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Selection of a Critical Time Scale of Real-Time Dispatching for Power Systems With High Proportion Renewable Power Sources

YUE CHEN[1], ZHIZHONG GUO[1], HONGBO LI[2], YI YANG[3], GUIZHONG WANG[2], ABEBE TILAHUN TADIE[1], OUYANG ZHIBIN[4], AND ZHE DING[1]

[1]School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China
[2]Electric Power Research Institute of HITZ, Harbin Institute of Technology at Zhangjiakou, Zhangjiakou 075000, China
[3]Shenyang Power Supply Company, State Grid Liaoning Electric Power Supply Company Ltd., Shenyang 110000, China
[4]State Grid Taizhou Power Supply Company, State Grid Jiangsu Electric Power Supply Company Ltd., Taizhou 225300, China

Corresponding author: Yue Chen (ycchenyue@foxmail.com)

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ABSTRACT The power prediction error of uncertain renewable energy sources (URESs) affects the power balance of a power grid. In the power systems with high proportion renewable power sources (PSHPRPSs), automatic generation control (AGC) cannot accommodate the day-ahead power prediction error. The dispatching control system (DCS) of PSHPRPSs adds real-time dispatching links to modify the day-ahead dispatching plan so that the grid power error is within the range of AGC accommodation. This paper proposes a critical time scale (CTS) selection algorithm based on time aggregation characteristics for real-time dispatching of PSHPRPSs and calculates the annual CTS of real-time dispatching of power grids. The uncertainty function is used to describe the relationship between the prediction error of the URESs and the prediction lead time. The total uncertainty function is calculated based on the time aggregation characteristics and is used to select the annual CTS of real-time dispatching. The proposed algorithm quantitatively describes the relationship between the CTS and the operation proportion of URESs and also AGC accommodation capacity. The calculated annual CTS not only ensures the power balance of the power grid, but also avoids the daily change of the CTS. Using the data of URESs in the Irish power grid, the feasibility of the proposed method was verified. The research results of this paper are helpful to accommodate the day-ahead power prediction error of URESs and maintain the safe operation of power grid.

INDEX TERMS Uncertain renewable energy sources, power prediction error, real-time dispatching, critical time scale, time aggregation characteristics.

I. INTRODUCTION

An increasing interest in wind and solar power over the past two decades has been largely driven by the need to reduce the use of fossil fuels and address the threat of global climate change. However, random and intermittent characteristics exist in wind and solar power. Power systems with high proportions of uncertain renewable energy sources (PSHPRPSs) [1], [2] are particularly susceptible to the uncertainty of power availability, and day-ahead power prediction errors are higher for PSHPRPSs compared those that a higher proportion of non-renewable power sources [3], [4]. To maintain the safe operation of a power grid and maximize the use of renewable energy sources, PSHPRPSs should accommodate the power prediction errors of uncertain renewable energy sources (URESs).

Previous research on how PSHPRPSs should best accommodate power prediction error of URESs has mainly focused on three aspects. First, researchers have attempted to improve the day-ahead prediction accuracy of URESs so that PSHPRPSs can reduce their day-ahead power prediction errors [5]–[10]. However, even with these efforts, power prediction errors are still quite large owing to the inherent uncertainty of the URESs. Second, researchers have examined

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the utility of conventional and energy storage power sources as reserve power sources to accommodate power prediction errors of URESs [11]–[14]. Third, researchers have developed a dispatching control system (DCS) with a power accommodation capability for PSHPRPSs. This system accommodates the power prediction error of URESs step by step through multiple predictions [15]–[17].

The power prediction errors of traditional power grids, compared with those of PSHPRPSs, are smaller, and their day-ahead dispatching plan is more accurate, thereby allowing automatic generation control (AGC) to balance day-ahead power errors. Therefore, the DCS of a traditional power grid only includes two links: day-ahead dispatching and AGC. In contrast, PSHPRPSs contain a high proportion of URESs, and the day-ahead prediction errors are significant, so AGC alone cannot accommodate the day-ahead power prediction errors. Therefore, the DCS of PSHPRPSs should add a short time scale power balance link to maintain the power balance of power grids. To address significant day-ahead prediction errors in PSHPRPSs, [18] proposed a three timescale DCS that is coordinated by day-ahead dispatching, real-time dispatching, and AGC. Similarly, [19] proposed a four timescale DCS that is coordinated by day-ahead dispatching, rolling planning, real-time dispatching, and AGC. Overall, research on the DCSs of PSHPRPSs has mainly focused on the addition of short time scale dispatching links [20]–[23]. Literature [24]–[27] used prediction / scheduling / control coordination to accommodate the power prediction error of URESs by adding multiple time scales. To avoid too many short time scale power balance links affecting the work efficiency of power grid DCSs, this paper uses a three-time scale DCS.

The DCS of PSHPRPSs formulates a day-ahead dispatching plan based on the day-ahead power forecast and a real-time dispatching plan based on the real-time power forecast. Due to the large errors in the day-ahead dispatching plan of PSHPRPSs, the real-time dispatching should modify the day-ahead dispatching plan so that the power grid error is within the range of AGC accommodation. When setting a real-time dispatching plan, the critical time scale (CTS) of real-time dispatching affects the power balance of the power grid and the operating efficiency of the DCS. A CTS that is too small will reduce the operating efficiency of the power grid DCS, while a CTS that is too large will result in a AGC that cannot accommodate the residual power prediction error and a reduction in grid safety. Therefore, it is especially important to select a suitable CTS for real-time dispatching of PSHPRPSs. Previous researchers examining the design of DCSs [28]–[31] set the CTS of real-time dispatching to 0.25 h, 1 h, or 4 h. However, these researchers usually choose the CTS of real-time dispatching based on experience rather than theoretical research. Wang *et al.* [32] designed the uncertainty function to select the CTS of real-time dispatching by describing the functional relationship between the power prediction error of URESs and the prediction lead time. However, CTSs that are selected by this method change with the different daily prediction error. For an actual power grid DCS with a constant share of URESs, the CTS for real-time dispatching should be certain for one to several years.

