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Efficient whole-process carbon intensity calculation method for power users in active distribution networks

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With the tightening restrictions on carbon emission globally, the carbon intensity of the economic is receiving more attention than ever, but the results obtained by conventional methods are not accurate enough for the responsibility division. To change this situation, a power flow tracking method aimed at the distribution networks and an electricity-consumption-based carbon intensity calculation framework are proposed in this paper. Firstly, to overcome the obstacles created by the three-phase asymmetries and the scale expansion of the networks while processing power flow tracing, a phase-split calculation regime and a high-efficiency power flow tracing method are proposed, respectively. On that basis, a whole-process carbon intensity calculation framework is reported. By adding simplified models about industrial production processes, this paper gives the calculation route from the energy consumption to the carbon intensity for each user in the distribution network. Finally, we emulated with the IEEE 34 bus and 123 bus test feeders and analyze the numerical results, to prove the efficiency and effectiveness of the framework proposed.

KEYWORDS

active distribution network, carbon intensity, asymmetric distribution, power flow tracing, power flow modeling

1 Introduction

As the world pays more attention to the emissions of greenhouse gases, how to achieve the balance between carbon emission reduction and economic development has become a common concern of all social groups (Song and Xia, 2022; Yuan and Zheng, 2022). The carbon intensity of the economy (called carbon intensity, CI) refers to the carbon emission per unit GDP (U.S. Energy Information Administration, 2022), which represents the advanced level of low-carbon technology for a company or a group, comparing with peers. In order to make people more active in the low-carbon career, it is necessary to provide appropriate rewards and punishments for enterprises with different CI. The electricity carbon emissions account for nearly 50% of the total (Zhang et al., 2021), with the

improving electrification in the production processes (Ciller et al., 2019; Wu et al., 2022), the carbon emissions related to the usage of the electricity should be taken into consideration when calculating CI. However, this type of carbon emission is unintuitive, so the tracking of the carbon emissions flow in the power system has become an integral part of CI calculations (Kang et al., 2015).

At present, two categories of methods are used to extract the corresponding relationship between electricity consumption and carbon emission, namely the statistical methods (Wang et al., 2013; Chen et al., 2018) and the carbon flow analysis methods (Sun et al., 2016; Cheng et al., 2020). On the one hand, the statistical methods calculate the total energy consumption in a long period of time. While being utilized in traditional distribution networks, the slight inaccuracy of these methods can be ignored considering the low penetration rate of renewable sources in the network, and its high-efficiency advantage is highlighted. However, for the active distribution networks with distributed renewable sources (Le et al., 2022; Ma et al., 2022), the calculation results of the statistical methods are too rough, to deduce the load users' whole-process CI.

On the other hand, the carbon flow analysis methods are based on active power flow in the distribution network. The first step of these methods is to associate the electricity consumption of each load with the output electricity of the sources in the distribution network (power flow tracing, PFT). The second step is to calculate the carbon emissions efficiency of each power source in the distribution network, by dividing the gross carbon emission by the output active power of the source. Finally, calculate the carbon emission corresponding to all electricity consumption according to the above results. The utilization of these methods relies heavily on the amount and accuracy of data. As the distribution networks grow in size and operational complexity, the loss and the inaccuracy of required data are becoming inevitable (Deka et al., 2018; Huang et al., 2021), which causes difficulty in striking a balance between economy and accuracy when tracing the power flow by the conventional methods. Additionally, these PFT methods can only analyze the three-phase balanced power grids, which is unsuitable for the distribution networks with asymmetric loads and lines (Kwon et al., 2015; Tellez et al., 2015). However, the carbon flow analysis methods can achieve a fair division of carbon emission responsibilities in theory. Therefore, after correcting the deficiencies above, the carbon flow analysis methods can be utilized to calculate the CI of the distribution network's users, efficiently and accurately.

After simplifying the power flowing model in the transformer with delta connections, this paper proposes a high-efficiency PFT method for the active distribution networks based on the radial nature (Arefi et al., 2020; Shaheen et al., 2021) of the networks. On that basis, a framework is proposed to calculate load users' CI, which only needs the users' electricity consumption and a small amount of the state information of the related distribution network. The innovations are as follows:

1) A method to separate the distribution network into three independent one-phase networks.
2) A subgraph selecting method for the selection of the required data, together with a high-efficiency PFT method for the selected data.
3) A CI calculation framework considering the carbon emissions related to the electricity consumption.

The remainder of this paper is organized as follows: Section II introduces the proposed PFT method for a three-phase unbalanced distribution network; Section III shows the CI calculation framework for the load users, and demonstrates the application mode of the framework with simplified models; Section IV verifies the efficiency and effectiveness of the proposed method and framework by analyzing the structures and numerical results of several IEEE test feeders; Section V concludes the paper and introduces the work plans in the future.

2 Power flow tracing method for asymmetric distribution networks

2.1 Phase separation for the distribution networks

Due to the possible asymmetries in the loads, lines, and other equipment in the distribution networks, the power flow and the loads' electricity consumption are relatively independent between phases. Therefore, for the accuracy of the final results, the proposed PFT method separates the three phases of the distribution network and calculates them independently. However, there are two major types of participants in the distribution networks that have power flow between phases, the loads and the transformers, and the solutions to these two obstacles are introduced respectively as follows.

For the loads. The active power input to each phase of all loads can be measured by the smart meters, and the values of the phase-wise loads are recorded as a matrix P_M in the form of $L*3$, L is the quantity of the loads, the 1st, 2nd, and 3rd element in the ith row of the matrix represent the power absorbed by the load i from the 1st, 2nd, and 3rd phase of the buses, respectively.

