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Time-synchronized carbon flow metering scheme for electric power transmission, transformation, and distribution networks

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Faced with the pressure of energy conservation and emission reduction, the power industry is urgently requires low-carbon transformation. The carbon flow calculation theory redistributes the actual carbon generated by the power plant to the branch and loads customers with the power flow. This paper first introduces the theory of carbon flow calculation and the carbon metrics corresponding to the electricity metrics. Second, a time-synchronous technology is introduced for the carbon flow calculation of transmission, transformation, and distribution networks, and a time-synchronous-based carbon metering system is conceived. The impact of time deviation on carbon metering is elucidated through simulation experiments of IEEE14 standard nodes, and finally, relevant suggestions are made for future research ideas and technical routes.

KEYWORDS

carbon flow, carbon metering, power flow, time deviation, time-synchronous

1 Introduction

Given the energy crisis and global warming, various countries around the world are making efforts to save energy and reduce emissions in various ways. Coal-fired power generation is the main source of CO_2 generation in the power industry, so renewable new energy generation represented by wind power and photovoltaic power generation is currently entering the power system in high proportion. Although new energy generation can significantly reduce the production of CO_2 , this type of power generation is unstable. Therefore, the power industry cannot be zero carbon and coal-fired power generation cannot be replaced entirely. Carbon measurement and carbon trading are currently the promising management approaches used to achieve carbon reduction. Drawing on the cyclic transfer of carbon elements in ecology (Richey et al., 1978), some scholars have now proposed the concept and theory of carbon emission streams for the power industry (Xu et al., 2019) and (Sun et al., 2022).

Carbon emission is calculated by using the energy consumption and statistical emission factors of different fossil fuels, which is mainly attributed to the source side of direct emission, which is calculated based on statistically empiric methods. However, these carbon emission accounting methods have insufficient theoretical basis with irrationality and unfairness, and it is difficult to promote multi-party carbon

reduction while only the direct carbon emission source is responsible (Hu et al., 2022). An increasing number of researchers are becoming aware of the need to look at carbon emissions from the perspective of the whole system, taking into account the actual characteristics of the power system, and have proposed many corresponding methods to deal with the problem. In order to account for carbon emissions from the consumption-based perspective, Zhou et al. (2012) and Kang et al. (2012) proposed the carbon emission theory to distribute the responsibility of carbon emission to the load side by tracking the whole process from the source to the load. Zhou et al. (2012) define some basic concepts of carbon emission flow in power networks. An analytical model for carbon emission flow is proposed in Kang et al. (2015) to quantify the carbon emission accompanying the power delivery process. The model of the carbon emission flow can take into account the operational characteristics and the network features of the power system and elaborately characterize the relationship between power delivery and carbon emission flow. A calculation model for the carbon emission flow is also proposed in the article. A directed graph-based method for tracing the carbon flow is proposed in Sun et al. (2016). Yan et al. (2021) put forward a real-time carbon flow algorithm of the electrical power system based on the network power decomposition and solve the limitations of the current method and problems given as follows: the hidden carbon flow was unevenly allocated and the carbon reduction contribution of the new energy units cannot be quantified. A data-driven approach conducted with the Bayesian interference regression is proposed by Wang et al. (2021) to carry out the carbon emission flow model to cope with the drawbacks of the conventional emission calculation. Qin et al. (2022) present a deep reinforcement learning-based multi-objective optimal carbon emission flow solving method that handles the generator dispatching scheme by utilizing the current power system state parameters as known quantities. Cheng et al. (2018b), Wei et al. (2022), Cheng et al. (2018a), and Huang et al. (2022) propose different analytical models and calculation methods for carbon emission flow in multiple energy systems or integrated energy stations. Zhang et al. (2021) and Yang et al. (2023) establish the carbon emission analysis model of the distribution systems with prosumers which combined with the perfect system power flow (PF) theory and considered the network loss and prosumers.

