Adaptive MPC-based load frequency control for microgrids with renewable energy

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ABSTRACT

In this paper, a novel load frequency control (LFC) approach based on adaptive model predictive control (AMPC) is proposed for a microgrid system (MG) with distributed energy resources. A simplified internal prediction model (first-lag system consisting of a gain and a time constant) is applied to online state estimation of the AMPC. The parameters are updated iteratively using unscented Kalman filter (UKF). The MG model with high penetration of renewable energy sources (RESs), such as photovoltaic (PV) and wind turbine (WT) power generations, is carried out to verify the effectiveness of the proposed approach. The simulation results show that the proposed AMPC approach can effectively cope with the frequency stability problem due to the disturbances of the PVs, WTs, and load. In addition, the authors indicate that the control performance of the proposed method is better than the tuned proportional-integral (PI) controller.

KEYWORDS Microgrid; load frequency control; model predictive control; renewable energy sources; unscented Kalman filter
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1. Introduction

Recently, power systems consisting of a large amount of renewable energy sources (RESs), such as photovoltaic (PV), wind turbine power (WT), and battery energy storage systems (BESSs) have been attracting attention for the realisation of a carbon-neutral society, especially microgrid (MG) systems. Conventional generators, such as thermal and diesel energy generators (DEGs) are primarily used to regulate supply and demand. However, the increase in RESs has reduced the output ratio of the conventional generators. The reduction in the number of generators affects the inertia of the systems. This also decreases the frequency regulation capability of the power system. Therefore, the maintenance and improvement of the system stability are an important issue that must be addressed, especially the frequency stability.

Many techniques have been developed and proposed for designing the load frequency control (LFC) to achieve power system frequency stability, such as H-infinity control (Summan et al., 2022), fuzzy logic strategy, machine learning, and artificial neural networks (ANNs) (Tungadio et al., 2019). The fuzzy logic strategy usually combines with different controllers to obtain an optimal control, such as an optimal fuzzy-based tilt-integral-derivative (FTID) controller is proposed for MG frequency (Rai et al., 2022) and adaptive intelligent self-tuning model predictive control based on a type-2 fuzzy system is presented for the MG frequency problem (Zhao et al., 2022). Adibi et al. (2022) propose an online reinforcement learning approach for LFC of MG.

The model predictive control (MPC) technique with an internal prediction model can realise high prediction accuracy and robustness. As a result, more and more researchers have reported the MPC techniques for the (Gbadega et al., 2021; Wang et al., 2022). Recently, some optimisation algorithms, such as particle swarm optimisation (PSO) and fuzzy logic algorithms, etc., are used to tune the MPC parameters (Fan et al., 2022; Negahban et al., 2022). Kalman filters are applied to MPC to estimate the system performance and MPC parameters (Wang et al., 2022). Kumar et al. (2022) propose an MPC method for hybrid power systems, whose parameters are estimated and updated via the application of a quasi-oppositional harmony search algorithm. These approaches can tackle the power system frequency problem effectively.

This paper proposes an LFC approach for an MG with RESs using adaptive MPC (AMPC). It is difficult for the MG frequency stability to maintain the required frequency range due to a lot of uncertain RESs being used. Therefore, the authors developed a nonlinear discrete-time AMPC controller to tackle the power system frequency problems.

This paper applies a first-order prediction model (PM) for AMPC to approximate the system performance. The parameters of the PM are estimated and updated by using an unscented Kalman filter (UKF) online. Therefore, this process can obtain an optimal system operation. An MG system model includes DEGs, PV, WTs, BESSs, and large disturbances, which are carried out to confirm the performance of the proposed AMPC approach. The simulation results demonstrate that the proposed AMPC approach has an ability to address the MG frequency fluctuations caused by the WTs, PV, and large disturbances. Finally, the control performance of the proposed AMPC shows better results than the conventional proportional-integral (PI) controller.

A novel AMPC method for an MG LFC scheme is proposed in this paper, whose main contributions include:

- A first-order PM is applied in the proposed AMPC method, which can approximate the system performance. Therefore, it can decrease the computation burden compared with the detailed high-order model.
- The proposed AMPC method has a fast response speed to compensate for the uncertainty of the RESs. Therefore, the MG frequency problems caused by the RESs are addressed effectively.
- From the MG operator's viewpoint, the proposed AMPC method does not require skill. It can realize the automatic tuning for several disturbances.

The rest of this paper is described as follows. First, Section 2 describes the design of the AMPC. Then, simulation cases and results are given in Section 3. Finally, Section 4 describes the conclusions and discussions of this study.