The paper examine the operation mode of DCSs of PSHPRPSs from the viewpoint of power balance. The CTS of real-time dispatching is calculated by the uncertainty function of URESs, and the influence of various parameters on the CTS is examined. According to the time aggregation characteristics of an uncertainty function, this study propose a CTS selection algorithm for real-time dispatching of PSHPRPSs. This study then verify the feasibility of the proposed method of CTS selection using data from the Irish grid's renewable energy source to calculate the annual CTS of the Irish grid. The simulation results show that the CTS of the PSHPRPSs proposed in this paper not only ensures the power balance of the grid but is also conducive to the efficient operation of the power grid DCS.

The remainder of this paper is structured as follows. Section II describes the DCS of PSHPRPSs and puts forward a definition of critical time scale. Section III proposes a CTS selection algorithm based on time aggregation characteristics. Section IV verifies the accuracy of the proposed algorithm by using the CTS selection algorithm to calculate the CTS of the Irish power grid. Finally, the conclusions of this work are presented in Section V.

II. CRITICAL TIME SCALE OF REAL-TIME DISPATCHING

This section describes the operation process of PSHPRPSs' DCS and proposes a definition of CTS for real-time dispatching. The uncertainty function is established according to the statistical relationship between the power prediction error of URESs and the prediction lead time. The CTS formula is established based on the uncertainty function of the URESs, and the influence of each parameter on the CTS is explained.

A. DISPATCHING CONTROL SYSTEM OF POWER SYSTEMS WITH HIGH PROPORTION RENEWABLE POWER SOURCES

The DCSs of PSHPRPSs consist of day-ahead dispatching, real-time dispatching, and AGC. The day-ahead prediction error of URESs is large, leading to the inaccuracy of day-ahead dispatching. According to the real-time power prediction, the real-time dispatching is formulated to modify the day-ahead dispatching plan, so that the power grid error is controlled within the accommodation range of AGC. The three dispatching links are connected step by step to form a "prediction-correction" power balance within the DCS.

In this paper, the power generated by thermal power, hydropower, nuclear power, energy storage power, and active load is called controllable power P_c. The power of wind and solar power is called uncertain renewable energy power P_{ures} and is a "negative load power." The grid load power P_l is combined with P_{ures} into an equivalent load P_{el} with uncertainty characteristics and is defined by equation (1).

$$P_{el} = P_l - P_{ures} \tag{1}$$

1) DAY-AHEAD DISPATCHING

The formulation of a day-ahead dispatching plan is based on the day-ahead equivalent load prediction power P_{el}^d. The controllable power P_c^d is used to balance the day-ahead equivalent load prediction power $P_{el}^d P_{el}^d$. The balance question is defined as:

$$P_c^d - P_{el}^d = 0 \tag{2}$$

Due to the large prediction error associated with URESs, the prediction error of the equivalent load power is large. To maintain the safe operation of a power grid, the day-ahead dispatching needs to arrange reserve power for real-time dispatching and AGC to accommodate the error of the day-ahead equivalent load power prediction.

2) REAL-TIME DISPATCHING

In PSHPRPSs, the day-ahead power prediction error of URESs is large, resulting in an AGC that cannot accommodate the day-ahead power prediction error. Therefore, the DCS adds a real-time dispatching link to predict the real-time equivalent load power. The difference between the real-time prediction value P_{el}^r and the day-ahead prediction value P_{el}^d of the power grid equivalent load is called the day-ahead prediction error ΔP_{el}^d and defined as follows:

$$\Delta P_{el}^d = P_{el}^r - P_{el}^d \tag{3}$$

In real-time dispatching, the reserve power P_c^r is used to balance the day-ahead power prediction error so that the grid equivalent load prediction error is controlled within the range of AGC accommodation. The power balance equation is as follows:

$$P_c^r - \Delta P_{el}^d = 0 \tag{4}$$

3) AGC

The power measurement value of AGC for equivalent load of PSHPRPSs is the actual value of equivalent load. The difference between the measured value P_{el} and the real-time prediction value P_{el}^r of the equivalent load is called the real-time prediction error ΔP_{el}^r, defined as follows:

$$\Delta P_{el}^r = P_{el} - P_{el}^r \tag{5}$$

The AGC uses the frequency modulation reserve power P_c^a of the power grid to accommodate the real-time prediction error of the equivalent load and maintain the power error of the equivalent load at 0. The power balance equation is defined as follows:

$$P_c^a - \Delta P_{el}^r = 0 \tag{6}$$

4) OPERATION MECHANISM OF DCS FOR PSHPRPS

Operators of PSHPRPSs make day-ahead dispatching plans and set reserve power based on the day-ahead forecast of equivalent loads. According to the real-time prediction value of equivalent load, the reserve power is used to accommodate day-ahead power prediction error ΔP_{el}^d. According to the AGC measurement value of equivalent load, the real-time prediction error ΔP_{el}^r is accommodated by using the frequency modulation reserve power. However, the accommodation capacity of AGC is limited. Grid power balance can be maintained if the real-time dispatching controls the power error ΔP_{el}^r within the accommodation capacity of the AGC. Therefore, the equivalent load real-time prediction error ΔP_{el}^r should satisfy the AGC constraint defined as follows:

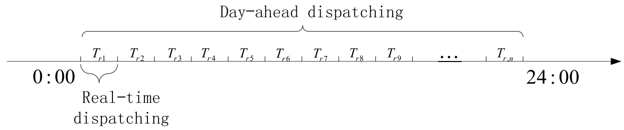

FIGURE 1. Time series diagram of DCS for PSHPRPSs.

$$\left|\Delta P_{el}^r\right| \le \sigma \tag{7}$$

where σ is the accommodation capacity of AGC.

