frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 19 March 2024
DOI 10.3389/fenrg.2024.1360272

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OPEN ACCESS

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RECEIVED 22 December 2023
ACCEPTED 08 February 2024
PUBLISHED 19 March 2024

CITATION
Kuo X, Hongxuan Z, Wenzu W, Jingpeng C and Qixing L (2024), The design of an improved index system for frequency control in China Southern Power Grid.
Front. Energy Res. 12:1360272.
doi: 10.3389/fenrg.2024.1360272

The design of an improved index system for frequency control in China Southern Power Grid

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Introduction: In order to dispatch frequency regulation resources in regional power grids efficiently and promote the development of spot markets, China Southern Power Grid (CSG) established the unified frequency regulation control area. However, the existing regional control performance standards (CPS) for evaluating the performance of frequency control in bulk power systems is no longer suitable for the unified frequency control mode.

Method: This paper proposed an innovative frequency control performance standard, named tertiary control performance standards (TCPS) and used Gaussian mixture model (GMM) and folded normal distribution (FND) to describe the distributions of frequency deviations and power deviations of tie line.

Result and Discussion: Based on these probability models, the parameters of the proposed TCPS can be determined optimized. Finally, case studies were carried out with the practical data from CSG and indicated that the parameters of proposed TCPS index could be calculated and improved the control performance for the real time power balance of the regional power grid with spot markets.

KEYWORDS

regional spot market, control performance standards, frequency control performance, regional power grid, distribution models

1 Introduction

Nowadays, the controllable generators with large capacities in China are dispatched by dispatch and control centers at different levels, such as the dispatch and control center of China Southern Power Grid (CSG) and provincial dispatch and control centers. These generators with large capacities are valuable resources for the frequency control of power systems and are dispatched by different dispatch and control centers. The frequency control system of power systems consists of three loops: a primary frequency control loop, a secondary frequency control loop, and a tertiary frequency control loop. The secondary and tertiary frequency control tasks are primarily conducted by the provincial dispatch and control center and the dispatch and control center of CSG (Jaleeli and Vanslyck, 1999; Yao et al., 2000; Power system frequency regulation and automatic generation control committee, 2006; Wang, 2015a). Such a traditional operation method has some drawbacks. First, the decentralized frequency regulation strategy for all regulation resources may cause local optimization in the provincial power grids rather than global optimization in regional power grids. Second, under the environment of regional spot markets, the frequency regulation services provided by the generators in different provinces need to compete in the same market, which does not meet the requirements of market fairness (Wang, 2015b). In order to establish a more efficient mechanism for dispatching frequency regulation resources and promote the construction of the regional spot market, CSG has established a unified frequency control area in 2018. The frequency regulation resources were allocated by a unified control module, ensuring the global optimization of frequency regulation resources and fair competition in the market environment.

The control performance standard (CPS) for regional power grids, initially proposed in North America (Chang et al., 2016), has become one of the most widely used evaluation indices of reliability for real-time power balance (Wang, 2012; Xiong, 2012; Zhang et al., 2015; Zhao et al., 2016a). China has made some improvements to the North American CPS (Wang, 2000; Yu et al., 2012; Weng et al., 2013). Some literature studies have investigated the impacts of wind power integration on the CPS and proposed concepts such as wind-to-fuel-equivalent power plants (Li et al., 2016) and improvements in CPS assessment and settlement methods (Jing et al., 2011; Yu et al., 2011; Chen, 2014; Yan, 2014; Zhao et al., 2016b; Zhang, 2016; Lu, 2018; Wei et al., 2019; Zhao, 2019; Zhao et al., 2019). Some literature studies have improved the CPS and proposed new evaluation indices such as the ES index (Wang, 2019), DT index (Wang, 2019), and C index (Zhang et al., 2016) to address the performance evaluation problems of AGC control under complex scenarios (Shan et al., 2015; Chang et al., 2019; Cao et al., 2023). For the evaluation of the power control performance of the tie-line, researchers have proposed an innovative T2 index (Yang et al., 2015; Liu et al., 2017).

Although the above indices have improved the traditional CPS, they are still insufficient to adapt to the unified frequency control zone of CSG and the environment of the regional spot markets. There are two major limitations. First, the CPS indices are widely applied to evaluate the performance of secondary frequency control for provincial dispatch and control centers in China. However, the establishment of the unified frequency control zone in CSG improved the traditional operation method of implementing secondary frequency control within each provincial dispatch and control center. The short-term power balance within 1 min to 10 min in the unified frequency control zone in CSG was maintained and controlled by a unified control module. Second, the CPS indices focus on the control accuracy of the area control error (ACE) for the provincial dispatch and control centers in the short term. As a consequence, the system operators need to adjust the output power of all generators frequently. Such an operation method could not be adopted within the competitive trading mechanism; it contributes to the development of the power spot market, including auxiliary services.

Considering the various factors of power system operation, including grid security, efficiency, and spot market construction, this paper proposes a set of innovative indices for evaluating the performance of frequency control, named tertiary control performance standards (TCPS) (Jaleeli and Vanslyck, 1999; Yao et al., 2000; Power system frequency regulation and automatic generation control committee, 2006), to facilitate the development of spot markets and improve the control performance of power balance in real time.

2 The TCPS index system

In order to improve the CPS indices, which cause excessive and frequent adjustments in the short-term time scale of 1–10 min, the proposed TCPS indices are represented with details in this section.