2. The design of the AMPC

2.1. MG system model

In this paper, it is assumed that a frequency response model represents the actual complicated MG system, as shown in Figure 1. Figure 1(a) shows an actual MG system diagram. An MG system operator can regulate the DEGs to maintain the desired system frequency based on his/her experiences. Figure 1(b) shows a block diagram of the MG system including the governor, the DEGs, and the BESS, which is equivalent to Figure 1(a). An actual MG system includes DEGs, electric loads, RESs, and other devices. They can communicate with each other through the signal line and power transmission through the transmission line, which are shown in Figure 1(a) by a blue line and black line. The following state-space equation represents the actual MG system's dynamic performance, which is used to design the AMPC controller.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + Ew(k) \\ y(k) &= Cx(k)\,, \end{aligned} \tag{1}$$

$$x(k) = \begin{bmatrix} \Delta P_g(k) & \Delta P_t(k) & \Delta f(k) \end{bmatrix}^T, \tag{2}$$

The first-order system models with different time constants are used to represent the behaviors of WTs, PV, and BESSs, as shown in the following.

$$\frac{1}{T_{pv}s+1}, \tag{3}$$

$$\frac{1}{T_{wt}s+1}, \tag{4}$$

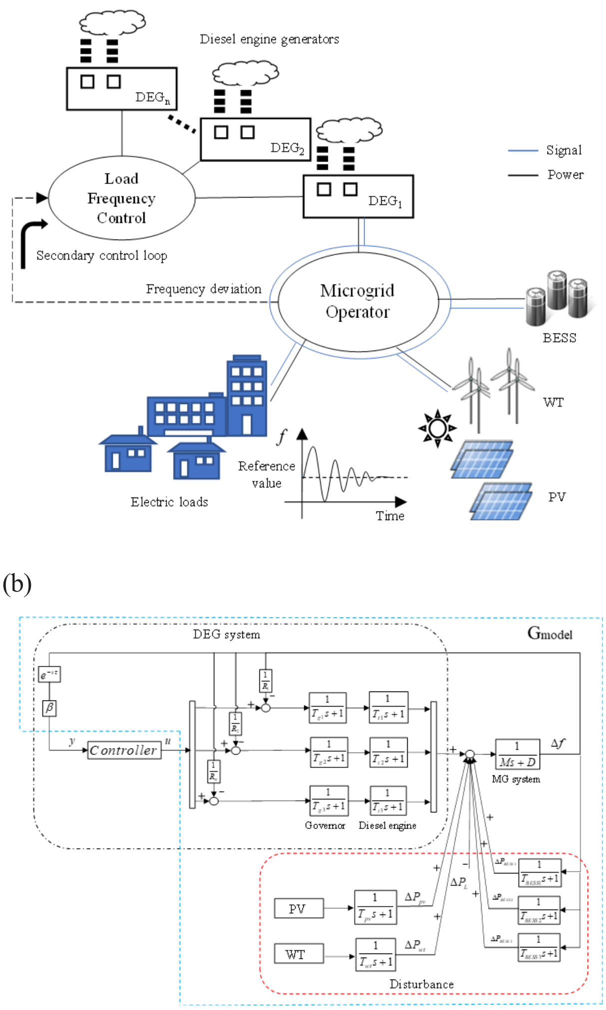
$$\frac{1}{T_{BESS}s+1}, \tag{5}$$

It is required to balance the generation with load demand in the LFC scheme. Therefore, an equation can be obtained based on the balance between the generation and load consumption.

$$\Delta P_t + (\Delta P^{+}_{BESS} - \Delta P^{-}_{BESS}) = \Delta P_L - \Delta P_{pv} - \Delta P_{wt}\,. \tag{6}$$

A frequency instability issue is caused by the RESs and electric load. Therefore, a BESS is applied to supplement unbalance and mitigate the rapid fluctuation.

(a)



(b)

Figure 1. MG system model for frequency control: (a) actual MG system diagram; and (b) block diagram of MG system.

2.2. The proposed AMPC approach

More RESs are installed into the low-inertia MG system. As a result, small system parameters and load demand changes can affect system stability, especially the frequency stability. The objective of this paper is to design an LFC controller to solve the MG frequency problem. A nonlinear discrete-time AMPC controller has been developed to address the frequency fluctuation problem in our previous work.

In this paper, the proposed AMPC approach is used for Equation (1) and it must have high control requirements to achieve optimal control performance, such as high robustness and a fast response speed because of the frequency problem caused by the RESs and large disturbances with a large uncertainty.