The time series diagram of the DCS for PSHPRPSs is shown in Figure 1:

Real-time dispatching is nested within the constraints of day-ahead dispatching (Fig. 1). $T_{r,n}$ represents the nth real-time dispatching cycle, which is nested in the day-ahead dispatching. In this paper, the length of the real-time dispatching cycle is called the CTS of real-time dispatching. A CTS that is too short will increase the number of real-time dispatching cycles and reduce the operation efficiency of the DCS. A CTS that is too long will result in a real-time prediction error that exceeds the accommodation capacity of the AGC. Therefore, it is essential to select a suitable CTS of real-time dispatching for the optimal performance of a DCS of PSHPRPSs.

B. DEFINITION OF CTS FOR REAL-TIME DISPATCHING

1) CTS OF REAL-TIME DISPATCHING BASED ON AN UNCERTAINTY FUNCTION

The power prediction error and prediction lead time of URESs follow the law of probability and statistics [33]. The longer the prediction lead time, the larger the prediction error; the shorter the prediction lead time, the smaller the prediction error. The root mean square relative error was used by [34] to calculate the relationship between the power prediction error of URESs and the prediction lead time.

Here, this paper use the uncertainty function to describe the relationship between the power prediction error and the prediction lead time of the URES, previously defined in [35], as follows:

$$E_{ures}(t) = A_{ures}\left(1 - e^{-\frac{t}{\tau_{ures}}}\right) \tag{8}$$

where, A_{ures} is the amplitude of the uncertainty function, and τ_{ures} is the time constant of the uncertainty function. $E_{ures}(t)$ is the power prediction error of URESs affected by the prediction lead time.

It is assumed that the proportion of URESs in the PSHPRPSs is β. Subsequently, the total uncertainty function of the PSHPRPSs is defined as follows:

$$E_g(t) = \beta E_{ures}(t) = A_g\left(1 - e^{-\frac{t}{\tau_g}}\right) \quad (9)$$

where, A_g is the amplitude of the total uncertainty function and τ_g is the time constant of the total uncertainty function. $E_g(t)$ is the total power prediction error of URESs affected by the prediction lead time.

In the real-time dispatching process, the size of the real-time power prediction error depends on the lengths of the prediction lead times. In order to maintain power balance, the real-time power prediction error of the power grid should be within the AGC accommodation capacity. Therefore, (7) can be replaced with:

$$A_g\left(1 - e^{-\frac{t}{\tau_g}}\right) \leq \sigma \quad (10)$$

where, σ is the accommodation capacity of the AGC.

According to (9) and (10), in order to maintain the power balance of power grid, the real-time prediction time of the power grid should satisfy (11):

$$t \leq \tau_{ures} \ln \frac{\eta A_{ures}}{\eta A_{ures} - \sigma} \quad (11)$$

Therefore, the CTS T_r of real-time dispatching is defined by:

$$T_r = \tau_{ures} \ln \frac{\eta A_{ures}}{\eta A_{ures} - \sigma} \quad (12)$$

According to (12), since $T_r > 0$, each parameter should satisfy the relationship of:

$$0 < \frac{\sigma}{\eta A_u} < 1 \quad (13)$$

2) RELATIONSHIP BETWEEN CRITICAL TIME SCALE AND PARAMETERS

The relationship between the CTS and the URESs' proportion β in PSHPRPSs is shown in Figure 2.

3) EFFECT OF ALGORITHM PARAMETERS ON CTS

a: THE RELATIONSHIP BETWEEN THE CTS AND THE URESs' PROPORTION β

The CTS is inversely proportional to the proportion of URESs in PSHPRPSs, with larger proportions of URES, resulting in smaller CTSs (Fig. 2). Therefore, the CTS of real-time dispatching should be smaller for PSHPRPSs.

b: THE RELATIONSHIP BETWEEN THE CTS AND THE AGC ACCOMMODATION CAPACITY σ

The CTS is approximately proportional to the AGC accommodation capacity σ of the PSHPRPSs, with an increase in the accommodation capacity of AGC, resulting in a gradual increase in the CTS (Fig. 3). However, for certain power grid, the adjustment range of the AGC accommodation capacity is not large.

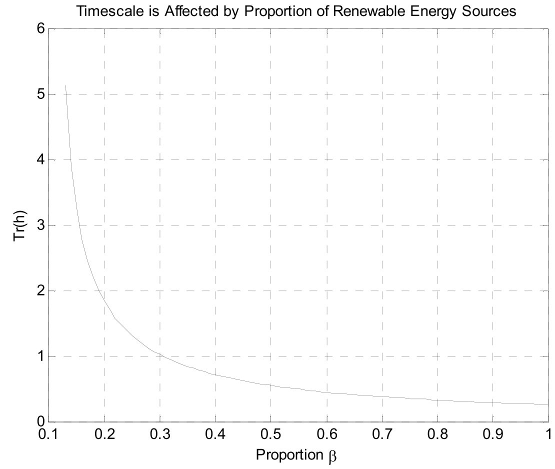

FIGURE 2. Relationship between CTS and the proportion β of URESs in PSHPRPSs.

