1. Salima ASANOVA[1], 2. Murodbek SAFARALIEV[2], 3. Nurlan ASKARBEK[1], 4. Sergey SEMENENKO[2], 5. Erkin AKTAEV[1], 6. Anastasia KOVALEVA[2], 7. Egor LYUKHANOV[2], 8. Elena STAYMOVA[2]

Kyrgyz state technical university, Republic of Kyrgyzstan (1), Ural federal university, Russian Federation (2)
ORCID: 1. 0000-0003-4538-934X; 2. 0000-0003-3433-9742; 4. 0000-0001-9813-9067; 7. 0000-0002-4577-593X .

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Calculation of power losses at given loads and source voltage in radial networks of 35 kV and above by hierarchical-multilevel structured topology representation

***Abstract**. This paper provides structured hierarchical-multilevel approach to the regimes and power losses calculation in distribution power networks of 35 kV and above at given loads and power source voltage level. It based on hierarchical-multilevel structure form representation of the radial power network initial graph and using of traditional engineering two-step method. This approach usage make it possible to obtain a universal (for arbitrary power network configuration and complexity) and efficient (in terms of the computational operations number and computer memory consumption) algorithm.*

***Streszczenie.** W artykule przedstawiono ustrukturyzowane, hierarchiczno-wielopoziomowe podejście do obliczania zakresów i strat mocy w sieciach dystrybucyjnych o napięciu 35 kV i wyższych przy zadanych obciążeniach i poziomie napięcia źródła zasilania. Opiera się on na hierarchiczno-wielopoziomowej strukturze odwzorowania początkowego wykresu radialnej sieci elektroenergetycznej i zastosowaniu tradycyjnej dwuetapowej metody inżynierskiej. Zastosowanie tego podejścia pozwala na uzyskanie uniwersalnego (dla dowolnej konfiguracji i złożoności sieci elektroenergetycznej) i wydajnego (pod względem liczby operacji obliczeniowych i zajętości pamięci komputera) algorytm. (**Obliczanie strat mocy przy danych obciążeniach i napięciu źródła w sieciach promieniowych o napięciu 35 kV i wyższych za pomocą hierarchiczno-wielopoziomowej strukturalnej reprezentacji topologii**)*

Keywords: distribution power networks, power losses, structured hierarchical-multilevel approach, tree structure, oriented graph, topology analysis.
Słowa kluczowe: sieci dystrybucyjne, straty mocy, ustrukturyzowane podejście hierarchiczno-wielopoziomowe, struktura drzewiasta, zorientowany wykres, analiza topologii.

Introduction

According to [1-3], in opposite to the power losses calculation tasks in networks with $U_{nom} \geq 35$ kV , the features of power losses calculation tasks in distribution power networks (DPN) with voltage level of $U_{nom} < 35$ kV nclude: overhead lines charging power accounting, Q_C; overhead lines corona losses accounting, ΔP_{cor}; taking into account power losses $\Delta \underline{S}$ at sections during power flows $\underline{S}$ calculation; taking into account the longitudinal ΔU and transverse δU voltage drop components in the power network sections, calculated according to the actual voltage level U, not by the nominal one.

Power networks with $U_{nom} \geq 35$ kV are similar by configuration to 6-20kV networks but from the operating information point of view are sufficiently provided and more adjacent to the DPN [2].

These specific power networks with $U_{nom} \geq 35$ kV features indicate that in order to determine power losses, it will be necessary to solve the regims calculation problem, i.e. determination of unknown voltage levels in nodes, power flows and power losses in their sections (linear and transformer) [4-11]. These calculations [1-3] perform, as a rule, at a given power source voltage level and constant load values on the low-voltage side of step-down consumer substations (such initial information setting method has the best meets the operating conditions and is conventional for the considered power networks).