Figure 2 gives the structure of the proposed AMPC approach which combines with a UKF for capturing the optimal system operation. Meanwhile, the parameters and system performance are estimated using a UKF online to obtain the optimal control operation.

The following area requirement (AR) control signal is determined using the system output (y) in Equation (1) for the LFC controller. A desired frequency value (ref=0) is applied to the AMPC method to minimise the AR signal.

$$\begin{aligned} AR &= y(t) \\ &= \beta \Delta f(t) \end{aligned}, \tag{7}$$

The proposed AMPC method is based on the optimal feedback theory. Therefore, an optimal feedback gain (K_{MPC}) of AMPC is computed using the following equation, which can provide a control measurement signal.

$$\begin{aligned} \Delta u(k) &= -K_{MPC}\, x(k) \\ u(k) &= u(k-1) + \Delta u(k) \end{aligned}. \tag{8}$$

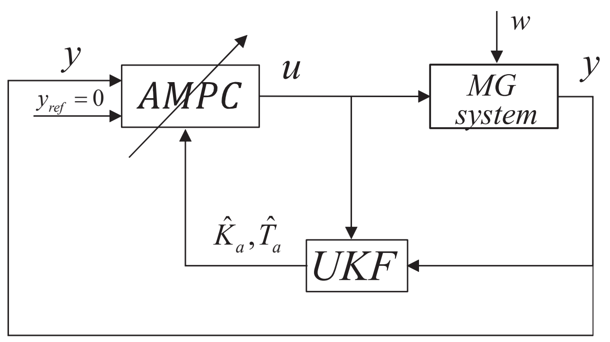


Figure 2. The structure of AMPC using a UKF.

2.3. Prediction model for AMPC

The future system performance can be predicted using the internal PM (G_{model}). In this paper, from a low computation burden point, a simplified first-order PM is proposed for AMPC, which can approximate the system performance, as follows.

$$G_{\text{model}}(s) = \frac{K_a}{T_a s + 1}, \tag{9}$$

Generally, a first-order lag system-based model is used in the power system frequency control, such as a mechanical governor or gas and steam turbines (Bevrani, 2008; Kundur, 1994). The authors have investigated the performance of the internal prediction model based on the first-order lag system and second-order lag system. A first-order or second-order lag system can represent the behaviour of the power system with high accuracy in the desired range (Wang et al., 2022). Based on the investigations, the first-order lag system model in Equation (9) with minimal parameters has been determined to maintain the MG system's performance for load frequency control.

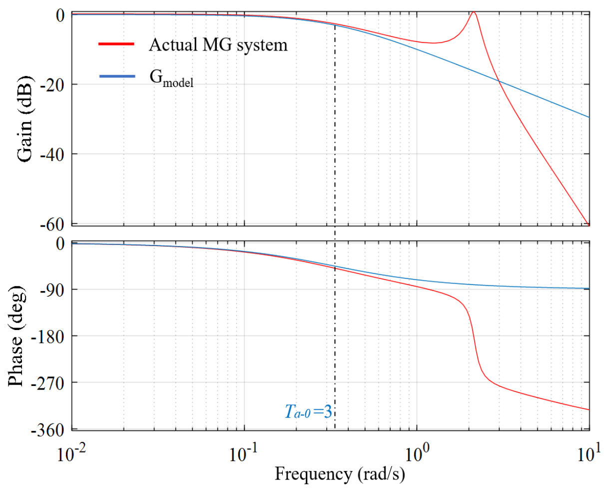


Figure 3. Bode plot.

Figure 3 shows the bode plot of Equation (9) and the MG system. It is used to set the initial values ($K_{a\text{-}0}$, $T_{a\text{-}0}$) of Equation (9). It can be observed that the proposed Equation (9) can suitably approximate the MG system performance with a fast response speed due to the time constant being larger than 3 seconds.

Figure 2 gives the estimation structure, which shows how the UKF utilises the measured values (u, y) of the MG system to estimate the parameters of Equation (9) online. In the UKF, the parameters' estimation computation is repeated every T_s=0.1 seconds while updating the K_{MPC} of the AMPC. The following formulations are applied to the UKF for estimating the parameters of Equation (9).

$$\begin{bmatrix} x(k+1) \\ \theta(k+1) \end{bmatrix} = \begin{bmatrix} A(\theta) & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} x(k) \\ \theta(k) \end{bmatrix} + \begin{bmatrix} b \\ 0 \end{bmatrix} u(k), \tag{10}$$