Although the theory of carbon flow measurement has been established and widely promoted in recent years, the assurance of carbon measurement accuracy is still topic requiring urgent study. In this paper, the influence of time deviation on the error of carbon flow measurement is studied. A satellite synchronization method to add time labels to the carbon flow calculation data is proposed to make the carbon flow allocation in transmission and distribution and the carbon flow measurement on the load side more accurate. In this study, we use the IEEE-14 standard system to realize the carbon flow distribution and measurement of power transmission, transformation, and distribution. First, based on the carbon flow measurement theory, a single-carbon flow calculation is performed. Second, the load fluctuation data of a typical day at 24 points per day are input into the IEEE-14 standard system for continuous carbon flow simulation calculation. Then, based on the 24-point load data, data sets of 48 points per day and 96 points per day are generated for calculation again. Finally, the deviation analysis of the loaded carbon flow under three different sets of conditions is carried out.

2 Carbon flow theory

2.1 Basic theory of the transformation of electricity to carbon

The basic principle of the transformation of electricity to carbon is carbon flow theory (CFT). In addition, the main idea is to quantify the state of carbon emissions in a power system based on the distribution of PF. A power system carbon flow is a virtual network flow that exists on the PF and is used to characterize the carbon emissions in the power system that maintains the PF on any branch. A power system carbon flow is equivalent to labeling each PF with carbon emission. The carbon flow in the power system originates in the power plant and eventually enters the load nodes via the power grid. Similar to electricity generation, carbon flow is generated by generators. It is consumed by electricity consumers through the carbon flow.

The CFT is based on the PF tracking theory. There are some differences between carbon emission flow analysis and PF analysis. On one hand, the initial conditions for the calculation of the carbon emission parameters of power systems are derived from the results of PF calculation. Therefore, all the factors affecting the distribution of system PF will affect the distribution of carbon emission flow, such as the topology of the power system forms the same basic constraints in carbon emission flow analysis as in PF calculation; on the other hand, carbon emission flow is also related to the carbon emission characteristics of the power plant with unique boundary conditions. In addition, the carbon emission flow is mainly affected by the distribution of the active power since the energy consumption is mainly related to the active power. Although the reactive power affects the active power loss in the grid, which has an impact on the distribution of system carbon emissions, the carbon emission flow can be approximated to be affected by the active power of the system only when the net loss is neglected.

2.2 Concepts of electricity-to-carbon transformation in power systems

Calculations of electricity-to-carbon transformation are used to measure the production, consumption, and transmission of carbon in the power system. Some vital basic concepts of electricity transforming to carbon are introduced as follows: carbon flow, carbon flow rate, and carbon flow density (CFD). CFD describes the relationship between carbon flow and active power in power systems. CFD is divided into two categories according to the branch and node, namely, branch carbon flow density and node carbon potential, respectively.

2.2.1 Carbon flow

Carbon flow is a basic concept in CFT. Carbon flow characterizes the magnitude of carbon flow in a branch or load. The carbon flow is defined as the cumulative amount of carbon emissions in a given branch or load in a certain time range. The unit of carbon flow is the same as that of carbon emission. Currently, the international unit of carbon emissions is generally expressed in tCO_2 or $kgCO_2$, which means that the mass of carbon dioxide is used as the basis for calculating the mass of greenhouse gases in the gas being emitted.

2.2.2 Carbon flow rate

The carbon flow rate (CFR) is defined as the carbon flow that passes along with the PF per unit of time, at a value equal to the derivative of the CFR with respect to time, as shown in (1).

$$CFR = \frac{dF}{dt}. \tag{1}$$

2.2.3 Branch carbon flow density

The carbon emission flow of the power system is dependent on the PF. Therefore, it is necessary to combine the carbon emission flow with the PF. Furthermore, carbon emission in the power system is mainly related to active power. To characterize the combination of both, the ratio of the CFR of any branch of the power system to the active power is defined as branch carbon flow density (BCFD).

$$\rho = \frac{CFR}{P}, \tag{2}$$

where ρ represents the ratio of the CFR of any branch to the active PF in the power system.