As for the transformers. On the one hand, the transformers without delta connections can be directly regarded as the lines in the power-flow perspective, because there is no power flowing between phases. On the other hand, since the current in the delta circuit is not acceptable for the safety and stability of the distribution networks, the conditions that the asymmetric power flowing into the delta-connected transformers are

FIGURE 1
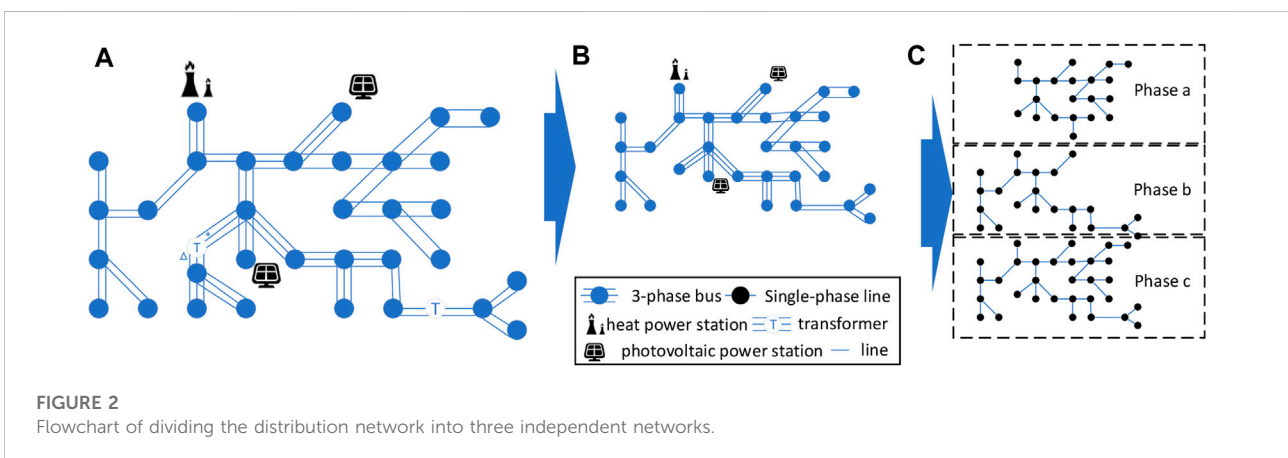Power flow diagram of the star-delta transformer.
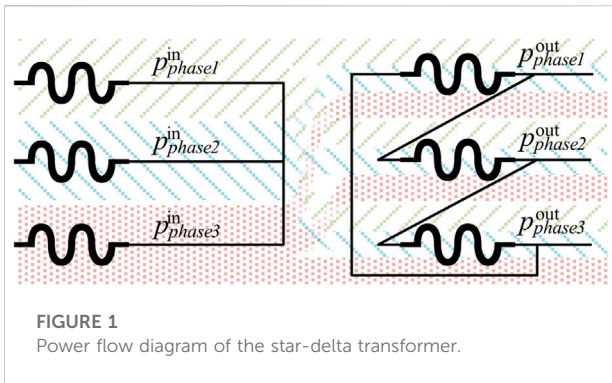
extremely rare, and such situation will not be discussed in this paper. Additionally, the power flow in the transformer is distinct between different operation states, so further research about it is expensive and with limited benefits. Accordingly, we assume that the output power of each phase has the same power composition, that is, the output power of each phase is provided by all input phases, and each input phase accounts for 1/3. Figure 1 shows the power flow of a star-delta transformer. Assuming the transformers as the loads is good enough for the calculation process of the proposed PFT method, and the utilization of this power flow model is illustrated in Section 2.1.
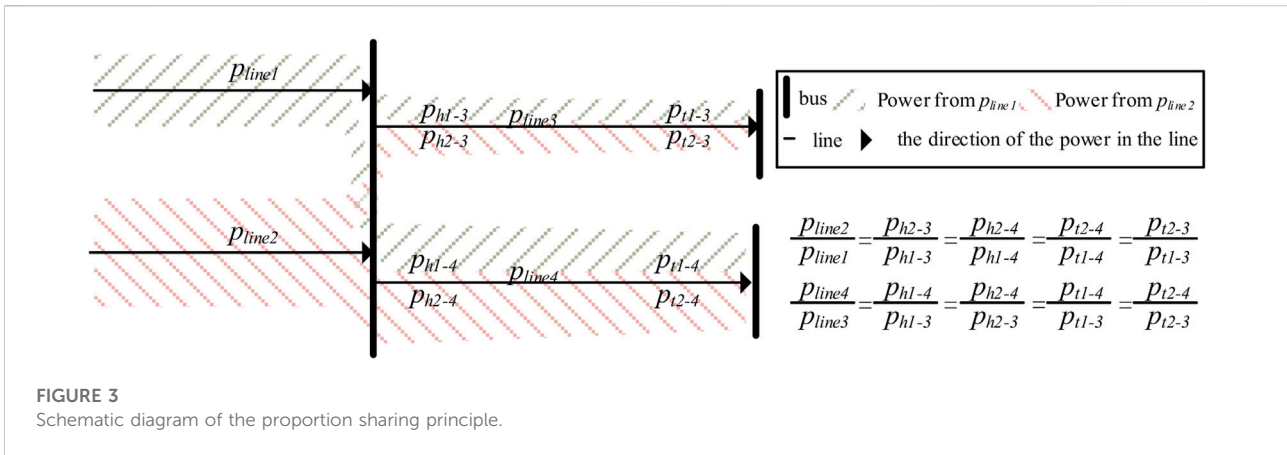
In practice, the first thing to do is to convert the other transformers into the lines firstly. At the same time, convert each transformer with delta connection into three loads, each load in a phase. Then, record the power flowing into each phase of the transformer as the related load in that phase. Considering that the load data is recorded phase by phase at the beginning, the distribution network has already divided into three independent networks after the above processes. Figure 2 shows the process of converting a three-phase asymmetric distribution network into three independent one-phase networks.