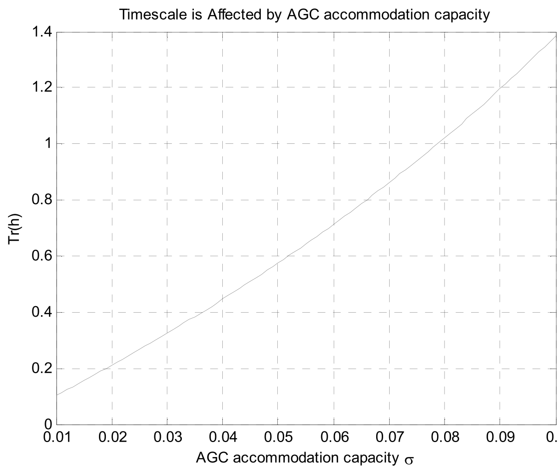

FIGURE 3. Relationship between CTS and AGC accommodation capacity of PSHPRPSs.

c: THE RELATIONSHIP BETWEEN THE CTS AND THE UNCERTAINTY FUNCTION AMPLITUDE

The CTS is inversely proportional to the uncertainty function amplitude of the URESs, with larger uncertainty function amplitudes resulting in smaller CTSs (Fig. 4). For a given uncertainty function amplitude, systems with larger proportions of URESs had smaller CTSs (Fig. 4). This correlation indicates PSHPRPSs that have large uncertainty function amplitudes should use smaller CTS for the optimal operation of renewable energy grids.

d: THE RELATIONSHIP BETWEEN THE CTS AND THE UNCERTAINTY FUNCTION TIME CONSTANT

The CTS is directly proportional to the uncertainty function time constant of the URESs, where larger uncertainty function time constants result in larger CTSs (Fig. 5). For a given uncertainty function time constant, systems with larger the proportions of URESs had smaller CTSs (Fig. 5).

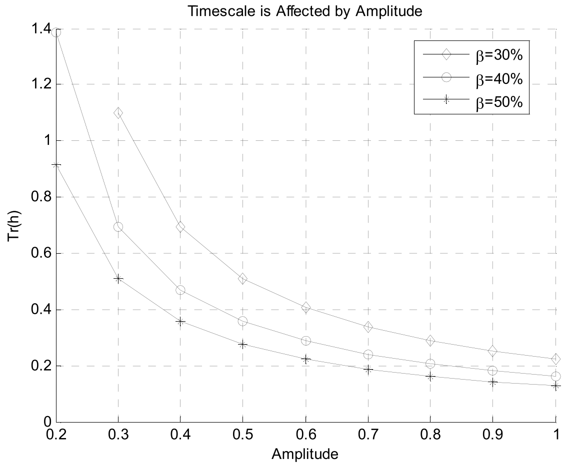

FIGURE 4. Relationship between CTS and the uncertainty function amplitude of URESs.

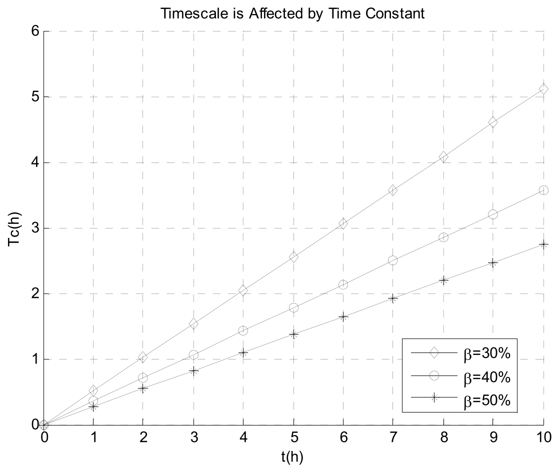

FIGURE 5. Relationship between the CTS and the uncertainty function time constant of the URESs.

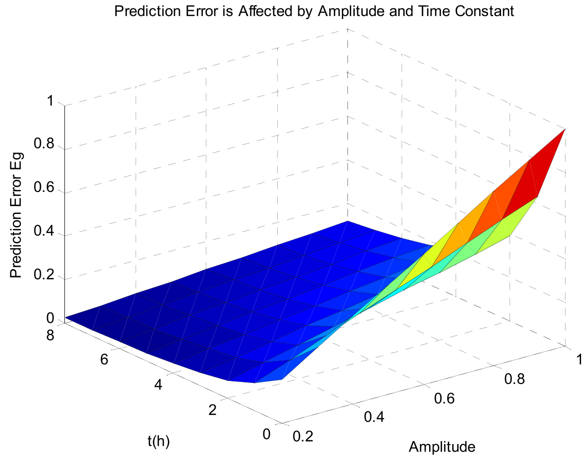

FIGURE 6. Relationship among the power prediction error of URESs, the uncertainty function amplitude, and the time constant.

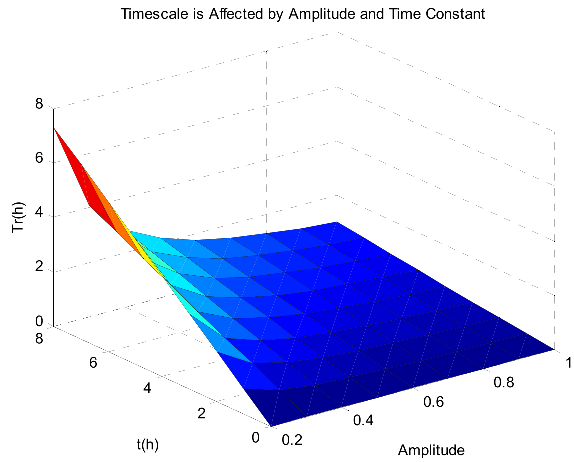

FIGURE 7. Relationship between the CTS, the uncertainty function amplitude, and the power prediction error of URESs.

e: THE RELATIONSHIP AMONG PARAMETERS IN (9)

According to (9), the power prediction error of URESs is affected by both the amplitude and the time constant of uncertainty function. When the uncertainty function amplitude increases and the time constant decreases, the power prediction error gradually increases (Fig. 6). The CTS of real-time dispatching decreases with an increasing uncertainty function amplitude and a decreasing time constant (Fig. 7). Together, these results indicate that the CTS decreases with an increase in the power prediction error of URESs.

