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An improved ship power flow algorithm based on ordered GBDL tree sets

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Abstract. An improved power flow algorithm for ship power grid based on ordered GBDL tree sets is proposed. By using the virtual node method to simplify the network structure, and using the iterative results to correct the power of the vir-tual node to speed up the iterative speed and to ensure that the number of nodes in the tree can be sorted by the degree of the Bridge layer nodes. The results show that the average execution time of the algorithm is smaller than that of the breadth priority search number power flow algorithm in the multi-station connected ship power grid.

Key words. Ship power system, Power flow calculation, Ordered GBDL tree sets.

1. Introduction

In recent years, the ship power simulation training system has developed rapidly. During its operation process, it is necessary to respond to the user's actions frequently, resulting in the continuous change of the network topology of the simulation power system so as to put forward high requirements for the real-time performance of power flow calculation of ship power simulation training system[1-3].

The current ship power flow calculation mostly adopts back/forward method and its improved methods[4-12]. In the process of recursion and traversal, the above methods use the width first traversal method of the graph [4,5] to sort and number the ship power grid nodes. However, the backbone power supply network of the existing large ships often has the situation of multi-station connection of more than 3 power stations and its network topology is mostly of "Stub" shape, "Mu" shape and even more complex structures. For the above network topology, the breadth-first traversal ship power grid node numbering method is used. For the recursion and traversal of backbone bridge nodes and branches, due to the randomness of the node numbering, the situation that the node has no solution and the new search of solved node is required often oc-curs. It will disrupt the recursion and traversal method of

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power flow calculation according to the number, increase the complexity of topology analysis and prolong the iteration duration of power flow calculation so that the meaning of the number cannot be fully reflected.

In order to solve the above problems, this paper proposes an improved ship power flow calculation algorithm based on the ordered GBDL tree set. This algorithm is used to conduct power flow calculation of the power grid of large ships with more than 3 power stations. For the recursion and traversal of back-bone bridge nodes and branches, the recursion and traversal of the network can be done according to the order or reverse order of the node and branch number, reducing the complexity of the topology analysis and shortening the calculation time.

2. Ordered GBDL tree set theory

Definition 1: Some GBDL tree in the ship power grid is called as GBDL_i and some connected GBDL_i set is $S_{\mathrm{GBDL}} = \{\mathrm{GBDL}_1, \ \mathrm{GBDL}_2, \cdots\}$. All node sets in S_{GBDL} are S_N and all branch sets are S_{Br}, all bridge branch sets are S_{BBr}; other branches except bridge branch are called as ordinary branch and its set is S_{CBr}.

Definition 2: In some running state, the set of a connected GBDL tree is called as a GBDL tree set.

Definition 3: The GN set in each GBDL tree is defined as generation node set $S_{\mathrm{GN}} = \{\mathrm{GN}_1, \mathrm{GN}_2, \ \cdots\}$, BN set is defined as bridge node set $S_{\mathrm{BN}} = \{\mathrm{BN}_1, \mathrm{BN}_2, \ \cdots\}$, DN set is defined as distribution node set $S_{\mathrm{DN}} = \{\mathrm{DN}_1, \mathrm{DN}_2, \ \cdots\}$, LN set is defined as electric node set $S_{\mathrm{LN}} = \{\mathrm{LN}_1, \mathrm{LN}_2, \ \cdots\}$ and union set of DN and LN is defined as distribution and electric node set $S_{\mathrm{DLN}} = S_{\mathrm{DN}} \cup S_{\mathrm{LN}} = \{\mathrm{DN}_1, \mathrm{DN}_2, \ \cdots, \mathrm{LN}_1, \mathrm{LN}_2, \cdots\}$.

Definition 4: The layer of some node N^k in GBDL_i is defined as the grade of this node L_{N^k}. The grade number is from small to large according to the order of $G \to B \to D \to L$. The higher the grade, the smaller the number. BN is the root of GBDL tree with the grade number of 1, so the grade number of GN is 0, and the grade number of DN and LN is greater than 1.

Definition 5: Let any path in S_{GBDL} be P_i, all P_i connected nodes constitute an ordered node set, of which, the node sequence is defined as, and there must be an only branch connection between two adjacent nodes. The length of the path is defined as p.

Rule 1: When the ship power grid runs, there is only one BN for any GBDL tree, namely $S_{\mathrm{BN}} = 1$.

