

MODEL PREDICTIVE CONTROL (MPC) AND PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLERS FOR LOAD FREQUENCY CONTROL SCHEME

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Abstract

This study aims to examine the use of Proportional Integral Derivative (PID) and Model Predictive Control (MPC) in Load Frequency Control (LFC). A balance between the generation and the load is necessary to ensure the consistency of the electrical supply. These days, MPC techniques are becoming popular due to their merits over conventional PID controllers. In this study, performance of the designed PID and MPC schemes has been tested and compared for two area interconnected power system. This system consists hydro unit in area-1 and three Thermal units in area-2. A step load perturbation scenario in both areas has been obtained to evaluate the effectiveness of the designed control strategies. The results show that both the designed control approaches performed successfully however, the MPC scheme outperform the PID scheme in terms of time domain specifications like reduced oscillation and smaller settling time. It can be concluded that MPC can be used as a secondary controller for LFC applications in future research.

Keywords: Automatic Control Error (ACE); Load Frequency Control (LFC), Proportional Integral Derivative (PID), Model Predictive Control (MPC)

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Introduction

The supply and demand of electricity must be balanced to maintain reliability. One method to do this is to apply load frequency control (LFC). It is not only essential for the power system to function, but it also helps to uphold the system's frequency within a suitable range. Since power system is a network of many control areas, LFC also ensures to take care of net power interchange between areas.

The heart of LFC is the controller that is used to keep the balance by forcing system's frequency and tie-line flow at their normal values (Mokhtar *et al.*, 2022; Ahmed Khan *et al.*, 2023).

Related Work

In literature, researchers have presented various studies in order to design an optimal LFC scheme utilizing an optimal controller.

The study reported in Kumar *et al.* (2022a) digs into frequency issues in a multiarea deregulated power system. The big bang big crunch (BBBC) algorithm is employed to optimize a Fractional order based Proportional integral derivative (FOPID) controller, resulting in enhanced performance and superior results. When combined with Superconducting Magnetic Energy Storage (SMES) unit, the FOPID controller exhibits remarkable efficacy. Furthermore, the Neural Network based Internal Model Control (NN-IMC) technique is introduced in (Kumar *et al.*, 2021b), which significantly improves the system's responsiveness. Although the FOPID and NN-IMC control systems work well together, the NN-IMC system has superior overshoot and undershoots performance as well as settling time. Due to its compliance with North American Electric Reliability Corporation (NERC), Control Performance Standards 1 & 2 (CPS1, and CPS2), the NN-IMC system is a solution for big energy networks operating in a regulatory-free environment. The shift to hybrid power systems with Renewable (RE), and Energy storage (ES) has improved flexibility but challenges frequency stability. Therefore, the paper (Ahmed Khan *et al.*, 2023), reviews LFC strategies, and frequency stability mechanisms (e.g., RoCoF, wind turbine control, demand response) and highlighted research gaps.

The paper reported by Mokhtar *et al.* (2022), presented an adaptive-Load Frequency Control (LFC) to address frequency challenges from load variations and renewable energy disturbances like Wave Energy Conversion Systems (WECS) and Photovoltaics (PV) systems. With auto-tuned parameters, the controller enhances robustness and outperforms classical LFC methods. A Load

Frequency Control (LFC) scheme in a deregulated scenario using communication delays and GA-PID controller has been reported in (Singh *et al.*, 2018). The various results presented the effectiveness of the given approach. A flexible resource in real-time control has its importance in a high renewable penetrated power system. A Model predictive control (MPC) using online feedback algorithm has been reported in (Qi *et al.*, 2022). The MPC performs optimally and balances the frequency and load. The effectiveness of Model Predictive Control (MPC) with high wind power has been reported in (Ersdal *et al.*, 2014). The results evident that the designed MPC gives better performance than PI control. A Load frequency control (LFC) utilizing MPC has been designed in order to eliminate mitigates frequency disturbances caused by wind power intermittent nature (Yang *et al.*, 2019). A predictive model is reported to optimize signals and improve frequency response. This paper reported an adaptive-Model Predictive Control (MPC) that considers nonlinearity such as governor dead band and constraints. Simulations on a two-area system proved that the designed MPC performs better than conventional controllers for various conditions (Zeng *et al.*, 2017). A comparison of Imperialist Competitive (ICA) and Genetic (GA) algorithm PID controllers for a two-area (without GRC) and a three-area power system (with GRC) has been reported in (Kumar *et al.*, 2016). Results show that ICA- PID performs superior than GA- PID. A Multiarea automatic generation control (AGC) using the Imperialist Competitive (ICA) tuned PID has been reported for A 75-bus hydro-thermal system, in deregulated scenario. A comparative study between ICA-tuned PID and GA-tuned PID shows the superiority of ICA-PID in terms of settling time and oscillations (Kumar *et al.*, 2017). This paper proposed a distributed model predictive control (D-MPC) for load frequency control (LFC). A multi-area power system (deregulated) using contracted and uncontracted load has been reported. The controller was designed considering generation rate constraints and load setpoints. Simulation results (three-area) showed improved performance while following system constraints (Ma *et al.*, 2017). This paper stated a photovoltaic (PV)-thermal system which optimizes PV operation at maximum power point (MPP). A model predictive controller (MPC) was used to address LFC issues to ensure fast convergence and minimal oscillation. The results demonstrate that MPC outperforms GA-based PI, firefly-based PI, and conventional PI controllers (Gulzar *et al.*, 2019).

This paper reported an autonomous demand side management system (DSM) to enable two-way communication for smart grid. Using game theory, an energy consumption scheduling for users utilizing time-differentiated pricing has been formulated. Simulation results show that this method reduces energy costs, and individual electricity charges (Mohsenian-Rad *et al.*, 2010). This paper reported an optimal scheduling model for microgrid and utilizes demand responses to adhere source and load prediction. A day-ahead robust optimization and intraday model predictive control (MPC) has been introduced. It is shown that MPC corrects the day-ahead plan by addressing high-frequency errors and confirm the feasibility and effectiveness of the model (Zhang *et al.*, 2021). A robust distributed Model Predictive Control (DMPC) algorithm for interconnected systems is proposed, with a mathematical model for frequency control. The robustness is analyzed using parameter and structural uncertainties and validated under various load changes and uncertainties (Liu *et al.*, 2016).

A robust load frequency control (LFC) for multi-area power system to manage wind energy integration utilizing Model predictive control (MPC) which tracks wind power output is presented in (Hu *et al.*, 2024).

The small-signal load frequency model is proposed to incorporate parameter change. Results on four-area system illustrate the efficiency of the proposed model. This paper reported a load frequency MPC strategy for balancing load demand in power systems with wind, clean coal, and dual-fuel gas turbines (GTs). The MPC shows stability, with increased wind integration (Afaneh *et al.*, 2022).

The study given in Banis *et al.* (2020) compares a target-adjusted and classical MPC schemes. The target-adjusted MPC can be used as an alternative to classical MPC.