The regimes calculation method [1-3] of radial power networks when setting the specified operating parameters is iterative, moreover each iteration includes the following two stages:

at the **first** stage (from bottom to top), power flows and power losses in lines and transformers from loads to the power source are determined;

at the **second** stage (from top to bottom), the nodes voltages from the power source to the loads are calculated. The procedure (two stages) is repeated until the specified calculation accuracy is obtained.

Technique analysis shows that its implementation will require solving the problem of network topology analyzing and universal effective algorithm developing for its solution, suitable for any radial power network configuration.

This paper provides structured hierarchical-multilevel approach to the regimes and power losses calculation in distribution power networks of 35 kV and above at given loads and power source voltage level. The advantage of this approach is the usage of the Petri nets calculation apparatus [12,13] for its implementation that make it possible to build a self-organizing multicomponent computational algorithm, acceptable for its implementation on a computer, modification and interpretation as well as from the standpoint of organizing parallel-sequential computations with the purpose of increasing calculation speed.

Methods

A ramified power network of 35 kV and higher with n nodes and m sections (linear and transformer) with a tree structure and one nominal voltage is considered. Considered to be given: network diagram; loads; resistance and conductivity of sections; power supply voltage. It is required to determine: unknown nodes actual voltage levels; power flows and losses at sections; power losses in the network at whole.

Further, the radial power network 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 $i\in L\setminus L_0$; Γ_i – is the set of arcs $i\in L\setminus L_0$; L_0 – is the set of graph terminal vertices (L, Γ) , i.e. terminal (load) network nodes; $L\setminus L_0$ – is the set of intermediate graph vertices (L, Γ) including its root *i* = 0, i.e. intermediate nodes, including the network power source node.

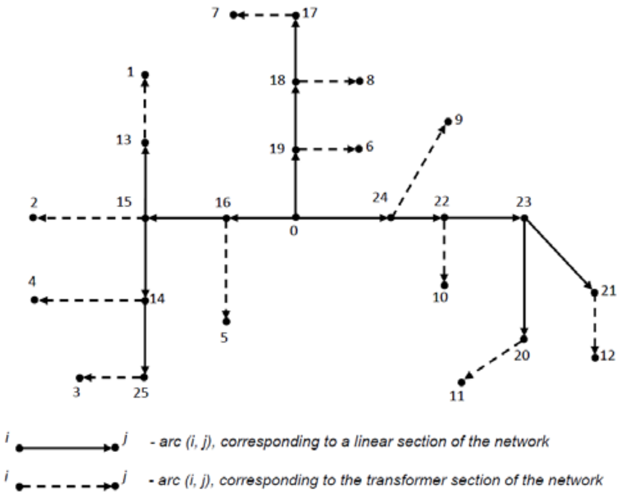

Fig. 1. Radial power network graph

To each terminal arc $(i, j)\in \Gamma^{TA}$ of the network graph (L, Γ) , where Γ^{TA} - the set of terminal arcs:

(5) $\Gamma^{TA}=\{(i, j)\in \Gamma \mid j\in L_0\}$,

corresponds to a two-winding transformer, the which equivalent circuit is shown in Figure 2, *a*. Each intermediate arc $(i, j)\in \Gamma\setminus\Gamma^{TA}$ corresponds to a power transmission line which equivalent circuit is shown in Figure 2, *b*.

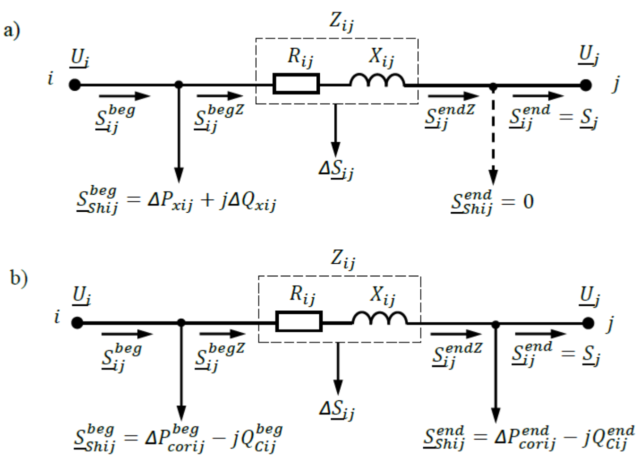

Fig. 2. Power network sections equivalent circuits, where *a* is the transformer section equivalent circuit, *b* is the linear section equivalent circuit

