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doi:10.15199/48.2021.11.19

Elementwise power losses calculation in complex distribution power networks represented by hierarchical-multilevel topology structure

Abstract. *Complex ramified distribution power networks (DPN) 6-20 kV are characterized by large dimension, development dynamism, insufficient regime information completeness and reliability. Structured hierarchical-multilevel approach to the elementwise calculation of power losses in DPN is proposed. The DPN structural model is described. A substantive description of this approach is given on the example of ramified DPN with n nodes and m sections (transmission line and transformer) with a tree structure.*

Streszczenie. *Złożone rozgałęzione Sieci Elektroenergetyczne (DPN) 6-20 kV charakteryzują się dużym wymiarem, dynamiką rozwoju, niewystarczającą kompletnością informacji o reżimie i niezawodnością. Zaproponowano ustrukturyzowane hierarchiczno-wielopoziomowe podejście do pierwiastkowego obliczania strat mocy w DPN. Opisano model strukturalny DPN. Merytoryczny opis takiego podejścia podano na przykładzie rozgałęzionego DPN z węzłami n i odcinkami m (linia transmisyjna i transformator) o strukturze drzewa. (**Obliczanie strat mocy w złożonych sieciach dystrybucyjnych reprezentowanych przez hierarchiczną-wielopoziomową strukturę topologii**)*

Keywords: power transmission, power quality, power distribution, structured hierarchical-multilevel approach, tree structure, oriented graph, topology analysis.
Słowa kluczowe: transmisja mocy, jakość mocy, rozkład mocy, ustrukturyzowane podejście hierarchiczno-wielopoziomowe, struktura drzewa, graf zorientowany, analiza topologiczna.

Introduction

Well known, power losses in power systems consist of the following components [1-8]: load power losses in lines and transformers; transformers idle losses; corona losses in overhead lines; power consumption for substations own needs; power consumption in compensating devices; losses in substation reactors; losses in measuring current and voltage transformers and their secondary circuits, including electricity meters.

Power losses calculation is representative in part of specific contribution of transmission lines and transformers load losses to the total losses amount. This estimation is strongly related with network structural intricacy and calculation complexity. [5, 9]. A significant part of power energy is transmitted through highly ramified distribution networks of 6-20 kV, which operate mostly in a radial mode.

They are characterized by large dimension, development dynamism, insufficient regime information completeness and reliability. In these networks losses magnitude can reach up to 70% of the power system total losses amount, therefore, the objective losses assessment is extremely important for considered networks. In this way it is important to develop efficient algorithmic solutions in terms of implementation convenience as well as acceptable computational complexity.

Taking into account the complexity of ramified distribution power networks (DPN), this work proposes a structured hierarchical-multilevel approach to the power losses elementwise calculation. The use of Petri nets calculation apparatus [10,11] for this approach provides the capability to obtain a self-organizing multicomponent computational algorithm, suitable for application on any computer and appropriate for modification and interpretation.

Methods

A ramified DPN with *n* nodes and *m* sections (transmission line and transformer) with a tree structure is considered.

Determination of the load power losses in the whole network and each section is required. Considered to be given: DPN scheme, section impedance, load currents.

Further, the DPN scheme is represented in the form of a directed graph (L, Γ) with a tree structure, where L – is a set of network nodes (graph vertices); Γ – is a mapping of the set L to L, showing how the nodes of the network from the set L are connected to each other, i.e.:

(1) $$\Gamma : L \to L, \quad \Gamma(i) \subset L, \quad \forall i \in L \backslash L_0,$$

(2) $$\Gamma \subseteq L \times L, \quad \Gamma_i = \{i\} \times \Gamma(i), \quad \forall i \in L \setminus L_0,$$

(3) $$\Gamma = \bigcup_{i \in L \setminus L_0} \Gamma_i, \quad L \setminus \{0\} = \bigcup_{i \in L \setminus L_0} \Gamma(i), \quad L_0 \subset L$$

(4) $$\Gamma(i) = \varnothing, \quad \Gamma_i = \varnothing, \quad \forall i \in L_0 \ ,$$

where $\Gamma(i)$ – is the set of terminal arc apexes (oriented edges), for which the initial vertex is the node $i \in L \backslash L_0$; Γ_i – is the set of arcs $i \in L \backslash L_0$; L_0 – is the set of graph terminal vertices (L, Γ), i.e. terminal (load) network nodes; $L \backslash L_0$ – is the set of intermediate graph vertices (L, Γ) including its root $i = 0$, i.e. intermediate nodes, including the network power source node.

