from the other controller, solving, and reporting the solution. The APMonitor local server runs with Apache 2 and PHP 8 on a computer equipped with a 12th Gen Intel(R) Core(TM) i7 CPU and 16 GB of RAM. The average solution time for DMPC 1 is 0.01995 s and for DMPC 2 is 0.0473 s. The average step size is 2.94×10^{-3} s and the total 4075-solution run time is 105.72 s.

2.2. Model Representation

In the proposed system, an inverter and a synchronous generator regulate the power demand in their respective areas. During power fluctuations due to changes in load demand, both systems share the power accordingly. In the proposed algorithm, DMPC directly controls the power output. Therefore, each system can be described as one equivalent inverter and generator system with series impedance, as shown in Figure 3.

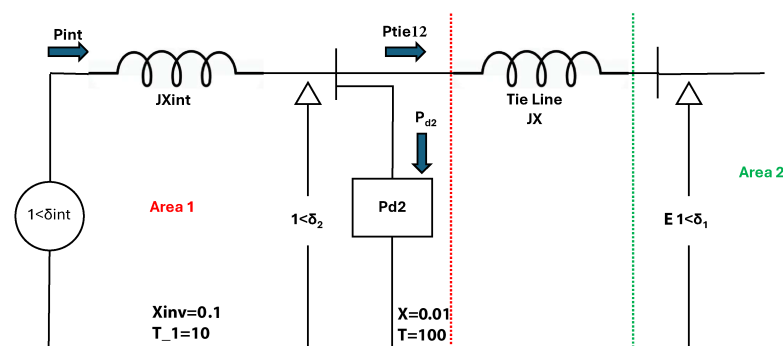


Figure 3. Equivalent grid-connected inverter model.

The simplified conventional synchronous machine is shown in Figure 4. It consists of a generator and a load, with the generator governor providing droop-based frequency regulation. The conventional generator is modeled using the standard linear model [29].

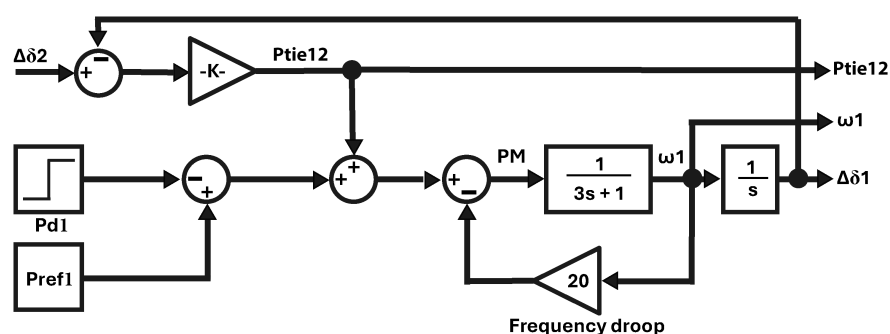


Figure 4. Simplified synchronous generator model.

The AC microgrid system consists of a grid-following inverter (GF-I) and a load. Although the power supplied by the inverter can be changed according to a reference power setting, the grid-following inverter does not provide frequency regulation. In this system, the DC load flow approximation is used to model the network. Thus, voltage magnitudes are assumed to be 1 p.u., lines are modeled by their inductive series reactance, and power flow in lines is linearized in terms of voltage phase angular differences. The inverter is modeled as a power controller and a phase-locked loop (PLL) that generates a voltage phase angle corresponding to the desired power output, as shown in Figure 5. The PLL tracks the grid frequency.

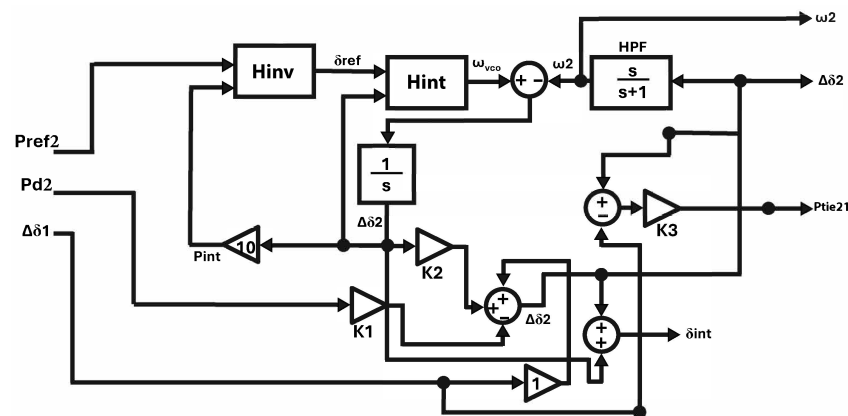


Figure 5. Simplified grid-connected single-inverter model.