The following designations are adopted here: $\underline{S}_{ij}^{beg}$, $\underline{S}_{ij}^{end}$ - power flows respectively at the beginning and at the end of the section $(i, j)\in \Gamma$; $\underline{S}_{ij}^{begZ}$, $\underline{S}_{ij}^{endZ}$ - power flows respectively at the beginning and at the end of the resistance $\underline{Z}_{ij}$ at the section $(i, j)\in \Gamma$; $\underline{S}_j$ - power flow through the node *j*є*L* (since the power flows are directed from the power supply node *i=0* to the set of load nodes L_0 (see Figure 1), then $\underline{S}_{ij}^{end}=\underline{S}_j$, $\forall (i, j)\in \Gamma$; $\underline{U}_i$, $\underline{U}_j$ - node voltages, respectively, at the beginning and at the end of the section $(i, j)\in \Gamma$; $\underline{S}_{Shij}^{beg}$, $\underline{S}_{Shij}^{end}$ - power flowes (losses) in shunts, i.e. in transverse branches, respectively, at the beginning and at the end of the section $(i, j)\in \Gamma$; $\Delta \underline{S}_{ij(k)}$ - power losses in resistance $\underline{Z}_{ij}$; ΔP_{xij} - active power losses in transformer steel for magnetization reversal (hysteresis) and eddy currents; ΔQ_{xij} - reactive power losses in the transformer steel for its magnetization; ΔP_{corij} - active power losses to the corona (or in isolation); ΔQ_{cij} - charging power.

Further, to calculate regime parameters above following parameters of the network elements are used: R_{ij}, X_{ij} - respectively active and reactive resistance of the section longitudinal branch $(i, j)\in \Gamma$; g_{ij}, b_{ij} - respectively active and reactive conductivity in the section transverse branches $(i, j)\in \Gamma$.

For the directed network graph shown in Figure 1:

$$L=\{0, 1, 2, ..., 25\}\,; \quad L_0=\{1, 2, 3, ..., 12\}\,;$$
$$L\backslash L_0=\{0, 13, ..., 25\}$$

sets $\Gamma(i)$, Γ_i $\forall i\in L\setminus L_0$ from (1)-(4), corresponding to this example are given in the table; set of arcs Γ is obtained using the formula from (3), i.e. the union of the sets Γ_i , $\forall i\in L\setminus L_0$ (see Table 1).

Table 1. Sets $\Gamma(i)$, Γ_i , $\forall i\in L\setminus L_0$

№	Sets $\Gamma(i)$, $\forall i\in L\setminus L_0$	Sets Γ_i , $\forall i\in L\setminus L_0$
1	Γ(0)={16, 19, 24}	Γ0={(0, 16), (0, 19), (0, 24)}
2	Γ(13)={1}	Γ13={(13, 1)}
3	Γ(14)={4, 25}	Γ14={(14, 4), (14, 25)}
4	Γ(15)={2, 13, 14}	Γ15={(15, 2), (15, 13), (15, 14)}
5	Γ(16)={5, 15}	Γ16={(16, 5), (16, 15)}
6	Γ(17)={7}	Γ17={(17, 7)}
7	Γ(18)={8, 17}	Γ18={(18, 8), (18, 17)}
8	Γ(19)={6, 18}	Γ19={(19, 6), (19, 18)}
9	Γ(20)={11}	Γ20={(20, 11)}
10	Γ(21)={12}	Γ21={(21, 12)}
11	Γ(22)={10, 23}	Γ22={(22, 10), (22, 23)}
12	Γ(23)={21, 21}	Γ23={(23, 20), (23, 21)}
13	Γ(24)={9, 22}	Γ24={(24, 9), (24, 22)}
14	Γ(25)={3}	Γ25={(25, 3)}