III. CRITICAL TIME SCALE SELECTION BASED ON TIME AGGREGATION

Keeping the CTS of real-time dispatching unchanged will reduce the workload of dispatchers and improve work efficiency. Therefore, if the proportion of URESs is constant, the CTS should remain unchanged in the actual operation process of power grid dispatching. This constancy is challenging to achieve for URESs because these power sources are affected by seasonal climate change. Here, this study propose a solution to seasonal uncertainty function of the power grid based on the time aggregation characteristics of the uncertainty function. The seasonal CTS is solved according to the seasonal uncertainty function, after which the annual CTS is selected.

A. TIME AGGREGATION OF THE UNCERTAINTY FUNCTION

The uncertainty function corresponding to the total time period T is E. The uncertainty functions corresponding to time period $T_1, T_2, \cdots, T_n$ are $E_1, E_2, \cdots E_n$ respectively.

The uncertainty function E_i corresponding to any period T_i is defined as follows:

$$E_i(t) = \sqrt{\frac{1}{T_i} \cdot \int_{T_{i-1}}^{T_i} \varepsilon_i^2(t)\, dt} \tag{14}$$

where, ε_i is the power prediction error of the URESs during the T_i period.

The total uncertainty function E corresponding to the total time period T is defined as follows:

$$E(t) = \sqrt{\frac{1}{T} \cdot \int_{T_1}^{T_n} \varepsilon^2(t)\, dt} \tag{15}$$

The relationship between the total time period T and each time period $T_1, T_2, \cdots, T_n$ is defined as follows:

$$T = T_1 + T_2 + \cdots T_n \tag{16}$$

The relationship between the each time period uncertainty function $E_1, E_2, \cdots E_n$ and the total uncertainty function E is defined as follows:

$$\sqrt{\frac{1}{T} \cdot \int_{T_1}^{T_n} \varepsilon^2(t)\, dt} = \sqrt{\frac{1}{T} \cdot \sum_{i=1}^{n} \int_{T_{i-1}}^{T_i} \varepsilon^2(t)\, dt} \tag{17}$$

According to (13), (17) can be simplified as follows:

$$E^2(t) = \rho_1 \cdot E_1^2(t) + \rho_2 \cdot E_2^2(t) + \cdots + \rho_n \cdot E_n^2(t) \tag{18}$$

where ρ_i is defined as follows:

$$\rho_i = \frac{T_i}{T}, (i = 1, 2, \cdots, n) \tag{19}$$

when $+\infty$ is selected for time t, $E(+\infty) = A$. According to (18), the relationship between the amplitude A_i of each time period uncertainty function $E_1, E_2, \cdots E_n$ and the amplitude A of the total uncertainty function E is defined as follows:

$$A = \sqrt{\sum_{i=1}^{n} \rho_i \cdot A_i^2} \tag{20}$$

The relationship between the derivative function of the uncertainty function $E_1, E_2, \cdots E_n$ in each time period and the derivative function of the total uncertainty function E is defined as follows:

$$\left(\frac{dE(t)}{dt}\right)^2 + E(t)\frac{d^2E(t)}{d^2t} = \sum_{i=1}^{n} \rho_i \left(\left(\frac{dE_i(t)}{dt}\right)^2 + E_i(t)\frac{d^2E_i(t)}{d^2t}\right) \tag{21}$$

Because $E(0) = 0$, (21) can be simplified to:

$$\left(\frac{dE(0)}{dt}\right)^2 = \sum_{i=1}^{n} \rho_i \left(\frac{dE_i(0)}{dt}\right)^2 \tag{22}$$

The initial value of the derivative function of uncertainty function E is defined as follows:

$$\frac{dE(0)}{dt} = \frac{1}{\tau} \tag{23}$$

where τ is the time constant of the uncertainty function.

According to (22), the relationship between time constant τ_i of uncertainty function $E_1, E_2, \cdots E_n$ in each time period and time constant τ of total uncertainty function E is defined as follows:

$$\tau = \frac{\prod_{i=1}^{n} \tau_i}{\sqrt{\sum_{i=1}^{n} \left(\rho_i \prod_{j=1}^{i-1} \tau_j^2 \cdot \prod_{l=i+1}^{n} \tau_l^2\right)}} \tag{24}$$

According to (20) and (24), the amplitude A and time constant τ of the total period uncertainty function are calculated by using the amplitude A_i and time constant τ_i of each period uncertainty function.

B. SELECTION OF THE CRITICAL TIME SCALE FOR REAL-TIME DISPATCHING

The calculated value of the CTS is generally not an integer, which is not conducive to the actual dispatching operation of a power grid. In this paper, the CTS is converted to an integer by setting the resolution of the CTS of the power grid as ΔT, and then selecting $\frac{1}{2}h$, $\frac{1}{3}h$, $\frac{1}{4}h$, $\frac{1}{6}h$, $\frac{1}{12}h$ in order of priority. When the proportion of URESs is $\beta = 1$, (25) is verified from $\frac{1}{2}h$ to $\frac{1}{12}h$ in turn. When it is verified that a certain resolution ΔT_i satisfies (25), the resolution ΔT of the CTS of the power grid takes this value.

$$A_g\left(1 - e^{-\frac{\Delta T}{\tau_g}}\right) \le \sigma \tag{25}$$

The CTS $T_{r,k}$ and resolution ΔT of real-time dispatching should satisfy the following:

$$T_{r,k} = k \cdot \Delta T \tag{26}$$

where $T_{r,k}$ represents the kth level CTS.