Rule 2: When the ship power grid runs, in any GBDL tree, for any GN, $|\mathrm{L}_{\mathrm{GN}} - \mathrm{L}_{\mathrm{BN}}| \leq 1$. That is, BN is the same as GN or directly connected by a branch.

Rule 3: When the ship power grid runs, between any two GBDL trees, if there is bridge path connection, only one bridge path is connected.

Description: The above rules are determined by the design of ship power grid.

First, define the ordered GBDL tree and ordered GBDL tree set and then give some properties related to the node optimization number.

Definition 6: (Ordered GBDL tree) All nodes in some GBDL tree in the ship power grid are sorted and numbered continuously by breadth-first search and the

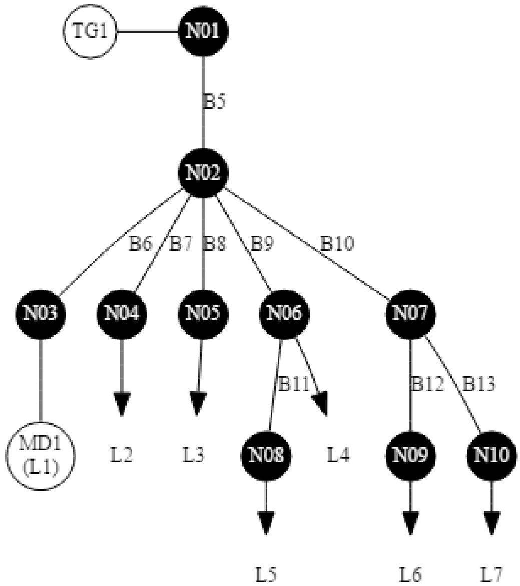

Fig. 1. The ordered GBDL tree of GBDL tree set in the ship grid basic structure

node with smaller number of layers shall be numbered firstly. The number of nodes of the same layer depends on its own degree, and the node with smaller degree shall be numbered firstly. The branches in the tree are sorted and numbered too. One with the smaller number among two-end nodes is the head end node FN and the other with larger number is end node TN. The ranking of the branches is first made by the size of FN. If FN is the same, it is carried out according to the size of TN. The GBDL tree formed by the node and branch numbering of GBDL tree by this method is called the ordered GBDL tree.

Figure 1 is the GBDL tree in the typical structure of ship power grid. The ordered GBDL tree is shown in the figure. B represents the branch number, N represents the node number and L represents the load number.

Definition 7: (Bridge branch) In the ship power grid, the branch set connecting the ordered GBDL tree is called bridge branch set, denoted as $S_{\text{Bridge}} = \{\text{Bridge}_1, \text{Bridge}_2, \cdots \text{Bridge}_n\}$, and the grade of bridge branch Bridge_k is higher than that of all other branches.

Definition 8: (S_{BN} internal subgrade and numbering rules) Let the corresponding distribution and bridge central node set of S_{GBDL} be S_{BN}, the subgrade of any BN_k in S_{BN} is defined as the number of all other BN connected, namely the degree of BN_k. BN_k with higher the subgrade shall be numbered firstly.

Definition 9: (Ordered GBDL tree set) For a connected GBDL tree set of the ship power grid, the trees in this tree set are sorted according to the subgrade of S_{BN} and then the nodes of all trees are numbered according to the rank of each tree and grade of trees and nodes. After the completion of numbering of all nodes in the tree set, all branches in the tree set are uniformly numbered according to the principle of branch numbering based on the ordered GBDL tree and bridge branches. The GBDL tree set formed after the numbering of nodes and branches of GBDL tree set by this method is called the ordered GBDL tree set, denoted as OS_{GBDL}.

For example, for GBDL tree set in the typical structure of multi-station ship power grid with 3 stations, its ordered GBDL tree set is shown in the figure.

The numbering method of ordered GBDL tree set is different from the breadth search numbering method. The difference is that the trees are classified according to the degree of BN node and then sorted based on this. The sorting within each layer of the tree set should be consistent with the tree sorting.