2.2 Process of the efficient power flow tracing method

Due to the scale expansion of the distribution network, the cost for the data collection has risen sharply (Kaiyuan and Xueshun, 2018; Yahya et al., 2020). Thus, a PFT method that only utilizes minimal data is helpful to deal with this situation. To this end, we define the subnet in the distribution network with the following rules: all buses in the subnet can be connected to any bus in the subnet, and the connection route is composed of the buses and lines that belong to that subnet. At the same time, record the proportion of the power from different sources in the load as the power proportion (PP) of that load. It is obvious that in each one-phase network, the PP of the loads will be the same when the subnet's power injection only happens in one bus. Based on the radial feature of the distribution network, this paper uses the above settings and proposes a PFT method that requires less data. The process of the method can be divided into three main steps, and the first step is to find the redundant data while processing PFT:

1) Converting the transformers with delta connections into three loads, each in a phase, the value of each load is the input power to the related phase of the transformer
2) Representing the distribution network as a graph, in which edges represent lines and nodes represent buses (Rusek et al., 2020), the features of each node is the same as those of the related bus.
3) Finding all nodes that are connected to power sources, and find the shortest path between each pair of these nodes (Krasnobayev et al., 2020).Then, recording all nodes on these paths as the minimum node set (MNS), and record the subgraph only including the nodes in the MNS as the minimum subgraph.

FIGURE 2
Flowchart of dividing the distribution network into three independent networks.

FIGURE 3
Schematic diagram of the proportion sharing principle.

Clearly, for each subgraph obtained by the above processes, the quantity of the buses that has inflowing power is equal or less than 1. Therefore, the PP of the loads in the whole distribution network can be broadcasted by those in the minimum subgraphs. So, the second step is to analyzing the topology and power flow of the minimum subgraph, and calculate the PP of the loads in each phase of it. The specific method is as follows:

1) Generate three independent networks by the method in Section 2.2 and transform them into three one-phase graphs as in the first step.
2) For each graph, delete the nodes in the MNS, and divide the nodes and the lines remained into multiple subgraphs according to their connectivity.
3) Add the nodes in the MNS that are directly connected to each subgraph to that subgraph, if a node in the MNS is connected to multiple subgraphs, merge the node and the subgraphs into one subgraph. The subgraphs created in this step are denoted as remained subgraphs (RS), each RS is related to a single node in the MNS.
4) Record the total power consumption of each RS as the load of the related node. Then, use the traditional PFT method, to calculate the PP of the loads in the minimum subgraph.

The traditional power flow tracking method uses the proportion sharing principle (Rao et al., 2012) to analyze the power flow of the network, and obtain the position where all power from each source is finally consumed. The proportion sharing principle can be explained from two aspects: for the lines, among the power flowing at the beginning and end of a single line, the proportion of power from different power sources is the same; for the buses, the percentage of power from each input terminal is the same in each output terminal. Figure 3 shows the schematic diagram of the proportion sharing principle. Under the constraints of the above principles, a bus-by-bus iteration is used to calculate the PP for the loads in the minimum subgraph related to the three phases. The three-phase PP of the loads can

be represented as the proportional matrix $E_i = [\varepsilon_i^{(1)}, \varepsilon_i^{(2)}, \varepsilon_i^{(3)}]^T$, where i is the id of each load; $\varepsilon_i^{(k)} = [\varepsilon_{i1}^{(k)}, \varepsilon_{i2}^{(k)}, ..., \varepsilon_{iJ}^{(k)}]$; J is the total amount of power generation equipment; $\varepsilon_{ij}^{(k)}$ represents the proportion of the power flowing to the kth phase of load i that comes from source j.

The results above can be broadcasted to the loads outside the minimum subgraph, and by which, the result of the PFT can be deduced in the third step as:

1) While regarding the delta-connected transformers as loads, for each RS in each one-phase graph, the PP of loads in that RS is the same as the PP of the load which that RS was equivalented to.
2) According to the simplified power flow model of the transformer with delta connections in Section 2.2, for the transformer iu that the input power of which was equivalented as load iu in the previous steps, the proportional matrix of the downstream loads can be calculated as:

$$E_{id^{(o)}} = [\varepsilon_{iu}^m, \varepsilon_{iu}^m, \varepsilon_{iu}^m]^T \qquad (1)$$

$$\varepsilon_{iu}^m = \left(\varepsilon_{iu}^{(1)} + \varepsilon_{iu}^{(2)} + \varepsilon_{iu}^{(3)}\right)/3 \qquad (2)$$

where $E_{id^{(o)}}$ is the proportional matrix of the load $id^{(o)}$ downstream of the transformer iu. $\varepsilon_{iu}^{(k)}(\forall k \in (1, 2, 3))$ is the kth row of the load iu's proportional matrix.

3) For each load in the distribution network, obtain the power magnitude from the sources as: $S_i = P_M[i] \cdot E_i$, where $P_M[i]$ is the ith row of P_M, and the jth value of S_i ($\forall j \in \{1, 2, ..., J\}$) represents the active power in load i from generator j.

The introduction of the proposed PFT method is above, and the flowchart of it is shown in Figure 4.

According to the differences between the process of the proposed and the conventional PFT methods, it is clearly that the proposed method reduces the requirement of the data and while remaining the accuracy of the results, which will be verified in Section 2.2.

FIGURE 4
Flowchart of PFT method proposed in this paper.