A simulation model is implemented in MATLAB Simulink. Transfer functions and state-space models are derived for DMPC and validated using the Simulink model. The detailed system model analysis and corresponding nomenclature are given below.

- P_{ref1} : Power setting for the synchronous generator.
- P_{ref2} : Power scheduled at the inverter.
- P_{d1}, P_{d2} : Loads in Area#1 and Area#2, respectively.
- P_{g1} : Power setting for the synchronous generator from a DMPC controller.
- P_{g2} : Power setting for the inverter from a DMPC controller.
- P_{tie12} : Tie-line power from Area#1 to Area#2.
- P_{tie21} : Tie-line power from Area#2 to Area#1.
- P_{int} : Actual power from the inverter.
- δ_{ref} : Desired internal angle for the inverter.
- δ_{int} : Actual internal angle for the inverter from the power controller (synchronous frame or absolute).
- δ_1 : Terminal voltage angle for the synchronous generator (synchronous frame).
- δ_2 : Terminal voltage angle for the inverter (synchronous frame).
- $\tilde{\delta} = \delta_{int} - \delta_2$: Internal voltage angle of the inverter relative to the terminal voltage angle.
- ω_1, ω_2 , and ω_{inv} : Area#1, Area#2, and inverter PLL frequencies (p.u.), respectively.
- Tie-line inductive reactance, $X_{tie-line} = 0.01$ p.u.
- Inverter output inductive reactance, $X_{inv} = 0.1$ p.u.

To analyze the system in detail, the complete modeling of each area is discussed below. The synchronous generator in Area#1 can be modeled as

$$s\omega_2 = \frac{1}{Ms + D} \left(P_{ref1} - \frac{1}{R}\omega_2 - P_{d1} - P_{tie21} \right). \quad (6)$$

where M is the inertia constant, D is the damping constant, and R is the droop value, and the parameters are given in Table 2.

Table 2. Parameter values for inertia (M), damping (D), and droop (R) for the synchronous generator model.

Parameter	Value
M	0.03 (pu·s/rad)
D	1.0 (pu/pu)
R	0.05 (pu/pu)

For Area#2, the inverter power controller is defined as

$$\Delta\delta_{inv} = H_{inv}(\Delta P_g - \Delta P_{int}), \quad (7)$$

where H_{inv} controls the actual inverter power based on the references and is defined as

$$H_{inv} = K_p^{inv} + \frac{K_i^{inv}}{s}. \quad (8)$$

The incremental deviation in the inverter's internal frequency based on the deviation in the inverter's power angle and internal power angle can be calculated as

$$\Delta\omega_{vco} = H_{int}(\Delta\delta_{inv} - (\Delta\delta_{int} - \Delta\delta_2)) \quad (9)$$

where

$$H_{int} = K_{p_int} + \frac{K_{i_int}}{s}, \quad (10)$$

and

$$\Delta\delta_{int} - \Delta\delta_2 = \frac{1}{s}(\Delta\omega_{vco} - \Delta\omega_2). \quad (11)$$

Also, the deviation in the inverter terminal phase angle can be calculated as

$$\Delta\delta_2 = \left(\frac{1}{T}\right)[T_1(\Delta\delta_{int} - \Delta\delta_2) + T\Delta\delta_1 - \Delta P_{d2}] \quad (12)$$

where $T_1 = \frac{1}{X_{inv}} = 10$, $T = \frac{1}{X_{tie-line}} = 100$, X_{inv} is the inverter output inductive reactance, and $X_{tie-line}$ is tie-line inductive reactance.