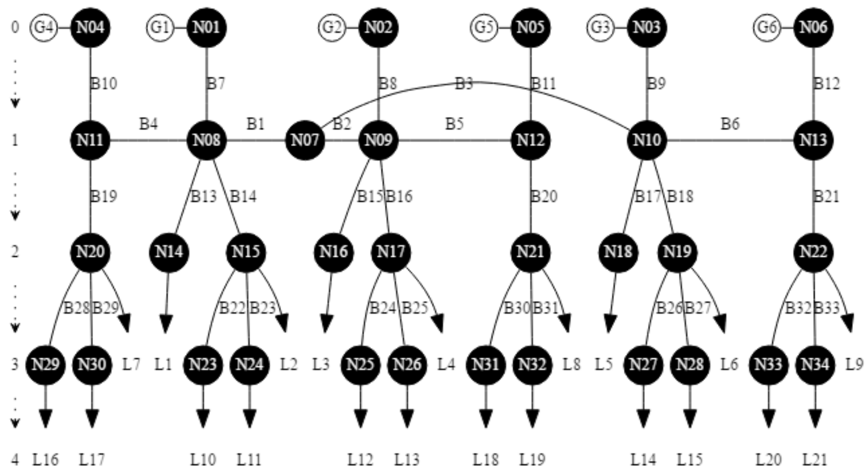

Fig. 2. The ordered GBDL tree set of GBDL tree set in the typical structure of multi-station ship power grid

3. Research on power flow algorithm based on ordered GBDL tree set

Theorem 1: The undirected graph of any ordered GBDL tree set is an undirected tree.

Demonstration: According to the definition of ordered GBDL tree set, the internal nodes of $\forall OS_{GBDL}$ are connected without loop, which is in accordance with the definition of undirected tree. Quod erat demonstrandum.

Theorem 1 guarantees that the ship power grid topological analysis and power flow calculation based on ordered GBDL tree set can refer to the nature of the tree.

Theorem 2: Based on the numbering sequence of the ordered GBDL tree, each iteration of the ship power flow calculation with the back/forward method or node potential method is always solved.

Demonstration: Given $\forall GBDL = (S_N, S_{Br})$, where $|S_N| = n$, so $|S_{Br}| = n - 1$. The total number of grades of GBDL is m. Let the number of the ith nodes be

$n^i = \left|S_N^i\right|$, thus

$$n = \sum_{i=0}^{m-1} n^i = \sum_{i=0}^{m-1} \left|S_N^i\right| . \tag{1}$$

In essence, the difference between back/forward method and node potential method is the calculation of motor load. For demonstration, based on ordered GBDL tree, this paper adopts the back/forward method to calculate the power flow of ship power grid, ignoring the three-phase imbalance and interphase impedance of cables and taking the motor branch as a parameter variable static load. As a result, the algorithm for the kth iteration is as follows:

First, according to the numbering sequence of ordered GBDL tree, the flow calculation of the node N_j and related branches of the ith layer is as follows:

$$P\left(N_j, i, k\right) = P\left(L_j, i\right) + \sum_{h \in H} \left[P\left(N_h, i+1, k\right) + \frac{\left|S\left(N_h, i+1, k\right)\right|^2 R_{Br(j \to h)}}{\sqrt{3}U\left(N_h, i+1, k-1\right)}\right] . \tag{2}$$

$$Q\left(N_j, i, k\right) = Q\left(L_j, i\right) + \sum_{h \in H} \left[Q\left(N_h, i+1, k\right) + \frac{\left|S\left(N_h, i+1, k\right)\right|^2 X_{Br(j \to h)}}{\sqrt{3}U\left(N_h, i+1, k-1\right)}\right] . \tag{3}$$

$$S\left(N_j, i, k\right) = P\left(N_j, i, k\right) + iQ\left(N_j, i, k\right) . \tag{4}$$

$$\cos\varphi\left(N_j, i, k\right) = \frac{P\left(N_j, i, k\right)}{\left|S\left(N_j, i, k\right)\right|} . \tag{5}$$

$$\left|I\left(N_j, i, k\right)\right| = \frac{\left|S\left(N_j, i, k\right)\right|}{\sqrt{3}\left|U\left(N_j, i, k-1\right)\right|} . \tag{6}$$

$$\angle I\left(N_j, i, k\right) = \angle U\left(N_j, i, k-1\right) - \varphi\left(N_j, i, k\right) . \tag{7}$$

Where: $S\left(N_j, i, k\right)$ is the three-phase injection complex power of node N_j of the ith layer, $P\left(L_j, i\right)$ and $Q\left(L_j, i\right)$ are three-phase active power and reactive power of load L_j of node N_j of the ith layer. $I\left(N_j, i, k\right)$ is three-phase injection current of node N_j of the ith layer. $U\left(N_j, i, k-1\right)$ is line voltage of node N_j of the ith layer in the $k-1$th iteration, which is known. N_h is the node of the $i+1$th layer related to node N_j. $Br(j \to h)$ is the branch connecting node N_j and N_h. $R_{Br(j \to h)}$ is its resistance and $X_{Br(j \to h)}$ is the reactance.