The study reported in Yang *et al.* (2020) proposed an MPC-based LFC that can incorporate varying system inertia because of large wind generation. The state-space model is updated in order to improve performance. Results of a two-area system show the effectiveness of this model.

An architecture based on cloud edge end collaboration control using model predictive control (MPC) is reported for interconnected power systems (IPS). The proposed model can handle model uncertainty, load deviations, and communication delays (Gorbachev *et al.*, 2023).

A tracking model predictive control (MPC) utilizing economic dispatch (ED) for multi-area networks is presented for frequency control. MPC is used to control the system. Results of the two-area

system show improved economic and dynamic performance of the proposed controller (Asuk and Trodden, 2023).

A novel adaptive intelligent MPC for load frequency control (LFC) in microgrids (MG) is reported, utilizing the state-of-charge (SoC) of EV batteries. The proposed model is compared with others under various conditions and it shows the superior performance (Khokhar and Parmar, 2022).

This study presents model predictive control (MPC) for allocation of power for primary frequency regulation while utilizing multiple distributed energy storage (DES) aggregators. A distributed interior point method is used and Simulation results show the model's effectiveness in allocating power, reducing state-of-charge shifts, and ensuring continuous DES participation (Mao *et al.*, 2023).

As renewable energy integration increases and fossil fuel plants depleted, the need for frequency regulation increased. A buffer storage and demand forecasting model, utilizing Robust MPC and affine policies, to provide frequency reserves have been presented. In a real-world experiment, this system effectively offers reserves, tracks regulation signals, and meets heating demands. Affine policies reduce system costs, increase reserves, and minimize performance gaps compared to ideal control system (Bünning *et al.*, 2022). This paper uses aggregated inverter air conditioners (IACs) for frequency regulation, employing Model Predictive Control (MPC) with a predictive compensation method (PCM) to address communication delays. Results show that MPC along with PCM outperforms proportional-integral (PI) control in order to provide better response, robustness, and stability (Zhao *et al.*, 2022). This study introduces a hybrid Grey Wolf Optimizer - Pattern Search (HGWO-PS) based MPC for LFC in an islanded two-area microgrid. The method reduces complexity and cost while damping frequency and power deviations. Simulations show that the HGWO-PS-based MPC outperforms other control methods (Amiri and Hatami, 2023).

This paper presents a shrinking-horizon MPC for load-frequency control, using centralized control for single-area and distributed control for multi-area systems. It improves performance with a linear state-space model and minimizes rescheduling costs. Simulations on IEEE test systems show that the proposed method outperforms existing controllers in terms of dynamic performance and reduces rescheduling costs by up to 38% compared to conventional PI controllers (Das and Sengupta, 2024). Table 1 shows the Benefits and limitations of the studies discussed in the related work section.

This literature study shed light on the changing landscape of power system control in order to prepare a basis for future research and practical applications.

The structure of the remaining paper is as follows: Section 2 introduces the modeling of the power system, while Section 3 comprehensively presents both the control approaches. The outcomes achieved through all control schemes are disclosed

in Section 4, with the analysis of the study reaching its conclusion in Section 5.

Test System Modeling

In the event of a load imbalance, adjustments to the prime mover's speed are made to counter the effects, consequently impacting the system's

Table 1. Benefits and limitations of the studies discussed in the related work section

Authors	Benefit	Limitation
Kumar <i>et al.</i> , 2022a	Enhanced performance with FOPID controllers optimized using BBBC algorithm; works well with SMES unit.	Does not address integration with hybrid systems or other energy sources.
Kumar <i>et al.</i> , 2021b	NN-IMC technique improves overshoot, undershoot, and settling time, ensuring compliance with CPS1 & CPS2 standards.	Increased complexity due to neural network integration.
Ahmed Khan <i>et al.</i> , 2023	Reviews LFC strategies and highlights frequency stability mechanisms like RoCoF, demand response, etc.	Limited focus on practical implementation of identified research gaps.
Mokhtar <i>et al.</i> , 2022	Adaptive LFC with auto-tuned parameters ensures robustness against load and renewable energy disturbances.	Effectiveness in large-scale, interconnected systems not demonstrated.
Singh <i>et al.</i> , 2018	GA-PID controller for deregulated scenarios shows effectiveness under communication delays.	Limited scope for hybrid energy systems.
Qi <i>et al.</i> , 2022	Online feedback-based MPC ensures optimal frequency-load balance.	High computational demand for real-time applications.
Ersdal <i>et al.</i> , 2014	MPC with high wind power provides better performance compared to PI control.	Limited to high wind energy scenarios; may not generalize well.
Yang <i>et al.</i> , 2019	MPC mitigates frequency disturbances from wind power intermittency with predictive optimization.	Limited focus on broader energy system integration.
Zeng <i>et al.</i> , 2017	Adaptive MPC considers nonlinearity (e.g., governor deadband) and performs better than conventional controllers.	Complexity in nonlinear model design.
Kumar <i>et al.</i> , 2016	ICA-PID outperforms GA-PID in settling time and oscillation reduction.	Applicability limited to smaller or simpler systems.
Ma <i>et al.</i> , 2017	Distributed MPC improves performance under constraints in deregulated, multi-area power systems.	Computationally intensive for large systems.
Gulzar <i>et al.</i> , 2019	MPC ensures fast convergence and minimal oscillations, outperforming PI-based controllers.	Implementation complexity increases for multi-area systems.
Mohsenian-Rad <i>et al.</i> , 2010	Game theory-based DSM reduces energy costs and individual charges.	Focused on user-level benefits; system-level impact not discussed.
Zhang <i>et al.</i> , 2021	MPC corrects day-ahead plans by addressing high-frequency errors effectively.	Limited scalability to large grids with diverse resources.
Liu <i>et al.</i> , 2021	Robust DMPC analyzes uncertainties and handles load changes effectively.	Validation limited to certain scenarios; scalability not demonstrated.
Hu <i>et al.</i> , 2024	MPC-based LFC for multi-area systems effectively manages wind energy integration.	Does not address broader renewable energy sources or hybrid systems.
Afaneh <i>et al.</i> , 2022	MPC balances load demand in systems with wind, clean coal, and dual-fuel GTs.	Limited to specific generation types; lacks generalizability.
Banis <i>et al.</i> , 2019	Target-adjusted MPC offers an alternative to classical MPC.	Comparative performance improvement is marginal.
Yang <i>et al.</i> , 2020	MPC-based LFC incorporates varying system inertia with better performance in wind-rich scenarios.	Model limited to scenarios with significant inertia variations.
Gorbachev <i>et al.</i> , 2023	Cloud-edge collaboration-based MPC handles uncertainties, load deviations, and communication delays effectively.	Implementation may require extensive infrastructure upgrades.
Asuk and Trodden, 2023	Economic MPC improves dynamic and economic performance for multi-area systems.	Focused primarily on cost optimization rather than broader system reliability.
Mao <i>et al.</i> , 2023	MPC with distributed energy storage allocates power effectively and reduces SoC shifts.	Does not explore broader system-level impacts beyond storage systems.
Bünning <i>et al.</i> , 2022	Robust MPC with affine policies offers frequency reserves and reduces system costs in real-world experiments.	Focused only on specific renewable scenarios; broader applicability not addressed.
Zhao <i>et al.</i> , 2022	MPC with predictive compensation improves response, robustness, and stability in delay-sensitive systems.	Limited focus on delay-sensitive applications only.
Amiri and Hatami, 2023	HGWO-PS-based MPC reduces cost and complexity while damping frequency deviations.	Limited scalability and validation in multi-area systems.
Das and Sengupta, 2024	Shrinking-horizon MPC minimizes rescheduling costs and outperforms conventional PI controllers in dynamic performance.	Limited to IEEE test systems; lacks real-world validation.