FIGURE 5
Flowchart of the CI calculation framework.
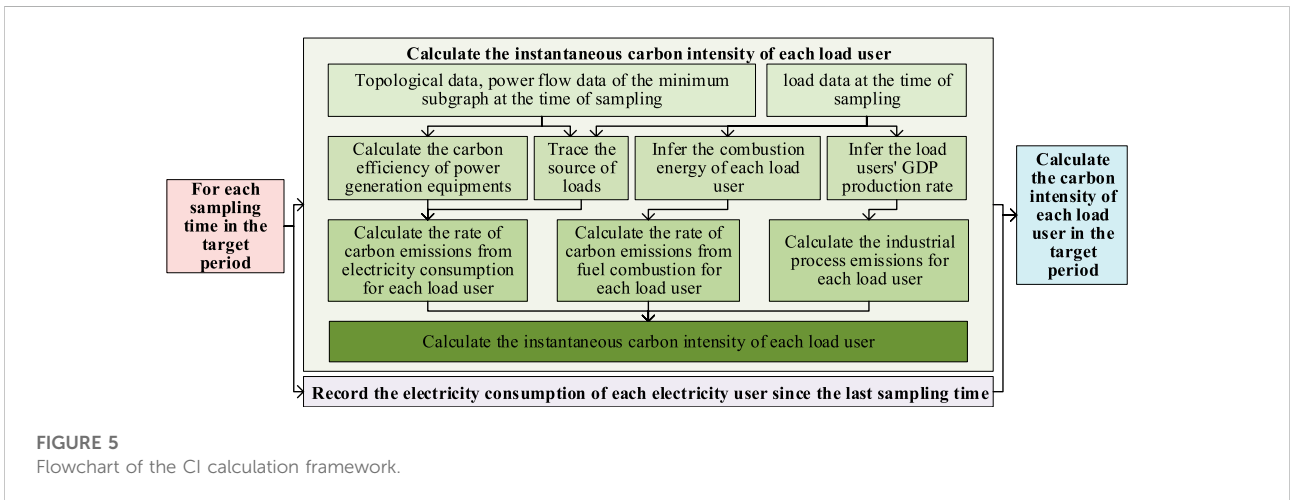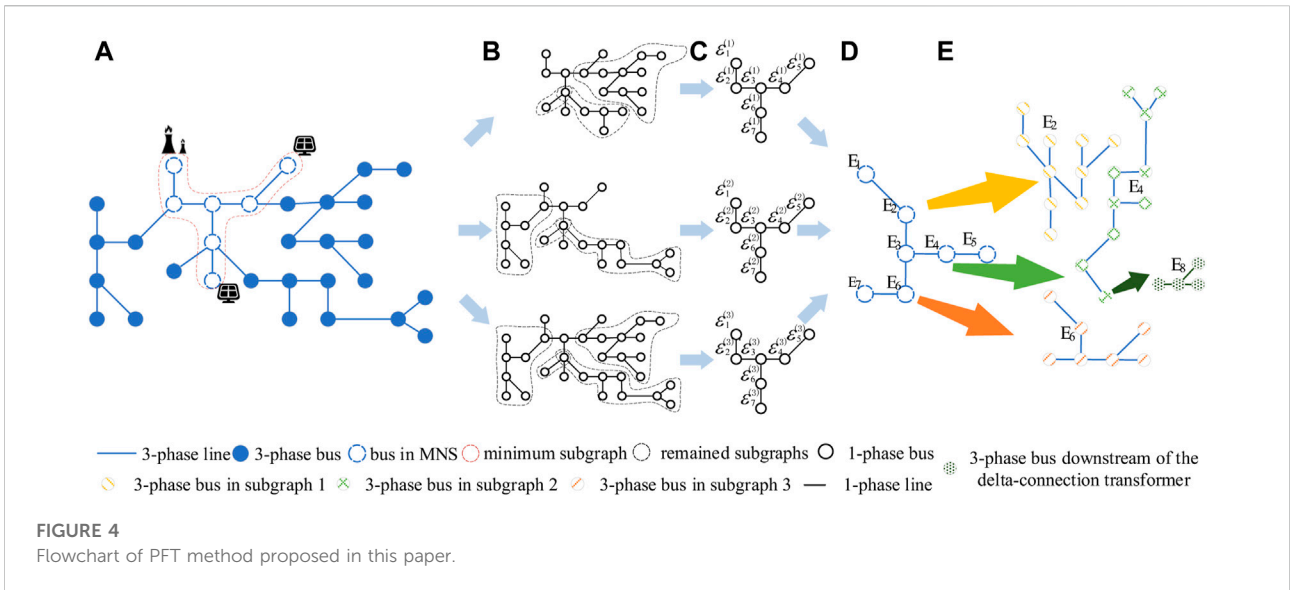
It is worth noting, when there are sources in both sides of the delta-connected transformer, the power-injection side should be calculated as a load firstly. Then, calculate the PP for the output power of each phase of the transformer. By treating the output of the transformers as the power sources, the PP of all loads in the network can be calculated by the proposed method.

3 Whole-process CI calculation framework

Industrial Carbon emissions can be divided into the industrial process emissions and the energy consumption emissions. The former refers to the carbon emissions produced by physical or chemical changes other than combustion. The latter refers to carbon emissions deduced by fuel combustion and other forms of energy usage. At present, the carbon emissions related to the usage of combustion energy are based on the statistical methods. In those methods, the industrial process emissions are calculated by multiplying the referred carbon emission ratio by the product output, for each production. The energy consumption emissions are calculated likewise, and the referred ratio is multiplied by the consumption of electricity and fuels. Due to the uncertainty of combustion efficiency under different production environment conditions, the results are often insufficient. Considering the strong correlations between the usage of different types of energy, this paper makes a few assumptions and simplified models. Accordingly, we report a framework to calculate the

whole process carbon emissions of the load users based on their electricity consumption, as shown in Figure 5.