Accordingly, after the completion of flow calculation of node and related branches of the ith layer, all output power of nodes of the i-1th layer is the sum of end power of all outflow branches and consumed power of all branches, and so on until the 0th layer (the layer of GN node). Thus the iteration of the flow of all branches in the kth iteration has been completed.

Then according to the numbering sequence of ordered GBDL tree, solve the voltage $U\left(N_j, i, k\right)$ of all nodes in the kth iteration sequentially, with the algorithm as follows:

$$U\left(N_j, i, k\right) = U\left(N_l, i-1, k\right) - Z_{Br(l \to j)} I\left(N_l, i, k\right) . \tag{8}$$

Where: $U\left(N_l, i-1, k\right)$ is the voltage of node N_l of the $i-1$th layer only related to N_j after the kth iteration and $Z_{Br(l \to j)}$ is the impedance of the branch connecting node N_l and N_h.

Because the in-degree of all nodes is 1, when the voltage of the node of the ith layer is calculated, the voltage of all nodes of the i+1th layer can be obtained by the head end voltage of the only one injection branch minus the voltage drop of all branches, and so on until the m-1th layer. Thus the iteration of the voltage of all nodes in the kth iteration has been completed. The kth iteration is finished.

The initial condition of the iteration is the apparent power of real load L_j of the known node N_j:

$$S\left(L_j, i\right) = P\left(L_j, i\right) + iQ\left(L_j, i\right) . \tag{9}$$

Output voltage of the generator unit, namely voltage of GN node $U\left(N_0, 0\right)$ and

$$\left(N_0, 0\right) = U\left(N_j, i, 0\right) . \tag{10}$$

$$\left(N_0, 0\right) = U\left(N_j, i, 0\right) . \tag{11}$$

$$\begin{aligned} S\left(N_j, m-1, k\right) &= P\left(N_j, m-1, k\right) + iQ\left(N_j, m-1, k\right) \\ &= P\left(L_j, m-1\right) + iQ\left(L_j, m-1\right) . \end{aligned} \tag{12}$$

That is, the voltage of all nodes in the initial iteration is the same as the voltage of GN node and the voltage of GN node remains unchanged after any iteration. The power of the real load on each node in each iteration is known.

End condition for iteration is:

$$\max \left| \frac{U\left(N_j, i, k\right) - U\left(N_j, i, k-1\right)}{U\left(N_0, 0\right)} \right| < \varepsilon . \tag{13}$$

Where: ε is the proper small enough positive real number.

The above process ignores the three-phase imbalance and interphase impedance between cables. Considering the three-phase imbalance and interphase impedance, the derivation process is similar, not described here.

From the above derivation process, for the ship power grid meeting the initial conditions of normal power flow calculation, based on the numbering sequence of ordered GBDL tree, the back/forward method or node potential method is used to solve the power flow of all nodes and branches in the tree sequentially if it is reverse order while solving the voltage of all nodes in the tree according to the order. Therefore, all unknown parameters required by the ship power flow calculation can be calculated under the ordered GBDL tree grid model. Quod erat demonstrandum.

Theorem 3: Based on the numbering sequence of ordered GBDL tree set, each iteration of the ship power flow calculation with the back/forward method or node potential method is always solved.

Demonstration: In order to visualize the demonstration process, compare Figure 1 and Figure 2. If the ordered GBDL tree set shown in Figure 2 is conducted with reverse iteration with the back/forward method or node potential method according to the number, all S_{DLN} nodes and related branches are the same as the single ordered GBDL tree, which are solved. The only difference is that for solving the branch $\mathrm{Br}_{\mathrm{GN}\to\mathrm{BN}}$ between GN and BN in each reverse iteration, firstly, it is necessary to solve the output power of GN node and then solve the flow of $\mathrm{Br}_{\mathrm{GN}\to\mathrm{BN}}$. At this time, it can be obtained by reference to the power distribution relationship between the generators in the node potential method.

$$\begin{aligned} S_G(r,k) &= P_G(r,k) + iQ_G(r,k) \\ &= K_p(r)\,P_{Lsum}(k) + iK_q(r)\,Q_{Lsum}(k)\ . \end{aligned} \tag{14}$$