Each terminal vertex $i \in L_0$ of the network graph (L, Γ) is associated with the load current J_i, and each arc $(i, j) \in \Gamma$ - is associated with the resistance R_{ij} and the current I_{ij} of the corresponding network section. It should be noted that the current I_{ij} of the arc (i, j) is equal to the current I_j, flowing through the terminal vertex j of this arc (the current of the j-th network node).

The proposed approach description for solving this problem is accompanied by an example of a DPN, presented in the form of a directed graph diagram, shown in Figure 1.

The network graph under consideration (Fig. 1) has:

$$L = \{0, 1, 2, ..., 21\}, \quad L_0 = \{1, 2, 3, ..., 13\},$$
$$L \setminus L_0 = \{0, 14, 15, ..., 21\},$$

sets of $\Gamma(i)$, Γ_i, $\forall i \in L \backslash L_0$ from (1) - (4), corresponding to this example are shown in Table 1; the set of arcs Γ is obtained using formula (4), i.e. the union of the sets of Γ_i, $\forall i \in L \backslash L_0$ (Table 1).

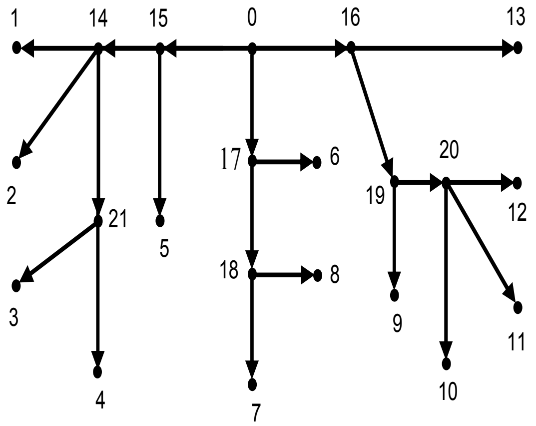

Fig. 1. Distribution power network graph

Table 1. The sets of $\Gamma(i)$, Γ_i, $\forall i \in L \backslash L_0$ to example 1

№	Sets $\Gamma(i)$, $\forall i \in L \backslash L_0$	Sets Γ_i, $\forall i \in L \backslash L_0$
1	$\Gamma(0) = \{15, 16, 17\}$	$\Gamma_0 = \{(0,15), (0,16), (0,17)\}$
2	$\Gamma(14) = \{1, 2\}$	$\Gamma_{14} = \{(14,1), (14,2)\}$
3	$\Gamma(15) = \{5, 14\}$	$\Gamma_{15} = \{(15,5), (15,14)\}$
4	$\Gamma(16) = \{13, 19\}$	$\Gamma_{16} = \{(16,13), (16, 19)\}$
5	$\Gamma(17) = \{6, 18\}$	$\Gamma_{17} = \{(17,6), (17,18)\}$
6	$\Gamma(18) = \{7, 8\}$	$\Gamma_{18} = \{(18,7), (18,8)\}$
7	$\Gamma(19) = \{9, 20\}$	$\Gamma_{19} = \{(19,9), (19,20)\}$
8	$\Gamma(20) = \{10, 11, 12\}$	$\Gamma_{20} = \{(20,10), (20,11), (20,12)\}$
9	$\Gamma(21) = \{3, 4\}$	$\Gamma_{21} = \{(21,3), (21,4)\}$

Power losses ΔW_{ij} in each branch $(i, j) \in \Gamma$ during the Δt time interval are determined as follows:

(5) $$\Delta W_{ij} = 3 \cdot \Delta t \cdot R_{ij} \cdot I_{ij}^2 = 3 \cdot \Delta t \cdot R_{ij} \cdot I_j^2.$$

The current $I_{ij} = I_j$ of the network section (i, j) is determined as the sum of the load currents passing from the power source through this section:

(6) $$I_{ij} = I_j = \sum_{k \in L_0^{(i,j)}} J_k, \quad \forall (i, j) \in \Gamma,$$

where $L_0^{(i,j)}$ – is the set of load nodes, for which supplying currents of these loads J_k, $\forall k \in L_0^{(i,j)}$, from the power source pass through the section (i, j).