3.1 Related models and parameters

For the high-accuracy of the framework, the detailed information that describing the generation processes is indispensable for the construction of the models. Due to the fact that no model can achieves absolute unity in all situations, the simplified models are utilized to illustrate how the proposed framework extract CI from the electricity consumption. The models and the parameters are as follows:

The user corresponding to load i is marked as user i, and we assume that the industrial process emission per GDP is a constant value for user i, denoted as μ_i^t. For each industrial power user, we assume that the required energy from electricity and combustion are constant when generating each unit of GDP, and the demands are p_i^E and p_i^B for user i, respectively. The corresponding relationship between carbon emissions and power generation (Wang et al., 2022) of thermal power source j is:

$$\lambda_j = \varsigma_j \tau_j \left(1 - v_j\right) \frac{M_{co_2}}{M_c} \sum_{n=0}^{2} b_j^{(n)} Power\left(P_j^E, n-1\right)$$

where λ_j is the tons of carbon emission per kWh of the power source j. $b_j^{(n)}$ is the characteristic parameter related to the carbon emission efficiency of the source j. ς_j, τ_j, and v_j are the carbon content rate, carbon oxidation rate and carbon capture rate of the source j, respectively. M_{co_2} and M_c are the molar masses of carbon and carbon dioxide, 12 g/mol and 44 g/mol, respectively. P_j^E is the output power of the source j. $Power\left(P_i^B, n-1\right)$ is the $(n-1)^{th}$ power of P_j^E. The c_j of each renewable power source is 0, and the λ_j of all power sources constitute the vector $\gamma_G = [\lambda_1, \lambda_2, ..., \lambda_J]$.

The corresponding relationship between the combustion power and carbon emissions of industrial users is similar to that of thermal power plants, and the expression is:

$$\lambda_i^B = \varsigma_i \tau_i \left(1 - v_i\right) \frac{M_{co_2}}{M_c} \sum_{n=0}^{2} b_i^{(n)} Power\left(P_i^B, n-1\right)$$

where λ_i^B is the carbon emission generated by user i per kWh combustion energy. $b_i^{(n)}$ is the characteristic parameter related to the carbon emission efficiency of user i. ς_i, τ_i, and v_i are the carbon content rate, carbon oxidation rate and carbon capture rate of the user i 's combustion equipment, respectively. P_i^B is the combustion power of user i.

3.2 Calculation process of CI

For the calculation of instantaneous CI: According to the operating status of the distribution network and the active power

flowing to each load, by the PFT method Section 2.2 in and the parameters in Section 3.1, the instantaneous CI of the related user can be obtained. The calculation is as follows:

The carbon emission ratio conducted by electricity consumption for user i is $c_i^e = S_i \cdot \gamma_G^T$, where γ_G^T is the transpose of γ_G. Besides, the GDP generation rate of user i can be calculated by the related active power usage P_i and the parameter P_i^E, as $g_i = P_i/p_i^E$. Accordingly, the combustion power of user i can be calculated like $P_i^B = g_i * p_i^B$, the carbon emission related to which is calculated by $c_i^B = P_i^B * \lambda_i^B$. Therefore, the energy consumption emissions ratio of user i is $c_i = c_i^B + c_i^e$, and the energy-consumption-part CI μ_i^c is obtained by dividing c_i by g_i. Combining the above results, the instantaneous CI of user i is $\mu_i = \mu_i^c + \mu_i^t$.

As for the CI calculations in a period of T seconds. The sampling frequency of the input power and the energy consumption of each user is ϕ hertz, and the sampling time points are denoted in sequence as $\{t_0, t_1, ..., t_{T*\phi}\}$. The long-term carbon intensity of the users can be calculated by the instantaneous carbon intensity $\mu_i^{(t_m)}$ at each time point, with the electricity consumption $w_i^{(t_m)}$ in the corresponding time period. where $w_i^{(t_m)}$ is the power consumption of the load i between time t_{m-1} and time t_m, the unit is kWh. With the above parameters, the total GDP and the total carbon emission of user i can be calculated as $G_i = \sum_{m=1}^{T*\phi} w_i^{(t_m)}/p_i^E$ and $C_i = \sum_{m=1}^{T*\phi} w_i^{(t_m)} * (\mu_i^{(t_m)} + \mu_i^{(t_{m-1})})/2 p_i^E$, respectively. Therefore, the CI of user i in the target time period is $M_i = C_i/G_i$.
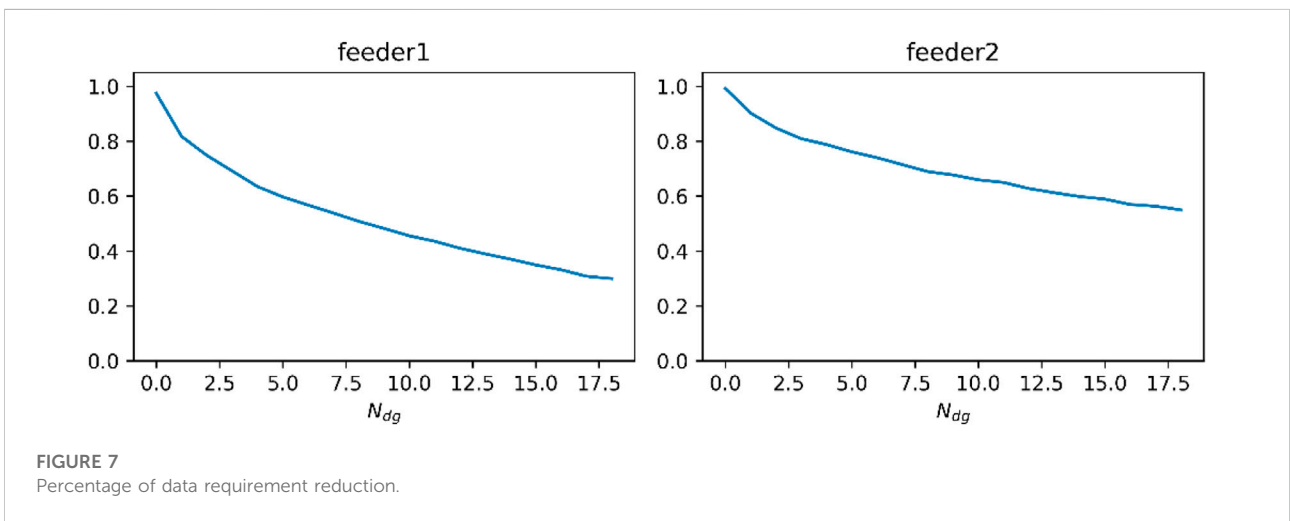
4 Case study