Where,

$$x(k) = [\Delta f(k)], \tag{11}$$

$$\theta(k) = [K_a(k) \;\; T_a(k)]^T, \tag{12}$$

$$A(\theta)=\left[-\frac{1}{T_a(k)}T_s\right], \tag{13}$$

$$b=\left[\frac{K_a(k)}{T_a(k)}T_s \;\; 0 \;\; 0\right]^T. \tag{14}$$

2.4. Rolling optimisation

Figure 4 shows the rolling optimisation process of the MPC technique. The parameters of the internal prediction model are updated by the UKF online. In the prediction horizon (*Np*), the proposed AMPC method can predict the future state values of the system based on the updated Equation (9). In the control horizon (*Nc*), the optimal control measurement (*u*) is computed based on the optimisation theory. Meanwhile, the length of the *Np* and *Nc* affects the proposed AMPC performance, computation burden, and stability. The mismatch *Np* and *Nc* even lead to instability of the system (Wang, 2009).

An optimality theory-based MPC is designed to minimise the objective function with constraints. The following objective function is applied for the proposed AMPC controller to consider the satisfied frequency range and minimisation cost.

$$\begin{aligned}\min J=&\sum_{h=1}^{N_p} x(k+h\mid k)^T \boldsymbol{Q}\, x(k+h\mid k)\\&+\sum_{h=0}^{N_c-1}\Delta u(k+h\mid k)^T \boldsymbol{S}\,\Delta u(k+h\mid k)\end{aligned}, \tag{15}$$

To maintain the system frequency within an acceptable range and consider the control cost, among others, the frequency deviation is a critical factor that must be considered in the proposed AMPC approach. Therefore, the constraints are applied to the proposed AMPC approach, as shown in the following.

$$\begin{cases}\Delta f^{\min}\le \Delta f\,(k)\le \Delta f^{\max}\\ u^{\min}\le u\,(k)\le u^{\max}\end{cases}, \tag{16}$$

Figure 5 shows the control process, which consists of offline and online processes. The parameters' estimation and the optimal operation of the online process are achieved.

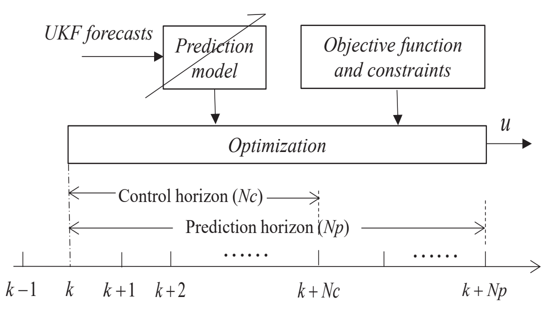


Figure 4. Rolling optimisation.

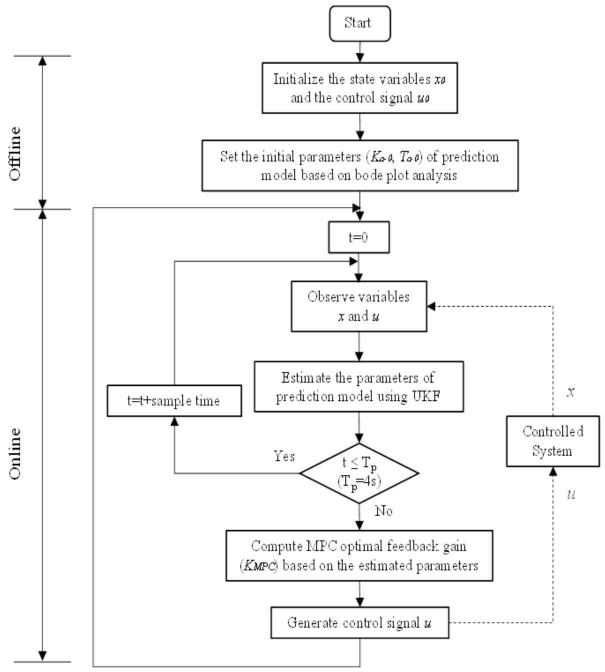


Figure 5. Proposed control process.

3. Results and discussions

3.1. Simulation case

An MG system model in Figure 1, whose parameters are shown in Table 1, is carried out to determine the performance of the proposed AMPC approach. The simulations are carried out on MATLAB/Simulink R2021b software. The initial values of Equation (9) are chosen to be $K_{a\text{-}0}$=1 and $T_{a\text{-}0}$=3 through Figure 3. The PV and the WT outputs are shown in Figure 6. The parameters of the PV, WT, and BESS are listed in Table 2. The simulation time is set to 1800 seconds.