The unit of carbon flow density is $kgCO_2/(kWh)$. In the generator nodes, the BCFD is equal to the carbon emission intensity of the generator. In the load nodes, the BCFD is equal to the carbon emission value of the generation side caused by the consumption of unit power transmitted by the branch line.

2.2.4 Node carbon potential

The CFT defines the physical quantity that describes the carbon emission intensity of nodes by carbon emission flow, named node carbon potential (NCP). e_{nt} is used to describe the NCP of node n at time t .

$$e_{nt} = \frac{\sum_{i \in N^+} P_{it} \rho_{it}}{\sum_{i \in N^+} P_{it}} = \frac{\sum_{i \in N^+} R_{it}}{\sum_{i \in N^+} P_{it}}, \tag{3}$$

where the unit of NCP is $kgCO_2/(kWh)$, the same as that of BCFD. NCP equals the weighted average of the BCFD ρ_{it} of all branches flowing into node n with respect to the active power P_{it} .

The physical meaning of the NCP is the value of carbon emissions caused by the consumption of a unit of electricity at that node. For a power plant node, its NCP is equal to the real-time generation carbon emission intensity of the power plant.

2.3 Node carbon potential vector

The primary goal of carbon emission flow calculation in a power system is to calculate the carbon potential of all nodes. To calculate the node carbon potential vector (NCPV), three matrices should be constructed first which are the node active flux matrix (P_N), the branch PF distribution matrix (P_B), and the generator injection distribution matrix (P_G). In addition, they are constructed from the PF calculation results. According to (4), the NCP of the power system can be calculated as follows:

- P_N is an N -order diagonal matrix that describes the contribution of the generator set and other nodes to the NCP of a node in the system.
- P_B is used to describe the active power flow distribution of the power system. This matrix contains the topology structure information of the power network and the steady-state active power flow distribution information.

- P_G is a $K \times N$ matrix. It is defined to describe the connection between all generating sets and the power system. In addition, it represents the active power injected into the system by the unit.
- E_G is a vector representing the carbon potential of the system generator. As a known condition for the calculation of the carbon emission flow, subsequent calculations are carried out.

$$E_N = (P_N - P_B^T)^{-1} P_G^T E_G. \tag{4}$$

3 Time-synchronized measurement carbon system

Figure 1 shows a transmission and distribution carbon metering system based on time synchronization. The metrics of the PF calculation are time-stamped by configuring satellite synchronization signals to the power measurement devices of the transmission and distribution. After the carbon flow is calculated, it is measured and recorded by the time marker alignment. This allows for more accurate carbon flow calculations in order to provide credibility for the carbon trading market and other subsequent expansion applications.

Considering the time factor, the equation of carbon measurement is rewritten as (5) according to the CFT.