We use IEEE 37-bus and 123-bus test feeder (namely feeder1 and feeder2) to verify the advancement and effectiveness of the method in this paper.

Firstly, we prove the necessity of dividing the distribution network into three phases for the PFT. There are only delta-connected generators in feeder1, the topology and the lines parameters of all three phases are the same, the phases are also symmetric. So, the result of the PFT will remain accurate whether the distribution network is divided into three independent networks. However, the topology diagram of each phase in feeder two is shown in Figure 6. There is topology inconsistency among different phases, and most of the loads are only connected to 1 or 2 phases of the network. Therefore, it is more convincing to divide the distribution network into three before processing PFT.

Then, this paper verifies the efficiency and the effectiveness of the data usage by using the method we proposed, the verification is divided into two aspects.

On the one hand, we calculated the reduction of the required data by comparing the quantity of the nodes in the minimum subgraph and the whole graph. Specifically, we add N_{dg} ($\forall N_{dg} \in \{1, ..., 20\}$) distributed photovoltaic devices at the

FIGURE 6
The topology of each phase in feeder2.

FIGURE 7
Percentage of data requirement reduction.
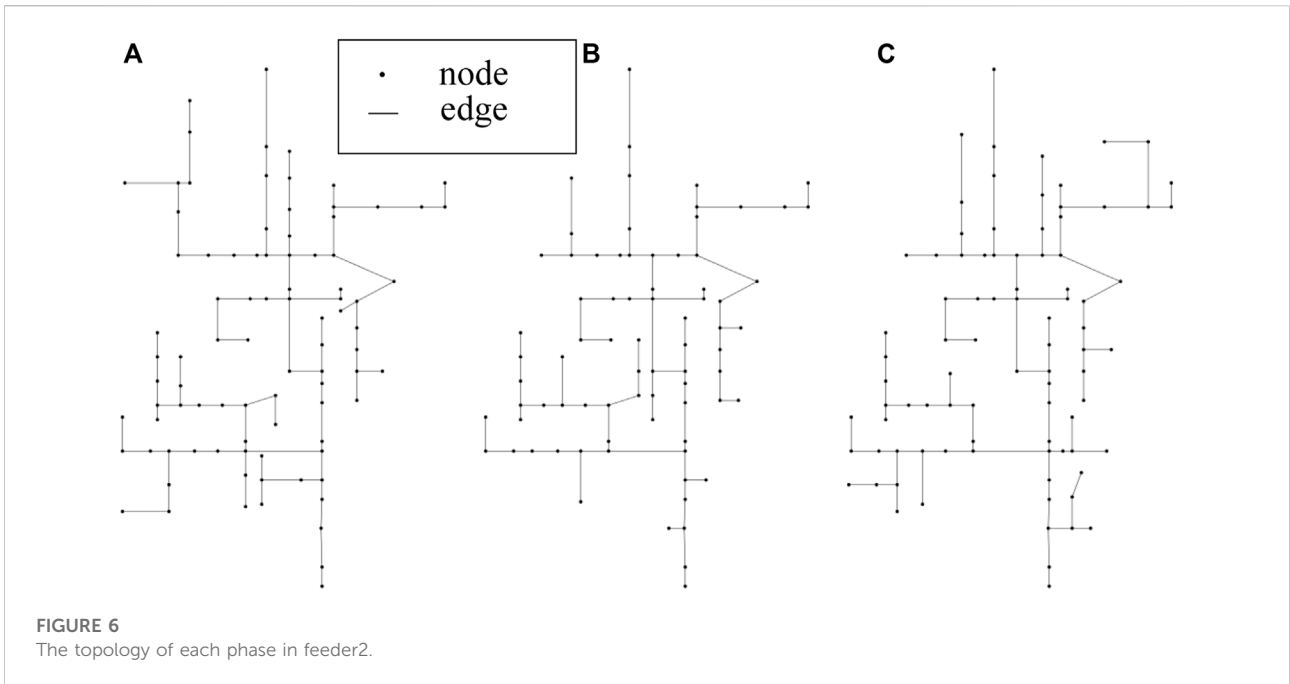
non-repetitive random buses in both test feeders, then calculate the number of buses that are needed for the proposed PFT method. Repeat 1,000 times and average the number of required nodes, divide by the number of buses in the feeder, and get the proportion of nodes that need to be sampled. The values obtained by subtracting this proportion from 1 can infer the improvement of data utilization efficiency when using the method proposed in this paper. The values correspond to different N_{dg} in both feeders are shown in Figure 7.