Table 3 gives the simulation cases. In case 1, a continuously varying step change is used to determine the effectiveness of the previous AMPC. Meanwhile, case 1 is used for the comparison. The proposed AMPC with N_P=20 and N_C=2 are applied to case 2 for comparison. In case 2, the disturbance condition is the same as in case 1. In case 3, it is assumed that a rapid step change disturbance from 600 to 650 seconds is used to determine the effectiveness of the proposed method. Because in an actual MG system, due to it having low inertia and small capacity, the introduction of large-capacity loads can affect the dynamics of the system. As a result, it is necessary to determine the performance of the proposed method under a sudden load change condition. At the same time, it is assumed that a large number of RESs are installed in the MG system. The number of units reduces to balance the generation and load demand and to avoid the frequency instability. As a result, the MG system has low inertia and damping with these parameters (*M*, *D*), which is used to identify the performance of the proposed MPC method.

The proposed AMPC method is compared with a conventional PI controller. The optimal parameters (K_P=0.02, K_I=-0.1) of proportional (K_P) and integral (K_I) are determined via trial and error. The simulation period is divided into four terms (I, II, III, IV) with 450 seconds intervals to compare with the previous method and the conventional PI controller, as shown in Figure 6(a). The total capacity of MG is assumed to be 5MW (1 pu).

Table 1. Parameters of MG.

D [pu/Hz]	M [pu s]	β [pu/Hz]	R_1, R_2, R_3 [Hz/pu]	T_{g1}, T_{g2}, T_{g3} [s]	T_{t1}, T_{t2}, T_{t3} [s]
0.012	0.200	0.345	3.000 3.000 3.000	0.200 0.200 0.160	1.100 1.100 0.700

Table 2. Parameters of BESSs, PV, and WT.

T_{BESS1} [s]	T_{BESS2} [s]	T_{BESS3} [s]	T_{PV} [s]	T_{WT} [s]
0.100	0.110	0.130	1.8	1.5

Table 3. Case study.

<table>
<tr><th></th><th>System model</th><th>Controller</th><th>Input to system</th><th>Load disturbance</th><th>WT</th><th>PV</th></tr>
<tr><td>Case 1</td><td rowspan="2">Figure 1</td><td>Previous AMPC (WANG et al., 2022) (N_P=10, N_C=2)</td><td rowspan="3">UKF & MPC Control Input</td><td rowspan="2">Figure 6 (a)</td><td colspan="2" rowspan="2">Figure 6 (a) and (c)</td></tr>
<tr><td>Case 2</td><td rowspan="2">Proposed AMPC (N_P=20, N_C=2)</td></tr>
<tr><td>Case 3</td><td>Figure 1 with low inertia (M=0.08, D=0.01)</td><td>Figure 6 (b)</td><td colspan="2">Figure 6 (a)</td></tr>
</table>

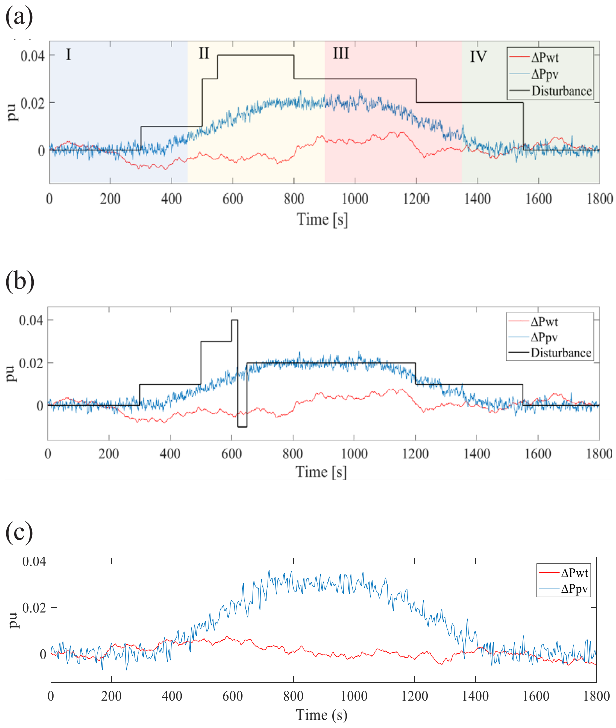


Figure 6. (a) PV_1, WT_1 output, and disturbance in case 1; (b) PV_1, WT_1 output, and disturbance in case 3; and (c) PV_2, WT_2 output.

3.2. Simulation results

The simulation results are discussed in this section. Figure 7 shows the performance of the previous AMPC method for case 1. The performance of the proposed AMPC is shown in Figure 8 for case 2. Figure 9 shows the comparison results between the proposed AMPC and PI controller. Figure 10 shows the simulation results for case 3. The comparison results based on case 3 are given in Figure 11. In those cases, the AMPC approach combines with a UKF to estimate the parameters of Equation (9) online.