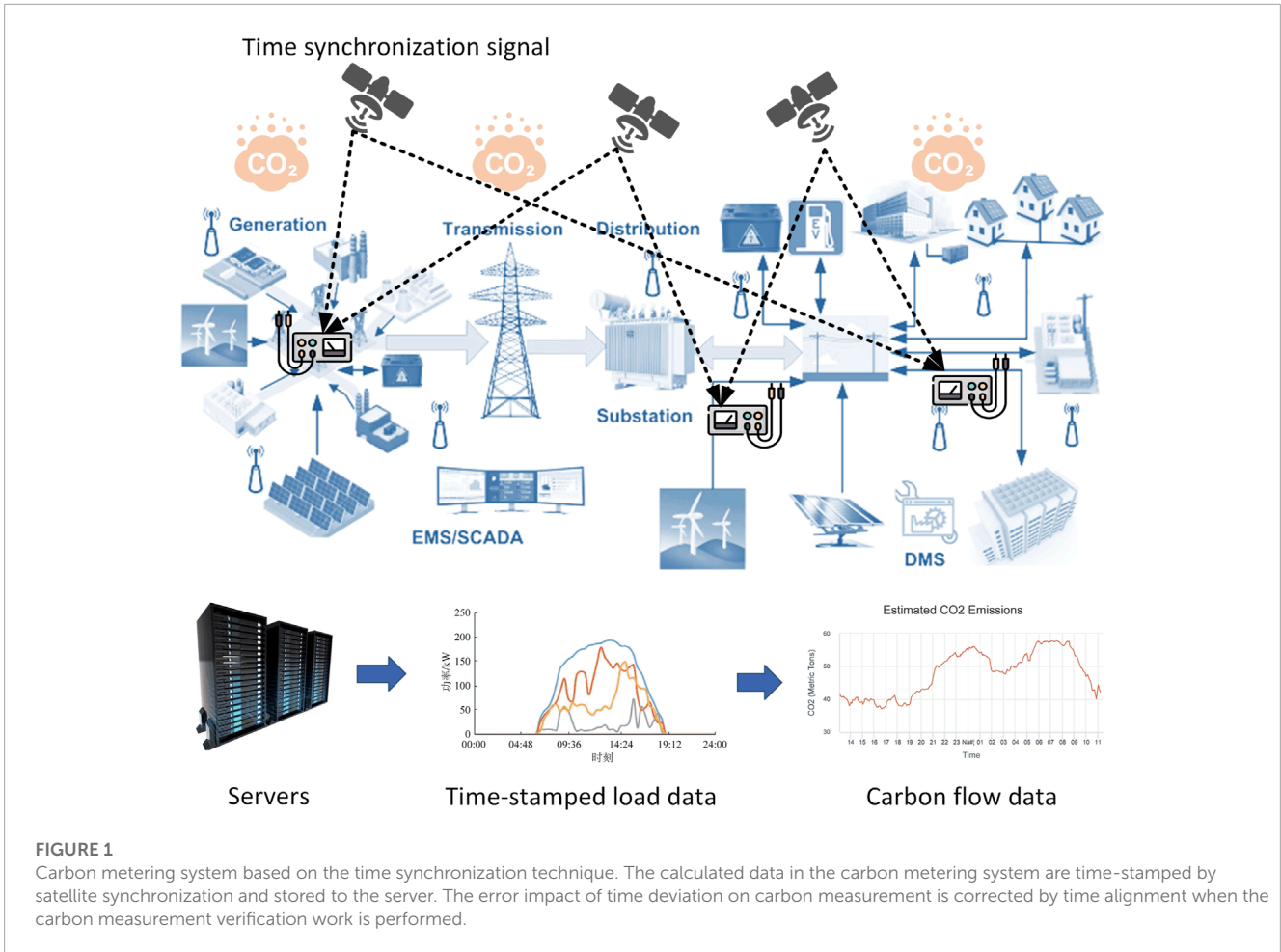
$$R_L = \sum_{t \in \Phi^T} E_N(t) P_L(t), \tag{5}$$

$$\Delta R_L = \sum_{t \in \Phi^T} E_N(t \pm \Delta t) P_L(t \pm \Delta t) - \sum_{t \in \Phi^T} E_N(t) P_L(t). \tag{6}$$

4 Carbon flow calculation framework for power systems

The time deviation calculation framework of the carbon emission flow in the power system based on the matrix analysis method is shown in Figure 2, and the carbon flow calculation times k and typical load matrix P within a certain time are initialized first. We then perform the following four steps for carbon flow calculation. Error analysis was carried out after the aforementioned calculation.

1. The distribution of the active power flow at time i is calculated, and the matrices P_N , P_B , and P_G are established;
2. It is determined whether magnetic flux matrix P_N satisfies the following conditions: $|P_N| \neq 0$. If it is not satisfied, the node corresponding to the row is removed in which the diagonal element of P_N is 0, and the group and line are connected to it from the system. Otherwise, we proceed to the next step.
3. The carbon potential E_N of all nodes in the power system is calculated first. Then, the distribution matrix of the branch carbon flow rate and load carbon flow rate vector is obtained based on the results.
4. The program judges whether the current cycle count i is equal to the preset count k . If not, we proceed to step 1. Otherwise, the calculation is finished.