As shown in the figure above, the amount of the required data is greatly reduced by using the proposed method when

processing PFT. When the quantity of the distributed sources is less than 1/5 of the number of buses, the amount of the required data is decreased by over 50%, and the efficiency of data usage is boosted by more than 100% in average. The result proves that the requirement of data has significantly reduced, which demonstrates the high efficiency of the method we proposed.

On the other hand, we verify the effectiveness of the proposed method. On the basis that the PFT is processed phase by phase, the conventional PTF method has already achieved people's expectations to the fairness (Wang et al.,

FIGURE 8
Schematic diagram of topology and photovoltaic location of feeder 1 and feeder two.

FIGURE 9
Standard curve of photovoltaic output.
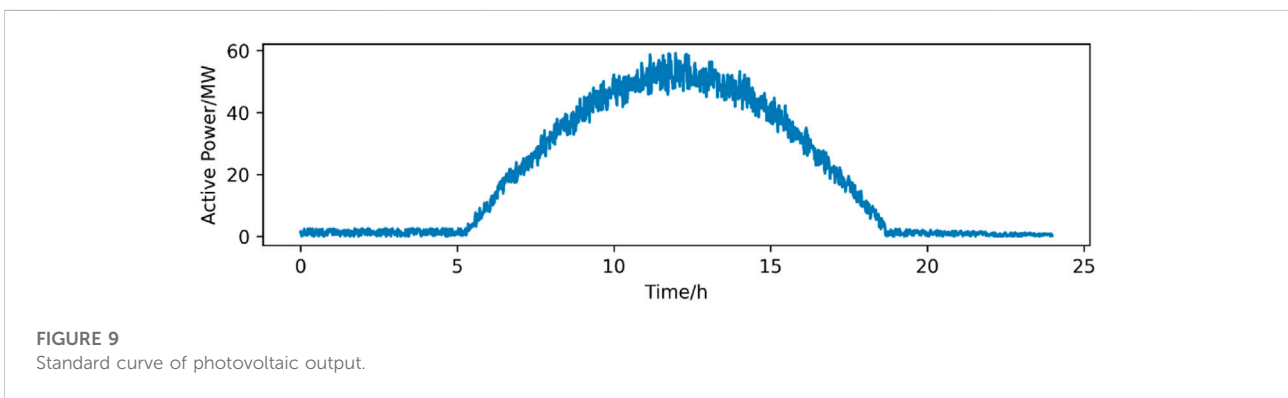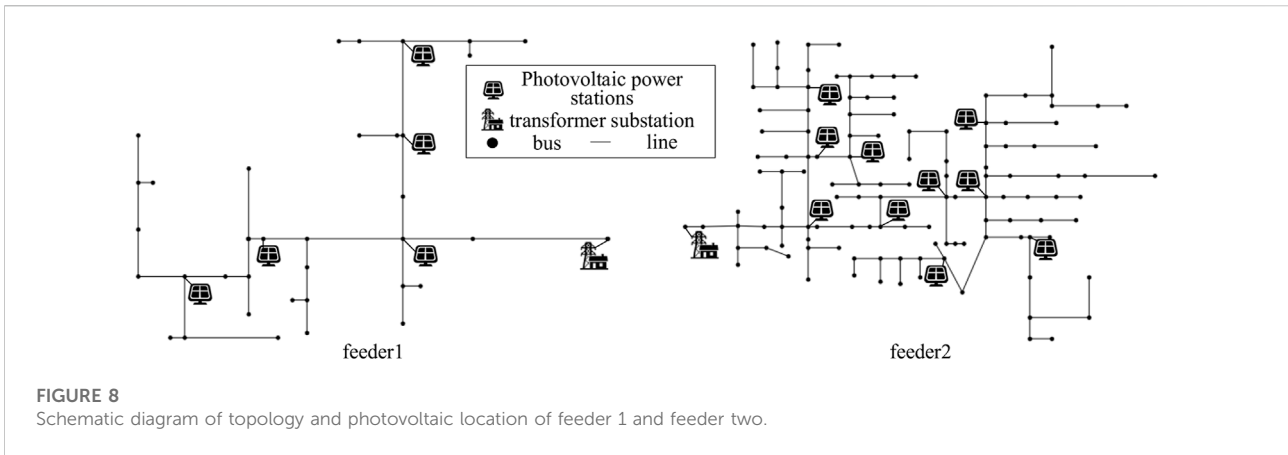
2022). Therefore, we verify the effectiveness of the proposed method by comparing the users' carbon emission, which are deduced by the proposed method (PM) and the conventional method (CM), respectively. The emulation software is OpenDSS. 5 and 10 distributed photovoltaics are set in the feeder1 and feeder2 respectively, the power from the abspanntransformator is regarded as the power from one thermal power station, and its carbon emission efficiency is calculated by the formula in 3.1. The topology of the distribution network and the location of each distributed power generation equipment are shown in Figure 8. The photovoltaic output curve of each day is the standard curve shown in Figure 9 multiplied by a random number from 0 to 1. All parameters related to industrial production are random numbers. The input power of each load is generated by the minute as the average power for that minute, and the value of it fluctuates randomly between 0 and 1 times the initial value of the feeders. The load is sampled every 15 min to obtain the active power consumption of the load within 15 min, as well as the power at that moment. We use both PFT methods to obtain the carbon emissions related to the electricity consumption of each load in 1 month. The results are shown in Table 1, where each users' ID (UI) corresponds to a load user.

By comparing the results calculated by the two methods, it can be found that the carbon emissions calculated by the two methods are equal for all users. Therefore, the method described in this paper uses only a small amount of data to achieve the trustworthy results that traditional methods require several times the data.

The monthly CI of each load users in both feeders are given in Table 2, in t/GDP.