2.1 Limitations to the CPS index system

The CPS was proposed by the North American Electric Reliability Council (NERC) in 1997 and is currently the most widely used evaluation indices for frequency control in China. In CSG, the CPS indices consist of two indices: CPS1 and CPS2.

2.1.1 CPS1 index

The CPS1 index can be represented in Eqs 1, 2 as follows:

$$\frac{ACE_{AVE-min}\cdot \Delta F_{AVE-min}}{10B}\leq \varepsilon_1^2, \tag{1}$$

$$ACE = B\times \Delta F + \Delta P. \tag{2}$$

Here, $ACE_{AVI-\mathrm{min}}$ refers to the average value of the 1-min ACE. $\mathbf{ACE}>\mathbf{0}$ indicates a positive deviation, while the negative value of the ACE indicates negative deviations. $\Delta F_{\mathrm{AVE-min}}$ represents the average value of the 1-min frequency deviation. $\Delta F>0$ indicates that the system frequency exceeds the target value, while $\Delta F<0$ represents that the system frequency is lower than the target value. B represents the coefficient of control area frequency deviation, with the unit of MW/0.1 Hz. ε_1 is the control objective of the root mean square (RMS) value of the average 1-min frequency deviation over the span of 1 year of the interconnected grid. The number 10 in Eq. 1 indicates that the evaluation period is 10 min. Considering the Eq. 3,

$$CF_{\mathrm{min}} = ACE_{AVE-\mathrm{min}}\cdot \Delta F_{AVE-\mathrm{min}}. \tag{3}$$

When CF_{min} is negative, it means that the control area generates more active power than loads with negative frequency deviations or less active power than loads with positive frequency deviations in 1 min, which indicates the generators in this region contribute to the frequency control. Otherwise, when CF_{min} is positive, it indicates that the active power generated from the generators within the region has negative effects on the frequency control in that minute. When $CF_{\mathrm{min}}<10B\varepsilon_1^2$, it indicates that although the total generated active power in the control area is not conducive to the frequency control of the regional power grid, its value remains within acceptable limits. When $CF_{\mathrm{min}}>10B\varepsilon_1^2$, it signifies that the value has surpassed the permissible range, and an assessment will be conducted.

To expand CPS1 for evaluating the control performance during the assessment period, the following requirements should be satisfied, the details are represented in Eq. 4 as follows,

$$\frac{\sum (ACE_{\mathrm{AVE-min}}\cdot \Delta F_{\mathrm{AVE-min}})}{10B\cdot n}\leq \varepsilon_1^2. \tag{4}$$

Here, n represents the number of minutes in the assessment period. Therefore, the CPS1 indices during the assessment period can be calculated in Eqs. 5, 6 as follows:

$$CPS1 = (2 - CF)\times 100\%, \tag{5}$$

$$CF = \frac{\sum (ACE_{\mathrm{AVE-min}}\cdot \Delta F_{\mathrm{AVE-min}})}{10B\cdot n\varepsilon_1^2}. \tag{6}$$

2.1.2 CPS2 index

The CPS2 index requires that the average absolute value of ACE be controlled within the specified range of L_{10} during the assessment

TABLE 1 Standard of CPS.

Range of CPS1	Whether to check CPS2	Whether CPS is qualified	Reason
CPS1 ≥ 200% (CF ≤ 0)	NO	Qualified	When the frequency fluctuates, each control interval is encouraged to support one another, and exemption from the CPS2 assessment occurs when CPS1 > 2
100% ≤ CPS1 < 200% (0 < CF ≤ 1)	YES	If CPS2 is qualified, CPS is qualified. Otherwise, CPS is unqualified	When 1 ≤ CPS1 < 2, it indicates that the active power regulation behavior in the control area has limited influence on the frequency quality of the regional power grid, and the CPS2 determines whether CPS is qualified
CPS1 < 100% (CF > 1)	NO	Unqualified	CPS1 < 1 indicates that the active power regulation behavior in the control area has exceeded the tolerance range of the regional power grid, and it is directly regarded as unqualified

In the current CPS control performance evaluation standard of CSG, the CPS1 index is the primary assessment criterion. If the value of the CPS1 index is greater than 2 or smaller than 1, the CPS evaluation result can be determined by the CPS1 index. When the value of the CPS1 index is between the interval (Jaleeli and Vanslyck, 1999; Yao et al., 2000), the CPS2 index will be imported to determine if the CPS indices is qualified.

period, with a typical value being 10 min, the details are represented in Eq. 7 as follows,

$$\begin{cases} \dfrac{\sum |ACE_{\mathrm{AVE-min}}|}{n} \leq L_{10} \\ L_{10} = 1.65 \cdot \varepsilon_{10} \cdot \sqrt{(10B) \cdot (10B_{Net})} \end{cases} . \tag{7}$$

In the above equation, B_{Net} represents the frequency deviation coefficients of the entire interconnected power grid. ε_{10} represents the control objective of the root-mean-square deviation of the average frequency deviation of 10 min for the interconnected power grid over 1 year. The constant 1.65 is derived from the assumption that the ACE follows a normal distribution.