Where: $S_G(r,k)$ is output complex power of r# generator unit in the kth iteration, $K_p(r)$ and $K_q(r)$ are the proportion of active power and reactive power of r# generator unit in the total consumed power, which meets

$$\begin{gathered} \sum_{r=1}^{R} K_p(r) = 1 \\ \sum_{r=1}^{R} K_p(r) = 1 \end{gathered} \tag{15}$$

$$S_{\mathrm{Lsum}}(k) = P_{\mathrm{Lsum}}(k) + iQ_{\mathrm{Lsum}}(k)\ . \tag{16}$$

Where: $\mathrm{S}_{\mathrm{Lsum}}(k)$ is the total consumed power of power grid in the kth iteration. Because the consumed power of all branches of $\mathrm{S}_{\mathrm{Bridge}}$ has not been calculated, the consumed power of $\mathrm{S}_{\mathrm{Bridge}}$ has not been included in the $\mathrm{S}_{\mathrm{Bridge}}$.

The power flow of $\mathrm{Br}_{GN\to BN}$:

$$|I(r,k)| = \frac{|S_G(r,k)|}{\sqrt{3}\,|U(r,k-1)|}\ , \tag{17}$$

$$\angle I(r,k) = \angle U(r,k-1) - \varphi(r,k)\ . \tag{18}$$

$$P(BN_r,k) = P_G(r,k) - \frac{|S_G(r,k)|^2 R_{Br(GN\to BN)}}{\sqrt{3}\,|U(r,k-1)|}\ . \tag{19}$$

$$Q(BN_r,k) = Q_G(r,k) - \frac{|S_G(r,k)|^2 X_{Br(GN\to BN)}}{\sqrt{3}\,|U(r,k-1)|}\ . \tag{20}$$

Where: $I(r,k)$ is the output current of r# generator unit in the kth iteration, $U(r,k-1)$ is the output voltage of r# generator unit in the k-1th iteration,

$P\left(\mathrm{BN}_r, k\right)$ and $P\left(\mathrm{BN}_r, k\right)$ are respectively the injection active power and reactive power of BN node of r# generator unit in the kth iteration.

When the calculation of $\mathrm{Br}_{\mathrm{GN}\to\mathrm{BN}}$ is completed, the power flow of S_{BN} and S_{Bridge} shall be solved. At this time, the power grid can be simplified into the structure in Figure 3.

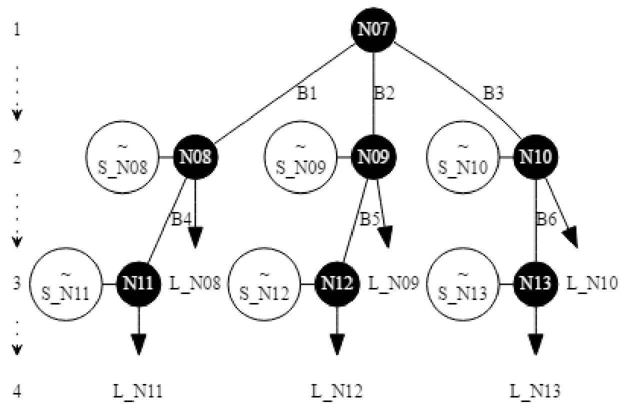

Fig. 3. The simplify network of Fig 2 power grid

Bridgelayer iteration solution

In Figure 3, S_N08 represents virtual injection power of node 8 in the simplified power grid, and L_N08 represents virtual output load of node 8 in the simplified power grid. Among them, let the power of virtual injection power be equal to $\mathrm{S}(\mathrm{BN}_r, k)$ and let the power of virtual output power be equal to the total output power of the nodes. In this case, the network in Figure 3 can still be regarded as an ordered GBDL tree and the power flow of the simplify network can be solved according to the iteration method in Theorem 2. The difference from Theorem 2 is that the formula for calculating the injection power of each node is changed to:

$$P\left(Br(j \to h), u\right) = \frac{\left|S\left(N_h, i+1, u\right)\right|^2 R_{Br(j\to h)}}{\sqrt{3}U\left(N_h, i+1, u-1\right)}. \tag{21}$$

$$Q\left(Br(j \to h), u\right) = \frac{\left|S\left(N_h, i+1, u\right)\right|^2 X_{Br(j\to h)}}{\sqrt{3}U\left(N_h, i+1, u-1\right)}. \tag{22}$$

$$\begin{aligned} P\left(N_j, i, u\right) =& P\left(L_j, i\right) - P\left(S_j, i, u\right) \\ &+ \sum_{h\in H}\left[P\left(N_h, i+1, u\right) + P\left(Br(j\to h), u\right)\right] \end{aligned} \tag{23}$$

$$Q\left(N_j, i, u\right) = Q\left(L_j, i\right) + -Q\left(S_j, i, u\right)$$

$$\sum_{h\in H}\left[Q\left(N_h,i+1,u\right)+P\left(Br(j\to h),u\right)\right]. \tag{24}$$