From Figure 7, it is noticed that the previous AMPC (WANG et al., 2022) has an ability to address the MG system frequency problem due to the influence of the WT, PV outputs, and the disturbance. A small prediction error between the real value and the UKF estimation value is also observed in Figure 7(a), which determines the UKF with high accuracy to estimate the state value.

Figure 7(b) shows the simulation results of the UKF estimation parameters. It can observed that the estimation process is almost from 0 to 100 seconds. In this process, the UKF can learn and estimate the optimal parameters for the current MG system. The results show that the step change is the main effect for UKF estimation. Finally, the K_a and T_a parameters almost converge to a constant value at K_a≈0.969, T_a≈1.860.

Figure 8(a) exhibits that the proposed AMPC with a fast control speed to cope with the frequency fluctuation is caused by the rapid step change. The MG frequency deviation quickly approaches the correct value. Meanwhile, Figure 8(b) gives the estimation of parameters result, which shows that the UKF with a fast convergence speed estimates the parameters of the PM despite the system conditions changing sharply.

A comparative result between the proposed AMPC and PI control is given in Figure 9. The results verify that the proposed AMPC has a better performance than the PI control.

Figures 10 and 11 show the results for case 3. Figure 10(a) shows that the proposed method can cope with the frequency fluctuation effectively when RESs and the rapid step change inputs from 600 to 650 seconds are imported in low-inertia circumstances. Figure 10(b) shows that the UKF has a fast ability to estimate the parameters and converges to the corrected values (K_a≈0.995, T_a≈2.642) quickly. However, the amplitude of estimation has increased due to the reduced inertia of the MG system. Figure 11 shows that the proposed method performs better than the conventional PI control. The PI control does not converge to the desired frequency range fast and has a larger overshoot than the proposed method.

Comparison data of the frequency deviation are summarised in Table 4. The minimisation (Min), and the maximisation (Max) indices are used to evaluate the performance based on the results of cases 1 and 2 during the four terms (I, II, III, IV). From the results, the proposed AMPC approach represents a better stability performance than the others during the simulation time. Comparative analysis data with standard deviation (STD) of frequency deviation are given in Table 5. These results show that the proposed AMPC approach has a better performance than the PI control. The computational burden of the proposed AMPC is shown in Table 6. The proposed AMPC method expends computational burden to realise the optimal control, especially on the online process. From Table 6, the UKF accounts for about 29%, the optimal process accounts for about 50%, and others (the offline process) account for about 21% of the total computational burden.

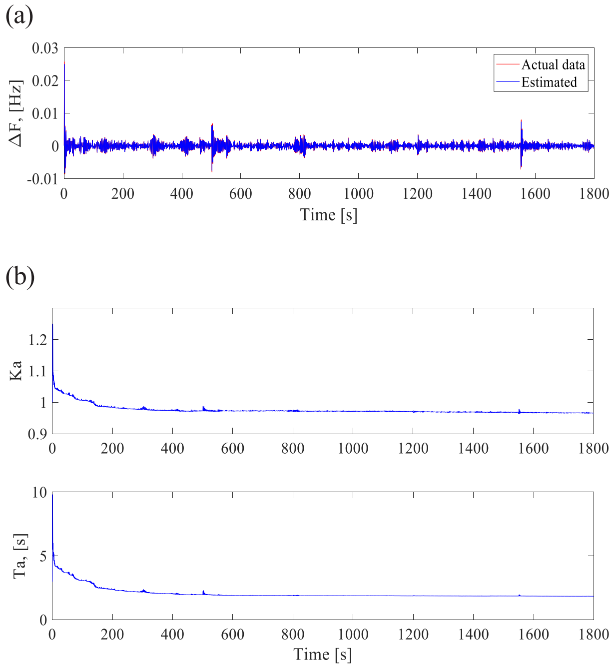


Figure 7. Previous AMPC (Wang et al., 2022) in case 1: (a) MG frequency fluctuation; and (b) Internal prediction model parameters by using the UKF.