2.1.3 The evaluation of control performance based on CPS indices

The control performance of each control area should meet both CPS1 and CPS2 standards. The details are represented in Table 1 as follows:

2.1.4 Limitations to the CPS index system

Since the implementation of the CPS indices in 2007, the quality of frequency control has improved in CSG. However, with the implementation of the unified frequency control area in CSG and the establishment of regional spot markets, the CPS indices encounter some limitations as follows:

1. Before the establishment of the unified frequency control area in the CSG, the CPS indices were primarily used to evaluate the frequency control performance of each control area within 1–10 min, which aligns with the time scale of secondary frequency control. After the establishment of the unified frequency control area in CSG, the coordinated flat frequency control (CFFC) system was applied to coordinate and allocate the secondary frequency control set points for various provincial dispatch and control centers. However, the compatibility between the CPS evaluation indices and the new secondary frequency control architecture of CSG is insufficient (Song, 2015).
2. Under the current clearing rules of the spot and auxiliary service markets, the secondary frequency regulation of the units only responds to the frequency deviation Δf during real-time operation and does not respond to the power deviation of the inter-provincial tie-line. Therefore, it is in conflict with the ACE component of CPS indices (Shi, 2016).
3. There are some inherent defects in CPS indices. For example, the parameters of the CPS indices are calculated based on the assumption that both ACE and Δf follow normal distributions. It may cause large errors when the distributions of ACE and Δf are not normal. Moreover, the assessment method that takes short-term averaging values to calculate CPS indices reduces the evaluation result of CPS indices (Ge et al., 2001).

Taking the above factors into consideration, the CPS assessments were canceled for the provincial dispatch and control centers in the early stages of the frequency regulation auxiliary service market of CSG. However, after the cancellation of the assessments, the quality of frequency control was reduced, and the frequency deviation could not be controlled back to zero in some periods. Therefore, it is necessary to propose new evaluation indices for frequency control in power systems with tie-line connections.

2.2 The TCPS index system

To ensure that the new indices can be compatible with the unified frequency control architecture of CSG and adapt to the regional spot markets, the design of indices should be guided by the following three objectives: first, the new indices need to maintain the frequency quality for the whole power grid, ensure the security of the regional grid, and implement dispatch schedules. Second, considering the needs of regional spot market construction, the new indices should reduce the times of manual adjustment by dispatch and control centers, ensure a fair market competition environment, and reduce the operation costs of the power grid. Third, the new indices can overcome the defects of the traditional decentralized dispatch mode of frequency regulation resources and improve the efficiency of resource allocation. The TCPS index system has been proposed in this paper to achieve these objectives. For the proposed index system, the main highlights are listed as follows:

1. Compared with the time interval of 10 min for the traditional CPS indices, the time scale was increased to 15/30 min in this

paper to evaluate the active power balance in the tertiary frequency control loop for the power grids.

2. Following the design ideas of CPS1 and CPS2, this paper improves the method of determining the key parameters for the improved TCPS1 and TCPS2 indices. It also proposes a new method for determining the optimal threshold for the TCPS indices.
3. Improvements are made to the exemption mechanism of the operation data, along with the formulation of detailed exemption rules under some situations, such as the cases of bad weather and recoveries from complex accidents, ensuring these data were deleted for the evaluation and take no effect for the calculations with the indices.

The proposed TCPS indices consisted of TCPS1, TCPS2, and a minute-level TCPS index.

2.2.1 TCPS1 index

The TCPS1 index is similar to the CPS1 index, and its definition was given in Eq. 8 as follows:

$$\boldsymbol{TCPS1} = (\mathbf{2} - \boldsymbol{CF}) \times \mathbf{100\%}, \tag{8}$$

$$\boldsymbol{CF} = \frac{\sum(\boldsymbol{ACE}_{\mathbf{AVE-min}} \cdot \Delta\boldsymbol{F}_{\mathbf{AVE-min}})}{\mathbf{10}\boldsymbol{B} \cdot \mathbf{30}\boldsymbol{\varepsilon}_1^2}. \tag{9}$$

Compared with CPS1, the assessment time scale for TCPS1, as shown in Eq. 9, was increased to 30 min, which was represented by $n = 30$ in Eq. 6. Increasing the assessment time scale could avoid situations where the CPS1 index becomes unqualified under the time scale of 10 min due to the actions caused by the secondary frequency control. As a result of increasing the assessment period of TCPS1 to 30 min, the proposed TCPS1 index focuses on the control actions of active power in the 10–30-min time scale.

2.2.2 TCPS2 index

During the assessment period of 30 min, the TCPS2 index requires controlling the average absolute value of the power deviations of the tie-line to be lower than the threshold, which is expressed as follows:

$$\frac{\sum|\Delta\boldsymbol{P}_{\mathbf{AVE-min}}|}{\boldsymbol{n}} \le \boldsymbol{L}_{\mathbf{30}}. \tag{10}$$

Here, $\Delta\boldsymbol{P}_{\mathbf{AVE-min}}$ is the average value of the power deviations of the tie-line per minute. The mean of the ACE in CPS1 was replaced by the mean of $\Delta\boldsymbol{P}$ in TCPS1, as shown in Eq. 10. The signs of ACE and $\Delta\boldsymbol{F}_{\mathbf{AVE-min}}$ were required to be different as in TCPS1. The TCPS2 index focuses on evaluating the power deviations $\Delta\boldsymbol{P}$ for inter-provincial tie-lines to avoid overload situations. If the calculation method of CPS1 is kept the same, the threshold $\boldsymbol{L}_{\mathbf{30}}$ in Eq. 10 should be calculated as follows:

$$\boldsymbol{L}_{\mathbf{30}} = \mathbf{1.65} \cdot \boldsymbol{\varepsilon}_{\mathbf{30}} \cdot \sqrt{(\mathbf{10}\boldsymbol{B}) \cdot (\mathbf{10}\boldsymbol{B}_{\boldsymbol{Net}})}. \tag{11}$$