5 Results and discussions

The IEEE-14 node standard model is used to validate the time-synchronized carbon metering scheme proposed in this paper. Without considering network losses, the DC PF calculation method is used for solving. The previously mentioned simplified considerations are mainly used to illustrate the calculation results of the time deviation affecting carbon metering in transmission and distribution networks.

5.1 Carbon flow calculation simulation in the IEEE-14 standard system

As shown in Figure 3, it is assumed that G1 is a thermal power generator with high carbon potential, G2 and G4 are gas-fired generators with relatively low carbon potential, and G3 and G5 are new energy power plants (wind power or hydropower), where the generators do not produce CO₂ and have zero-carbon potential. We initialize the carbon potential vector $E_G = [875, 525, 0, 520, 0]$ of the generator set, and the carbon potential unit of the generator set is gCO_2/kWh . Table 1 shows the results of standard carbon flow calculations, including Node active flux, node carbon potential and carbon flow rate. Specifically, the Node active flux represents the

active power at the node, the node carbon potential represents the ability to generate carbon emissions at the node, and the carbon flow rate represents the rate at which carbon emissions flow through the node.

5.2 Carbon metering at different time scales

Figure 4 shows the load carbon flow rate of 11 loads in the IEEE-14 standard system. The CFR is different for each load, and we can see from the graph that the third load user produces CO₂ at a significantly higher rate than the other load users due to the difference in electricity consumption. It is evident that the trend of the CFR for each load is almost the same as the trend of the load. This indicates that carbon emissions are related to the intensity of electricity consumption. The carbon emission stream reflects the rate of CO₂ production by customers using electricity. In order to calculate the amount of CO₂ produced by a load user in a fixed period of time, the CFR needs to be integrated for that period of time. Therefore, for more accurate carbon metering, the time factor must be taken into account.

In practical engineering applications, the integral approach to carbon measurement is replaced by cumulative sums. Suppose that

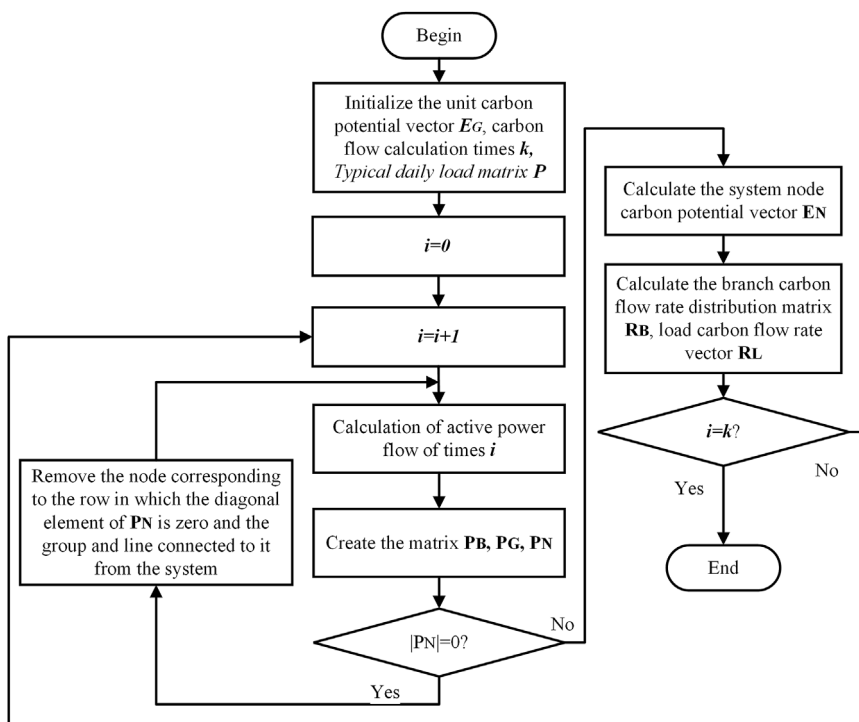


FIGURE 2 Flow chart of the continuous carbon flow calculation incorporating time factor.