Total power losses in the network ΔW_C is the sum of losses in all its branches:

(7) $$\Delta W_C = \sum_{(i,j) \in \Gamma} \Delta W_{ij}.$$

There is information uncertainty in formula (6), since the set $L_0^{(i,j)}$ is not determined. This set can be obtained only by solving the topology analyzing problem of the initial network graph. To overcome uncertainty without topology analyzing this work proposes a hierarchical-multilevel approach to load power losses calculation.

The following notion is to be introduced: vertex $\forall i \in L \backslash L_0$ of a network graph is called information-secured if the currents I_j, $\forall j \in \Gamma(i)$ are determined.

A structured hierarchical-multilevel approach to the elementwise load power losses calculation consists of the following steps (see Fig. 2).

Step 0. Form a set of zero hierarchy level vertices ($s = 0$) from the terminal vertices of the initial network graph, i.e. set L_0 and calculate corresponding vertices currents:

(8) $$I_i = J_i, \quad \forall i \in L_0.$$

Set up ΔW_C initial state equal to zero, i.e.: $\Delta W_C^{(0)} = 0$.

Step 1. Calculate the next hierarchy level: $s = s + 1$.

Step 2. Set up initial state of sets L_s^B, L_s^H:

(9) $$L_s^B = L \backslash L_0, \quad L_s^H = L_0.$$

Step 3. Generate s-th level informational-secured vertices set L_s of hierarchy:

(10) $$L_s = \{i \in L_s^B \mid \Gamma(i) \subseteq L_s^H\}.$$

Step 4. Calculate the current I_j for each vertex $i \in L_s$:

(11) $$I_i = \sum_{j \in \Gamma(i)} I_j, \quad \forall i \in L_s.$$

Step 5. Calculate power losses ΔW_{ij} for each branch $(i, j) \in \Gamma_i$, $\forall i \in L_s$:

(12) $$\Delta W_{ij} = 3 \Delta t R_{ij} I_j^2, \quad \forall (i, j) \in \Gamma_i, \quad \forall i \in L_s.$$

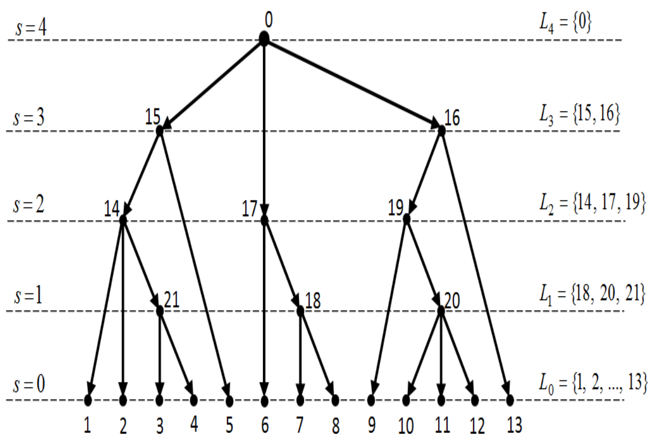

Fig. 2. Hierarchical-multilevel structure of the initial network graph (L, Γ)

Step 6. Sum the branch power losses to determine the total network power losses ΔW_C:

(13) $$\Delta W_C^{(s)} = \Delta W_C^{(s-1)} + \sum_{(i,j)\in\Gamma_{L_s}} \Delta W_{ij},$$

where $\Gamma_{L_s} = \bigcup_{i\in L_s} \Gamma_i$.

Step 7. Calculate the next hierarchy level using the formula (10).

Step 8. Calculate the new state of the sets L_s^B, L_s^H :

(14) $$L_s^B = L_{s-1}^B \setminus L_{s-1},$$

(15) $$L_s^H = L_{s-1}^H \bigcup L_{s-1},$$

where $L_s^B \bigcup L_s^H = L,\ \forall s \in \{1, 2, 3, ...\}$.

Step 9. If $L_s^B \neq \emptyset$ (or $L_s^H \neq L$), then go to step 3, otherwise go to step 10.

Step 10. Calculate s_{max} level maximum number in the network hierarchical-multilevel structure:

(16) $$s_{\max} = s - 1.$$

Step 11. Stop.