However, the distributions of the power deviations of the tie-lines do not follow normal distributions, and there is no significant linear relationship between the B parameter and the power deviations of the tie-lines in some practical cases. Therefore, $\boldsymbol{L}_{\mathbf{30}}$ in the proposed TCPS index system does not follow the calculation method shown in Eq. 11. The value of $\boldsymbol{L}_{\mathbf{30}}$ in the index system of the TCPS can be flexibly adjusted according to the load scenarios and different operation modes of power systems. The detailed calculation method of $\boldsymbol{L}_{\mathbf{30}}$ will be represented with details in Section 3 of this paper.

2.2.3 Minute-level and 30-min-level TCPS indices

The TCPS indices mainly focus on the performance of tertiary frequency control in the power systems. In order to prevent provincial dispatch and control centers excessively pursuing a negative average of the ACE in a 30-min period, which can result in overregulation or reverse regulation, this paper proposes minute-level TCPS scores, denoted as $\mathbf{Score\_tcps}_{\boldsymbol{min}}$, and 30-min-level TCPS scores, denoted as $\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$. Both TCPS1 and TCPS2 are scored by $\mathbf{Score\_tcps}_{\boldsymbol{min}}$ for each minute within an assessment period of 30 min. The details are represented as follows:

$$\mathbf{Score\_tcps1} = \begin{cases} \mathbf{0} & \mathbf{CF_{min}} > 1 \\ \mathbf{50} & \mathbf{0} < \mathbf{CF_{min}} \le \mathbf{1} \\ \mathbf{100} & \mathbf{CF_{min}} \le \mathbf{0} \end{cases}, \tag{12}$$

$$\mathbf{Score\_tcps2} = \begin{cases} \mathbf{0} & \Delta\boldsymbol{P}_{\mathbf{min}} > \boldsymbol{L}_{\mathbf{30}} \\ \mathbf{50} & \Delta\boldsymbol{P}_{\mathbf{min}} \le \boldsymbol{L}_{\mathbf{30}} \end{cases}, \tag{13}$$

$$\mathbf{Score\_tcps}_{\boldsymbol{min}} = \mathbf{min}\{\mathbf{Score\_tcps}1 + \mathbf{Score\_tcps2}, \mathbf{100}\}. \tag{14}$$

According to Eqs 12–14, if tertiary frequency control in the control area results in $\mathrm{CF_{min}} \le \mathbf{0}$ or $\mathbf{0} < \mathrm{CF_{min}} \le \mathbf{1}$ and $\Delta\boldsymbol{P}_{\mathrm{min}} \le \boldsymbol{L}_{\mathbf{30}}$ at the same time within 1 min, the control area can obtain a full score of 100; otherwise, only 50 or 0 can be obtained. The definition of the 30-min-level TCPS score, $\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$, can be represented as follows:

$$\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}} = \frac{\mathbf{1}}{\boldsymbol{n}} \sum_{\boldsymbol{n}} \mathbf{Score\_tcps}_{\boldsymbol{min}}, \boldsymbol{n} = \mathbf{30}. \tag{15}$$

In general, $\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$ should be larger than a certain threshold $\boldsymbol{S}_{\mathbf{0}}$, such as 70.

2.2.4 Performance evaluation system based on TCPS indices

The CPS mainly comprises three indices: TCPS1, TCPS2, and $\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$.TCPS1 and $\mathrm{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$ are the dominant indices. Only when 100% ≤ TCPS1 < 200% and $\mathbf{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}} > \boldsymbol{S}_{\mathbf{0}}$, TCPS2 determines whether TCPS is qualified for the assessment period. The criteria for the assessment are shown in Table 2.

The reason for using TCPS1 as the dominant index is that the regional power grid encourages each control area to maintain a negative ACE within a 30-min time scale to ensure the security of frequency control. The reason for using $\mathrm{Score\_tcps}_{\mathbf{30}\,\boldsymbol{min}}$ as another dominant index is that the regional power grid encourages each control area to smooth the minute-level ACE curves for avoiding unnecessary overcorrection and overshoot.

3 The calculation method of the key parameters for the TCPS index system

3.1 The calculation method of the L_ 30 parameter in the TCPS index system

The $\boldsymbol{L}_{\mathbf{30}}$ parameter is one of the key parameters in TCPS2 indices. Based on the practical operational data on $\Delta\boldsymbol{P}$ and $\Delta\boldsymbol{f}$ from various control areas within CSG, this paper makes a detailed analysis of the

TABLE 2 Criteria for the assessment with TCPS indices.