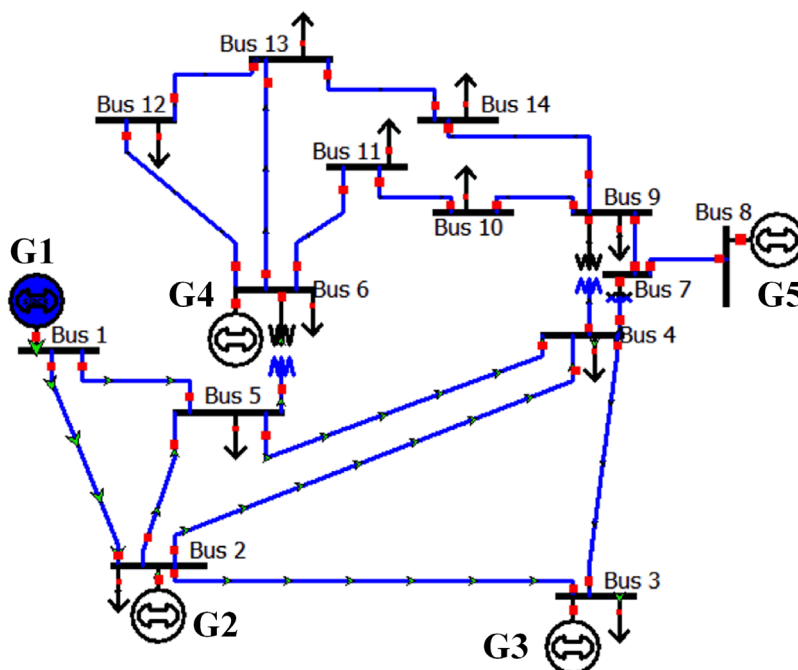


FIGURE 3 IEEE-14 standard system.

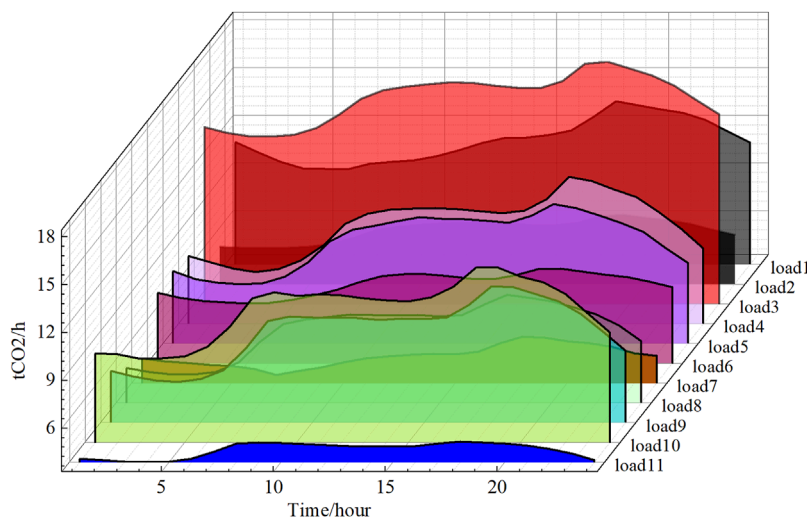


FIGURE 4
Load carbon flow rate visualization results for IEEE-14 standard systems.

TABLE 1 Standard system carbon emission flow calculation results.