frequency. The governor of generators plays a pivotal role in overseeing these speed changes, stabilizing at a constant governor speed once the adjustments are nullified. However, due to the variable nature of the load governor speed, lacking a fixed point, an additional control mechanism is introduced, incorporating an integrator to rectify any deviation and restore the system to its standard value, known as the reset point.

In this study, authors have selected two area power system consisting of Thermal and Hydro units in each area, in order to evaluate the effectiveness of the controllers. The PID and MPC control structures have been selected to work as a secondary control scheme.

System configuration

The power system in Area-1 integrates hydroelectricity generation. The hydropower unit is used to generate a clean and sustainable energy, by utilizing the potential of hydro resources to produce electricity. Hydropower is an environmentally

friendly resource that plays a crucial role in maintaining grid stability and meeting the energy demands. However, Area 2 consists of three thermal generating units. These thermal areas utilise a variety of fossil fuels or alternative thermal sources to generate electricity. Thermal power plants in Area 2 offer a dependable and adaptable source of electricity generation that can effortlessly adapt to fluctuating demand levels and grid conditions. Hydropower in Area-1 and thermal power generations in Area-2 guarantees a dependable and effective power supply for the entire interconnected system.

Simulation: MATLAB/Simulink, R2023b.

Testing case: Step load Perturbation

Performance metrics: Oscillations, settling time, tie-line power deviations, frequency and area control error (ACE) deviations.

Figure 1 shows the research flowchart, which shows the work methodology proposed in this study.

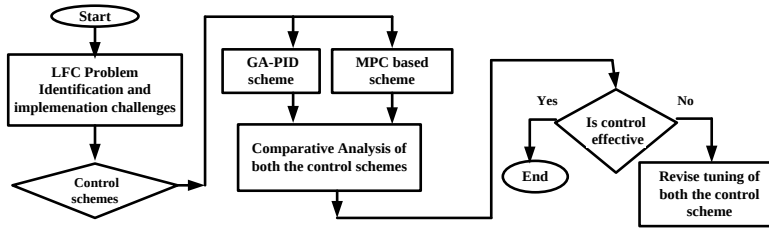


Figure 1. Research Flowchart

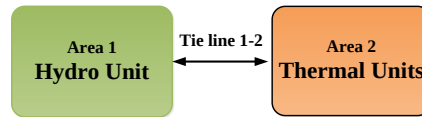


Figure 2. Diagram consisting of both areas

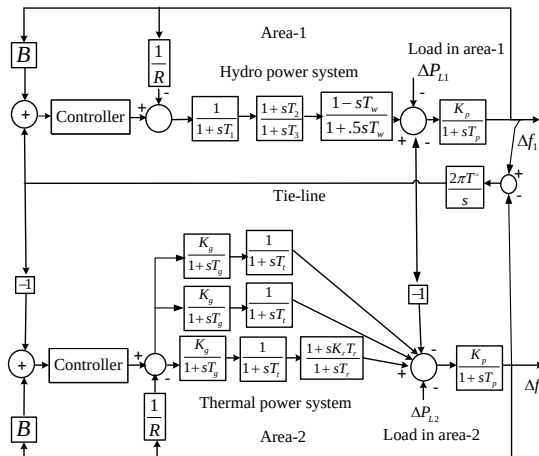


Figure 3. Block diagram of the test system

Figure 2 shows single line diagram of Hydro unit and Thermal units connected using Tie-line power between areas. The Block diagram of the complete power system is given in Figure 3.

Where, $T_1 = 0.019\text{sec}$, $T_2 = 5\text{sec}$, $T_3 = 28.93\text{sec}$ are the hydro unit governor time constant, governor rest time and transient droop time, respectively. $T_w = 1\text{sec}$ is water time constant.

$K_g = 1$ and $T_g = 0.08\text{ sec}$, are the thermal governor gain and time constant. $T_t = 0.5\text{ sec}$ is the thermal turbine time constant. $K_r = 0.5$ and $T_r = 10\text{ sec}$ are the reheater gain and time constant. $K_P = 120$ and $T_P = 20$ are the power system gain and time constant. $T_o = 0.01$ is the synchronizing coefficient of power.

Highlights of the work

The main work carried out in this study is as follows:

- A Model Predictive Control (MPC) scheme is proposed for a comprehensive LFC analysis of a two-area hybrid system.

- A comparative performance between the Model Predictive Control (MPC) and GA-tuned PID is carried out based on test system.
- Results show that the MPC control scheme is better than the PID scheme in terms of oscillations and settling time.

The MATLAB implementation of the Figure 3 is given in Figure 4. The simulation was run for 50 seconds, and the results were obtained for a load perturbation case.

Control schemes

This section is dedicated to clarifying the structure and optimization algorithm utilized for determining optimal parameters for different controllers.

PID (Proportional-Integral-Derivative) control is a basic and simple scheme which has numerous applications in many other fields than power system.