Range of TCPS1 (%)	Score_tcps$_{30\,min}$	Whether to check TCPS2	Whether TCPS is qualified
TCPS1 ≥ 200	≥ S_0	No	Qualified
	< S_0	No	Unqualified
100% ≤ TCPS1 < 200	≥S_0	Yes	If TCPS2 is qualified, TCPS is qualified; otherwise, TCPS is unqualified
	< S_0	No	Unqualified
TCPS1 < 100	≥S_0	No	Unqualified
	< S_0	No	Unqualified

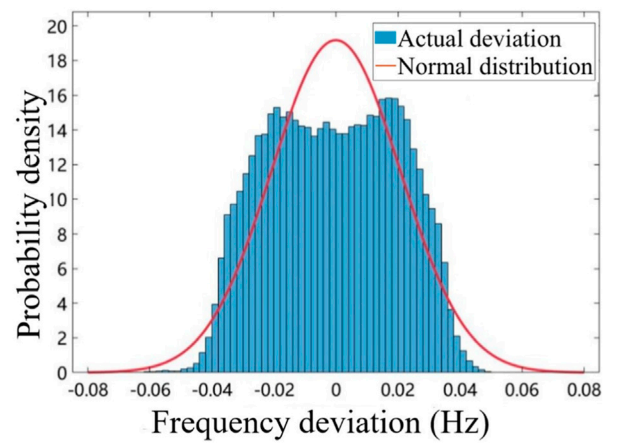

FIGURE 1
Actual frequency distribution of the central and eastern main networks of China Southern Power Grid.

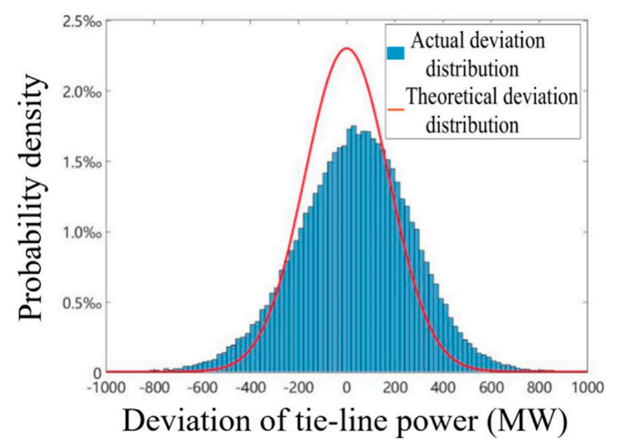

FIGURE 2
Actual deviation distribution of the tie-line and theoretical deviation distribution of tie-line power.

practical data and draws the following statistical conclusions, which are applied to guide the calculation of L_{30}.

1. As shown in Figure 1, due to the existence of the dead zones of primary and secondary frequency control, the frequency deviations Δf may not follow a normal distribution or even a unimodal distribution. Considering this fact, a GMM can be applied to describe the practical frequency distributions. The standard GMM can be represented as follows:

$$P(x|\theta) = \sum_{k=1}^{K} \alpha_k \phi(x|\theta_k). \tag{16}$$

Here, $\sum \alpha_k = 1$ and $\phi(x|\theta_k)$ represent the normal distribution, which is given as follows:

$$\phi(x|\theta_k) = \frac{1}{\sqrt{2\pi}\sigma_k} e^{-\frac{(x-\mu_k)^2}{2\sigma_k^2}}. \tag{17}$$

The GMM, as described in Eqs 16, 17, can be applied to describe the non-unimodal distribution shown in Figure 1 for the frequency deviations Δf.

As shown in Figure 2, the distributions of ΔP may not fully follow Eq. 7 as $L_{10} = 1.65 \cdot \varepsilon_{10} \cdot \sqrt{(10B) \cdot (10B_{Net})}$. However, the distribution of ΔP is similar to a normal distribution.

In order to satisfy the needs of the operation of the power grid and consider the scenarios of the TCPS2 index, where the TCPS2 index was applied only when 1 < TCPS1 < 2, the dataset C of ΔP needs to be processed as follows:

1. In the time scale of minutes, the dataset of ΔP that satisfies 1 < TCPS1 < 2 was built and named as set C1.
2. Based on C1, the samples of ΔP during periods of power grid accidents, such as HVDC and large generator accidents, are excluded, and the new dataset was named C2.
3. ΔP in dataset C2 was assumed to follow the normal distribution as $\Delta P \sim N(0, 1)$; therefore, $|\Delta P|$ satisfies the folded normal distribution. The details are represented in Eq. 18 as follows,

$$\begin{aligned} F(x) &= \Phi\left(\frac{x-\mu}{\sigma}\right) - \Phi\left(\frac{-x-\mu}{\sigma}\right) \\ &= \Phi\left(\frac{x-\mu}{\sigma}\right) + \Phi\left(\frac{x-\mu}{\sigma}\right) - 1 \\ &= \int_0^x \frac{1}{\sigma\sqrt{2\pi}}\left(e^{-\frac{1}{2}\left(\frac{y+\mu}{\sigma}\right)^2} + e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2}\right)dy, x \in [0, \infty). \end{aligned} \tag{18}$$

The cumulative distribution function of ΔP can be represented in Eq. 19 as follows:

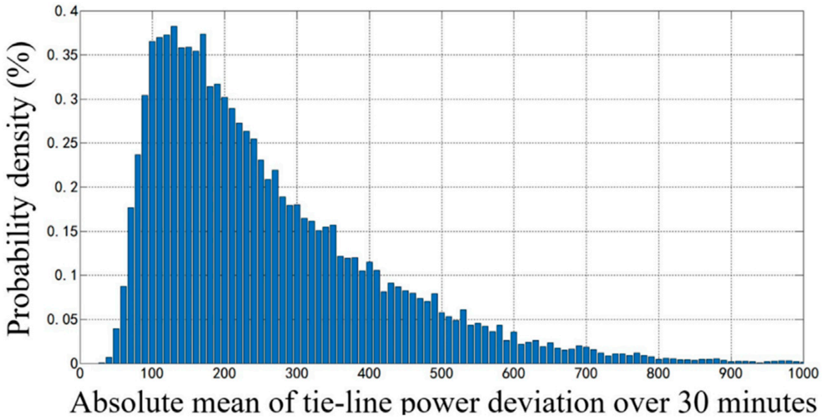

FIGURE 3
Actual distribution of the 30-min absolute mean value of tie-line power.