Where: $P\left(S_j,i\right)+iQ\left(S_j,i\right)$ represents the power of virtual injective power of node N_j, $P\left(Br(j\to h),u\right)+Q\left(Br(j\to h),u\right)$ is the consumed power of branch $\mathrm{Br}(j\to h)$ and the meaning of other symbols remains unchanged.

Because $S\left(S_j,i,u\right)=P\left(S_j,i,u\right)+iQ\left(S_j,i,u\right)$ is the virtual injection power of N_j after the uth iteration and denoted as the consumed power of S_{Bridge} in the initial iteration, after the completion of reverse solution of the power flow of node N_j and related branches, the virtual injection power shall be corrected and regarded as the virtual injection power of the $u+1$th iteration:

$$\begin{aligned}S\left(S_j,i,u+1\right)=&S\left(S_j,i,u\right)+K_p\left(j\right)\sum_{h\in H}\left[P\left(Br\left(j\to h\right),u\right)-P\left(Br\left(j\to h\right),u-1\right)\right]\\&+iK_q\left(j\right)\sum_{h\in H}\left[Q\left(Br\left(j\to h\right),u\right)-Q\left(Br\left(j\to h\right),u-1\right)\right]\end{aligned} \tag{25}$$

Where: The calculation result of $S\left(S_j,i,u+1\right)$ is regarded as the results of the ordered GBDL tree set in the kth iteration.

By Theorem 1, for $\forall\mathrm{OS}_{\mathrm{GBDL}}$, its corresponding graph is undirected tree, therefore, $\forall\mathrm{OS}_{\mathrm{GBDL}}$ can be simplified into the simplify network of Bridge layer iteration solution shown in Figure 3.

4. Example verification and result analysis

34-node power system shown in Figure 2 is taken as an example to verify the proposed algorithm. The test method is as follows: sort the branch sets in the power grid according to the number in Figure 2 to form the ordered branch set, respectively disconnect each branch in this ordered branch set, and then test the power flow calculation results with the power flow algorithm based on the ordered GBDL tree set number and the power flow algorithm based on breadth-first search number through the computer program to obtain the average execution time of the corresponding algorithm.

The average execution time of the above power flow algorithm is shown in Table 1.

Table 1. The algorithm average execution time

Name of two algorithms	Average execution time/μs
Power flow algorithm based on ordered GBDL tree set number	513
Power flow algorithm based on breadth-first search number	598

It can be seen that in the above test environment, in terms of the power flow calculation, the average execution time of the power flow algorithm based on ordered GBDL tree set number is 513μs and that of power flow algorithm based on breadth-first search number is 598μs. The former is less than the latter.

5. Conclusion

Aiming at the multi-station ship power grid, this paper uses the breadth-first traversal ship power grid node numbering method to conduct recursion and traversal for the backbone bridge nodes and branches in which the situation that the node has no solution and the new search of solved node is required often occurs. This paper proposes the ordered GBDL tree set theory and puts forward an improved ship power flow algorithm according to this theory so that each GBDL tree in the tree set can be sorted according to the degree of Bridge layer node. For the iterative solution of power flow of Bridge layer, the method of virtual nodes is used to simplify the network structure and the iteration results are used to correct the power of the virtual nodes so as to accelerate the iteration speed and guarantee the correctness of results, effectively solving the problem that the node may has no solution temporarily and the new search of solved node is required when the breadth-first traversal ship power grid node numbering method is used for multi-station ship power grid. Through example verification, in the multi-station ship power grid, the average execution time of the power flow algorithm based on ordered GBDL tree set number is less than that of power flow algorithm based on breadth-first search number.

The real-time performance of the proposed algorithm in this paper has been verified through practical calculation example, but the average execution time of this algorithm has not been analyzed and proved. The next step is to prove that the execution time of this algorithm is better than the power flow algo-rithm based on breadth-first search number through the derivation of mathe-matical formula.

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