The incremental deviation in the inverter power can be calculated as

$$\Delta P_{int} = T_1(\Delta\delta_{int} - \Delta\delta_2). \quad (13)$$

The deviation in Area#2's frequency is given by

$$\Delta\omega_2 = H_\omega \Delta\delta_2, \quad (14)$$

where the transfer function of the inverter terminal frequency ω , H_ω , is given by

$$H_\omega = \frac{s}{s+1}. \quad (15)$$

Substituting (12) in (14) gives

$$\Delta\omega_2 = H_w \left(\left(\frac{T_1}{T} \right) \left(\frac{1}{s} \right) (\Delta\omega_{vco} - \Delta\omega_2) \right) + \Delta\delta_1 - \left(\frac{1}{T} \right) \Delta P_{d2}. \quad (16)$$

Substituting and rearranging (9) gives

$$\Delta\omega_{vco} = \alpha^{-1} \gamma \Delta\omega_2 + \alpha^{-1} H_{inv} H_{int} \Delta P_g \quad (17)$$

where

$$\alpha = 1 + \frac{H_{int}}{s} H_{inv} T_1 + \frac{H_{int}}{s}, \quad (18)$$

$$\gamma = \frac{H_{int}}{s} H_{inv} T_1 + \frac{H_{int}}{s}. \quad (19)$$

The inverter terminal frequency can be obtained by substituting (17) in (16),

$$\begin{aligned} \Delta\omega_2 &= H_w \left(\frac{T_1}{T} \left(\frac{1}{s} (\Delta\omega_{vco} - \Delta\omega_2) \right) + \Delta\delta_1 - \frac{1}{T} \Delta P_{d2} \right) \\ &= \frac{H_w}{s} \frac{T_1}{T} \Delta\omega_{vco} - \frac{H_w}{s} \frac{T_1}{T} \Delta\omega_2 + H_w \Delta\delta_1 - \frac{H_w}{T} \Delta P_{d2}. \end{aligned} \quad (20)$$

Simplifying (20) gives

$$\begin{aligned} \Delta\omega_2 &= \beta^{-1} \frac{H_w}{s} \frac{T_1}{T} A^{-1} H_{int} H_{inv} \Delta P_g + \\ &\quad \beta^{-1} H_w \Delta\delta_1 - \beta^{-1} \frac{H_w}{T} \Delta P_{d2}, \end{aligned} \quad (21)$$

where

$$\beta = 1 - \left(\left(\frac{H_w}{s} \right) \left(\frac{T_1}{T} \right) \alpha^{-1} \gamma \right) - \left(\left(\frac{H_w}{s} \right) \left(\frac{T_1}{T} \right) \right) \quad (22)$$

The tie-line power between the inverter and the synchronous machine is calculated as

$$P_{tie21} = -P_{tie12} = T(\delta_2 - \delta_1). \quad (23)$$

2.3. State-Space Models

Based on the mathematical equations, a detailed state-space model is derived using the Matlab Model Linearizer [30]. The physical meaning of the state vector produced by the MATLAB Model Linearizer depends on the structure of the underlying Simulink model. Each state in the linearized model corresponds to an internal state variable from blocks that maintain memory, such as integrators, state-space blocks, or discrete delays. Thus, the interpretation of these states is inherently tied to how the system is modeled. When the model uses physical integrators representing physical quantities—such as positions, velocities, or currents—these states reflect small perturbations around the operating point. Conversely, when the model consists of algorithmic or control-oriented blocks, such as the inverter and generator considered in this work, the states may represent internal computational states rather than directly physical variables.

The resulting state-space model for the inverter is given as

$$\dot{\mathbf{x}}_{inv} = A\mathbf{x}_{inv} + B\mathbf{u}_{inv} \quad (24)$$

$$\mathbf{y}_{inv} = C\mathbf{x}_{inv} + D\mathbf{u}_{inv} \quad (25)$$

where $\mathbf{x}_{inv} \triangleq [x_1, x_2, x_3, x_4]^T$ is the state vector, $\mathbf{y}_{inv} \triangleq [\omega_2, x_1, x_2, x_3, x_4]^T$ is the output vector, and $\mathbf{u}_{inv} \triangleq [\Delta\delta_1, \Delta P_{d2}, \Delta P_{g1}]^T$ is the input vector. The inverter's four states represent internal small-signal dynamics around the operating point and do not correspond directly to physical variables. The matrices of the inverter state-space model are given below.