$$CDF(x) = P(X \le x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{y^2}{2}} dy = 0.5 + \frac{1}{\sqrt{2\pi}} \int_{0}^{x} e^{-\frac{y^2}{2}} dy = \Phi(x). \tag{19}$$

The result can be represented in Eq. 20 as follows:

$$\frac{1}{\sqrt{2\pi}} \int_{0}^{x} e^{-\frac{y^2}{2}} dy = \Phi(x) - 0.5. \tag{20}$$

Finally, we can get Eq. 21:

$$CDF(z) = P(|X| \le z) \frac{1}{\sqrt{2\pi}} \int_{-z}^{z} e^{-\frac{y^2}{2}} dy = 2(\Phi(x) - 0.5) = 2\Phi(x) - 1. \tag{21}$$

Thus, the analytical expression for the cumulative distribution of ΔP can be obtained. Even in cases where the distribution of ΔP does not follow a normal distribution, as shown in Figure 2, the distribution of ΔP is similar to a normal distribution, especially in the tail regions of the distribution. Based on the above analytical derivation, the distribution of $|\Delta P|$ is similar to that of ΔP in the tail region. Therefore, the cumulative distribution of $|\Delta P|$ can be calculated analytically. Based on the practical data on the absolute value of 1-min power deviations, the 30-min absolute mean value of power deviations $|\Delta P|_{\mathrm{AVE-30\,min}}$ can be obtained, as shown in Figure 3. The standard deviation of this distribution can also be obtained with the 1-min dataset. It is indicated that the distribution of the $|\Delta P|$ in the 30-min time scale is more close to the normal distribution in the tail region. In this manner, L_{30} can be calculated as follows:

$$L_{30} = |\Delta P|^{90}_{AVE-30\,min}. \tag{22}$$

A percentile of 90 was chosen to determine the value of L_{30}, according to the distribution of $|\Delta \mathrm{P}|_{\mathrm{AVE-30\,min}}$, and this value was denoted as $|\Delta P|^{90}_{AVE-30\,min}$ in Eq. 22. $|\Delta P|^{90}_{AVE-30\,min}$ can be obtained according to the percentile of 95% for ΔP. Such a percentile is close to the percentile of 95.44% for 2σ in the normal distribution. In this paper, $\mathbf{L_{30}}$ is calculated based on practical data, which makes it more suitable for practical projects. Moreover, it can be revised iteratively and is more flexible than CPS2.

3.2 The calculation method of S_0 in the TCPS index system

The purpose of setting the 30-min TCPS index $\mathbf{Score\_tcps}_{30\,min}$ is to minimize the occurrences of unnecessary reverse and overcorrection regulation for dispatch and control centers in each control area. The proposed index encourages maintaining ACE control results better than the average level. The $\mathbf{Score\_tcps}_{30\,min}$ index does not require the control accuracy of active power in the time scale of 1–5 min. It requires that the average score of this index over the 30 min time scale should be higher than the reference value S_0. Therefore, the value of S_0 should be set slightly lower than the average value of the current practical results.

The calculation method of the S_0 parameter can be given as follows:

1. Obtain the annual data on $\mathbf{CF_{min}}$ and ΔP_{min} of each control area and exclude samples during the periods of the grid faults.
2. Calculate $\mathbf{Score\_tcps}_{min}$ in 30 min intervals, according to Eq. 15, and obtain set S of annual TCPS results.
3. Calculate S_0 using the following equation with α ranges from 0.1 to 0.2.

$$\begin{cases} \mathbf{Score\_tcps}_{30\,min} \in S \\ S_0 = \left(Score_{tcps_{30\,min}}\right)_\alpha \\ P\left(Score_{tcps_{30\,min}} \le S_0\right) = \alpha. \end{cases} \tag{23}$$

The S_0 parameter designed in this paper can be calculated based on the practical dataset and is not be determined by a constant coefficient of 1.65, as shown in Eq. 7. The results can be adjusted and iteratively refined with improvements in the operation results for all dispatch and control centers.

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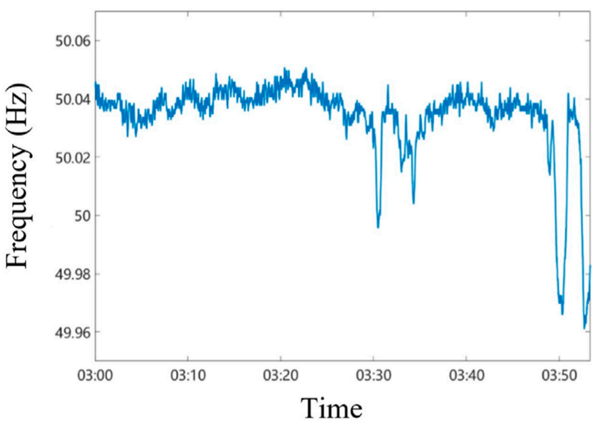

FIGURE 4
Frequency data on the early morning of the specified day.