Node	Node active flux (MW)	Nodal carbon potential [gCO ₂ /(kWh)]	Load carbon flow rate (tCO ₂ /h)
1	120	875	0
2	110.5,932,544	748.1,632,733	10.93,814,706
3	73.57,501,109	129.1,414,292	5.596,679,603
4	89.88,505,434	568.0052428	14.3,555,373
5	88.0852,264	819.1,536,971	7.499,515,928
6	76.01,341,889	745.1,278,433	7.785,691,809
7	56.99,832,813	375.7,372,018	0
8	20	0	0
9	82.16,043,468	435.0483,994	7.658,418,003
10	10.98,703,683	511.427,293	4.783,890,898
11	10.46,265,415	745.1,278,433	5.449,268,944
12	15.01,662,534	745.1,278,433	6.501,985,561
13	43.7,689,606	745.1,278,433	8.852,416,829
14	82.78,371,069	547.722,066	3.462,479,812

the calculation of the i th carbon flow calculation is executed at t_i time and repeated at the next t_{i+1} time, then the CO₂ generated by the load user at that time is the product of the CFR at time i and the step size at that time $CFR \times (t_{i+1} - t_i)$. Therefore, we investigated the effect of different time-scale carbon flow calculations on load-side CO₂ metering. The time scales were set to three groups, 24 points/day, 48 points/day, and 96 points/day for a typical day. Based on the 24 points/day data, two additional control groups were generated by interpolation to ensure consistent load trends. In addition, a random fluctuation of $\pm 0.5\%$ of the load was added to the control group data generation to represent the real random fluctuation of the load.

The CO₂ measurement results for a typical day are calculated for each load user, and the CO₂ measurement results and corresponding

measurement errors are shown for the 48 points/day and 96 points/day settings for the corresponding load users. As shown in Table 2, the majority of load users have larger CO₂ metering values with more points calculated than in the 24 points/day case, which is due to the finer time scale and the fact that the metering result values are closer to the integral value performance. Furthermore, the CO₂ measurement results for a typical day are calculated for each load user, and the CO₂ measurement results and corresponding measurement errors are shown for the 48 points/day and 96 points/day settings for the corresponding load users. From Table 2, it can be seen that the majority of load users have larger CO₂ metering values with more points than in the 24 points/day case because the time scale is finer and the metering

TABLE 2 Results of carbon flow data by load of the IEEE-14 standard system under different time granularity values ($\pm 0.5\%$ fluctuation).

Load user	24	48	96	Error of 48 points/day	Error of 96 points/day
1	185.2981	185.2052	185.0922	-0.0929	-0.2059
2	111.8478	111.9578	112.0965	0.11	0.2487
3	293.0119	293.0698	293.1193	0.0579	0.1074
4	200.9887	200.8009	200.7386	-0.1878	-0.2501
5	210.5182	210.5315	210.5837	0.0133	0.0655
6	148.1337	148.1408	148.1347	0.0071	0.001
7	91.01507	91.05984	91.07082	0.04477	0.05575
8	167.3023	167.4886	167.5051	0.1863	0.2028
9	194.6604	194.7532	194.7933	0.0928	0.1329
10	249.5946	249.7856	249.8115	0.191	0.2169
11	79.02887	78.92707	78.85742	0.8982	0.82855
total	1931.4	1931.72	1931.803	0.32	0.403

TABLE 3 Carbon metering experiments with different load fluctuation percentages.

Load user	Referencing data	Percentage of load fluctuation		
		$\pm 0.5\%$	$\pm 1\%$	$\pm 2\%$
1	248.1146	248.0958	247.9399	248.0634
2	150.546	150.5783	150.5102	150.229
3	370.7626	370.7491	370.8202	371.1662
4	222.8634	222.7915	222.8891	222.7419
5	229.3166	229.4014	229.2723	229.2059
6	187.2176	187.2272	186.9811	187.0954
7	112.9285	112.9538	112.9642	113.1269
8	185.0045	184.9278	184.9069	184.6272
9	211.9663	212.0297	212.0135	212.1763
10	271.9932	271.971	272.0274	271.8747
11	93.09391	93.11448	93.05235	93.03928
Total	2,283.807	2,283.84	2,283.377	2,283.346

TABLE 4 Absolute error in carbon metering for different load fluctuation percentages.