$$A_{inv} = \begin{bmatrix} 0 & 0 & 0 & -0.625 \\ 1 & 0 & 0 & -1.938 \\ 0 & 2 & 0 & -4 \\ 0 & 0 & 8 & -12.1 \end{bmatrix} \quad (26)$$

$$B_{inv} = \begin{bmatrix} 0 & 0.00625 & -0.625 \\ 0.00625 & 0.01312 & -1.312 \\ 0.025 & 0.01375 & -1.375 \\ 0.1 & 0.011 & -1.1 \end{bmatrix} \quad (27)$$

$$C_{inv} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (28)$$

$$D_{inv} = \begin{bmatrix} 0 & -0.01 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (29)$$

Similarly, the Matlab Model Linearizer is applied to the synchronous generator model, yielding a state-space model representation where $\mathbf{x}_{gen} \triangleq [\Delta\delta_1, \Delta\omega_1]^T$ is the state vector, $\mathbf{y}_{gen} \triangleq [\delta_1, \Delta\omega_1]^T$ is the output vector, and $\mathbf{u}_{gen} \triangleq [\Delta\delta_2, \Delta P_{d1}, \Delta P_{g2}]^T$ is the input vector. Here, the second output for $\mathbf{y}_{gen}$ corresponds to frequency deviation, scaled by a constant factor defined in the C matrix. The state-space matrices for the synchronous generator are provided below.

$$A_{gen} = \begin{bmatrix} 0 & 0.333 \\ -100 & -7 \end{bmatrix} \quad (30)$$

$$B_{gen} = \begin{bmatrix} 0 & 0 & 0 \\ 100 & -1 & 1 \end{bmatrix} \quad (31)$$

$$C_{gen} = \begin{bmatrix} 1 & 0 \\ 1 & 0.333 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (32)$$

$$D_{gen} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (33)$$

2.4. Controllability and Observability of Subsystems

To determine whether the subsystems are controllable, a controllability test has been performed for the generator and inverter. The controllability matrix is given by

$$\mathbf{Z} \triangleq [\mathbf{B}, \mathbf{AB}, \mathbf{A}^2\mathbf{B}, \mathbf{A}^3\mathbf{B}]. \quad (34)$$

The rank of $\mathbf{Z}_{inv}$ for the inverter is 4. The rank of $\mathbf{Z}_{gen}$ for the generator is 2. Both ranks are equal to the number of states of their respective state-space models, implying that each subsystem is controllable and suitable for use in the MPC design.

The observability matrix is given by

$$\mathbf{O} \triangleq \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \mathbf{CA}^2 \\ \mathbf{CA}^3 \end{bmatrix} \quad (35)$$

The rank of $\mathbf{O}_{inv}$ for the inverter is 4. The rank of $\mathbf{O}_{gen}$ for the generator is 2. Both ranks are equal to the number of states of their respective state-space models, implying that each subsystem is observable and suitable for use in the MPC design.

3. Controller Design Using Distributed Model Predictive Control (DMPC)

3.1. DMPC Setup

The Distributed Model Predictive Control (DMPC) scheme is configured to maintain the tie-line power exchange at zero during steady-state operation. The setup parameters used in the APMonitor optimization framework are summarized in Table 3. These parameters define the prediction, control, and step horizons, as well as solver configuration settings, that determine how frequently control actions are updated and how the optimization problem is solved over time. The value for the prediction horizon is 10, for the control horizon is 6, and for the step horizon is 6, with a value of 200 max iterations allowed. Controlled variables are model variables that are included in the objective of a controller or optimizer. States are model variables that may be measured or are of special interest for observation. The variables set up in the AP Monitor are shown below.

Table 3. APMonitor parameter setup.

Category	Area 1-DMPC	Area 2-DMPC
Manipulated Variable	Generator Active Power Adjustment ΔP_{g1}	Inverter Active Power Adjustment ΔP_{g2}
Controlled Variables	Frequency deviation Δf_1 ; phase angle deviation $\Delta \delta_1$; coordination error	Frequency deviation Δf_2 ; phase angle deviation $\Delta \delta_2$; coordination error
Power Constraints	$-10 \leq \Delta P_{g1} \leq 10$	$-10 \leq \Delta P_{g2} \leq 10$
Communication Assumptions	Ideal, synchronized; no delay modeled	Ideal, synchronized; no delay modeled

DMPC employs the objective function in (1), along with a set of tuned parameters, to generate the system inputs and drive the tie-line power toward zero. The parameters in (1) (p_{ij} , q_i , and r_i) were adjusted to achieve satisfactory performance, and their functions and values are listed in Table 4 and Table 5, respectively. With appropriate tuning, the objective function effectively minimizes the tie-line power flow, ensuring convergence to zero.