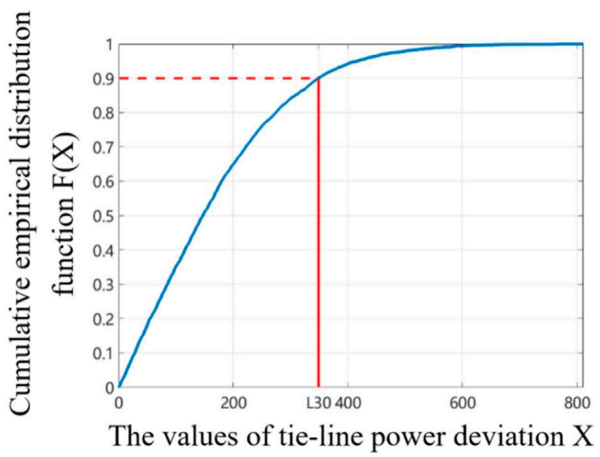

FIGURE 5
Calculation of the L_{30} parameter.

4 Examples of dispatching the control performance evaluation based on the TCPS indicator system

4.1 Frequency quality evaluation in the early stages of the frequency regulation auxiliary service market

Since September 2018, the frequency regulation auxiliary service market has started the trial operation of settlements in Guangdong province. In the early stages of setting up the auxiliary service market, the CSG's central dispatching canceled the CPS assessment of the provincial dispatch and control centers. During this period, the RMS of the minute-average frequency deviations of CSG increased by approximately 0.001 Hz, which equals to approximately 4%, and the frequency quality was reduced.

Moreover, the frequency was maintained at some specified value for a long time, several times. As shown in Figure 4, on a certain early morning during this period, the frequency was kept at approximately 50.04 Hz for more than 30 min. After canceling the CPS assessment, the dispatch and control centers did not implement effective tertiary frequency controls, resulting in continuous deployment and even exhaustion of the secondary frequency regulation reserves in some periods. As a result, similar cases occurred during the same period. Therefore, it is necessary to design reasonable evaluation indices for tertiary frequency control.

4.2 Comparison of frequency control performance with TCPS and CPS indices

The calculation results of S_0 and L_{30} parameters in the TCPS indices are shown in Figures 5, 6. Compared with the traditional CPS2 indices, the $\boldsymbol{L_{30}}$ parameter in TCPS2 indices could get a higher score for frequency control. However, the S_0 parameter is designed to improve the control quality of frequency control on the 15–30-min time scale. Compared with the current CPS assessment standard, the assessment criteria for TCPS indices should be slightly relaxed to solve the defects of overly strict CPS evaluation indices.

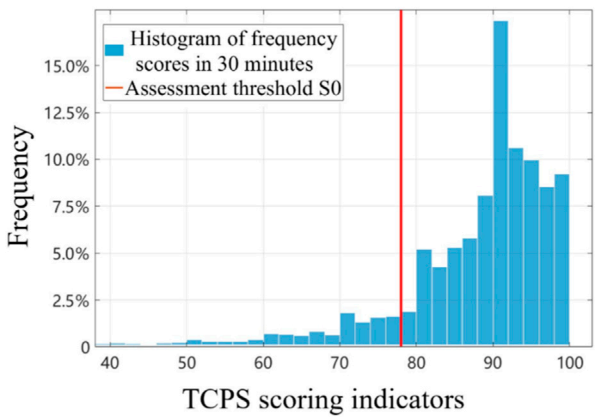

FIGURE 6
Calculation of the S_0 parameter.

To calculate the analytical expression of the GMM represented in Section 3.1, the following steps should be followed:

1. Calculate the log likelihood function of the GMM.

$$\xi(\boldsymbol{\theta}) = \sum_{i=1}^{m} \log p(\mathbf{x}, \boldsymbol{\theta}), \tag{24}$$

where the specific normal distribution $\boldsymbol{\kappa}$ for each individual sample will affect the results of Eq. 24, and it can be transformed into

$$\xi(\boldsymbol{\theta}) = \sum_{i=1}^{m} \log p(\mathbf{x}, \boldsymbol{\kappa}, \boldsymbol{\theta}), \tag{25}$$

$$\sum_{i} \log p(\mathbf{x}^{(i)}, \boldsymbol{\theta}) \geq \sum_{i} \sum_{\boldsymbol{\kappa}^{(i)}} Q_i(\mathbf{z}^{(i)}) \log \frac{p(\mathbf{x}^{(i)}, \boldsymbol{\kappa}^{(i)}, \boldsymbol{\theta})}{Q_i(\mathbf{z}^{(i)})}. \tag{26}$$

TABLE 3 TCPS results of dispatch and control centers A and B.

TCPS assessment result	Dispatch and control center A		Dispatch and control center B	
	TCPS2 qualified	TCPS2 unqualified (%)	TCPS2 qualified	TCPS2 unqualified (%)
TCPS1 > 2	3.18% (score ≥ S_0)		9.52% (**score** ≥ S_0)	
	0.68% (**score** < S_0)		1.42% (**score** < S_0)	
1 < TCPS1 < 2	82.91% (**score** ≥ S_0)	2.68	64.98% (**score** ≥ S_0)	3.18
	5.99% (**Score** ≤ S_0)		14.42% (**Score** ≤ S_0)	
TCPS1 < 1	4.56%		6.48%	
Overall qualified rate	86.09%		74.5%	

TABLE 4 CPS assessment results of dispatch and control centers A and B.