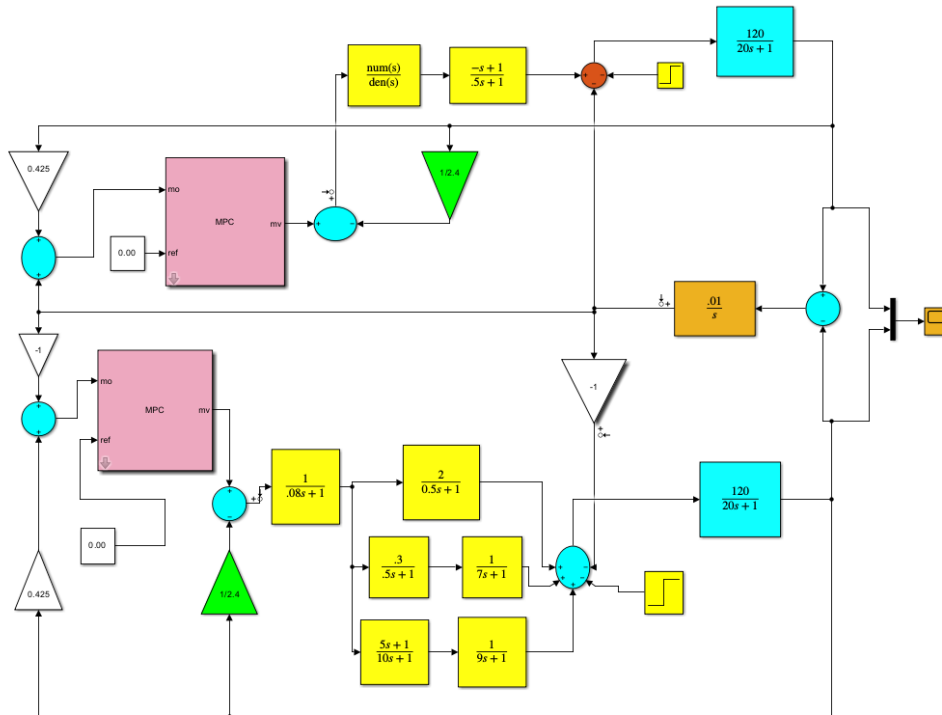


Figure 4. Simulink diagram of two area systems

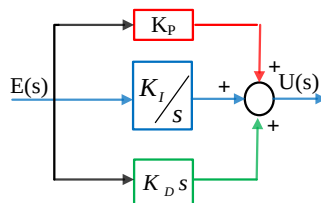


Figure 5. Block diagram representation of PID control

Figure 5 depicts the model utilized in the PID Control. The further explanation about its structure, mathematical equations can be explored from the references.

The parameters of the PID controller have been determined utilizing a popular optimization technique named as genetic algorithm (GA). The objective function in order to obtain the parameters is minimization of the area control error (ACE), and given in (1).

$$F = \frac{1}{m} \sum_{i=1}^m [(B_i \Delta F_i + \Delta P_{tie_{i-error}})^2] \quad (1)$$

Here, m = Number of areas.

B = frequency bias,

Δf = frequency deviation

ΔP_{tie} = deviation in tie-line power.

Figure 6 shows the cycle of GA used to implement the controller.

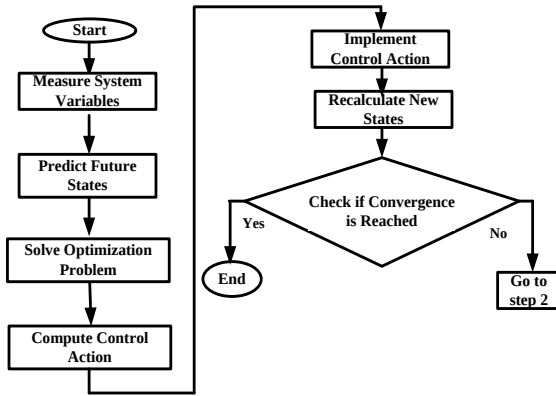


Figure 6. GA flow cycle

The steps to design a controller using GA are as follows:

- **Initialize Population** (generate random PID parameters: K_p , K_i , K_d)
- **Evaluate Fitness** (run simulation with current PID parameters and calculate the error index)
- **Select Parents** (based on fitness, select individuals for crossover)
- **Crossover** (combine selected parents to create new offspring)
- **Mutation** (randomly alter parameters for variation)
- **Evaluate Fitness of New Population** (run simulation with new parameters)
- **Check Termination Criteria** (e.g., number of generations or desired fitness level)

Yes: go to last step

No: Go back to step 4

- **Select Best PID Parameters** (choose the PID parameters with the best fitness)

Model Predictive Control

Model Predictive Control (MPC) serves as a prominent control scheme among various control methodology. The fundamental concept behind Model Predictive Control (MPC) is to efficiently address optimization problems. The current approach utilizes a model to forecast the future dynamics of the system. Considering the present and future circumstances and constraints, this approach has the potential to significantly minimize cost function.

The formulation of MPC consists of a predictive model of the system, a cost function, and constraints. Using x to represent the system state at time t , u as the control input, and y as the output. Following that, the predictive model can be written as follows in equation (2):

$$\begin{aligned} x(t+1) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \quad (2)$$

Here, A , B , and C are matrices that characterize the system dynamics. The control input u is calculated by solving optimization problem. The cost function includes a combination of control effort and state tracking terms.

The general form of the cost function J is:

$$J = \sum_{k=0}^{N-1} \|y_{t+k} - r_{t+k-1}\|^2 Q + \|u_{t+k} - u_{t+k-1}\|^2 R \quad (3)$$

Here, N = prediction horizon, Q and R = positive definite weighting matrices, and r_{t+k} = the reference trajectory.

Model Predictive Control (MPC) provides substantial advantages in handling system limitations by effectively incorporating input and output constraints into the optimization issue. Typically, constraints can be written as:

$$u_{\min} \leq u_t \leq u_{\max}$$

$$y_{\min} \leq y_t \leq y_{\max}$$

Where, $u_{\min} \leq u_t \leq u_{\max}$ is known as input constraints used to limit the control input within specified range in order to keep control implementable and practical one, and $y_{\min} \leq y_t \leq y_{\max}$ is output constraints in order to maintain system performance within specified limit.

The Flowchart of the MPC employed in this study is illustrated in Figure 7.

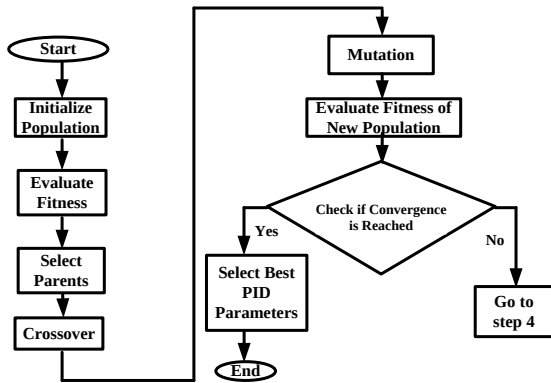


Figure 7. Flowchart of MPC scheme

The steps of the MPC flowchart are as follows:

- Begin the control process.
- Collect the current state or output of the system.
- Forecast behavior over a prediction horizon.
- Minimize a cost function while respecting constraints.
- Determine the optimal control input.
- Apply the control input to the system.
- Update the system state after applying control.
- If the system meets the desired state, the process ends.
- Otherwise, repeat the cycle.

Figure 8 shows the working model/structure of the MPC scheme. As it can be seen from Figure 8

that MPC works on to reduces/eliminates error between the plant and predicted model in order to provide the optimal control.