Table 4. Description of optimization function weights.

Term	Weight Factor	Action	Effect
p_{ij}	Deviation in angle between area i and area j	Adjust the tie-line power	Determines how strongly area i aligns its predicted angle with area j
q_i	Deviation in frequency	Control area i Frequency	Minimizes the frequency error
r_i	Generator power change	Actuator smoothing	Regulates generator power adjustment

Table 5. Value of objective function tunable parameters.

Area 1	Area 2
p_{12} : 9,750,000	p_{21} : 1,750,000
q_1 : 1,250,000	q_2 : 1,250,000
r_1 : 0.001	r_2 : 0.001

For parameter p_{ij} , the higher the value, the more power Area 1 and Area 2 are allowed to generate. If the value is extremely low, it will cause an undershoot in the power generated and will be unable to optimally satisfy the desired load. If the value is extremely high, it will cause an overshoot and produce more power than what is needed for the load. For parameter q_i , the higher the value, the more the system will try to keep the power generated as linear as possible. If the value is extremely low, it will cause the power generated to be nonlinear. If the value is extremely high, it will be very linear and unable to supply power to the load. For parameter r_i , the higher the value, the less effort the controller puts into keeping the power via the tie-line close to 0 as much as possible. If this value is not tuned properly, the controller will not manipulate the variables needed to maintain a power flow through the tie-line of 0 in the most optimal way.

3.2. Observer Design for State Estimation

With the given Simulink inverter model, it is not possible to easily access the states due to how the structure is modeled. Therefore, a state observer has been created, which is given by

$$\dot{\hat{\mathbf{x}}} = A\hat{\mathbf{x}} + B\mathbf{u} + L(\mathbf{y} - C\hat{\mathbf{x}}), \quad (36)$$

where $\hat{\mathbf{x}}$ is the estimation of state vector $\mathbf{x}$. Defining the error state, $\tilde{\mathbf{x}}$, as $\tilde{\mathbf{x}} \triangleq \mathbf{x} - \hat{\mathbf{x}}$, we have

$$\dot{\tilde{\mathbf{x}}} = (A - LC)\tilde{\mathbf{x}}, \quad (37)$$

where the observer gain vector, L , is selected such that the eigenvalues of the matrix $(A - LC)$ all have negative real parts, which guarantees that $\tilde{\mathbf{x}}$ converges to zero exponentially. A larger vector value of L enables faster convergence to the actual states; however, it also increases sensitivity to noise and raises the likelihood of oscillatory responses. Conversely, a smaller vector value of L enhances stability but results in slower convergence and reduced responsiveness to changes. In this work, L is tuned and selected as $L = \begin{bmatrix} 600 & 260 & 80 & 33 \end{bmatrix}^T$. The value of L was determined using pole placement. The observer poles were first selected by analyzing the eigenvalues of the linearized inverter model and placing eigenvalues approximately 5 to 10 times faster than the dominant system nodes. This ensures fast estimation of error convergence and maintains numerical

robustness. This then led to the pole set $[-10, -8, -6, -20]$. The corresponding gain vector L was then computed using the pole placement method.

4. Results and Discussions

4.1. Power–Load Simulation Results

In the simulation analysis, the main objective of the controller, as shown in Figure 6, is to maintain the tie-line power at zero. As mentioned in Section II, both areas will only share power during load transients. During the transient, individual areas will respond to the fluctuation in power and ramp up their power generation. Therefore, in the simulation, the load demand in each area is changed during specific time intervals to test the performance of the proposed DMPC. In Figure 6a, the dotted lines represent the load demands and the solid lines represent the reference power generated from the DMPC controllers in each area. The detailed time interval and load changes are given in Table 6.