CPS assessment result	Dispatch and control center A		Dispatch and control center B	
	CPS2 qualified (%)	CPS2 unqualified (%)	CPS2 qualified (%)	CPS2 unqualified (%)
CPS1 > 2	5.12		11.07	
1 < CPS1 < 2	73.84	13.74	61.48	17.7
CPS1 < 1	7.29		9.75	
Overall qualified rate	78.96		72.55	

Eq. 26 indicates the lower bound of Eq. 23. Obtaining the value of $\mathbf{Q_i}(\mathbf{z}^{(i)})$ is an important step in the calculation, and it can be obtained as follows:

$$Q_i\left(\kappa^{(i)}\right) = \frac{p\left(x^{(i)}, \kappa^{(i)}, \theta\right)}{\sum_{\kappa} p\left(x^{(i)}, \kappa, \theta\right)} = p\left(\kappa^{(i)} \middle| x^{(i)}, \theta\right). \tag{27}$$

Based on the Bayes' formula, it can be obtained as follows:

$$p\left(\kappa^{(i)} = j \middle| x^{(i)}, \phi\right) = \frac{p\left(x^{(i)} \middle| \kappa^{(i)} = j, \phi\right) p\left(\kappa^{(i)} = j, \phi\right)}{\sum_{\iota=1}^{k} p\left(x^{(i)} \middle| \kappa^{(i)} = \iota, \phi\right) p\left(\kappa^{(i)} = \iota, \phi\right)}. \tag{28}$$

Eq. 28 can be solved using maximum likelihood estimation. The result is represented in Eq. 29 as follows:

$$\theta \coloneqq \arg\max_{\theta} \sum_{i} \sum_{\kappa^{(i)}} Q_i\left(\kappa^{(i)}\right) \log \frac{p\left(x^{(i)}, \kappa^{(i)}, \theta\right)}{Q_i\left(\kappa^{(i)}\right)}. \tag{29}$$

The best estimation results of the GMM can be obtained by calculating the partial derivative of each parameter. According to the best estimation results, the quantile results of the GMM can be obtained. In practical cases, the optimal result of S_0 can be calculated based on the evaluation results of TCPS indices. In this paper, the 30-min threshold S_0 was calculated as 78, as shown in Figure 6.

After the establishment of the TCPS index system, the dispatch and control center of CSG conducted the TCPS assessments for all provincial dispatch and control centers within the unified frequency control area of CSG from May to September 2020. Meanwhile, the traditional CPS indices were also calculated as a reference. As shown in Tables 3, 4, TCPS1 of dispatch and control center A was kept within the interval (Jaleeli and Vanslyck, 1999; Yao et al., 2000) in more than 90% of the operation periods, indicating effective control over the power deviations of the tie-line. The comprehensively qualified rate was 86.09%. For the dispatch and control center B, the number of periods for TCPS1 > 2 is relatively high, which indicates that the dispatch and control center responded to the frequency deviations actively, providing inter-provincial power support. However, in the 30-min average score index, $Score\_tcps_{30\,min}$, its score was poor. Its score was lower than the assessment threshold S_0 in more than 15% of the assessment intervals. Its comprehensively qualified rate is 74.5%.

Comparing Tables 3, 4, the comprehensive qualified rates of both dispatch and control centers A and B were reduced under the traditional CPS indices with shorter evaluation periods. After the unified frequency control mode replaced the traditional mode, the traditional CPS indices were not suitable to evaluate the frequency quality, and the proposed TCPS indices could coordinate the generation units more effectively.

5 Conclusion and prospect

With the establishment of the unified frequency control zone in CSG and the development of the regional spot markets, the traditional CPS indices have encountered some limitations. The authors proposed an innovative frequency control performance index system called TCPS and methods for calculating the key parameters. The findings of this paper can be summarized as follows:

(1) The practical operation data on CSG were collected to verify the evaluation results of the TCPS indices. The results showed that the TCPS indices can effectively evaluate the frequency control quality at the 30-min level for provincial dispatch and control centers.

(2) Moreover, since the dispatch and control center of CSG implemented the TCPS indices with a longer evaluation time period of 30 min, the RMS value of frequency deviations has decreased by approximately 0.002 Hz in June 2020 compared with 2019. The occurrences of the frequency deviations that could not be controlled back to zero have been significantly reduced by 70%.
(3) The construction of the unified frequency control area by CSG adapts to the development of the regional auxiliary service market and the power spot markets, improving the dispatch efficiency of frequency regulation resources. It breaks the barriers of inter-provincial frequency regulation resources and establishes a new technical framework.
(4) In accordance with the unified frequency control zone, the dispatch and control center of CSG has innovatively proposed a TCPS index system. Currently, the system could evaluate the control quality of tertiary frequency control effectively and improve the operation security of the bulk power system of CSG.

In the future, the TCPS index and assessment system could improve the control quality for all provincial dispatch and control centers and be compatible with the autopilot systems for CSG.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

XK: writing–original draft and writing–review and editing. ZH: writing–original draft and writing–review and editing. WW: writing–original draft and writing–review and editing. CJ: writing–original draft and writing–review and editing. LQ: writing–original draft and writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

Authors XK, ZH, WW, CJ, and LQ were employed by China Southern Power Grid.

Publisher's note

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