The data requirement of the conventional CI accounting method is different from which of the proposed method, these two methods are not comparable. So, we analyze the advantages of our method from a mechanism prospect. The proposed method has a much smaller requirement of the data quantity, because the usage of each type of production raw materials are not indispensable. At the same time, the proposed method can tell the difference in CI under different working conditions, instead of calculating all carbon emissions from energy usage by a standard ratio. In conclusion, the proposed framework has the potential boost the accuracy and efficiency when calculating the CI of each user.

TABLE 1 Monthly carbon emission calculated by TM and PM.

	UI	0	1	2	3	4	5	6	7	8	9	10
Feeder1	CM(t)	20,515	1,479	1869	883	2,377	33,608	1,365	1,076	3,010	1,493	3,306
	PM(t)	20,515	1,479	1869	883	2,377	33,608	1,365	1,076	3,010	1,493	3,306
	UI	11	12	13	14	15	16	17	18	19	20	21
	CM(t)	960	1716	3,061	918	3,160	838	1704	945	34,173	2,840	1825
	PM(t)	960	1716	3,061	918	3,160	838	1704	945	34,173	2,840	1825
	UI	22	23	24								
	CM(t)	807	1900	4,157								
	PM(t)	807	1900	4,157								
Feeder2	CM(t)	3,914	2,154	4,837	2,121	4,774	1951	4,466	3,409	4,434	2,100	318,651
	PM(t)	3,914	2,154	4,837	2,121	4,774	1951	4,466	3,409	4,434	2,100	318,651
	UI	11	12	13	14	15	16	17	18	19	20	21
	CM(t)	1938	3,855	11,471	3,367	3,784	3,632	3,674	3,485	1741	1776	3,820
	PM(t)	1938	3,855	11,471	3,367	3,784	3,632	3,674	3,485	1741	1776	3,820
	UI	22	23	24	25	26	27	28	29	30	31	32
	CM(t)	3,964	3,721	3,689	1881	1961	2,419	1890	3,940	1846	4,706	33,327
	PM(t)	3,964	3,721	3,689	1881	1961	2,419	1890	3,940	1846	4,706	33,327
	UI	33	34	35	36	37	38	39	40	41	42	43
	CM(t)	22,191	3,270	3,810	5,351	4,034	4,951	3,363	2015	1960	2,293	1925
	PM(t)	22,191	3,270	3,810	5,351	4,034	4,951	3,363	2015	1960	2,293	1925
	UI	44	45	46	47	48	49	50	51	52	53	54
	CM(t)	4,046	3,817	7,928	9,319	7,700	1889	3,827	1925	3,773	3,786	4,315
	PM(t)	4,046	3,817	7,928	9,319	7,700	1889	3,827	1925	3,773	3,786	4,315
	UI	55	56	57	58	59	60	61	62	63	64	65
	CM(t)	3,734	130,596	8,382	6,753	4,305	6,069	1949	2,340	9,841	2,685	5,803
	PM(t)	3,734	130,596	8,382	6,753	4,305	6,069	1949	2,340	9,841	2,685	5,803
	UI	66	67	68	69	70	71	72	73	74	75	76
	CM(t)	5,305	5,070	4,646	5,060	2,668	2,592	3,787	6,492	4,005	2023	4,357
	PM(t)	5,305	5,070	4,646	5,060	2,668	2,592	3,787	6,492	4,005	2023	4,357
	UI	77	78	79	80	81	82	83	84			
	CM(t)	4,061	12,540	4,222	32,744	1792	37,410	3,961	1804			
	PM(t)	4,061	12,540	4,222	32,744	1792	37,410	3,961	1804			

TABLE 2 The CI of users in both feeders.

	UI	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Feeder1	CI	234	138	163	48	272	331	26	26	126	54	80	257	144	47	73
	UI	15	16	17	18	19	20	21	22	23	24	15	16	17	18	19
	CI	80	113	243	50	690	216	106	211	60	127	80	113	243	50	690
Feeder2	CI	95	102	38	106	76	24	91	67	67	69	368	92	90	54	20
	UI	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	CI	47	62	57	76	80	10	120	117	80	114	108	95	41	104	25
	UI	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
	CI	26	41	74	38	117	81	108	103	75	64	42	59	21	58	94
	UI	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
	CI	114	140	107	129	86	52	42	84	43	47	96	55	27	92	51
	UI	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
	CI	86	89	91	7	59	86	39	67	136	86	39	110	127	72	64
	UI	75	76	77	78	79	80	81	82	83	84					
	CI	30	112	95	70	84	520	112	192	81	8					

5 Conclusion

In order to obtain a more accurate CI for the load users in the distribution network, this paper proposes a high-efficiency PFT method suitable for three-phase-asymmetric distribution networks. The proposed method splits the distribution network into three one-phase networks, and solves the obstacles brought by the asymmetries of the lines and loads in the network. Additionally, the method makes the best of the radial feature of the distribution network, and overcomes the challenges brought by the scale expansion of it. Furthermore, we proposed the simplified models describing the energy-carbon relationship of power sources, as well as the production processes of the load users. On that basis, a calculation framework about the users' whole process CI is proposed. Although there are a few assumptions in the proposed framework, after perfecting the simplified model, the user's CI can be obtained more precisely by the user's electricity consumption.

In the future, we intend to additionally increase the precision and practicality of the CI calculation in two aspects. Firstly, we intend to focus on the distribution network with distributed storage devices, and study the flow of carbon emissions in the temporal and spatial dimensions. Secondly, we plan to use deep learning methods to replace the simplified models in this paper, and improve the accuracy of the results of the CI while maintaining the calculation speed.

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

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

Authors ZS, YD, FS, and YS were employed by the company Economic Research Institute of State Grid Zhejiang Electric Power Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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