The sets of terminal arcs of the considered network graph, i.e. Γ^{TA} sets of arcs corresponding to distribution transformers (6):

$$\Gamma^{TA}=\{(13,1), (15,2), (25,3), (14,4), (15,5), (19,6), (17,7), (18,8), (24,9), (22,10), (20,11), (21,12)\}.$$

As noticed above, to calculate the regimes and power losses in radial power networks with U_{nom} ≥ 35 kV at given loads at the terminal nodes $\underline{S}_i$, $\forall i\in L_0$ and power source voltage $\underline{U}_0$ (at *i*=0) two-stage iterative method is used [1-3].

Within each k-th iteration calculation is performed in two stages:

- at the **first** stage (from bottom to top) the regimes parameters $\underline{S}_{ij(k)}^{end}$, $\underline{S}_{Shij(k)}^{end}$, $\underline{S}_{ij(k)}^{endZ}$, $\Delta\underline{S}_{ij(k)}$, $\underline{S}_{ij(k)}^{begZ}$, $\underline{S}_{Shij(k)}^{beg}$, $\underline{S}_{ij(k)}^{beg}$ of all sections $(i,\ j)\in\Gamma$ are determined according to a certain sequence from the loads to the power source. At this stage, in the calculation formulas, the voltages calculated at the second stage of the previous $(k\text{-}1)$-th cycle of the iteration are taken as the voltages of the network nodes $\underline{U}_{i(k-1)},\ \forall i\in L\setminus\{0\}$.

  For $k = 1$, $\underline{U}_{i(0)}=U_{nom},\ \forall i\in L\setminus\{0\}$
- at the **second** stage, the nodes voltages $\underline{U}_{i(k)},\ \forall i\in L\setminus\{0\}$ from the power supply to the loads are calculated in reverse order (from top to bottom) according to the known source voltage $\underline{U}_0$ and the power flowes $\underline{S}_{ij(k)}^{begZ},\ (i,j)\in\Gamma$, determined at the first stage of the current k-th iteration cycle.

Here, to establish and organize such calculation the following concepts are introduced:

- at the **first** stage of the calculation, the network graph vertex $i\in L\setminus L_0$ is called information-secured if the flows $\underline{S}_j,\ \ \forall j\in\Gamma(i)$ are defined;
- at the **second** stage of the calculation, the network graph vertex $j\in L\setminus\{0\}$ is called information-secured if voltage level $\underline{U}_i$ at the beginning of section $(i,j)\in\Gamma$ is determind.

Taking into account the introduced concepts initial network graph can be represented by appropriate transformations, in the form of a hierarchical-multilevel structure (for the considered example of a network, see fig. 3, containing information on the information-secured computations sequence to determine the power flows at first stage and network nodes voltages at the second stage.

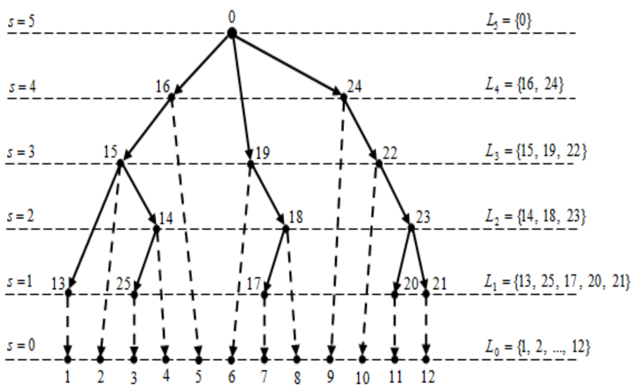

Fig. 3. Initial network graph (L,Γ) hierarchical-multilevel structure

The proposed approach contains the following steps.