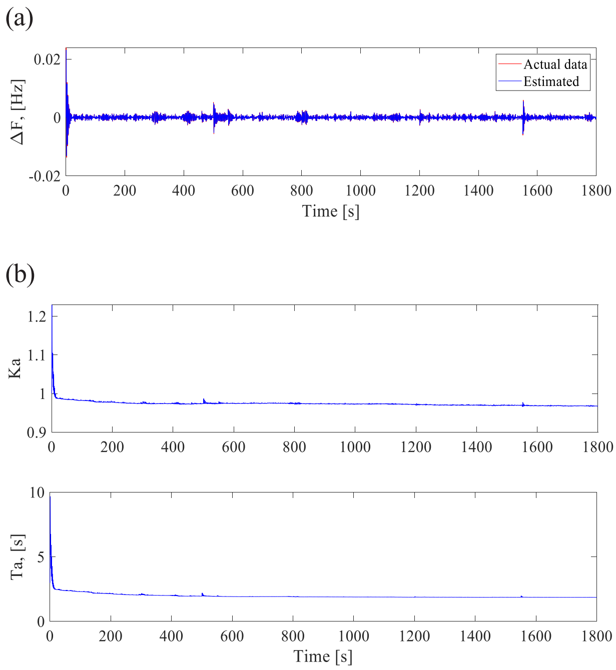


Figure 8. Proposed AMPC in case 2: (a) MG frequency fluctuation; and (b) internal prediction model parameters by using the UKF.

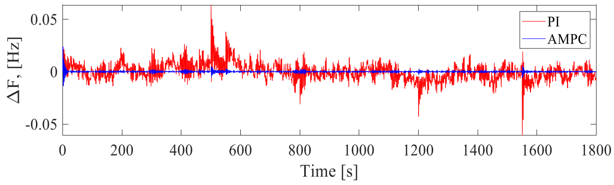


Figure 9. Comparison data based on case 2.

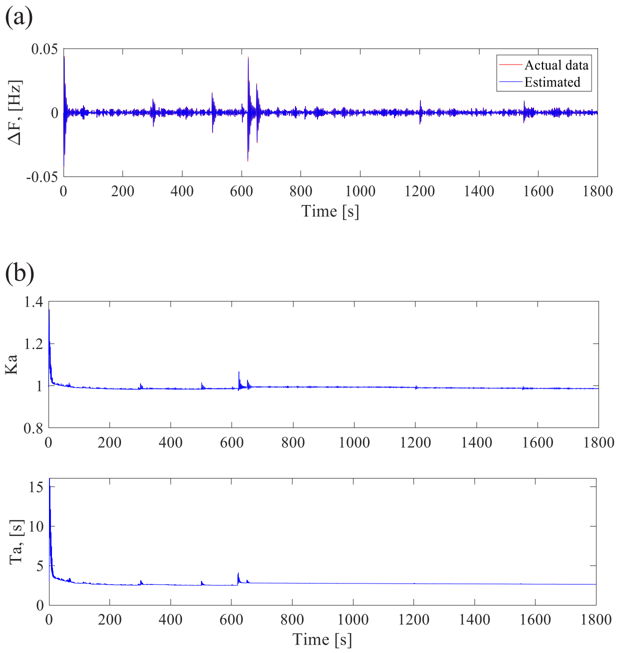


Figure 10. Proposed AMPC in case 3: (a) MG frequency fluctuation; and (b) Internal prediction model parameters by using the UKF.

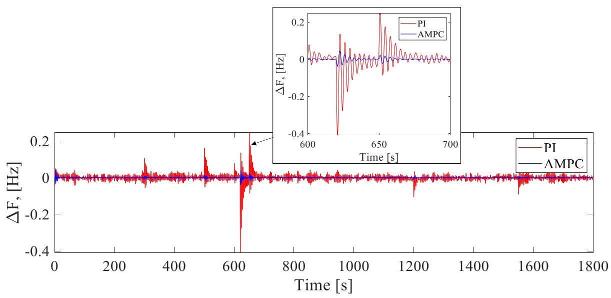


Figure 11. Comparison data based on case 3.

Table 4. Comparative data analysis.

Parts	Indices (Hz)	PI	Previous AMPC (Wang et al., 2022)	Proposed AMPC
I	Min.	-0.014	-0.008	-0.013
	Max.	0.024	0.017	0.021
II	Min.	-0.030	-0.007	-0.005
	Max.	0.062	0.007	0.005
III	Min.	-0.041	-0.003	-0.002
	Max.	0.017	0.003	0.002
IV	Min.	-0.059	-0.007	-0.005
	Max.	0.020	0.008	0.006

Table 5. Comparative data analysis using STD.

PI	Previous AMPC (Wang et al., 2022)	Proposed AMPC
0.0081Hz	0.0012Hz	0.0010Hz

Table 6. Computational burden of the proposed AMPC for a 1800 s simulation time.