Implementation

The sets $L,\ L_0,\ L \setminus L_0,\ \Gamma(i),\ \Gamma_i,\ \forall i \in L \setminus L_0$ for the considered network graph (Fig. 1) are shown in example 1.

Step 0. The zero level $s = 0$ of hierarchical multilevel structure is under consideration (Fig. 2). The node currents (load currents) correspond to this level:

$$I_1 = J_1,\ I_2 = J_2,\ ...,\ I_{13} = J_{13}.$$

Network losses adder initial state: $\Delta W_C^{(0)} = 0$.

Step 1. Next level of hierarchy (**first** level): $s = s + 1 = 1$.

Step 2. The vertices set where search for informational-secured vertices of the **first** level is performed:

$$L_1^B = \{0, 14, 15, ..., 21\}.$$

The vertices set of all levels obtained before the search for information-security vertices of the current **first** level:

$$L_1^H = \{1,\ 2,\ 3,\ ...,\ 13\}.$$

Step 3. The set of informational-secured vertices of the current **first** level of the hierarchy:

$$L_1 = \{i \in L_1^B \mid \Gamma(i) \subseteq L_1^H\} = \{18,\ 20,\ 21\}.$$

Step 4. Currents corresponding to vertices from the set L_1 (see step 3):

$$I_{18} = I_7 + I_8,\quad I_{20} = I_{10} + I_{11} + I_{12},\quad I_{21} = I_3 + I_4.$$

Step 5. Power losses corresponding to arcs from the set Γ_{18}:

$$\Delta W_{18,7} = 3\cdot\Delta t\cdot R_{18,7}\cdot I_7^2,\ \Delta W_{18,8} = 3\cdot\Delta t\cdot R_{18,8}\cdot I_8^2 \ .$$

Power losses corresponding to arcs from Γ_{20}:

$$\Delta W_{20,\,10} = 3\cdot\Delta t\cdot R_{20,10}\cdot I_{10}^2,\ \Delta W_{20,\,11} = 3\cdot\Delta t\cdot R_{20,11}\cdot I_{11}^2,$$

$$\Delta W_{20,\,12} = 3\cdot\Delta t\cdot R_{20,12}\cdot I_{12}^2$$

Power losses corresponding to arcs from Γ_{21}:

$$\Delta W_{21,\,3} = 3\cdot\Delta t\cdot R_{21,3}\cdot I_3^2,\ \ \Delta W_{21,\,4} = 3\cdot\Delta t\cdot R_{21,4}\cdot I_4^2.$$

Sets Γ_{18}, Γ_{20}, Γ_{21} were previously defined in Tab. 1 of example.

Step 6. Losses adder state in the network of the **first** level of the hierarchy:

$$\Delta W_C^{(1)} = \Delta W_C^{(0)} + \sum_{(i,j)\in\Gamma_{L_1}} \Delta W_{ij} =$$

$$= \Delta W_{18,7} + \Delta W_{18,8} + \Delta W_{20,10} + \Delta W_{20,11} + \Delta W_{20,12} + \Delta W_{21,3} + \Delta W_{21,4},$$

where:

$$\Gamma_{L_1} = \bigcup_{i\in L_1} \Gamma_i = \Gamma_{18} \bigcup \Gamma_{20} \bigcup \Gamma_{21} =$$

$$= \{(18,\ 7),\ (18,\ 8),\ (20,\ 10), (20,\ 11),\ (20,\ 12),\ (21,\ 3),\ (21,\ 4)\}.$$

Step 7. Next level of hierarchy (**second** level): $s = s + 1 = 1 + 1 = 2$.

Step 8. The vertices set where search for informational-secured vertices of the **second** level is performed:

$$L_2^B = L_1^B \setminus L_1 =$$

$$= \{0, 14, 15, ..., 21\} \setminus \{18, 20, 21\} = \{0, 14, 15, 16, 17, 19\}.$$

The vertices set of all levels obtained before the search for information-security vertices of the current **second** level:

$$L_2^H = L_1^H \bigcup L_1 = \{1,\ 2,\ 3,\ ...,\ 13,\ 18,\ 20,\ 21\}.$$

$$L_2^B \bigcup L_2^H = L = \{0, 1, 2, ..., 21\}.$$

Step 9. Since $L_2^B \neq \emptyset$ (see step 8), then go to step 3.