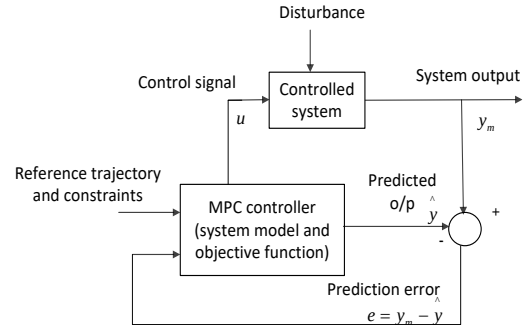


Figure 8. MPC Control Structure

Figure 9 shows the MATLAB implementation of the MPC scheme. It can be seen from the Figure that:

- The figure demonstrates that the MPC successfully tracks the desired output with minimal overshoot and steady convergence to the setpoint.
- The stepwise input response and smooth output behavior reflect the controller's ability to handle system dynamics effectively.
- Fine-tuning the prediction and control horizons, constraints, and weights can further enhance system performance.

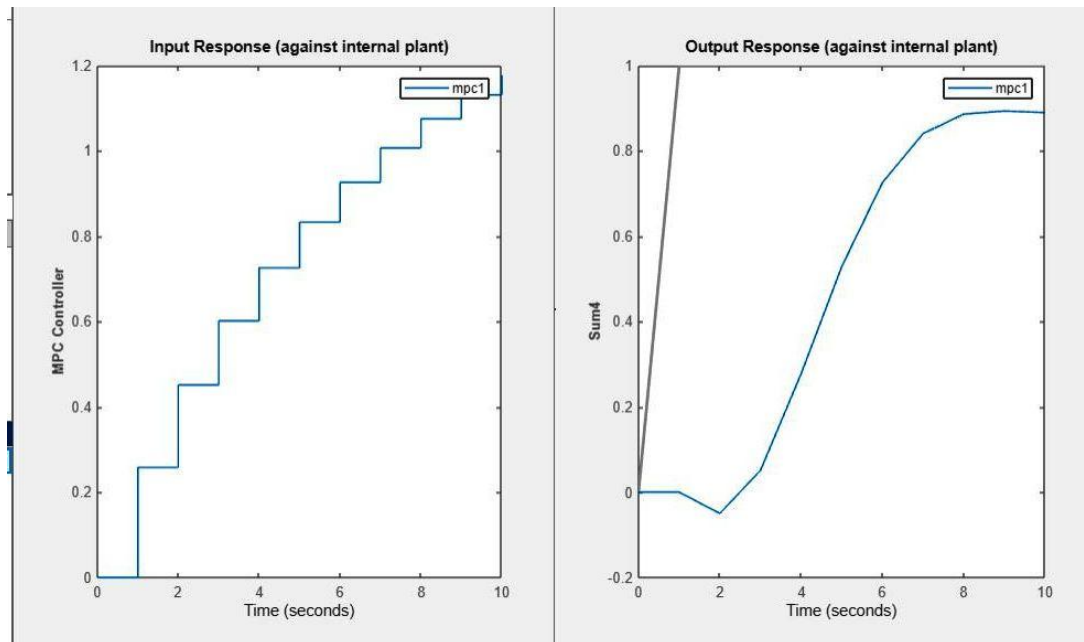


Figure 9. MPC controller in MATLAB

Result and Discussion

A study has been conducted in order to find the effectiveness of the control system in managing the power system. The goal of this analysis is to ensure a comprehensive understanding of the system's ability to handle frequencies, enhance distribution, and promote undisturbed power transfer between different areas. When analyzing the performance of the two-area system, researchers consider various crucial factors such as response time, controller effectiveness, and energy efficiency. This study provides valuable insights that can be utilized for future improvements and adjustments to meet the constantly evolving energy needs and enhance overall effectiveness.

Step load disturbance in all both areas

In order to know the effective performance of the designed control scheme a step load perturbation of 0.1 per unit (pu) has been considered in area 1 and area 2. This load deviation results in the change in speed of generators of both areas. This speed changes in further affect the system frequencies. It is possible for the frequency response undergo a transition whenever there is a disruption in the load. The system will transition to the steady state level once it has reached a stable state, which is the point

at which the frequency will stabilize at a new equilibrium point. This frequency deviation must be settled to the normal values as soon as possible, and this is where the role of controller is. A good controller is the one which bring back the frequency with minimum settling time and minimum overshoot and undershoots.

The frequency deviation result is shown in Figure 10. It is seen that both the controllers achieve the steady state value in the last. However, MPC results in smaller oscillations and smaller settling time compared to PID control scheme.

Variations in load conditions result in a dynamic response that promptly modifies the generator output to restore equilibrium between supply and demand. As the system reaches a stable state, it undergoes a consistent pattern where the generator stabilizes at a different operating point as the variables vary. The efficacy of this outcome is contingent upon the efficacy of current control mechanisms, encompassing regulators and frequency controllers.

The load perturbation of 0.1 pu in area 1 has successfully taken via the generators of area-1. It can be seen from the Figure 11a that PID and MPC both achieved the change in generation of 0.1 pu at last, however, the generators with MPC can reach to their desired value more smoothly.

The load demand of area-2 has been shared by the three Thermal generators as shown in Figures 11b - 11d, respectively. In all the results, it is evident that the MPC controller can regulate the generation much faster than PID control scheme, in order to settle the meet the demand.

In the interconnected power system, the net interchange of power must follow the desired value. At load deviation, apart from the system frequency, net interchange of power also affects, which must be settle to the specific value in smaller time. The tie-line power result is given in Figure 12. It is seen that; MPC scheme settles tie-line power deviation in a much smaller time than the PID scheme.

Tie line power, Frequency deviation, and area control errors are three major indicators to show the impact of a load perturbation on any area, which shows the imbalance between generation and the load of that area. A change in any of them can cause the system frequency to deviation from the scheduled one on the occurrence of a load disturbance. For a good control approach, the ACE must be eliminated within the required time duration to avoid the multiple harmful effects.

The results of area control errors of area-1 and area-2 area shown in Figures 13(a) and 13(b), respectively. It is seen from the Figures that MPC eliminates errors much effectively and in smaller time than PID scheme, in order to provide a good control approach.