Initial network graph representation in the form of hierarchical multilevel structure.

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

Step 1. Set up initial state of sets $L_s^B,\ L_s^H$ (if $s=0$):

(6) $$L_0^B=L\setminus L_0,\ \ L_0^H=L_0\,.$$

Step 2. Calculate the next hierarchy level number: $s=s+1$.

Step 3. Form the set of L_s – information-secured vertices of s-th hierarchy level:

(7) $$L_s=\{i\in L_{s-1}^B\mid\Gamma(i)\subseteq L_{s-1}^H\}.$$

Step 4. Calculate the $L_s^B,\ L_s^H$ sets new state:

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

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

where $L_s^B\bigcup L_s^H=L,\quad\forall s\in\{0,\,1,\,2,\,...\}$.

Step 5. If $L_s^B=\varnothing$, (or $L_s^H=L$), the go to step 6, else go to step 2.

Step 6. Calculate s_{max} level maximum number in the network hierarchical-multilevel structure: $s_{max}=s$.

Step 7. Establish load values $\underline{S}_j,\ \forall j\in L_0$ and power source voltage level U_0 – voltage of the node $i=0$.

Calculation of the steady state and power losses in radial network

Step 8. Calculate $k=0$ and set nodes voltage levels $\underline{U}_{i(0)},\ \forall i\in L\setminus\{0\}$ on $k=0$-th iteration cycle equal to U_{nom}:

(10) $$\underline{U}_{i(0)}=U_{nom},\quad\forall i\in L\setminus\{0\}.$$

Step 9. Return to the hierarchy zero level: $s=0$.

Step 10. Calculate next iteration step number: $k=k+1$.

First stage. Power flows calculation from bottom to top (see Fig.3).

Step 11. Calculate the next hierarchy level number: $s=s+1$.

Step 12. Calculate power flows $\underline{S}_{i(k)},\ \forall i\in L_s$, in the nodes corresponding to the information-secured vertices from L_s of s-th hierarchy level:

Calculate power flows at the beginning of sections $\underline{S}_{ij(k)}^{beg}$, $\forall(i,j)\in\bigcup_{i\in L_s}\Gamma_i$ in the following sequence:

- calculate the powers at the ends of the sections:

(11) $$\underline{S}_{ij(k)}^{end}=\underline{S}_{j(k)},\quad\forall(i,j)\in\bigcup_{i\in L_s}\Gamma_i$$

- calculate the power in shunts at the ends of the sections:

(12) $$\underline{S}_{Shij(k)}^{end}=\begin{cases}0, & for\ j\in L_0,\\ \Delta P_{corij(k)}^{end}-jQ_{cij(k)}^{end}, & for\ j\notin L_0,\end{cases}\quad\forall(i,\ j)\in\bigcup_{i\in L_S}\Gamma_i,$$