	Online		Offline	Total
	UKF estimation	Optimal process	Others	
Average computational time	8.180 s	14.121 s	5.813 s	28.114 s

Figures 12 and 13 show the simulation results based on the case 2 parameters for a sudden load change at 1200 s from large-capacity users. The results show that the MG system frequency fluctuation can be addressed by the proposed method. Meanwhile, Figure 13 shows that the conventional PI control has a sharp overshoot. However, the proposed method finds it difficult to predict the future system performance when particularly large disturbances are introduced into the system, which needs to be studied in future work.

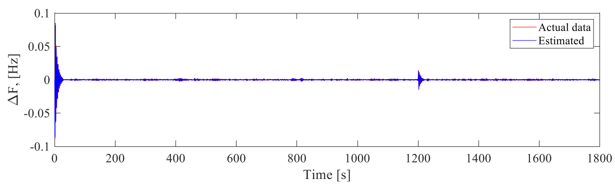


Figure 12. Sudden load change at 1200 s.

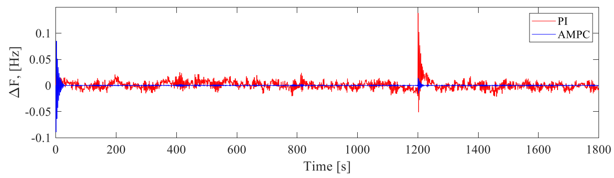


Figure 13. Comparison data based on the sudden load change case.

4. Conclusion

In this paper, a novel AMPC-based load frequency control method is proposed for the MG system's frequency problem issue. These results show that the proposed AMPC method has a high response speed and robustness to cope with this issue. The comparison data also show that the proposed AMPC approach has a better ability to address the frequency problem than the PI controller. However, the proposed AMPC method also expends a lot of time to estimate the state values. This will be improved in future works.

Although the simulation results verify that the MG system can be represented by a simplified first-order model, there are some oscillations in the estimation parameters process, and it is desirable to propose an approach to reduce these oscillations.

The parameters are automatically tuned, but the initial control values, such as Np and Nc must be set manually. In addition, it is necessary to consider an optimal method for setting the initial values. This paper has improved the performance of MPC by adjusting the Np, but the computational burden increases as the Np increases. At the same time, the mismatch between Np and Nc even lead to the instability of the system and a reduction in control performance, especially in the transient stability systems. Therefore, it is necessary to select appropriate Np and Nc in different systems.

Furthermore, the author will make comparisons with other LFC methods to confirm the performance of the proposed AMPC approach. Meanwhile, the proposed method will be applied to a connected multi-area MG system to identify the performance of it.

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Appendix A

The state-space equations of Equation (1) are given as follows.

$$\boldsymbol{A}=\begin{bmatrix} -\frac{1}{T_g} & 0 & -\frac{1}{RT_g} \\ \frac{1}{T_t} & -\frac{1}{T_t} & 0 \\ 0 & \frac{1}{M} & -\frac{D}{M} \end{bmatrix}, \quad \text{(A1)}$$

$$\boldsymbol{B}=\begin{bmatrix} \frac{1}{Tg} & 0 & 0 \end{bmatrix}^T, \quad \text{(A2)}$$

$$\boldsymbol{C}=\begin{bmatrix} 0 & 0 & \beta \end{bmatrix}, \quad \text{(A3)}$$

$$\boldsymbol{E}=\begin{bmatrix} 0 & 0 & -\frac{1}{M} \end{bmatrix}, \quad \text{(A4)}$$

Governor speed droop (R) and the MG system damping constant (D) present the frequency response characteristic (β) as follows.

$$\beta = D + \frac{1}{R}. \quad \text{(A5)}$$

The constraints are set to the proposed AMPC approach as shown in the following Table A.

Table A. The constraints of Δf and u.

	Δf	u
Max.	0.2	0.2
Min.	-0.2	-0.2

Appendix B

Nomenclature

$\boldsymbol{A, B, C, E}$	State-space matrices
K_a , T_a	The adaptive model gain and time constant
	The time constant of the governor and DEG
T_{pv}, T_{wt}, T_{BESS}	The time constant of the PV, WT, and BESS
W	Disturbance and load
U	Input measurement signal
	Input measurement signal deviation
	Governor output deviation
	Diesel engine output deviation
	k moment
	Sample period
	Weight matrices
	Weight matrices
Y	System output
	Frequency response characteristic
R	Governor speed droop characteristic
D	Damping constant
M	Inertia
	Frequency deviation
K_P, K_I	The proportional gain and the integral gain of the PI
	Power discharge and charge of BESS
N_p	Prediction horizon
N_c	Control horizon