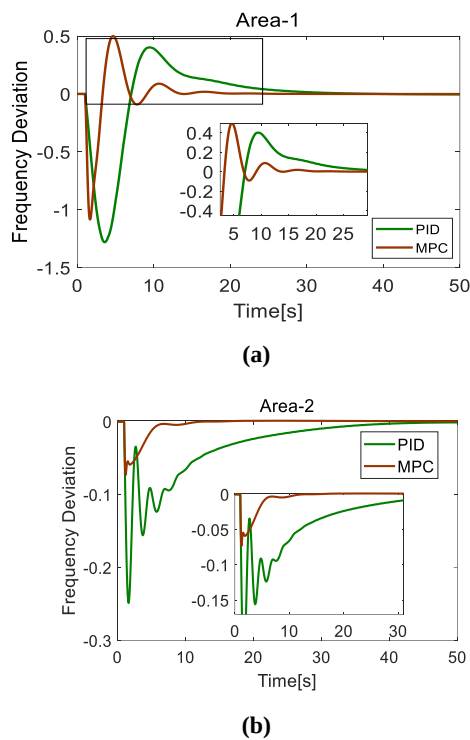
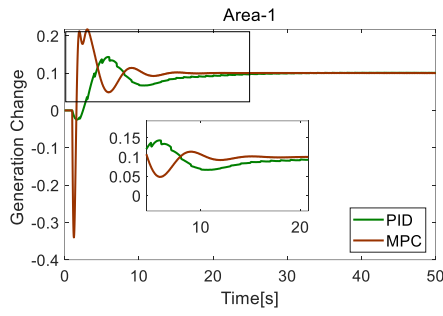


Figure 10. (a). Frequency deviations (area-1) and (b). Frequency deviations (area-2)



(a)

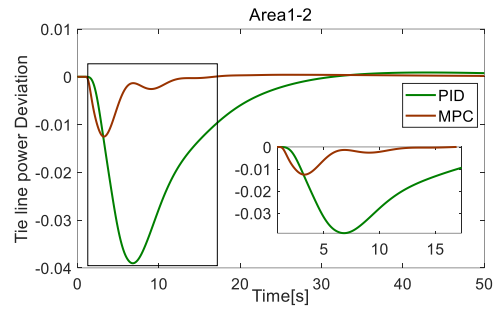
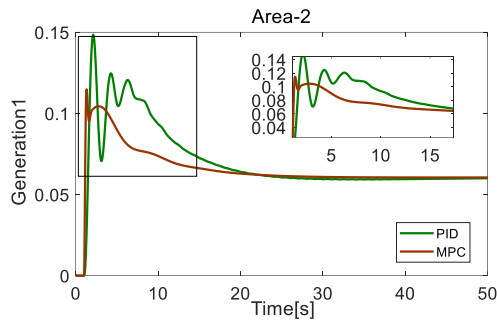
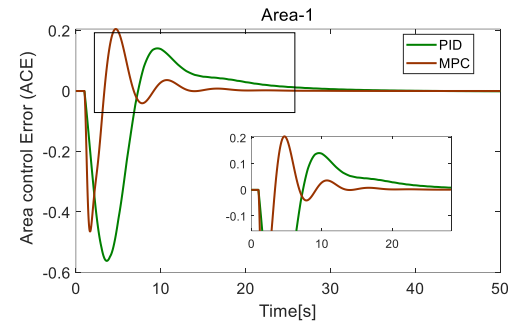


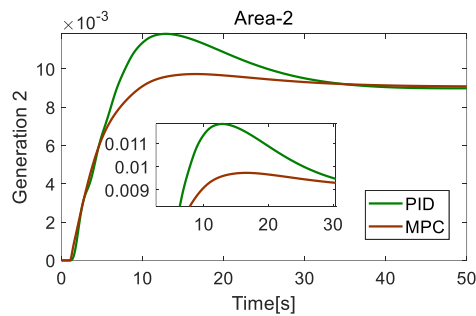
Figure 12. Tie-line power deviations.



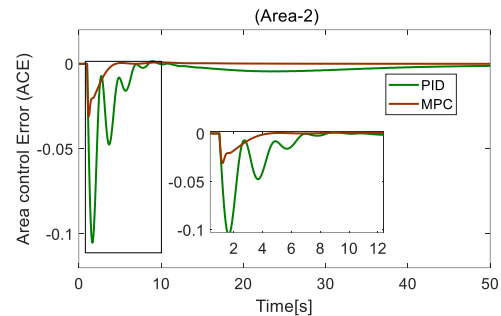
(b)



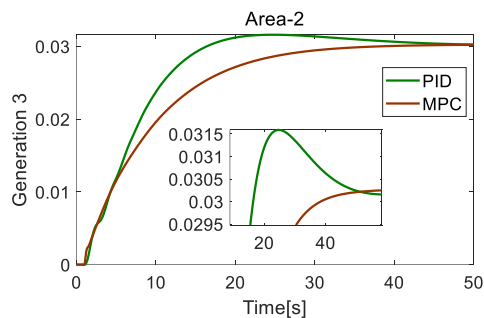
(a)



(c)



(b)



(d)

Figure 11. (a). Change in generation (area-1), (b). Change in generation [area-2(Thermal-1)], (c) Change in generation [area-2(Thermal-2)] and (d) Change in generation [area-2_(Thermal-3)]

Figure 13. (a). Area Control error (area-1) and (b). Area Control error (area-2)

Discussion on Results

These Figures prove beyond doubt that MPC management is effective and can be used for a secondary control scheme. With MPC control technology, flexibility in generators (Gencos) and tie-line flow in all areas has been found. The importance of the MPC control method in controlling the load frequency is reflected in its rapid response and efficiency. The comparison of the above controllers is given in Table 2.

In summary,

- MPC generally produces lower mean values, which indicates less fluctuation in the system compared to PID.

Table 2. Performance Comparison of PID and MPC Controllers

	Controllers	Mean	Peak	Percent Overshoot Relative to PID (%)	Valley	Percent Undershoot Relative to PID (%)	Standard Deviation	Settling time (s)	Settling Time Reduction (%)
1	PID	-0.0204	0.4018	100	-1.280	100	0.2398	40	0
	MPC	-0.00154	0.499	124	-1.084	84.7	0.123	25	37.5
F2 (area2)	PID	-0.0175	0	100	-0.2485	100	0.0344	50	0
	MPC	-0.0015	0.00123	12.3	-0.0729	29.3	0.0089	25	50.0
Tie line (area1-2)	PID	-0.00401	0.000897	100	-0.0390	100	0.009474	50	0
	MPC	-0.000354	0.0004229	47.2	-0.0125	32.1	0.00191	25	50.0
Area control error (area1)	PID	-0.0127	0.1409	100	-0.5616	100	0.1035	40	0
	MPC	-0.00100	0.2048	145.3	-0.4646	82.8	0.0526	25	37.5
Area control error (area2)	PID	-0.00346	0.00159	100	-0.1052	100	0.01004	45	0
	MPC	-0.000307	0.000864	54.3	-0.0307	29.2	0.00256	20	55.5

- MPC has smaller standard deviations, implying that it tends to keep the system more stable.
- MPC shows improved control over PID in most cases, especially in reducing peak and valley values, which is indicative of better overall system performance.

(a) *Main Findings of this Study*

- **Faster Settling Time:** The Model Predictive Controller (MPC) significantly reduces settling time compared to the PID controller across all cases, with reductions of up to 50%. This demonstrates MPC's ability to achieve faster system stabilization.
- **Reduced Overshoot and Undershoot:**
 1. In most cases, MPC exhibits lower overshoot compared to PID, with reductions of up to 70.7% (Tie Line). This indicates improved damping and better control over system fluctuations.
 2. Overshoot for MPC is slightly higher in some cases (e.g., Area Control Error for Area-1) but remains acceptable, showing MPC can effectively maintain control even with higher peaks.