For any PSHPRPSs, the total uncertainty function $E_g(t)$ is calculated according to (20) and (24). Assuming that the CTS T_r of real-time scheduling is the kth level CTS $T_{r,k}$, it satisfies the following inequality constraint:

$$\begin{cases} \beta A_g\left(1 - e^{-\frac{T_{r,k}}{\tau_g}}\right) \le \sigma \\ \beta A_g\left(1 - e^{-\frac{T_{r,k+1}}{\tau_g}}\right) > \sigma \end{cases} \tag{27}$$

According to (26), the constraints of (27) can be changed to:

$$\frac{\tau_g}{\Delta T}\ln\frac{\beta A_g}{\beta A_g - \sigma} \ge k > \frac{\tau_g}{\Delta T}\ln\frac{\beta A_g}{\beta A_g - \sigma} - 1 \tag{28}$$

For any PSHPRPSs, the total uncertainty function is $E_g(t)$. If the proportion of URESs β, the amplitude of the uncertainty function A_g, and the time constant τ_g satisfy (28), then the CTS of the real-time dispatching for the power system is the kth level CTS $T_{r,k}$.

C. SELECTION OF ANNUAL CTS

In contrast to non-renewable power sources, the power prediction error of URESs is greatly affected by seasonal variations in climate. In this paper, the uncertainty function of each season is calculated based on the time aggregation characteristics of the uncertainty function according to the power prediction error of URESs in different seasons. The CTS of real-time dispatching for each season is calculated according to the uncertainty function of each season (Fig. 8).

The intersection point of the uncertainty function curve and the AGC accommodation capacity curve of each season is the CTS of real-time dispatching for each season (Fig. 8).

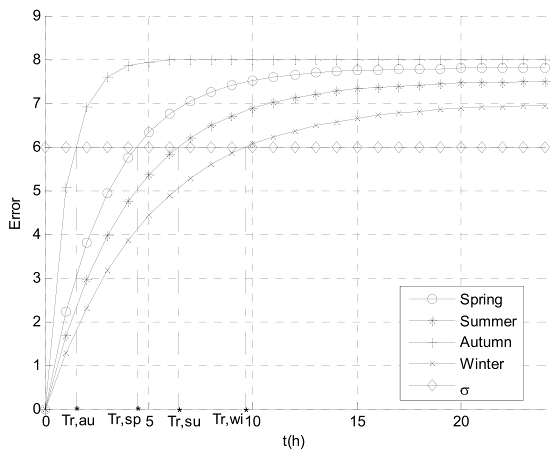

FIGURE 8. Seasonal uncertainty functions.

If $T > T_{cr}$, the power prediction error of the URESs cannot be completely accommodated, resulting in the power of grid imbalance. Therefore, for a PSHPRPSs, in order to completely accommodate the power prediction error of URESs, the time scale of real-time scheduling should satisfy $T \leq T_{cr}$. For the uncertainty function of different seasons, different CTSs are calculated. The time scale of each season has its own constraint. The annual CTS should meet the requirements of the CTS for each season. According to (29), the annual CTS is the minimum value of the CTSs for each season, i.e.,

$$T_r = \min\{T_{r,sp}, T_{r,su}, T_{r,au}, T_{r,wi}\} \tag{29}$$

where, $T_{r,sp}$, $T_{r,su}$, $T_{r,au}$, $T_{r,wi}$ are the CTS of spring, summer, autumn, and winter, respectively. T_r is the annual CTS of PSHPRPSs.

D. STEPS TO SELECT THE CTS

The CTS selection algorithm for real-time dispatching of PSHPRPSs is performed with the following steps (Fig. 9).

1) The ARIMA model is used to predict the generation power of URESs.

2) The uncertainty function E_i of each dispatching cycle is calculated.

3) According to (20) and (24), the amplitude A and time constant τ of the total period uncertainty function are calculated by using the amplitude A_i and time constant τ_i of each period uncertainty function.

4) According to (25), the CTS resolution ΔT of the power grid is selected.

5) According to (28), the level of the CTS for each season of the power grid is calculated.

6) According to (26), the CTS of the grid for each season is calculated.

7) Based on the principle that the annual CTS needs to meet the requirements of the CTS for each season, the annual CTS is selected according to (29).

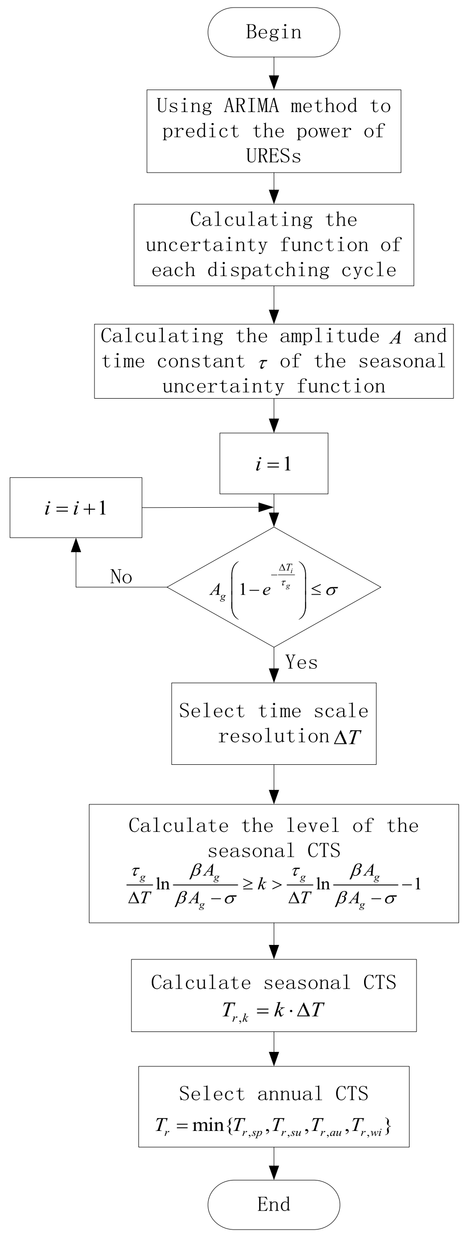

FIGURE 9. Steps in the CTS selection algorithm for real-time dispatching of PSHPRPSs.