Second iteration at $s = 2$.

Step 3. The set of informational-secured vertices of the current **second** level of the hierarchy:

$$L_2 = \{i \in L_2^B \mid \Gamma(i) \subseteq L_2^H\} = \{14, 17, 19\}.$$

Step 4. Currents corresponding to vertices from the set L_2 :

$$I_{14} = I_1 + I_2 + I_{21};\ I_{17} = I_6 + I_{18};\ I_{19} = I_9 + I_{20}.$$

Step 5. Power losses corresponding to arcs from Γ_{14}:

$$\Delta W_{14,1} = 3\cdot\Delta t\cdot R_{14,1}\cdot I_1^2,\quad \Delta W_{14,2} = 3\cdot\Delta t\cdot R_{14,2}\cdot I_2^2,$$

$$\Delta W_{14,21} = 3\cdot\Delta t\cdot R_{14,21}\cdot I_{21}^2.$$

Power losses corresponding to arcs from Γ_{17}:

$$\Delta W_{17,6} = 3\cdot\Delta t\cdot R_{17,6}\cdot I_6^2,\quad \Delta W_{17,18} = 3\cdot\Delta t\cdot R_{17,18}\cdot I_{18}^2.$$

Power losses corresponding to arcs from Γ_{19}:

$$\Delta W_{19,9} = 3\cdot\Delta t\cdot R_{19,9}\cdot I_9^2,\quad \Delta W_{19,20} = 3\cdot\Delta t\cdot R_{19,20}\cdot I_{20}^2.$$

Step 6. Losses adder state in the network of the **second** level of the hierarchy:

$$\Delta W_C^{(2)} = \Delta W_C^{(1)} + \sum_{(i,j)\in\Gamma_{L_2}} \Delta W_{ij} = = \Delta W_C^{(1)} + \Delta W_{14,1} +$$

$$+ \Delta W_{14,2} + \Delta W_{14,21} + +\Delta W_{17,6} + \Delta W_{17,18} + \Delta W_{19,9} + \Delta W_{19,20},$$

where:

$$\Gamma_{L_2} = \bigcup_{i\in L_2} \Gamma_i = \Gamma_{14} \bigcup \Gamma_{17} \bigcup \Gamma_{19} =$$

$$= \{(14, 1), (14, 2), (14, 21), (17, 6), (17, 18), (19, 9), (19, 20)\}$$

Step 7. Next level of hierarchy (**third** level):

$$s = s + 1 = 2 + 1 = 3 .$$

Step 8. The vertices set where search for informational-secured vertices of the **third** level is performed:

$$L_3^B = L_2^B \setminus L_2 =$$
$$= \{0, 14, 15, 16, 17, 19\} \setminus \{14, 17, 19\} = \{0, 15, 16\}.$$

The vertices set of all levels obtained before the search for information-security vertices of the current **third** level:

$$L_3^H = L_2^H \cup L_2 = \{1, 2, 3, ..., 13, 18, 20, 21\} \cup \{14, 17, 19\} =$$
$$= \{1, 2, 3, ..., 13, 14, 17, 18, 19, 20, 21\};$$
$$L_3^B \cup L_3^H = L = \{0, 1, 2, ..., 21\}.$$

Step 9. Since $L_3^B \neq \emptyset$ (see step 8 of **second** iteration), then go to step 3.
Third iteration at $s = 3$.
Step 3. The set of informational-secured vertices of the current **third** level of the hierarchy:

$$L_3 = \{i \in L_3^B \mid \Gamma(i) \subseteq L_3^H\} = \{15, 16,\}.$$

Step 4. Currents corresponding to vertices from the set L_3:

$$I_{15} = I_5 + I_{14}, \quad I_{16} = I_{13} + I_{19}.$$

Step 5. Power losses corresponding to arcs from Γ_{15}:

$$\Delta W_{15,5} = 3 \cdot \Delta t \cdot R_{15,5} \cdot I_5^2, \quad \Delta W_{15,14} = 3 \cdot \Delta t \cdot R_{15,14} \cdot I_{14}^2;$$