Frequency (Area-1)

MPC achieves a 37.5% reduction in settling time and a 15.3% higher overshoot than PID. However, the undershoot is reduced by 15.3%, indicating better stability.

Frequency (Area-2)

MPC demonstrates significant improvement, with a 50% reduction in settling time and much lower overshoot (12.3%) and undershoot (29.3% of PID), making it highly effective in this scenario.

Tie Line (Area-1-2)

Overshoot and undershoot are significantly reduced (47.2% and 32.1% of PID values, respectively), alongside a 50% reduction in settling time, showcasing MPC's superior performance in tie-line dynamics.

Area Control Error (ACE)

While MPC shows slightly higher overshoot in ACE1 case, the undershoot and settling time are greatly improved, indicating a trade-off for quicker system recovery.

(b) *Strengths and Limitations*

In Load Frequency Control (LFC), PID controllers offer simplicity and efficiency, making them effective approach. However, PID shows higher peak-to-valley oscillations and a larger standard deviation. The higher peak values in certain responses like frequency (area-1) suggest PID's ability to respond aggressively to load changes, but it offers less consistent performance. In contrast, MPC controllers provide smoother, more stable control, with lower standard deviation and smaller peak-to-valley variations, ensuring better long-term system stability. However, MPC requires more computational resources and is more complex to implement. Overall, MPC is better suited for dynamic, constrained systems like LFC.

Conclusion

This paper conducts an extensive investigation into the analysis of frequency deviation within an interconnected power system encompassing two areas. The study focuses on implementing two control schemes (Proportional Integral Derivative (PID) and Model Predictive Control (MPC)

emphasizing diverse load changes, particularly a step load deviation affecting areas 1-2. The primary objective guiding the design of these control strategies is to minimize the area control error, with the optimization of PID controller parameters achieved through the application of the Genetic Algorithm (GA) method.

The paper employs time-domain simulations to rigorously assess the performance of each controller, meticulously examining the dynamic behavior of critical system parameters such as frequency, generation, tie-line power, and Area Control Error (ACE). The presentation of results from all approaches in Table 2 enables a comprehensive comparative analysis. Notably, the findings underscore the superior time-domain characteristics of the MPC-based control scheme, particularly in terms of minimizing overshoot/undershoot and optimizing settling time. Consequently, the study establishes the MPC control scheme as a compelling and effective choice for critical applications, such as Automatic Generation Control (AGC) or Load Frequency Control (LFC). This insightful exploration contributes valuable perspectives to the field, shedding light on the practical implementation of diverse control strategies and their impact on the stability and reliability of interconnected power systems.

With the growing advancements in soft computing (Kumar *et al.*, 2020, 2021b, 2022a, 2022b; Pushkarna *et al.*, 2022 and 2024), intelligent metaheuristic techniques (Kumar *et al.*, 2024) may be employed to tune the gain parameters of the PID controllers for optimal results.

References

- Afaneh, T., Mohamed, O., and Abu Elhaija, W. (2022). Load frequency model predictive control of a large-scale multi-source power system. *Energies*, 15(23):9210. <https://doi.org/10.3390/en15239210>
- Ahmed Khan, I., Mokhlis, H., Mansor, N.N., Illias, H.A., Awal, L.J., and Wang, L. (2023). New trends and future directions in load frequency control and flexible power system: A comprehensive review. *Alexandria Engineering Journal*, 71:263-308. <https://doi.org/10.1016/j.aej.2023.03.040>
- Amiri, F., and Hatami, A. (2023). Load frequency control for two-area hybrid microgrids using model predictive control optimized by grey wolf-pattern search algorithm. *Soft Computing*, 27(23):18227-18243. <https://doi.org/10.1007/s00500-023-08077-0>
- Asuk, A., and Trodden, P. (2023). Feedback optimizing MPC for load frequency control and economic dispatch. *IFAC-Papers On Line*, 56(2):10935-10940. <https://doi.org/10.1016/j.ifacol.2023.10.781>
- Banis, F., Guericke, D., Madsen, H., and Poulsen, N.K. (2020). Load-frequency control in microgrids using target-adjusted MPC. *IET Renewable Power Generation*, 14(1):118-124. <https://doi.org/10.1049/iet-rpg.2019.0487>
- Bünning, F., Warrington, J., Heer, P., Smith, R.S., and Lygeros, J. (2022). Robust MPC with data-driven demand forecasting for frequency regulation with heat pumps. *Control Engineering Practice*, 122:105101. <https://doi.org/10.1016/j.conengprac.2022.105101>
- Das, A., and Sengupta, A. (2024). Model predictive control for resilient frequency management in power systems. *Electronics Engineering*, 106(5):6131-6157. <https://doi.org/10.1007/s00202-024-02352-5>
- Ersdal, A.M., Fabozzi, D., Imsland, L., and Thornhill, N.F. (2014). Model predictive control for power system frequency control taking into account imbalance uncertainty. *IFAC Proceedings Volumes*, 47(3):981-986. <https://doi.org/10.3182/20140824-6-ZA-1003.01631>
- Gorbachev, S., Guo, J., Mani, A., Li, L., Li, L., Dou, C., Yue, D., and Zhang, Z. (2023). MPC-based LFC for interconnected power systems with PVA and ESS under model uncertainty and communication delay. *Protection and Control of Modern Power Systems*, 8(4):1-17. <https://doi.org/10.1186/s41601-023-00325-7>
- Gulzar, M.M., Rizvi, S.T.H., Javed, M.Y., Sibtain, D., and Salah ud Din, R. (2019). Mitigating the load frequency fluctuations of interconnected power systems using model predictive controller. *Electronics*, 8(2):156. <https://doi.org/10.3390/electronics8020156>
- Hu, Z., Zhang, K., Su, R., and Wang, R. (2024). Robust cooperative load frequency control for enhancing wind energy integration in multi-area power systems. *IEEE Transactions on Automation Science and Engineering*, 22:1508-1518. <https://doi.org/10.1109/TASE.2024.3367030>
- Khokhar, B., and Parmar, K.P.S. (2022). A novel adaptive intelligent MPC scheme for frequency stabilization of a microgrid considering SoC control of EVs. *Applied Energy*, 309:118423. <https://doi.org/10.1016/j.apenergy.2021.118423>
- Kumar, N., Tyagi, B., and Kumar, V. (2016). Multi-area AGC scheme using imperialist competition algorithm in restructured power system. *Applied Soft Computing*, 48:160-168. <https://doi.org/10.1016/j.asoc.2016.07.005>
- Kumar, N., Tyagi, B., and Kumar, V. (2017). Multi-area deregulated automatic generation control scheme of power system using imperialist competitive algorithm based robust controller. *IETE Journal of Research*, 64(4):528-537. <https://doi.org/10.1080/03772063.2017.1362965>
- Kumar, R., Ashfaq, H., Singh, R., and Kumar, R. (2024). A heuristic approach for insertion of multiple-complex coefficient-filter based DSTATCOM to enhancement of power quality in distribution system. *Multimedia Tools and Applications*. <https://doi.org/10.1007/s11042-024-19778-5>
- Kumar, R., Diwania, S., Khetrapal, P., and Singh, S. (2022a). Performance assessment of the two metaheuristic techniques and their hybrid for power system stability enhancement with PV-STATCOM. *Neural Computing and Applications*, 34(5):3723-3744. <https://doi.org/10.1007/s00521-021-06637-9>
- Kumar, R., Diwania, S., Khetrapal, P., Singh, S., and Badoni, M. (2021b). Multimachine stability enhancement with hybrid PSO-BFOA based PV-STATCOM. *Sustainable Computing: Informatics and Systems*, 32:100615. <https://doi.org/10.1016/j.suscom.2021.100615>
- Kumar, R., Diwania, S., Singh, R., Ashfaq, H., Khetrapal, P., and Singh, S. (2022b). An intelligent hybrid Wind-PV farm as a static compensator for overall stability and control of multimachine power system. *ISA Transactions*, 123:286-302. <https://doi.org/10.1016/j.isatra.2021.05.014>