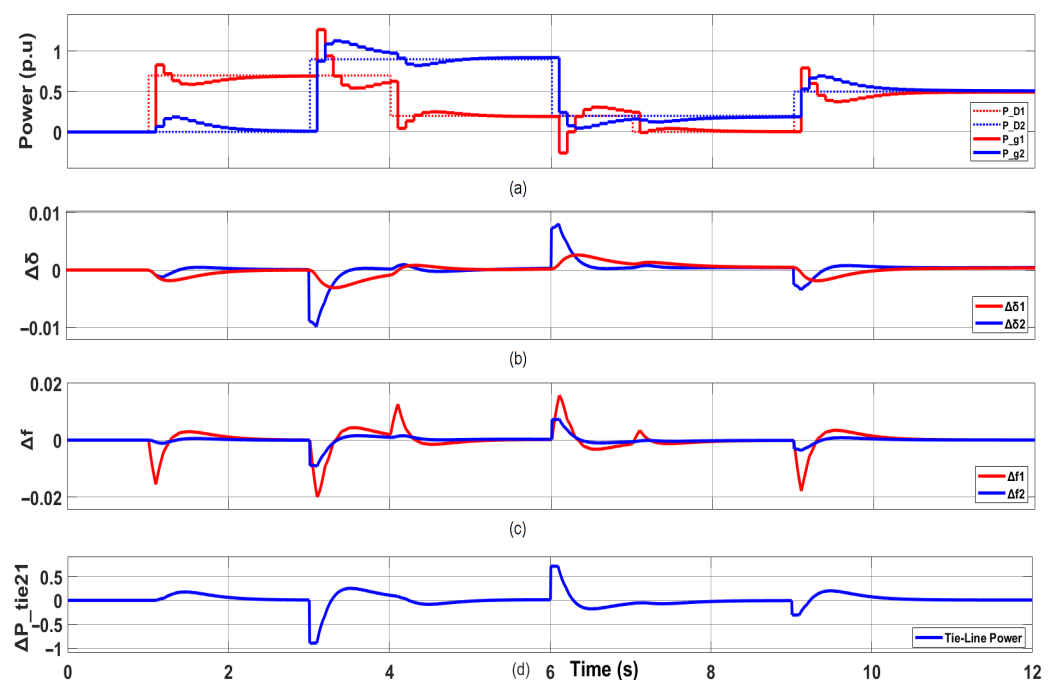


Figure 6. Simulation results showing (a) power demand with actual power generation, (b) deviation in angle, (c) deviation in frequency, and (d) change in tie-line power.

Table 6. Simulation time interval with load demand.

Time Interval (s)	Area#1 Load (p.u.)	Time Interval (s)	Area#2 Load (p.u.)
$0 \leq t < 1$	0	$0 \leq t < 3$	0
$1 \leq t < 4$	0.7	$3 \leq t < 6$	0.9
$4 \leq t < 7$	0.2	$6 \leq t < 9$	0.2
$7 \leq t < 9$	0	$9 \leq t < 12$	0.5
$9 \leq t < 12$	0.5		

As shown in Figure 6a, from time $t = 0$ s to 1 s, the initial load demand is zero for both areas, and thus the DMPC controller is generating a zero reference power command. Therefore, there is no deviation in phase angle and frequency, as shown in Figure 6b,c. As stated in the main objective, Figure 6d validates that the tie-line power during this interval

is zero. At time $t = 1$ s, the Area#1 load demand is changed to 0.7 p.u. It can be observed that the DMPC controller follows the reference load demand and generates the required power. During this transient, as shown in Figure 6b,c, there is a deviation in angle and frequency, which results in a change in tie-line power, as shown in Figure 6d. Similarly, during the same time interval, the Area#2 load demand changes from 0 to 0.9 p.u at $t = 3$ s. During this interval, DMPC responds to the load demand by changing $\Delta\delta$, as shown in Figure 6b,c. This results in a power flow from Area#1 to Area#2, as shown in Figure 6d. It can also be observed that both areas respond to the fluctuation in the load and achieve a steady state when each area meets its power demand. At $t = 4$ s, the Area#1 load demand is decreased from 0.7 to 0.2 p.u. This change in load results in deviations for delta and frequency, as shown in Figure 6b,c. Once power satisfies the new load demand, it can be shown that the steady state is achieved once again. This process is consistently observed to occur every time there is a change in load. At $t = 6$ s, the Area#2 load is changed to 0.2 p.u., at 7 s, the Area#1 load is set to zero, and at 9 s, both areas have an equal load demand of 0.5 p.u. During all these time intervals, the DMPC controller generates the power demand accordingly and strives to keep the power in the tie-line equal to 0. This validates the performance of the proposed DMPC controller with a synchronous generator and an inverter.