IV. SIMULATION RESULTS

This study used Irish renewable energy source data [36] to verify the proposed CTS selection algorithm for the real-time dispatching of PSHPRPSs. The proposed algorithm was used to select the CTS for the Irish Island power grid. Simulations were performed in MATLAB 8.3.0.532 (R2014a) on a personal computer with an i5-4200M CPU, 2.50 GHz processor, and 4.0 GB RAM.

In this case, the ARIMA method was used to predict the power generation of URESs in Ireland. According to the power prediction error, the amplitude and time constant of the uncertainty function of each season were calculated. The amplitude and time constants of the seasonal uncertainty function in Ireland are presented in Table 1.

TABLE 1. Parameters of Irish island seasonal uncertainty function.

Season	Amplitude	Time constants
Spring	0.339	1.64
Summer	0.341	1.62
Autumn	0.279	0.52
Winter	0.344	1.45

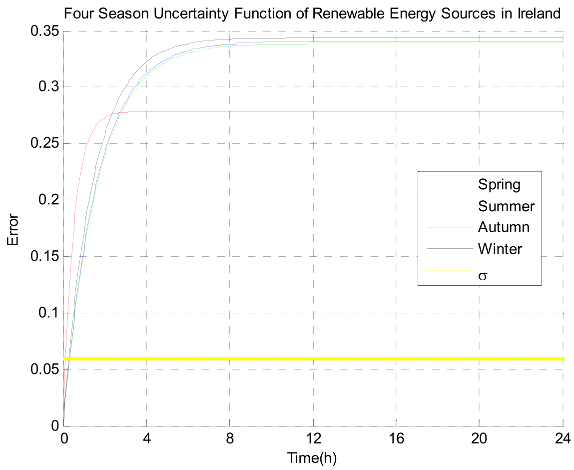

FIGURE 10. Uncertainty functions of URESs in Ireland for four seasons.

TABLE 2. Seasonal CTS of the Irish Power Grid.

Season	Spring	Summer	Autumn	Winter
Calculated value of CTS (h)	1.75	1.72	1.04	1.57
Level of CTS	3	3	2	3
Adjusted value of CTS (h)	1.5	1.5	1	1.5

The abscissa of the intersection of the seasonal uncertainty function and the AGC accommodation capacity line is the seasonal CTS (Fig. 10). Before the uncertainty function is saturated, under the same prediction lead time, the uncertainty power prediction error in autumn is the largest and the CTS is the smallest (Fig. 10). This result indicates that in order to maintain the safe operation of the Irish power grid, the CTS should be based on the CTS for autumn.

The time scale resolution was used to adjust the calculated value of the CTS to an integer. The seasonal CTS was calculated according to the seasonal uncertainty function, and the calculation (Table 2). According to (29), the annual CTS of Ireland is 1 h, and the annual CTS should meet the needs of each seasonal CTS.

If the daily CTSs are larger than the annual CTS, then the annual CTS can meet the demand of the daily real-time dispatching. The ratio of the total number of days that met the demand to the total number of days per year was used to evaluate the accuracy of the annual CTS, defined as follows.

$$P_{er} = \frac{N}{365} \times 100\% \tag{30}$$

where, N is the number of days that the annual CTS meets the requirements.

TABLE 3. Annual critical time scale evaluation index of Irish power grid.

CONDITION	TOTAL DAYS OF THE YEAR	N	P_{er}
VALUE	365	365	100%

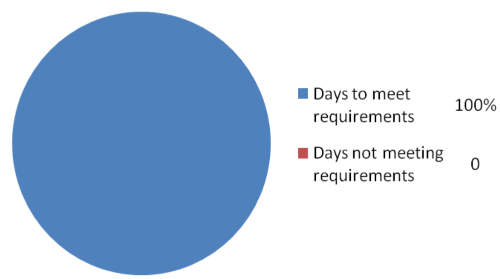

FIGURE 11. Annual critical time scale evaluation index of Irish power grid.

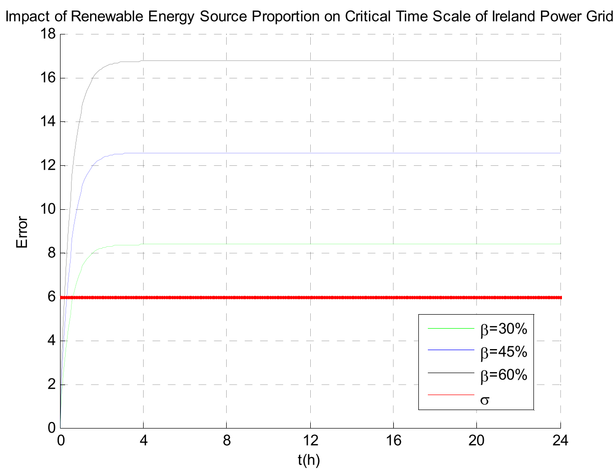

FIGURE 12. Total uncertainty function corresponding to the different proportions of URESs.

TABLE 4. CTS for real-time dispatch of Irish power grids with different proportions of URESs.

Proportion (%)	30	45	60
Calculated value of CTS (h)	1.15	0.84	0.73
Level of CTS	2	1	1
Adjusted value of CTS (h)	1	0.5	0.5

Using (30), P_{er} was 100%, demonstrating that the annual CTS satisfied the CTS requirement for each dispatching day throughout the year (Fig. 11; Table 3). These results suggest that the annual CTS calculated using the algorithm proposed here satisfies the CTS requirements of the Irish power grid. Simulation results verify the accuracy of the annual CTS selection algorithm proposed in this paper.