Load user	Percentage of load fluctuation		
	$\pm 0.5\%$	$\pm 1\%$	$\pm 2\%$
1	0.018734	0.174,671	0.051192
2	-0.03238	0.035722	0.316,917
3	0.013465	-0.05761	-0.40366
4	0.071867	-0.02578	0.121,498
5	-0.0848	0.044379	0.110,702
6	-0.00951	0.236,506	0.122,285
7	-0.02533	-0.03569	-0.19843
8	0.076695	0.097592	0.377,364
9	-0.06343	-0.04718	-0.20996
10	0.02225	-0.03415	0.118,494
11	-0.02057	0.041561	0.054638
Total	0.033	-0.43	-0.461

result values are closer to the integral values. However, we also note that the CO₂ metering results for some load users are small in the control group, such as the first load user and the fourth load user. During the execution of the simulation experiment, the loads added random fluctuations, leading to such unpredictable results. The occurrence of this phenomenon suggests that it is necessary to add time synchronization to the carbon metering system for synchronous alignment of the time scale. Finally, we also found that the CO₂ metering values generated by all load users in the IEEE-14 standard system on a typical day under the simulation arithmetic of this experiment are 0.403 and 0.32 tons of CO₂, which are larger than the results of the baseline case for the 96-point/day case and the 48-point/day case, respectively. If

time synchronization is ignored, the cumulative measurement errors over time will lead to questionable accuracy and fairness of carbon metering.

5.3 Error analysis of load fluctuation at the 96 points/day time scale

Based on the analysis in subsection 5.2, we concluded that the carbon measurement accuracy at high sampling rates is closest to reality. This sub-section explores the impact of data bias at a time granularity of 96 points/day. The results of the load carbon flow are shown in Table 3, and the absolute errors of the error data and the

original data are shown in Table 4. The data units in Table 3 and Table 4 are tCO_2 .

As shown in Table 4, the size of the random fluctuation of the data causes the absolute error of the total carbon emission of the system in a single day to be less than $0.5tCO_2$. However, as the fluctuation increases, the absolute error also increases. For a single load node, the absolute error caused at $\pm 2\%$ data fluctuation is an order of magnitude higher in the total carbon flow for more than 70% of the loads compared to the results for $\pm 1\%$ as well as $\pm 0.5\%$. However, the carbon flow results for loads caused by $\pm 0.5\%$ and $\pm 1\%$ fluctuations are not significantly different in order of magnitude. In addition, there is even an absolute error in the total load carbon flow caused by $\pm 0.5\%$ data deviation, which is greater than the absolute error in the total load carbon flow caused by $\pm 1\%$ fluctuation.

6 Conclusion

This paper introduces the time synchronization technique to power system carbon flow calculations and provides relevant work for more accurate carbon flow measurement. Carbon flow in transmission, transformation, and distribution accompanies the PF calculation. Considering that the source follows the load movement, the deviation of the load monitoring can lead to an error in carbon flow measurement. The necessity of introducing time-synchronous technology into carbon flow metering is illustrated by combining the arithmetic example of the IEEE14 node. The findings of this study are summarized in the following three points:

1. There are measurement errors in carbon measurement at different time granularities, and the finer the time granularity, the closer the carbon measurement results are to the true value.
2. In the case of the high sampling rate of the carbon metering system, the magnitude of load fluctuation also has an impact on the carbon metering error.
3. Time synchronization technology should be included in the technical scope of carbon metering for transmission, transformation, and distribution grids to improve the credibility of carbon verification.

Future work can focus on data-driven carbon flow prediction based on data to further improve the stability of this system's work.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FZ: conceptualization, data curation, and writing-original draft. JY: conceptualization, funding acquisition, supervision, writing-review and editing, and writing-original draft. XY: formal analysis, project administration, validation, and writing-review and editing. CY: resources, visualization, and writing-review and editing. SL: investigation, methodology, software, and writing-review and editing.

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Conflict of interest

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