4.2. State Observer Results

As discussed in Section 3.2, the state estimator is created, with inputs $\Delta\delta_2$, ΔP_{d2} , and ΔP_{g1} given by the dynamic equations derived and $\Delta\omega_2$ given by the Simulink model of the inverter. The outputs of the observer are the four auxiliary states of the simulation model of the inverter. The comparison between the state estimates and the true state values is shown in Figure 7. It can be seen that all state estimates converge to their actual values in approximately 1 s and follow the actual state values accurately, which demonstrates the quality performance of the proposed state estimator.

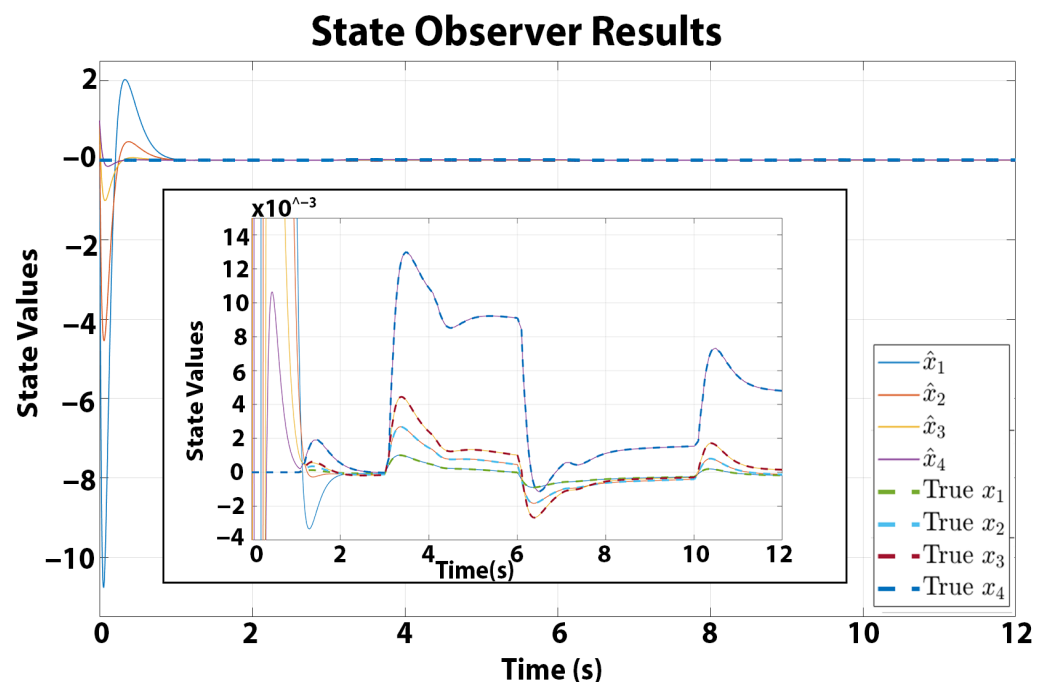


Figure 7. State observer: Solid lines represent states generated by the observer, and dashed lines represent actual states of the system.

5. Conclusions

This paper presents a distributed model predictive controller (DMPC)-based grid-connected inverter system. The DMPC is designed to maintain the frequency in each area, ensuring that the power flow between areas is zero in the steady state. It can be observed that each area controller shares limited parameters and works collaboratively to regulate the system without relying on a single centralized controller. This demonstrates that DMPC enables multiple grid-connected inverters to coordinate power sharing, maintain voltage and frequency stability, and enhance power quality by utilizing local predictive controllers that exchange minimal information, providing a scalable, robust, and efficient control solution for modern microgrids. Future work includes a multi-area system with real-time implementation in Opal-RT and testing the plug-and-play capability.

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Abbreviations

The following abbreviations are used in this manuscript:

DMPC	Distributed Model Predictive Control
MPC	Model Predictive Control
LFC	Load Frequency Control
MG	Microgrid
DER	Distributed Energy Resource
APOPT	Advanced Process OPTimizer
IPOPT	Interior Point OPTimizer
GF-I	Grid-Following Inverter
PLL	Phase-Locked Loop
SV	State Variable
CV	Controlled Variable

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