Power losses corresponding to arcs from Γ_{16}:

$$\Delta W_{16,13} = 3 \cdot \Delta t \cdot R_{16,13} \cdot I_{13}^2, \quad \Delta W_{16,19} = 3 \cdot \Delta t \cdot R_{16,19} \cdot I_{19}^2.$$

Step 6. Losses adder state in the network of the **third** level of the hierarchy:

$$\Delta W_C^{(3)} = \Delta W_C^{(2)} + \sum_{(i,j) \in \Gamma_{L_3}} \Delta W_{ij} =$$
$$= \Delta W_C^{(2)} + \Delta W_{15,5} + \Delta W_{15,14} + \Delta W_{16,13} + \Delta W_{16,19},$$

where:

$$\Gamma_{L_3} = \bigcup_{i \in L_3} \Gamma_i = \Gamma_{15} \cup \Gamma_{16} = \{(15, 5), (15, 14), (16, 13), (16, 19)\}.$$

Step 7. Next level of hierarchy (**fourth** level):

$$s = s + 1 = 3 + 1 = 4.$$

Step 8. The vertices set where search for informational-secured vertices of the **fourth** level is performed:

$$L_4^B = L_3^B \setminus L_3 = \{0, 15, 16\} \setminus \{15, 16\} = \{0\};$$

The vertices set of all levels obtained before the search for information-security vertices of the current **fourth** level:

$$L_4^H = L_3^H \cup L_3 =$$
$$\{1, 2, 3, ..., 13, 14, 17, ..., 21\} \cup \{15, 16\} = \{1, 2, 3, ..., 21\};$$
$$L_4^B \cup L_4^H = L = \{0, 1, 2, ..., 21\}.$$

Step 9. Since $L_4^B \neq \emptyset$ (see step 8 of **third** iteration), then go to step 3.
Fourth iteration at $s = 4$.
Step 3. The set of informational-secured vertices of the current **fourth** level of the hierarchy:

$$L_4 = \{i \in L_4^B \mid \Gamma(i) \subseteq L_4^H\} = \{0\}.$$

Step 4. Currents corresponding to vertices from the set L_4:

$$I_0 = I_{15} + I_{16} + I_{17}.$$

Step 5. Power losses corresponding to arcs from Γ_0:

$$\Delta W_{0,15} = 3 \cdot \Delta t \cdot R_{0,15} \cdot I_{15}^2, \quad \Delta W_{0,16} = 3 \Delta t R_{0,16} I_{16}^2,$$
$$\Delta W_{0,17} = 3 \Delta t R_{0,17} I_{17}^2.$$

Step 6. Losses adder state in the network of the **fourth** level of the hierarchy:

$$\Delta W_C^{(4)} = \Delta W_C^{(3)} + \sum_{(i,j) \in \Gamma_{L_4}} \Delta W_{ij} = \Delta W_C^{(3)} + \Delta W_{0,15} + \Delta W_{0,16} + \Delta W_{0,17},$$

where:

$$\Gamma_{L_4} = \bigcup_{i \in L_4} \Gamma_i = \Gamma_0 = \{(0, 15), (0, 16), (0, 17)\}.$$

Step 7. Next level of hierarchy (**fifth** level):

$$s = s + 1 = 4 + 1 = 5.$$

Step 8. The vertices set where search for informational-secured vertices of the **fifth** level is performed:

$$L_5^B = L_4^B \setminus L_4 = \{0\} \setminus \{0\} = \emptyset,$$

The vertices set of all levels obtained before the search for information-security vertices of the current **fifth** level:

$$L_5^H = L_4^H \cup L_4 = \{1, 2, 3, ..., 21\} \cup \{0\} = \{0, 1, 2, ..., 21\},$$
$$L_5^B \cup L_5^H = L = \{0, 1, 2, ..., 21\}.$$

Step 9. Since $L_4^B \neq \emptyset$, then go to step 10.
Step 10. The levels maximum number in a hierarchical-multilevel network structure:

$$s_{\max} = s - 1 = 5 - 1 = 4 \text{ (see Fig. 2).}$$

Step 11. Stop.

Conclusion

On the example of a complex ramified DPN, a structured hierarchical-multilevel approach to the elementwise power losses calculation was proposed and its effectiveness was shown. With approach implementation the usage of Petri nets apparatus allowed to obtain a self-organizing multicomponent computational algorithm convenient for adaptation on any computer, modification and interpretation.

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