- Kumar, R., Singh, R., and Ashfaq, H. (2020). Stability enhancement of multi-machine power systems using Ant Colony Optimization-based static synchronous compensator. *Computers and Electrical Engineering*, 83:1-17. <https://doi.org/10.1016/j.compeleceng.2020.106589>
- Kumar, R., Singh, R., Ashfaq, H., Singh, S.K., and Badoni, M. (2021a). Power system stability enhancement by damping and control of Sub-synchronous torsional oscillations using Whale Optimization Algorithm-based Type-2 wind turbines. *ISA Transactions*, 108:240-256. <https://doi.org/10.1016/j.isatra.2020.08.037>
- Liu, X., Zhang, Y., and Lee, K.Y. (2016). Robust distributed MPC for load frequency control of uncertain power systems. *Control Engineering Practice*, 56:136-147. <https://doi.org/10.1016/j.conengprac.2016.08.007>
- Ma, M., Zhang, C., Liu, X., and Chen, H. (2017). Distributed model predictive load frequency control of the multi-area power system after deregulation. *IEEE Transactions on Industrial Electronics*, 64(6):5129-5139. <https://doi.org/10.1109/TIE.2016.2613923>
- Mao, T., He, S., Guan, Y., Liu, M., Zhao, W., Wang, T., and Tang, W. (2023). A novel allocation strategy based on the model predictive control of primary frequency regulation power for multiple distributed energy storage aggregators. *Energies*, 16(17):6140. <https://doi.org/10.3390/en16176140>
- Mohsenian-Rad, A.-H., Wong, V.W.S., Jatskevich, J., Schober, R., and Leon-Garcia, A. (2010). Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid. *IEEE Transactions on Smart Grid*, 1(3):320-331. <https://doi.org/10.1109/TSG.2010.2089069>
- Mokhtar, M., Marei, M.I., Sameh, M.A., and Attia, M.A. (2022). An adaptive load frequency control for power systems with renewable energy sources. *Energies*, 15(2):573. <https://doi.org/10.3390/en15020573>
- Pushkarna, M., Ashfaq, H., Singh, R., and Kumar, R. (2022). A new analytical method for optimal sizing and siting of Type-IV DG in an unbalanced distribution system considering power loss minimization. *Journal of Electrical Engineering & Technology*, 17(5):2579-2590. <https://doi.org/10.1007/s42835-022-01064-9>
- Pushkarna, M., Ashfaq, H., Singh, R., and Kumar, R. (2024). An optimal placement and sizing of type-IV DG with reactive power support using UPQC in an unbalanced distribution system using particle swarm optimization. *Energy Systems*, 15(1):353-370. <https://doi.org/10.1007/s12667-022-00551-2>
- Qi, X., Zheng, J., and Mei, F. (2022). Model predictive control-based load-frequency regulation of grid-forming inverter-based power systems. *Frontiers in Energy Research*, 10:932788. <https://doi.org/10.3389/fenrg.2022.932788>
- Singh, A., Kumar, N., Joshi, B.P., and Singh, B.K. (2018). Load frequency control with time delay in restructured environment. *Journal of Intelligent and Fuzzy Systems*, 35(5):4945-4951. <https://doi.org/10.3233/JIFS-169778>
- Yang, D., Wang, B., Cai, G., Ma, J., Tian, J., Chen, Z., and Wang, L. (2020). Inertia-adaptive model predictive control-based load frequency control for interconnected power systems with wind power. *IET Renewable Power Generation*, 14(8):1146-1154. <https://doi.org/10.1049/iet-rpg.2020.0018>
- Yang, J., Sun, X., Liao, K., He, Z., and Cai, L. (2019). Model predictive control-based load frequency control for power systems with wind turbine generators. *IET Renewable Power Generation*, 13(15):2871-2879. <https://doi.org/10.1049/iet-rpg.2018.6179>
- Zeng, G.-Q., Xie, X.-Q., and Chen, M.-R. (2017). An adaptive model predictive load frequency control method for multi-area interconnected power systems with photovoltaic generations. *Energies*, 10(11):1840. <https://doi.org/10.3390/en10111840>
- Zhang, J., Qin, D., Ye, Y., He, Y., Fu, X., Yang, J., Shi, G., and Zhang, H. (2021). Multi-time scale economic scheduling method based on day-ahead robust optimization and intraday MPC rolling optimization for microgrid. *IEEE Access*, 9:140315-140324. <https://doi.org/10.1109/ACCESS.2021.3118716>
- Zhao, N., Gorbachev, S., Yue, D., Kuzin, V., Dou, C., Zhou, X., and Dai, J. (2022). Model predictive-based frequency control of power system incorporating air-conditioning loads with communication delay. *International Journal of Electrical Power & Energy Systems*, 138:107856. <https://doi.org/10.1016/j.ijepes.2021.107856>

Appendix

Abbreviation	Full Form
LFC	Load Frequency Control
FOPID	Fractional Order Proportional Integral Derivative
BBBC	Big bang big crunch
MPC	Model Predictive Control
NN-IMC	Neural Network Internal Model Control
CPS1/CPS2	Control Performance Standards 1 & 2
NERC	North American Electric Reliability Corporation
AGC	Automatic Generation Control
ICA	Imperialist Competition Algorithm
PI	Proportional-Integral
PV	Photovoltaic
WECS	Wind Energy Conversion Systems
RoCoF	Rate of Change of Frequency
SMES	Superconducting Magnetic Energy Storage
GRC	Generation rate control
ICA-PID	Imperialist Competitive Algorithm tuned PID controller
GA	Genetic Algorithm
EV	Electric Vehicle
MPLFC	Model Predictive Load Frequency Control
MG	Microgrid
IACs	inverter air conditioners