The proportion of URESs in the power grid exaggerates the total uncertainty with increasing CTSs of real-time dispatching in the Irish power grid (Fig. 12; Table 4). The CTS of the real-time dispatching for the Irish power grid gradually decreases with an increase in the proportion of URESs (Fig. 12). Therefore, we can predict that as the Irish power grid increases the proportion of renewable energy sources, the CTS of the power grid will decrease.

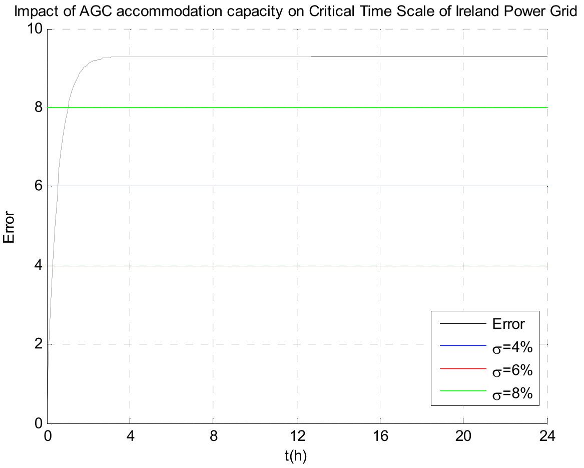

FIGURE 13. Influence of AGC accommodation capacities on the CTS of real-time dispatching for the Irish power grid.

TABLE 5. CTS of real-time dispatching for the Irish power grid corresponding to different AGC accommodation capacities.

AGC accommodation capacity (%)	4	6	8
Calculated value of CTS (h)	0.79	1.04	1.52
Level of CTS	1	2	3
Adjusted value of CTS (h)	0.5	1	1.5

The CTS of real-time dispatching gradually increases with the increase in the AGC accommodation capacity of the Irish power grid (Fig. 13; Table 4). This result indicates that adding AGC regulating units to the Irish power grid will help increase the CTS of real-time dispatching and reduce the frequency of real-time dispatching.

In this section, the algorithm proposed in this paper is used to calculate the CTS for the Irish Island power grid. Based on the analysis of the influence of the proportion of URESs on the CTS of real-time dispatching in the Irish power grid, we conclude that the CTS of real-time dispatching will decrease as the proportion of URESs increases in this grid. By analyzing the influence of AGC accommodation capacity on the CTS of real-time dispatching, we show that adding AGC regulating units serves to increase the CTS of real-time dispatching. The simulation results verify the accuracy of the proposed algorithm

V. CONCLUSION

The AGC of PSHPRPSs cannot accommodate the power prediction error of power grids. The DCS adds real-time dispatching to rectify the day-ahead dispatching plan, and the control power error is within the AGC accommodation capacity. If the CTS of real-time dispatching is extremely large, it will cause the power grid to be unbalanced and if it is extremely small, it will increase the frequency of real-time dispatching and reduce the operational efficiency of the DCS. To maintain the safe and efficient operation of a power grid, this paper proposes a CTS selection algorithm for the real-time dispatching of PSHPRPSs based on the characteristics of time aggregation. The proposed algorithm quantitatively depicts the relationship between the annual CTS of real-time dispatching and the prediction error, operation proportion of URESs, and AGC accommodation capacity of URESs. Calculating the total uncertainty function through time aggregation characteristics ensures that the CTS of real-time dispatching is stable over a year. The CTS of the PSHPRPSs proposed in this paper not only ensures the power balance of the grid but is also conducive to the efficient operation of the power grid DCS. In comparison with the existing literature, the main contributions of this work can be summarized as follows: (1) this paper reveals the time aggregation characteristics of the uncertainty function of URESs and proposes a CTS selection algorithm for real-time dispatching based on the time aggregation characteristics. (2) The CTS of annual real-time dispatching for PSHPRPSs is calculated to ensure that the CTS does not change every day.

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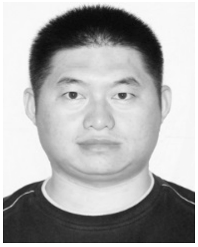
YUE CHEN is currently pursuing the Ph.D. degree in electrical engineering with the Harbin Institute of Technology. His research interests include optimal dispatching theory of power systems, optimal power flow of power systems, and renewable energy power systems.

ZHIZHONG GUO received the Ph.D. degree from the Harbin Institute of Technology, in 1989. His research interests include automation of power systems, power system stability analysis and control, power system optical measurement technology, research on operation and dispatching technology of consumer-type pumped storage power stations, and research on key technologies of large-scale wind power generation bases wait.



HONGBO LI received the master's degree. His research interests include measurement technology of power optical sensor and research on operation and dispatching technology of consumer-type pumped storage power stations.

YI YANG received the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 2019. His current fields of interests include power system analysis, power system optimal dispatching, and power system transient analysis.

GUIZHONG WANG received the master's degree. His research interests include renewable power generation, grid information monitoring, and research on operation and dispatching technology of consumer-type pumped storage power stations.

ABEBE TILAHUN TADIE is currently pursuing the Ph.D. degree in electrical engineering with the Harbin Institute of Technology. His research interests include power system operation and control, power system optimization, renewable energy integration, energy storage and optimization, and smart micro grid.

OUYANG ZHIBIN received the master's degree from the Harbin Institute of Technology. His research interests include full-waveform protection based on optical current transformers and has performed research on reducing the impact of protection action time on power system stability in-depth exploration.

ZHE DING is currently pursuing the master's degree in electrical engineering with the Harbin Institute of Technology. His research interests include renewable energy grids, optimal power flow of power systems, and power system stability analysis and control.