where

(13) $$\Delta P_{corij(k)}^{end}=U_{j(k-1)}^2 g_{ij}^{end};$$

(14) $$Q_{cij(k)}^{end}=U_{j(k-1)}^2 b_{ij}^{end};$$

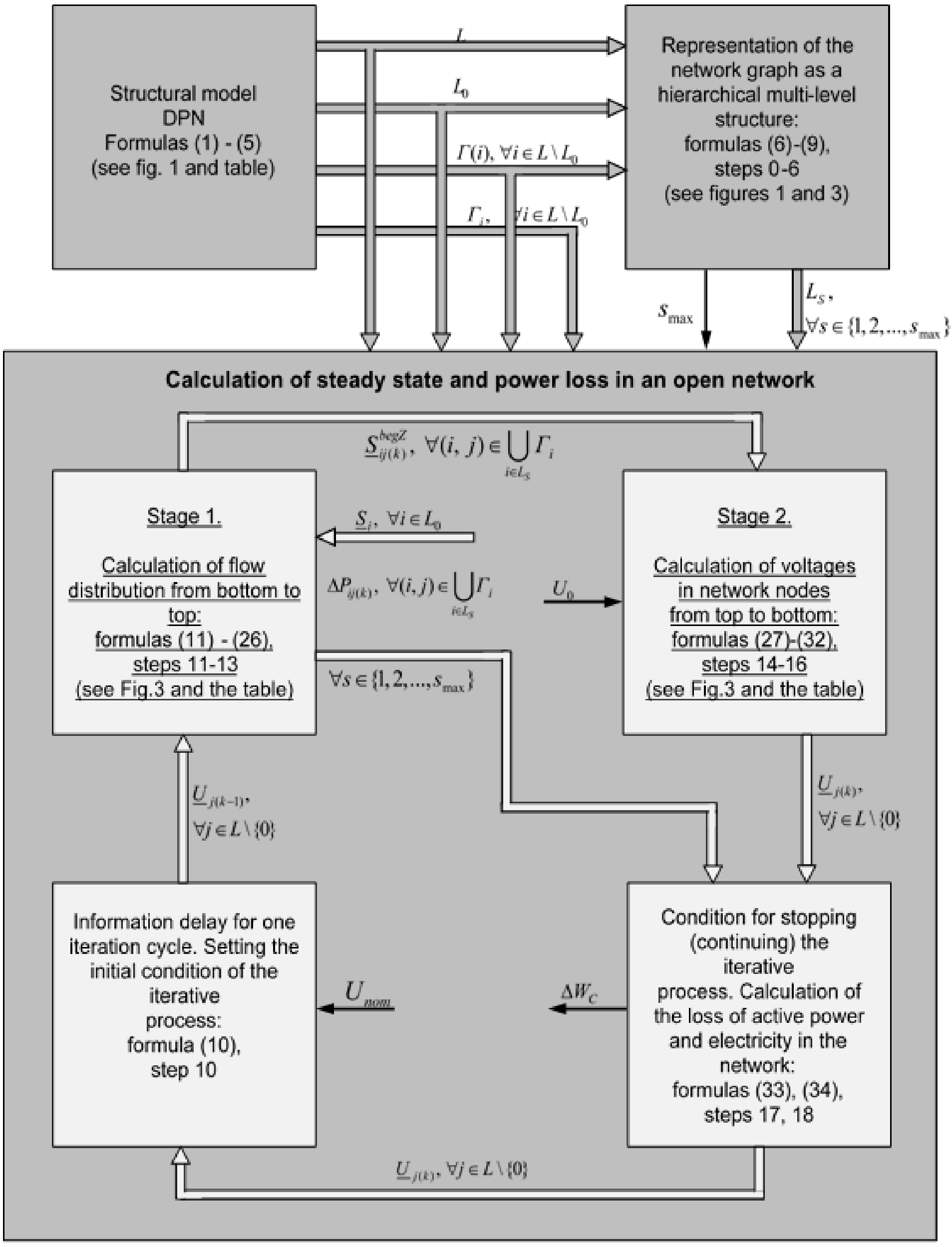

Fig. 4. Functional diagram of a structured hierarchical-multi-level approach to calculating modes and power losses in open electric networks with $U_{nom} \geq 35$kV

- calculate the power at the ends of the resistances of the sections:

(15) $$\underline{S}^{endZ}_{ij(k)} = \underline{S}^{end}_{ij(k)} + \underline{S}^{end}_{Shij(k)}, \quad \forall (i,\ j) \in \bigcup_{i\in L_S} \Gamma_i\ ;$$

- calculate power losses in the resistances of the sections:

(16) $$\Delta \underline{S}_{ij(k)} = \Delta P_{ij(k)} + j\Delta Q_{ij(k)}, \quad \forall (i,\ j) \in \bigcup_{i\in L_S} \Gamma_i\ ,$$

where

(17) $$\Delta P_{ij(k)} = \frac{(S^{endZ}_{ij(k)})^2}{U^2_{j(k-1)}} R_{ij};$$

(18) $$\Delta Q_{ij(k)} = \frac{(S^{endZ}_{ij(k)})^2}{U^2_{j(k-1)}} X_{ij}.$$

- calculate the power at the beginning of the resistances of the sections:

(19) $$\underline{S}^{begZ}_{ij(k)} = \underline{S}^{endZ}_{ij(k)} + \Delta \underline{S}_{ij(k)} = P^{begZ}_{ij(k)} + jQ^{begZ}_{ij(k)}, \quad \forall (i,\ j) \in \bigcup_{i\in L_S} \Gamma_i;$$

- calculate the power in shunts at the beginning of the sections:

(20) $$\underline{S}^{beg}_{Shij(k)} = \begin{cases} \Delta P_{xij(k)} + j\Delta Q_{xij(k)}, & for\ j \in L_0, \\ \Delta P^{beg}_{corij(k)} - jQ^{beg}_{cij(k)}, & for\ j \notin L_0, \end{cases} \quad \forall (i,\ j) \in \bigcup_{i\in L_S} \Gamma_i,$$

where

(21) $$\Delta P_{xij(k)} = U^2_{i(k-1)} g^T_{ij};$$

(22) $$\Delta Q_{xij(k)} = U^2_{i(k-1)} b^T_{ij};$$

(23) $$\Delta P^{beg}_{corij(k)} = U^2_{i(k-1)} g^{beg}_{ij};$$

(24) $$Q^{beg}_{cij(k)} = U^2_{i(k-1)} b^{beg}_{ij};$$

- calculate the power at the beginning of the sections:

(25) $$\underline{S}^{beg}_{ij(k)} = \underline{S}^{begZ}_{ij(k)} + \underline{S}^{beg}_{Shij(k)}, \quad \forall (i,\ j) \in \bigcup_{i \in L_S} \Gamma_i;$$

Having power $\underline{S}^{beg}_{ij(k)}, \ \forall (i,\ j) \in \bigcup_{i \in L_S} \Gamma_i$, determined on the basis of calculation formulas (11) - (25), calculate the power flows at the nodes $\underline{S}_{i(k)}, \forall i \in L_S$, corresponding to the information-secured vertices from L_s of the *s*-th hierarchy level:

(26) $$\underline{S}_{i(k)} = \sum_{j \in \Gamma(i)} \underline{S}^{beg}_{ij(k)}, \quad \forall i \in L_S.$$

Step 13. If $s<s_{max}$, then go to steo11, else go to step14.

Second stage. Calculation of network nodes voltages from top to bottom (see Figure 3).

Step 14. Calculate the voltages at the beginning of the sections $\underline{U}_{j(k)}, \forall j \in \bigcup_{i \in L_S} \Gamma(i)$, corresponding to the information-secured vertices from $\bigcup_{i \in L_S} \Gamma(i)$ of the *s*-th hierarchy level:

- calculate the voltage drops in the sections:

(27) $$\Delta \underline{U}^{begZ}_{ij(k)} = \Delta U^{begZ}_{ij(k)} + j\delta U^{begZ}_{ij(k)}, \quad \forall (i,\ j) \in \bigcup_{i \in L_S} \Gamma_i,$$

where

(28) $$\Delta U^{begZ}_{ij(k)} = \frac{P^{begZ}_{ij(k)} R_{ij} + Q^{begZ}_{ij(k)} X_{ij}}{U_{i(k)}},$$

(29) $$\delta U^{begZ}_{ij(k)} = \frac{P^{begZ}_{ij(k)} X_{ij} - Q^{begZ}_{ij(k)} R_{ij}}{U_{i(k)}};$$

- having voltage drops

$$\Delta \underline{U}^{begZ}_{ij(k)}, \quad \forall (i,\ j) \in \bigcup_{i \in L_S} \Gamma_i,$$

determined on the basis of formulas (27)-(29), calculate nodes voltages at the end of sections $\underline{U}_{j(k)}, \forall j \in \bigcup_{i \in L_S} \Gamma(i)$ their magnitude $U_{j(k)}$ and angles (phases) $\delta_{j(k)}$:

(30) $$\underline{U}_{j(k)} = \underline{U}_{i(k)} - \Delta \underline{U}^{begZ}_{ij(k)},$$

(31) $$U_{j(k)} = \sqrt{(U_{i(k)} - \Delta U^{begZ}_{ij(k)})^2 + (\delta U^{begZ}_{ij(k)})^2},$$

(32) $$\delta_{j(k)} = arctg \frac{\delta U^{begZ}_{ij(k)}}{U_{i(k)} - \Delta U^{begZ}_{ij(k)}}.$$

Step 15. Calculate the next hierarchy level number: *s=s-1*.

Step 16. If *s>0*, then go to step 14, else go to step 17.

Step 17. If $|U_{j(k+1)} - U_{j(k)}| > \varepsilon, \ \forall j \in L_0$, then go to step 10, else go to step 18.

Step 18. Calculate the active power total losses ΔP_C and electrical energy losses ΔW_C:

(33) $$\Delta P_C = \sum_{(i,j) \in \Gamma} \Delta P_{ij};$$

(34) $$\Delta W_C = \Delta t \cdot \Delta P_C,$$

where *Δt* is the time interval during which the source voltage level and the load power value are constant, i.e.

(35) $$\underline{U}_0 = const, \quad \underline{S}_j = const, \quad \forall j \in L_0.$$

Conclusion

In this work, a structured hierarchical-multilevel approach for regimes and power losses calculation in radial power networks of 35 kV and above at given loads and power source voltage level has been developed. It is based on the representation of the initial radial network graph in the form of hierarchical-multilevel structure and on the usage of conventional (manual) engineering two-stage method, where the calculation is performed in a certain sequence moving through the network structure from bottom to top (stage 1) and top to bottom (stage 2).

This approach application has made it possible to obtain a universal (for an arbitrary configuration and network complexity) and efficient (in terms of the computational operations number and computer memory consumption) algorithm.

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***Authors**: PhD Salima Muratovna Asanova, Department of The Theoretical Foundations of Electrical Engineering, Kyrgyz State Technical University, Bishkek, 720044, Kyrgyzstan, e-mail: a_sm07@mail.ru; post–graduate student Murodbek Kholnazarovich Safaraliev , Department of Automated Electrical Systems, Ural Federal University, 19, Mira Street, Ekaterinburg, 620002, Russian Federation, e-mail: murodbek_03@mail.ru; post–graduate student Nurlan uulu Askarbek, Department of The Theoretical Foundations of Electrical Engineering, Kyrgyz State Technical University, Bishkek, 720044, Kyrgyzstan, e-mail: ibraev9191@mail.ru; PhD Sergey Igorevich Semenenko, Department of Automated Electrical Systems, Ural Federal University, 19, Mira Street, Ekaterinburg, 620002, Russian Federation, e-mail: sinissem@gmail.com; Erkin Tulkunovich Aktaev, Department of The Theoretical Foundations of Electrical Engineering, Kyrgyz State Technical University, Bishkek, 720044, Kyrgyzstan, e-mail: aefaiz@yandex.kz; post–graduate student Anastasia Andreevna Kovaleva, Department of Automated Electrical Systems, Ural Federal University, 19, Mira Street, Ekaterinburg, 620002, Russian Federation, e-mail: a.kovalenik@yandex.ru; post–graduate student Egor Anatolevich Lyukhanov, Department of Automated Electrical Systems, Ural Federal University, 19, Mira Street, Ekaterinburg, 620002, Russian Federation, e-mail: ealuhanov@yandex.ru; senior lecturer Elena Dmitrevna Staymova, Department of Automated Electrical Systems, Ural Federal University, 19, Mira Street, Ekaterinburg, 620002, Russian Federation, e-mail: e.d.staymova@urfu.ru;*

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